Information Worlds: Interactive Visualizations and Storytelling using Augmented, Virtual and Mixed Reality

by

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PhD Dissertation

Presented in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Dedicated to the love of my life,

Chryssa

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Abstract

The research work presented in this thesis aims to contribute a generic and holistic approach for generating applications substituting (Virtual Reality), enhancing (Augmented Reality) or interweaving physical and virtual worlds (Mixed Reality) in an effort to visualize large data volumes that belong to demanding domains such as Big Data or Cultural Heritage.

Towards this end, a framework is proposed, based on the concepts of Information Worlds and Information Things, to depict the physical or imaginative environments that encapsulate information through distinct elements in a scalable and easily perceivable data model. The framework provides more than 15 ready-to-use components which can be directly integrated in applications and an extensive architecture which allows future additions. Moreover, the framework supports the definition and visualization of personalized stories (either generated by professionals or by end users). In terms of interaction, this thesis proposes the usage of multimodal, natural means of interaction, seamlessly integrating Augmented, Virtual and Mixed Reality applications in Ambient Intelligence environments.

The Information Worlds framework can constitute a valuable asset for the creation of dynamic visualizations using X Reality, providing interoperability with various data sources, ready to use tools to visualize information, extensibility for additional components and a scalable conceptual model which suits diverse needs.

The use case of a smart museum is presented, depicting highly interconnected and sparsely located information in the demanding context of Cultural Heritage using augmented and virtual reality. Moreover, the use case of a real time data center infrastructure management application showcases the framework's ability to cope with high velocity, large data volumes which are congested. Results of this work have been deployed in public space installations, temporary exhibitions and international conferences. Each use case has been evaluated by more than 20 users in order to assess the final results produced by the Information Worlds framework in terms of usability and user experience. The excellent results reported in the evaluation illustrate the potential of AR, VR and MR in terms of efficiency and technology adoption by end users, but also constitute a motivation for further improving and extending the presented framework.

Περίληψη (Abstract in Greek)

Η παρούσα διατριβή στοχεύει να συνεισφέρει μια γενική και ολιστική προσέγγιση για τη δημιουργία εφαρμογών που αντικαθιστούν (Εικονική Πραγματικότητα), επαυξάνουν (Επαυξημένη Πραγματικότητα) ή συνυφαίνουν πραγματικούς και εικονικούς κόσμους (Μεικτή Πραγματικότητα) σε μια προσπάθεια να απεικονίσει μεγάλους όγκους δεδομένων που ανήκουν στους απαιτητικούς τομείς των Μεγάλων Δεδομένων και της Πολιτιστικής Κληρονομιάς.

Με αυτό το σκοπό παρουσιάζεται ένα πλαίσιο χρήσης (framework) βασισμένο στις έννοιες των Κόσμων Πληροφορίας και των Αντικειμένων Πληροφορίας για να αναπαραστήσει υπαρκτά ή εικονικά περιβάλλοντα που περιλαμβάνουν αντίστοιχα πληροφορία που ανήκει σε διακριτές οντότητες, ενώ ωστόσο είναι ευέλικτο και διαλειτουργικό με ποικίλες πηγές δεδομένων. Το πλαίσιο παρέχει περισσότερα από 15 δομικά στοιχεία (components) τα οποία μπορούν να ενσωματωθούν απευθείας σε εφαρμογές και μια επεκτάσιμη αρχιτεκτονική που επιτρέπει μελλοντικές προσθήκες. Επιπλέον, το framework υποστηρίζει τον ορισμό και την οπτικοποίηση προσωποποιημένων ιστοριών (οι οποίες έχουν δημιουργηθεί από επαγγελματίες του τομέα ή από τελικούς χρήστες). Αναφορικά με την αλληλεπίδραση, η διατριβή αυτή προτείνει τη χρήση πολυτροπικών, φυσικών μεθόδων αλληλεπίδρασης και ενσωματώνει απρόσκοπτα εφαρμογές Επαυξημένης, Εικονικής και Μικτής Πραγματικότητας σε περιβάλλοντα Διάχυτης Νοημοσύνης.

Το πλαίσιο χρήσης Κόσμοι Πληροφορίας μπορεί να αποτελέσει ένα πολύτιμο δομικό στοιχείο για τη δημιουργία δυναμικών οπτικοποιήσεων μέσω της Χ Πραγματικότητας (X Reality), παρέχοντας διαλειτουργικότητα με διάφορες πηγές δεδομένων, έτοιμα προς χρήση εργαλεία απεικόνισης πληροφορίας, επεκτασιμότητα για την προσθήκη επιπλέον στοιχείων και ένα νοητικό μοντέλο που καλύπτει μια πληθώρα αναγκών και μπορεί να επεκταθεί.

Παρουσιάζεται η υπόθεση χρήσης ενός έξυπνου μουσείου το οποίο απεικονίζει πυκνά διασυνδεδεμένη και αραιά τοποθετημένη στατική πληροφορία στο απαιτητικό πλαίσιο της Πολιτιστικής Κληρονομιάς χρησιμοποιώντας επαυξημένη και εικονική πραγματικότητα. Επιπλέον παρουσιάζεται η υπόθεση χρήσης μιας εφαρμογής διαχείρισης υποδομών ενός κέντρου δεδομένων (data center), αναδεικνύοντας τη δυνατότητα των Κόσμων Πληροφορίας να ανταπεξέλθουν σε μεγάλους όγκους δεδομένων που αλλάζουν με μεγάλη ταχύτητα και είναι περιορισμένα χωρικά. Τα αποτελέσματα αυτής της διατριβής έχουν εγκατασταθεί σε δημόσιους χώρους, σε εκθέσεις και διεθνή συνέδρια. Η κάθε υπόθεση χρήσης έχει αξιολογηθεί από περισσότερους από 20 χρήστες ούτως ώστε να αξιολογηθεί το τελικό αποτέλεσμα που παράγεται από τους Κόσμους Πληροφορίας ως προς την ευχρηστία και την εμπειρία χρήσης. Τα εξαιρετικά αποτελέσματα που εξήχθησαν από την αξιολόγηση αναδεικνύουν τις δυνατότητες που έχουν η Επαυξημένη, η Εικονική και η Μεικτή Πραγματικότητα αναφορικά με την αποδοτικότητα και την υιοθέτηση της τεχνολογίας από τους τελικούς χρήστες, ενώ παράλληλα αποτελούν ένα κίνητρο για την περαιτέρω βελτίωση και επέκταση του παρουσιαζόμενου πλαισίου χρήσης.

Abbreviations and Acronyms

- AmI: Ambient Intelligence
- AR: Augmented Reality
- CIDOC CRM: CIDOC Conceptual Reference Model
- CRS: Coordinate Reference System
- GIS: Geographical Information Systems
- HMD: Head Mounted Display
- IDE: Integrated Development Environment
- IOT: Internet of Things
- JSON: JavaScript Object Notation
- MMOG: Massive Multiplayer Online Game
- OLAP: Online Analytical Processing
- OWL: Ontology Web Language
- RDF: Resource Description Framework
- VR: Virtual Reality
- XML: eXtensible Markup Language
- XR: X Reality

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1. Introduction

1.1. Information Visualization

Images have been an effective way to communicate both abstract and concrete content since the prehistoric era, where cave paintings were used to illustrate human lives. Other forms of visualizations throughout history include written languages (such as the Egyptian hieroglyphs), geometry and paintings, such as Leonardo da Vinci's revolutionary methods of technical drawing for engineering and scientific purposes, and statistical graphics which were only utilized after the 18th century.

Visualization is any technique for picturing or shaping visual elements to communicate a message. According to the Merriam Webster Dictionary definition[1], visualization can be defined as the formation of mental visual images or the act or process of interpreting in visual terms[1]. Images, diagrams and animations are widespread forms of visualization which aid in the perception of complex information.

Visualization has been an ever-expanding application, since it is applied in a variety of domains such as education, engineering and science. Visualizations are around us and help us navigate (e.g. maps and floorplans), educate ourselves (e.g. graphs in school books), perceive changes over time (e.g. charts) or even for entertainment (e.g. comics and films); they have evolved from static pictures to dynamic animations that are able to enrich existing content and communicate more complex data.

1.2. Technology and Information Visualization

Technology has opened a world of opportunities for the visualization of information that would be otherwise underutilized and hard to comprehend using traditional means. Moore's law [366] back in the 1960s, which depicted the exponential growth of the transistors in integrated circuits, proved accurate for several decades and will continue to apply for the years to come, even if the growth speed presents minor variations. The exploitation of modern technology advancements, such as high resolution displays but also augmented and virtual reality devices, fosters interactivity and rich content visualizations in a personalized and enjoyable way. In parallel, the storage space and the processing power increase, thus allowing to model ever-larger available bulks of information.

Technology has the potential to breathe new life into the visualization domain by providing interactive experiences instead of extensive textual descriptions, static prints or audio guides. Novel interaction devices have been developed and are generally accessible to end users at reasonable costs, thus allowing the provision of rich human-computer interaction to everyone. These devices include RGB and depth cameras, smartphones, smart watches and microscopic sensors which can be wearable or embedded in our surroundings. Besides each offering different interaction means, they can all be used in combination to facilitate natural and multimodal interaction.

Despite being a field of extensive research, information visualization still faces several challenges in terms of tailoring the implemented systems to fit a wide variety of presentations and presenting information such as streaming data, multimedia and storytelling [470]. Additionally, many requirements are difficult

[1] https://www.merriam-webster.com/dictionary/visualization

to be addressed using a single generic approach that fits everything. As analyzed by Liu et. al. [267], information visualization approaches face major technical challenges, which can be summarized as follows:

- **Visual Scalability:** The challenge of visual scalability refers to the ability of the visualization tools to present large datasets in terms of element count and element data volume, ranging from a handful of items to huge collections of data entries.
- **Integrated analysis of heterogeneous data:** Input data for visualization stems from a variety of data sources in different formats, each focusing on different information aspects and characteristics, making interoperability difficult to achieve. For instance, semantic information is completely different from statistics, as semantic models focus on expressing various attributes and characteristics, whereas statistics mainly illustrate variable values.
- **In-situ visualizations:** In-situ visualization implies the dynamic arrival of new data and the real-time automatic update of the generated visualizations. An indicative example may involve the update of visualizations from a sensory infrastructure with incoming new data.
- **Errors and uncertainty:** Information provided often contains errors or inaccurate values, especially in the context of big data retrieval. For instance, sentiment analysis in social network posts frequently fails to comprehend users' posts, as sentences may be ambiguous or sarcastic.

1.3. About this research work

This dissertation proposes the concept of merging real and virtual worlds to facilitate immersive information visualization in an effort to drive the evolution of visualizations using new technologies, such as X-Reality. Although this concept is not recent, this work aims to create a holistic approach via a framework which matches the visualization requirements across diverse areas of information visualization, such as Big Data and Cultural Heritage.

To this end, this dissertation presents a conceptual model reports on the design of a framework for generating applications able to substitute, enhance and interweave physical and virtual worlds via Virtual, Augmented and Mixed Reality respectively. In terms of data provision, the framework is created to be flexible enough to model and support the use of diverse data types, thus facilitating its integration with various data sources. This framework, named Information Worlds, provides several ready to use visualization components which can be reused among different display modalities, while also allowing the straightforward addition of new ones. Furthermore, the framework allows the integration of entire applications with minimal effort. Moreover, the presented framework facilitates the narration of stories as an interactive tool to transfer messages and illustrate information relationships beyond simple event sequences (e.g. cause-effect). In order to showcase the framework's capabilities, this dissertation reports on two use cases, in the contexts of Cultural Heritage and Big Data, and their evaluations correspondingly. The envisioned scenarios are explained and the final evaluation results are presented and thoroughly analyzed. Finally, this dissertation aims to elaborate the findings stemming from this work and contribute towards the areas of Cultural Heritage, education, infotainment and Big Data.

Chapter 2 discusses research work related with this thesis in an effort to present state of the art literature but also to highlight areas of potential contribution. In order to achieve this, data types, data models and visualizations are presented as the basis on which Ambient Intelligence, Virtual Reality and Augmented

Reality can build upon. Finally, efforts which are related to the content of this work are presented, elaborating on their findings and challenges.

Chapter 3 reports on the aims of this thesis, highlighting potential areas of contribution. This chapter refines the challenges and defines the impact that the framework is expected to have.

Chapter 4 presents the conceptual model that is proposed in order to support information organization and modelling. It proposes a scalable way to classify information into different components and ultimately support storytelling and narratives.

Chapter 5 discusses the identified user groups involved with the framework, presenting their goals and requirements.

Chapter 6 reports on the framework's structure and the final components provided. It discusses the connection capabilities in terms of data provision, design decisions taken and showcases the final results that can be shown to the end users along with the interaction techniques provided.

Chapter 7 presents the capabilities of this work with regard to storytelling, elaborating on the way that narration is supported and can be created by the stakeholders involved.

Chapter 8 discusses the actual implementation of the framework and how the previously explained features were created, starting from the entire architecture and presenting all the software components ranging from the core engine and assistive libraries implementation to the assembly of entire Information Worlds.

Chapter 9 reports on the use cases that were created so as to illustrate the capabilities of the proposed framework and correlates what end users experience to what internally happens in the framework.

Chapter 10 presents the results of the conducted evaluation sessions and elaborates on the findings in terms of usability and user experience assessment.

Chapter 11 discusses the potential impact of the presented work on different areas, showcasing how this framework can contribute in different domains and presenting the related publications.

Chapter 12 summarizes the findings of this work and presents future directions.

Finally, Chapters 13 and 14 contain the related bibliography and resources related to the evaluation process respectively.

2. Background and Related Work

This chapter aims at establishing the foundations for creating a generic framework which can visualize diverse data, create story narratives and facilitate natural user interaction in the context of Ambient Intelligence environments. In order to achieve this, this chapter elaborates on state-of-the-art research that was conducted across various domains that are related to information visualization on X-Reality environments.

Data visualizations primarily rely on what is being visualized (content) and how this can be accomplished, (the means). The analysis of challenges raised by the diversity of the various data types is presented as a solid ground upon which visualization approaches can flourish, ranging from fundamental components to present information with specific characteristics to creating entire ecosystes that encapsulate a multitude of such components. Such ecosystems are created to meet the requirements of contexts such as Cultural Heritage, Big Data and narratives. The breakdown and classification of structural components can act as an indicator in terms of future research directions so as to combine and extend existing solutions, but also give prominence to the areas which can be improved.

In addition to analyzing previous approaches on designing data visualization ecosystems, this chapter also illustrates how these ecosystems can be integrated and presented in virtual and mixed reality environments; moreover, these approaches are analyzed in terms of the capability to be combined with Ambient Intelligence environments. This is done with regard to providing the context in which structural elements will be utterly shown to end users.

Finally, an analysis of X-Reality frameworks is essential for defining the gaps and designate areas of improvement this work should focus on. This section acts as the capstone of defining the goals and motivation of this work, pointing out research directions which are not covered by previous approaches.

Figure 1 presents an overview of this chapter’s structure, visualizing the path from analyzing the various data types, presenting visualization approaches in applications, interaction methods and Ambient Intelligence and finally X-Reality components and relative frameworks.

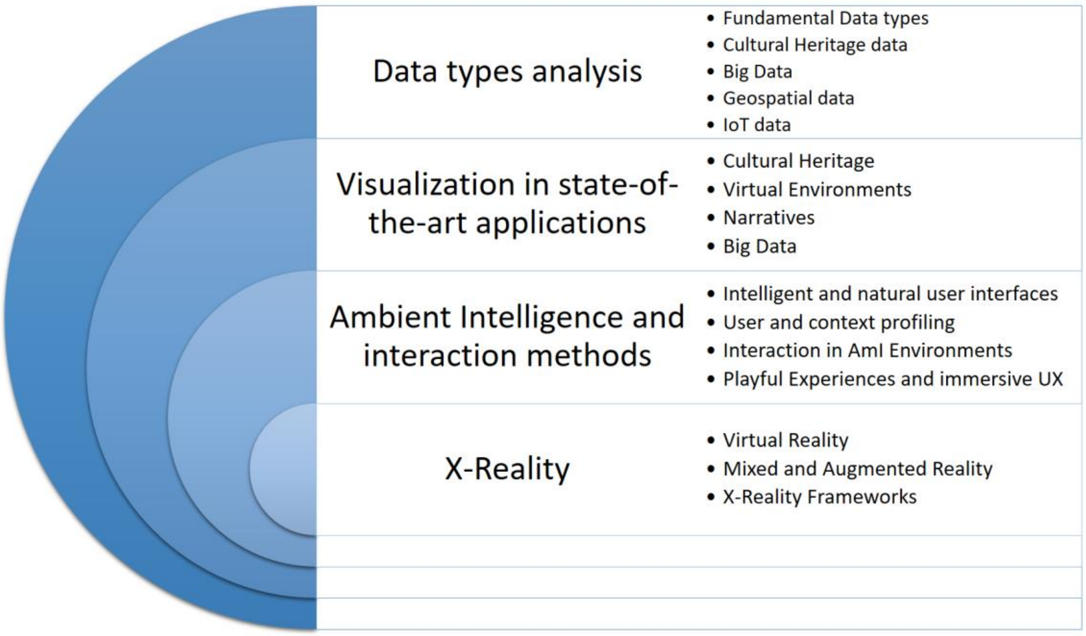


Figure 1: Related work overview and structure

The subsequent sections are structured as follows: Section 2.1 introduces the various data types and their characteristics. Section 2.2 presents the data types, related to this work, that are employed in state-of-the-art research domains, including Data Modelling and the application of ontologies to represent knowledge. Section 2.3 analyzes existing approaches for data visualizations. Section 2.4 presents the vision of Ambient Intelligence and its relation to information visualization. Sections 2.5 and 2.6 present state-of-the-art reviews of virtual reality and mixed and augmented reality respectively, while Section 2.7 analyzes frameworks found in literature which are tightly related to the work presented in this dissertation. Finally, Section 2.8 discusses the conclusions of the literature review presented in all the previous sections.

2.1. Data Types

Data is a set of values that represent qualitative or qualitative variables. According to Oxford Dictionaries[2], it is defined as Facts and statistics collected together for reference or analysis. The following sections classify data types in accordance with their nature based on the taxonomy presented by Schneiderman [379]. This taxonomy is presented so as to provide a solid ground upon which discussion regarding complex information types and state-of-the-art visualizations can take place in the following sections.

2.1.1. Spatial Data (1D, 2D and 3D)

One dimensional data can be thought as a piece of information that identifies an object's characteristic along one set. A typical one-dimensional example is time, an object's length or weight and in general anything that can be measured within one dimension.

[2] https://en.oxforddictionaries.com/definition/data

Two dimensional data involve information that extends along two axes, such as a person's weight over time, a floorplan or a place's location on earth. A typical example in research and commercial domains is Geographic Information Systems which provide data with respect to their location in space.

Three dimensional data describe information such as volume or anything that can be described in the world around us. Such examples include 3D computer models and surface renderings.

2.1.2. Temporal Data

Temporal information appears in numerous forms and fields. Usually, temporal data consist of several values of one or more variables that change over time. The analysis of the data distribution over time is a common operation performed on temporal data.

In addition, the time dimension provides the context for any type of information, such as spatial or relational, and constitutes a perspective that can be added to almost any type of information. Timelines are employed for visualizing temporal data in the context of pattern recognition multimedia presentation [115], history representation [187], and faceted navigation [483].Timelines are useful for focusing on the temporal aspect of information and illustrating temporal distribution, dispersion and distance of events. Another version of timelines employs a spiral representation for presenting temporal information [6].

Chart visualization tools such as time series [184 and 444] and scatter plots [46] are an alternative for displaying temporal information, mainly focusing on the statistical aspects of the data. This approach is more suitable for getting an overview of the information rather than the details.

Finally, an alternative for visualizing time-oriented data involves Parallel Coordinates [199], an approach which is widely adopted in the context of big data visualizations (see section 2.3.8). This approach can produce various insights that would be otherwise difficult to gain, however, it requires extensive usage for one to become familiar with it.

An interesting aspect of temporal information visualization involves the combination of timelines with a geospatial display, as presented by [275], displaying the locations of twits on a world map that offers the ability to associate temporal information to places that are related.

2.1.3. Multi-dimensional Data

Multidimensional data are data belonging to many dimensions, numbering from a minimum of six to millions [445]. In a manner similar to knowledge, multidimensional data belong to a range of different classifications, thus providing information from different perspectives and creating the picture of the item as a whole.

Relational databases constitute an indicative example of multidimensional information. For example, a relational database storing information about a car includes data about its production location and time, brand, price, available colors and the model, creating an n-dimensional data cube [409]. In the aforementioned example, the production location contains geospatial data, the production date, temporal information, the brand and model descriptive characteristics, etc.

As mentioned in [393], the nature of large multidimensional databases requires their visualization to be data-dense in order to display many dimensions of large subsets of data, to provide multiple display types, so as to cover a wide range of different tasks, and to allow exploration for supporting analysis through data inspection. The authors propose the employment of tables to select and view database data, in conjunction with supplementary displays that illustrate the selected data's additional dimensions.

2.1.4. Network and hierarchical Data

Network data contain information that links different items in a specific manner, describing the relationship type between individual elements. Several types of links can be considered when taking into account the characteristics of the network, such as whether it:

- Has a root element (e.g. information propagation from one source)
- Is directed or not (e.g. streets are directed whereas computer networks are not)
- Contains cycles (e.g. alternate routes between cities)
- Is hierarchical (e.g. organization structure of a company).

In general, network data can be pictured as the content of a graph illustrating the connections between distinct elements, which can be further explored through the traversal of the nodes it consists of. Additionally, the link can include the direction of the relationship if the relationship is not bidirectional, as in the case of somebody who owns a car.

The World Wide Web constitutes an indicative example of linked data, as web pages are interconnected, creating a global information space that relates different documents in an abstract way, as it does not define the relationship type but only links to other documents.

2.1.5. Combination of Data Types

The presented classification of data types does not organize them into distinct categories independent of each other; on the contrary, these categories aim to distinguish information in accordance with its characteristics and provide insights into how it can be optimally manipulated and presented to end users so that it is perceived and explored optimally. Data are usually related to other data or stored within multidimensional data entries which contain different data types.

Any data type should be correlated to its context, as it can have a completely different meaning when examined from a different perspective. For instance, as mentioned by Aigner et.al. [7], space and time are the two fundamental dimensions that represent the way the world around us is at a certain time. In conjunction, they provide context for information that would otherwise be unclear: for instance, owning a car in Europe during the first half of the 20th century would have completely different implications in comparison to the 21st century. Similarly, a 50% decrease in car speeds on a highway at a certain time of a day might indicate a flow issue that could be possibly related to an accident, but if that moment belongs to rush hours or the day is at the end of holidays, it is expected.

Information nowadays is not limited to strictly cut off data, but is enhanced with additional information often referred to as metadata. Metadata can be defined as “data about the meaning, content, organization or purpose of data” [381] and describe an item’s content comprising supplementary information; for instance, a book’s metadata may include its publication date, its author, its page count, its publisher etc. Therefore, events happening over time are extended to entities holding further details as well as relationships with other entities. Their relationships may have different form and meaning, dependent upon their definition of the used semantic data models.

Finally, another domain of data types combination is semantic information. Semantic information describes relations between data, which can be of any type. An indicative example for semantic relations in combination with geospatial data are examined by [257]. CIDOC-CRM [104] is an ontological approach to model information about elements and also describes relations between them.

2.2. Data types employed in state-of-the-art applications

One of the main aims of the research work presented in this thesis includes the ability to model large amounts of information. This involves information storage in a format that the presented framework will be able to process, thus allowing to make it available for a variety of applications. Such an example of application is the context of Ambient Intelligence environments, where applications are integrated and networked in the user’s environment and have the ability to share resources such as content data.

A data model can be described as an abstract model which defines the organization, storage and retrieval of real information [382]. Additionally, a data model standardizes how elements relate to one another, as well as to properties of the real world entities. A semantic data model, which is also referred to as conceptual data model, is a technique to define data within the context of its interrelationships with other data. The use of a semantic data model is essential in order to allow information to include the kind of relations between data elements.

The following sections present an overview of data types and their representation in accordance to their context of use; each context define data structures to hold certain characteristics so as to achieve corresponding goals.

2.2.1. Information representation related to Cultural Heritage

Cultural Heritage constitutes an information-rich domain with diverse data types, constituting a demanding area of research. Various visualization approaches and strategies have been developed in an effort to showcase tangible and intangible heritage [135, 447 and 466]. Despite the efforts such as [128] [285] towards digitizing information and creating data models with semantic information regarding Cultural Heritage, yet the majority of information remains unstructured. Large amounts of data include unstructured information in the form of multimedia such as images, videos, textual descriptions and analyses, and audio content.

One of the directions of the research work presented in this report includes the systematic modelling of a large amount of information. This involves the ability to store information in a format that is openly accessible and easy to be queried, thus allowing to process it and facilitate the creation of a variety of CH visualization applications.

The main approaches in terms of information modelling and storage can be differentiated in two main domains which are presented in the following sections. The first approach is ontologies-based and focuses on the ability to semantically annotate information and performing complex queries, whereas the other group of approaches aims at creating efficient data sources serving in real time data which is easily scalable.

2.2.1.1. Ontologies

A potential approach for data modelling is the use of ontologies. Ontologies can be defined as "an explicit specification of a conceptualization" [169], defining the relationships and concepts to describe and represent an area of knowledge. Ontologies define and classify concepts and entities and the relationships between them. According to [286], ontologies are used for the characterization of possible relationships and for the definitions of possible constraints on these relationships. Ontologies can act as the medium for information systems to support collection management, conservation, research and presentation [105] [105].

2.2.1.1.1. Triples

Triples constitute a way to describe a single fact, namely subject, predicate and object. The subject and the object define the resources that are referenced, while the predicate defines their relationship. For instance, when describing the relationship between a parent A and a child B, the corresponding triple would either be that A (subject) is a child of (predicate) B (object) or that B (subject) is a parent of (predicate) A (object).

2.2.1.1.2. RDF Schema

The Resource Description Framework (RDF) [345] is a general-purpose language for presenting information, mainly in the Web. RDF is composed of three basic parts: resources (the elements described), properties (relationship between elements) and classes (way of grouping elements).RDF extends triples by defining the type of the predicate as well as the object and the subject. For instance, it allows the classification of an "is-a" relationship using a subClassOf property or a type for the classification of an element in a certain class. Its specification designates the usage of RDF for the description RDF vocabularies. The major advantage of RDF is the provision of a flexible and efficient way to manage information, as data relationships can be explored from different perspectives and large scale data can be read in a relatively fast.

2.2.1.1.3. OWL

The Web Ontology Language (OWL) [458] is a family of knowledge representation languages that can be used by applications that need to process information content, rather than simply presenting information to humans. An OWL Ontology is able to describe a domain in terms of classes, properties, individuals, characteristics and properties of web resources [26]. In contrast to RDF which defines **how** to write information, OWL defines **what** to write. OWL is represented through RDF triples (and typically expressed using RDF/XML syntax) and is a way of enriching RDF with semantic information, offering automated reasoning and inferencing. For instance, OWL allows the description of equality (e.g. sameAs), relationships between classes (e.g. disjointWith) or even class property restrictions (e.g. allValuesFrom).

2.2.1.1.4. Ontologies for Cultural Heritage - CIDOC-CRM

CIDOC-CRM provides an extensible ontology for concept and information in cultural heritage and museum documentation [104 and 108]. Since 2006, it is the international standard (ISO 21127:2006) for the representation and the controlled exchange of cultural heritage information.

CIDOC-Conceptual Reference Model (CRM) provides a common and extensible semantic framework that is able to map any cultural heritage information. Its purpose is to allow domain experts and implementers to conceptually model data and act as a mediator between different sources of cultural heritage information. Several compatible models and collaborations exist that use and extend the CIDOC CRM, such as CRMgeo [107] for refining spatial and temporal classes and properties, CRMinfo [91] for describing human activity, things and events happening in space-time and CRMdig [90] for item provenance and physical measurement process. Doulaverakis et al. [111] adopt CIDOC and use ontologies as a tool for information retrieval and online search inside multimedia heritage collections. Another approach using CIDOC CRM is the automatic reasoning in semantic repositories based on property propagation [418].

2.2.1.1.5. Ontologies Digital annotations

An annotation can be defined as a note added by way of comment or explanation[3]. Digital annotations can be applied for improving the user's comprehension [210]. As described by [5], digital annotations can also be an effective means of interaction between users and knowledge stored in digital form. The annotations can express personal opinions, enrich an information resource or act as a mediator for sharing an opinion.

According to the lexical and syntactic constructs used to express annotations can be categorised as follows [85]:

- By medium: lexical (text or hyperlink), visual (icon or high-lighting), or acoustic (audio signal).
- By locality of reference: Annotations may refer to entire texts, parts of texts or both
- By process: textual, link and semantic. Textual annotation involves adding some form of free text commentary to a document, link annotation provides information in the form of the contents of a link destination, and semantic annotation, finally, assigns markup elements according to a specified model, which take values from controlled vocabularies, and it aims at both human readers and software agents.

Finally, [124] employ 3D annotations as a way to meaningfully associate the spatial representation of a 3D shape with other related information. In this way, collections can be semantically enriched providing a natural layer for presenting and interacting with additional information related to the objects in the

[3] https://www.merriam-webster.com/dictionary/annotation

collection. Thus, once a 3D collection is built, 3D annotations can support further applications, such as incorporating historical material; or information on the condition of the artefacts, in order to support their monitoring and preservation over time.

2.2.1.1.6. Ontologies for Navigation

Location services have been researched and used for a long time in mobile networks. A fundamental requirement for ubiquitous environments is the ability to sense users' actions and therefore, track and follow them in both outdoor and indoor spaces. Apart from the technical implementation of user tracking, a key factor in building upon user localization is the provision of semantic information about user actions in order to support the creation of Ambient Intelligence.

Indoor spaces mainly cover the interiors of buildings where human activities take place, while outdoor spaces describe both built and natural environments excluding constructed interior areas. Outdoor spaces are traditionally examined by geospatial science and GIS systems, while there is currently a gap on indoor spaces research. According to [228], an average percentage of time spent indoors reaches 87% and therefore the modelling of human activities in indoor spaces is imperative.

OntoNav [415] constitutes a user-centric integrated navigation system for indoor environments that allows both geometric and semantic modeling of environments, supporting the navigation and the description of paths. [372] focuses further on the representation and route finding of indoor production environments.

Based on OntoNav, [224] presents an ontology-based user modelling for outdoor spaces in the context of pedestrian navigation and wayfinding. Another approach is ONALIN [121] focuses on route description which is not necessarily optimal, either in space (shortest distance) or time (fastest travel time).

Other studies focus on creating a navigation ontology that supports both indoor and outdoor spaces. [478] present ongoing work towards an ontology that supports the construction of a collection of micro-worlds that are semantically modeled and can be applied in either indoor or outdoor spaces. The proposed ontology can be used to describe models at a higher semantic level, including concepts as connectors, obstacles and nodes. Another example of a pedestrian navigation system that is employed in both indoor and outdoor environments is presented by [145] in the context of NAVIO project [346] that provides a navigation service in the area of a Vienna Technical University.

2.2.1.1.7. Ontologies for Storytelling

Stories and narratives can be described, in a broad sense, as "unique sequences of events, mental states, or happenings involving human beings as characters or actors" [56]. Stories include all the descriptive events and entities that constitute the plot of a narration. They include ideas and bindings between the existing entities which are presented either implicitly or explicitly during a plot presentation. These concepts are perceived by the individuals watching the flow of a story and shape the knowledge patterns which are stored in the human memory, thus communicating messages between the story creators and the viewers. Furthermore, this process adds up value to story presentation and differentiates simple event sequences from stories, as stories include the implicit and explicit bindings between the individual events, especially when the story is presented in an interactive manner [89].

Ontologies are a common technique employed in research about the modelling and the storage of narratives. Ontologies are able to depict entities, along with their attributes, and describe their relationships. In this direction, [298] present research work towards ontology-based text modelling using the Rhetorical Structure Theory [274] by formulating text relations.

In the domain of cultural heritage, Curate Ontology [294] is an approach based on CIDOC CRM, representing narratives in the forms of stories and plots. According to the authors, the stories are event sequences which can be either presented straightforwardly or be interpreted by different plots, allowing a story to have many different plots. Furthermore, the authors decompose a story in events (incidents), facets (dimensions over which an event can be described) and event descriptions (expressive attributes and variables). Another approach is presented by Ribaud [347], in which CIDOC CRM is used to create stories in the context of a web-based wiki.

2.2.1.2. Alternate data representations

Another interesting approach in state-of-the-art literature is the integration of Cultural Heritage data within Big Data key-value structures. This sector does not focus on being able to represent complex relationships between the stored data, but on the storage and mainly on the retrieval of data. Therefore, the presented components are meant to be performant and scalable, making them suitable for huge data volumes.

Such an example is SCRABS [8], where the authors present their work that includes distributed data models such as MongoDB and HDFS and showcase their work through a scalable prototype for the management and context-driven browsing of cultural environments. Moreover, [236] propose SuperSQL, a database storage and querying technique for retrieving Cultural Heritage content in the context of a virtual museum.

Several efforts have taken place to organize and structure this information: New York's Metropolitan Museum of Art [406] has created a large dataset with information on more than 420.000 artworks in its collection for unrestricted commercial and non-commercial use. Europeana [128] is an established digital platform for CH, providing access to digitised works and semantic information related to CH in European Union. Information is structured using the Europeana data model (EDM) [106], thus allowing finer granularity and richer metadata. Additionally, Open Heritage, Google's cooperation with CyArk [95 and 152], aims to allow users to remotely explore iconic locations in 3D by providing access to 3D Cultural Heritage monuments.

2.2.2. Geospatial Data

Geographical information is different from other information in that the data, as a special characteristic, refer to either objects or phenomena with a specific location in space and therefore have a spatial address [237]. The visualization of the location of the objects or phenomena is called a map, which shows how objects can be located in a system of reference.

Geographical Information Systems (GIS) traditionally perform storage and analysis of spatial data by performing operations on data which are spatially referenced to the earth. According to Burrough and McDonnell [61], a GIS is "...a powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes". One of the first attempts to thoroughly describe GIS is presented by [273], presenting an extensive literature review of GIS definitions and applications.

In order to define and correlate spatial data, the existence of a Coordinate Reference System (CRS) is essential. The CRS may involve global, large-scale spatial data for cases such as input from Global Positioning System (GPS) devices, or a point of reference in the case of data represented in a small-scale environment like a room. [12] Presented a software program named GeoDa, a tool for non-GIS specialists aiming at analyzing information by presenting a map view along with statistical graphics views. Geospatial data are used in a variety of cutting-edge technologies and systems [40]. Their applications include environmental observations [471], urban planning [371] and agriculture [74].

2.2.3. Big Data

The term “Big Data” emerged as a scientific domain during the 1990s and gradually became a field of major academic interest during the 2000s. Since 2010, Big Data became a focus of attention across various sectors, including trade, business intelligence, large-scale organizations and start-up companies.

A widely accepted definition of Big Data is still under discussion and there is little progress regarding a commonly acceptable answer to the fundamental question of how big the data has to be to qualify as ‘big data’. De Mauro et al. [101] combine several definitions for Big Data as “representing the Information assets characterized by such a High Volume, Velocity and Variety to require specific Technology and Analytical Methods for its transformation into Value”. Big data has the potential to capitalize on the insights generated from data retrieval in several domains [77] such as scientific research, personalized recommendations, e-government, administration and security.

Laney [245] introduced one of the first and most widely embraced attempts to define Big Data. The author suggested that Volume, Variety, and Velocity (or else the three Vs) are the three dimensions of challenges in data management. Volume refers to the magnitude of data. The thresholds that discriminate data from big data, however, are vague, as they keep increasing due to the soaring of sensors supplying data. Variety refers to the heterogeneity of the data, while velocity refers to the rate at which data is generated, retrieved and processed. Data creation rate is currently increasing rapidly with smartphones and sensors, and is expected to multiply in the era of the Internet of Things. Data intensiveness is highlighted on the survey presented by Chen and Zhang [76], also presenting the characteristics that define the challenges and approaches that shape the research aims currently explored.

In addition to the three Vs, other dimensions that characterize other aspects of Big Data are described in literature. The factor of veracity [110], which describes the quality of the data, is an additional important characteristic that provides assessment of the data. Finally, another term is value [186], which describes the dimension of the data values in the context of Big Data integration.

Due to the vague nature of Big Data, several research fields are involved in the process of its management and manipulation. Such fields include, but are not limited to, storage, operations, analytics, security, ethics and visualization. This work will focus on the classification of the major Big Data types, on the existing visualization techniques and on potential future directions of visualization and interaction with Big Data in the context of Ambient Intelligence environments.

2.2.4. IOT Data

Information nowadays is rich and interconnected. Information is not enclosed in a specific system, but is omnipresent in our surroundings, producing networks which create an Internet of Things (IOT). IoT envisions a future where the sensing and actuation functions blend into the background and access to new information sources offers new capabilities [172]. Key IoT applications include healthcare industry, food supply chain, transportation and logistics [96]. Additionally, IoT can be employed in the domain of cultural heritage in the context of smart museums [78].

The modern information and communications technologies and services aim to facilitate the merging of the digital and real dimension in order to create smart environments, mainly by employing sensors and smartphones [23]. The IoT concept describes worlds in which information is massively distributed, transforming any real world object into an entity which can participate in a large network and be queried and discovered [361].

According to [484], the architectural model of IoT can be split into three layers, (i) the sensing layer, including the process which involves devices and sensors for data acquisition, (ii) the network layer, involving the data transfers across sensors, middleware and applications and (iii) the application layer, where IoT applications are deployed in combination with the functionalities provided by the middleware.

Information networks are able not only to describe things, but also ideas, society characteristics and culture. However, things constitute the physical entities around us and are the principal area of interest of individuals [17], as they are tangible entities which all individuals can easily perceive.

The network of the objects that are part of IoT worlds are applied for providing both input and output. Atzori et. al. employ IoT networks to create complex applications including direct interactions with objects and humans in the context of social networks [18].

2.3. Data visualization

Visualization was first defined by McCormick et. al. [282] as “a computing method, which transforms the symbolic into the geometric, enabling researchers to observe their simulations and computations. Visualization offers a method of seeing the unseen. It enriches the process of scientific discovery and fosters profound and unexpected insights“. According to the Merriam Webster Dictionary definition[4], visualization is the process of making a mental model of something or putting it into visible form. As analyzed by Schneiderman [379], user interaction involves four fundamental stages: Overview first, zooming in, filtering and finally details-on-demand. These stages of interaction are employed with minor variations in the vast majority of the existing systems and match the human cognitive model of exploration, where an individual first looks at a new environment, then goes near and afterwards decides their next actions. The following sections describe widespread approaches for data visualization related to both the data provided and the goal of the visualization.

[4] https://www.merriam-webster.com/dictionary/visualization

2.3.1. Maps

Geospatial data are present both in the context of Big Data and IoT technologies. The significance of spatial data characteristics was mentioned in 1970 by Tobler's first law of geography [411], where "near things are more related than distant things" regardless of information interconnections. Several domains employ geospatial data for decision making, including marketing [33], meteorology [357] and demographic analytics [383].

Interactive maps are the prevalent interface applied for geospatial information. Maps constitute a geographic visualization based on a common point of reference that displays information with regard to their location in space. The point of reference is usually in correspondence with a common mental model in order to increase perception and orientation, such as placing the map's north towards the upper side of the display and placing a map legend at a corner.

Navigating in a geospatial representation requires the user to be able to perform some actions, such as changing the scale, map projection, level of generalization and field of view; pan, move, browse across the "map" extent; access attributes relating to spatial objects including related information; and manipulate the design representation parameters (such as color, texture, and speed) [70]. Interface tools to support these tasks should be designed in such a manner so as to correspond to cognitive usability principles. Finally, in terms of geospatial hypermedia, Kraak and van Driel [238] proposed "hypermap navigation" as a means of displaying interconnected information with distinct visualizations, based on the links between data.

2.3.2. Graphs

Graphs are mathematical structures that model pairwise relations between objects. A graph data structure consists of a finite set of vertices (also referred to as nodes or points), together with a set of edges (also known as arcs or lines) for an undirected graph and as arrows, directed edges, directed arcs, or directed lines for a directed graph.

Graph drawing or graph visualization constitutes an interdisciplinary research field that combines methods from mathematics and computer science to create two or three dimensional representations of graphs in accordance with the domains of geometric graph theory and information visualization. Graph drawing is a distinct area of research that extends beyond the scope of this work, and therefore, this work will approach visualizations generated for information presentation (such as conceptual graphs) rather than graph theory problems. Graphs is a common technique used for displaying the correlation between different entities. Their main advantage is the user's ability to start from a specific node and explore neighboring nodes, especially when visualizing data sets that describe networks or relationships. The survey reported by Beck et al. [27] describes a trend towards the combination of graphs with interactive timelines in order to include potential temporal characteristics of the information. Furthermore, graph visualizations simplify exploration by providing operations like sampling, filtering, partitioning and clustering [331], while they can also support several abstraction layers [35] in order to provide meaningful views according to the scope of the visualization, ranging from overview to detailed view.

Graphs in general can be classified to force-directed, orthogonal, hierarchical and matrix representations [28]. Force-directed graphs are an approach used for drawing undirected graphs with straight edges. The initial approach on force-directed graphs was presented by Fruchterman and Reingold [140] as a modification of the spring-embedder model proposed by Eades [122]. According to Fruchterman, the principles for graph drawing were that vertices connected by an edge should be drawn near each other and that vertices should not be drawn too close to each other. Therefore, the sparseness of the nodes depends on their total count and on the available space. Another implementation of force-directed graph drawings, improved in terms of quality and performance, is presented by [194]. Finally, Holten and Van Wijk [189] use edge bundling for the creation of force directed graphs. Thus, the visualization is simplified, reducing visual clutter and providing more coherent results.

One of the prevalent techniques to visualize hierarchical graph data is tree layouts [230]. Tree visualizations are a widely adopted technique that can be used to display data such as family trees. They include a root node, which can be pictured as the starting point of the hierarchy, and through intermediary nodes conclude to a set of nodes that have no further connections (leaves). Another approach presented by [220] creates tree visualizations that are created in accordance with their temporal aspects. Hyperbolic trees are another approach for visualizing and manipulating large hierarchies, laying out the hierarchy in a uniform way on a hyperbolical plane and mapping this plane onto a circular display region [244]. Hyperbolic trees were employed by Lamirel et. al. [243] in an effort to visualize hierarchies generated through clustering multidimensional data. Finally, cone trees [353] are a tree visualization alternation, in which each node's children are always placed according to a cone's shape. Tree maps are an alternate way of the depiction of hierarchical data [378]. Their typical characteristic is the fact that they fill a rectangle extending along a two dimensional plane. Each node is depicted by a rectangle whose size depends upon its individual data that is visualized. For instance, when visualizing a file structure of a computer's file system, each file's size could be considered as the visualization size determining factor. Tree maps were extended in three dimensions by [41], having however contradictory results as, on the one hand, it produced richer results, but, on the other, users faced navigational and perceptional issues. Another interesting addition on tree maps was the division of hierarchies in different squares as proposed by [54], which required more visualization space but produced clearer results.

Radial view is a form of node graph visualization that can be either interactive [206] or animated [479]. Radial view graphs are sometimes drawn onto a timeline providing a mapping between space and time, which according to [417] provide a better overview of time in comparison to approaches which employ animations.

In a matrix graph visualization, such as [127], vertices are depicted as rows and columns of the matrix, while the cell color depicts whether two vertices are connected. According to [148], a matrix constitutes an alternative which can be efficiently used supplementary to node-link diagrams.

2.3.3. Tag Clouds

Tag clouds are visualizations that provide an aggregation of terms such as tags, being able to illustrate collections of heterogeneous data. Tag clouds, also referred to as word clouds, combine diverse terms (tags) which vary in size, color, shape and occupying area in the visualization. Therefore, they constitute a versatile visualization tool as they are able to depict both structured and unstructured data as they do not require any specific format for their input. On the other hand, they do not focus on the visualization of data connections or relationships.

Several algorithms have been developed by tag cloud generators, such as [216] presented by Kaser and Lemire for web-based visualizations and [292] which focuses on the generation of a semantic social tagging system.

Despite being relatively simple, tag clouds are able to inherently support a variety of input contexts and can be applied for a variety of tasks. These tasks, according to [351], can be classified into the following categories:

- **Search**: users are able to seek and find an element they are interested in and retrieve additional information on demand
- **Browsing**: tag clouds support the casual exploration of the data collection provided, looking for arbitrary information through the visualization
- **Impression formation and presentation**: tag clouds are able to provide the general idea over a topic at a glance, thus allowing users to both get an overview but also retrieve more trivial information when looking at less prominent items
- **Recognition or matching**: the shape that a tag cloud creates can illustrate the context of the visualized components

Bateman et. al. [24] perform an assessment of the tag cloud visual properties that attract the users' attention. The visual properties of a tag that the authors aptly identify include font size, font weight, color, intensity, number of pixels, tag width, tag area, number of characters and position. According to the results of this work, font size and font weight have stronger effects than intensity, number of characters, or tag area; but when several visual properties are manipulated at once, there is no one property that stands out above the others.

2.3.4. Virtual worlds and Data Exploration

One of the first attempts to create multiple worlds to manipulate large amounts of information is the Rooms system presented by Henderson and Card [181]. The authors create manifold workspaces in order to reduce space contention, increase clarity and organize information in a window-based environment. Additionally, the workspaces can be previewed and managed through a view that includes all the workspaces from which the user can and switched to the one of interest. The Rooms system was evolved by "Information Visualizer" [352] to support real time interaction and visual abstractions. "Information Visualizer" also introduced custom 2D and 3D views, such as the perspective wall and the cone trees, that that produced more intuitive visualizations matching the needs of the data to be visualized.

As far as information retrieval is concerned, usually a set of documents are provided and the user is interested in information relevant to a point of reference. In order to assess the performance of a retrieval or recommendation system, the metrics of recall and precision are usually taken into consideration.

Feiner and Beshers back in 1990 presented n-Vision [133], a testbed for the exploration of n-dimensional worlds that depict values and functions of an arbitrary number of variables. n-Vision was able to present an array of components, such as charts, that could be seen one next to another, thus allowing straightforward value comparison between the different worlds (values) visualized.

An interesting approach was presented by Waterworth in 1994, proposing the adoption of Information Islands to allow the interactive visualization of a wide range of information [457]. The proposed system was able to present hierarchically-structured information employing components ranging from macroscopic to microscopic in scale. The concept of this work involved the adoption of islands placed in an archipelago to depict information segments that could be further analysed to buildings, floors, etc. to illustrate hierarchies at larger depths. This approach was well suit for the representation of a hierarchical tree-like structure, but fails to reflect more complex interconnections, such as many-to-many relationships. In terms of exploration, the author suggested the creation of two environments, a public and a private, to represent the information that is visible for everyone or contains personal data about the ongoing exploration respectively.

In the domain of Cultural Heritage visualization, [98 and 99] present a web-based visualization of Cultural Heritage data, which is enhanced by a 3D visualization of a virtual world. The virtual world consists of various doors, each depicting a semantic relation of the currently examined content. This process allows interactive navigation, where users create their own exploration paths and examine the presented information. In addition to free environment exploration, the navigation based on predefined paths is proposed by [143], providing a more passive experience but also allowing the highlight of specific points of interest.

A multivariate data exploration tool is the TripAdvisor$^{N\text{-}D}$ [301] system proposed by Nam and Mueller, which analogizes the exploration of multidimensional data to a sightseeing trip. The authors decompose the activity in five tasks (sights identification, trip planning, travelling, examining details as well as orienting and localizing), tasks which are analogous to the exploration process. The system employs chart components (e.g. scatterplots) to illustrate the variable values and provides a variety of options to use, but, on the other hand, it creates a rather complex user interface which is suitable mainly for data experts to use.

2.3.5. Cultural Heritage Visualizations

Cultural Heritage is an information-rich domain which is fruitful for visualization. Limitations in exploring institutions such as museums are obstacles often experienced by visitors [456]. Another issue when exploring public institutions is time constraints, which may force users to explore information at a higher speed than preferred [142]. To this end, more than a few approaches aim at creating virtual museums [223 and 377] which are often provided on-site at the institutions [69] aiming to supplement physical exhibitions via Virtual Reality. European Union funds several research efforts in terms of shaping the future of virtual museum; such an indicative example is ViMM [450], which is aimed to provide an updated definition about virtual museums and how they can be enhanced by narratives and Mixed Reality. In this direction, recent efforts on integrating cross reality within cultural heritage institutions [126] are focusing on shaping the multimodal museums of the future.

Rather than simply constituting an additional layer to exhibitions, the enhancement of Cultural Heritage institutions through interactive Mixed Reality exhibits add value to the overall user experience [278], especially if combined with personalization to each user's interests [326]. Interactive storytelling in mixed reality environments bridges digital and physical information, augmenting the real world and offering interaction which corresponds to the user's actions in the physical space. Storytelling can be employed for associating tangible and intangible information; such an example is [195], where the authors compound information for the promotion of indigenous cultural heritage. In this direction, visualizations of virtual environments regarding cultural heritage data can assist and supplement, but not replace, in vivo visits to institutions.

Sooai et. al. [386] created virtual 3D environments presenting 3D models which users can experience by employing virtual reality views using mobile phones. Furthermore, monuments can be inaccessible for a variety of reasons: the excavation process is not yet complete, renovations are taking place or even their state is fragile. Therefore, visualizations of such sites can provide access to people who would not be otherwise able to explore them. Furthermore, items may be located in a protected area like a museum. In this case, the only way to perceive an environment containing the various elements found inside it is by augmenting existing environments with the items or by incorporating virtual environments containing the items. Finally, a 3D cave display enriched with haptic interaction modalities in order to recreate the process of an ancient monument construction is presented by [81], combining virtual reality with playful interaction. In the context of virtual museums, [395] analyze the way that users experience a virtual museum visit and interact with the virtual user interfaces.

Digital Cultural Heritage content is combined with physical 3d replicas by Bugalia et al. [59] in order to provide a virtual tour in architectural sites using Mixed Reality. This approach has the advantage of moving in a wall-projected 3D virtual environment while also extending a physical model to act as a minimap to assist navigation. Head-mounted displays are employed in the context of Cultural Heritage foundations for holographic AR and additionally support Virtual Reality visualizations [328]. Virtual Reality can act as a medium to visualize cultural heritage exhibits otherwise unavailable to users as well as reenactments of historical events, such as the battle of Thermopylae [80]. Such examples can include elements which are under conservation or even stolen [407], offering hands-on experience regarding unattainable content. Moreover, Augmented Reality is employed by [315] to enhance user experience and provide valuable insights on Cultural Heritages sites in vivo.

A different approach using tangible objects are souvenirs which summarize narratives as they were presented to users [330], acting as personalized keepsakes of their visit in Cultural Heritage institutions. These physical artefacts can act as a channel which connects Mixed Reality with online applications. Online applications can include panoramic 360 views [171] which can be experienced at the comfortable environment of a person's home using head mounted displays.

Finally, an interesting approach at Geevor Tin Mine Museum [212] combines Augmented Reality, Virtual Reality and 3d printed objects with the common goal of adding value to the overall user experience. The technologies are employed for enriching visits (Augmented Reality), providing access to inaccessible areas (Virtual Reality) and souvenirs which the users can keep respectively (3D printing).

2.3.6. Combination of data visualizations

Reflecting the way different data types are interconnected, several approaches exist that combine visualizations to build upon the enhancement of information perception. These approaches in general combine different views to visualize diverse data types and present relations between entities, if any. An indicative early example of multi-display visualization is presented by [352], where the authors utilize completely different visualizations for the rendering of the data in the optimal way.

Eccles et. Al. present GeoTime [123], a system for geo-temporal event visualization that is capable of presenting automatically generated narratives to assist analysts in identifying, extracting, arranging and presenting stories within the data. The authors use X and Y axes to represent space and Z axis to represent time and use a secondary view at the right side of the display to present the story's progress.

Semantic timelines [208] constitute another indicative example of combining semantic information with temporal data. Visualization of complex semantic data is accomplished using different types of arrows to connect events inside a timeline. The arrows implementing this idea are color-coded as well as shape coded (for instance dotted), while a legend describes the meaning of each type of arrow. SemaTimes [387] is another approach that visualizes semantic temporal information, employing a faceted display consisting of different panels that presents other aspects of the data provided.

As far as multidimensional data is concerned, Kandogan [214] proposed Star Coordinates, a system that presents information clusters on a circle sharing the same origin at the center.

2.3.7. Narrative Visualizations

Static visualizations have been traditionally employed to support storytelling in the form of text, diagrams and images. The adoption of dynamic approaches utilizing state-of-the-art 2D and 3D graphics is emerging in an effort to explore the full potential of interactive narration. As stated by Wojtkowski and Wojtkowski [470], visual storytelling can be adopted to provide intuitive and fast exploration of very large data resources in real time. Current research focuses on how narratives can be told using Virtual Reality [57], creating methods and principles that define the ways that VR can generate added value to storytelling. Moreover, storytelling using MR and AR applications has the potential to foster creativity, combining education, social interaction and gamified user experiences [487].

Film making and comics constitute an applied field of storytelling using visualizations, from which several characteristics can be considered to have been incorporated into interactive applications. Extra-pictorial elements [270] such as callouts (e.g., insets or lines to denote zooming) and annotations are used to enrich a narrative. Moreover, continuity editing techniques in cinematography [45], such as matching on objects or actions, can be applied to connect different scenes and assist the viewer to sustain a focus of attention.

Segel and Heer [375] place narrative visualizations along a spectrum of author-driven and reader-driven approaches in a non-mutually exclusive manner. This classification separates the approaches with regard to the way that stories unfold: author-driven approaches form a narration which is defined a priori and the viewer follows the flow of the narration, while in reader-driven cases the viewer has higher interactivity to make decisions regarding the story exploration. In the vast majority of narrative visualizations these approaches are combined, creating hybrid narrations that serve both purposes.

Storyscope [472] is a tool for presenting museum stories using web-based visualizations. The authors propose dossiers, which are visualization templates for heritage objects, describing events expressed through CIDOC CRM ontologies. Additionally, their approach includes reasoning for the extraction of story plots. Storyscope also embraces the concept of annotations describing the events of a story, in order to extract features that are correlated to other events [295]. Annotations can be created through an editing interface, offering an environment that enables on-the-fly tagging of visualized elements. Finally, another similar approach is Storyspace [294], a web interface created to visualize narrations modelled through curate ontology.

2.3.7.1. Means of storytelling

Tangible items are employed in some cases of interactive museum installations. For instance, [278] employ smart replicas to present stories interactively, providing various different perspectives of an existing museum exhibition

Sound constitutes a communication channel which is often neglected and turns into a Cinderella aspect of visualizations [260]. Auditory narratives constitute an additional technique for presenting stories in a less pervasive manner: auditory input usually acts complementarily to vision, allowing users to channel their attention to the exhibits. Area-triggered narrations were employed by [408], aiming to keep users' focus on the exhibits instead of a mobile display by providing context-sensitive information. Salo et al. [360] enrich curated auditory storytelling by visitor-created content, allowing users to express their emotions about artefacts through communicating messages with others. Finally, MR storytelling can be performed in the CAVE installations [300], where the user takes the role of the main character in the story.

2.3.7.2. Storytelling Authoring

Authoring refers to the process of creating narrations that form a digital story. In terms of authoring, the most common story types are character-based stories [72], linear timeline-based stories [39] and ontology-based stories [71]. Character-based stories unfold a story from the side of a character, unveiling information while users perceive their environment as if they are the protagonists of the virtual scenery. Linear time-based stories illustrate events in accordance to their chronological characteristics, providing a temporal continuum of a narration. Ontologies allow information modelling and reasoning, thus facilitating the definition and provision of dynamic narratives generated from semantic representations of Cultural Heritage artefacts [294].

Custom authoring tools are also present in literature. These tools are aimed to be used by Cultural Heritage experts, i.e. curators, in order to structure information which can be on a later stage be integrated in storytelling. In terms of authoring virtual worlds, Lu et. al. [271] presents an editing environment for facilitating the construction of 3D museums. Additionally, narratives description and structuring is also performed using authoring tools. The meSch approach [349] allows curators to define narratives (stories), the appliances and the devices (infrastructure capabilities), and the rules that govern the interaction. Ardito et al. [15] create a similar tool for storytelling creation and customization, focusing on the aspects of smart objects integrated in the cultural heritage installations. More focus on the navigational aspects of virtual tours is offered by [79], as curators are allowed to create views of interests and define timed walkthroughs in virtual environments. Finally, another interesting approach facilitating storytelling creation through data modelled in CIDOC-CRM ontologies [104] is GeneraTour [264], thus allowing content reusability and reasoning on an established formal model for Cultural Heritage content.

2.3.8. Big Data Visualizations

Big Data Analytics refer to the process of studying, exploring and reporting on Big Data, aiming at assisting the human decision making process. Apart from reporting and visualization, operations that belong to several research fields are involved, such as predictive analytics, data mining, anomaly detection, statistical analysis and text analytics. Data analytics is an influential factor for decision making widely used by companies, while researchers try to verify or disprove scientific models, theories and hypotheses. The prevalent approach for visualizing large volumes of data includes visual analytics, aiming at data scientists and analysts rather than non-experts. As mentioned in [94], research challenges regarding Big Data analytics involve both structural approaches and visualization concerns. The structural approaches refer to the infrastructure that allows making operations on Big Data, while visualization concerns encompass the nature of the data source in terms of presentation.

A fundamental characteristic of Big Data is its multidimensional nature. Big Data comprises massive information with several aspects. For instance, information about a specific car not only contains data about the car itself, such as model, production start date, horsepower, acceleration, but also data regarding sales: how many cars were sold, the sale location, the color of the cars, etc. This information comprises different dimensions of the data that create different perspectives, which can be retrieved and analyzed on demand.

Integrated Development Environments (IDE) are employed by data scientists and engineers in order to collect data and export visualizations in programming languages such as R [341]. Web analytics are shown mainly in the form of charts, tables and maps for geo-located information.

2.3.8.1. Analytics / Tables-charts / OLAP

The first step towards visualizing multidimensional data sets includes the identification of the involved aspects that need to be presented. Current approaches that cope with this issue mainly involve OLAP [35] (Online Analytical Processing), which aims to provide a mechanism for the analysis of Big Data from multiple different perspectives. OLAP is applied as a means of interactive filtering out extrinsic information. Several data storage models for the core implementation of OLAP are found in literature, including Multidimensional OLAP systems (MOLAP), Relational OLAP (ROLAP) and Hybrid OLAP (HOLAP). This work will not focus on the different core approaches that allow OLAP operations, but instead on the visualization aspects that arise at a higher level.

The OLAP tools enable users to analyze multidimensional data interactively from various perspectives. OLAP consists of five basic analytical operations: consolidation (roll-up), drill-down, pivoting, slicing and dicing [165]. The applied operations change the selection of the visualized components on the fly and update the view according to the user's actions.

A traditional interface for analyzing OLAP data is a pivot table, or cross-tab, which is a multidimensional spreadsheet produced by specifying one or more measures of interest and selecting dimensions to serve as vertical (and, optionally, horizontal) axes for summarizing the measures [93]. Pivot tables are a widespread visualization model, which provide a detailed data presentation to users that are familiar with it. Additionally, they can be easily transformed to serve additional dimensions of information through the application of color-coding or rows/columns merging. However, the efficiency of the tables declines for larger data sets, as users are unable to locate specific information, recognize patterns or get an overview of the displayed data sets.

Another useful visualization component are parallel coordinates [177 and 200], which allow the display of multiple data dimensions on a 2D plane. The concept of parallel coordinates is the concurrent visualization of different values in a row, one after another. For instance, in the case of car comparison, car values regarding horsepower, fuel consumption, car dimensions, acceleration, etc., would be meaningful to be displayed on the same plot. This visualization technique holds the advantage of correlation between different data dimensions, e.g. horsepower and acceleration, which could depict the impact of one dimension on another. However, this applies only in the case where the dimensions are rendered adjacently; if another dimension intervenes between them, the visual clue disappears and the correlation is impossible to discover. Additionally, parallel coordinates are unable to visualize non-numerical values and can be difficult to comprehend for non-expert users.

In order to address the aforementioned drawbacks of tables and parallel coordinates, techniques such as pie charts, plots, graphs and trees are employed by state-of-the-art commercial tools. The leading software for Big Data Visualization, Business Intelligence and Analytics is Tableau [272], while other approaches include qlikview [339], Microsoft's Power BI [337] and others. Tableau provides default tools for rendering each specific data type, which can be overridden by the user on demand. Each visualization is selected to optimally represent a specific data type: for instance, cross-tabs are used for the visualization of discrete categorical data and lines for continuous quantitative information.

Even though OLAP tools are very efficient for Big Data retrieval and on demand visualization, they usually lack exploratory functionality. Furthermore, due to the complex nature of the operations supplied, OLAP tools tend to be cumbersome for novice users to manipulate.

2.3.8.2. Temporal Big Data Visualizations

Time classification is an aspect of Big Data, which is frequently meaningful. It constitutes a dimension that is often stored, either as supplementary information or as major descriptive value. Users are accustomed to perceiving time as an additional dimension of Big Data and are therefore able to easily perceive it as a dimension to any type of information. Time constitutes an important factor in various contexts, including decision making [73].

2.3.8.3. Big Data Geospatial Visualizations

Another type of information which is often an integral part of Big Data is space. The datasets can be static or dynamic in terms of location. Dynamic Big Data can be acquired through the usage of location-aware devices and the adoption of Geographical Information Systems (GIS) and correlate to both space and time. The quality of data, which poses an important issue in terms of geospatial data [256], is expected to improve, especially in the context of the Internet of Things (IoT).

Li et al. [259] use Big Data 3D visualization along with web-based dashboards in order to display infrastructure in Shenzhen and take geographic statistical analysis into consideration for assisting data analysis and enhancing the decision making process for social service agencies. Big Data in the context of urban environments in general correlate data sets with both time [191] and space [21].

2.3.8.4. Big Data 3D Visualizations

Traditional visualization techniques fall short in terms of efficient and intuitive display of the corresponding data sets; therefore, the need for a rich interactive visualization still constitutes both a business and a research challenge. In order to fill in the gap of inefficient visualization, some approaches in literature involve 3D visualization for OLAP [10 and 242]. However, 3D visualization approaches are not yet very popular.

The inclusion of an additional dimension to the visualization adds up to the efficiency of depicting the dimensions of Big Data. Since the human brain is trained to sense and act in three dimensions, it is optimized to perceive three dimensions in a natural manner. The third dimension constitutes an aspect of the rendered information easily perceivable by the user, thus enhancing potential exploration in a virtual world.

On the other hand, 3D visualizations have certain drawbacks. In general, they present a steep learning curve, as inexperienced users usually tend to be unable to orientate themselves in the virtual three-dimensional space or to manipulate the interface. The lack of 3D space perception does not only involve the virtual space itself, but also the lack of the exploration and identification of the visualized information. Interaction complexity with 3D user interfaces is also a significant burden due to the additional degrees of freedom requiring complex manipulation controls and a rich interaction vocabulary.

2.3.8.5. Big Data Visualizations using AR-VR

Virtual and augmented reality environments form an emerging approach that is capable of providing Big Data visualizations. Such environments in the context of Big Data constitute interdisciplinary efforts, combining the areas of 3D graphics, stereoscopic environments, computer vision and Big Data querying. The main advantage of virtual and augmented reality environments is better user experience and immersion, which allows the better perception of the visualized geometry. Furthermore, in comparison to traditional 3D visualizations, the users perceive themselves in the context of the visualization and thus orientate themselves more easily.

In an effort to capitalize improved perception, several approaches are related to the creation of analytics solutions [87 and 452] which can also be enhanced by annotations [419]. Similarly, Helbig et al. [180] use a virtual reality environment to visualize massive data in the context of Weather Research Forecast. Another interesting approach is the immersive visualization of a landscape in Mars [109], augmented with data describing the surface characteristics. Another approach which employs virtual reality to perform traffic monitoring using big geospatial data is presented by [258].

Future challenges on applying virtual and augmented reality to Big Data visualizations include multimodal interaction, display and equipment limitations [312]. Virtual and augmented reality is a growing research field, mainly due to the emergence of devices such as the Microsoft Kinect and LeapMotion that provide more natural interaction based on gestures and Oculus Rift, which puts virtual reality in play again in terms of mainstream visualization techniques. However, several challenges still exist when it comes to incorporating and enhancing traditional 2D desktop approaches in virtual space, as well as developing a suitable infrastructure at the side of Big Data to support additional needs that may rise.

2.3.8.6. Big Data Exploratory Analytics

Exploratory Analytics, or else Discovery Analytics, refers to the process of using visualization exploration techniques, in the context of Big Data, which aims at discovering new facts or characteristics of Big Data that users were previously unaware of [358]. Heer and Shneiderman [179] present a widely adopted taxonomy for interactive dynamics regarding visual analysis. The proposed taxonomy groups tasks in three high level categories: data and view specification, view manipulation and analysis process and provenance.

Faceted navigation, also mentioned as data and view specification, refers to the process of applying specific filters to the data sets provided in order to focus on the subset of interest. Faceted navigation can combine multiple visualization techniques to apply the most suitable ones to the corresponding type. Such an example is EDEN [389], where the authors use parallel coordinates and geographic visualizations to interactively refine the displayed values and thus offer exploratory analysis of Big Data by exploring relationships between entities. Another example of interactive faceted exploration is discussed in [473], which combines automatically generated and manually specified visualizations in order to improve support for data exploration.

2.4. Ambient Intelligence

Information technology has been continuously evolving since the introduction of computer systems, expanding the potential of technology assistance to people’s everyday life. The integration of computers in the human environment becomes essential in order to offer users the ability to simplify their lives and aid the accomplishment of their goals. Ambient Intelligence is a research field which aims at computers disappearing in the background and making the coexistence of humans and technology anthropocentric.

The term ambient is defined as ‘existing or present around you’ in MacMillan Dictionary[5] and as ‘relating to the immediate surroundings of something’ in Oxford Dictionaries[6]. According to E. Aarts and J. Encarnacao Ambient Intelligence (AmI) refers to “electronic environments that are sensitive and responsive to the presence of people” [3]. Ambient Intelligence envisions the invisibility of technology in our natural surroundings, present when we need it, context sensitive and autonomous [185]. AmI combines Ubiquitous Computing with intelligent User Interfaces in order to offer the users natural means of interaction.

Ambient Intelligence envisions a future where technology is interweaved with everyday living environments, anticipates users’ needs, and provides natural interaction with digital information [459].

In respect to human-computer interaction, Ambient Intelligence (AmI) environments involve primarily two aspects: context awareness and natural interfaces [86]. Context awareness includes the use of emerging technologies to infer the context of the interaction (e.g., the location and the activities of the

[5] http://www.macmillandictionary.com/dictionary/british/ambient
[6] http://oxforddictionaries.com/definition/english/ambient

user), whereas natural interfaces refer to human communication capabilities and implicit actions that should be employed as a means of interaction in AmI environments, instead of the explicit input used in traditional human-computer interaction.

Ambient Intelligence environments have the potential to support the visualization of Big Data and its multiple dimensions due to the wide range of displays and interactions combined, which can be both implicit and explicit [369]. Challenges and potential approaches for integrating Big Data visualizations into AmI environments are discussed in [118], presenting envisioned use case where context is applied in an intelligent manner so as to add value to existing visualizations.

2.4.1. Intelligent and Natural User Interfaces

Intelligent User Interfaces are a novel form of Human-Computer Interaction where computers apply multimodal input and output in order to support users' plans and goals. The input, such as gestures or gaze tracking, is acquired using a variety of sensors and cameras and is potentially imprecise and error tolerant. Intelligent User Interfaces are able to adapt according to the context of use and assist users to reach their goals.

Natural User Interfaces are by definition interfaces which are natural to use: the user is instinctively able to interact with a system with little or no training, while the user is able to quickly transition from novice to expert. Furthermore, the means of interaction that the user applies to manipulate a system are intuitive and similar to human communication, such as speech, gestures and physical navigation. Moreover, people in everyday life communicate both implicitly and explicitly: for instance, a person may talk to another in order to initiate communication, while they may walk away from another in order to avoid contact. In a similar manner, Intelligent and Natural User Interfaces are able to react to both implicit, e.g. proxemics interactions [168], and explicit user interactions, e.g. [115 and 117].

Intelligent user interfaces are typically characterized by one or more of the following properties [281].

- **Multimodal input**: they process potentially ambiguous, impartial, or imprecise combinations of mixed input such as written text, spoken language, gestures (e.g., mouse, pen, data glove) and gaze
- **Multimodal output**: they design coordinated presentations of features such as text, speech, graphics, and gestures, which may be presented via conventional displays or animated, life-like agents.
- **Interaction management**: mixed initiative interactions that are context-dependent based on system models of the discourse, user, and task. This new class of interfaces promises knowledge or agent-based dialogue, in which the interface gracefully handles errors and interruptions, and dynamically adapts to the current context and situation. The overarching aim of intelligent interfaces is to both increase the interaction bandwidth between the human and the machine (e.g., by increasing interactive media and modalities) and at the same time increase interaction effectiveness by improving the quality of interaction. For example, by explicitly monitoring user attention, intention, and task progress, an interface can explain why an action failed, predict a

user's next action, and warn a user about undesirable consequences of actions or suggest possible alternative actions.

2.4.2. User and Context Profiling

User profiling aims to outline the users' characteristics and contain attributes that describe each user. User Profiling may be achieved either **before** interaction, by portraying the potential user of an application based on its context of use, **during** interaction, by monitoring the user's actions, or **after** interaction [150]. User profiling may aim at either adapting the interface to suit the preferences of the user [367] or the content [190 and 289], so as to provide information based on the user's interests.

The objective of context profiling is to collect and represent attributes describing the environment in which the interaction process takes place. According to [232], a modelling system should be domain independent, expressive, adaptive and hold strong inferential capabilities. A widely accepted approach involves the embracement of ontologies [239 and 338] as a means of modelling and reasoning on the profile information. The data modelled and stored may, for instance, describe the surrounding environment (e.g. the physical space offered for interaction, the noise, lightning, and crowdedness) or the user's activities (idle, emergency situation, going to work).

According to [394], Ambient Intelligence requires the following characteristics from context modelling:

- Distributed Composition: composition and administration of a context model and its data varies with notably high dynamics in terms of time, network topology and source.
- Partial Validation: it is often required that modelling should be able to partially validate contextual knowledge
- Richness and Quality of Information: the context model should be able to describe the richness and the worth of known information.
- Incompleteness and Ambiguity: supplied information in Ambient Intelligence environments is often ambiguous and therefore the model should address this (for instance, by interpolating the data).
- Level of Formality: The model should be able to describe contextual facts and interrelationships in a precise and traceable manner.
- Applicability to existing Environments: the context modelling should be applicable to present Ambient Intelligence environments.

2.4.3. Context Awareness

Pervasive and ubiquitous computing aims to transform physical spaces into computationally active and intelligent environments, and envision a world where computers perceive their environment using both implicit and explicit information. Context-aware systems use context to provide more relevant services or information to support users performing their tasks, where context is any information that can be used to characterize the situation in which something exists or occurs. In this direction, several approaches exist in literature that aim to reach this goal mainly by using middleware and semantic decision making. Context awareness is a two-step process, where systems firstly receive information as input regarding their environment and secondly act according to reasoning.

Soldatos et. al. [385] present a framework implementation of middleware components which enable the integration of sensors, devices, actuators, perceptual components, context modeling elements, as well as other information fusion components, laying emphasis on integrating perceptual components, multimodal interfaces and situation recognition middleware.

A very popular and thorough approach that combines middleware and formal data models is presented by Gu et. al. [170]. The authors' approach involves the implementation of a middleware using a service-oriented architecture of context aware services and a formal context model based on ontology using Web Ontology Language to address issues including semantic representation, context reasoning, context classification and dependency.

Vieira et. al. [449] present a reasoning metamodel which supports building context models by making the concepts related to context manipulation explicit and by separating the context structure model from the systems' behavior

Finally, Lim and Anind present Intelligibility [262], a toolkit which provides automatic generation of eight explanation types (Inputs, Outputs, What, What If, Why, Why Not, How To, Certainty) for the four most popular decision model types (rules, decision trees, naïve Bayes, hidden Markov models) in context-aware applications. Intelligibility also supports the generation of explanation structures, querying mechanisms, constrain explanations, simplifying complex explanations and presenting the explanations to end users and other subsystems.

2.4.4. Interaction in Ambient Intelligence Environments

2.4.4.1. Interaction and user feedback

Visual cues constitute the dominant medium of providing interaction feedback and user guidance in 3d environments. Path drawing [197] is an established approach to indicate the direction towards elements in 3d environments, widely used for assisting user navigation. In this case, the system renders visual cues which lead to certain areas of the virtual environment, guiding the user towards a specific position. Ray-casting [48] displays a virtual ray in the direction which the user is pointing at, providing a clear feedback regarding the aim. This approach is employed for remotely manipulating objects, such as the magic wand [84] or world in a miniature [392].

Auditory feedback constitutes an additional channel for providing information to the users. While audio is usually employed as a secondary feedback in conjunction with visual feedback, it can be also used on its own [482] in the case of non-visual interaction.

Moreover, haptic force feedback is another medium for providing user feedback [359]. This approach is employed complementary to visual and auditory feedback, enriching user experience and further engaging users into the virtual environments.

2.4.4.2. Interaction Types

A variety of approaches exist that handle input in Ambient Intelligence environments. Each interaction technique has its own advantages and drawbacks and a common approach involves using combinations of technologies, i.e. multimodal input, in order to achieve finest results. The interfaces that employ multimodal input use two or more combined user input modes (e.g. speech, touch, gestures, gaze tracking etc.) in a coordinated manner with multimedia system output [314].

Carmigniani et. al. [68] provide a state-of-the-art extensive overview of modes of interaction as well as display modes in regard to Augmented Reality systems, which may be applied in a straightforward way to Ambient Intelligence environments. Papagiannakis et. al. [324] present a survey for the applications of Augmented Reality to ubiquitous computing, focusing primarily on the review of Mobile Augmented Reality Systems (MARS), presenting diverse approaches and their limitations. Furthermore, the authors link multimodal input to the accompanying interfaces, which are a new class of interfaces that aim to recognize naturally occurring forms of human language and behavior, and which incorporate one or more recognition-based technologies (e.g. speech, pen, vision) ». Multimodal systems enhance information visualization, replacing original WIMP (Windows, Icons, Menu and Pointers) interfaces with richer applications and accommodating users' perceptual capabilities.

FORTH's AmI Facility [162] incorporates a variety of services and applications, shaping a smart environment of ubiquitous computing. Famine, the middleware used to provide connectivity between the applications and services distributed within the facility [146], allows communication in a straightforward for programmers manner, regardless of the implementation programming language.

2.4.4.2.1. Voice interaction

Voice interaction refers to the technique by which the user may interact with the system by voice commands. This type of interaction is easy to use and very intuitive to the user, but its implementation is impeded by several factors. First of all, the recognition of voice commands is nowadays not very precise and robust, especially as noise increases. Even if this problem is solved by hardware or specialized algorithms, the next issue presented is the understanding of natural language, which is ideally the way voice interaction should work. Each sentence can be paraphrased in many ways and as a consequence the difficulty of analyzing user's meaning becomes a very complex issue.

Due to the limitations of voice interaction, its application is implemented through the use of specified commands. These commands, if applied as the only means of interaction, require a specific and strict scenario with well-defined dialogues [380]. In every state of the dialogue, the user may interact with the system by apparently choosing a command from a range offered in order to reach his goal. This approach may be appropriate if no other means of interaction apply efficiently, for instance, if the user is visually impaired [218]. Finally, speech interfaces may become unpleasant and irritating for the user if there is any trouble in communication with the system [213], when an extensive set of questions is necessary to clarify the user's commands. As a result, voice interfaces are mainly used as a secondary means of interaction, either through verbal commands or through emotion detection. In this case, the user is able to trigger certain features of scenarios in a natural way, while not using his hands.

2.4.4.2.2. Gestural interaction

Touchless interaction is mostly accomplished through gestures, which are defined by Kendon [221] as "a label for actions that have the features of manifest deliberate expressiveness". Gestures are widely used supplementary to other interaction modes to accomplish specific tasks, providing a natural way of interaction similar to everyday human to human communication. For instance, a user may respond to a yes/no dialogue by raising or lowering his or her hand in order to communicate with a system. However, the inclusion of gestures in a system's interaction repertoire holds some important drawbacks, such as the necessity to memorize the rules defined by the interface in order to communicate with the system. Apart from task-specific gestures, another common procedure includes pointing with a hand towards a specific direction so as to select an area or an object, usually using a cursor.

Gestures are a common approach which proves to be very intuitive to users and is widely used in literature [376 and 480]. Gestures can be defined as a form of non-verbal communication in which visible body actions communicate particular messages. Regardless of the means of interaction, gestures may be expressed through mouse, body or multi-touch interaction systems. Gesture recognition remains an issue around which much work exists in literature and comprises a field of continuous evolution. Currently, gesture recognition is in a relatively mature state where its identification is robust and allows experts to develop applications that rely explicitly on it for user's communications with systems. The overall user experience when employing hand gestures can be further improved via the appearance of the users' hands within the virtual environment, thus enhancing the feeling of presence in the environment and control over the application [400]. Furthermore, gestures with hands can be used to augment systems and allow additional interactions [183] when combined with other means of interaction such as simple touch.

In gestural interaction, the adoption of a cursor-like metaphor is widely adopted in order to provide responsive feedback. In terms of using the cursor to select items, two major classifications can be made: the **magic** approach, where the user's actions result in the interaction with the system using common magical beliefs such as raycasting with a magic wand, and the **natural** approach, where the real environment is replicated in the virtual one and users utilize their hands to physically touch the interactive elements. In general, the magic approach is preferred in the cases where interactive elements are placed far from the user's area, while the natural approach is utilized in environments where the elements are within reach.

While the action of element selection is straightforward in the natural approach, as the user presses or touches the item to choose, selection in the magic approach is more complicated as different metaphors can be applied. Wilson et al. [465] embed a button in a physical wand in order to select items. Another approach suggests the application of a cursor dwell time threshold as a click event [176 and 361]. Other solutions apply speech as a signal for making selections [43] but are limited by the addition of supplementary auditory constraints. Additionally, [111] employ pinching in the air to perform the act of selection. Finally, another approach includes the combination of a small time threshold to focus on an item and successively a click in the air (by pushing and pulling) [317], in order to eliminate accidental selection.

Gestures may not be limited to multi-touch and hands, but may be applied to feet as well. Sangsuriyachot et al. [364] propose using a foot platform able to recognize specific foot gestures which apply rotation to objects displayed on the surface to enhance user interaction in tabletop displays. Valkov et al. [442] use foot gestures to expand simple multi-touch interaction and boost navigation in dynamic and complex 3D Virtual Environments.

Locomotion Redirected walking or walking in place [344] is a locomotion technique where in place walking acts as a trigger to move towards the direction the user is looking at. Another approach involving body posture is the application of leaning [247] to control travelling velocity in virtual environments. Body postures and locomotion approaches have the advantage of being fun and straightforward to learn, but also result into the user's physical fatigue.

While engaging users and adding up value to the user experience, the use of locomotion and gestures must not be regarded as a suitable solution to all issues, especially in the case of body gestures, as extensive and continuous body movements may end up tiring users [25]. Another problem which arises when gestures are applied may be the precision and accuracy of interaction required by the user. For instance, spatial navigation in a 3d space using gestures may be more complex than other approaches, such as body tracking and exact mapping of user's movements.

2.4.4.2.3. Body interaction

As Stivers and Sidnell [391] describe, a user's body movement can be supplementary but greatly helpful in the field of natural interaction. Body movement indicates the pose of a user's body, which can be tracked and applied for selective interaction with the environment. In this case, the system may interpret a specific body pose in order to enable interaction in a specific manner. Papadopoulos et al. [321] use defined body poses recognition in order to allow navigation in 3d environments. According to their approach, whenever a user poses in a certain way, manipulation of a camera in a virtual 3d environment begins.

2.4.4.2.4. Eye and head tracking

Eye tracking and head tracking are types of interaction where the system monitors a user's eyes and head respectively in order to identify the direction pointed by the user. Due to the fact that users are not forced to act in any way apart from looking at what is of his their interest, gaze detection may be considered as the most natural interface.

Eye tracking interaction is a technique where users manipulate the system with their gaze. Jaimes et al. [205] group eye tracking systems into wearable and non-wearable, depending on whether special equipment is worn by the user. Wearable systems are in general more precise but concurrently require special equipment to be worn, while non-wearable are less accurate, often requiring calibration for each user yet unobtrusive.

Head tracking is widely used for Augmented and Virtual Reality systems, especially when virtual space is three dimensional. The main advantage of this technique in comparison to others is the fact that it offers information about the transformation of the user's head. Transformation includes the position of an item as well as its orientation, which is of significant importance in three dimensional spaces. As mentioned in [324], head tracking may be achieved also in combination with Head Mount Displays (HMDs), which additionally provide a wearable natural system display mode.

Head tracking is found in the vast majority of literature in cooperation with other means of interaction. Benko et al. [31] create an augmented space in a frame and use gestures to offer interaction with virtual objects, while head tracking is used to complement interaction through the manipulation of the camera in a virtual world. Another practice of head tracking is the increased accuracy of gesture recognition, firstly presented by Nickel et al. [304].

A significant issue as far as head tracking is concerned is the system's ability to understand whether the user is simply looking around and therefore head tracking should be ignored or the user's aim is to interact with the system.

2.4.4.3. Multiple User Interaction Approaches

2.4.4.3.1. Turn-taking

Turn taking is the process of users forming a time-based queue, where each user waits for the currently interacting one to stop interacting. Turn-taking is applied in many displays [168] when users are not able or not willing to interfere with another person's interaction. Such examples may be physical constraints, such as lack of space, or social constraints, e.g. a stranger prefers not to interfere with a couple playing a game on a public display.

The advantages of turn-taking are its clear mental model and the fact that it is often applied by users on their own in a manner similar to social habits. On the other hand, the major challenge for resolving conflicts of turn taking occurs when multiple users attempt to use a display at once. This situation is even more evident in the case of children, which have not yet developed social skills sufficiently and frequently attempt to take over control [67].

2.4.4.3.2. Remote Interaction

Remote interaction is a type of interaction where users interact with a public display without approaching or touching it. Such an indicative example is mobile devices [240], usually smart phones and tablets considering current technology. In the future, additional smart devices could be also included, such as smart glasses [342] or smart watches [37]. Additionally, custom controls [390] are employed for user input, allowing features such as selection and polling.

2.4.4.3.3. Polling

Polling is a procedure where users are asked a question and are expected to express their opinion. In literature, this is primarily expressed through multiple choice answers the users may choose from. Polling may take place either in real-time or over a predefined duration, according to its context of use.

A common implementation of polling involves buttons, as in the case of interactive lectures [53] and opinion expression regarding news [390] or mobile phones [217]. In the case of non-real-time results, users just make their selection and are usually able to see current results.

O'Hara et. al. [311] present an interactive MP3 Jukebox in the context of a bar, where users can select their music democratically or even upload their own.

Buchsbaumm et. al. [58] apply colored wands as input devices in order to allow real-time voting for large crowds. The authors use real-time polling as an input device, allowing the crowd to act collectively and in collaboration in order to play pong or a flight simulation game, as well as collectively design emoticons.

Finally, Valkanova et. al. [441] use Kinect in order to allow users to make their selections. An issue raised with this approach, however, was the privacy one, as some of the users raised concerns about exposing themselves in front of a camera.

2.4.4.3.4. Autonomous Interaction

The most common approach found in literature for dealing with multiple users is the parallel use of a shared interactive system, where people usually interact independently. The count of users varies and ranges from single users to as many as they can fit in the physical space.

In parallel usage, three primary approaches exist:

1. **Unrestricted usage**. The systems that belong in this category allow users to freely move and interact in space, limited only by physical constraints. Such an example is PaperView [160], where each user owns a paper which provides additional information according to its location in physical space.
2. **Dynamic space partitioning**. In this case, each user owns private space, which follows them [277]. This concept is often embraced by users on their own [297], as territoriality is often implied in a manner similar to social habits.
3. **Explicit space partitioning**. Another approach involves splitting a display, e.g. a tabletop, into territories where each user has their own space [158 and 279] and is usually able to share content with others.

An interesting finding from Jacucci [204] is the analysis of a multi-touch and multi-user system which supports parallel interaction: the authors analyzed the overall individual use, pair wise use and group use, finding that the most frequent use was individual (47%), followed by pair wise (35%) and group (18%). A configuration was labelled as individual if one person engaged in focused manipulation of one object or area of the screen without interacting or avoiding interaction with other users. It was labelled as pair if two users began to manipulate an object or objects together or talk and interact with each other while manipulating objects. It was labelled as group if three or more users engaged in the same manner as a pair.

An additional approach is the adoption of users' smart phones as an input device. Such an example is Panoptix Interactive Digital Wall [318], a system where users are able to display their own message on a large public display by posting it on a specific twitter address and Code Space [51], which contributes touch + air gesture hybrid interactions to support co-located interaction.

2.4.4.3.5. Collaborative Interaction

A frequent scenario is that people approaching an interactive display along with their friends do not just step in as individuals, but clearly team up in joint activities or start working on the same object. Teamwork is sometimes another way of dealing with physical obstacles, or it can be adopted because it is more entertaining that way, or both.

Benford et. al. [30] present URAY, a touring performance where various strategies are employed to interweave the fictional world of a digital game with the everyday physical world.

2.4.4.3.6. Competitive Interaction

Competition is a contest between people for a specific goal. As far as multi-user interaction is concerned, competition is vastly expressed through gaming: antagonism refers not only to reaching a goal, but also presents a correlation with other users. This approach intrigues users to interact with each other, moving the setup out of the picture, as users focus on each other. Competitiveness enhances user engagement, especially if users are familiar with each other: the fun factor is then increased, as people may tell jokes either during gameplay or afterwards.

Several examples exist in literature regarding competitiveness as it can be applied to a variety of circumstances. It can be applied for rehabilitation [30], advertising and gaming [159] – often referred to as advergaming – or for teaching [410].

2.4.5. Playful experiences and immersive User Experience

Immersion is based on covering physically a person's stimuli, namely vision, spatialized sound and haptic feedback [50]. In terms of visual representation, modern devices such as Oculus Rift, Samsung Gear VR, HTC Vive and Microsoft Hololens provide high resolution displays that offer sufficient immersion. Additionally, immersion in AR, VR and MR environments is largely affected by sound, as appropriate sound design has the potential to increase learner engagement [62] and increase the feeling of presence [137], especially when employing three-dimensional spatialized sound [231]. Finally, haptic feedback [313] is examined in literature as an additional means of increasing immersion. Kosmalla et al. [235] combine tactile feedback from physical worlds with a virtual rock-climbing environment in combination with full body movement and exertion.

Immersion is also strongly related to the interaction process: in addition to perceiving a Mixed Reality (MR) application with human senses, the interaction modality employed constitutes a decisive factor in feeling of immersion and the overall user experience. Contrary to mission critical domains such as a working environment, Cultural Heritage applications belong to a field in which users are more open to novel alternate interaction modalities. Requirements such as precision and efficiency are not fundamental in such a context, as users may be willing to sacrifice precision and overrule tiredness for entertainment and playful user experience [117].

Playfulness encourages exploration, foster creativity and stimulate social interaction by entertaining users and allowing them to escape from the reality [414]. Playful interaction is employed for attracting users towards public installations and therefore facilitating user engagement [464].

The factor of pleasure and engagement is apparent in applications which employ kinesthetic full body interaction [36]. Body movement and gestures constitute an aspect of our everyday life which is natural for everybody: therefore, the challenge of turning instinctive modalities to communicate messages with non-living objects provides a fascinating user experience [103]. For instance, in [88] interact with fields of abstract grass by moving in space. In addition, mid-air hand gestures following a cursor metaphor [454] are a common practice for selecting displayed elements at a distance. The cursor conceptual model is intuitive enough for users to perceive it and manipulate user interfaces [116]. Additional interaction modalities, like feet interaction [448] and smart objects [349] are also part of the interaction process and are applied either exclusively or complementary. Finally, a significant aspect of user experience is the fact that immersion is significantly improved when interacting with mixed reality environments without the burden of wearable equipment [268].

2.5. Virtual Reality

According to Greenbaum [166], "Virtual Reality is an alternate world filled with computer generated images that respond to human movements". Virtual Reality (VR) is an interdisciplinary field of research, including the domains of human-computer interaction (HCI), computer-generated imagery (CGI) and computer graphics. Virtual reality technologies (VR) offer unprecedented user experience when it comes to 3D visualization [397], constituting a domain that is employed in a variety of fields. Apart from research, consumers are enthusiastic to embrace the new technology: according to Google, the interest on Virtual Reality has increased 400% during 2016 [462], illustrating the mainstream attention that VR is gaining nowadays.

2.5.1. Research on Virtual Reality

The proliferation of Virtual Reality in the past few years is strictly related to hardware improvements that cover the increased technical demands for the provision of stereoscopic rendering. Head mounted displays (HMD) nowadays support high frame rate rendering (at least 120 frames per second, 60 for every eye) which provide smooth and flawless rendering, therefore improving user experience and reducing discomfort and virtual reality sickness.

VR systems make users perceive that they are physically present in the rendered non-physical world. This feeling of immersion is accomplished through the combination primarily of vision and secondarily of sound. Other approaches involve additional human senses such as touch [188] and olfaction [75].

VR allows the creation of novel paradigms for presenting cultural elements, rich in informative and emotional contents [280]. To this end, several approaches investigate different alternatives for interacting with virtual environments in a natural manner. Typical controllers accompanying commercial devices such Oculus Touch [310] and HTC Vive [193] controllers provide a widespread interaction method for precise input in virtual reality applications. Moreover, free hand interaction with camera-based hand tracking is also supported by cameras such as the LeapMotion sensor [250], where users' hands are replicated in the virtual world [476 and 254] and can be also augmented with tangible artifacts such as sand [139], reducing interaction precision but also fostering playfulness and improving the overall user experience.

Immersion in VR environments can be helpful for further engaging people into the virtual world, suspending the feeling of disbelief and stepping out of the real world into another dimension through which they can accomplish their own goals. These goals can be set by the creators of the virtual environments so that they are constructive and helpful across a variety of domains. User immersion and 3D visualizations provided by VR environments satisfy diverse needs across different domains.

Cultural Heritage constitutes another domain in which several efforts were made to over a long time [144]. Artifacts are also presented by [151] in an effort to showcase aspects of historical information through augmenting 3D geometry. Moreover, attempts to immerse users into entire virtual historical cities [343] aiming to provide them with a first-person perspective of their look and feel.

In the **healthcare** domain, the advantages of the application of Virtual Reality are twofold: it can be applied either for the training of doctors in a realistic environment without endangering a person's health (e.g. surgical skills training [164 and 443]) or for immersing patients in virtual environments and motivating them to perform rehabilitation exercises in a pleasant manner. As far as patient rehabilitation is concerned, VR is applied to cases such as stroke rehabilitation [203] and neurorehabilitation [66]. Finally, virtual reality applications are also used for educating and training medical faculty for surgical operations [323].

Tourism constitutes an additional area of VR application [171, 225]. In terms of location reconstructions, ancient environments enhanced with virtual humans are displayed in VR by [16]. Several implications of virtual reality are presented by [173] in the domain of tourism, including planning and management, marketing, entertainment, education, accessibility and heritage preservation.

VR constitutes an affective channel in terms of user experience and feeling generation, making it an efficient tool for **marketing**. The work presented by Riva et. Al. [350] confirmed the value of VR as an affective channel, illustrating the proficiency of virtual environments to invoke certain emotions which produce the corresponding affective reaction, such as anxiety and relaxation.Marketing VR provides an effective platform for experience marketing [370], able to further absorb and immerse users in advertisements in comparison to traditional approaches like television [249].

In terms of **education**, VR technologies are employed in collaborative virtual environments for the development of learning and communicating skills, such as E-Teatrix [316]. Furthermore, serious games are employed for education in the context of stories by [486], allowing users to experience a personal view of mythology.

2.5.2. Industry Virtual Reality Applications

Game engines and commercial SDKs are the main ground upon which industry and research are based in order to create Virtual Reality applications. The main game engines employed include Unity3D [433], Cry Engine [92], Unreal Engine [440], while other alternatives such as AppGameKit VR [13] and libGDX [261] are also used. Gaming constitutes the primary focus of industry related to virtual reality. Existing approaches include the following applications:

- First Person Shooter games, such as Robo Recall [354].
- Third person Role Playing Games such as Chronos[82], where users have to solve puzzles and confront enemies on a quest to save their homeland.
- Music games like AudioShield [19], where users try to catch music beats, experiencing music through an interactive mini-game based on automatic sound analysis.
- Simulation games like The Climb [405], where the user climbs virtual rock formations.
- Adventure games, such as Technolust [401] that looks like an interactive visual novel and Edge of Nowhere [125], where the protagonist tries to save his fiancée, which feels like a horror story.
- Multiplayer Cooperative games, such as Keep Talking and Nobody Explodes [219], where the users' goal is to disarm procedurally generated bombs.

Apart from gaming, documentaries and short film making is another domain that VR applications focus on. The New York Times present documentaries and reportages through NYTVR [303], immersing users in the sceneries where the stories are taking place. Within application [468] allows users to view VR content from distinguished creators.

Paint VR [130] and Google Tilt Brush [156] allow users to paint in a 360-degree environment, facilitating creativity in three dimensions and supporting the export of 3D content.

Finally, Google Arts and Culture VR App [153] presents cultural heritage information in a completely virtual environment.

2.6. Mixed and Augmented Reality

The virtuality continuum [290], presented back in 1994, describe the mixture of real and virtual environments using computer generated imagery (CGI). In recent literature, several visualization mediums are combined in order to build upon the advantages of each medium. An early approach is presented by [463], combining Augmented Reality, Virtual Reality and web visualizations in order to create value-added user experience and offering remote visiting.

2.6.1. Research on Mixed and Augmented Reality

Augmented Reality (AR) may be defined as a real-time direct or indirect view of a physical real-world environment that has been enhanced / augmented by adding virtual computer-generated information to it. According to [132] Augmented Reality (AR) refers to computer displays that add virtual information to a user's sensory perceptions. Augmented Reality enhances the user's perception of and interaction with the real world by superimposing virtual objects and cues upon the real world in real time [38]. Augmented Reality is not restricted to sight, but can potentially apply to all - human senses, such as touch, hearing and smell [336].

The first wave of research on Augmented Reality took place in the 1990s and research focus on AR flourished during the 2010s due to the hardware improvements that took place. The applications of AR technology, as stated by [22], included medical cases, manufacturing and repair, annotation and visualization, robot path planning, entertainment and military aircraft. Papagiannakis et. al. [324] present a survey for the applications of Augmented Reality to ubiquitous computing, focusing primarily on the review of Mobile Augmented Reality Systems (MARS), presenting diverse approaches and their limitations.

Interaction in Mixed and Augmented Reality is largely affected by the display medium provided to the end user. Typical AR applications based on mobile devices such as smartphones employ multi-touch as a well-known input mechanism with which the vast majority of users are familiar. On the contrary, in the case of installations which are capable of augmenting physical elements via light projection, such as tabletops, a variety of approaches are surveyed. Computer-vision based element recognition using RGB and RGB-D cameras can provide 3D hand tracking interaction [252] and gesture recognition [253]. Furthermore, computer vision based tracking can also facilitate touch interaction in 3D space even in cases where the touched elements bear no technological components such as metallic surfaces [161] and books [320]. Finally, the combination of various input techniques via multimodal interaction is also present in the context of AR and MR applications [55].

Augmented Reality experiences are available to more users than ever before due to the rise of mobile devices and web technologies. The ability of AR to extend and enhance the user's surrounding environment allows state-of-the-art AR applications to be employed in a wide range of domains.

In the domain of edutainment, the authors of [196] create a mixed reality environment in a natural history museum by interlacing living animals, improving the entertaining experience and providing educational information. In this direction, Mixed Reality is employed for enhancing the perception of tangible objects via haptics [102]. Additionally, Augmented Reality is employed by [276] to enhance physical books in an Ambient Intelligence learning environment.

Architecture constitutes an indicative domain where superimposing information on designs, such as floorplans, is very supportive. One of the applications of AR is urban planning and buildings preview [251], which utilized geolocational data to create augmented 3D views of building constructions over a physical map. Other approaches include architectural construction, inspection and renovation [460] as well as the construction of public large-scale structures like bridges [477].

Tourism applications can be used to augment real scenes, enriching the users' environment [138]. Han et. al. [174] presented the implications of AR in urban heritage tourism. Linaza et. al. [263] presented an approach for enhancing tourism through gamification of travel destinations.

Augmented Reality constitutes a sustainable marketing tool, as it enhances the customers' user experience and builds long-term brand benefits [60]. As stated by [34] AR grows user engagement as it constitutes a novel technology which captivates the users' attention. Another example of AR in marketing was the case of MINI advertisement, where the company superimposed a 3D car model on plain printed paper [291]. Augmented Reality can contribute in cultural heritage sites, as it has economic, experiential, social, epistemic, cultural and historical, and educational value [412].

Mixed reality (MR), sometimes referred to as Hybrid reality (encompassing both augmented reality and augmented virtuality) refers to the merging of real and virtual worlds to produce new environments and visualizations, where physical and digital objects co-exist and interact in real time. Mixed reality encompasses augmented reality and augmented virtuality as it does not take place in the physical or the virtual world, but in a combination of the two. Mixed Reality is applied to Ambient Intelligence in various contexts, including games, where mixed reality is applied to augment tabletop games [485] in order to preserve the physical artifacts of the game and cultural heritage [201], where Grammenos et.al. [163] use pieces of paper that host additional information upon placement over areas of interest.

Mixed reality installations are also created using room-scale worlds. Such an approach is presented by [215] by combining VR headsets and object tracking based, cave installations for facilitating storytelling [300] and cultural heritage [322]. Moreover, mixed reality headsets such as the Microsoft Hololens device [287] are also widespread in literature, employed in the context of product assembly [129], surgery operations [403] and anatomic pathology [175].

Finally, other approaches combine virtual and mixed reality by substituting the user of the VR device with an avatar [332], thus facilitating the feeling of presence in the context remote collaboration and assistance.

2.6.2. Industry Augmented Reality Applications

The proliferation of smartphones and high-end technology has let industry build upon the creation of augmented reality applications available to end users utilizing mass market devices. The hardware that is embedded in everyday devices is now capable of sensing the environment in detail, as gyroscopes, accelerometers and magnetometers are included in smartphones and high resolution cameras facilitate detailed picturing of the world around the users. In addition, the processing power and memory supported is sufficient for running applications that utilize the sensors concurrently with user interfaces that are computationally expensive. Finally, custom hardware is designed to suit the needs of tracking in the case of Tango Project [155] in order to optimize tracking, power consumption and processing power requirements. Other approaches include Apple's ARKit, where more than 13 million applications utilizing were downloaded in six months in 2018 [404], the widespread Vuforia AR SDK [451] and Kudan AR SDK [241].

To this end, a wide range of augmented and mixed reality applications has been developed and is available through the online market by independent developers, small and medium enterprises and large studios [293]. This section describes existing applications that are relevant with the research presented in this work.

In the domain of gaming, Pokemon GO [333] was a location-based augmented reality game released in 2016 with more than 500 million users that provided the incentive to be more active in the real world looking for virtual avatars mainly in public spaces. Ingress [198] was an earlier location-based Massive Multiplayer Game (MMOG) that is also a form of exercise (exergame) based on a science fiction plot.

Amikasa [9] is an augmented reality app that offers the augmentation of existing spaces with virtual items, such as furniture and electrical devices, in order to preview the surrounding environment with the selected items. In addition, the app allows users to shape their room in a virtual environment and try out how it is affected by different lighting conditions by changing curtains or by changing the floors and walls colors.

WallaMe [453] creates a world which is augmented by user-created messages. Each user can add stickers or textual messages and share them with either all the users of the application or with specified friends. Quiver [340] allows users to choose among a set of ready to print designs that can be tracked and augmented through the app, displaying 3D content and displaying short animated stories on top of the printed material.

In terms of guidance using augmented reality technologies, Augmented Car Finder [20] helps users to navigate towards their parking spot. GeoTravel [147] lets users create trips and places to visit, previewing the selected points of interest in the smartphone view and displaying corresponding indicators which can supply information such as current distance and historical data.

2.7. X-Reality visualization frameworks

Complementary to the previous sections presenting research and industry efforts focusing on Virtual and Augmented/Mixed Reality, this section discuss on the frameworks present in literature and in industry offering the ability to create X-Reality applications; the vast majority of such frameworks relies on game engines with VR capabilities like the ones described in section [2.5]. This section aims to highlight the efforts which take place at a higher level, providing the ground and tools which can assist the assembly of virtual and augmented/mixed reality application.

Such efforts include work on employing Virtual Reality in the context of Cultural Heritage: [222] record and visualize existing artefacts, [227] focus on photorealism in VR reconstructions and [234] only target on gamifying Cultural Heritage sites. In the same context, DynaMus [226] is a very interesting framework combining input from various Cultural Heritage sources that is able to showcase content dynamically in VR environments. Similarly, [233] present a framework utilizing content retrived from Europeana in VR environments. The main limitation of these efforts has to do with the absence of capability to integrate content into its context, i.e. a virtual environment, which can generate the feeling of presence. The experience of virtual museums is covered by [149], where the authors provide virtual museum environments along which the users can seamlessly switch in order to explore various content collections.

In the context of Mixed and Augmented Reality, several approaches have focused on creating systems and frameworks for information visualization. Mixed reality frameworks are mainly targeting CAVE installations [299] and room-scale mixed reality setups [215]. Multiple mixed reality environments are presented by Roo and Hachet [355], enhancing physical reality with different content in order to illustrate alternate perspectives of reality; this work however is only an application and not a complete framework.

As far as the domain of Augmented Reality visualization frameworks are concerned, [319] present an AR mobile phone application which is capable of super-imposing 3D reconstructions of archaeological sites and buildings over their current view, thus putting their initial look-and-feel into context nowadays. Efforts regarding the employment of AR applications in the context of museums and virtual collections also include Veholder [178], which discusses on the challenges and the potential of such approaches. Moreover, GoFind [365] present an AR application to dynamically retrieve content in which users are interested in and enhance their physical surroundings via images and videos.

Despite the fact that Virtual, Mixed and Augmented Reality share many characteristics and can reuse visualization components, there are very few efforts aiming to support them concurrently using a framework. One of the first efforts in this direction was VHD++ [335], a framework for reusing components in the context of X Reality setups. A very interesting example is presented by [212], where the authors present a thorough approach towards more adding value to the overall user experience by combining X Reality features such as AR, VR and tangible 3d printed artefacts. This research combines several aspects of the reality continuum interactively, but does not bring them under a common umbrella and a common conceptual model that can be further extended to other research areas. Furthermore, [52] present a framework along with preliminary AR and VR applications towards creating engaging storytelling. This work successfully merges AR and VR presenting narratives, but can only achieve this within one specific context without mixing other potential correlations.

Symmetrical reality is mentioned by [481], where the authors discuss the concept of correlating physical with virtual reality. This work analyzes the perspectives perceived when residing at virtual and at the physical side, when these are combined in a symmetrical manner.

X-Reality has the potential to correlate the physical world with symmetrical virtual ones, residing either in completely virtual environments (VR), partially visible within our physical surroundings (AR) or somewhere inbetween (MR), where the boundaries of the physical world is interwoven with the virtual one. To this end, there is currently a gap in research in terms of creating a framework which is able to holistically cope with the challenges of representing and visualizing multidimensional information using X-Reality in a scalable and flexible manner.

2.8. Conclusions

The previous sections illustrated the challenges with regards to designing and building a holistic approach which is suitable to visualize multitude of information types. To this end, a data type analysis was reported; in addition, the visualization approaches mentioned in state-of-the-art applications were presented with regard to their domains, ranging from Cultural Heritage and Big Data to virtual environments storytelling. Ambient Intelligence and interaction methods were analyzed in order to identify ways to capitalize on the ways that users can interact with smart environments. Moreover, state-of-the-art approaches for X-Reality were presented, including both industry and research outcomes, in an effort to identify trends and capabilities offered by modern technology.

These sections were presented so as to draw a complete picture about the fields that are tightly coupled with information visualization in X-Reality systems across diverse domains. This is aimed to act as the ground for defining the requirements and future research directions with regards to shaping an X-Reality framework.

As the final step for this literature overview, existing X-Reality frameworks are identified and analyzed in terms of their extendibility and adaptability for visualizing information in diverse contexts. This analysis helps identifying the current gap in creating a flexible and holistic approach which is not only capable of reusing components across Virtual, Augmented and Mixed Reality in various contexts, but also allows the integration of existing 3D applications within the virtual environments that are generated.

3. Motivation

Today, large data sources are ubiquitous throughout the world and their size will be ever-growing. Stemming from the massive increase of information availability, a new emerging field of research has evolved usually referred as Big Data. This research field, apart from the technical challenges in terms of implementing storage and retrieval, creates a volatile and unmanageable nature by definition. Big Data creates new prospects on gaining value from generated insights not only to analysts and data mining experts, but also to everyday users. The huge data size makes information retrieval and analysis a complex task regardless of the data type and context, presenting a challenge to improve the provided visualization techniques. Human cognitive limitations and the large data volume impair the perception of information [134], especially when taking into consideration the existence of relationships between elements.

The complexity of Big Data analysis presents an undeniable challenge: visualization techniques and methods need to be improved [312]. This fact is evident both in research and in industry, as a significant number of researchers and companies develop joint projects so as to visualize Big Data Analytics, establishing new interactive platforms and working on the supporting research in this area. Apart from traditional 2D interfaces, mainly generating dashboard-like visualizations primarily aiming to assist experts, the challenge arises to employ novel visualization methods and create novel visualization techniques which assist not only experts but the public as well.

To this end, Virtual Reality can assist in stepping away from planar images and charts into multi-dimensional visualizations. The adoption of Virtual Reality can assist visualization by improving usability and efficiency, as well as providing enhanced user experience. Stereoscopic rendering allows users to intuitively perceive the depth dimension without cognitive effort, while also engaging them via the creation of the feelings of immersion and presence [266]. Novel applications developed using Virtual Reality should be volatile and support actions such as navigating in virtual spaces [42], switching between different sub-spaces and views, allow manipulation of virtual elements [114], provide consistent, natural and easy to learn visualization metaphors, and provide rich interaction via multimodal input [413]. Moreover, cross-disciplinary efforts should combine the research fields of Human-Computer Interaction, Machine and Deep Learning, Computer Vision and Computer Graphics in order to combine the outputs and knowledge of each field in order to build a common ground for creating rich high-definition visualizations that are efficient in terms of performance, and natural as well as enjoyable from a user perspective [44 and 312].

By mixing (Augmented and Mixed Reality) or entirely substituting (Virtual Reality) the environment users perceive, or their combination also referred to as X Reality [325], can act as an efficient medium to transmit information to the human brain. Augmented and mixed reality systems are capable of smoothly interweaving information to a matching content, presenting it in a straightforwardly perceivable manner and improving human experience. Virtual Reality does not only provide an immersive platform to build upon, but provides an excellent visualization medium due to the sense of depth achieved via stereoscopic rendering. To this end, the need arises for modern systems and frameworks to take advantage of three-dimensional spaces in order to provide functionality which allows spatial data arrangement.

Big Data characteristics, namely volume, velocity and variety, raise the requirement of visualization systems to be responsive and completely scalable: responsiveness requires that the entire environments are dynamic and can be easily adapted, whereas scalability involves providing a clear model which is not limited to a specific volume. Moreover, flexibility limitations may prove traditional visualization approaches to be inadequate in the near future; Big Data requires systems to be adaptable to a variety of different data sources. Moreover, contemporary visualization methods [2.2.3] are not optimal in terms of tackling the cognitive limitations for the human brain to perceive complex relationships and large data volumes [312].

Due to the diverse nature of information, the need arises for designing a framework which not only provides a thorough set of ready to use components and micro-applications, but is also scalable and extendable to dynamically receive additional components. In addition, large data volumes, (collected by diverse data sources) require the ability for the framework to support grouping and organizing information into segments.

As discussed in section [2.3.8.1] regarding Big Data visualizations, the majority of existing approaches for the visualization of large volumes of information tend to focus primarily on the processes of information seeking, decision making and drawing conclusions, disregarding the provision of human-centered user interfaces in order to efficiently visualize the content. Despite the increasing interest in the storage, retrieval and visualization of rich data for experts, a relatively small portion of the effort focuses on the establishment of a conceptually simple and intuitive model that is appropriate for non-expert users.

Therefore, the framework should provide a simple mental model for information organization which can be easily perceived by end users. Apart from being appropriate in terms of scaling, this model should be provided in a manner which allows users to change between different environment visualizations seamlessly.

Widespread and well-established means of interaction, such as touch screens, are efficient for managing two dimensional displays, as input is naturally confined in two dimensions. However, when interacting with three-dimensional user interfaces, the need arises to provide interaction input in three dimensions as well: interaction complexity rapidly increases due to 6 degrees of freedom and a larger interaction vocabulary is required. Such rich interaction techniques are challenging to create without affecting the naturality, efficiency, gamification or precision of interaction.

Given that existing solutions are relatively narrow in scope and efficient in specific target domains, the need arises for a holistic approach to generate an adaptable and reusable framework which supports multimodal interaction in three-dimensional environments. The provided interaction techniques should combine efficiency with enhanced user experience, supporting the feeling of presence and immersion. Moreover, this should be achieved using reasonably priced display and sensory equipment, widely commercially available and requiring the minimum costs for deploying applications.

The nature of both Big Data and Cultural Heritage information hold a common impediment to data exploration: although the information itself is the same, the way and the sequence in which it is presented greatly affects the users' ability to perceive it. Domain experts, such as big data analysts and cultural heritage curators, are able to provide insights and correlations which are almost impossible for non-expert users to identify. Therefore, in addition to the augmentation of items and ideas, the need arises to narrate stories that utilize the different components and present them as a sequence of events. This way the visualization adds up value to the information itself, as it correlates the different information segments in non-obvious ways, shows a way of thinking, and explicitly presents the sequence of the story.

The adoption of state-of-the-art sensing and display devices, such as smartphones, cameras, AR and VR devices, can cover the processing and rendering requirements for facilitating visualizations which are rich both in terms of content and usability. To this end, the framework proposed in this thesis aims to contribute towards the adoption of Augmented, Virtual and Mixed reality via the design and implementation of a framework that fits contexts ranging from Big Data to Cultural Heritage visualizations. This goal is aimed to be accomplished by gamifying user interaction and facilitating the feeling of immersion and presence to the users, thus creating a fascinating experience while they explore three-dimensional environments.

4. Information Worlds

This research work aims to show the potential of applying augmented, virtual and mixed reality technologies towards visualizing information originating from Big Data and Cultural Heritage. The presented framework, named Information Worlds, facilitates the visualization of domain independent information in the context of Ambient Intelligence environments, by allowing to visualize rich information stemming from large data volumes in accordance with the stakeholders' interests. As in the real world, the data which this work aims to handle as input is multidimensional and interconnected. The objective of this framework is to provide the tools for creating virtual environments, produced either automatically or by experts, that will allow information exploration by end users. The framework is able to display different aspects of the data provided, presenting multidimensional information which varies in volume and interconnections in a user-friendly way that allows users who are not familiar with the subject to efficiently explore different types of content. Moreover, another goal of this research is the provision of adaptive user interfaces that offer personalized visualizations in accordance with each person's profile.

In terms of data sources, the framework is compatible with two major domains that result into complex visualizations: big data and the semantic web. The generated applications will not only be capable of displaying information originating from either data source, but also providing a common ground for content reusability. Furthermore, the envisioned framework supports interoperability between applications, allowing the orchestration of applications in accordance with users' actions and creating a unified ecosystem that surrounds users.

Currently, 3D virtual worlds are employed to shape environments which can be explored through interaction. However, so far they fail to coordinate narratives which correlate different environments in a coordinated manner. Therefore, the need arises for the enactment of adaptable applications that compose narratives using smooth transitions between events that shape different scenes and provide personalized experiences.

The following sections describe the concepts that lay the foundations of this research work. The concepts presented in this chapter aim to model information into elements that can represent the vast majority of data types, aiming to ultimately cover the widest possible range of visualization needs. The individual elements are discussed in detail, with each section presenting a specific notion that comprises a part of the model of Information Worlds.

4.1. The Concept

This work presents a framework which facilitates the creation of virtual or augmented worlds that visualize multidimensional information in the form of virtual universes, i.e. **Information Worlds**. The framework assists visualization creators in designing, customizing and bringing into existence envisioned environments or existing locations which are augmented with the provided information. Apart from defining the environments, the framework allows information organization in explicit components, assisting the unambiguous representation of semantic knowledge and making the interactive components apparent to the users.

Information Worlds can be constructed by making use of a multitude of constituent interactive entities that encapsulate information segments, i.e. **Information Things**. Information Things compose an internet of things surrounding, as they are entities distributed in the environment, clearly visible to end users, and create a network of items that users can explore. Information Things are comprised of interactive element templates, named **Information Pieces**, which are autonomous in terms of content, visualization and interaction. Information Pieces are able to depict both static information and dynamic content that varies over one dimension. Furthermore, **Information Bindings** are utilized to model and present relations across entities which can be of different types.

In addition to the locational distribution of information, Information Worlds also feature the concept of story narration. **Information Stories** are entities that contain information about a network of events which can be explored. They contain all the data available for depicting the complete story in a structured manner. This can be accomplished in a variety of ways by means of **Information Narratives**, each illustrating the story's big picture from a specific point of view. These aspects constitute a fundamental tool for information presentation in line with the context of use, the purport to be shown and the user's interests.

4.2. Information Worlds

The Information World is the environment in which a user begins the exploration of the visualized world. It can involve existing surroundings which are augmented with information, such as an archaeological site or any indoor space, or completely virtual if the physical environment does not fit the needs of the visualization, such as a ministry operation room or an imaginative world.

In any case, the selected environment is shaped in such a manner that it delivers the context for the provided information. Information organization and clustering in visualizations is performed according to certain characteristics creating an Information World. The system immerses users in an augmented reality or a virtual environment as a starting point, but it also will offer straightforward and seamless transition to additional worlds. Such additional worlds can be utilized as tools to represent different domains, provide diverse perspectives or even illustrate alternate realities.

The presented framework builds upon different visualization components, each illustrating another aspect of the visualized data. The world created by the virtual environment can be filtered to display only a portion of the information visible by default, creating a multi-faceted environment that illustrates different aspects in accordance with the user's interests.

4.3. Information Things

Our world perception correlates information with objects or notions in order to model and structure knowledge. The world around us contains information which is encapsulated in our surroundings, such as their color, shape, size, ingredients and position. In a similar manner, digital data also contain metadata that provide information about the data, which can be descriptive (e.g. title, author), structural (e.g. relationships with other data) or administrative (e.g. technical information). Metadata describe, provide context, indicate the quality or document other object (or data) characteristics [167]. These fragments of information can be considered as information clusters that are closely coupled.

Information Things are able to depict the fragmentation of information that is inherent in reality around us. For instance, a visualization of a large organization includes several departments which distribute / share knowledge among them. Heterogeneous information is spread across the environment, grouped into clusters (Information Things) that are distinct elements and sharing certain aspects and altogether comprise the Information World's knowledge.

Knowledge which resides on an Information Thing constitutes a distinct piece of information within a standalone entity. While this is usually a flaw, as it removes the connectivity to other data, it can be useful to organize information in an unambiguous cognitive model. The human brain is trained to obtain and perceive structured information [356] and therefore, by dividing information into clusters, it is easier to put it into context. Data clustering allows information categorization based on one or more characteristics, such as location, time or semantic meaning.

Furthermore, the fragmentation of Information Things can potentially lead to clusters containing a multitude of Information Things. These clusters can be defined as **Information Thing Groups**, which bundle Things in one entity when explored macroscopically, but are decoupled when viewing them up close. For instance, when presenting a 3D visualization of a library, each book can be presented as an Information Thing, but when showing the library overview, each sector of the room is treated as one entity with specific characteristics; on the other hand, when approaching the sector, Information Things corresponding to books are separated to provide all the details. Therefore, visual clutter is avoided and users perceive information in a clearer view.

Figure 2: An Information Thing with three accompanying Information Pieces

4.4. Information Pieces

Information Pieces constitute individual components of an Information Thing. They can be seen as monolithic modules that organize segments of data subsumed into an information unit and shape an entity waiting to be explored. They are able to depict a specific aspect of an element, creating an automatically generated visualization which can host various information types or relations. The framework provides an extendable set of templates which can be utilized to describe details about Information Things.

Information Things can represent static information by remaining constant but interactive, allowing on-demand exploration. When representing static information, Information Pieces may receive and add new information on the fly, but users have to explore the component to find the changes. For instance, if displaying a set of photographs, the addition of a new photograph will not necessarily take place on top of the ones visualized, but will possibly be hidden by others.

While the majority of data is persistent across a dimension, it can also change over another dimension, creating dynamic data segments. Such examples can involve several characteristics:

- An object's properties may change over time
  - Sound intensity
  - Item ingredients
- An object's properties may change in accordance with their location
  - Demographic characteristics can change across a country's different regions
  - Temperature
- An object's properties can be altered according to the viewer's location
  - A concrete wall looks solid and firm from a distance, but when moving closer, the dimples and holes that mark its surface are visible
- What-if scenarios / story telling
  - In agreement with a condition, the progress of a scenario may change: for instance, when using an AR mobile phone app that augments an interactive system, the augmentation depends upon the user's selections in the interactive system.

In terms of dynamic data, Information Things also support the presentation of data segments that change over one or more dimensions. This approach uses time to display the data segments moving, illustrating the changes that occur over time.

The visualization of an Information Thing showcasing dynamic information typically comprises an area over which information flows, in a manner similar to the way the water flows in a river. Indicative examples of potential Information Things applications include the display of news feeds and the presentation of meteorological animations designating weather changes over time in a specific area.

Figure 3: Concept of Information Pieces in Augmented Reality

4.5. Information Bindings

Entities which exist in the presented concept are standalone, well-defined units which conceptually and physically compose the virtual environments created using the framework. Entities are suitable for grouping data into clusters in accordance with specific characteristics; however, another fundamental aspect involves the relations between distinct elements.

Information Bindings are defined here as the means to model and present relations between entities, i.e. Information Worlds, Things and Pieces. The related entities may vary in type, as associations can be made between completely different items and for diverse reasons. For instance, a company can own a desktop computer (relation between an information world and a thing), the computer can be of a certain brand (relation between information things), and its technical characteristics can be identical to another computer (relation between information pieces). Information Bindings are depicted as concrete graphical elements that connect items directly if meaningful (e.g. two nearby exhibits), or can illustrate connections with more abstract elements, such as other information worlds.

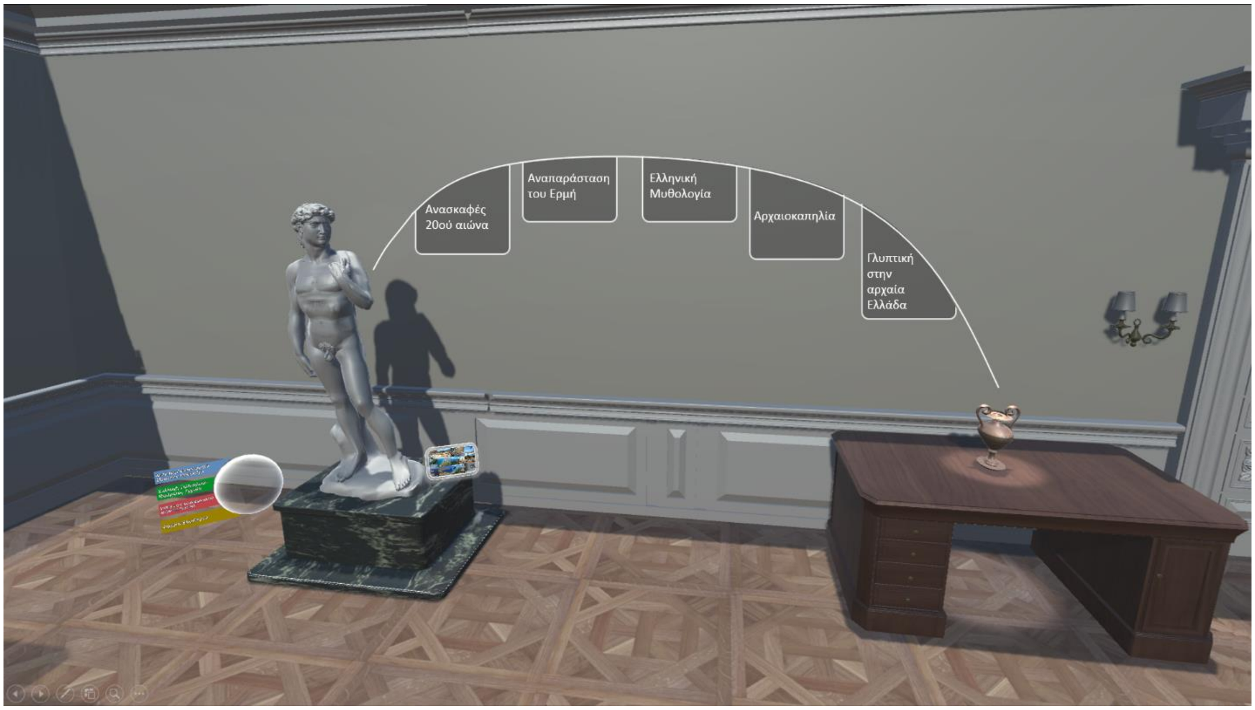


Figure 4: Example of a potential Information Binding visualization

4.6. Information Narratives

The nature of information can be similar to the way the human brain works: thoughts are formed by following a path from an initial notion and after several steps lead to an idea or a deduction [455]. Alike, information about separate items is interconnected semantically or physically, resulting into a process which is similar to graph exploration [461], by beginning from a specific item and leading to a variety of different endings.

Therefore, in accordance with visiting different elements within the framework (e.g. Information Worlds, Information Things and Information Pieces), the exploration of information can be elevated into the process of **Information Hopping**: users travel from an initial location to the final destination through a set of information things which they visit for a varying amount of time. The time spent on each node often designates the amount of interest on the corresponding island, weighting the hops of the travel.

Information Narratives provide means to describe and reproduce Information Hopping processes. They constitute a model which can depict a set of actions (e.g. visit Information Things, exploration of Information Pieces and display of certain content) and establish a sequence in which they are ordered. An example of Information Narratives could include events that related to paintings created over an artist's life. Information Narratives are an illustrative example of dynamic data changing over one dimension: the facts remain the same, while the illustrated content change over the dimension of time. In addition, narratives can define alternative paths that can be explored, offering a set of different narrations that can be presented according to the user's profile or the options chosen during the interaction.

Furthermore, Information Narratives are able to present information illustrating closeness of meaning and cause/effect bindings between entities. This process, which can be straightforward for experts using complex visualization tools, is not natural to non-experts, whereas stories and narrations can be more effective [97]. Therefore, the mechanism of information narratives can assist the process of critical thinking and binding associations between events, both for adults but especially regarding children [388].

4.7. Information Stories

Information Stories can be seen as a more complex alternative of Information Narratives: while Information Narratives are able to present a sequence of events, Information Stories are able to describe a network of events. Information Stories can, in terms of content, be considered as a superset of Information Narratives, as a story is able to model both the information presented in a narrative but also contain information that is not shown in the narrative. On the other hand, Information Narratives can be considered as traversals of an Information Story, in the sense that they present sequences of events that originate from the corresponding story. For instance, if the sequence of the presented events changes, then a new narration is generated, while the story remains identical. Finally, the provided storytelling techniques (either through Information Stories as a whole or through Information Narratives) are able to express all the contextual information that transform event sequences into an interactive narration, thus providing a thorough mechanism which improves user experience and shapes stories that add value to each event separately.

4.8. Information Worlds and the superstring theory

Dimensions are different facets of what we perceive to be reality. According to the superstring theory, there are at least 10 dimensions in the universe [334 and 402]:

- 1st Dimension – **Length:** Similar to X-axis
- 2nd Dimension – **Height:** Similar to Y-axis
- 3rd Dimension - **Depth:** Similar to Z-axis
- 4th Dimension - **Time:** any value in the first three dimension can change over time
- 5th Dimension - **Slightly different worlds**: In the fifth dimension, one world is different from another having the same starting point. An example of this dimension can be one person instead of going from place A to place B to go to place C.
- 6th Dimension - **Plane of slightly different worlds**: The sixth dimension creates a plane of different worlds, where one person can go from place A to any other place X.
- 7th Dimension - **Possible world with different initial conditions**: In the seventh dimension, you have access to a set of initial conditions. In the example of user going from place A to any place X, you have the ability to start from a list of places A_1 to A_N.
- 8th Dimension - **Plane of possible worlds with different initial conditions**: In the eighth dimension, there is an infinite number of initial conditions – the user can start from any initial position Y and reach any place X, resulting into infinite sets of initial conditions and potential branches.

- 9th Dimension - **All possible universe histories with all possible laws of physics and initial conditions**: In addition to the infinite sets of initial conditions and potential branches, different laws of physics can apply.
- 10th Dimension - **Universe where everything is possible**: In the tenth dimension, we reach a state where everything is possible.

Existing interactive approaches in information visualization utilize worlds (universes), either augmented or virtual, which picture a creation enriched with information. Information Worlds build upon the creation of additional dimensions, namely the 5th and 6th dimension of the superstring theory, in order to illustrate alternative aspects of data, and potentially involve the 7th dimension. Following this approach, the proposed framework builds upon the creation of multiple universes that host information ecosystems.

The Information Worlds framework is able to depict alternate versions of environments which can be unveiled either via interactive exploration or by storytelling. Therefore, different Information Worlds can depict an alternate version of the world which users are currently experiencing, thus satisfying the condition of the 5th of the superstring theory by allowing users to experience different realities beginning from the same starting point. Moreover, the framework is capable of supporting various alternatives of the virtual environments (either by creating structurally different worlds or by visualizing content which is dynamically provided), thus creating the 6th dimension which becomes available to the users.

For instance, Parthenon was built in 438 BC and was severely damaged in 1867 during an ammunition dump due to bombardment. If one Information World within an application developed by the framework visualizes the current state of the archaeological site, an additional Information World could render the way that the monument would look like if this had never happened, acting as a 5th dimension. Moreover, the 6th dimension is supported via additional versions of this alternate version of the initial Information World, which can be included within the application: additional Information Worlds can showcase the same environment with or without the expected physical decaying, with or without the statue of Athina, etc.

5. User Groups and requirements

This chapter aims at specifying the target user groups that are involved in the process of information visualization. These user groups include both people who participate in the creation of the environments that host the visualization and the individuals who benefit from the visualizations by exploring the provided information and perceiving the communicated messages. This user base sets specific requirements for the way the framework should be structured and developed in relation to aesthetics, usability, perception, learnability etc. Each of these requirements encompasses a specific user goal that should be achieved through the usage of the Information Worlds framework.

5.1. Stakeholders

This section identifies the stakeholders taken into account in the conducted research work, by analyzing the way that potential stakeholders are related to the framework and making an in-depth analysis of the target user groups involved in each of these fields.

5.1.1. Professional Users

The stakeholders that can be classified as professional users involve the experts and faculty who are involved in the process of shaping the various Information Worlds and analyzing the anonymous user data provided by the framework, generated by interaction monitoring. These user groups are not experiencing the final results as end users, but are involved in the iterative process of creating a final result, receiving feedback, updating the end application, receiving new feedback, and so on.

5.1.1.1. Visualization Creators

The first user group regarding the formation of a visualization is the people who create it, i.e. **Visualization Creators (UG1)**. Visualization Creators consist of a variety of professionals who can be specialized in different domains. Their expertise can be used in order to enhance the visualization in terms of aesthetics (e.g. designers and graphic artists) and provide suitable content (domain experts, e.g. archaeologists for a museum, infrastructure administrators for a data center, teachers for an educative application or even software applications that automatically add content). Moreover, the user group of Visualization Creators is also entailed in the information organization and the structure of the generated entities.

5.1.1.2. Analysts

Finally, the data collected during the interaction constitute a valuable source for insights regarding user interests, interaction patterns and profiles. Such information is examined by **Analysts (UG4)** in order to improve the applications in terms of content and presentation through automatically generated user feedback, and reach to valuable conclusions. The Analysts user group is closely coupled to UG1, the Visualization Creators, as they provide feedback regarding the actual usage of the application envisioned by the creators, which can be utilized to examine whether the goals in terms of information provision are accomplished.

5.1.2. End Users

The end users are the people experiencing the final application created with the framework. They are not involved in the process of creating the various environments, but only explore the information visualized, either occasionally or on a frequent base.

5.1.2.1. Occasional Users

A fundamental user group that will use the framework concerns the users who are not a priori familiar with the framework, i.e. **Occasional Users (UG2)**. This user group includes the users that are fond of getting informed about the visualized domain, either by visiting a physical establishment that contains tangible exhibits (e.g. museums, exhibitions or public spaces), or by virtually exploring places which they are unable or unwilling to visit in vivo (e.g. areas with restricted access, areas located far away from the users' physical location or even virtual areas). They have no prior experience using the systems created by the framework and therefore are unaware of the applied concepts and means of interaction.

5.1.2.2. Frequent users

Apart from occasional users, another category of individuals is those who regularly employ visualizations created by Information Worlds for their everyday needs, i.e. **Frequent Users (UG3)**. Individuals who belong to this user group employ the deployed systems as tools for accomplishing certain tasks, which can be either related to their profession or their personal interests.

5.2. User Goals

In order ot elicitate the user goals, focus groups and brainstorming sessions with visualization and interaction experts took place, discussing ideas regarding the various users and potential personas. Moreover, unofficial interviews with corresponding stakesholders were conducted in order to extract valuable insights. Finally, observation of users using the system took place during the creation of early prototypes. The resulted user goals for each of the aforementioned user groups are the following:

1. UG1 – Visualization Creators

- 1.1. Facilitate domain information visualization
- 1.2. Create virtual worlds
- 1.3. Immerse users in the virtual/augmented environment
- 1.4. Customize the created worlds
- 1.5. Apply special visual effects to the created worlds
- 1.6. Use existing spaces as input and augment them
- 1.7. Define interactive things, i.e. points of interest
- 1.8. Use components for presenting multimedia information
- 1.9. Use components for presenting 3d models
- 1.10. Support for incorporating well defined data sources as input, e.g. ontologies
- 1.11. Support for high-speed, real-time information provision
- 1.12. Correlate individual entities
- 1.13. Narrate custom stories
- 1.14. Offer interactive narration
- 1.15. Support computer generated content

2. UG2 – Occasional Users

- 2.1. Explore information in an entertaining manner
- 2.2. View personalized content
- 2.3. Efficiently visualize all content types

- 2.4. Explore relationships between entities
- 2.5. Context sensitive information
- 2.6. Easy to learn concepts
- 2.7. Communicate with other users

3. UG3 – Frequent Users

- 3.1. Efficient traveling using rich interaction vocabulary
- 3.2. Provide information at a glance
- 3.3. Reliable and robust
- 3.4. Communicate with other users

4. **UG4 – Analysts**

- 4.1. Log actions per user
- 4.2. Log actions per system and component used
- 4.3. Keep track of the selected content

5.3. User Requirements

System Requirements capture the intended functionality and behavior of the system so as to drive architectural decisions and validate the architecture. Requirements were captured combining various methods, such as brainstorming, focus groups, personas, interviews and observation. Additionally, scenarios were built and discussed with potential end users in order to shape the virtual environments and user interaction. In general, requirements are partitioned into functional requirements and non-functional requirements [269]. Functional requirements specify particular functions, tasks and results of a system, while non-functional requirements describe the overall system characteristics.

5.3.1. Functional Requirements

In general, functional requirements can be expressed in the form of “system must do <requirement>” and defines the plan for the implementation of the system design. This section presents the functional requirements for the design and implementation of a framework used for large information visualization using a multitude of state-of-the-art displays, such as large displays, augmented reality devices and virtual reality headsets, based on the user groups and goals defined in sections [5.1] and [5.2]. These requirements constitute the basis of the definition of the framework’s rationale and design decisions as presented in this thesis.

1. UG1 – Visualization Creators Requirements

- 1.1. UG1-G1 implies the framework’s ability to visualize information belonging to one or more domains.
- 1.2. UG1-G1 - UG1-G4 imply the ability to create highly customizable virtual worlds using state-of-the-art computer graphics effects in which users can be immersed in for a value-added user experience.
- 1.3. UG1-G1 - UG1-G4 imply that the framework should provide facilities for presenting information from various sources in different contexts and for different purposes (e.g. educational, advertising, decorative etc.).

1.4. UG1-G6 describes the capability of the framework to support the augmentation of both artificial worlds, but also real-world reconstructions. This process can act as a base to facilitate the creation of augmented environments by using the reconstructed environment to place the augmented entities or even create virtual worlds that are replicas of the real ones.
1.5. UG1-G7 implies that the framework should provide means to annotate existing or added items as points of interests containing additional information.
1.6. UG1-G8 implies the provision of ready to use reusable templates that are able to illustrate multimedia content by simply providing the preferred data.
1.7. UG1-G9 implies the provision of ready to use reusable templates that allow users to manipulate in three dimensions one or a sequence of 3D models by simply providing the selected models.
1.8. UG1-G10 and UG1-G11 imply that the framework should be compatible with semantic information and also support additional input methods for large data volumes.
1.9. UG1-G12 implies the ability of the framework to model entities which contain relationships with others.
1.10. UG1-G13 and UG1-G14 designate the requirement for the framework to represent dynamic stories which the users can narrate in an interactive manner.
1.11. UG1-G15 define the framework’s ability to support real time content generation and provision by input sources and the straightforward integration into the visualization.

2. UG2 – Occasional Users Requirements

2.1. UG2-G1 implies the framework’s ability to create visualizations that facilitate information exploration in an efficient way by meaningful surroundings and well-structured information.
2.2. UG2-G1 implies that entertainment should be one of the goals of the provided systems.
2.3. UG2-G2 describes the capability of the systems produced using the framework to adapt to their user’s preferences.
2.4. UG2-G3 describes the capability of the systems produced using the framework to adapt the content visualizations according to the display device used.
2.5. UG2-G4 implies the ability of the framework to represent relationships between entities in an intuitive manner and allow their exploration on demand.
2.6. UG2-G5 implies the context awareness that the framework should support by providing information which is related to the context of interaction.
2.7. UG2-G6 describes the requirement for the framework to introduce concepts which are easy for users to learn, providing an assistive cognitive model to facilitate the perception of the information structure.
2.8. UG2-G7 implies the ability of the framework to communicate messages between the users.

3. UG3 – Frequent Users Requirements

3.1. UG3-G1 and UG3-G3 illustrate the need for users to perform complex manipulations of the cameras in the virtual 3D world in an efficient and reliable way.
3.2. UG3-G2 implies the provision of an overview and details on demand in a straightforward manner.
3.3. UG3-G4 implies the communication should be one of the goals of the systems generated by the framework. The systems should promote collaboration and enhance communication between users.

4. **UG4 – Analysts Requirements**
    4.1. UG4-G1 implies that the framework should be monitoring user actions on a personal basis, providing the ability to gain insights into user goals on a personal level at a later stage.
    4.2. UG4-G2 describes the need for the framework to collect information regarding user actions on a system level, allowing the offline analysis of the components utilized and the pattern recognition of user actions
    4.3. UG4-G3 implies that another aspect which should be recorded is the content explored, providing information about the semantic relations of the selected data.

5.3.2. Non-functional Requirements

Functional requirements can be expressed in the form of “system must be <requirement>” and describes the implementation characteristics that should be taken into account in the description of the system architecture. In a similar manner to the functional requirements elicitation, non-functional requirements were captured using a variety of methods, including brainstorming, focus groups, interviews, observation and personas. The quality characteristics which the framework should embrace include the following:

- **Learnability:** This requirement implies that any application built using the framework should require the minimum effort by the users to learn. This characteristic is fundamental for any information visualization application and is imperative for the framework to cope with the diversity of the target users’ population as well as the wide range of domains that it can be utilized. Learning involves both the perception of the visualized information itself but also the structure of the provided components to augment an existing or a virtual space.
- **Memorability:** Memorability implies the provision of simple and self-descriptive applications that do not rely on the users’ ability to memorize the steps required to perform an action. The provided systems should be consistent in terms of functionalities and presentation, while also allowing users to explore visualization in the way they would navigate through information entities in the real world.
- **Efficiency:** The framework should provide the tools for the adept and effective information visualization through the optimal presentation of the provided data. Additionally, the framework should support the mechanisms for expressive human computer communication by providing rich and natural interaction vocabularies for enhancing operations such as traveling and item selection.
- **Scalability:** Scalability refers to the framework’s ability to handle increasing or decreasing workloads, both in terms of data input and the extensibility of the employed model. The framework should support a multitude of input modes, varying in size and type, which can be represented and visualized. Moreover, the set of templates used should be flexible and support the addition of new concepts or visualization components.
- **Maintainability:** The framework should provide mechanisms to support its maintenance, facilitating its transformation and evolution in terms of interaction, design, input and cross

platform support. When it comes to interaction, the framework should additionally create self-maintained applications with minimum feedback from the user.

- **Usability:** Usability refers to the process of getting to know a system and using it in a productive manner. The visualizations created by the framework should be responsive, performant in terms of rendering, user-friendly and intuitive to use. Thus, the efficiency of user interaction will be facilitated and the user experience will be improved.
- **Interoperability:** The requirement of interoperability refers to the framework's capability of operating in an input and output independent way. Thus, the systems developed will be compatible with a multitude of input sources and can be employed in a variety of display devices.
- **Performance:** Due to the integration of state-of-the-art input and output devices, the framework (along with the generated applications) should be designed and implemented in a computationally efficient manner, supporting adequate render and refresh rates. Thus, the user experience acquired will be immersive and appealing to the end users.
- **Consistency in design:** the various elements displayed should have a consistent look and feel and interaction methods should be uniform
- **Network Connectivity**: the end applications created with the framework should be able to update their input remotely over a network, but also be able to operate without connectivity.
- **Cross-device and cross-platform compatibility**: the developed framework should be flexible in terms of the devices it can be deployed to, providing ways for the end application to be exported in various devices and operating systems.
- **Immersion and presence:** this requirement refers to the need for the users to be immersed in the virtual environments (either within a Virtual Reality or within a Mixed Reality application), creating a fascinating experience which will be enjoyed by the end users.

6. The framework

This chapter presents the design rationale and the final shape of key elements that consist the core concepts of the Information Worlds framework. It presents the way data is structured and represented, along with the ways it is presented through reusable visualization components. Moreover, key aspects like the way that Information World switching is performed is analyzed. Moreover, recommendations and the post-visit environment are described. Finally, the interaction techniques provided with the framework are presented and discussed.

6.1. Data Representation

This section describes the capabilities of Information Worlds to retrieve different information types, give access to knowledge to other framework components, and finally to support synchronization among distinct components (or even deployed applications) based on an abstract classification of interaction phases.

6.1.1. Combination with existing systems

The framework aims to interoperate with existing systems that were developed in the context of the AmI Facility of ICS-FoRTH [162]. These systems are implemented in a variety of different programming environment, including Adobe Flash Builder / Actionscript 3.0 [4], Windows Presentation Foundation (WPF) [467] and Unity Game Engine [433].

The nature of AmI environments dictates the connection between standalone systems in order to orchestrate the users' interaction with the different elements. Moreover, diverse systems may examine different aspects of an element or even use the same data in a potentially different form. For instance, when viewing information about a monument, different photographs may be shown, but the item of interest is the same. Therefore, the need arises to orchestrate and classify the content used in an AmI environment so that it can be reused, but also exploited in order to shape the context of a user's actions or assist in the construction of the user profile. To this end, the framework proposes a centralized form of data storage and provision, where information is organized in a central component and available to any instance of Information Worlds deployed within the AmI environment.

6.1.2. Data Retrieval

Data retrieval refers to the process of fetching information from a data source into a format which can be used at runtime. The two major data types that this framework supports include structured semantic knowledge in the form of ontologies and large-volume data with high velocity. Input data may originate from a variety of sources, including xml/owl, SQL relational databases and NoSQL databases.

Ontology knowledge is stored using either xml/owl files or relational databases like MySQL. These models are exported to the higher levels of the architecture through a set of programming language classes developed manually using C#. Using the SemWeb.Net library, SPARQL queries can be executed for submitting queries to the ontologies in order to export knowledge and retrieve it through XML, which can be in turn deserialized and transformed into meaningful model instances.

In terms of knowledge which is not represented using ontologies, apart from small XML files which can be deserialized and used on the fly, mainly SQL and No-SQL databases are used to store data. These databases can be queried to retrieve the desired data, a process which can be materialized either locally within the deployed application or remotely using approaches such as http requests. If information retrieval is performed within the application, then the data is directly transformed into the application's native type, whilst when completed remotely data is wrapped in a proper format, such as json [211], before reaching the end application.

While the framework provides ready to user connectors (e.g. SQL and no-SQL), it transforms the retrieved information in an internal format which is common across all the components used in this framework. Moreover, ontology-based content can be passed to the framework in an automated manner, facilitating the transformation of various semantic knowledge formats (such as xml and rdf) to the framework's internal data representation format. To this end, additional custom connectors can be created to allow the integration of any other source in a way which can be easily automated, making the framework compatible and interoperable to any other data source. The internal representation of data is thoroughly presented in section [6.1.4].

6.1.3. Interaction Monitoring and Data Selection Synchronization

The framework supplies an interaction monitoring mechanism in order to capture user actions, reporting on user interaction with provided information and providing the ground for reasoning on the user's actions and infering about their interests. Reporting includes the item in discussion and the framework component used, if any, in order to provide insights into the interaction context in post-interaction analysis.

Ambient Intelligence environments create an ecosystem of interconnected systems that act in a coordinated manner; thus, user actions that take place with reference to a specific system influence user experience with other systems. Each part of the framework, either built using the framework or adapted to share the input data and communicate with other parts of the framework, is able to connect the actions performed by users to the Data Selection Synchronization mechanism. To this end, content selections performed within an interactive system deployed within an Ambient Intelligence environment has the potential to be connected to applications built with the framework to act accordingly: for instance, when a user performs explores information about Knossos in an interactive system showing information about Crete, an Augmented Reality application can instantly adapt to augment the interactive system with content regarding Knossos instead of Crete.

User actions can be used by the deployed applications to modify their visual representation in line with the user's profile. The framework therefore supports broadcasting events for the reported user actions based on content selections (either the information itself or the semantic meaning of the information), allowing other components or applications as a whole to adapt and provide personalized interaction.

The process of data selection reporting is implemented by keeping track of any content selection. The component provides functions which are automatically called when content elements are shown to the users, keeping track of when the user began and stopped examining them. Data Selection Synchronization is afterwards responsible for propagating this information to the AmI ecosystem.

6.1.4. Internal Data Representation

Apart from connectivity with external data sources, the framework internally stores data in a manner which is universal in terms of reusability across individual information templates. To this end, a common structure allows storage of any type of information that may be visualized in the framework, independently from the visualization aspects. The internal data representation is built in a way that allows the representation of semantic information but also content-based specific alternations. For instance, information regarding Knossos (e.g. including a title, photograph and short description) can be reused in several Information Piece Templates, including the Media Gallery [6.5.2.4] and the WordCloud3D [6.5.2.6]: in this case, the content can include information about its categorization and coloring within the WordCloud, which will be used by WordCloud3D but be omitted by the Media Gallery visualization. The fields of information stored are not required for content to be valid – for instance, content may not have a description or may not contain multimedia information.

Data representation is implemented as an extension of Unity3D's ScriptableObject structure [429]. This structure provides native item serialization which can be changed within the Unity3D environment and is also easily handled from code. The advantages of this approach are the following:

- Content changes can take place from within the Unity3D Editor without requiring coding skills or any technical background
- Content can be handled from code
    - External data sources can be directly integrated within the system, e.g. Met Museum Collection [283], CIDOC use cases [83] or any other custom data source such as databases.
    - Content import from other sources can take place using only few lines of code (import from MAGIC [116] was accomplished using a script of about 25 lines of code)
- Content is stored in a unity class which can be stored and retrieved in a format which is natively compliant with providing it over the network [6.1.4.2].
- Any extensions can be integrated in a straightforward manner

6.1.4.1. Data structure

Information which is language-specific (e.g. text and audio) is multilingual. The framework supports on the fly language addition (no coding changes required) and automatically selects the available one from the content. If a specific language is not found, a default fallback language exists and is used.

The attributes currently stored are the following:

- Unique ID (auto-generated)
- Title (multilingual)
- Description (multilingual)
- Image
- Video

- 3D Model
- Audio (multilingual)
- Start Date
- End Date
- Location longitude
- Location latitude
- Content specific transformation
    - Local Rotation
    - Local Translation
    - Local Scaling
- Bindings
    - Bindings to information worlds
    - Bindings to information things
    - Bindings to information pieces
- Transformation overrides
    - Local rotation
    - Local translation
    - Local scaling

Each visualization component is responsible for selecting both the data aspects shown and the way that information is presented to the user. For instance, data regarding the Colosseum, apart from a title and a description, can include both a photograph and a 3D model. Each visualization component (template) is able to select multimedia in accordance to its context (e.g. if presenting photographs of Rome, the picture will be shown, but in the case of a map, the 3D model will be rendered). Thus, data duplication is avoided, more flexibility is natively supported and the final content is personalized to the user with regard to the visualization medium employed.

It is often common for certain content to require minor transformations which are cumbersome to take place. Such cases mainly involve 3D content: scaling alternations or minor changes to the model's pivot require the model's re-import in a modelling application, its modification and re-export. Thus, the framework supports such transformations to be included as metadata which are used by the visualization in order for the content to appear as intended.

Multimedia information (i.e. images, videos, audio files and 3D models) are compiled within the Unity3D environment. Even though this approach requires an additional step instead of loading them directly in the application, it was chosen performance-wise (faster loading times and content compression).

Finally, the current implementation of data storage can be extended in a straightforward manner and be fully backwards compatible [Figure 5].

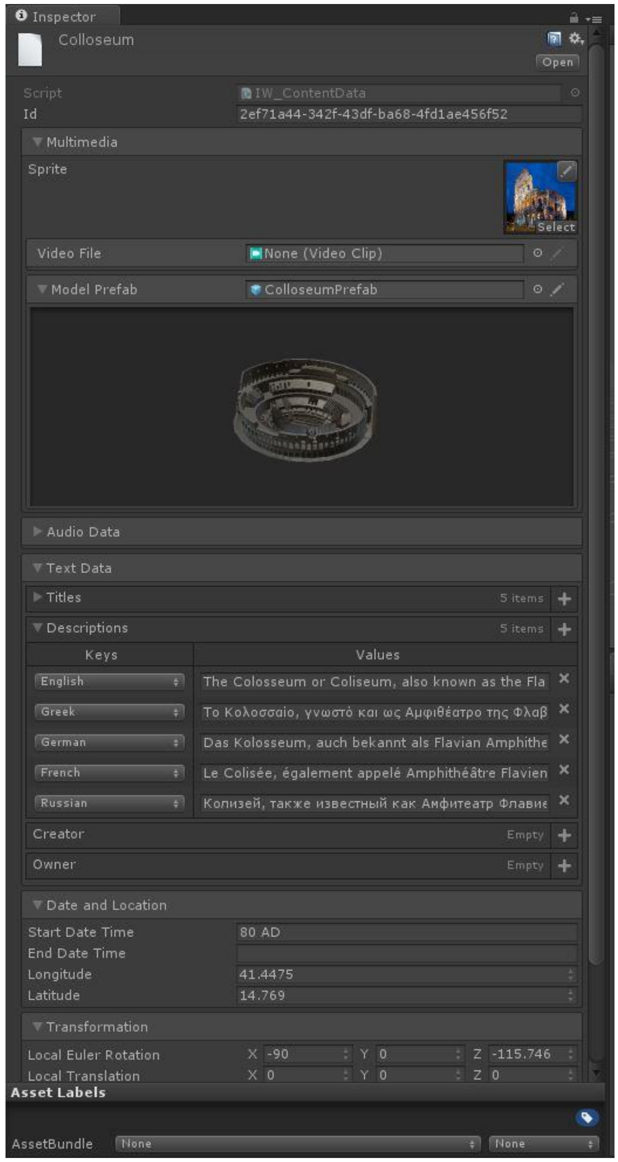


Figure 5: Screenshot of the user interface used to content data editing using the extensions created for Unity3D editor

6.1.4.2. Data provision to deployed applications

Content, including both metadata and multimedia information, is stored in classes which are serializable, in a way which is compliant to Unity3D's Asset Bundles [420]. This choice was taken for the following reasons:

- Allow remote content serving without requiring any changes to the final executable
- Offers content updates to any application instance automatically
- Provide data compression, required especially for multimedia which have large file sizes
- Serve content in a device-independent way
  - The only way for providing large files to mobile applications (both Android and iOS)

- AssetBundles can be created and updated (even remotely)
    - Using UnityEditor - suitable for non-programmers
    - Via code – allowing automation

As a result, each application instance created using the framework resolves its data from a content server. Therefore, the applications at startup search for the content server, check if their content is up-to-date, download the updates if any and cache them locally. In the case of connection issues, the applications use their locally cached content.

6.1.4.3. Data retrieval: the Asset Bundles Server

Unity's Asset Bundles [420] allow the standalone storage and retrieval of two distinct types of information: content (e.g. multimedia and any other custom serializable field) and Unity Scenes [428]. The Information Worlds framework takes advantage of this capability by creating a web server that provides remote access to scenes and content to all deployed instances of applications created with the framework. The applications, at startup, check for any updates related either to scenes or to content: if any update is found, data is downloaded and updated; if no connection is established or no updates are available, they run with their last known configuration. To this end, automatic updates both in terms of the application itself and in terms of served content is accomplished in a centralized manner, thus allowing the scaling and continuous updates of multiple application instances. The only limitation regarding remote updates includes coding and scripting, as source code files can't be at this time remotely updated.

Unity scene serving allows the update of scene visuals, offering multiple aspects to be altered after the application has been installed in a device. These changes include animations, user interfaces look and feel, 3D space modifications and even custom themes used for specific occasions (e.g., the application can be adapted for a seasonal occasion such as Christmas). Moreover, data with large volume demands (3D models, high resolution textures, etc.) can be shipped both without and with the content integrated: this is imperative especially in mobile application development, where limitations currently confine to a total size of 100MB for Android [11] and 4GB for iOS [202].

The framework's content is organized in chunks of data in the form of a standalone asset bundle, each belonging to a specific sector. As a result, the content can be organized and grouped with regard to its semantic correlations and meaning: for instance, one asset bundle can include content about Knossos, another one about 19th century data about Crete, etc. This allows data downloading on demand and content reusability, as the content is cached locally and only retrieved when it is required.

Finally, content related to the appearance of the applications developed with the framework is stored in a specific asset bundle. This decision was taken so that the look and feel of the user interfaces can be located in a specific location, allowing the centralized provision of visual themes.

It is worth noting that each asset bundle is completely dynamic and can be ultimately retrieved through a url (e.g., http://assetbundle.server:8085/Windows/InformationWorlds/KnossosContent/) which can be unique for any application instance and be remotely changed through configuration files.

6.1.4.4. Data retrieval: the Big Data Client

While data storage and retrieval can be achieved by the Asset Bundles Server in a dynamic and versatile manner, it may not be sufficient when handling Big Data. In this case, the performance requirements and the extensive data volumes (often in combination of frequent data updates) makes this approach inadequate. As a result, a standalone component, i.e. the Big Data Client, was designed and developed for Big Data retrieval.

The Big Data Client acts as an independent persistent data holder which can be connected to various data sources:

1. **SQL and No-SQL databases.** The framework establishes an uninterrupted connection to databases and directly queries for updated data. The Big Data Client can be configured to execute any type of query to retrieve the required information, which is directly mapped to any internal data storage format. To this end, data are returned directly, providing greater retrieval speeds.
2. **HTTP methods (GET/POST)**. The framework builds http requests (mainly GET requests) which retrieve the results in JSON format. This functionality might include a minor overhead in terms of architecture and performance, but has the ability substitute direct access to any data source. To this end, it is applicable in cases where direct access is not allowed or a level of abstraction between the data source and the final data destination is required.
3. **Web sockets**. The framework can be connected to Web Sockets so as to establish a two-way communication with the data source. Therefore, the Big Data Client can be instructed to perform specific actions, such as visualization changes or content updates. Such an example can be any incoming event which can trigger specific actions: in the case of a discrepancy or an alert, it can drive the application perform changes or retrieve additional information and thus facilitating custom implementations which are common in Big Data visualizations. While web sockets can facilitate immediate queries to the server to provide data updates, it can also be used in combination with both direct database access and HTTP methods.

Due to the excessive data volumes that are required for Big Data visualizations, it is often required that the data representation is altered for a more minimal representation of the information in order to reduce the space required. As a result, potential classes containing the required information can be designed to directly map to the format in which data is fetched from the data sources. Interoperability with the Information Things, Pieces and Templates can be accomplished through overriding specific programmatic functions and interfaces, making the custom Big Data sources completely compatible with all the framework's components.

6.1.5. Data Logging

The framework supports the recording of the users' actions via logging. Logging is performed by capturing and storing users' actions at an application level, i.e. the Information World and the Information Thing explored, but also the specific Information Piece used for retrieving content. At a higher level, logging performed by the framework depicts user actions in terms of data visualized, by keeping track of the semantic meaning of the explored information. Data logging is accomplished through the Data Selection Synchronization component discussed in section [6.1.3]. Users' actions can be saved upon exiting the application and be available for offline analysis.

6.1.6. User- and auto-generated Content

The visualized data often need to be dynamic: it is common for the input to change due to reasons that are not related to visualization, and also for the users to generate their own content (e.g. by creating their own personal collection of Information Things and Pieces in various worlds). Thus, the framework supports the update of information which is designated as editable by the users. In addition, real time changes provided on the fly by external sources (e.g. applications and web services) can be forwarded to the related deployed applications, which are in turn able to download them. The altered content can involve any type of data, ranging from multimedia changes, such as an image replacement to attribute marking, or variable corrections.

End user content creation in public spaces in the context of edutainment is proposed by [265], allowing users to create environments, artefacts and characters. Furthermore, [29] present a 3D urban modelling application which can be used for the reconstruction of urban areas by non-expert users, i.e. the public. The components provided by the framework natively support their immediate visualization update, depicting the changes and, if required by the interaction scenario, informing the users about the updates. Moreover, the framework provides the mechanisms to capture and store generated content dynamically and can be easily extended to provide it to other users.

Indicative examples of user-generated content include the users' photographs captured either by the framework or explicitly provided by the users. Similarly, auto-generated content includes data exploration paths which are kept anonymously and can provide useful insights to expert and other users regarding potential areas of interest.

6.2. Information Thing Indicator

The virtual environments created by Information Worlds may consist of a multitude of items, some of which are decorative; others provide the context for the exploration and others that are interactive elements that contain information. Therefore, the need to illustrate the interactive components arises, i.e. the Information Things, which can be discovered and selected.

The Thing Indicator template represents the Information Thing in conjunction with a design element that it hosts, such as a 3D model or an image. The Thing Indicator facilitates the highlighting of the hosted element with effects like glow, additional lighting, custom rendering (e.g. vignette, reflective, toon shading etc.). These effects can be used either independently or in combination by the creators of the content, allowing the customization of the virtual scene.

Moreover, the Thing Indicator template delivers a few "smart" characteristics in terms of interaction. The template offers the execution of supplementary actions to designate a user's ability to interact with it, such as slight animations (e.g. temporarily scale up by 10%), video playback over a still image or even a change in lighting. These actions are triggered by specific events a priori defined to the framework; such examples are the case of a user looking near the area where Thing Indicator is placed or the absence of interaction for a certain timeout.

Figure 6: An Information Thing Indicator, representing Knossos Throne

The Information Thing Indicator is expanded once the user approaches or selects (according to the corresponding interaction scenario) an Information Thing to explore. The expansion unveils the related Information Pieces (previously hidden so as to avoid visual clutter), surrounding the indicator which will be transformed to provide the context of the information presented. Finally, the Information Thing Indicator provides characteristics that are adaptable to the user's profile, such as customized messages, and deliver representations that enhance the Information Thing, such as highlighting points of interests.

6.3. Cut scenes

Information Worlds exist independently but are usually not loaded at the same time for performance reasons. In order for the framework to be dynamic, the various Information Worlds are loaded on the fly, allowing direct transition from one to another. Often the scenes of different Information Worlds have various loading times, ranging from milliseconds to several seconds.

To this end, the transition should be accomplished keeping the following requirements:

- Design and implement a generic mechanism that applies to all types of environments and works for any scaling
- Support larger loading times, i.e. several seconds
- Provide a pleasant user experience
- Prevent the users from feeling claustrophobia
- Provide small visual cues that orient users during the transition

As a result of the aforementioned requirements, it was decided that an intermediate step is required for the transition from one environment to another, so as to enable the loading and construction of the new Information World.

The initial implementation of the framework involved applying a custom shader for dissolving any rendered 3D model, creating a more precise effect of each item in the world being dissolved and unveiling a background. The reverse process is applied for showing the new environment, by making the models appear gradually. However, while this solution works well for models using the same or similar texture scaling, the visual results is often problematic. In the cases where texture tiling was very small, such as rounded and smaller surfaces, the effect was not evident; on the other hand, large surfaces such as walls are commonly scaled by 3D modelling applications and appear render artifacts which are larger than the expected ones. Moreover, the lighting and shading of the environment's model would be less accurate and a flicker would appear when switching from the dissolving shader to the final one used for rendering the models by default.

Therefore, a different approach was followed: instead of changing the rendering of the entire environments, a large cube of about 10 by 10 meters would be rendered on top of everything else on demand. This cube will start from completely transparent and gradually resolve, and once the final surroundings are ready, it will be again dissolved to completely transparent.

In more details, once the cube hides all the user's surroundings, the original environment is unloaded. The appearing cube displays a galaxy of stars surrounding the users, as if the users are flying in space. After being unloaded, the framework starts loading the next environment, and once fully loaded and initialized, the cutscene environment dissolves [Figure 7] and the users feel as if they arrive on a new location.

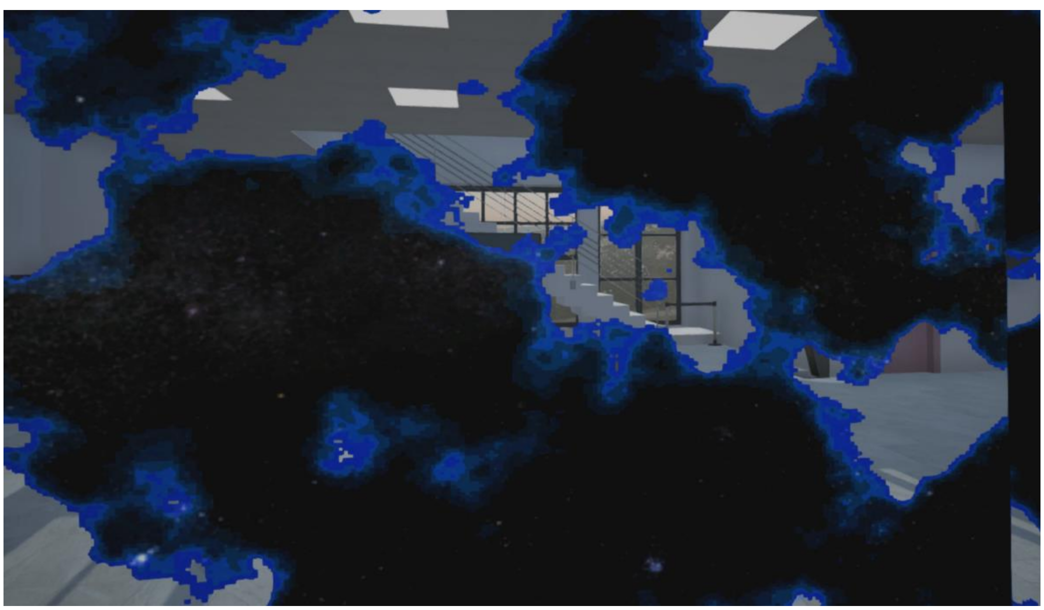


Figure 7: Dissolving of the new world

6.4. Switching Information Worlds

Users should be able to instantly switch to other Information Worlds. This can be accomplished using two different modes: by stepping on teleport areas which are clearly designated with a distinct 3D model, or by showing a special menu on demand.

6.4.1. Information World switching menu

The menu is rendered as a cylindrical user interface surrounding users on demand. This menu [Figure 8] displays all the available worlds from which the user can select the one of interest and instantly switch to that. The menu displays an indicative screenshot and a title for each Information World and is dynamically populated, showing the current world and all other available worlds users can switch to.

Figure 8: Information World switching menu

6.4.2. Information World teleportation switchers

Another common case involves the direct relationship of one Information World to another. To this end, the option of instantly switching to another environment is often needed: a certain sector/area of an environment can be examined in more detail in another world. For instance, a section of a museum presenting artefacts regarding Minoan civilization may be directly related to a reconstruction related to the Minoan civilization, such as the Knossos Throne Room. In this case, a designated area can assist the flow of the user's exploration by offering the ability to directly proceed to that environment.

The 3D model used to designate the teleportation area was chosen to be a futuristic stand in order to match the mental model of instantly travelling in space, while also being differentiated from the other surroundings [Figure 9].

Figure 9: Teleportation gate

6.5. Information Piece Templates

The framework provides ready-to-use implementations of Information Pieces, which can be directly placed in the position the visualization creators [5.1.1.1] select. The following sections present their design and implementation, highlighting their capabilities and presenting indicative figures of how the final outcome may look like when integrated within Information Worlds.

The framework supports two types of templates, each serving a different purpose:

- **Information Pieces which exist in place**: These components are integrated into the virtual environment and exist within it, allowing direct user interaction. Indicative examples of these components can be an image gallery, a map and anything from which the user is able to instantly retrieve information.
- **Information Pieces which exist within elements**: In certain cases, the need arises for some components to be unavailable for immediate interaction. This is supported for various reasons:
    - For scenography and interaction reasons: users are further immersed if stepping into another room when approaching a display. To this end, the feeling of presence is increased and they are totally free to interact within the displayed environment.
    - In order to imitate reality: if a virtual world contains interactive displays (e.g. a television screen which contains a video game), the user is able enter the televisions' world and immerse within. Therefore, a smooth transition is required from when the displays are not in use and when users enter the environments within.

- In order to further enhance the user experience in virtual reality: in the case of a 3D room existing in place within a virtual television, the user's view of the room would be flattened and the stereoscopic rendering would not be available. Thus, the 3d room requires to be loaded independently of the display which encapsulates it.
- For implementation reasons, so as to support computationally intensive components, either in terms of GPU (rendering) or in terms of CPU.
- For implementation reasons, in order to support the straightforward integration of existing applications. It is very common for 3D applications to place elements outside of the user's frustum: however, when these applications are meant to be integrated within another application, there needs to be the opportunity of creating them without the user noticing them.

6.5.1. Assistive Templates

The templates presented in this section are not meant to present any specific information, but aim to enhance the users' navigation in the virtual world and improve user experience.

6.5.1.1. Decorative Templates

Apart from the elements that contribute to the provision of information in an interactive way, additional components are used for enriching the visualization without providing additional functionalities. These items generate improved designs, improving user experience and immersing users in the virtual worlds. The decorative templates provided by the framework primarily involve 3D models; however, additional elements can be incorporated, such as area lights or particles to be used for special effects (e.g. smoke).

Additionally, these decorative templates can be applied in a personalized manner. Such an example may be a video which is subtitled in line with the user's native language. Furthermore, decorative templates can also be interactive: in the case of a video that plays in a virtual television, it could be activated or deactivated according to whether the user is looking towards it, thus creating a playful experience in a simple and very intuitive way. Finally, entire environments could even change based on the user's profile: for instance, if the user is a gamer, a virtual room visualization can have decreased lighting and equip the user with a virtual spotlight or a torch to explore it, gamifying the process of learning.

6.5.1.2. Minimap

Minimaps are components which provide a wide view of the whole virtual world when examining parts of it. Usually, when in indoor spaces, our surroundings occlude other rooms or areas. As a consequence, it is common to lose perception of the orientation in space, especially when someone is not familiar with the space or is focused on another task. The provision of a minimap [Figure 10] is indispensable for the users to perceive the general picture of the environment while also localizing themselves within their surroundings.

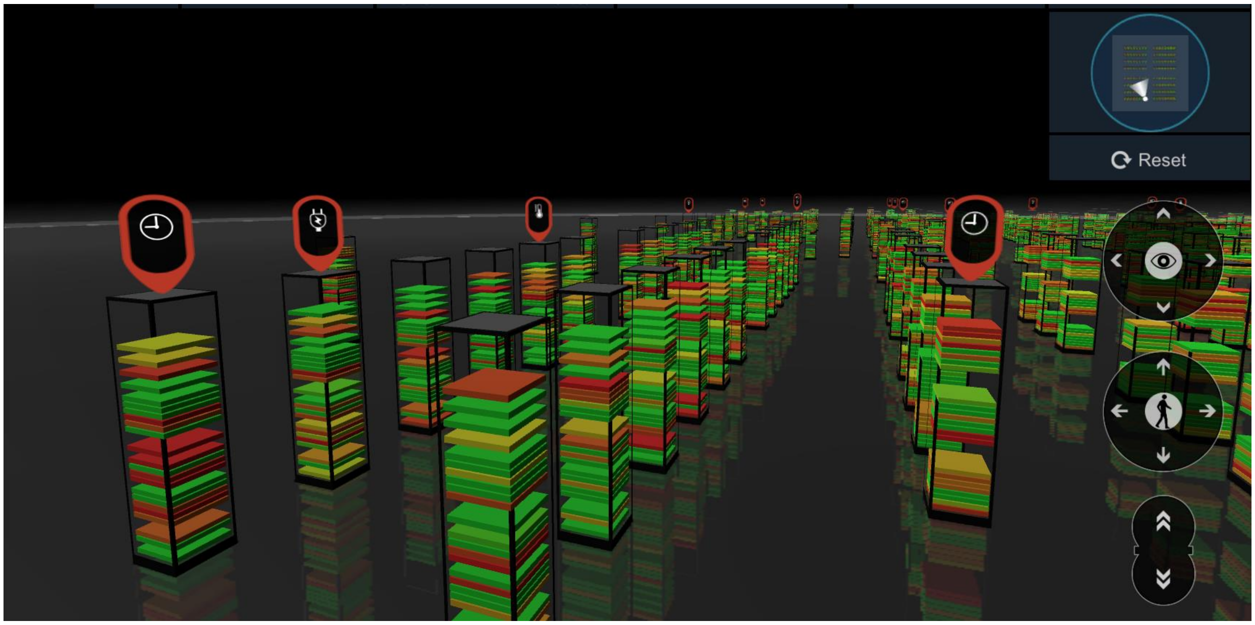


Figure 10: The Minimap assistive tool (top right corner)

6.5.1.3. Navigation Assistant

Another requirement for virtual worlds is user guidance along specific paths. This requirement is prevalent in the context of interactive storytelling [7], in order for the narrator to assist the user follow the story flow. In addition, the guidance is optional for users as they can ignore it and follow their own path, choosing to act independently, and therefore its visualization should be clear but unobtrusive. The framework supports two approaches in terms of assisting navigation presented in the following sections: Navigation Guide and Navigation Actuator.

6.5.1.3.1. Navigation Guide

The Navigation Guide component acts as an indicator that illustrates paths that lead to specific areas of the augmented or virtual environments. It is applied for way-finding and providing visualization cues that highlight a route along their surroundings, leading to the defined locations. The input for the component will involve two or more items located in the user's environment and the route planning. The framework's component automatically calculates the necessary route and renders the corresponding path accordingly. The displayed components are rendered over the ground along the route users have to follow to reach their destination. The Navigation Guide is meant to be used as guidance which is optional. However, it also is the only option if the users have to physically move in the environment: such a case are the augmented reality environments.

The implementation of the above feature is based on Unity3D's Navigation feature [435]. The process of generating the areas in which users can navigate is straightforward, as the 3d models used in the Information World are used as the bounds in a process known as navigation mesh baking [437]. In addition, visualization creators [5.1.1.1] can alternate the allowed areas where users can move by designating any areas they want as impassable. To this end, the procedure of generating a navigation area is an automated process, yet fully customizable to match the needs of the vast majority of navigation requirements.

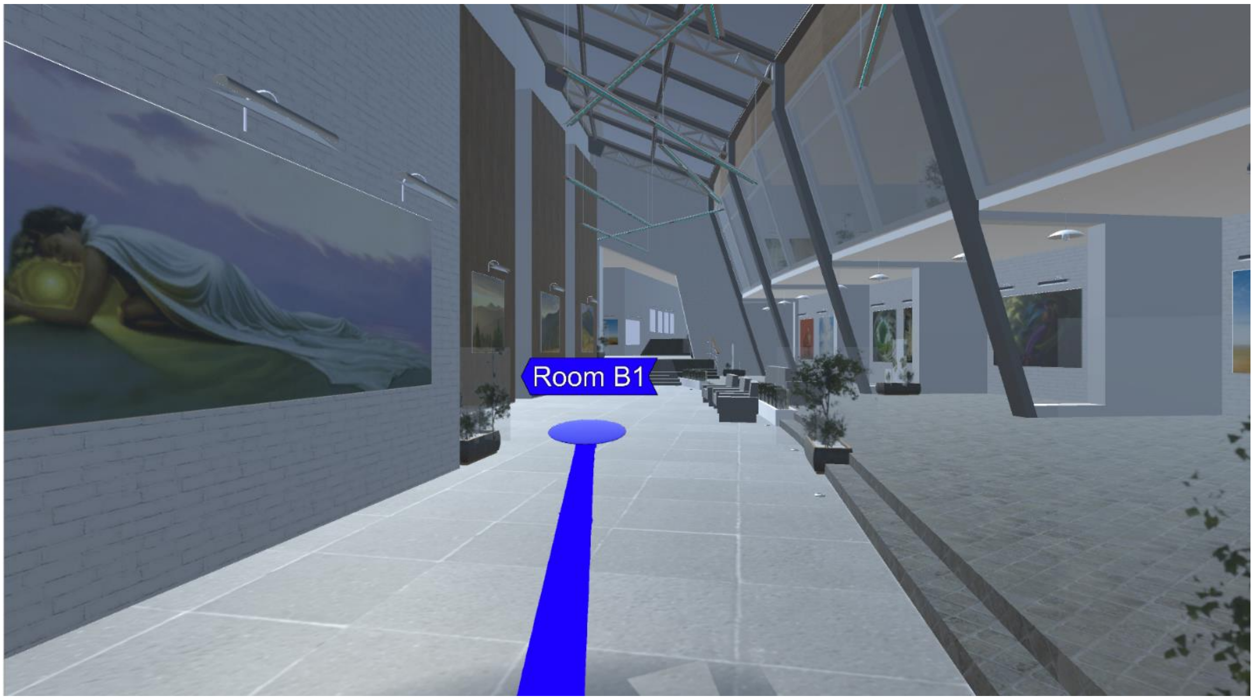


Figure 11: The Navigation Assistant Template concept design

Figure 11 above presents the concept design of the Navigation Guide, while Figure 54 presents the implementation which can be used in virtual reality environments. The implementation calculates the spots where users have to turn in order to reach their final destination and decorates them with indicative signs, indicating their target. This is designed so that user can differentiate between several paths they can follow and select the one they are interested in. Moreover, these signs can be clicked so that the users are immediately taken to their final destination, without having to travel on their own until they reach their final target. This is implemented in combination with Navigation Actuator described in the following section [6.5.1.3.2].

6.5.1.3.2. Navigation Actuator

When users' movement does not take place in the physical surroundings, the option arises for applications to move them in the virtual environment they exist. To this end, Navigation Actuator acts in a similar manner to Navigation Guide, but instead of presenting the paths, acts upon the users' position and moves them accordingly. The Navigation Actuator provides two options for moving the users, each holding their own advantages and drawbacks presented in the following table:

Instant teleportation	Smooth movement
+ quick action with immediate effect, saving time	+ immersive view of the virtual environment
- disorientation may arise as users lose their sense of space and movement	+ assists user orientation

- reduced immersion and hurting user experience	- small time overhead
	- may cause motion sickness (mainly in virtual reality setups)

Both actions are completely equivalent in terms of their final result and can be therefore switched in accordance to the user's preferences. In order to reduce motion sickness, user movement has a predefined velocity which does not change over time.

6.5.2. Information Piece Templates for static visualizations

The following sections illustrate the customizable templates which are provided by the framework as ready-to-use components able to present the various aspects of the specified input. Each template is purposed to provide efficient visualization that maximizes the perception for any particular data type, covering the most common types of information.

6.5.2.1. Timeline

A common procedure when exploring historical information is detailed and often exhaustive information exploration in a chronological sequence. Sequential navigation may be of great benefit so as to iterate through all events visualized, arranged in chronological order.

Figure 12: The Timeline Information Piece Template

The implementation of this work's timeline visualization is based upon TimeTunnel [115], which focuses primarily on event information representation, while transforming secondary information to be absorbed by the environment.

TimeTunnel employs a time tunnel metaphor, i.e., a long corridor along which events are placed in chronological order, using distance to represent time. Information entries are organized in individual events containing segments of data that conceptually reside within the same element. Each event is shown as a slice that reside at the right side of the corridor in the form of a 'showcase'. This extendable 'showcase' includes the event's fundamental information (i.e. name, date/time and optionally description or figure) but also encapsulates additional content. This additional content may comprise of any type of multimedia information, including textual entries, images, videos, 3D models.

Moreover, another fundamental characteristic of timelines is the segmentation of time dimension in distinct parts which are usually referred as periods. Periods categorize groups of events and share common characteristics that categorize all events belonging to them. Periods in the Timeline Information Piece are optional and can be omitted if not needed. If provided, periods are rendered on the top side of the corridor along with an indicator that designates the user's period currently exploring. Moreover, the period currently examined also follows users' movement at the left side of the corridor just above the floor.

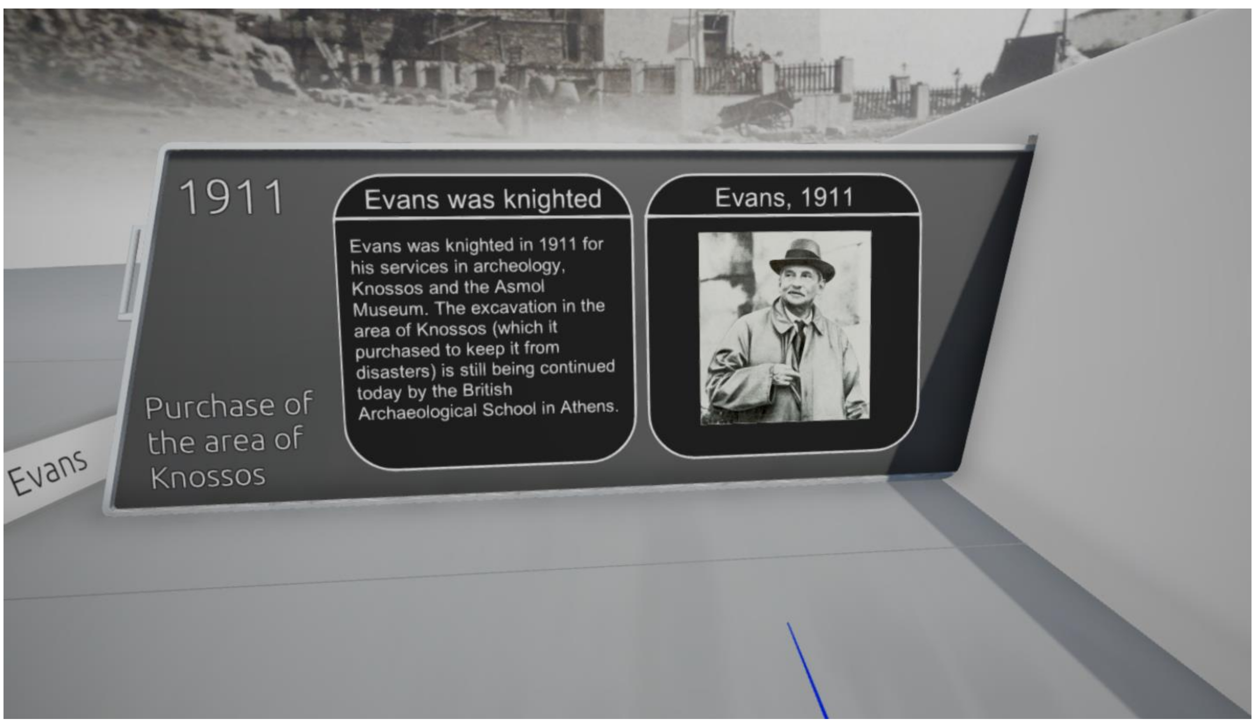


Figure 13: Event details in the Timeline Information Piece Template

The content encapsulated within each event is organized into a list of elements which can be linearly explored. Three elements within an event are visible at a time, in order to provide as many items as possible while also maintaining readability and clarity. Upon selection, these elements appear at a larger scale in front of the users so as to allow a detailed inspection of its details.

6.5.2.2. Augmented Map

Apart from time, location constitutes an important characteristic that describes and classifies information. The correlation of space allows human brain to classify entities and localize them [474], creating a clear view of what happened where. The human brain has been trained over the centuries to use maps to navigate and assist orientation, as it provides clear points of reference that can be used to define the relative location of entities.

A fundamental component the framework described in this research work provides is a map which can be enriched to present information over a two dimensional plane. The augmented map provides ad-hoc standalone components that support multimedia, metadata and semantic information that can facilitate the visualization geospatial information arranged in accordance to their physical location.

The Augmented Map template supports rendering on virtual environments as well as superimposing in real environments for augmenting physical maps. This way, the location-based exploration of data can be performed on the basis of a representation the users are familiar with.

Figure 14: The Augmented Map Information Piece Template concept design, augmenting Heraklion's city center

The Augmented Map template allows the presentation of any type of content, using the available prefabs (reusable templates) described in section [6.7]. The prefabs for the Augmented Map Template are designed to indicate the precise position of each content, designating their location in the map. Apart from pins containing two dimensional information (such as images and text), 3D geometry (such as buildings) can be directly placed at their physical location within the map.

An indicative illustration of the view provided by the Augmented Map Template is presented in [Figure 15], where a map of ancient Italy is augmented with historical information including buildings, archaeological sites and ancient cities' locations.

Figure 15: Augmented Map

6.5.2.3. Graph View

Graphs are a common technique used for displaying the correlation between different entities. Their main advantage is the user's ability of starting from a specific node and exploring neighboring nodes, especially when visualizing data sets that describe networks or relationships. Additionally, users are generally familiar with the concept of relations between entities illustrated by graphs.

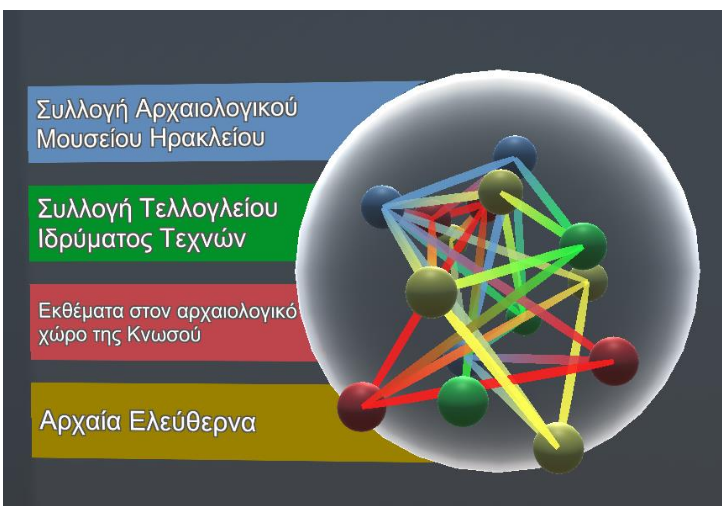


Figure 16: Preview of a Graph View Information Piece Template

The Graph View generates interactive graph drawings that are dynamically generated. The nodes rendered facilitate information hosting, such as titles, so as to provide a clear view at a glance. In addition, the lines linking the nodes may have their color set either based on the corresponding nodes colors or by the type of their relation.

Another feature that Graph View supports is the capability to collapse a group of nodes into a single one. For instance, in the case of a graph presenting the location where statues were excavated in Greece, the nodes that display statues excavated in Knossos can be bundled into a single node, Festos into another, etc., so that the resulting graph shows significant clutter reduction and clearly visible high-level node grouping. In an equivalent manner, the collapsible graph subset can be expanded, either automatically when the user explores that region of the graph or on demand, when selected by the user.

6.5.2.4. Media Gallery

Multimedia information is one of the most widespread type of data related to entities, which can be very descriptive and exemplify aspects that would be otherwise difficult to perceive, while being also enjoyable and straightforward for the users. The Media Gallery Information Piece Template [Figure 17] is used to exhibit multimedia information to end users. The main goal of the Media Gallery component is to provide a straightforward way for easily and efficiently browsing and exploring large collections of multimedia, i.e., images and videos.

Figure 17: The Media Gallery Information Piece Template

The key requirements include that its users should be able to perform the following:

- Have a quick overview of the entire collection.

- Focus on a single item and obtain additional information (e.g., a short description) but also easily browse items in the vicinity of the selected one.
- Zoom in on the details of the selected item.

Based on the above two distinct views/modes are provided respectively:

- A two-dimensional grid containing large thumbnails of the multimedia elements of the collection. Since the system is used from a certain distance, the thumbnails' size is fixed in order to ensure the visibility of their contents. Users can scroll the grid horizontally and vertically in order to view items which lie beyond the screen boundaries. To minimize the gesture distance between items located at opposite ends of the grid, the grid wraps around in both axes.
- If users select to focus on a single item, it appears in full screen accompanied by a descriptive caption. This mode also allows scrolling to adjacent items on both axes, as well as changing the caption's language.

6.5.2.5. Object Manipulator

The visual representation of objects can be in the form of a three dimensional model, reconstructing digitally its physical shape in high detail. Digital 3D models can be utilized in the case of absence of the item itself, such as its unavailability to exhibit, or can be related to the potentially too small or large scale that makes it impractical to examine in detail. Therefore, the exploration of an item's fine points can be feasible through an interactive visualization of its reconstruction.

The Object Manipulator constitutes a component that is either placed directly within an Information Thing or creates an additional environment in which users can view the item in detail [111]. If there are few items to show in an Information Thing, the framework supports the immediate placement of the interactive element in the user's current surroundings, but in the case of a collection of items, it is able to provide an additional environment which presents them as a whole. In any case, Object Manipulator allows users to grasp three dimensional items and manipulate them, i.e. move, rotate or scale them in virtual space.

The Object Manipulator Information Template [Figure 19] delivers an intuitive manner to visualize and manipulate 3D models. In addition to moving and rotating the 3D elements directly, users are able to directly apply additional functionality tightly related to 3D object transformation. Users can also scale elements by pinching them, thus facilitating natural interaction. Moreover, the template allows users to set the 3D elements to indefinitely rotate along the Y axis, viewing the 3D model from various perspectives.

The template allows users to grasp three dimensional items and manipulate them, i.e., move, rotate or scale them in virtual space [Figure 18]. The application employs for each exhibit a metallic item (manipulator) which the users can grasp with one hand to move and rotate. The manipulator only appears if the user's hand is near the item. Once holding an item from the manipulator, another metallic item appears below the item with a sphere on the other side, which the users can grab with their other hand in order to scale (maximize or minimize) the exhibit.

Figure 18: Manipulation of a 3D Cultural Heritage object

Lighting constitutes another primary aspect that is related to 3D models. The template allows users to use two available spotlights which highlight aspects of the models. These lights can be switched on/off and dragged to any place, providing flexibility to the user to examine any aspect of the model at will.

Figure 19: The Object Manipulator Information Piece Template

The manipulation of the virtual 3D exhibits takes place using the users' bare hands. This component is primarily meant to be used in combination with gestural interaction and more specifically the Leap Motion sensor [250].

During the preliminary user tests, the users' vast majority tried out scrutinizing their hands' visualization within the virtual world, examining their fingers' tracking and corresponding movement in the virtual environment. Moreover, all users' actions that have to do with the exhibits' manipulation take place with the hand facing away from the users' eyes.

In order to take advantage of the hands' state when not used to interact with the exhibits, it was decided that additional information could be retrieved by viewing the hand's inner side [Figure 20]. To this end, details about the 3D model which the user is inspecting can be retrieved using a menu which rests at the inner side of the user's left hand. This menu is initially invisible and appears when the users turn their hand to face their eyes. The menu refers to the last item selected and can be pinned at any time using the pin button at the top right side. It contains panel to display detailed information that accompany it (i.e. title, description and images). Furthermore, the actions described earlier on the corresponding exhibit can be applied through the options at the bottom side of the menu.

Figure 20: Interacting with the menu appearing on user's hand

6.5.2.6. WordCloud3D

WordCloud3D is a three dimensional version of a tag cloud. It has the potential to visualize any type of information, both structured and unstructured data, in a straightforward manner that can provide some key points at a glance, but also generate the impression of information as a whole.

In comparison to traditional two dimensional tag clouds, this component utilizes three dimensions to display the entities provided. As a result, it is capable of partially hiding existing items that are not the ones on focus, by placing them at the back side of the 3D volume. Thus, this component delivers the means to adapt its visualization to the context provided by other parts of the framework. WordCloud3D supports the alternations on the tags' visual representation by modifying their font size, font weight, color and placement: as a result, certain tags may appear more evidently, according to their importance.

While idle, the WordCloud3D template is indefinitely rotating along the X axis. This occurs so that while exploring the environment, the user perceives the tags shown to be coming forth and moving backwards. However, upon interaction (i.e. the user points at the WordCloud3D and/or selects an element) the template stops moving the tags, allowing the user to aim at the item of interest. After a short period of user inactivity, the template continues its rotation.

In terms of content, WordCloud3D has the potential to facilitate the display of diverse terms which sparse coherence: even though it groups information segments, they might be not related to each other. This template's characteristic allows visualization creators to incorporate individual items that may not be directly related to the Information Thing's subject, but constitute dimensions which are linked from a perspective that the user could not expect them to be related. To this end, these terms can trigger the users' attention and allow them to retrieve additional information on demand.

In addition to displaying individual terms, upon user selection, WordCloud3D hosts an area where details are shown [Figure 21] in the form of a callout linked to the term in subject. The callout is able to host textual and multimedia information in an optimal way, as it adapts to the information available so as to be more readable [6.7].

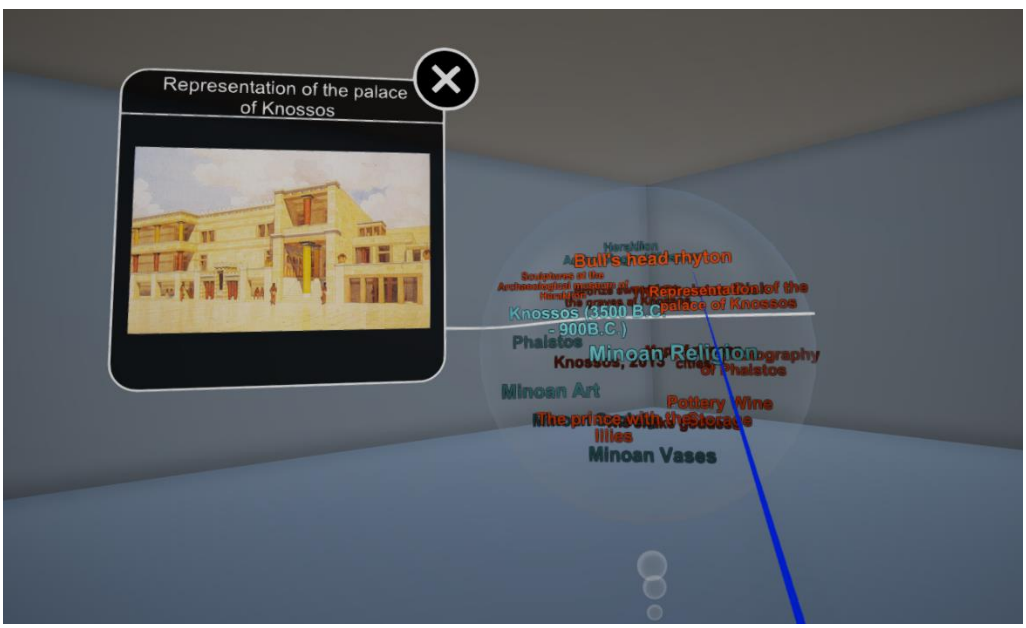


Figure 21: The Wordcloud3D Information Piece Template

WordCloud3D constitutes a reusable component that can be placed in an Information Thing. It does not generate additional environments, as it is meant to be an agile component that is both able to act as an Information Piece, but also be integrated into other Information Pieces, such as the Timeline and the Object Manipulator.

6.5.2.7. Callout Presenter

The Callout Presenter template [Figure 22] is a flexible component which can be employed for augmenting any visible item. It is built to support both textual and multimedia information and presents it in the form of a callout originating from the defined position and spreading to any direction (left or right). Moreover, the callouts are optimized to host the data in an optimal way by using adaptable user interface prefabs as described in section [6.7]. This template for Information Pieces is suitable not only for completely virtual or mixed reality environments, but also for augmented reality setups. In the latter case, visualization creators can define actual points of the physical world to be augmented with additional information which extends along all 3 axes.

Figure 22: The Callout Presenter Information Piece Template

Callout Presenter renders the callouts in three different formats:

- As steady non-rotating callouts
- As callouts face the users, but only rotate along the Y axis
- As callouts facing the users

These formats are provided so that visualization creators can select from the format which is most suitable for the requirements of each Information World and the specific needs of any spatial arrangements within the environment.

Finally, the template is not only capable of providing one piece of information, but also a dynamic set information. In this case, each information item corresponds into one callout, and the entire set of callouts is placed upon a hemisphere of a specified radius, where the items on the left side of the hemisphere extend leftwards while the ones on the right rightwards.

6.5.2.8. Text Presenter

The Text Presenter is a template used to present extended textual information. Textual information is a fundamental type of information widely offered for the vast majority of domains, having the ability to present material such as intangible heritage, stories and concepts that cannot be materialized or pictured. This template supports textual information in combination with descriptive images.

The Text Presenter template provides textual information adapted to the needs of the device and the technology used. For instance, when using the framework in an augmented reality setup, presenting text using a plane in 3D space would be tiring for the user, while showing it full-screen would be more suitable.

Text Presenter visualizes the textual information in the place where it is defined. However, often the need arises to display textual information related to an element (e.g. an Information Thing or an Information Piece) which has a slight offset in order to avoid occlusion. To this end, the Text Presenter template has the ability to appear at a small distance towards the predefined direction, but dynamically linked to the origin of the element it is related to [Figure 23].

Figure 23: The Text Presenter Information Piece Template

6.5.2.9. List Presenter

The List Presenter component presents sets of information which are included in a collection [Figure 24]. The component shows information collections in a row which the users can sequentially explore. To this end, the component displays text, images and videos as elements appearing at the entire area that the List Presenter occupies. The elements can be directly switched from one to another, providing the medium for displaying a dynamic presentation of information which users can explore at their own pace.

Figure 24: the List Presenter Information Piece Template

6.5.2.1. BeThereNow

The BeThereNow Information Piece Template is an individual component that allows users to view themselves within digital landscapes, works of art and generally any image collection. Its implementation is based upon the BeThereNow! application [119] and makes use of the capabilities of Kinect One sensor [288] in order to perform background subtraction. The template works like a magic mirror, where users watch themselves in the display, as if they were standing in various sceneries.

The template integrates the UI components used by the List Presenter Information Piece Template [6.5.2.9] in order to present a list of images from which the users are able to select the one they prefer in order to appear as if they are there. Moreover, it applies meaningful, elegant and aesthetically pleasing means of changing the displayed sceneries.

The users are rendered in front of the landscapes, superimposing only the parts of the color image that corresponds to them. Rendering is performed using computer graphics shaders in order to maximize performance and achieve the highest possible framerate while having the lowest possible impact on the rendering time required. Moreover, few graphics rendering passes are used in order to smooth out the final outcome generated by the sensor's camera, performing anti-aliasing and gradually smoothing out the users' contours so as to achieve the optimal visual results possible. The users' image is dynamically updated and completely excluded from all interactions with the UI elements that are rendered behind them. As a result, interaction can be accomplished seamlessly allowing dragging the background images and interaction with menus such as the ones providing recommendations [6.6].

Figure 25: User interacting with BeThereNow

6.5.2.2. Charts Presenter

Information which varies over one dimension, such as time, is often more meaningful if examined in conjunction with the corresponding dimension. Deductions can be made by examining the relation of the different characteristics with the changed dimension, such as a variable that changes over time (e.g. population over time) or per attribute (e.g. faulty components per brand).

Additionally, the human brain often perceives information quicker and more efficiently when pictured. Such examples are pie charts, which commonly present percentages: even though they are less accurate than the actual percentage value, they are useful to get an overview at a glance.

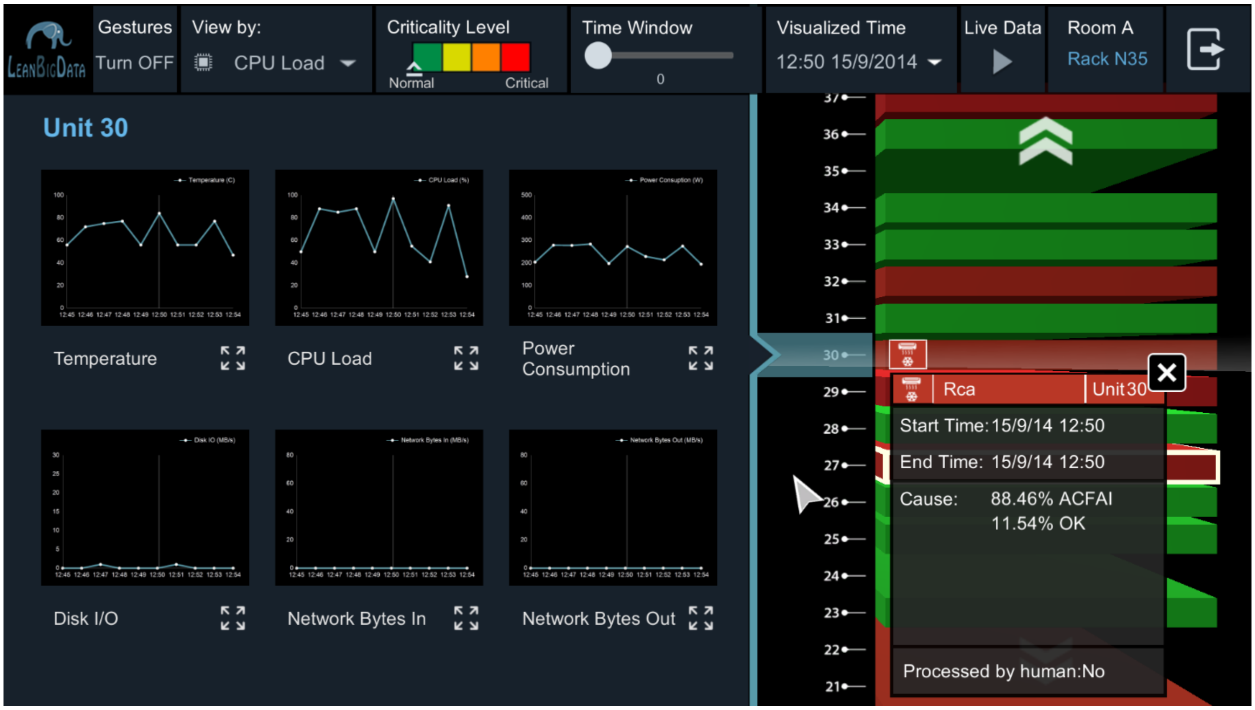


Figure 26: The Charts Presenter Information Piece Template

The presented framework provides a template for presenting a variety of widespread charts, including pie, bar, box plot, radar and bubble charts [Figure 26]. Therefore, it is capable of supporting the analysis of quantitative information, a task which is useful for recognizing patterns in the progress of a variable over a dimension.

6.5.2.3. Audio Source

Audio content is another widespread type of data that accompanies visible information. The framework provided the Audio Source template [Figure 27], which supports the visualization of a descriptive icon and provide the means to begin and stop sound playback. The Audio Source template provides two types of audio playback:

- Three-dimensional sound playback, allowing the audio source to be located in the area of its visual representation and the user to perceive that the sound originates from that location. To this end, user auditory input assists user orienting in the 3D space and capture his/her attention towards the sound source.
- Two-dimensional sound playback, facilitating the playback of more ambient sounds. This is supported so as to provide information without spatial characteristics: such an indicative example may be audio description for areas in which the user navigates (e.g. a description or an ambient music being played upon user entering a room).

Apart from audio being applied for providing content to users, audio is employed as an additional feedback mechanism during the user's interaction. User interfaces rendered in the 3D space are supplemented with 3D audio sources, providing richer user experience and auditory feedback to users' actions.

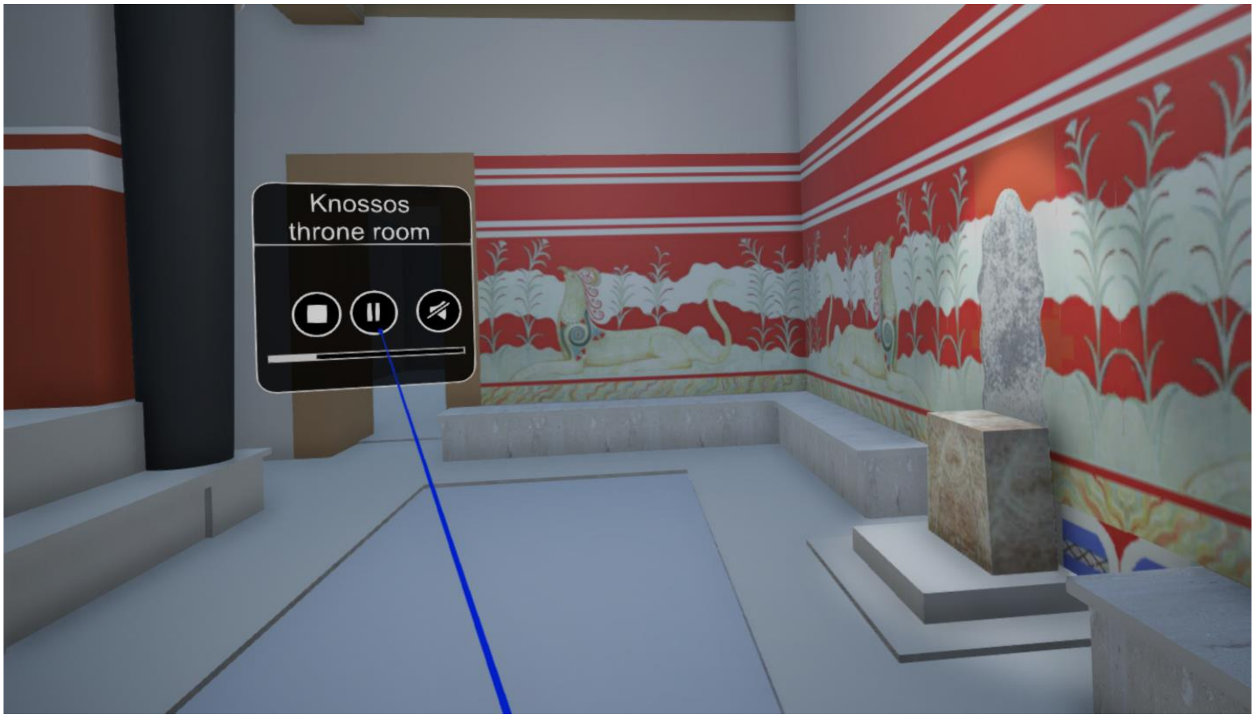


Figure 27: The Audio Source Information Piece Template

6.5.2.3.1. Text to Speech Source

Besides the playback of sounds, the framework provides a component for speech synthesis. This component is multilingual, allowing the synthesis of text in all the supported languages. Similarly to the Audio Source template, the Text to Speech Source is able to emit the sound in 3D space or as a flat 2D sound.

6.5.3. Video Player

A common usage scenario of Information Templates involves displaying video content. Therefore, the Video Player Information Piece Template is used to facilitate video playback in accordance to the context in which the user is experiencing the virtual environment, allowing for instance feature demonstration using videos that simulate a process via playback. The following variations of the Video Player are natively supported:

- **Area Triggered Video Player**: This template variation includes a video paused at its first frame, which begins playback when the users approach it, continues playing the video while they rest next to the video and stops when they step away from it.
- **Look-at Triggered Video Player**: The component is a video player which plays only while the user is looking at it. It is built in that manner so as to support the illusion of elements coming to life by a user's simple motion.

6.5.4. Information Piece Templates for dynamic visualization

Supplementary to the visualization of static information using Information Pieces templates, the framework also provides templates which can be applied for the visualization of dynamic information and are designed to exhibit fluid information. These templates not only allow traditional static content, but also have the ability to add new information on the fly, integrating it in the current flow.

6.5.4.1. Mirror of Thoughts

The Mirror of Thoughts template is capable of showing information flows passing over the users' heads or at the sides of their bodies. The information flows might consist of a variety of elements, such as images, videos and tags. As the users stand in front of a virtual mirror [Figure 28], they watch themselves immersed in a virtual stream of information. This template delivers an appropriate mechanism to visualize data related to the user, as it relates information with the user in an immediate manner.

An indicative use case of the Mirror of Thoughts template could be the analysis of a person's visit to a museum, as it could incorporate a personalized summary of the user's experiences in the museum, or a set of recommendations when arriving at the museum. Moreover, it allows information to follow users as they move in the virtual space.

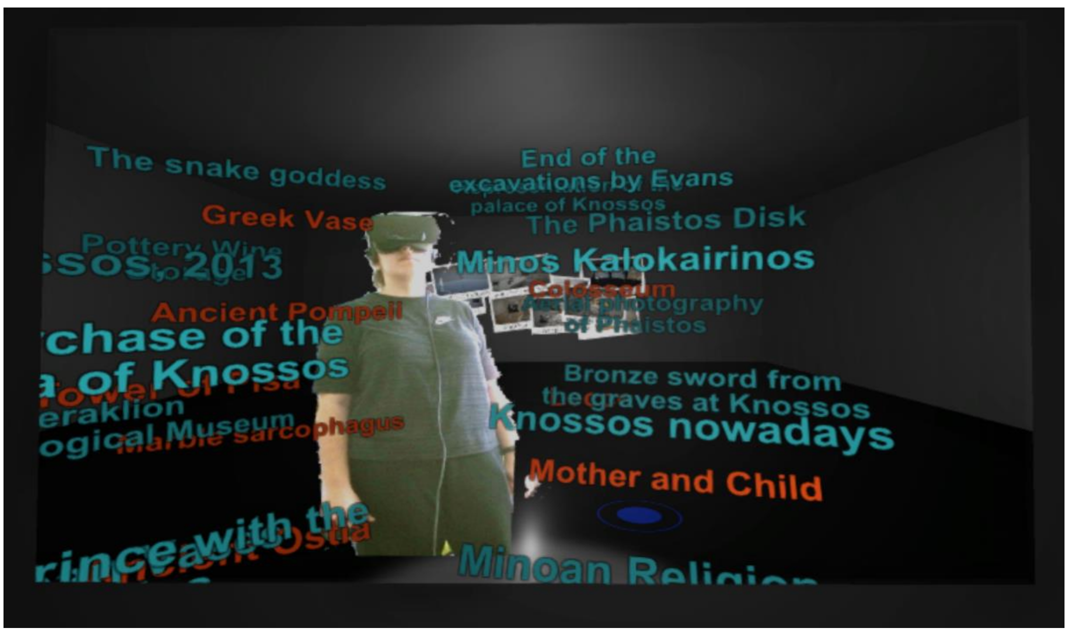


Figure 28: A user shown in the Mirror of Thoughts Information Piece Template

Mirror of thoughts is provided in two different alternatives:

- **As an actual mirror in a display**: in this mode, the aim of the component is to be integrated in physical installations, where users physically move in space. In this case, the component overlays information upon tracking and identifying a user in space. This alternative is mainly focused on augmented and mixed reality environments.

- **As a mirror in a virtual environment:** in this case, the component performs background subtraction and acts as a mirror in the virtual environment. The component appears as a typical mirror reflecting the virtual environment, which is however augmented with the users' actual figures along with content they have already experienced. Thus, this alternative is created for use in environments presented in virtual reality.

6.5.4.2. Flowing Media Gallery

This component is a permutation of the Media Gallery Information Piece template. It is very similar to Media Gallery, but the multimedia content is not static, as it follows a flow. The flow continues while the user passively watches it, but stops upon interaction, so as to allow users to examine the item they are interested in. Any item upon selection is cloned and comes forward, displaying its title, and the original item is dimmed in the flow.

Even though the core characteristics in terms of implementation remain very similar, the Flowing Media Gallery component provides differences in terms of its presentation. Media Galley is usually displayed in a typical aspect ratio for images (e.g. 16:9 and 4:3 for landscape and 9:16 or 4:3 for portrait content), so as to match the content's full screen size. Flowing Media Gallery is on the contrary independent of the content's aspect ratio: it is meant to be used in aspect ratios wider than 16:9, e.g. 32:9. Therefore, the environments can host wider virtual displays that match each concept's visualization needs but also permits more content to be displayed at once and users to be able to instantly retrieve them. The grid on which the content is placed in the component is smaller than the typical size of Media Gallery Information Piece template: the default dimensions provided are 2:2 for typical displays and 4:2 for wider ones, but can be straightforwardly defined by a configuration variable that suits the involved stakeholders.

6.5.5. Custom Information Pieces

Apart from the provided templates for Information Pieces visualization, the framework allows the integration of additional standalone Information Pieces serving specific purposes. These components extend the framework and further enrich visualizations, promoting the scaling of the framework by the components' reuse. Moreover, custom Information Pieces are able to be tailored to fit the visualization needs for specific requirements.

While collections of ready to use Information Pieces can cover the vast majority of information visualizations, certain specific cases will always solutions which are tailored to fit the precise requirements of each application. As a result, the framework is built in an extensible way so as to facilitate the easy integration of custom implementations within the framework's core structure.

6.5.5.1. The Details Previewer Information Piece

Data representations integrated within the framework may hold specific information which can't be visualized in an optimal way. This need is evident especially in the context of Big Data scenarios, where custom specific metrics and data are meant to be visualized.

Such an example may involve previewing elements to retrieve their state. In the context of the Infrastructure Management and Monitoring use case [9.2], which belongs to the domain of Big Data visualization, the necessity rose to swiftly preview the state of each server shown to the user. Therefore, the Details Previewer Information Piece was developed to promptly display the issues detected for specific server racks: once the user hovers over a server at which an error is recognized, additional information is provided in the form of a UI pop-up presenting the error's details [Figure 29]. The alert details shown for each server, include its start and end time, potential causes of the issue and whether any person has already noticed it.

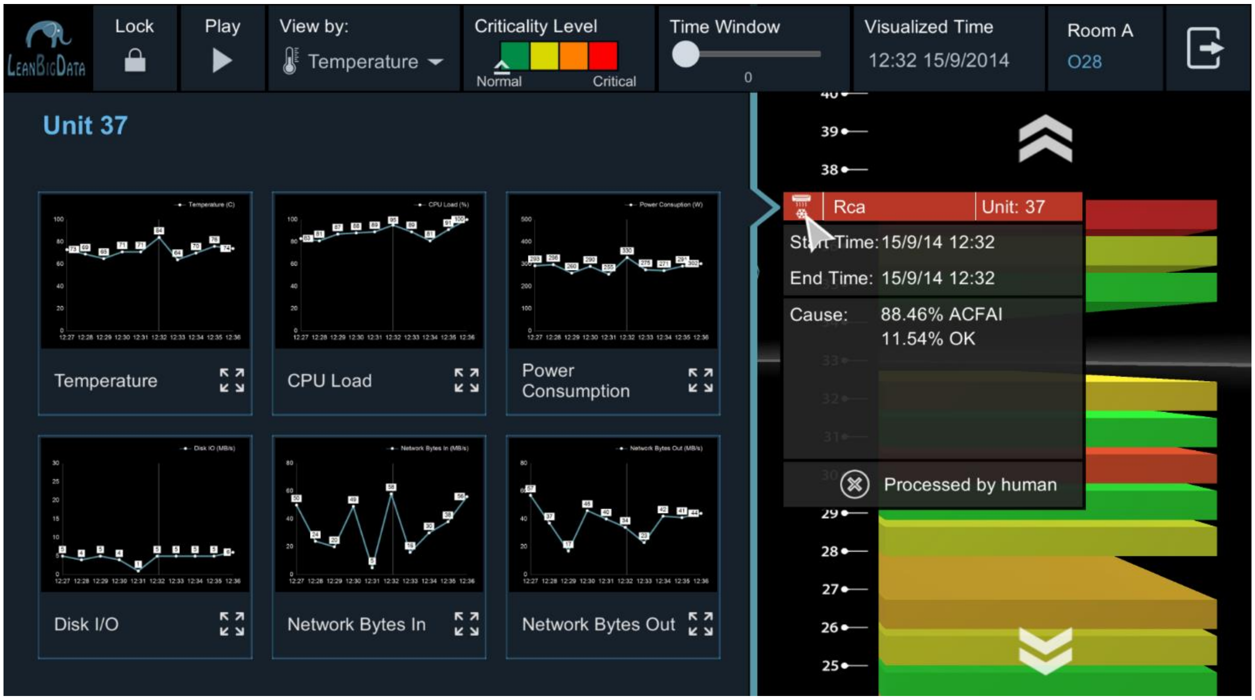


Figure 29: UI pop-up presenting the error's details

6.5.5.2. BeThereNow with Mixed Reality Server

Generic templates do not always cover specific visualization needs; specific implementations, which may not be reusable in general, should also be supported so as to cover particular needs. Augmented reality constitutes a visualization domain where digital content is tailored to match the requirements of the physical world and therefore the framework should support customized implementations. An indicative example can be the capitalization of interactive systems deployed in AmI environments, which contain fruitful information on users' aims and the context of use. Systems which are connected with the framework can be augmented with additional information, which they are not natively capable of presenting; an example is a 2D application presenting photographs can be enhanced by 3D models or 360 degree videos.

Moreover, the framework can be employed for presenting alternate designs, application scenarios or modifications of existing systems. For instance, a virtual fitting room can be altered to present user thoughts and a green screen application can be modified to support post-processing effects or provide interaction with the virtual background. This type of components constitutes an example of mixed reality expansions, where mobile app based augmented worlds are presented on top of mixed reality physical installations, allowing the preview of different realities over already modified worlds. Another example of a custom Information Piece is the BeThereNow application [119], an application that performs background subtraction in order to immerse users into various landscapes and can be used in different domains, including tourism, marketing and advertising. When a user approaches a BeThereNow installation with an AR application, the augmented environment can preview in front of existing installations the different domains in which it can be employed: e.g., when displaying a local landscape in the tourism domain, the AR application can display users inside an environment that corresponds to another domain, such as an advertisement of a product. In this case, the results create a world within a mobile application which augments a world that shows mixed reality environments.

Physical mixed reality installations can be augmented with additional applications - such an indicative case is BeThereNow [119]. This is a typical scenario of a mixed reality application which is able to track users' position in real space and can provide this information to any other application which is integrated within the Ambient Intelligence infrastructure.

In order to facilitate the application of applications (e.g. augmented reality mobile apps) to existing MR systems, an individual component has been designed and implemented so as to facilitate the in-between communication. The developed component, i.e. Mixed Reality Server (MRS) in Figure 30, retrieves data from the MR system describing users' location in a coordinate space defined by the MR system's position. MRS exposes two types of information: user locational data and MR application context.

User locational data regard each user's unique id and skeletal 3d transformations which describe necessary positions and rotations of skeletal joints. The communication exchange regarding positional data between MRS and AR client applications is accomplished via web sockets in order to support real-time bidirectional information flow.

MR Application context includes exposed data regarding the application's state in real-time, allowing interested client applications to be aware of the displayed content in an agreed coordinate system. The provided information is not limited to the rendered multimedia, but also includes semantic information, content metadata and points of interest within the elements.

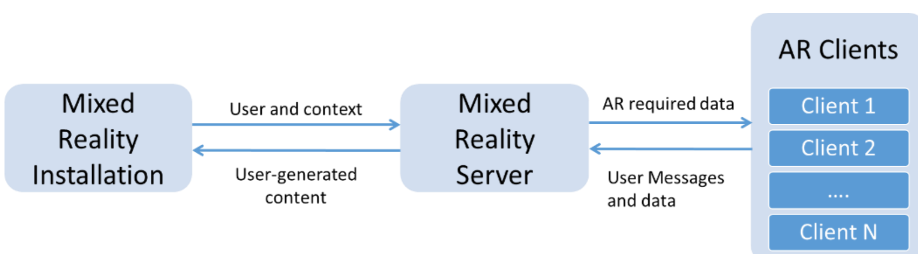


Figure 30: Component architecture

Two individual components were designed and implemented to illustrate the potential of AR for adding value to interactive mixed reality systems using Mixed Reality Server. Both prototypes were implemented to support full body skeletal tracking, using the Kinect One depth sensor [288]. Skeletal joints transformation (position and rotation) are transformed from the sensor's space to the application's display space. At a later stage, MRS provides each skeletal joint transformation in real world coordinates both as the points in which people are physically located and in which they are rendered in the MR display; thus, each AR application is able to superimpose information either in front of the users or on top of the application.

6.5.5.2.1. HelloThereNow

A prototype application has been developed in order to illustrate the potential of using applications running in mobile devices in combination with mixed reality applications. The prototype, which extends BeThereNow [119], is named *HelloThereNow*, and aims at allowing users to superimpose information on the MR display. The overlaid information can be either placed over sections of the background or follow a specific user, if visible on the display.

Firstly, information laid over background artefacts can annotate aspects of the illustrated elements. For instance, in the scenery of a market with traditional items, users can annotate the products sold with a message sharing their personal opinion. Such an example is shown in Figure 31, where a woman has shared her personal experience of the traditional showcased products.

Figure 31: View of the AR application on a mobile device as a user assigns an element to follow user's movement in the MR display

The feature is accomplished via real time streaming of the necessary data, such as image and coordinate data. In order to elaborate on the application of AR to MR systems an individual component has been designed and implemented so as to facilitate the in-between communication. The developed component, i.e. Mixed Reality Server (MRS) in Figure 30, retrieves data from the MR system describing users' location in a coordinate space defined by the MR system's position. MRS exposes two types of information: user locational data and MR application context.

6.5.5.2.2. BeThereThen

BeThereThen, is another application which aims to assist social interaction in the cultural heritage domain, facilitating storytelling and user-generated content. The developed prototype offers the ability to exhibit historical aspects of the displayed landscapes through suggested photographs or videos. Users are capable of choosing specific elements from a multimedia collection related to the currently shown landscape using an AR mobile application. The users are able to interactively unveil in their own private display aspects of the CGI shown in the public MR display. The background landscapes where the application users are virtually standing in can be filled in with user-generated content, such as views of the same landscapes at different time periods through historical photographs or graphic representations. This is accomplished either by completely replacing the background or by brushing the preferred areas of the MR environment via touching the AR display. Upon completion, the users are able to instantly take a real-time photograph of the users in front of the MR display immersed in their personal background. An indicative view of the MR display is shown in Figure 32 here a user is standing in front of the Venetian fortress of Castello a Mare (Koules) in Heraklion. A large section of the fortress is fused with a photograph of the early 20th century, creating a unique mixture of the initial background with a historical representation.

Figure 32: A view of the MR display

6.6. Recommendations

Recommendations constitute an integral part of visualization systems, as they provide users with personalized content with higher probability to be of interest. They can provide connections which might otherwise not be evident to users, which are either manually designated or automatically deduced. More specifically, they can be a key element in the demanding field of Cultural Heritage information visualization by illustrating aspects which implicitly correlate information segments. The Information Worlds framework facilitates such recommendations on different conceptual levels, as it is able to link entire Information Worlds, individual Information Things, Information Pieces or even specific content.

This work facilitates recommendations provision using two different approaches: by correlating previous user experience with currently shown elements and by connecting shown items with others to which they might be related.

Recommendations are often related to associating displayed elements with other content, leading users to other information sources which potentially interest them. Especially when exploring information, this approach can prove to be very assistive as it allows users (once they have located an item of interest) to timely locate other sources without having to browse through other information.

Another form of recommendations involves the connection of users' interests or profile with content that is most probably useful. This is implemented on an Information Piece level, as recommendations are dynamically generated, correlating users with the Information Piece they are currently exploring. As a result, this mechanism can be connected to various recommendation data sources, related to:

- User history: Automated recommendation sources/engines, such as ontologies, can be combined with the history of user actions to dynamically provide references to existing elements within the visualization shown. Such recommendations can be either used to link specific elements which are directly related to each other or implicitly connected by their semantic categorization.
- User profiling: In accordance to the users' interests and/or profiles, it can provide links generated either before usage or at runtime. Such links might not be as specific as user history based recommendations and are usually more abstractly generated in accordance to content classification and semantic meaning.

The recommendations are currently implemented as ready to use 2D user interfaces. The user interfaces present the two forms of recommendations by using different corresponding icons located at the left (recommendations about content related to currently shown elements) and at the right (recommendations within this Information Piece that is related to the users' profiles/actions history) side of the user interface [Figure 33].

Figure 33: The two forms of content recommendations presented to the user

Both of these icons can be selected to expand a menu towards the center of the user interface: in the case of content related recommendations, the menu appears from the left side [Figure 34], while in the case of personalized information the menu appears from the right side [Figure 35]. The content of the menus is dynamically populated and filled with information regarding content data. Each entry matches a specific selectable recommendation; by pressing it, users are directly transferred to the corresponding element (Information World, Information Piece, Information Thing or specific content). This is accomplished in combination with other framework elements such as the SceneManagerBase implementation [8.3.2.3] (for content selection), ScenesManager [8.3.2.2] (for Information Things selection) and Information Worlds Manager [8.3.2.1] (for Information Worlds switching).

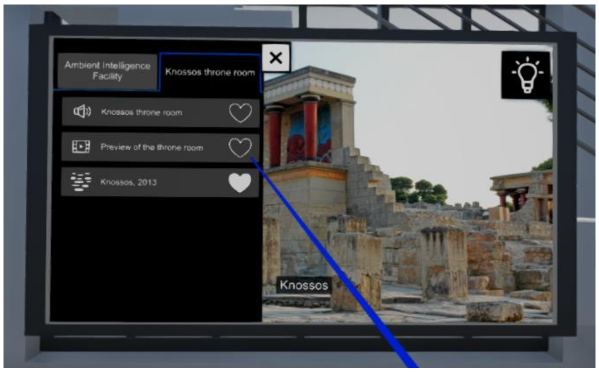


Figure 34: Recommendations related to the content currently shown

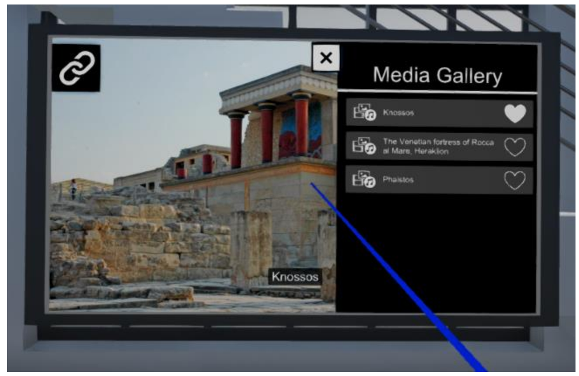


Figure 35: Recommendations about content presented within the specific information piece template

Moreover, recommendations are presented in a consistent manner. Given that the recommendation visualization is presented in a non-intrusive manner, it can act as a consistent mechanism which supportively enhances content exploration on demand, without affecting the user experience.

Figure 36: Alternate design of Information Worlds recommendations including a list of personalized content displayed in the Timeline Information Piece Template

6.7. User Interface adaptation and reusability

Information ready to be visualized includes multimedia (i.e. image, audio, video, text and 3D models) which is presented in a similar way across several Information Pieces. Information can combine several of the aforementioned multimedia, raising different requirements in terms of user interface layout in correspondence to the types of data available. For instance, in the case of presenting information about a certain location, the available data may include (apart from a title) a long textual description and a photograph of the location. When having a segment of the entire virtual space, the photograph can be shown at full size when not accompanied by a description; on the contrary, when both textual information and a picture are present, the picture will have to be scaled down so as the text to be large enough to be read by the user.

The framework provides several ready to use Unity prefabs [426], i.e. Content Presenter Prefabs, which are common among different Information Pieces. These act as standalone entities, which are responsible for presenting the content which is assigned to them and informing the Information Pieces they belong to about user interactions. In addition to the existing implementations of Content Presenter Prefabs, developers or graphic designers can create their own prefabs by either reusing existing scripts or extending them in order to add their own custom implementation [8.3.5.3].

The prefabs (Unity3D templates) presented in the following sections illustrate the various illustrations that can be altered to provide a common design for the generated visualizations. To this end, they can be changed to create a common look and feel across the different Information Worlds.

6.7.1. Content Presenter 2D Prefabs

The ready to use 2D prefabs are Unity UI panels which can be placed within a UI Canvas [431] in the virtual 3D environment. The panel canvas resolution independent and scale according to the space they have available. In order to match different aspect ratios that may host the panels, different implementations are provided (square-1:1, landscape-16:9/4:3, portrait-9:16/3:4) [Figure 37, Figure 38] that optimize their layout accordingly.

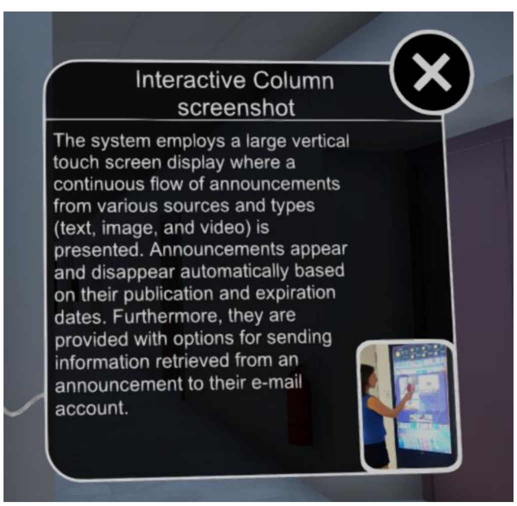


Figure 37:Prefab for presenting content with textual description with a portrait image

Figure 38:Prefab for presenting content with textual description with a landscape image

6.7.2. Content Presenter 3D Prefabs

While the majority of content presentation can be implemented in two dimensions, the need arises in certain cases to facilitate visualizations using 3D Content Presenter Prefabs. Such an example is the presentation of 3D models, where certain 3D artifacts can act as wrappers hosting the showcased models. Object Manipulator [Figure 39] [6.5.2.5] utilizes a prefab where the 3D models are placed over a ring that can be manipulated.

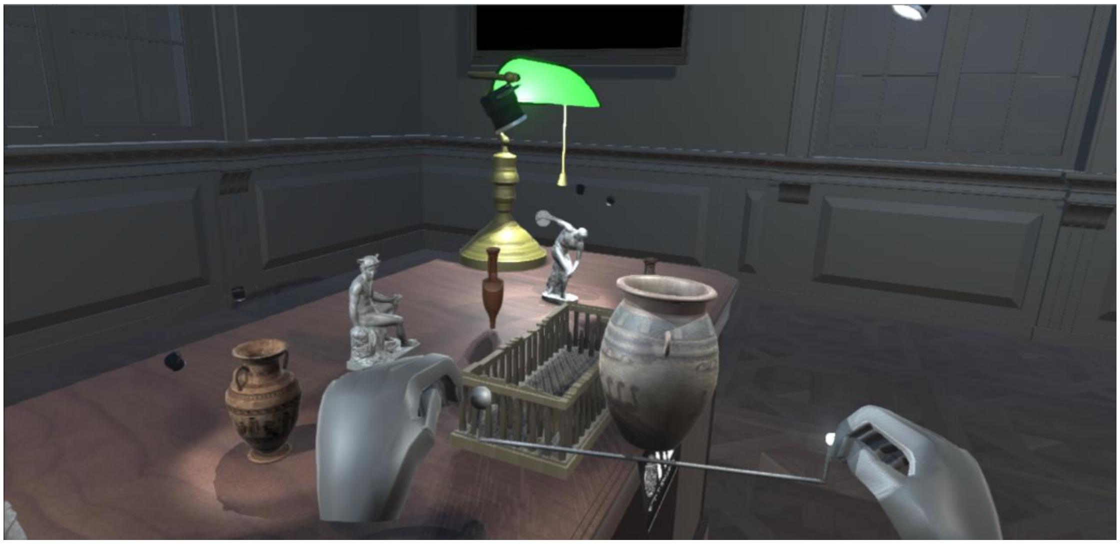


Figure 39: Object Manipulator

Augmented Map [6.5.2.2] hosts two types of Content Presenter Prefabs: one for hosting 3D models and another one for displaying images/text. The prefabs for the 3D models can be fully customized, providing flexibility over the model's rotation and scaling in terms of its integration within the map [Figure 40].

Figure 40: Augmented Map

Finally, Callout Presenter [6.5.2.7] uses a variety of different prefabs that consist of a UI Canvas which originate from a provided anchor point and extend towards any direction. [Figure 41]

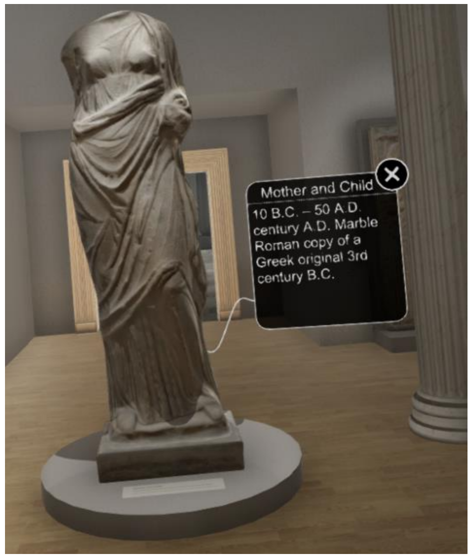


Figure 41: A Text Callout prefab used by Callout Presenter

6.8. Post-Visit

The framework also includes a separate auto-generated feature that presents a summary of the user's experience. This feature is targeted to illustrating in a fully personalized manner a users' visit, providing snapshots of key moments they experienced while using the application created with the framework. Additionally, it provides an overview of the content they explored, wrapping up information spanning across different Information Worlds, Information Things and Information Pieces. This is accomplished using a separate environment, implemented via an additional generic-purpose Information World [8.6.6], which is automatically generated and presented when users choose to end their exploration. The implementation of this feature is described in section [8.3.8].

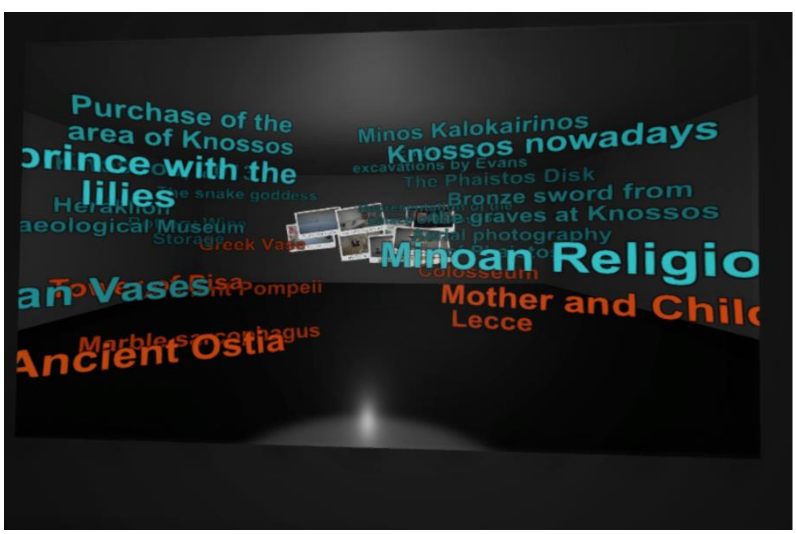


Figure 42: The Post Visit Room

The additional Information World comprises of a Mirror of Thoughts Information Piece Template [6.5.4.1] which is customized to present the content users viewed. This is implemented via feeding it with data captured by the Information Worlds Logger [8.3.13], and results into the users seeing themselves augmented with tags about the content they viewed during interacting with the various Information Worlds.

Furthermore, the screenshots captured by the scene loaders [8.3.4] are presented in the form keepsakes looking similar to Polaroid picture frames [Figure 43]. The choice of employing a frame was made in order to embed a short description in the in the form of multilingual text. They are randomly placed over a wall which users are free to explore.

Figure 43: The post visit screenshots presented as photographs

6.9. Interaction

The term interaction techniques refer to the way human activities are translated to computer-oriented actions. Traditionally, in the context of mainstream computing, the prevalent interaction technique is point and click. However, a variety of interaction techniques exist in Ambient Intelligence environments, allowing systems to receive multimodal input (i.e. using a combination of modalities), either in an implicit or in an explicit manner.

6.9.1. Explicit Interaction

Explicit interaction refers to the process of an initiation of a discrete action, where the user expects a timely response. It constitutes the primary method for providing input to an application and offers the ability to fully explore the potential of the system.

6.9.1.1. Input Manager

Explicit interaction is handled by the Input Manager component of the framework. This module, which is incorporated in every application built with the framework, is responsible for orchestrating the interaction techniques applied and acts as a mediator between the interactive components and the user. Input Manager is the component responsible for receiving input from a variety of sources and propagate it to the corresponding framework component (e.g. Information Things and Information Pieces).

The Input Manager component creates and coordinates the input modules registered within the system. The framework's templates are created using Unity's native UI selection components in combination with the corresponding custom 3D UI controls, making the implementation of the input method orthogonal to the interactive elements. Apart from pointer input, the Input Manager performs the interpretation of raw input to high level events with semantic meaning, e.g. the arbitrary values of a rotation sensor are translated to events such as "Rotate Left Event" or "Looking towards North West".

6.9.1.2. Travelling in Virtual Environments

This work supports performing travelling both in two and in three dimensions, according to the requirements collected for the specific use case.

6.9.1.2.1. First-person movement

First-person movement is the typical way in which travelling is performed in 3D environments. It matches the mental model of the users walking inside the virtual world and is easily perceived by even novice users, as they usually feel in control of the situation. This approach is also well suit specifically for Virtual Reality environments, as users experience the view of the virtual world as if they were there.

A typical implementation of first-person travelling is accomplished via joysticks, either physical or virtual. Such example are the Oculus Touch Controllers handheld devices which are employed by the framework to support 2D movement as described in section [6.9.1.3.2.1]. Moreover, the implementation of first-person movement can ignore the Y-axis changes when employing gestures that inherently provide such functionality [6.9.1.3.2.2].

6.9.1.2.2. *Fly-over module*

While certain 3D applications follow the mental model of first-person movement in space, where the user's viewport moves along the horizontal axes similarly to the way that people walk in space, other applications provide the elasticity to also move along the Y axis.

In terms of travelling in virtual environments along three dimensions (movement in X, Y and Z axes), this work proposes the employment of mid-air gestures for head-mounted VR devices, allowing the users to interact with the virtual world in a natural manner without additional equipment. The benefit of gestural interaction is twofold: it allows users to both select elements and travel in space. In order to move in space, the users can perform a specific hand pose and move it towards the preferred direction and the user's view will fly accordingly in the virtual world. Flying in a virtual environment allows the unobstructed movement in space in 3 dimensions, providing a travelling technique which is applicable to the vast majority of virtual environments.

Apart from navigating using gesture-based interaction, with the aim to support multimodality, the framework will provide navigation controls to provide equivalents for all the potential gestures. The navigation controls will be placed on the side of the screen. More specifically, the navigation controls will be implemented as follows:

- The first control moves the camera up, right, down or left.
- The second control moves the camera forward, backward and supports rotation (i.e., implements the metaphor of moving in the room).
- The third control features two buttons, one to elevate and one to lower.

It should be noted that the controls are implemented following a joystick approach. Therefore, it is not required that a user carries out consecutive click actions to one of the four arrows of the button. Instead, a more "continuous" interaction is pursued as follows: once a user "clicks" on the control - by carrying out the select gesture - a knob appears, indicating the currently selected area of the control, which can be anywhere in the periphery of the circle. As long as a user keeps one fist closed (therefore a "re-lease" action is not carried out), they can move the knob by moving the pointer finger of their other hand and therefore alter the direction of the movement in a continuous manner. In addition, the joystick-like controls are sensitive in terms of speed, as their effect is increased when the knob is moved towards the radius of the circle and eliminated when approaching the center.

6.9.1.3. *Gestural and Device-based Interaction*

The facilitation of gestures in the context of various applications is essential for providing a modern and intuitive way of interacting with the environment. The interaction techniques used for the manipulation of the system should be robust and tolerant to possible user behaviour that does not match the exact system specifications: the framework should be able to prevent reacting in such a way that may be unexpected by the user.

State-of-the-art computer vision based approaches for users' interaction are mostly focused on the processing of images acquired by depth sensors such as Kinect [288] and Leap Motion [250]. Each device serves different interaction requirements. The Kinect sensor is more appropriate for interaction from distance and in front of large displays, making use of the whole body and hands. On the other hand, Leap Motion is commonly used in systems which require interaction close to the user and finger-based item selection. Gloves, wands (Wii etc.) and remote controls can also achieve user interaction and navigation both at a distance and close to the user, but require the user to hold the devices. Computer vision approaches are more unobtrusive and offer a more natural user interaction with the environment since users just use their bare hands.

6.9.1.3.1. Selection in Virtual Environments

This research work adopts a pointer-like metaphor to provide feedback to the user regarding the actions that take place when using their hands. If supported by the input device, the pointer will be in the form of a one-to-one representation of the user's hands in the virtual space (e.g. LeapMotion Component [6.9.1.3.2.2]) or in the form of the handheld device used (e.g. Oculus Touch Controllers [6.9.1.3.2.1]). Otherwise, the use of a cursor is imperative, especially in the remote handling of intangible interfaces where the user has no clear perception of how their movement is handled by the system (e.g. Kinect Component [6.9.1.3.2.3]).

Even though selection using the natural approach [2.4.4.2.2] is performed straightforwardly, the magical approach encompasses a variety of selection techniques. In terms of the magical approach, this research work proposes the use of pinching towards an item and pointing and clicking, in a manner similar to the way a mouse button click is performed.

Selection using handheld devices is carried out by pressing buttons which are directly integrated within them. As a result, the mapping of buttons to corresponding actions is straightforward, but has the drawback of requiring from users to remember the button they have to press to perform selection.

Pinching is performed by pointing over an item and touching the pointer and the index fingers. It is a well-defined movement which is clear to the end user and matches the metaphor of picking an item. Additionally, in terms of tracking, if the tracking device is placed in front of the users' eyes (e.g. head mount displays) or over the head, it can be usually tracked robustly.

Point and click, finally, involves the sequential pointing of an element and the action of closing the pointer finger. This process resembles the mouse click selection and therefore appears natural to end users. Its detection can be recognized by pointing and either tracking a fist or a pinch gesture, since both of them can represent the hiding of the pointer.

6.9.1.3.2. Supported technologies and sensors

The framework supports state-of-the-art sensors which are accurate, stable, unobtrusive and reasonably priced, including Microsoft's Kinect and LeapMotion [250]. The implementation of each sensor's gesture recognition provides equivalent functionality but the interaction vocabulary is adapted to match the individual capabilities and constraints. Additionally, hand tracking components facilitate visual feedback for pointing in the virtual world in order to improve usability and user experience.

6.9.1.3.2.1. Handheld devices (Oculus Touch Controllers)

The framework is fully compatible with handheld devices that accompany commercial virtual reality solutions such as the Oculus Touch Controllers [310] which are combined with Oculus Rift. Handheld devices provide very precise interaction at the cost of the additional burden of carrying a device. Oculus Touch Controllers were chosen as an interaction medium for the following reasons:

- They provide 6 degrees of freedom, allowing unconstrained user movement
- They are handheld and very comfortable to hold
- Several buttons are provided that can trigger different actions
- Certain triggers can assist in selecting items intuitively
- Additional joysticks are integrated within the device
- They provide programmatic SDK for their integration within Unity3D applications

The controllers' 6 degrees of input allow the users to move the device in three dimensions and rotate them at will. These actions are mapped in a one-one representation with the virtual world. Moreover, the direction the controllers are pointing at is rendered through a graphic ray, providing intuitive and precise user feedback regarding their pointing. The multitude of buttons allows the immediate mapping of the functionalities offered by the framework immediately. As a result, the users are able to travel in the virtual space both using a joystick but also by employing the point and click metaphor, approaches which are very common for 3D games in traditional displays and Virtual Reality headsets.

The actions prompted by the controllers' buttons and the triggers are summarized in the following table:

Button	**Corresponding Action**
Joystick	Travel in space along the X and Y axes
Pointing finger trigger	Select (click) an element or teleport to this location
Middle finger trigger	Iterate through the available languages
Button A	Toggle world selection menu visibility
Button B	Toggle favorites menu visibility

As illustrated in the following figure [Figure 44], the buttons are augmented with descriptive images regarding the action they are carrying out.

Figure 44: Oculus Touch buttons augmentation

6.9.1.3.2.2. LeapMotion Component

LeapMotion [250] is a modern sensor that allows full hand joint articulation tracking in a distance of up to one meter. In combination with its small size and the absence of additional power demands, it constitutes a convenient solution for gestures in head mounted displays such as virtual reality headsets.

The interaction techniques for VR environments presented in this work are based on the Leap Motion sensor placed in front of an Oculus Rift, which displays a virtual world to the users. This setup allows free user movement in space, enabling them to turn their head towards any direction. Gesture recognition is accomplished with the camera placed in front of the user's head and therefore the user's hands are never occluded by the user's torso, which is a shortcoming for different setups where the depth sensor is placed in a static position.

Given the sensor's capability for relatively robust and accurate full hand articulation tracking, the users' hands are rendered in the virtual world in a one-to-one mapping to the physical world, creating the feeling of a mixed reality environment as the users perceive the hands that appear in their VR view as their own, and thus are confident that they have full control of the system. In order to move in space, several alternatives were examined. The users can close their fist and move it towards the preferred direction and the camera moves accordingly.

Gestural Navigation

Four alternatives for navigating using gestural interaction are proposed. The under-lying approach relies on the concept of being able to perform a specified hand posture in order to travel in space, whilst not interfering with the ability to point in the virtual environment. In all cases, the gesture is initiated when the user performs a posture and while the posture is tracked, the view of the virtual world moves with regard to the offset vector which is defined by the starting point and the current hand's position.

- **Closed fist [**Figure 45**]:** the user's hands are closed in order to travel in space. This approach employs the movement metaphor of superman, as they are able to freely look in any direction and travel in virtual space in the direction of the offset vector. The cognitive model used is straightforward, as the users' actions are augmented in a magic way through the common magical belief of the super hero's ability to fly.
- **Open palm [**Figure 46**]:** the user's hands are open in order to travel in space. This approach is identical to the closed fist technique, but applied with the posture of keeping the hand open with all fingers extended.
- **Open palm-normal vector [**Figure 47**]:** the gesture is performed while the users keep their hands open, resulting into movement along the axis that is perpendicular to the open palm's plane, both in the front and in the back side of the palm (the positive and the negative values). The concept of this gesture is that the users define the direction towards which they want to travel by pointing with the open hand.
- **Open palm with all fingers extended (along palm's normal vector, analyzed) [**Figure 48**]:** the gesture performed is identical to the open palm-normal vector technique, but analyzes the palm's normal vector with regard to the coordinate system of the users' heads in three axes. The

analyzed vector is split into vectors on three axes (x, y and z) and movement is performed along the dominant one, while the movement on the other axes is ignored. As a result, the users are able to move only in one direction at a time (i.e. left-right, up-down and forward-backward), offering increased precision and eliminating accidental movements in other axes, with the drawback of requiring multiple gestures to move in two directions (e.g. front and right).

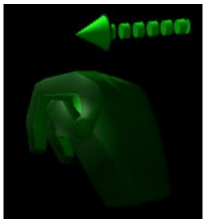


Figure 45:Closed Fist Gesture

Figure 46: Open palm Gesture

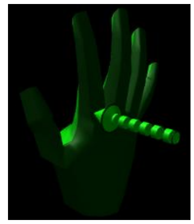


Figure 47: Open palm-normal vector Gesture

Figure 48: Open palm with all fingers extended Gesture

Furthermore, the movement speed is defined by the length of this vector, allowing the users to increase the travelling speed by moving their hand further away from the starting point.

The presented approach aids orientation by employing an arrow placed above the user's hands, indicating the applied gesture direction and scaled according to the movement speed [Figure 49]. Even though the feedback of movement in the virtual space might be sufficient in the case of travelling in environments with nearby points of reference, such as the ground, walls or trees, when travelling at a distance from displayed elements, such as flying over a world, in space or in underwater environments, the movement speed and direction may be unclear.

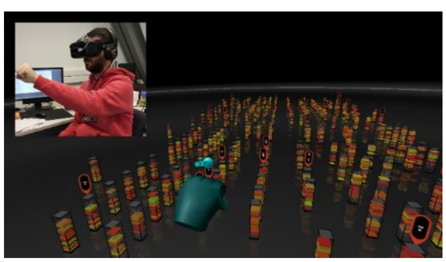


Figure 49:Navigation in VR

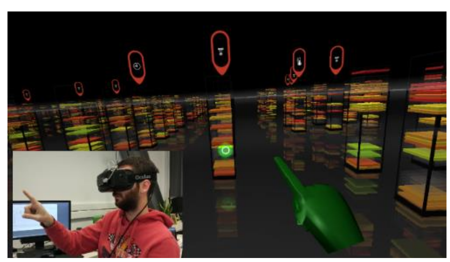


Figure 50:Point and select using gestures in VR

Interaction with elements – the magical approach

The first interaction metaphor for interacting with elements is following the magical approach, where users' hands act as pointer devices allowing to select components beyond their reach. This metaphor is well suit in cases where interaction is meant to be carried out remotely and not requiring any contact with the elements.

To this end, directing the pointer finger at an item is used for aiming at an element. In order to provide intuitive feedback, the pointing direction is lighted at all times, creating a projection of the pointing ray. Moreover, if users are pointing over an interactive item, a circular cursor is placed on the interactive element to designate the ability to select it [Figure 50]. Selection is accomplished through pinching, following the metaphor of clicking with a mouse.

Interaction with elements – the imminent approach

While remote interaction provides an easy way to interact with elements, the imminent approach of touching items and interfaces enhances presence and provides a more immersive user experience. Therefore, having the ability to select elements via touching them or even to directly manipulate them as in the real world adds up great value to the entire user experience.

Information World supports imminent interaction for manipulating elements especially designed for cases like the Object Manipulator component [6.5.2.5]. In this case, users are capable of moving and rotating objects as if they are holding them in real life, thus enhancing the feeling of immersion as users can imitate physical actions entirely. Moreover, through the supplied controls, they can also scale items by simply stretching them, allowing them to view elements in larger size. Finally, the imminent approach can also be combined by additional menus embedded within users' hands as shown in [Figure 20].

6.9.1.3.2.3. Kinect Component

The Kinect sensor is manufactured for optimal tracking at a minimum distance of one meter to a maximum of about 6. It provides full-body skeletal tracking for up to 6 users and it can track the following 4 distinct hand states:

- **Open**: the posture of keeping the hand open with all fingers extended.
- **Closed:** the posture where the user's hands are closed, similarly to making a fist.
- **Lasso:** the pointing posture, where the user's pointer is the only open finger.
- **Unknown**: the state of the hand is unclear or is not performing any of the aforementioned gestures.

The Kinect Component supplies both time-based selection and selection in accordance with actions performed by the users' hands by utilizing the supported Kinect's SDK [288]. Both techniques are offered in a transparent way, as the components within the framework do not have their implementation differentiated. The decision to employ one of the two supported versions can be based on the distance at which the user interacts with the deployed system (when further away the accuracy of the hand tracking state is reduced) and with respect to the way surroundings interfere with the sensor's recognition performance.

Interaction using the Kinect Component is accomplished in a manner similar to the magical approach of interacting with elements using the LeapMotion Component [6.9.1.3.2.2] is implemented: users are capable of pointing towards the desired direction and select any interactive element by performing a "click" action.

6.9.1.4. Multi-touch Interaction

Multi-touch input is natively supported by Unity3D Game Engine on which the framework is built. Therefore, the components created and offered foster the engine's capabilities and inherently provide multi-touch interaction across all the supported devices, i.e. desktop applications (Windows or Mac) and smartphones (Android or IOS). Multi-touch is also employed for selecting elements in Augmented Reality applications, while travelling is carried out by physically moving in space.

6.9.2. Implicit Interaction

According to [368], implicit human computer interaction is "an action, performed by the user that is not primarily aimed to interact with a computerized system but which such a system understands as input". Implicit interaction is based on contextual information and complements explicit interaction in a manner similar to the way body language supplements speech during a human to human communication.

6.9.2.1. Positional Interaction

Ambient intelligence can employ positional tracking as an additional interaction technique, despite body posture not being a traditional interaction modality. Computer vision algorithms can be employed to gather and analyze data allowing applications to mimic and understand user posture.

This research aims to incorporate positional tracking in the supported interaction methods, increasing users' immersion and providing supplementary input to explicit interaction devices. Additionally, this work provides "smart" elements that utilize position and gaze tracking, such as items that awake when looking at them or lighting alternations which enhance stories narration and unveil information.

6.9.2.1.1. Device-based

State-of-the-art SDKs are heavily dependent on positional tracking for the user of the head mounted display, both in AR and in VR setups. Therefore, modern devices integrate multimodal tracking of their transformation (i.e. rotation and position) using a variety of input methods, such as accelerometers, gyroscopes, magnetometers, depth and RGB cameras, thus providing a multitude of raw information which can be exploited to infer their transformation. Google's Daydream [154] provides inside-out positional tracking system, which will be replaced by WorldSense [157] for the new devices [475], greatly increasing accuracy through in a reliable manner. Oculus Rift [308] provides positional tracking in an area in front of an accompanying camera, whilst HTC Vive [192] provides positional tracking in room-sized areas.

The framework presented in this work is based upon existing state-of-the-art positional tracking, including technologies such as project Tango [155] and ARCore [14]. Visualized information is responsive to the location of the user's handheld device, creating a form of implicit interaction that influences user experience positively. Furthermore, this approach promotes kinesthetic interaction and matches the metaphor of virtual space exploration, creating a feeling that encourages interactivity.

6.9.2.1.2. Device-free

Modern sensors, including RGB cameras and depth cameras, are able to recognize human movements in space using computer vision algorithms. The framework aims to provide components which integrate such technologies and offer interaction without the burden of holding or wearing tracking devices. The applied technologies offer remote skeletal tracking, acting as the basis for creating ecosystems which detect human motion and allow the environment to react to user actions.

7. Storytelling and Narratives

The framework supports ways to model stories which are defined either a priori or at runtime. These stories, which constitute a graph ready to be explored by end users, can produce different visualization outcomes with respect to the way they are narrated.

The framework firstly supports the narration of the stories freely, allowing the users to explore the provided story at will. Therefore, users can explore information without restrictions, choosing the items of interest and creating their own path through the story. This approach, despite having the advantage of letting users select only the information they are interested in, has certain drawbacks:

- Users may not discover key elements, as they might not notice them in the visualization. On the contrary, the coherence of the narration is ensured and the complete picture can be experienced when employing narratives [375].
- Users may not make correlations that are important, as the exploration takes place in accordance with their own way of thought. As a result, they will not make inductions that they would not imagine on their own and will not train their thought to work in a different manner, thus leading to a failure to exploit the insights [2].
- Their experience will not be personalized. Their exploration of the story could be adapted to suit the needs and interests of a user group they belong to [446]. For instance, in the case of an ancient temple exploration, engineers could be shown the technical details of the construction to match their professional expertise.
- The narrations will not reach their educational potential if information is not presented into the context [398]. In the case of children or users that are not familiar to the story narrated, the exploration could result in a partial exploration, missing the bigger picture that could be exemplified by the proficiency of an expert.

Due to the aforementioned weaknesses of unguided exploration, the need of custom narratives arises. The framework thus provisions the creation, storage and customization of narratives that can be utilized to explore different facets of stories.

The primary application of narratives is the provision of custom walk-throughs, which illustrate the key elements of a story and depict aspects of information that enhance the story visualization. Such walk-throughs can be user-generated, generated automatically or by visualization creators [5.1.1.1].

The narratives are stored as lists containing a sequence of elements ready to be presented to the end users. Once the lists are finalized and populated, the framework automatically handles the narratives' presentation to the users via the Navigation Assistant [6.5.1.3]. Using the Navigation Assistant component, the framework guides the user through the presented items sequentially. The guidance is accomplished by moving the user in the virtual environment to the next element. According to each element's type (i.e. Information World, Information Thing, Information Piece or specific content within an Information Piece) the framework guides the user to it and takes all necessary steps to display it. For instance, if a narrative involves the presentation of a content shown in an Information Piece, the framework not only moves the user to the area where the Information Piece is located, but also displays the specific element (e.g. an image is shown in full screen using the Media Gallery, tag information appears in the WordCloud3D, etc.). Finally, when displaying content which lies within a certain Information Piece, the user is not moved, but the Piece switches to the next element.

7.1. Creation and editing of Information Worlds

The creation and assembly of Information Worlds is accomplished using the Unity3D Editor interface [421]. The editor interface was chosen as an option due to the high flexibility offered in terms of 3D models manipulation and drag and drop features. Users are able to use existing templates (Unity prefabs [426]) provided in the form of drag and drop components. The templates correspond to the notions defined by the framework, i.e. Information Things and Pieces. The process of world creation and editing involves all the visualization creators [5.1.1.1], mainly graphic creators, domain experts and a person familiar to the Unity3D interface.

7.1.1. Scene creation and rendering effects

Apart from utilizing the provided templates, users are able to customize them as well, creating the look and feel that matches the visualized environment. For instance, in the context of an Information World that presents a museum's hall, the components applied will look futuristic if the museum is about technology, but they will be more fluid and abstract if the content is about surrealism. This is accomplished using either themes that can be applied globally (for the entire world) or per element, if a specific component is meant to differ from the others. Such themes can consist of rendering effects which take place either during rendering or as post-processing effects.

The effects employed for scene rendering can be marked as having a global effect, i.e. apply to any information world the user visits. However, the effects can be marked as scene-only, therefore being applied to a specific information world only and replacing any existing global effects.

7.1.2. Scene customization

The environment that is created to render an Information Thing does not only consist of the interactive elements that are provided by the framework, but also displays secondary elements, such as the virtual scene floors, walls, lights, decorative components, etc. These components are not fundamental for the information provision; yet, they provide a context in which the users are immersed into, greatly affect user experience and complement the story presented by the framework.

The framework allows the visualization creators [5.1.1.1] to configure the Information Thing as desired, using rich state-of-the-art 3D effects provided by Unity Game Engine. In addition, the framework provides a library of ready to use components that can be applied to enhance scene realism or embellish magical aspects and create a feeling of magic.

Furthermore, the framework is fully compatible with Unity3D's rendering pipeline, thus allowing the baking of custom lighting and boosting the final application's performance without compromising the render results.

7.1.3. Narratives Creation

As far as the custom narratives are concerned, the content provided as input to the framework and the editor interface allows the creation of Information Worlds. The framework assists the construction of narratives, which can be done by professionals [5.1.1] or by end users [5.1.2].

Narratives constitute of a set of elements that are presented sequentially, defined by their unique identifier. This set not only contains content elements (e.g. a person's photograph), but can also include any type of information modeled within Information Worlds: an entire Information World, an Information Thing, an Information Thing or even specific content. Apart from the sequence in which they will be shown to users, the presentation of these elements can be timed so that the user experience is optimized in accordance to each element's importance.

7.1.3.1. Automatic narratives creation

Two types of automatic narratives creation can be integrated within the Information Worlds framework.

Firstly, narratives can be created directly from within the data sources that provide the content to be presented; such an example may be ontology-based creation of narratives (which can of course be manually altered by visualization creators) that are directly imported into the framework.

Secondly, narratives can also be created from within the framework itself based on previous users' interaction: the framework anonymously keeps track of each user's interactions within the visualization by modeling it into sets of actions performed within the various Information Worlds. This information can be later used in order to create narrations of the most popular elements examined by users, either on a global scope, or on a profile-based analysis by analyzing user logs in accordance to a profile-based categorization.

7.1.3.2. Narratives creation by experts

The framework provides content experts [5.1.1.1] with the tools to shape the Information Worlds, along with all the corresponding components (Information Things and Information Pieces), customize the look and feel of the environment, and dictate the provision of the events that establish the narration.

To this end, the framework supports the assembly of lists containing elements of any type. Visualization creators are able to drag and drop the element they want to include in a narrative onto the corresponding narrative and customize its timing. Moreover, the creators of the narratives do not have to explicitly define all the intermediate steps, as the framework is able to fill in the steps automatically. For instance, the framework automatically switches from one Information World to another if an element belongs to any other.

7.1.3.3. Narratives creation by end users

Apart from ready to use narrations created by experts, the end users are also allowed to create their own stories while using the framework. This is accomplished through the favorites option [Figure 51] which is shown next to each content presented. Users are able to create collections of elements they like and edit it using the favorites menu [Figure 52]. Once the users' collections are finalized, a guided tour can be initiated on demand, containing the information stored.

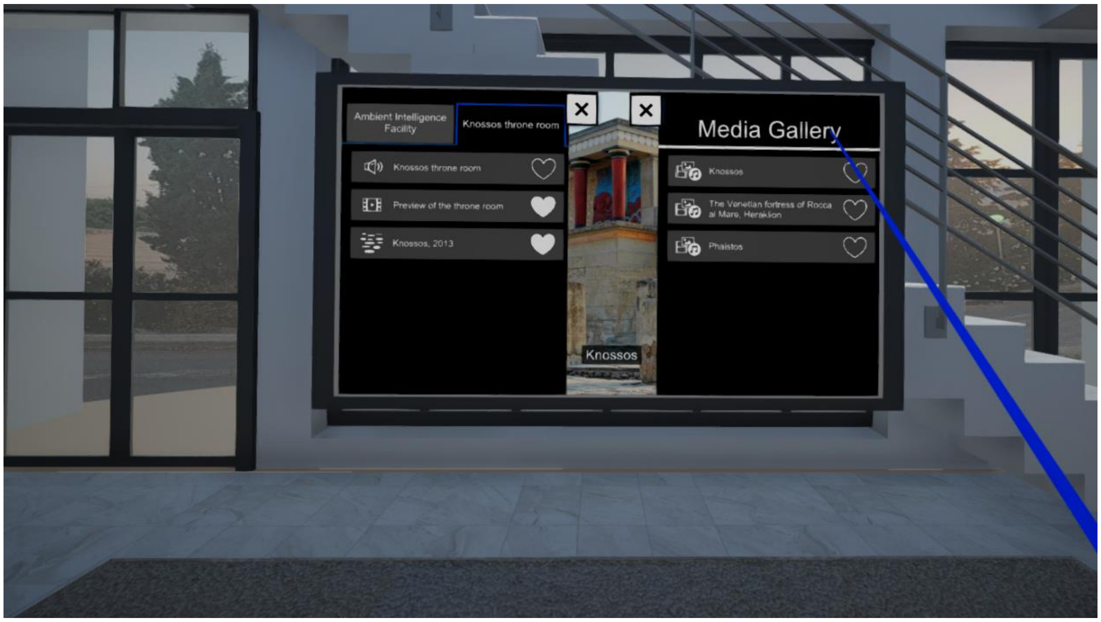


Figure 51: The option "favourites"

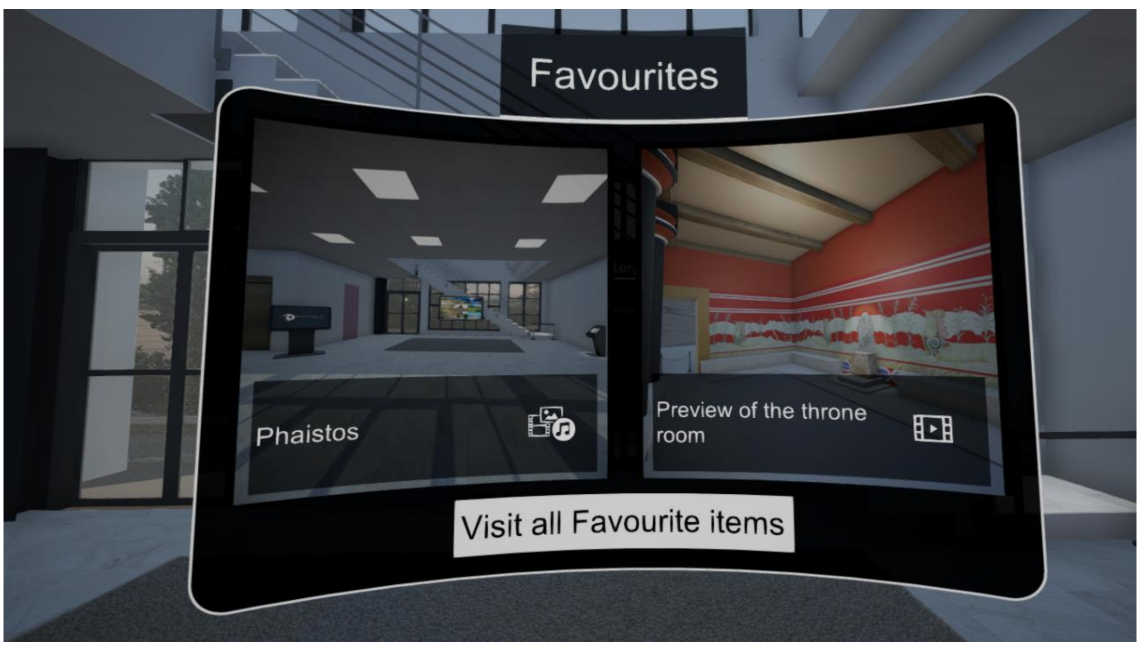


Figure 52: The favourites menu

Apart from manually generating the narratives, the framework's internal logging system can also be applied as input of the elements to showcase. To this end, the user's entire visit can be replayed in an entirely automated way.

The narratives can hold diverse meaning in accordance to their context of use. Some usage scenarios are presented in chapter [9], where various aspects of storytelling are illustrated in the context of Cultural

Heritage and Big Data visualizations. In the case of the Smart Museum use case [9.1], user-created narratives present highlights of their visits, acting as a summary of the elements they appreciated during their visit. In the case of the Infrastructure Management and Monitoring use case [9.2], these narratives can indicate items of interest in terms of the operation of a data center.

8. Framework Implementation

This chapter presents the overall structure of the framework's implementation along with details regarding the decisions taken for the final implementation of this research work. The architecture and the core engine components are initially presented, along with the utility libraries created. Moreover, content serving and retrieval is presented. The indicative Information Worlds created as use cases are presented in order to illustrate the framework's capabilities. Finally, the implementation of the individual Information Piece Templates is thoroughly presented.

8.1. High level framework Architecture

An overview of the framework's architecture is presented in [Figure 53]. The diagram presents a simplified view of the overall framework's structure for the sake of clearance and so as to highlight the components developed according to their importance within the presented work.

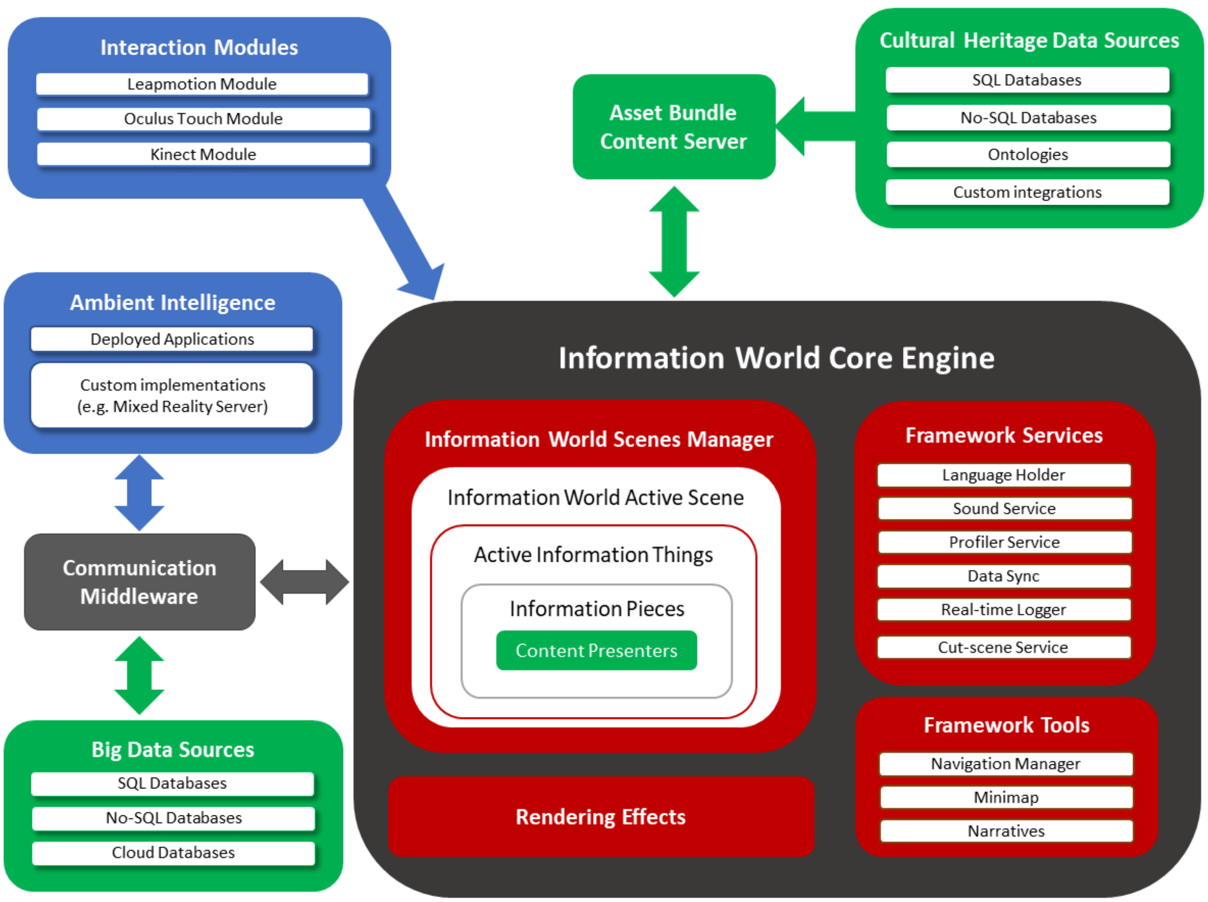


Figure 53: Framework Architecture

The following sections describe the implementation of each component in depth, presenting their challenges and illustrating the rationale behind the conceptual design of the framework.

8.2. Symbolic Links and framework scalability

An important decision taken for the development of the framework was the usage of symbolic links [396]. In computing, a symbolic link (also symlink or soft link) is a special type of file that contains a reference to another file or directory. The added benefit of symlinks is that applications cannot tell the difference between a symlink and the original file or folder.

The approach of using symbolic links was followed due to the fact that Unity3D does not allow referencing a Unity3D project from another Unity3D project. Therefore, in order to reuse an existing Unity3D project, all the scripts and resources used within a project have to be placed under the project's root folder, creating a monolithic result. This fact has several side-effects, including the following:

- Each application does not require all the functionalities and components provided by the framework.
    - Interaction methods have to be integrated within the same project (e.g. LeapMotion, Oculus Touch Controlllers, Kinect), also carrying their dependencies.
    - Information Piece Templates most probably will not all be used in each application developed
    - Typically, only one data source (e.g. database or asset bundles server connection) will be used in one application
- Information Piece Templates can't be updated independently
    - Certain code updates may break the Unity3D's scene structure if using subversion systems
- All content needs to be placed in the specific folder structure, resulting in huge data volumes
- A Unity3D project can have only one build target at a time
    - Creating applications for mobile devices and desktop pc applications on the fly is not feasible.
    - Switching build targets requires re-importing all code and content assets, which is a time-consuming process

In any of these two cases, the process to create a new instance of the framework, the steps required are the following:

- The library containing the project's core source code needs to be included as a plugin
- A symbolic link to the framework's "Required" project folder needs to be created
- A symbolic link to the visualization templates is required. This can be achieved in one of the following ways:
    - Create a link to the framework's "Sym" folder, which is a symbolic link folder linked to all the available template implementations
    - Create links only to the template implementations the project will use

For any Information Piece Template implementation to be integrated within the framework:

- The library containing the project's core source code needs to be included as a plugin
- A symbolic link to the folder containing only the required scripts and assets

Therefore, the path of creating symbolic links for each Unity3D project that does not belong to the core engine of the framework was followed. This approach allows the direct integration of a project located in a different folder within the framework as if it was within the project's folder. Each ready to use component provided by the framework can be developed independently, and any external component can be inserted on the fly without interfering with the engine's core components. Moreover, any project that will use the framework will be independent of others, while also allowing the maintenance of the framework in a centralized way.

8.3. Information Worlds Core Engine

This section presents the components that belong to the core of the framework's engine.

8.3.1. Asset Bundles Manager

Whereas source code is delivered with the application, the framework is built to work with Unity3D scenes being delivered through asset bundles remotely provided. Two main types of content are stored in asset bundles: content data and scene data. This decision was taken so as to facilitate remote mass updates across all deployed applications in an automated manner. As a result, each scene with its accompanying data (e.g., prefabs, scenes, textures, etc.) is encapsulated in a corresponding asset bundle. Moreover, content data are organized into asset bundles, grouped according to their context.

At the deployed application side, this is implemented using the Asset Bundles Manager, a persistent script responsible for downloading data from the Asset Bundles Server [8.5]. The script downloads both of the available asset types packed in asset bundles, content and scene assets. It is responsible for establishing the connection to the server and download the assets asked, while also resolving any potential dependencies across the different asset bundles. The Asset Bundles Manager provides an API for any client script to download (either asynchronously – which is typically used - or synchronously) straightforwardly.

This component supports data caching: any asset downloaded will be stored in local storage for any future downloads; any consequent requests will provide the cached elements, if the server does not reply that the content cached is outdated. Caching persists along sequential executions of the application and allows the application to work even if no connection to the Asset Bundles Server can be established, provided that the application has ran at least once and all content is already cached.

8.3.2. Scene Management

Scene management refers to the way that the framework handles Unity3D scenes. Unity3D scenes can be considered as standalone entities containing objects placed in the 3D space and can be loaded in two modes [438]:

- **Single**, where all items existing in the currently loaded scene are unloaded and all items belonging to the new scene are loaded.
    - Items that are needed not to be unloaded can be flagged [432] so as to persist across all scenes. All objects in the framework that belong to the framework's core components (e.g. singleton patterns) are flagged with this option.
    - The scene loaded in single mode is considered as the main Unity3D scene loaded. This affects certain aspects of the Unity3D project, as the main scene is the only scene applicable for functionality such as navigation and path finding.

- **Additively**, where all actively loaded scenes are not affected by loading a new scene additively.
    - Additively loaded scenes can be added and removed on the fly asynchronously almost without affecting user experience

The following sections present how the Information Worlds framework handles scene loading and organizes information so as to offer a scalable and performant approach which is as straightforward to use as possible.

8.3.2.1. Information Worlds Management

The Information Worlds defined within the framework contain entities (Unity3D GameObjects [434]) which establish the entire virtual environment. The entire environment contains the static 3D geometry that constitutes the visual aspects of the user's surroundings, but also includes the dynamic content which resides in it, i.e. the Information Things and the Information Pieces. These components often include multimedia content and are resource-intensive both to load and to maintain. For instance, in the case of an environment consisting of several rooms, there is no need to load the Information Things on areas which are not directly visible to the end user.

One Information World usually consists of several Scene Loaders [8.3.4] which can

This approach is also embraced for the dynamic loading of the 3D geometry in order to further improve loading times; however, it should be noted that it is quite common that 3D models that consist the entire geometry require additional processing in order to be split to segments that are loaded on the fly.

To this end, the Information Worlds environment includes at least the following elements:

- **3D geometry**. The geometry can either include the entire environment's geometry or be split into parts which are dynamically loaded.
- **Baked navigation meshes** (used by Navigation Assistant [6.5.1.3]) for the entire Information World environment
- A **SceneManagerBase** implementation (discussed in section [8.3.2.3])
- **Scene Loaders** (discussed in section [8.3.4]), which are the entities responsible for loading additional elements, including Information Things, Information Pieces and 3D geometry.
- **Rendering effects** applied in a global scope, if any.
- **Additional lighting,** if any.

8.3.2.2. The Scenes Manager

The Scenes Manager is a persistent script implemented with the singleton pattern, responsible for the management of the various scenes in the executable's lifetime. Any Unity3D project that exists interacts with the framework needs to include a SceneManagerBase (described in the following sections) script implementation.

The Scenes Manager component is responsible for keeping track of the actively loaded SceneManagerBase instances and provides a public API that other entities (such as the Scene Loaders [8.3.4]) can use to load additional scenes. Moreover, the Scenes Manager component maintaining a mapping of all the existing Scene Loaders with the corresponding loaded scenes so as to be able to correlate them.

Additionally, Scenes Manager organizes and orchestrates loading and initializing a scene and gracefully unloading it. In order to facilitate the different requirements of scene loading, a list of the additively loaded scenes and a stack of the loaded within another element scenes [6.5] is kept. When loading additional scenes, certain events are needed to be propagated to the end Unity3D scenes for the loading and unloading procedure:

- The successful scene initialization is accomplished by providing various callbacks (e.g. load scene, initialize scene, download content, update scene loader's initial image, and scene ready).
    - Loading an Information World scene. In this case, the Scenes Manager cooperates with Cut Scene Manager [6.3 and 8.3.3] in order to show the transition visual effect while the user waits for the new world to be loaded.
    - Loading an Information Piece which exists in place [6.5]. When an Information Piece resides within a 3D geometry (e.g. a virtual television), an image is initially shown. The Information Piece template will be asynchronously loaded, allowing users to interact with their environment in the meanwhile. Once the Information Piece is ready, the initial image is faded out and the Information Piece appears.
    - Loading an Information Piece which exists within another element [6.5]. In this case, the active Information World is temporarily unloaded and the Information Piece is loaded in cooperation with the Cut Scene Manager [6.3 and 8.3.3].
- The successful scene unloading is accomplished by providing various callbacks (e.g. keep screenshot if needed, update scene loader's initial image, start unloading the scene, scene unloading finished).
    - Unloading a scene which exists in place [6.5]. Correspondingly to loading a scene, when unloading the Information Piece, the image initially shown in the Information World is smoothly faded in.
    - Unloading a scene which exists within another element [6.5]. In this case, the active Information World is restored and the Information Piece is unloaded in cooperation with the Cut Scene Manager [6.3 and 8.3.3].

8.3.2.3. The SceneManagerBase script

The SceneManagerBase script contains an implementation of the basic functionality of managing a scene and implements the core callbacks for initializing, updating and unloading a scene. The implementation combines Unity3D callbacks (such as OnEnable, OnDisable, etc.) and callbacks called from the ScenesManager described in the previous section. The callbacks are implemented as C# virtual functions [65] so as to be capable of being overridden and are the following:

- **InitiazeSceneCallback**: Developers can use this point to attach code for scene initialization, such as content loading and scene organization.

- **OnSceneReadyCallback**: Developers can use this point to enable user interaction with the loaded scene. At this place, the script automatically unveils the scene content to the user if any such object is defined.
- **OnPreSceneUnloadCallback**: At this point, a screenshot of the scene is automatically taken if specified. This is done so that the transition to the unloaded environment is smooth. Developers can use this point to execute any code before actually unloading the scene.
- **UnloadSceneContent**: Developers can use this callback to add any code needed after any screenshot is taken and just before actually unloading the scene content.

The canvas screenshot rendering process is an asynchronous process due to internal Unity3D implementation. As a result, the corresponding code provides access to callbacks before capturing the screenshot and immediately after as well.

Another fundamental implementation of the SceneManagerBase script involves handling **content selection**. The script also provides a callback for selecting specific content (if any). In addition, it keeps track of the content available within the scene so as to be the element responsible for facilitating content selection. The script provides the API for any content to inform it about selection changes and at any time keeps the currently selected content. Finally, SceneManagerBase provides a callback for placing code for resetting the scene when instructed to do so by the ScenesManager.

8.3.2.4. The SceneManagerBase with Asset Bundles

SceneManagerBase with Asset Bundles Content is a script implementation inheriting from the SceneManagerBase implementation. In addition to the items defined for SceneManagerBase, the implementation takes as input a string parameter which is used for retrieving its content from the Asset Bundles Manager [420]. Moreover, primarily for testing purposes, the content used can be overridden and be directly assigned from the project's resources, bypassing the pipeline of downloading the content.

Moreover, the script contains a pre-filled set of prefab GameObjects. Several scenes may require prefabs which are meant to be common among an Information World. For instance, the different content types need corresponding prefabs which will be otherwise needed to be explicitly set for each scene integrated in the framework. Using this functionality, the prefabs can be set only once and be either used by all the scene instances or overridden on demand without affecting the others.

8.3.3. Cut Scene Management

As described in section [6.3 and 8.3.3], switching between different environments is accomplished using an intermediate step similar to the cut scenes shown in cinematography. This is implemented using the CutSceneRenderingManager, showing the overlay dissolving effect which allows the background processes to independently while the end user sees a 360 degrees' view of galaxies. This component is interwoven with the ScenesManager [8.3.2.2] and the Active Information Worlds Manager [8.3.4.4] components, so as to allow the synchronization of scene loading/unloading.

The implementation of this process is carried out through a custom rendering shader which can turn a material from completely opaque to completely transparent and vice versa. The shader is set to render a cube on top of any other graphic object in the application, therefore obscuring any other 3D model of the information world. The cube contains a cubemap textured material of a galaxy, creating the illusion of flying in space. The entire process of dissolving/resolving the cube takes approximately 1 second, which is enough time for the user to perceive that their world is tearing apart, but not to notice the fact that dissolving does not occur at the objects' surface.

The following table presents the process followed in accordance with what the user sees:

What is actually happening	What the users see
An overlay cube is resolved	The world around them is dissolving and the space becomes visible at the background
The active Information World is unloaded	They are viewing galaxies in space
The new Information World is loaded and initialized	They are viewing galaxies in space
The overlay cube is dissolved	A new world around them is put together

8.3.4. Scene Loaders

Scene Loaders are scripts which are used by Unity3D GameObjects in order to allow the dynamic loading of elements that are Unity3D scenes. These scenes can actually instantiate Information Things, Information Pieces, entire Information Worlds and additional Information World segments.

In addition, Scene Loaders are used as a link between instantiated Unity3D scenes and the active Information World. ScenesManager handles loaded scenes in an agnostic way, disregarding the semantic characteristics each loaded scene may have. Moreover, SceneManagerBase (the script for maintaining certain Information Things or Pieces) is actually a reusable component that loads the content specified and acts accordingly. To this end, the two-way connection between Information Worlds and Things/Pieces is accomplished through the Scene Loaders. This choice was made keeping in regard two concepts:

- Each reusable template should be content and context agnostic, i.e. act independently.
- Scene Loaders are active within the scope of the Unity3D project regardless of whether the corresponding scenes are loaded. This allows:
    - The connection from one Information Thing or Piece to another or even to another's content. Such an example may be a specific content selection.
    - Propagating screenshot capturing events to SceneManagerBase scripts for unloading.
    - The capture and storage of indicative screenshots used by Post-Visit Manager [8.3.8].

Scene Loaders have their functionality implemented, but are not meant to take decisions regarding when to load the corresponding scene. This decision was taken for the sake of improved modularity, as different scripts or triggers can be connected to them. Such examples include:

- Area triggered scene loading scripts, which fire when the users step into a predefined area
- Looking at scene loading scripts, which fire when the user is looking at the predefined area
- Automatically loading scripts, which fire when enabled – even at startup

8.3.4.1. Scene Loader Script

The Scene Loader script provides a ready to use implementation for the loading additional scenes to an already loaded Information World. This implementation contains code which can be overridden by scripts inheriting from this class in order to support additional functionality, such as Asset Bundle Scene Loaders and World Scene Loaders.

The Scene Loader Script asks from the ScenesManager to load any required Unity3D scenes and waits for the new scene to load to update the reference kept for the SceneManagerBase that is responsible for the newly loaded scene.

In addition to the base implementation, the script also attempts to create a screenshot for the newly loaded scene, so as to provide the Post-Visit Manager with indicative screenshots of the users' experience.

A common issue for the captured screenshots has to do with the loading times. During early user testing, it was noticed that the screenshots captured immediately after loading a scene were not indicative of the users' viewpoint of the scene. As a result, the script was improved to capture an early screenshot of the new scene, but also to keep waiting until the user looks (almost) exactly at the scene: when this happens, an updated screenshot is captured, overwriting the previous one.

8.3.4.2. Asset Bundle Scene Loader Script

The Asset Bundle Scene Loader Script inherits from Scene Loader Script and additionally loads the defined scene from the Asset Bundles Manager [8.3.1]. The implementation of screen capturing is overridden so as to timely capture a corresponding indicative screenshot only once the scene's content has been successfully loaded by making use of the events provided by SceneManagerBase with Asset Bundles (described in section [8.3.2.4]).

8.3.4.3. World Scene Loader Script

The World Scene Loader Script inherits from the aforementioned Asset Bundle Scene Loader Script, but also performs additional actions related to Information Worlds scene loading. In more detail, the script additionally registers itself to the Active Worlds Manager explained below.

8.3.4.4. Active Information Worlds Manager

The management of Information World Scene Managers is carried out by the implementation of the WorldSceneManagersHolder script. This singleton keeps track of the active Scene Loaders which contain Information World scenes and the currently loaded Information World.

The script communicates with all the World Scene Loader and SceneManagerBase scripts so as to implement, along with the Cut Scene Manager, the process of transitioning between different scenes and Information Worlds.

8.3.5. Content Data

The framework presented in this work holds an internal way to represent data thoroughly described in section [6.1.4]. The following sections describe way that content information is modeled and implemented within the Unity3D environment, presenting the approaches followed for supporting information belonging either to the Cultural Heritage or to the Big Data domain.

8.3.5.1. Cultural Heritage content storage

General information is stored in an internal format as described in section [6.1.4]. This format is aimed to be well suit for a variety of domains including the demanding field of Cultural Heritage. The existing implementation is extendable, as it provides a default implementation for common fields as described in section [6.1.4.3].

The implementation of the data storage is based on Unity3D's Scriptable Objects [429]. Scriptable Objects allow saving and storing data directly from within the Unity3D editor interface. Additionally, massive content generation can be facilitated through scripting, as Scriptable Object creation and addition to the Unity3D environment is feasible. To this end, Cultural Heritage data sources (such as ontologies and databases) are integrated to the framework in an automated manner.

Furthermore, Unity3D allows the customization of the editor interface through editor scripting [422]. These scripts allow the creation, modification and duplication of custom data structures, such as the ones implemented for storing content. As a result, the Visualization Creators [5.1.1.1] are able to use the Unity3D editor interface not only for assembling the envisioned environment, but also to interactively create the content they want to insert into the environment.

8.3.5.2. Big Data content storage and update

Big data storage and runtime representation in 3D environments requires performant implementation in terms of both occupying space and retrieving. To this end, the data structures designed for generic purpose information representation are not optimal when visualizing Big Data: on the contrary, any implementation which is to be used needs to be optimized.

The use case of Data Center Infrastructure Management presented in section [9.2] is an indicative example of a storing large data volumes frequently updated in real-time. In this case, a custom implementation was required to store the metrics for the servers being monitored.

Custom data structures, only containing the fields required to store the metrics, were employed. Additionally, information regarding the detected anomalies were also modeled and stored within corresponding data structures.

Given that the data related to the data center were processed and updated at real-time independently of the visualization, a connector was required to the server containing this information. The implementation of Big Data content retrieval and visualization update was implemented using a hybrid approach, combining polling and event-based data updating. Polling is used for retrieving the updated values for the specified data center room and event-based updates take place for server-side notification pushing regarding updated values for the data center room's metrics.

At startup the visualization polls the Big Data server to retrieve the last known state of the data center and visualize the environment accordingly using HTTP requests. Meanwhile, a web socket connection is established, allowing two-way communication between the server and the visualization application. This web socket connection was used to notify the visualization application for updates regarding the data center room currently visualized. In addition to providing data updates, the web socket informs the visualization of anomalies detected and provides the corresponding data in JSON [207] format.

8.3.5.2.1. Servers Visualization

A C# dictionary [63] is used to keep all server racks information within the Information World (data center room), hashed by their unique ID. For each rack, an array contains the set of per sever metrics provided by the data source via an instance of a DataCenterServersUpdater script. This script is responsible for coloring the servers existing within the rack (if any) according to the metric displayed.

In terms of rendering, the data center rooms comprise of tens of thousands of servers updated and rendered in real time. In order to improve the application's framerate, the framework takes advantage of Unity3D's GPU instancing capabilities [423] by implementing a custom shader for rendering the server racks and the servers: GPU instancing allows the batch rendering of 3D objects sharing the same mesh at once. In order to facilitate the different coloring of each server according to its state, per-instance data are provided to the meshes' shaders so as to render the geometry accordingly.

8.3.5.2.2. Anomalies Visualization

The visualization of the detected anomalies is performed by the RackAnomaliesVisualizer script, which is instanced once per each server rack. The script instances are notified by the data source connector about updates on the detected anomalies and updates the visualizations accordingly: if the rack is explored in detail, the RackAnomaliesVisualizer script displays each anomaly in front of every server, whereas in the case of the data center overview is rendered, the script renders anomalies information aggregated at the rack level.

8.3.5.3. Information World Content Presenters

Another fundamental script of the framework involves the presentation of content to the end users. The framework provides a base implementation for all content presenters via the ContentPresenterBaseScript. The script is attached to any prefab used by the Information Pieces to display content and is responsible for wrapping the visual elements within it. The script acts as a mediator for any Information World element to the actual Unity3D GameObject that renders the information. The ContentPresenterBaseScript also implements the necessary functionality to inform the SceneManagerBase that is accountable for it about user viewing the specific content.

8.3.6. Activities Management

Information Worlds make use of the concept of activities in order to provide an infrastructure for processes that are related to user actions and need to be executed sequentially. These processes may be completely diverse, ranging from automated sequences performed by the system itself to actions waiting to be performed by the end user. The following sections present the implementation of the infrastructure by firstly describing indicative fundamental activities implemented as well as the management.

Furthermore, the activities can be also used as a source of history of user activity. Since they can represent any type of process, they can store information about users' actions and implement an undo/redo pattern. To this end, they provide the means to implement not only the storage of users' actions, but also be directly used in both an automatic playback of their actions but also to allow users to return to their previous element (e.g. Information World, Piece or Thing).

8.3.6.1. Activity Script

Activities are provided via the ActivityScriptBase class, which provides an implementation which can be overridden. It gives access to the core callbacks which include the activity start, activity in progress and the activity finished states (all including both pre- and post- state callbacks). The activities' states can be changed using the corresponding enumeration, which is then automatically evaluated by the Activities Manager so as to update the queue to be executed.

8.3.6.1.1. Visit Information World Activity

The Visit Information World Activity script is used in order to allow the loading of an entire Information World using the scene management scripts presented in section [8.3.2]. This activity is responsible for blocking its execution until the new information world is fully downloaded and initialized, either ready to be explored by the end user or for any other activity to follow.

8.3.6.1.2. Visit Information Thing Activity

The Visit Information Thing Activity script is responsible for navigating the user to the Information Thing defined. It makes use of the Navigation Manager [8.3.7] in order to assist users perform the navigation towards the corresponding Information Thing on their own via a visualization or directly navigate them to the location where they can examine it.

8.3.6.1.3. Visit Information Piece Activity

The Visit Information Piece Activity script is responsible for navigating the user to the Information Thing defined and also expose the corresponding Information Piece. Similarly to Visit Information Thing Activity, it makes use of the Navigation Manager [8.3.7] to allow users reach their destination.

8.3.6.1.4. Visit Information Piece Content Activity

The Visit Information Piece Content Activity script is responsible for navigating the user to the Information Thing defined, expose the corresponding Information Piece and instruct the Information Piece to display the specified content.

8.3.6.2. The Activities Organizer and the Activities Manager

The Activities Manager script is responsible for keeping a queue of the activities pending as well as the activities already executed. It provides the API for other scripts to register their own Activity Scripts and also provides them with programmatic callbacks if notifications about each activity's execution progress is needed. In order to be as generic and reusable as possible, the Activities Manager is completely agnostic on the actual type of the activities it is currently executing and updating.

A common requirement of activities to be executed involves the dependence on other elements or even activities which are implied. An indicative example use case of such a dependency is the loading of an Information Thing which lies within an Information World other than the currently loaded one. As a result, the Activities Organizer script was implemented in order to act as a mediator for every incoming request to the Activities Manager. This script automatically generates the intermediate steps for any activity to be ultimately performed, injecting any required activities before the actual activity provided. The organizer acts in a smart manner by not taking into regard the current state of the Information World application, but evaluating the state in which the application will be when the activity will be performed. As a result, the process of adding new activities becomes straightforward to be directly used by any element transparently.

8.3.7. Navigation Management

In terms of navigation management, the presented work employs two different mechanisms for assisting user navigation within both completely virtual and augmented physical world environments. In order to facilitate both the navigation assistive visualization and navigation actuation, the framework provides two distinct implementations that correlate users with their aim within the framework.

8.3.7.1. Navigation Visualizer

The Navigation Visualizer component creates the visual elements that assist user travelling within both the physical world, which is essential in the case of augmented reality environments, and for virtual worlds, acting as a supportive mechanism which can guide users reach potential target locations. The Navigation Visualizer takes into account the baked scene information which is known a priori [8.3.2] in order to guide the users reach their target location by rendering visual elements indicating the direction toward which they should move.

Due to the fact that users in augmented reality environments have to physically move towards their goal, this can be the only mechanism to assist user navigation. On the contrary, this component can be used in virtual reality environments not only to guide the users, but also to allow them to instantly reach their target. This is accomplished through indicative interactive menus, which the users can select to directly move using the Navigation Actuator presented in the following section [8.3.7.2]. This option is rendered at the next corner point along the path from the user's current position towards the target [Figure 54].

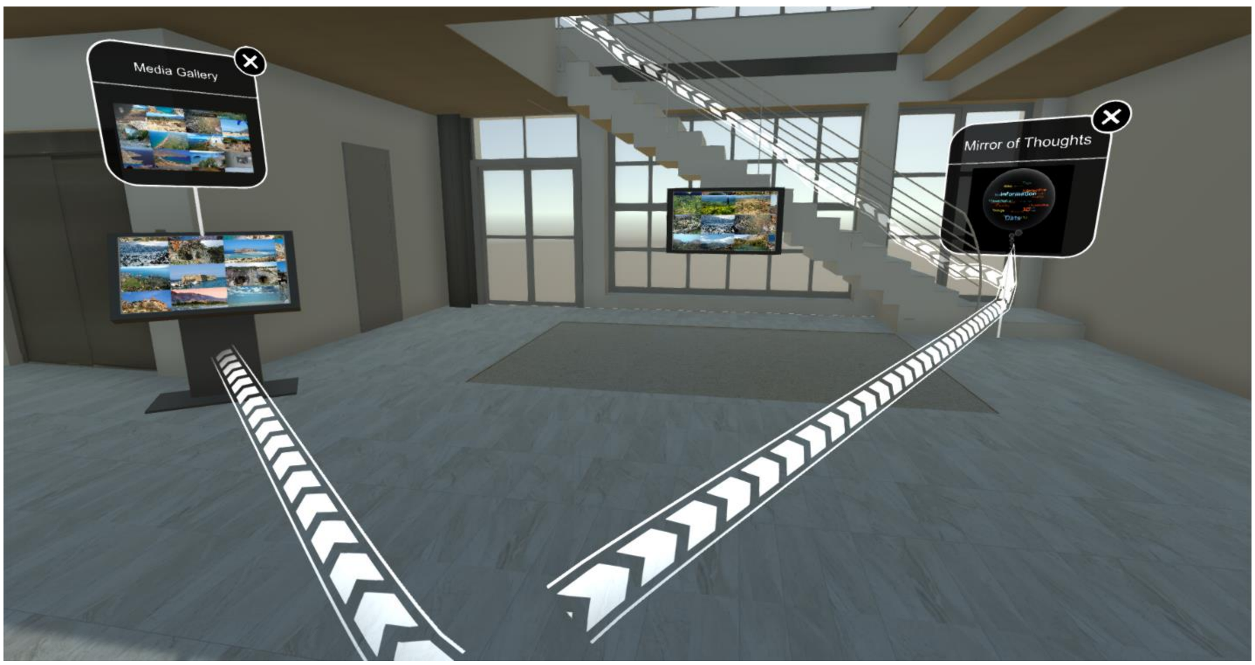


Figure 54: Navigation assistant indicating two available paths towards Information Things within the user's Information World

The visualization of paths along which users can move in order to reach their final destination is rendered via lines placed at the floor. These lines are dynamically created from the users' position and reach the final destination, feature which is implemented using Unity3D's navigation mesh agent [436] in combination with the trail renderer component [439]. The final destination area is designated via a particle effect, indicating the place where the user should move in order to reach the final target [Figure 55]. The Navigation Visualizer component is not only capable of creating paths at the same level, but also connect to areas belonging to different floors within a virtual building.

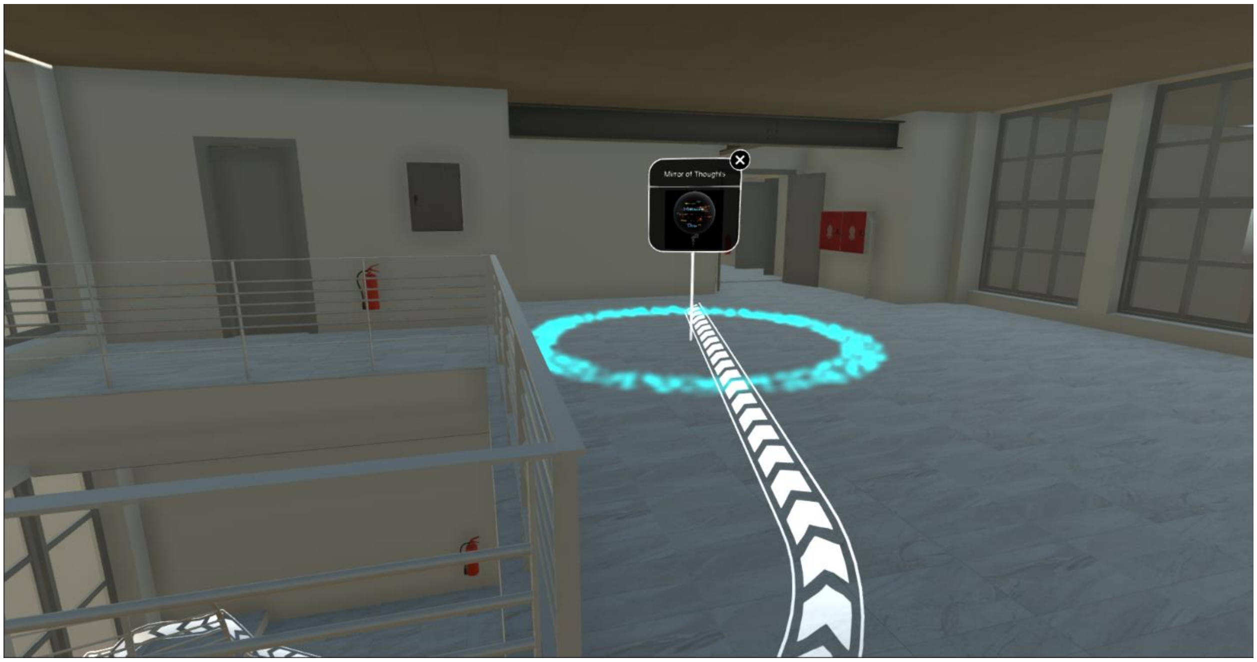


Figure 55: The particles effect used to highlight the Navigation Visualizer's destination area

8.3.7.2. Navigation Actuator

The Navigation Actuator element is responsible for taking the user to the target location. This component is only applicable for virtual environments, where the users' location can be changed without them being required to physically move in space. Navigation Actuator implements two means of travelling, instant teleportation and smooth travelling a steady speed.

Instantly travelling has the advantage for the users to reach their target location without any delay and accomplishing their goals at once. This approach can be more effective in terms of execution speed. However, certain drawbacks are unavoidable. Firstly, users lose their sense of space, especially in the case of movement from/to locations which are not near each other or have visual elements in between the users' origin and final position. While this drawback is not so important when users are partially aware of the environment, it can make them completely disoriented if they are completely unaware of the spatial distribution of elements. Moreover, by performing this unnatural movement, users' immersion of exploring their surrounding is broken, deteriorating their user experience.

Smooth travelling at a relatively steady movement speed is in general preferred due to the fact that it preserves continuity within the users' exploration of the virtual worlds. As a result, users keep track of the spaces they are moving inside and feel more confident about their whereabouts. However, especially when employing stereoscopic rendering, the likelihood of motion sickness is significantly increased, as users experience a movement they are not in control of.

In general, the drawbacks of teleporting can be ignored in every day usage scenarios for the sake of performance or in the case of users very sensitive to motion sickness. On the other hand, in the cases of end users simply exploring virtual worlds at their own pace, smooth movement should be preferred.

8.3.8. Post-Visit Manager

The Post-Visit Manager is the script responsible for orchestrating the process of structuring the user's post visit experience. It instantiates the scripts required (Mirror of Thoughts Feeder [8.3.8.1] and Memories Presenter [8.3.8.3]) so that the users' surroundings are populated in accordance with their experience of the virtual environment.

8.3.8.1. Mirror of Thoughts Feeder

Mirror of Thoughts Feeder is a script which acts as a data source to the Mirror of Thoughts Information Piece template [6.5.4.1]. The script retrieves information about the users' sessions and provides them so that users can ultimately watch themselves being surrounded by the content they have seen during their usage of the application created by the Information Worlds framework.

8.3.8.2. Screenshots Holder

The Screenshots Holder script keeps track of all the screenshots captured by the SceneLoader scripts [8.3.4.1]. It is implemented using the singleton pattern and provides the suitable public API for any script to register or update a new screenshot, access existing screenshots and resetting its state in order to allow a new user session.

8.3.8.3. Memories Presenter

The Screenshot Presenter component allows the rendering of the screenshots captured throughout a user's visit in the post-session environment which is automatically created by the framework. It retrieves the corresponding screenshots from the Screenshots Holder [8.3.8.2] and renders them on a virtual wall in the context of the users' Post-Visit experience described in section [6.8].

8.3.9. Information Worlds Logging Manager

Information Worlds Logging Manager constitutes an integral part of the framework as it is responsible for keeping track of the users' actions within the visualized environment. It is informed by the core implementation of fundamental scripts, such as scene management scripts [8.3.2.3], content presentation scripts [8.3.5] and information world scripts [8.3.2.1], about the activities which are carried out during the users' experience within the final application. The events which the Information Worlds Logging Manager is able to keep track of include Information World changes, Information Thing and Information Piece selections and viewing specific content (including the Information Thing/Piece that they belong to).

In addition to providing an informative trace of the users' activities, carried out in either an interactive context (when the user performs the actions himself/herself) or in a more passive context (when storytelling is carried out). To this end, the Information Worlds Logging Manager provides the basis for allowing the users to undo their last action and visit a previous element by employing an undo/redo pattern. Therefore, the elements are stored within a stack and the pushing/popping of users' activities provide a mechanism for implementing a history across which the users can navigate in combination with the Activity Management scripts described in section [8.3.6].

8.3.10. Audio Manager

The Audio Manager script is provided so that centralized orchestration of the audio playback by the framework. The various instances of audio sources are each responsible for playing their own sound. In addition to that, the sound sources register themselves to the Audio Manager, which in turn performs any modifications in accordance to the audio source type (e.g. sound effect, ambient sound, audio content, etc.).

8.3.11. Language Manager

The Language Manager script keeps track of the language currently selected by the user in any application created using the presented framework. It is implemented as a singleton and exposes a public API for any script to retrieve the current language or even change it. In addition, the script provides public events which any other scripts can use in order to be notified about language changes so that they can update themselves. Examples of elements which are language-dependent and include corresponding scripts include multilingual texts, audio sources and video content.

8.3.12. Web Sockets Manager

The Web Sockets Manager script contains an implementation of a C# web sockets endpoint, allowing the two-way communication with other applications or services running either locally on the same device or on other devices across the network. The Web Sockets Manager provides a ready to use implementation of connection establishment and reconnection in case of failures, while also providing notification mechanism about incoming requests to any interested party. The implementation of the Web Sockets Manager class is currently overridden by two scripts within the framework, one in the case of the Data Center Infrastructure Management and Monitoring use case [9.2] and one for the creation of the BeThereNow Mixed Reality Server [6.5.5.2].

The first implementation is closely related to the retrieval of updates originating from the Big Data data sources. To this end, Web Sockets Manager is extended so as to make the anomaly detection mechanism updates (provided by external sources) available to the elements within the framework. Moreover, this implementation also allowed the visualization application to refresh the data visualized [6.1.4.4] due to updates that are noticed in the data source.

The implementation regarding the custom Information Piece described in section [6.5.5.2] is related to creating client/server implementations that are responsible for retrieving/providing accordingly user tracking data. Therefore, the Web Sockets Manager is overridden to retrieve user skeleton data and notify the corresponding client implementation about updates on the users' joints position and rotation.

8.3.13. Error Logger Service

The Error Logger Service offers the ability to keep track of several types of logging information, i.e. debug messages, informative messages, warnings data and error logs. In addition to the profound assistance during the development of the framework, the Error Logger Service supports the classification of any message in accordance to a specific context. The implementation of this feature was eminent due to the high complexity of the framework and the various scopes that reside within it. An indicative example of such classifications can be scene management, content viewing, information pieces, user interaction, etc.

8.3.14. Rendering Effects

The framework fully supports the integration of all the rendering effects that the Unity3D platform provides. An indicative example of rendering effects which are attached to the main camera used to render the virtual environments is the Unity3D Post-Processing Stack [425]. By integrating this set of rendering effects, the framework creates photorealistic renderings of the geometry via effects such as ambient occlusion, antialiasing, screen-space reflections, vignette and eye adaptation.

The rendering effects which are applied to the main camera are configured to match typically lit environments; on demand, however, the default configuration can be overridden by any Information World. Such an example includes the case where certain spaces need to be over-lit (and almost color-burned) in order to provide complex shading effects: in this case, a post-processing effect where eye adaptation is differently configured can provide improved results.

Moreover, custom effects such as the dissolving shader [8.3.3] used by the Cut Scene Manager [6.3] are also supported and fully integrated within the rendering pipeline which is used to produce the final graphical outcome.

8.3.15. Unity3D Layers and Tags

Unity3D enables the classification of different elements (gameobjects) into different layers [424]. The layers are employed for the developers in order to designate and treat the elements in a different manner in terms of rendering and physics calculations.

As far as rendering is concerned, the framework presented in this work uses different layers for custom rendering effects in order to allow lighting to affect only parts of the virtual scene. To this end, this option allows certain lights to affect specific gameobjects that, for instance, belong to an individual Information Piece. An indicative example is WordCloud3D [6.5.2.6], where there was the need to lit the tags depending on their distance from the camera, making items near the user to be colorful while items further away to render as dark gray. This effect was achieved by overriding all environment lighting and using only point lights, which were placed near the camera, thus creating a linear color rendering effect. Moreover, these point lights only affected the specific layer where only the tags belonged to.

The layers are also used for ignoring certain elements from the default rendering process. This option is applied at the BeThereNow! Information Piece Template [8.7.2], so as (a) not to render the raw sensor data but only the final outcome, and (b) to create custom rendering paths and render in different passes by using additional cameras.

Unity3D layers were also used by the engine’s physics system for the facilitation of the navigation and pathfinding features, enabling to block users from visiting certain areas. Moreover, the different layers were used by the custom raycasting implementation to allow custom actions to be designed for navigation. Such an example is teleportation: users should be able to click on surfaces to travel; on the other hand, users are not supposed to teleport into certain areas (e.g., moving very close to objects or walls might allow them to partially see through the geometry) [Figure 56]. As a result, a different layer was implemented for objects (e.g. quads or cubes) invisible to the users which define the areas where they can teleport to; teleportation raycasting only calculates gameobject in this layer and ignores all others.

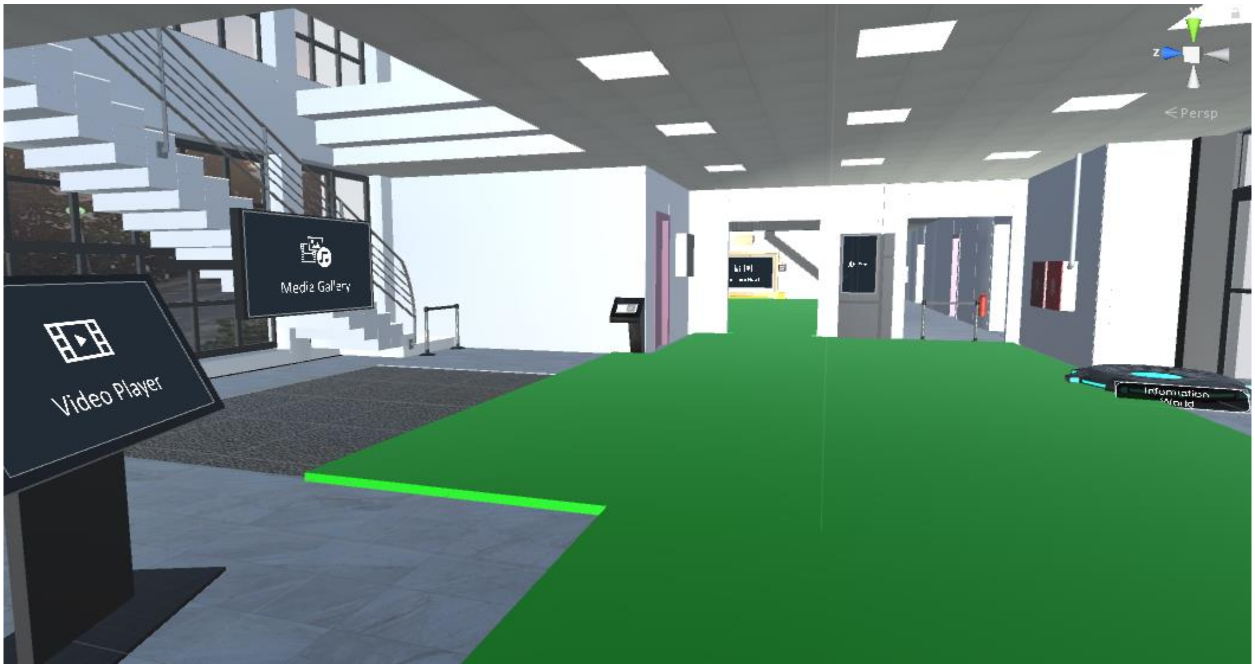


Figure 56: The invisible teleportation geometry (painted green) for the Ambient Intelligence Facility Information World

Finally, Unity3D tags [430] were used for tagging of gameobjects in certain categories that are not related to rendering or physics. Such an example is Information Things [4.3], which the users can select to move to. In this case, the position which designates the target location is implemented via a gameobject tagged in a specific manner, which the framework knows how to interpret.

8.4. Utility Libraries

Unity3D is a game engine which facilitates scripting-based development. In compliance with this direction, several scripts were developed and reused in a variety of cases in order to serve the same purpose. These scripts were parts of the framework but did not belong to its core implementation and neither had any dependencies on any other features of the framework. On the other hand, they constitute a considerable amount of effort that can be reused by any application developed with the Unity3D game engine.

8.4.1. Runtime scripts

The runtime scripts that belong to the Utility Libraries are the scripts which are aimed to be used at the final executable application developed with the framework. They can be used as-is by any developer extending the framework or be customized to match other needs that may arise.

8.4.1.1. Transformation Assistive Scripts

The scripts that have to do with Unity3D GameObject transformation belong to this category. They offer functionality related to performing specific actions, including:

- Rotating an element along the specified axis/axes (LookAtScript)
- Making an element facing another element (LookAtScript)
- Making an element raising an event when at a certain distance from another one (DistanceBasedTriggeredScript)
- Reversing the normals of the mesh renderer (ReverseNormalsScript)

- Making an element fade in over a specified time (FadeInScript)
- Making an element fade out over a specified time (FadeOutScript)
- Making an element raising an event when camera is facing it (LookAtCameraTriggeredScript)
- Implementing a screen capture to a texture (ScreenCaptureScipt)
- Creating a curved line to connect to another element (CurvedLineConnectorScript)
- Making an element persist across single scene loading (DontDestroyOnLoadScript)
- Making a scroll rectangle snap to the child content (SnappingScrollRectScript)

8.4.1.2. Helper classes / extensions

The helper classes are static C# classes that other extend existing classes via extension methods [64]. They are developed in order to provide implementations for functionality regarding enumerations, object destruction, GameObject scaling, transformation matrices operations, Unity3D UI operations and transformation calculations.

8.4.1.3. Curved User Interface

Another type of scripts used by the framework involve the ability to generate curved user interfaces. These user interfaces are implemented by actually performing matrix transformations to Unity3D's Canvas [431] implementation. The scripts apply different shapes perceived by the end user (e.g. cylinder, sphere and ring) while also maintaining interoperability with Unity3D's UI input mechanisms.

8.4.2. Editor Utilities

Apart from scripts which are executed by the end application created by the framework, several other assistive scripts are implemented in order to facilitate efficient content creation. These scripts are created to be ran at the Unity3D Editor environment by the Visualization Creators [5.1.1.1] so as to create new content, either from directly by inserting new information or by retrieving information from existing formats.

8.4.2.1. Content Creation

Content data is stored in classes which inherit from the ScriptableObject class [429], which is a class suitable for storing asset data. The base class of all content, ContentDataBase, is a serializable structure which contains the most common information attributes described in section [6.1.4]. The various ContentDataBase entries are added to collections with each collection being the content of an Information Piece.

This class can be further extended by other classes so as to support Information Piece-specific information: such examples are TimeTunnel (where content is linked to its belonging event) and Wordcloud3D (where individual tags can have the color defined). This information is used only by compatible Information Pieces and is ignored by al others.

While the content can be also programmatically created, a typical scenario of creating content includes the Visualization Creators [5.1.1.1] manually entering information. Therefore, the framework provides scripts which allow the immediate creation of new content assets directly by offering a corresponding action at the context menu of the Unity3D editor interface [Figure 57]. Once the new asset is created, it can be filled with information as described in section [6.1.4.1]

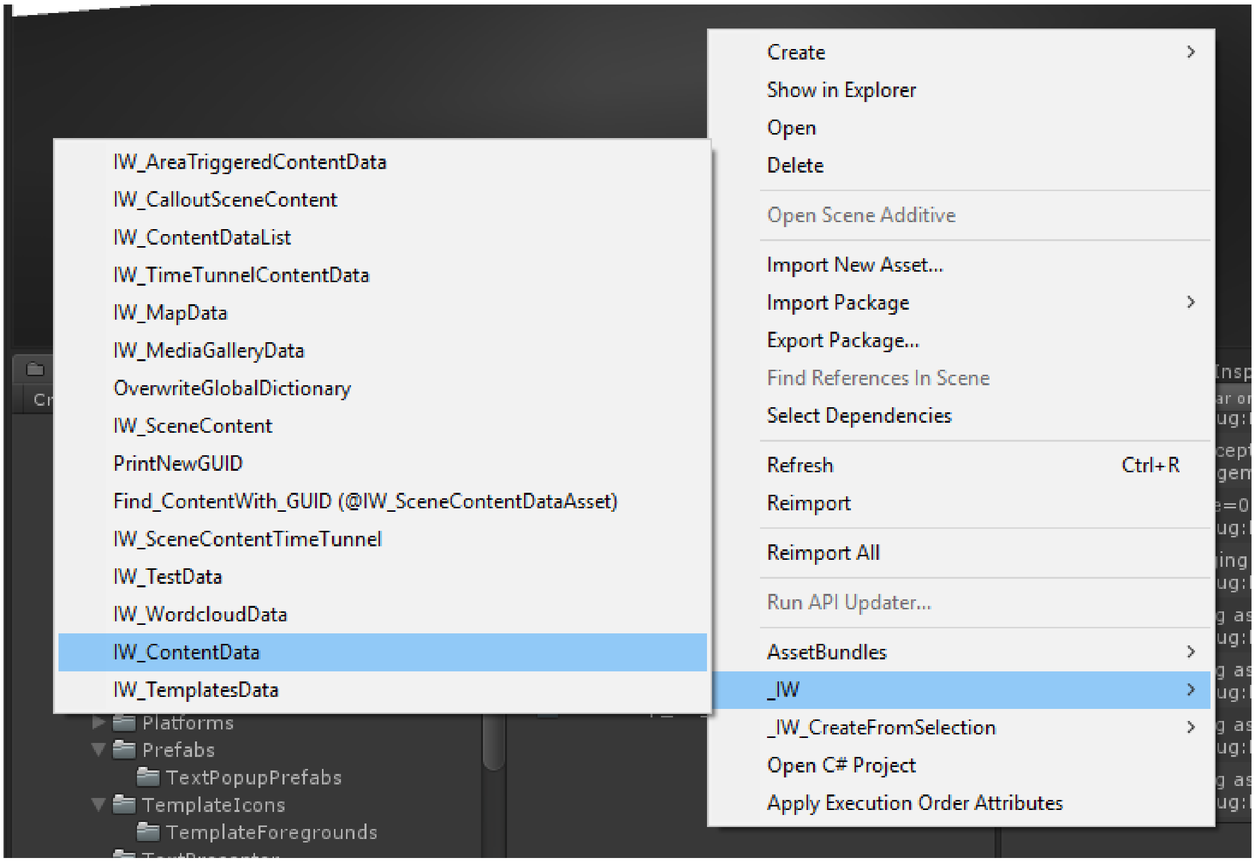


Figure 57: The Unity3D editor interface custom extension for content and content data creation

8.4.2.1. Content editing

Apart from providing the ability to create entirely new elements, the framework also allows users to alter existing assets. Content type changes from specific content types (e.g. TimeTunnel or Wordcloud3D content) to the base type and vice versa is also supported by keeping the common fields and setting the other fields to their default values, without requiring the users to re-enter all the data [Figure 58].

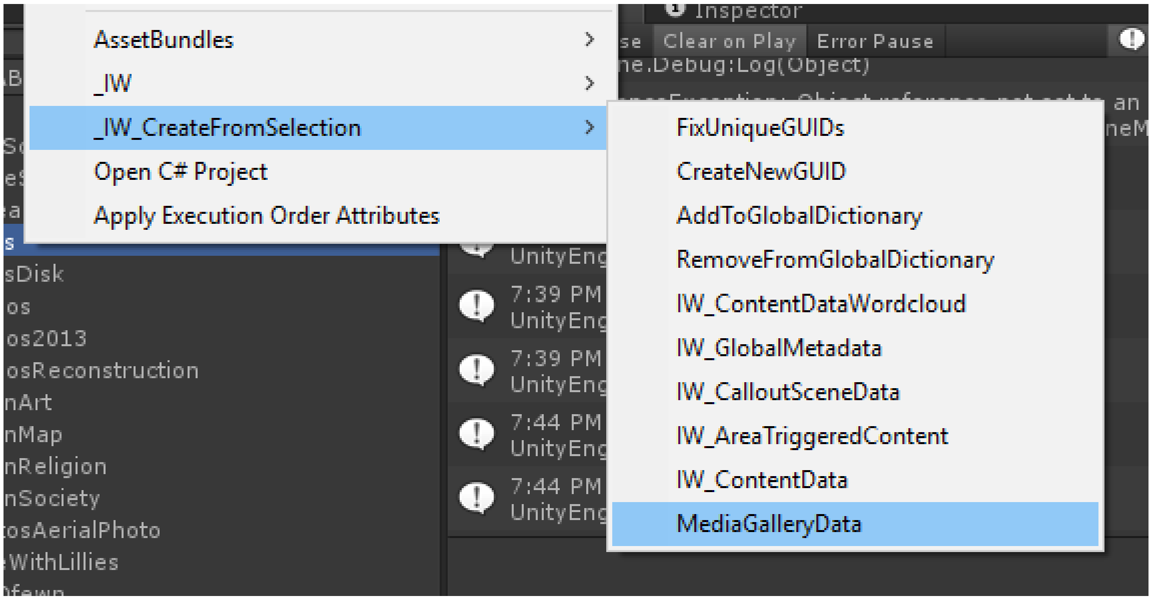


Figure 58: The Unity3D editor interface extension for changing the selected elements

8.4.2.2. Batch Imports

Interactive applications implemented for presenting multimedia content are often created using their own configuration files for content loading. Given that the framework allows content creation via code, a custom implementation which directly parses the configuration of another interactive system (MAGIC [116]). The parser retrieves the images and videos from the configuration, along with their titles in all available languages, and creates the corresponding collection of ContentDataBase elements, ready to be used as content in any Information Piece.

8.5. Asset Bundle Server

8.5.1. Asset Bundle Content

The content built with the editor is compiled into Unity3D asset bundles. Each asset bundle consists of a file containing the actual data to be served and of an additional descriptive file (manifest) which provides unique identification and versioning information. These files are provided to the Asset Bundle Server in order to be available to the end application.

The Asset Bundle Server is a service implemented using an http server listening at a specified port and waiting for incoming connections. It exposes each asset bundle's manifest and source content, which can be retrieved independently by Asset Bundle Manager instances [8.3.1].

8.5.2. Content Building and deploying

Content building is performed within the Unity3D editor using the scripts which are described in [8.4.2]. The generated compiled asset bundles are then provided to the Asset Bundles Server (either automatically or manually), replacing the existing ones if any. The Asset Bundles Server automatically refreshes the exposed asset bundles upon each request immediately without requiring to be restarted.

8.6. Information Worlds

The various environments that constitute the Information Worlds integrated in the framework are implemented as typical standalone Unity3D projects; they are linked to the main framework using symbolic links [396], maintaining their independence. Each Information World contains all the graphical assets that constitute the entire virtual environment, including 2D textures, 3D model geometry and any potential prefabs reused as visual elements within them.

The static geometry included in the Information World is baked in order to facilitate navigation and pathfinding at the end applications. Moreover, complex lighting which is created so as to provide an optimal end result is assembled and baked in order to improve the performance of real-time photorealistic rendering.

8.6.1. Knossos Reconstruction

The Knossos Reconstruction Information World contains the entire 3D geometry of the virtual environment. The model (retrieved from 3D Warehouse [229]) is restructured and enhanced with additional rooms so as to provide a more complete environment in which the end user can navigate. Moreover, decorative geometry is also included in the form of ready to use prefabs that are instantiated within the users' surroundings.

Figure 59:The throne room in the Knossos reconstruction Information World

Knossos Reconstruction includes the following Information Piece Templates:

- Decorative Templates [6.5.1.1]
- Timeline [6.5.2.1]
- Audio Presenter [6.5.2.3]
- Wordcloud 3D [6.5.2.6]
- Text Presenter [6.5.2.8]
- Look-at Triggered Video Player [6.5.3]

8.6.2. The Ambient Intelligence Facility

The Ambient Intelligence Facility Information World includes a precise representation of FORTH's Ambient Intelligence building, which is modelled as 3D meshes. These elements are rendered with real time lighting and post-processing effects, providing a photorealistic result. The Unity3D project created designates the areas available for the user to travel inside and blocks areas which are unavailable, such as the development spaces in which researchers are currently working at.

Figure 60:The Ambient Intelligence Facility as rendered using the Information Worlds framework

The Ambient Intelligence Facility includes the following Information Piece Templates:

- Decorative Templates [6.5.1.1]
- Callout Presenter [6.5.2.7]
- Media Gallery [6.5.2.4]
- Flowing MediaGallery [6.5.4.2]
- BeThereNow [6.5.5.2]
- List Presenter [6.5.2.9]
- Look-at Triggered Video Player [6.5.3]

8.6.3. The Virtual Museum

The Virtual Museum Information World includes the 3D geometry that assemble a virtual museum including different locations, such as ancient Greece and ancient Rome, spanning across different historical eras. The museum, similarly to real cultural heritage institutions, showcases exhibits which in the case of a virtual environment consist of 3D models. Different lightings of the environment are baked, including day and night lighting, so as to provide an immersive and photorealistic end result which gives prominence to the elements showcased.

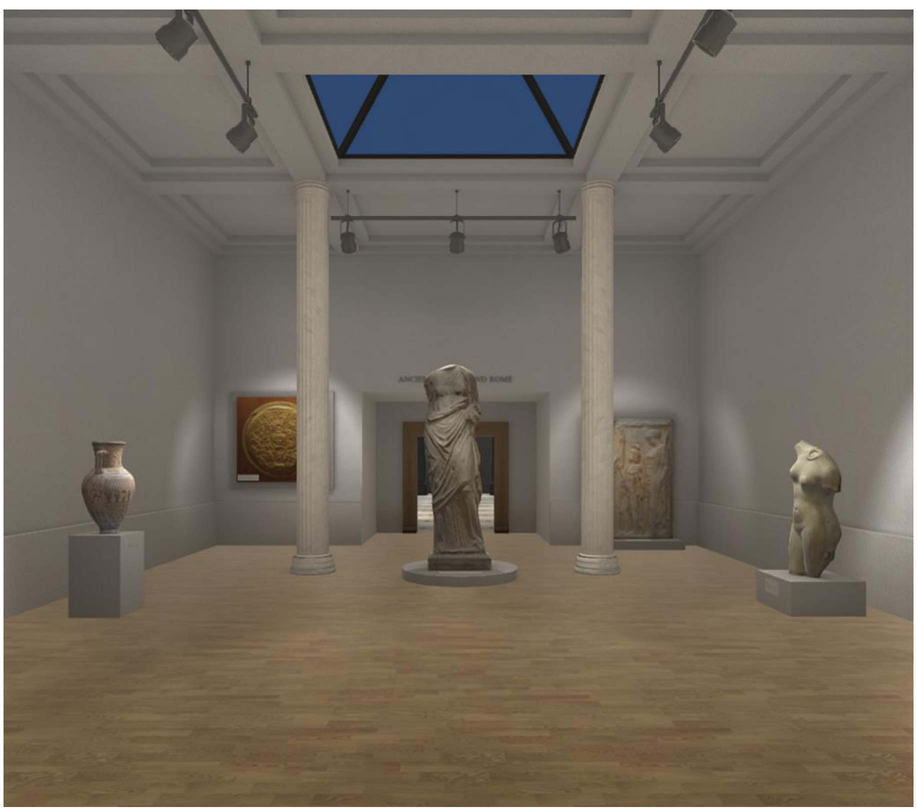


Figure 61: The virtual museum Information World

The Virtual Museum Information World includes the following Information World Templates:

- Callout Presenter [6.5.2.7]
- Text Presenter [6.5.2.8]
- Augmented Map [6.5.2.2]
- Object Manipulator [6.5.2.5]
- Media Gallery [6.5.2.4]
- Area Triggered Video Player [6.5.3]

8.6.4. The Augmented World

The Augmented World involves an indicative physical world augmented with additional information provided by the Information Worlds framework. The implementation of this world is based on Vuforia [451] in order to provide object recognition and localization. The scripting components provided by Vuforia are used to recognize a set of objects, both 3D models and 2D images, and identify them in the 3D space. To this end, this functionality is combined with the concepts and elements provided by the framework in order to augment physical artefacts with all the reusable components provided by Information Worlds.

The deployment of the augmented world can take place in any mobile platform such as Android and iOS by building the corresponding app via the Unity3D interface. The implementation was tested using an Android Samsung Galaxy A5 2017 smartphone within the premises of FORTH's Ambient Intelligence Facility. The objects recognized included structural elements of interactive systems (e.g. televisions and custom constructions) as well as screenshots of the deployed applications. The structural elements are passed to the tracking component as 3D geometry that can be identified from different perspectives; on the contrary, the screenshots (either depicting the entire interface or specific content shown in the application) are identified as long as the device is facing towards the display.

Simultaneous Localization and Mapping (SLAM) was commercially available by Google's Project Tango and its support has currently moved to ARCore [14] in order to stop requiring additional device hardware, as Tango compatible phones included a depth camera in addition to the RGB. In a similar manner, Apple's ARKit [404] is using inertial odometry to perform user localization and perform the equivalent operations required to map the physical world to the virtual one, thus ultimately augmenting the real with the virtual world.

The SLAM functionality can be directly integrated into the framework's core engine similarly to all Virtual Reality Information Worlds. This can be achieved by combining the physical world with the virtual one (modelled in the Information World 3D geometry) and creating a 1:1 correlation between the two environments. In this case:

- Elements can be augmented similarly to the object recognition approach currently employed, as the device is identified to be located at a certain position with a certain rotation relatively to the corresponding element. As a result, the Information Things and Information Piece Templates can work as intended in all other regular cases.
- Navigation and pathfinding in the virtual world will exactly match the physical surroundings given that the physical environment is a priori known to the system. As a result, the Navigation Assistant and more specifically the Navigation Guide [6.5.1.3.1] (placed within the virtual world) will exactly match the physical world.

The Augmented World includes the following Information Piece Templates:

- **Callout Presenter** [6.5.2.7].

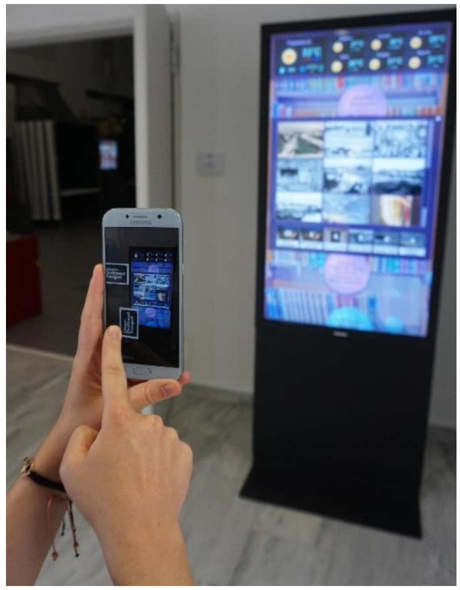


Figure 62: User interacting with callouts at the sides of an augmented interactive system

- **Augmented Map** [6.5.2.2] The implementation of this Information Piece Template has reduced functionality given that the Augmented Reality interface has different capabilities both in terms of interaction and in terms of processing power. Therefore, the objects showcased are static and can't be moved, but they can only be rotated automatically or manually via touch interaction.

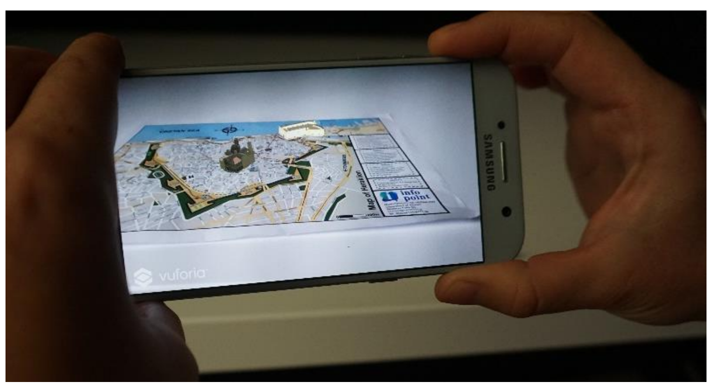


Figure 63: User discovers the augmented map of Heraklion city and the 3d objects are revieled on the map

- **Object Manipulator** [6.5.2.5]

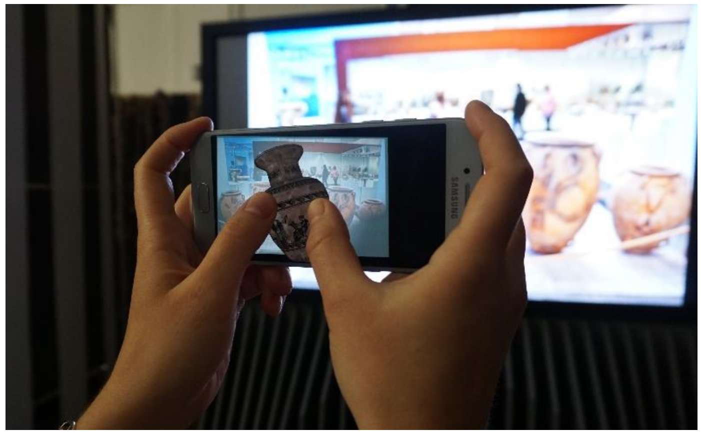


Figure 64: User manipulating an augmented 3d vase

- **Media Gallery** [6.5.2.4]

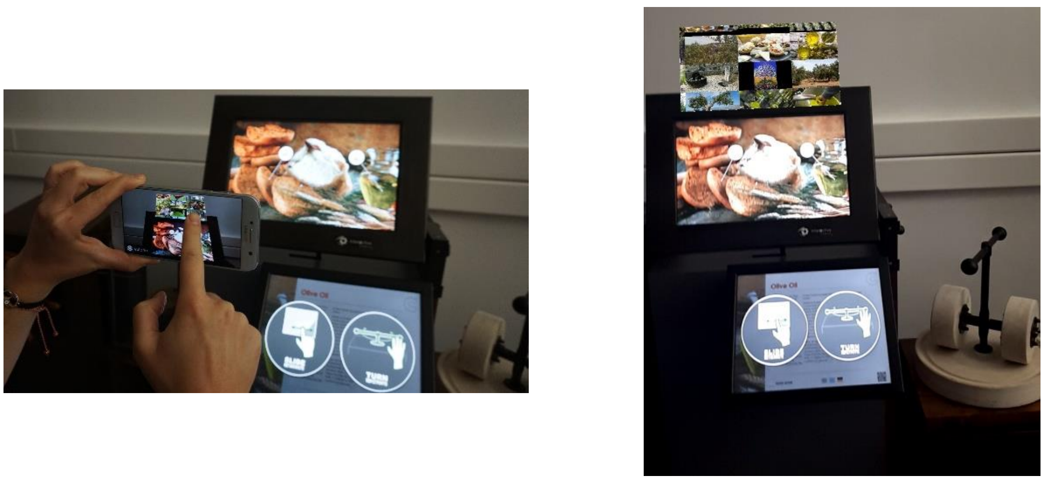


Figure 65: User interacting with a media gallery Information Piece Template augmenting an interactive system

- **Area Triggered Video Player** [6.5.3]

Figure 66: User interacting with an augmented video player

8.6.5. Data Center Infrastructure Management

Data Center Infrastructure Management Information World was implemented as a standalone Unity3D project enhanced by a variety of custom scripts to facilitate Big Data storage and retrieval, following an iterative design process [307]. The virtual world aims at helping data center experts to get an intuitive overview of a specific data center room, regarding its current condition. Additionally, the application facilitates the inspection of the racks and servers by the users and warns them, in an intuitive manner, about situations that need further investigation, such as an anomaly regarding a particular set of servers that may bring to surface malfunctions or degraded operation [113]. Taking into account the various contexts of use, ranging from an office to a control room, the application should be able to be deployed in a laptop or PC, featuring interaction with the mouse, as well as in a large display, supporting gesture-based interaction.

The Information World created includes rooms created dynamically in accordance to their physical layout and dimensions as provided by the corresponding data source [Figure 67]. The various data center rooms are all visualized in an abstract manner, so as to provide the maximum level of flexibility in terms of the variety of room arrangements supported. This minimal design is supported by a simple plain rendered with custom effects in order to create a clear but simple visual result. As far as servers and rack designs, the Information World includes all graphical elements and 3D models required to construct the data center visualization.

While the majority of the framework's code is kept at its core, the scripts developed only for this Information World were directly integrated within the corresponding Unity3D project, as they could not be reused by any other use case. Indicative examples of scripts which cannot be reused are related to the specific needs for retrieving the data from specific locations and classes implemented specifically for the efficient and optimal in terms of space and speed data storage.

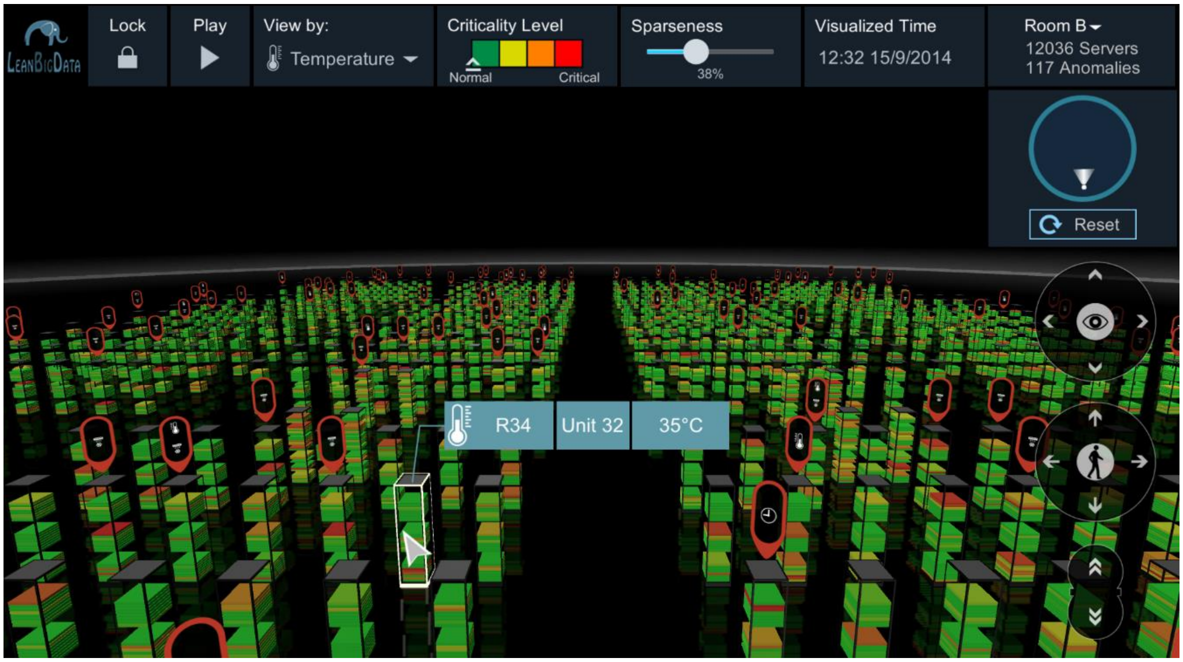


Figure 67: 3D Data Centre Overview

Each data center room can be controlled via the top-side menu [Figure 67, top]. This menu allows users to colorize the servers based on the selected metric and also selecting previous values in order to examine events that happened in the past. Moreover, the system offers filtering and arrangement options, allowing users to manipulate the information provided and focus on specific aspects of the data center. In more details, filtering according to the state of the displayed servers (color-coded) allows exclusion of elements which are not in the field of the user's interest, resulting in a comprehensible and clear view of the available information (e.g., the user can easily view all the servers in critical state). On the other hand, arrangement according to the level of sparseness of the data center, aids in defining the view of the data center (e.g., the servers can be densely placed in order to provide an overview of the data center or sparsely so as to facilitate examination of server values in detail over specific areas of the data center room). The selections performed via the top side menu are persistent across the various Information Worlds (i.e. data center rooms).

If the user clicks on a specific rack, the scene changes to the close-up view, the camera zooms in towards the selected rack and specifically displays the unit of the rack which is in the "worse situation", and which defines the criticality level of the server. While in close-up view [Figure 68], the user can select a specific unit of a rack, through a mouse click. Then, at the left side of the rack, six different charts are displayed, illustrating the history of the selected unit. If the user hovers the mouse pointer over a specific chart, then it expands in order to display a better view of the unit's history and how its values have changed over time.

Figure 68: Examining a specific server's temperature

The Data Center Infrastructure Management Information World includes the following Information Piece Templates:

- Callout Presenter [6.5.2.7]
- Charts Presenter [6.5.2.1]
- Text Presenter [6.5.2.8]
- Details Previewer [6.5.5.1]

8.6.6. Post-Visit Information World

Post-visit Information World is a generic environment reused by the framework in order to act as a simple geometry for presenting the elements the end users experienced during the usage of the applications developed using the framework. It includes the geometry that create a simple room with a mirror (in which they can see themselves using the Mirror of Thoughts Information Piece Template) and a canvas containing highlights of their visit.

The Post-Visit Information World includes the following Information Piece Templates:

- Mirror of Thoughts [6.5.4.1]
- Post-visit Manager [6.8]

8.7. Information Piece Templates Implementation

8.7.1. Media Gallery and Flowing Media Gallery

The implementation of these Information Piece Templates is based on the MediaGalleryScript, which is extending the framework's SceneManagerBase script [8.3.2.3]. It is responsible for providing the content to be visualized, initializing the key scripts used and maintaining the actively selected multimedia. After loading, the script provides MediaGalleryThumbnailsHolder script with the content to render, creating the images and videos grid. Moreover, an additional script (GridScroller), takes care of implementing the functionality of moving the multimedia grid, supporting both touch and button-based movement. Each visual element (i.e. image or video) contains a ContentPresenterBase script [8.3.5.3] and the corresponding multilingual description that accompanies the content. Moreover, the SnappingScrollRect script [8.4.1.1] is used to make the grid containing the content to snap at the visual elements shown.

Flowing Media Gallery contains alternations of the scripts used by MediaGallery, where specific functions are overridden so as to provide its flowing nature. The content grid is ever-moving, wrapping around when needed (by swapping the first with the last element in order to make circular lists in both X and Y axes). Additionally, each content's prefab spawns a pop-up clone of itself upon selection and additionally is self-disabled, until the pop-up is closed or a predefined timeout has passed.

8.7.2. Be There Now!

The implementation of the BeThereNow! Information Piece Template is based upon Kinect's SDK [288] Unity plugin. The sensor includes a depth camera in addition to an RGB one, allowing background subtraction based on depth input and user tracking algorithm.

8.7.2.1. Be There Now! Implementation

Microsoft Kinect's SDK provides a mapping from color to depth space, allowing the segmentation of RGB into foreground and background based on depth input; however, due the depth input providing smaller resolution (512*414 pixels for depth input versus 1920*1080 pixels for color input), the final RGB result appears to be pixelated.

In order to deal with this issue, the Be There Now! Information Piece Template implementation renders the final outcome in different passes. The foreground image (based on depth input) is colored as white pixels with a custom shader that smooths out the contour (making the neighboring background pixels semi-transparent) and is captured by a camera to a RenderTexture [427] with anti-aliasing in a first pass. As a next step, this capture is applied as an opacity mask to the RGB input on a separate render call. The result of this render call is finally captured to another RenderTexture, containing the final outcome that can be used by any geometry and UI element as a texture.

Finally, BeThereNow! includes a List Presenter Information Piece in order to render the various landscapes in which the users are immersed. As a result, the various backgrounds can be changed independently of the Kinect rendering, allowing the provision of additional information such as multilingual textual descriptions.

8.7.2.2. Mirror of Thoughts

The Mirror of Thoughts Information Piece Template contains a modified implementation of Be There Now!, where the backgrounds are replaced by a virtual mirror. The visual outcome of this modification is a mirror where users can see themselves in the virtual surroundings.

In addition to the virtual mirror, a modification of the WordCloud3D Information Piece Template [6.5.2.6] is created. This permutation, instead of placing tags along the surface of a sphere, places them onto two cylinders. These cylinders are combined with the user tracking functionality provided via Kinect and move according to the tracked user's joints, thus appearing at the sides of the users' torsos.

8.7.3. Wordcloud3D

The WordCloudManagerScript is the implementation that inherits from the SceneManagerBase script [8.3.2.3] and is the scene manager responsible for the creation and maintenance of the WordCloud3D Information Piece Template. The script also tries to interpret all provided content as WordCloud3D content (which holds additional information such as tag categorization, color, weight, etc.) and provides it to the WordCloudCreator. This script loads the provided content as instantiated prefabs each containing an instance of a WordCloudTagScript, which is an extension of the ContentPresenterBase script [8.3.5.3]. Finally, another important script within the WordCloud3D Information Piece Template is the SphereInfiniteRotator, which rotates the tags which are placed along the virtual sphere's surface indefinitely, as long as the user does not interact with any element.

8.7.4. TimeTunnel

The TimeTunnelManager inherits from the SceneManagerBase script [8.3.2.3] and is the scene manager responsible for creating the TimeTunnel Information Piece Template. This script loads all necessary content data and feeds the TimeTunnelEventsArranger script, which is responsible for generating the event slices extending along the corridor by instantiating one prefab per content. Every slice prefab includes an EventScript that hosts all the event content. The EventScript instantiates one prefab containing a ContentPresenterBase script [8.3.5.3] per content to host, thus creating a list of elements which belong to the specific event. This list may host any type of information, i.e. images, text, audio, video or 3D models.

Additionally, if the content provided contains information about time periods which are presented in the timeline, TimeTunnelManager provides the necessary data to the PeriodsHolderScript, which in turn creates the periods and places them with regard to the space they should occupy.

8.7.5. List Presenter

The ScrollingListManager is the main script that manages the List Presenter Information Piece Template, inheriting from the SceneManagerBase script [8.3.2.3]. Similarly to all scene managers, it retrieves the content to be displayed at the Information Piece and instantiates one prefab for each. Each prefab contains a ContentPresenterBase script [8.3.5.3] and is placed inside a Unity3D ScrollRectContent, creating a horizontal or vertical list of images, videos or audio tracks that are sequentially presented. The list is fully interoperable with any input source provided, including mouse, touch and any other custom input.

8.7.6. Callout Presenter

The CalloutPresenter Information Piece Template is managed by the CalloutPresenterManager, which inherits from the SceneManagerBase script [8.3.2.3]. The script creates one or more callout components at the sides defined, if any. Furthermore, according to the content configuration, the script adds a script controlling its visibility, including the AreaTriggeredEnabledScript and a LookatTriggerEnabledScript.

8.7.7. Charts Presenter

The Charts Presenter Information Piece Template contains ready to use implementations of widespread charts, including pie, bar, box plot, radar and bubble charts. These charts are generated using the C# chart implementation [1], rendered as textures and integrated within the Unity3D UI elements as images. The ChartsPresenterManager keeps track of the textures generated and provides a programmatic API used by other scripts to update the rendered values upon receiving new data. The ChartsArrangerScript is another script created within the Information Piece Template, responsible for updating the charts layout and orchestrating the animations used to switch between the different tabs rendered and to show them as full screen elements.

9. Use Cases

The presented framework aims to support the creation of exploratory visualizations that support personalized storytelling and users'collaboration for a variety of input data types and values. This chapter presents the envisioned scenarios which demonstrate potential use cases of applications created using the presented framework and provide valuable insights.

Firstly, the visualization of a smart museum containing interactive exhibits is presented in section [9.1]. The smart museum is tightly coupled with the domain of Cultural Heritage information visualization due to its nature; moreover, it may also include interactive standalone applications which are installed in-vivo, either demonstrated as physical entities or accompanying physical exhibits. The different interactive systems presented in the virtual environment constitute Information Things that may include additional Information Pieces, presented in a variety of means that correspond to the optimal visualization of the associated content. The interactive exhibits are an indicative example of elements which are heavily interconnected, but are confined to a small number and sparsely located.

Interactive exhibits were chosen as an indicative example of Information Things that contain rich semantic information, both as physical elements and as standalone interactive applications that encapsulate a multitude of data which present different information facets. Additionally, the selection of the museum as a scenario for information visualization was made, apart from covering an information-rich domain, with respect to the spatial arrangements applied in the context of a museum. Museums constitute an environment in which information is rich, but the surroundings contain exhibits which are reasonably loosely placed.

Section [9.2] presents a use case about infrastructure management and monitoring in the context of data centers. The data center environment is indicative an example of large volumes of constantly changing geo-located data needing to be monitored in real time. The rooms hosting the servers (Information Things) contain data volumes of a high velocity, generating condensed information which is placed within a room and needs to be shown in a single visualization. The data produced in the data center use case match the volume and velocity requirements to be characterized as Big Data, but have reduced variety, as only a handful of metrics exist, e.g. temperature, disk input/output, network bytes in, etc. Additionally, all the Information Things are of the same type, but have different variable values. They are relatively sparsely interconnected, as they share attributes such as brand, components such as disks manufacturers or routing devices.

Data center monitoring constitutes a demanding field of Big Data visualization applications where real time collaboration, decision making and actions should take place as fast as possible. Moreover, apart from the primary visualization component, several standalone applications exist that assist and guide data center experts to identify potential issues and handle them efficiently. Finally, the setups of rooms found in large data centers comprise a scenario where large information volumes are congested in a finite environment challenging the provision of both overview and on demand detailed views.

9.1. Smart Museum

Cultural Heritage constitutes a very suitable domain for the exploitation of information networks in a profitable for the viewer context. They can either be the original Cultural Heritage objects showcased for the visitors or can alternatively include interactive systems that host information about objects, habits and customs, events or even stories visualized in an explicit manner.

The different physical entities contain attributes that describe their characteristics, but they are also semantically linked with others. Some of the entities may share characteristics with others (e.g. a Caryatid and Winged Victory of Samothrace are both ancient Greek sculptures), but they also contain information describing their context, such as their location (e.g. a Caryatid belongs to the Erechtheion on the Acropolis at Athens). The various aspects of an element generate information networks which can be combined to create narratives (e.g. the construction of Acropolis) that belong to stories (e.g. the history of Acropolis). The following scenario depicts indicative aspects of the contributions of the presented work in the domain of cultural heritage. The scenario is narrated from the perspective of the user experience on the left side of the following table, whereas the right side presents the information from the framework's point of view.

Use case Description	Framework Representation
Tony and Anna are a young couple of tourists coming from Italy. Tony is an engineer and Anna is a linguist and visit Crete for their summer vacations. As they are walking down the Morosini Fountain at Heraklion, they notice the sign of the municipal Info-point. Since they have some time to spare, they decide to visit it in order to acquire information about places to see during their stay. Upon entering the area, they notice a set of interactive systems about different sightseeing places. Tony is a fan of cutting edge technologies and immediately notices a Virtual Reality headset which offers the virtual exploration of the archaeological site of Knossos. He wears the head mounted display and enters a virtual room containing instructions on how to use the supplied controllers, while also practicing their use in terms of navigation and selection on test elements. A teleportation gate captures his attention which he can use to enter the virtual reconstruction of Knossos palace. Tony virtually steps on the gate and enters the Throne Room.	The application represents an introductory practice room, Knossos and the Archaeological Museum of Heraklion (AMH) implemented as three distinct Information Worlds [4.2], visualized in a VR environment. Users employ the Oculus Touch controllers to travel in space and interact with the visualized components. The introductory room is an Information World provided in order for the users to familiarize themselves with the VR headset and practice common interaction methods used by the application.
On entering the virtual room, he notices that the throne is highlighted and upon approaching it, auditory feedback automatically starts providing information about the throne room. Tony examines the lit throne and decides to proceed to the next virtual room to further explore the area. The next	The throne is an Information Thing [4.3] in Knossos Information World, illustrated by a Thing Indicator [6.2], combined with an audio source [6.5.2.3]. The magical sphere is an

virtual room contains keywords presented in a magical sphere about diverse facts regarding the Minoan period, examining insights on unknown aspects of the civilization, such as commerce, religion and the absence of military forces. Tony then notices a virtual television presenting a futuristic corridor containing information about the excavations of Knossos archaeological site. Upon selecting it, he is immersed into a glassy corridor in surrounded by an engraved sky from Heraklion. He navigates along the corridor, examining a timeline about Sir Arthur Evans and is informed about facts regarding the excavations taking place during the late 19th and 20th century until today. Amongst the existing events regarding the excavation lies an entry about the Snake Goddess, an archaeological finding excavated by Sir Arthur Evans in 1903, and Tony selects to view more information about it. Detailed explanation of its meaning and about religion in the Minoan civilization is presented along with a high resolution photograph. Upon viewing the photograph, a recommendation appears to visit a virtual representation of the Archaeological Museum of Heraklion (AMH) and he selects to follow it. The surroundings of the Knossos reconstructions around him dissolve and he virtually teleports from Knossos to AMH, where he landed at the museum's entrance and automatically moved in front of a 3D high resolution model of the Snake Goddess. As he tries to reach out to the figurine in order to grasp it, a metallic handle appears below the model, which he uses to bring it in front of him and examine it in every detail. He is then able to apply custom lighting to the model in order to explore the different aspects of the model. Due to the model's small scale, he uses both of the controllers in order to scale it up and examine the model's every minor detail.	WordCloud3D Information Piece Template [6.5.2.6] which present additional data which is accompanied by textual descriptions and images. The Timeline Information Piece Template [6.5.2.1] about Knossos excavations is presented as a full-screen template. The events in the timeline are combined with personalized recommendations regarding the content currently examined [6.6], connecting an Information Piece with an Information Thing. The users can switch from one world to another [6.4] and be directly moved to the corresponding Information Thing in another world via the Activities Organizer [8.3.6.2] and the Navigation Actuator [6.5.1.3.2]. Dissolving is the visual effect rendered as a cut scene [6.3] takes place until the new Information World asynchronously is loaded [8.3.4]. Snake Goddess is showcased in an Object Manipulator Information Piece Template [6.5.2.5] in the AMH Information World is an Information Thing, represented by a 3D model. When users approaches it with their hands, the 3D model turns into an Information Piece and specifically into an Object Manipulator template [6.5.2.5].
During Tony's interaction with the VR application, his view is cloned to a public display which Anna is watching. She uses her new smartphone to use the displayed QR code to download, Cultural Heritage Augmented Reality App (CHARA), an Augmented Reality application for all the cultural heritage	In addition to Info-point, AMH is reconstructed in an AR Information World, reusing content and components presented in the World described in the VR case. AR

institutions of Crete. She starts the application which automatically detects that she is at the municipal Info-point and augments her current surroundings. Anna is standing in front of BeThereNow, an application projected on a wall which immerses users into various landscapes of Crete. She wants to try CHARA and therefore turns her smartphone towards the display, which in augmented reality displays Anna wearing traditional Cretan dresses. Later on, she turns her smartphone towards a desk with a printed map of Heraklion, which users typically explore using plain pieces of carton, and 3D models of points of interest such as the Koule Fortress and Saint Minas' church pop out of the surface. She imagines exploring the physical exhibits of AMH, and despite having visited the AMH a few years ago, urges Tony to download it as well and visit the museum in vivo. When choosing to exit the virtual world, Tony is shown screenshots of his visit, which he instantly downloads them to his smartphone.	applications are location-sensitive and choose the world to visualize in accordance to the users' position. HelloThereNow [6.5.5.2.1] is an Information Thing representing the application, in which a Custom Information Piece [6.5.5] is added. An Augmented Map [6.5.2.2] is presented over location of the printed map of Heraklion, presenting 3D content which is not supported by the existing interactive system. The keepsakes are shown using the Post-Visit Information World implementation [8.6.6].
When entering the museum, Tony and Anna place their smartphones on the entrance and open the CHARA, curious and eager to use the application for the first time. Anna, who is a linguist, is shown a media collection about the Linear A writing script used by the Minoans and todate undeciphered, whereas Tony sees pictures about constructions in the Phaistos and Knossos palaces. Moving on to the museums' main hall, they notice "Infocloud", an interactive system created by ICS-FORTH with which they interact, augmented by callouts describing its usage. Upon approaching it, Anna touches the system and retrieves additional information about Arkalochori Axe, an artifact which is believed to have been utilized for religious rituals and contains symbols. Anna uses CHARA to examine the symbols in detail, viewing the symbols in ultra-high resolution, and reading information about the debate on whether they belong to Linear A. CHARA recommends Anna to visit the Phaistos Disc, which is exhibited in the next room. Anna chooses to accept the recommendation and the application augments the room floor with directions to Phaistos disc and guides her to the exhibit.	The framework identifies users' location and presents AMH world. Each Media Gallery [6.5.2.4] contains data related to user profiling, which can add value to the exhibition, generating a more personalized user experience. Infocloud is an existing Ambient Intelligence application integrated into the framework, represented by an Information Thing, providing input about user selections. The selection of Arkalochori Axe results in the provision of a cut-down version of Object Manipulator [6.5.2.5] showing the 3D geometry rotating infinitely. Arkalochori Axe is semantically related to Phaistos Disc and therefore the framework recommends it to the user. A Navigation Assistant [6.5.1.3] is employed for user guidance

	towards the location of the desirable item.
The couple continues the visit together, exploring the various exhibits on display. Tony's mobile phone vibrates and Tony is informed about a wooden model of the Knossos palace, which they had missed as they were walking across the museum's corridors. Tony walks back and visits the wooden model, augmented by textual descriptions, while Anna reads about the religious rituals of the Minoan civilization. Tony is an engineer and due to his professional interests, he is excited to notice the innovative features of the palace, such as the existence of skylights, and shares the exhibit's location with Anna. Anna uses the minimap of CHARA which displays the augmented exhibits in the museum to approach the area where Tony is located and Tony uses the application as a starting point for explaining the principles of urban planning throughout the years.	The framework provides location-sensitive recommendations in accordance to the user's profile. The wooden model of the palace is an Information Thing which matches the user's professional interests and is thus recommended. It is augmented by a Callout Presenter [6.5.2.7], regarding Information Things (the wooden model). The worlds created using the framework include a mini map which aids navigation and orientation. In addition to Navigation Assistant, the Minimap [6.5.1.2] component highlights the area of interest.
CHARA displays information about the functionalities provided by the palace rooms and the neighboring facilities. It presents 3D vases containing olive oil and wine inside the storage facilities. Next to the facilities lays information about the commerce with the Egyptians but also regarding the history of wines in ancient Greece. Tony chooses to view the textual analysis, accompanied by historic evidence, regarding the relationships of the Minoan people with the Egyptians. Afterwards, the CHARA guides them towards the frescos located in a nearby showcase and displays a virtual restoration in front of the physical frescos. Upon moving nearby, a set of pictures of Egyptian wall paintings bearing resemblances to the showcased frescos is displayed, highlighting the associations between the two civilizations through art.	Information Pieces are placed on the wooden model, including Object Manipulator [6.5.2.5] (vases), Media Gallery [6.5.2.4] (multimedia), Text Presenter [6.5.2.8] (historic evidence) and Wordcloud3D [6.5.2.6] (keywords). These pieces contain semantic information about the Minoan civilization which is linked to the Egyptian civilization. The frescos restoration is an Information Thing Indicator, containing custom Information Pieces [6.5.5] to highlight the points of interest and Information Pieces for the additional information.
As Tony and Anna complete their visit, they walk past a television that displays a real time view of the museum's room. Upon approaching, they notice that the television acts as an augmented reality mirror and watch themselves surrounded	The framework performs real time monitoring of the actions performed by the users, either through the AR and VR applications, or through the

with information tags generated throughout their visit, generating a story that summarizes their experience. The information tags are placed around their bodies and create a 3D tag cloud where the tags placed on their left include the content they have explored, while on their right side additional related information, which is implicitly related, is shown. They decide to keep the generated wordcloud as a keepsake from their experience and also send it to Anna's cousin Giovanni, who is an archaeologist located in Athens, sharing their experience with their relative.	permanent physical installations registered within the framework. Their experience automatically generates a personalized story which summarizes their visit using a Mirror of Thoughts [6.5.4.1]. Finally, keepsakes can be shared for offline uses using web technologies.

9.2. Infrastructure Management and Monitoring

Data centers constitute a demanding environment that generates large amounts of information which is required to be handled in real time. A multitude of entities, thousands of servers and racks, are installed in predefined locations and are constantly monitored. Different data dimensions (i.e. metrics such as temperature, power consumption, etc.) which change over time are required to be visualized in a dense environment. Furthermore, disorientation may arise since the surroundings are similarly structured and items are visually similar. In terms of navigation and travelling, both extensive and sharp movements are needed, as the rooms are usually extensive. In order to maximize flexibility in terms of movement, users employ a fly-over approach, allowing them to move without being obscured by the server racks in place. Decision making and employee reactions should be responsive in order to avoid further implications. The following scenario is narrated from the perspective of the data center monitoring process on the left side of the following table, whereas the right side presents the information from the framework's point of view.

Use case Description	Framework Representation
A new application, GoogleApp, has been deployed by Google and within the data center premises of Google at Helsinki the administrators are monitoring the progress of network traffic and key performance indicators of the servers providing the new functionalities. David is the head of the administration team and is one of the most experienced employees at the data center. Steve is the employee who is responsible during the work shift and his assistant, Alfred, is a new employee who joined the administration team a few weeks ago. In order to keep track of the state of the data center, the DCMS software has been installed, which monitors the metrics of key server indicators, i.e. CPU usage, Disk I/O, Temperature and	The scenario illustrates several synchronized instances of the deployed application, which provide real time data for monitoring the data center room. Each data center room is represented by one Information World [4.2] containing thousands of servers, i.e. Information Things [4.3]. Each server is shown through an Information Thing Indicator [6.2], which is colored in accordance with the selected

Network Traffic. DCMS is able to provide real time remote visualization of all the data center rooms within the premises, displaying the current values of the metrics in a 3D environment where each server is colored according to the selected metric. DCMS is also capable of automatically detecting anomalies and analyzing their root cause.	metric. Due to very dense Information Things placement, the Information Things are grouped with respect to their physical location and semantic meaning into racks, i.e. Information Thing Groups [4.3]. Furthermore, Information Pieces [4.4] represent server anomalies, which are automatically provided to the visualization dynamically.
Steve has annotated the servers used for the GoogleApp, which are located in Room B, section S2. A few hours after the deployment of GoogleApp, the environment triggers an alarm notifying Alfred about an increase of a server's temperature in section S2 which is not analogous to CPU usage. Alfred wears his head mount display and applies gestures to navigate towards section S2 to examine the details. Upon approaching the area of interest, the annotations describing the potential anomaly are automatically shown, displaying the current temperature values. 10 seconds later, the visualization is refreshed and Alfred selects the temperature metric and filters out servers with expected values. In order to examine the previous values, Alfred selects the rack and examines per server details, containing previous and predicted future values presented in the form of charts. Alfred views all the chart metrics side by side, comparing their values and trying to find patterns between the value changes.	Using the editor interface, administrators are able to customize the visualization. The framework supports real time information provision (new anomaly and auto metrics refresh) and gestures [6.9.1.2] are employed for travelling in virtual space. The Information Pieces adapt their view to provide additional data in accordance with the user's location. Faceted display is provided by hiding Information Things and Pieces. Information Thing Groups are expanded and present Chart Presenter [6.5.2.1] Information Pieces per Information Thing (server).
Alfred is not certain about the state of the server and annotates the potentially problematic server rack for his supervisor to check. The desktop version of DCMS which Steve is using displays a message about the server in check and automatically focuses on the annotated rack. Steve suspects a potential fan failure and decides to check the server on spot. Steve uses his own smartphone to view the path towards the faulty component, which is highlighted. Upon reaching the defined rack, he locates the detected server slot in the rack with the reported temperature. The high temperature was reported due to a fan failure and therefore the employees shut down the server immediately. They mark the issue as handled, remove the server from the visualization and insert the	Item selection and annotations are communicated in real time regarding the issues raised. The framework presents visualization in AR, VR and high resolution displays. A Navigation Assistant [6.5.1.3] is employed to guide Steve to the rack and the server (Information Thing Indicator) is highlighted. Information Things can be altered by end users in real-time, allowing operations such as editing or deleting. User-generated content [6.1.6] is sent

malfunction description. Upon marking the issue, the application notes that it was the third faulty sensor malfunction in the past few weeks for this particular server brand.	to the framework's server and stored, adding input from the real world.
The next morning Steve reports to David what happened and uses DCMS to reproduce the incident and highlights the improved response times using the efficient visualization and collaboration features of DCMS. In order to illustrate the criticality of the issue and convince him to replace all the fan servers of the same brand, David shows the servers to be changed using a large television located at the control center.	Data Logging [6.1.5] and Narratives [6.9] are employed for the reproduction of the incident. The framework filters out servers based on their semantic characteristics (brand).

10. Evaluation

This chapter presents the findings of the evaluation sessions which were conducted in order to assess the use cases discussed in Chapter 9, the data center monitoring and smart museum respectively. The two use cases had common hypotheses, but also held differences due to their specific characteristics and goals. The evaluation process followed a similar structure, where a usability evaluation session was first conducted, and was followed by a user experience assessment, with alternations in terms of tasks and questionnaire in order to match the corresponding requirements. The following sections describe the corresponding processes, tasks and questionnaires and conclude with the findings stemming from the evaluation process and the analysis of the final results.

10.1. Usability Evaluation of the Data Centre 3D Visualization application

The development of the Data Centre 3D Visualization application has followed an iterative approach, continuously evolving the supported functionality, the User Interface and the interaction methods. Three major application versions can be identified during the evolution of the application, which are described in Table 1 and illustrated in Figure 69 and Figure 70. More specifically, the first version of the application aimed at providing a 3D visualization of a data centre room, while the second version incorporated gesture-based interaction and an updated user interface which better exploited the screen real estate and provided a more contemporary look-and-feel. The second version of the application was assessed through heuristic evaluation [306] by three User Experience (UX) experts. Based on the results of the evaluation, the third version of the application was implemented, featuring UI improvements and new functionality to support the user's spatial orientation in the visualised room [307].

Functionality		
Version 1	**Version 2**	**Version 3**
• 3D Visualization of the racks, following the metaphor of a room • Orbit camera • Filter displayed results by server attribute, criticality level, timestamp • Change view by sparseness • Navigation controls for zoom in/out and move forward/backward/right/left • Anomalies detection and notification • Close-up view of a selected rack • Detailed information through charts for a specific unit of a rack	• Navigation controls for translation and rotation of the camera • Play/pause of live data retrieval • Lock/unlock interaction with gestures • Data centre room selection	• Mini map • Reset room view • Units indexing in selected rack close-up view • Markers, value labels, and value for the currently visualized time on the chart in the full screen mode
Interaction		
Version 1	**Version 2**	**Version 3**
• Mouse movement: Raised pointer finger of one hand • Mouse click : Raised pointer finger of the one hand, closed fist which opens for the other hand	• Mouse click: Raised pointer finger of the one hand, open fist which closes for the other hand (click in the air) • Gestures to move and rotate the camera forward/backward/ left/right/up/ down	-

Table 1: Evolution of the Data Centre 3D Visualization application in terms of supported functionality and interaction methods. For each version only the changes or newly introduced features are listed

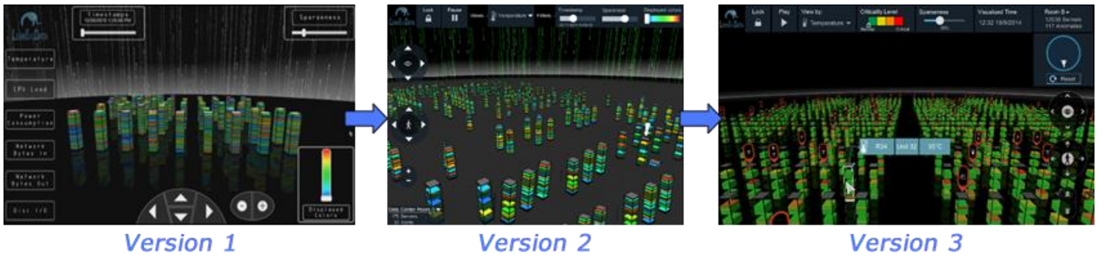


Figure 69: Evolution of the UI of the Data Centre room view across the three versions

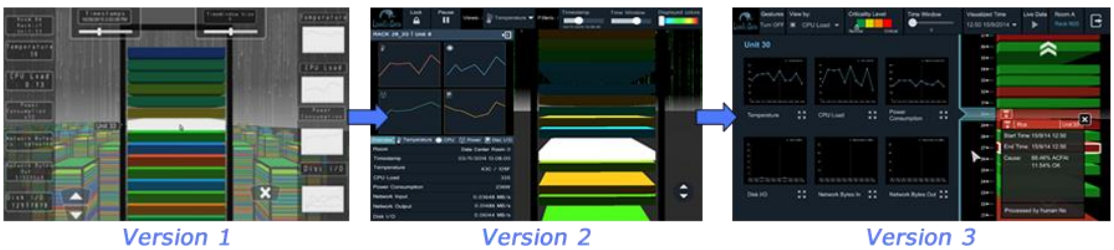


Figure 70: Evolution of the UI of the selected rack close-up view across the three versions

Although the system had already been evaluated by experts and updated accordingly, an additional evaluation by users was required, since even though heuristic evaluation [305] finds many usability problems that are not found by usability testing, it is also possible to miss some problems which can be discovered only through usability testing [307]. Heuristic evaluation and user testing should better be employed in an iterative approach, carrying out the heuristic evaluation first and trying to eliminate as many problems as possible before involving users. The main reason for this is that it is more effective to evaluate a system with end users when all known errors have been corrected, given that user-based testing requires many more resources (in terms of time, effort, and money) than heuristic evaluation.

To this end, a usability evaluation with end-users has been performed in the improved final version of the system (version 3), in two stages:

- A typical observation experiment has been carried out, involving 20 users, aiming to assess the usability of the system and the gestures' learnability [10.1.2]
- A UX assessment questionnaire has been delivered to 80 users, with the aim to evaluate their overall impression and subjective view regarding their experience from the system [10.1.3]10.1.2.

The two evaluation approaches are complementary and each is aimed at assessing different attributes of the system. More specifically, the observation of users while using the system aimed at revealing potential usability problems, evaluating the effectiveness and efficiency of the system, assessing the gestures vocabulary and its learnability, as well as users' fatigue, and retrieving explicit user feedback about likes, dislikes and potential suggestions through a semi-structured interview. However, another important parameter that should be studied for the system is that of the overall UX and users' feelings from their interaction with the system. These approaches, although complementary, were carried out separately, as the first requires considerably less users than the second. Literature has indicated that involving 20 users in a usability testing evaluation will find 95% of the problems of the system [131].

10.1.1. Usability testing through observation

Usability testing involved twenty participants who used the system in a laboratory setup, resembling however the envisioned context of use. In more details, the system was deployed in a 60’’ TV screen, placed in a large room. Users were asked to sit on a chair, which had been placed at a convenient position, so that the motion sensor would effectively detect the user’s hand gestures. Minor amendments were made to the placement of the chair, if needed, to better serve each individual user, in case the system was not responsive enough (e.g., shorter users and users with smaller palms were required to sit a little closer to the sensor than taller users or users with larger palms).

Three main hypothesis were formed and tested during the usability testing:

H1. The system can be used effectively in the envisioned context of use to serve the needs of monitoring a large data centre room

H2. The system does not impose physical strain over users

H3. Interaction gestures are easy to learn

Taking into account that the system addresses everyday users, and therefore users will be quite familiar with its features and functionality, the experiment comprised three phases, accomplished in three consecutive days for each user:

A. Acquaintance with the system. Each participant was individually introduced to the system, explaining all the functionality and interaction methods, and was allowed to explore it through free interaction. Each acquaintance session lasted for about twenty minutes.
B. Usability evaluation. Each user was asked to interact with the system following specific tasks, which were handed one-by-one. Additional details about the tasks, the process that was followed during the test and the results obtained are provided in section 10.2.3 below. Each usability evaluation session lasted approximately thirty minutes, with minor differences between users.
C. Post-test. Users were asked to navigate using gestures only, to specific targets marked on their screen, in order to assess the learnability of the gestures in terms of vocabulary and interaction efficiency. Additional details regarding the process and the results of the post-test session are provided in section 10.1.2.6 below. Each post-test session lasted approximately ten minutes, with minor divergences among users.
D. Participants were recruited with the aim to involve a balanced group of users with small, medium, and high expertise in interacting with software systems through a motion sensor. Given that the 3D Data Centre Visualisation system does not address first-time users only, but is intended to be used on a regular basis by its target audience, it was important to involve experienced users as well. Users’ demographic information with reference to their gender, age, and expertise in using motion sensors is described in Figure 71, Figure 72 and Figure 73.

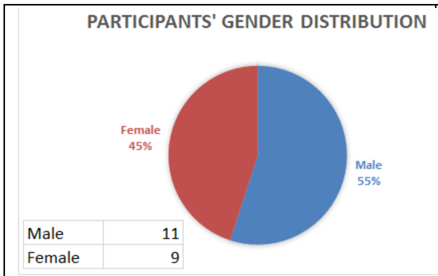


Figure 71 Usability test participants' gender distribution

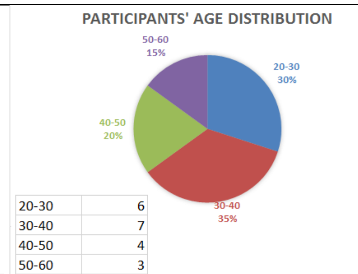


Figure 72 Usability test participants' age distribution

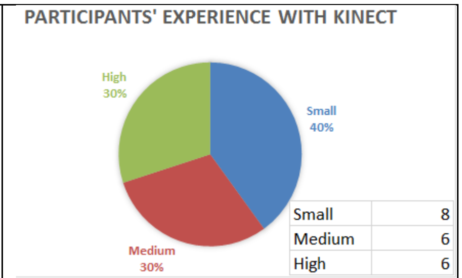


Figure 73 Usability test participants' experience with the motion sensor

10.1.2. Usability evaluation session

During the usability evaluation session, the participants were asked to execute specific tasks while they were observed and notes were kept regarding specific problems, comments, the time on task, and successful execution of the task. Once they completed the test scenario, they were asked their opinion about the system following a semi-structured interview approach [141]. Finally, they were requested to rate the physical strain in using the system as they perceived it on a scale from 1 to 10. This section describes in more detail the tasks that were assigned to the users, the metrics that were recorded, the main contents of the semi-structured interview, the usability evaluation test process as it was followed, and the results and findings obtained.

10.1.2.1. Tasks

The usability evaluation session involved the execution of a series of tasks, in the order given by the evaluator. The tasks revolved around a specific user scenario, according to which the user is a system administrator working for a multinational corporation that houses a large data centre with more than 5,000 servers. Part of the user's daily work routine is to assess the servers' state and locate any functional problems, a task which is accomplished through the 3D Data Centre Visualisation application. The tasks that constituted the entire evaluation scenario were the following:

- **Task 1**: Looking at the overview of Data Centre Room 1, you notice that a specific rack, namely N37, seems to have an indication of an anomaly. Select rack N37 in order to find out more details about the problem that occurred.
- **Task 2a (in close-up view):** Locate the server for which the anomaly alert was issued.
- **Task 2b:** What is the exact time that the problem was initiated?
- **Task 2c:** Seeing that the problem has already been resolved, you completed your inspection of the rack. Return to the room view, with all the racks of Data Centre Room 1.
- **Task 3a:** You would like to see the status of the servers regarding their temperature. Change the view of the displayed racks, so as to view racks by temperature.
- **Task 3b:** Filter the displayed racks, so as to view racks with servers in critical state.
- **Task 4a:** In a faraway location of the room (right back area) you notice that there are several racks with servers in critical state. Use gestures to navigate to the specific rack that will be indicated to you by the evaluator.

- **Task 4b:** Perform a 180^{O} rotation and return back to the place you started from, until you can see no further racks.
- **Task 4c:** Reset the view of the room.
- **Task 5a:** In another faraway corner of the room (left back corner) you notice that there are several racks with anomaly indication. Use the navigation controls to navigate to the rack that will be indicated to you by the evaluator.
- **Task 5b:** Using again the navigation controls, perform a 180^{O} rotation and return back to the place you started from, until you can see no further racks

It should be noted that all tasks were designed so as to have a clear ending condition (e.g., find a specific information, bring the room to a specific state, or perform a specific interaction) and that all participants were asked to navigate to the same racks for tasks 4a and 5a.

10.1.2.2. Metrics

The following metrics were recorded during the usability evaluation session, using appropriate recording sheets:

- Success in accomplishing the task, marked as (S) for success, (PS) for partial success, and (F) for failure.
- Time on task (in seconds) for all the tasks besides 2a and 2b where this recording would not be meaningful. In more detail, in task 2a users were asked to locate the specific unit for which an alert was issued. Since the unit was not visible at once and users were required to scroll, while each user might employ a different strategy for locating the server (some users first moved to the bottom and then to the top, while other users followed the inverse route) time would not be an illustrative performance metric. Likewise, the information requested for task 2b could be retrieved either by hovering over the alert or clicking on it, therefore the time would depend on the interaction strategy employed by each user.
- Number of tries, for all the tasks that involved executing the mouse click gesture, i.e., keep their pointer finger of the one hand raised, and have their closed fist of the other hand opened.

Additionally, handwritten notes were kept for users' comments and any suggestions which were provided by the users during their interaction with the system, as well as regarding the interaction flow, system errors, or other remarks that might lead to useful results.

10.1.2.3. Interview Questions

Following the scenario-based execution of tasks, users were interviewed to elicit their comments regarding the system, following a semi-structured interview approach. Semi-structured interviews are conversations in which the topics of the discussion are known before hand – therefore a preliminary set of questions can be prepared and used to guide the interview – but the conversation is free, and therefore it can vary between participants [141].

The questions that were asked were:

1. What is your general impression about the system that you tested?
2. What did you like the most about the system?
3. What did you like the least about the system?

4. On a scale from 1 (least strenuous) to 10 (most strenuous), please rate the physical strain that you think was imposed to you by using the system, where 1 is the minimum and 10 is the maximum strain.

All the provided answers were recorded by the evaluator, through handwritten notes.

10.1.2.4. Main Experiment

As soon as the user arrived at the usability evaluation room, they were welcomed and introduced to the evaluator and facilitator. The evaluator was responsible for steering the session, handing out the tasks one by one to the user, providing all the explanation (if and when appropriate), keeping notes, and asking questions to the user. The facilitator was a technical person, responsible for setting up the system and assisting in adjusting the user's distance from the sensor if needed, as well as for recording the time required to complete a task, where appropriate.

After welcoming the user and since the user had already been introduced to the system during the acquaintance session that had been held the previous day, the evaluator proceeded with explaining the purpose of the evaluation and the process that would be followed, as well as the recordings (e.g., time in task, number of tries) that would be made during each task. It was clearly explained to users that it was the system that was being tested and not the users themselves or their performance, and that they could stop the evaluation for any reason and at any time they wished during the experiment.

Then, participants were handed out two copies of the consent form to sign. Both copies were also signed by the evaluator, and one of them was returned to the participant. In summary, the informed consent form described the system, the purpose of the evaluation and the evaluation process. It also informed participants that their participation was voluntary and can be withdrawn anytime they wish, that they would not receive any reimbursement and that they would not have a direct benefit from the evaluation other than assisting in improving the system. In addition, it described how the participants' personal data are protected and provided contact details of the evaluator and the scientific advisor of the evaluation.

Once the consent form had been signed by the participant, tasks were handed one by one. The evaluator avoided answering questions and prompting the user as to how to proceed with carrying out the task. The only clarifications that were provided, if needed by any of the participants, were related to the description of the tasks themselves, in case they were not clear to the user. As the user proceeded with the execution of the tasks, the evaluator took notes on user comments, questions, and observations about the interaction that was taking place. Furthermore, the evaluator and the facilitator proceeded to the necessary metrics' recordings.

The interview and debriefing session followed the execution of tasks, allowing users to describe their overall experience with the system. Finally, participants were thanked for their time and effort and reminded of their next day post-test appointment.

10.1.2.5. Findings and results

10.1.2.5.1. Tasks Findings

The success rate of the application was very high. Success rate is defined as "the percentage of tasks that users complete correctly" [305]. For each task, the user's success is marked as (S) for success, (PS) for partial success, and (F) for failure. The total success rate is calculated by the formula:

*Success Rate = (TS + (PS*0,5))/Number of attempts*

TS is the total number of successful attempts, and PS is the total number of partial successful attempts. More specifically, for the evaluation of the 3D Data Centre Visualization application, the formula is produced as follows:

*Success Rate = (247 + (5*0,5))/259 = 0,96*

It should be noted that one participant was not given the last task to carry out, since the evaluator decided to stop the session, because too much effort was required from this user to use the system and the user had expressed that her shoulder was in pain before starting the evaluation. Therefore, the total number of attempts was 259 and not 260 as expected, given that 13 subtasks in total were expected to be carried out by 20 users.

The detailed analysis of users' success per task is presented in Figure 74, displaying user success per subtask. Successful task accomplishment is marked in green, partial successful accomplishment in orange and fail in red. It can be easily deduced that failures have been noticed for two types of tasks: tasks requiring selecting an option from a drop-down menu (tasks 3aii and 3bii) and tasks requiring navigation in the virtual environment through gestures (tasks 4a and 4b).

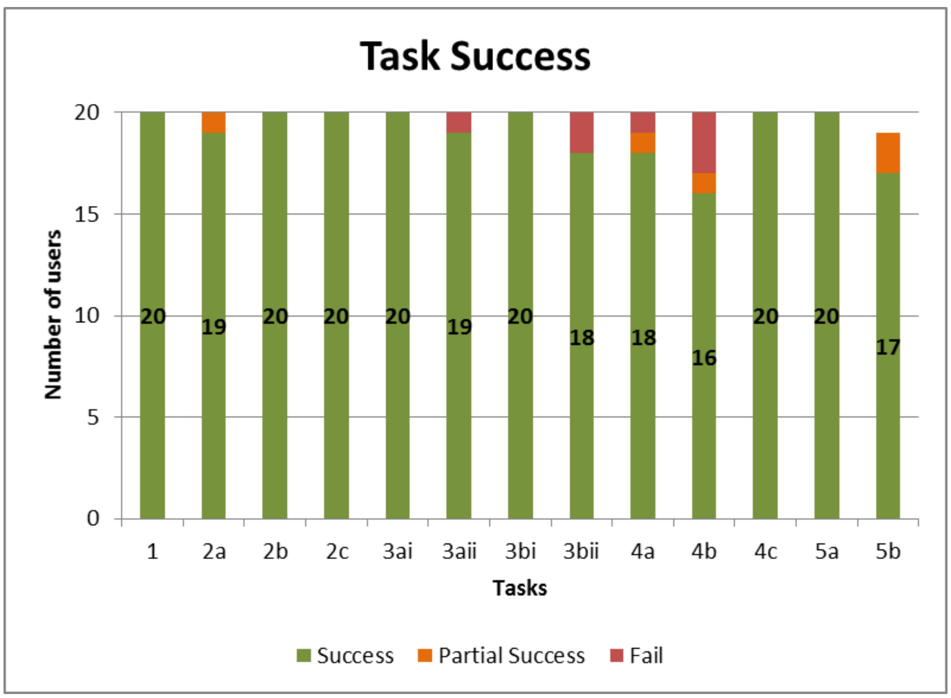


Figure 74: Total success rate

Task success was also examined as a factor that might be dependent on the user's gender, expertise with the motion sensor, or age. Initially, the success rate has been calculated for every value of the independent variables of the experiment and is illustrated in Figure 74. In more detail, Figure 75 illustrates the total success rate, as well as success rate per user gender (male vs. female users), experience in using the motion sensor (high, medium, small), and age (20-30, 30-40, 40-50, 50-60).

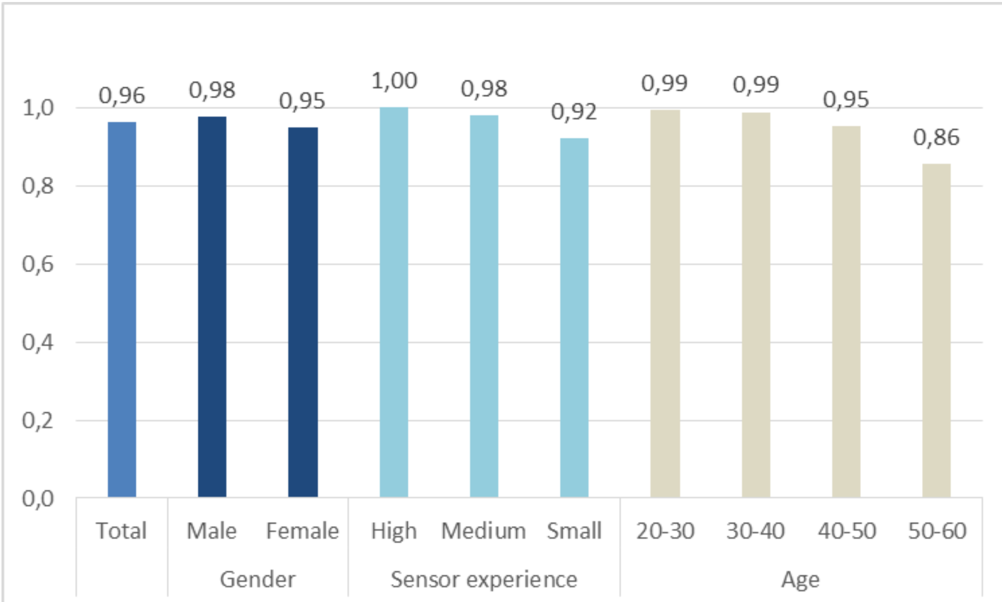


Figure 75: Success Rate: total success rate and success rate per gender, sensor experience and age for the user observation experiment

10.1.2.5.2. Findings stemming from structured interviews

During the interview, users were first asked to explain what they liked most as well as what they liked least about the system. The reported dislikes usually stemmed either from problems that users had faced during their interaction with the system, issues that did not confine them from achieving the task but imposed some difficulty nonetheless, or simple aesthetic preferences. Users' reported likes and dislikes were initially filtered to create one unified set of likes and dislikes, to eliminate data duplication. Then, they were combined with the evaluators' observations and were organized in a table making cross-references to the users involved, in order to locate any outliers. Finally, reported dislikes were filtered as to their impact, examining:

1. the number of users who reported the issue
2. the type of the issue (e.g. personal aesthetics, functionality problem, usability problem, etc.)
3. frequency with which the issue occurs
4. the impact of the issue if it occurs, assessing if it will it be easy or difficult for the users to overcome
5. the persistence of the problem, assessing whether users can overcome the problem once they know about it or will they repeatedly be bothered by it

In summary, the more appreciated features of the system were reported to be:

1. The 3D representation, which was engaging and offers benefits which cannot be provided by 2D visualizations
2. Navigation in the virtual world with gestures, which were mentioned as a like by 45% of the participants.
3. The overall user interface, which was nice and intuitive
4. The mini map, which facilitated the user's orientation in the virtual world
5. The criticality filters, allowing users to easily locate units in critical situations.

Dislikes were reported in a more sporadic manner, usually having each user report as dislikes the features that made it difficult for them to complete the tasks. These dislikes have been combined with the evaluator's observations and are reported below.

1. Using the system might require time which will be limited in critical situations. Although this was mentioned as a dislike by only one user, more users provided suggestions along this direction, i.e., as to how to improve locating servers in critical state and interacting with them, and are reported next.
2. The gesture for making a turn was rather slow.
3. A lag which was noticed in gestures imposed difficulties in interaction and was reported by a few users as a system attribute that they disliked.
4. The surrounding space is vast; instead the boundaries of the virtual world should be confined. This dislike was also reported by one single user. Although users weren't allowed to move outside the visualised area, this user found the fact that there were no walls frightening. Adding walls to the visualised data centre room was also provided as a suggestion by one more user, although not reported as a dislike. Future designs should explore whether adding walls would improve the overall user experience.

10.1.2.6. Post Test

The goal of the post-test session was to assess navigation in the virtual world through gestures, in order to assess the learnability of the gestures in terms of vocabulary and interaction efficiency. To this end, five targets were marked in the virtual world with numbers from 1 to 5 (see Figure 76) and users were asked to navigate from the one target to the other, flying through the number itself. The task was considered successful as soon as a user passed through the number. In addition to the task success, the required time was recorded. Once the users completed the task of navigating in the virtual world, they were asked if they had any additional comments or suggestions to provide and they were thanked for their participation. All the comment and suggestions retrieved from the post-test session have been included in the results reported in the previous section.

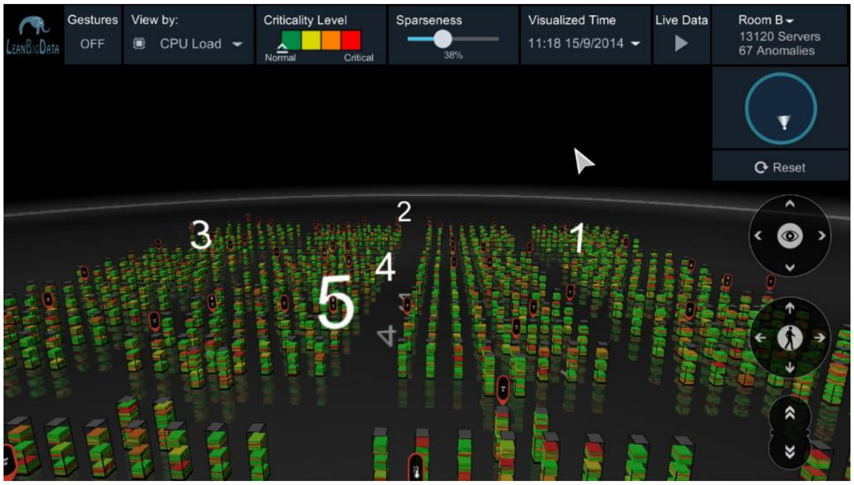


Figure 76 Numbered targets to be reached consequently by navigating in the virtual environment with gestures during the post-test evaluation

It should be noted that all the users remembered without any assistance or requests for help the gestures that they had to employ in order to navigate in the virtual world, both during the observation session and the post-test sessions. Thus, it can be concluded that the employed gestures are easy to learn.

The metrics that have been recorded for the tasks of the post-test experiment include whether the user was successful, the time required to complete the task, as well as the fatigue level as reported by the users themselves.

Table 2 presents for each task the actual success rate (%), as well as the Confidence Interval Lower Limit (CI [LL]), and Confidence Interval Upper Limit (CI [UL]), as these have been calculated with the adjusted Wald method.

	1	2	3	4	5
Success Rate (%)	100	100	94.44	94.44	94.44
CI [LL]	0.845	0.845	0.723	0.723	0.723
CI [UL]	1	1	0.999	0.999	0.999

Table 2 : Success Rate and Confidence Intervals per task for the post-test experiment

10.1.3. User Experience Assessment

The User Experience Questionnaire (UEQ) [246], also available in 14.4, was used to capture user impressions. The system was installed and extensively demonstrated to 80 participants of a full-day workshop in the context of the LeanBigData EU Project [248]. This questionnaire allows a quick assessment of the user experience of interactive systems as it supports users to immediately express feelings, impressions, and attitudes that arise after their interaction with a system. It contains the following 6 scales with 26 items:

- Attractiveness: Overall impression of the system. Do users like or dislike it?
- Perspicuity: Is it easy to get familiar with the product? Is it easy to learn how to use the product?
- Efficiency: Can users solve their tasks without unnecessary effort?

- Dependability: Does the user feel in control of the interaction?
- Stimulation: Is it exciting and motivating to use the product?
- Novelty: Is the product innovative and creative? Does it catch the interest of users?

Each item in the questionnaire has the form of a semantic differential, i.e., each item is represented by two terms with opposite meanings, for example: Attractive – Unattractive. The order of the terms is randomized per item, i.e., half of the items of a scale start with the positive term and the other half of the items start with the negative term and a seven-stage scale is used to reduce the well-known central tendency bias for such types of items. So, the items are scaled for -3 to +3, with -3 representing the most negative answer, 0 representing a neutral position, and +3 representing the most positive answer.

Example:

attractive	○	⊗	○	○	○	○	○	unattractive

This response would mean that you rate the application as more attractive than unattractive.

Of the 6 scales, *Attractiveness* is a pure valence dimension, while *Perspicuity*, *Efficiency*, and *Dependability* are pragmatic quality aspects (task and goal-oriented), and *Stimulation* and *Novelty* are hedonic quality aspects (not task or goal-oriented).

10.1.3.1.1. Process

During the workshop, the Data Centre 3D Visualization application was demonstrated and presented in details to the participants. Then, participants were allowed to have a short interaction with it and were handed the UEQ questionnaire to fill-in.

10.1.3.1.2. Results

A total of 80 people answered the questionnaire. However, during the analysis, questionnaires whose responses showed inconsistency in more than 2 scales were factored out. This was done by checking how much the best and worst evaluation of an item in a scale differ. If there was a big difference (>3) this is seen as an indicator for a problematic data pattern. This can be the result of random response errors or a misunderstanding of an item. Regardless of the reason, these questionnaires were left out from the analysis. So the end number of questionnaires that were used for the analysis was 60.

The results from the valid questionnaires are depicted in Table 3 and Table 4 below. Table 3 respectively shows the collective mean averages per scale. Values between -0.8 and 0.8 represent a neutral evaluation of the corresponding scale, values >0.8 represent a positive evaluation and values <0.8 represent a negative evaluation. As it is shown, the system scored higher in the attractiveness and hedonic qualities scales than the pragmatic ones. More specifically, the *Attractiveness*, *Stimulation*, and *Novelty* scales all received positive scores from 1.8 to 1.98. These scores are an indication that the participants found the showcased system to be innovative, engaging, and pleasant.

On the other hand, the pragmatic scales, *Perspicuity*, *Efficiency*, and *Dependability* received lower scores than the hedonic ones. *Efficiency* and *Dependability* received a 1.3 and 1.2 score respectively, which are positive values and greater than the 0.8 neutral point line, while *Perspicuity* (learnability) received a 0.75 score which is the lowest score of all the scales and just a little lower than the 0.8 neutral point line. Even though it is impossible to know exactly why we observed such a difference between the scores of the *Hedonic* and the *Pragmatic* scales, it can be partially justified by the fact that the Data Centre 3D

Visualization system is using innovative technologies (3D modelling) and user interaction modes (hand gestures) that are foreign to the average user in the context of interacting with a regular software application. And as a result, it is understandable to receive mixed feelings and impressions from the users. Uncertainty and insecurity in respect to how easily such a system can be learned and used in a dependable way is a natural phenomenon when dealing with new technological paradigms. However, from the user-based evaluations during which the participants had much longer exposure to the system and were given some training prior to using it, it was concluded that the users improved rather quickly in using the hand gestures to navigate through the 3D user interface of the system and in interacting with the menus.

UEQ Scales	
Attractiveness	⇧ 1.808
Perspicuity	⇨ 0.767
Efficiency	⇧ 1.321
Dependability	⇧ 1.217
Stimulation	⇧ 1.988
Novelty	⇧ 2.013

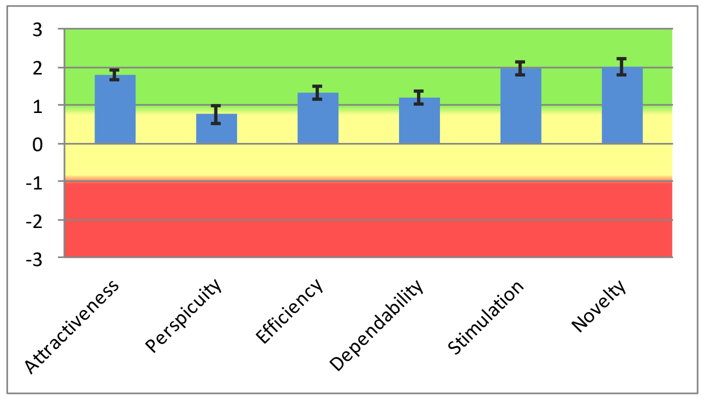


Table 3: Means per scale results and diagram

Item	Mean	Variance	Std. Dev.	No.	Left	Right	Scale	
1	⇧1.1	3.5	1.9	60	annoying	enjoyable	Attractiveness	
2	⇧1.8	1.6	1.3	60	not understandable	understandable	Perspicuity	
3	⇧1.5	1.6	1.3	60	creative	dull	Novelty	
4	⇩-1.0	2.6	1.6	60	easy to learn	difficult to learn	Perspicuity	
5	⇧2.1	1.0	1.0	60	valuable	inferior	Stimulation	
6	⇧1.8	1.0	1.0	60	boring	exciting	Stimulation	
7	⇧1.9	1.5	1.2	60	not interesting	interesting	Stimulation	
8	⇨ 0.6	1.3	1.1	60	unpredictable	predictable	Dependability	
9	⇧1.3	0.9	1.0	60	fast	slow	Efficiency	
10	⇧2.1	1.1	1.0	60	inventive	conventional	Novelty	
11	⇧1.6	1.2	1.1	60	obstructive	supportive	Dependability	
12	⇧2.0	1.1	1.1	60	good	bad	Attractiveness	
13	⇧1.1	2.3	1.5	60	complicated	easy	Perspicuity	
14	⇧1.9	1.3	1.1	60	unlikable	pleasing	Attractiveness	
15	⇧2.2	0.9	0.9	60	usual	leading edge	Novelty	
16	⇧1.9	0.9	0.9	60	unpleasant	pleasant	Attractiveness	
17	⇧1.1	1.2	1.1	60	secure	not secure	Dependability	
18	⇧2.2	1.0	1.0	60	motivating	demotivating	Stimulation	
19	⇧1.7	1.3	1.1	60	meets expectations	does not meet expectations	Dependability	
20	⇧1.8	0.8	0.9	60	inefficient	efficient	Efficiency	
21	⇧1.2	2.5	1.6	60	clear	confusing	Perspicuity	
22	⇧0.9	2.6	1.6	60	impractical	practical	Efficiency	
23	⇧1.4	1.7	1.3	60	organized	cluttered	Efficiency	
24	⇧2.1	0.8	0.9	59	attractive	unattractive	Attractiveness	
25	⇧1.9	1.0	1.0	60	friendly	unfriendly	Attractiveness	
26	⇧2.3	0.9	0.9	60	conservative	innovative	Novelty	

Table 4: Scores per item

10.1.4. Conclusions

The usability evaluation of the Data Centre 3D Visualization application followed a two-step approach, with the aim to assess different attributes of the system:

1. A usability evaluation experiment, involving 20 users, in order to evaluate the effectiveness and efficiency of the users while using the system, as well as the learnability of the gestures' vocabulary and interaction, and find out whether the system imposes any physical strain on the user.
2. A User Experience evaluation by demonstrating the system in a workshop and handling a questionnaire to the workshop participants in order to retrieve their feedback classified in five main categories, namely attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. Questionnaires were retrieved by 80 workshop participants, and after filtering out potentially biased answers, 60 valid questionnaires participated in the final UX analysis.

Analysis of the results of the usability evaluation experiment indicated the following conclusions:

1. High success rates (at least 70%) can be achieved even for the most difficult tasks for any user population.
2. Having prior experience with the motion sensor affects user performance.
3. Tasks requiring a selection of UI element through the mouse click gesture can be carried out efficiently, as we are 95% confident that it will take users of the general population at most 16 seconds and 3 tries to achieve a selection.
4. Tasks requiring selecting an option from a drop-down menu can be less efficiently carried out, as we are 95% confident that users of the general population will require at most 31.5 seconds to accomplish.
5. Navigating from the one end of the visualised room to the other with or without making any manoeuvres is the most time consuming task.
6. The usage of the system does not impose major physical strain on the users. Analysis of the data acquired indicates that we can be 95% confident that the general population will report a maximum of 4.08 fatigue level on a scale from 1 to 10.
7. A positive relation was found between the amount of time a user uses the system with the fatigue level they report, especially when users are required to perform often the mouse click gesture.
8. The gestures' vocabulary is easy to learn.
9. High success rates (at least 72%) can be achieved for navigating in the virtual world through gestures for any user population.
10. Users' efficiency in using the gestures to navigate in the virtual world improves over time.

Therefore, it can be concluded that the following hypothesis are confirmed:

H1. The system can be used effectively in the envisioned context of use to serve the needs of monitoring a large data centre room (conclusions 1, 3 and 9 above).

H3. Interaction with gestures is easy to learn (conclusions 8 and 10 above)

Regarding the second hypothesis, H2, that the system does not impose physical strain over users, it is 95% certain that users would rate their fatigue level as an average fatigue at most (conclusions 6 and 7 above).

Furthermore, the usability evaluation revealed six usability problems, four of which were classified as minor and two as major usability problems. The two major problems that were identified were that the system might occasionally stop recognizing user gestures, due to users' hand posture and hand anatomic details, as well as that handling drop-down menus could improve in terms of efficiency. In addition, the most appreciated features of the system were identified including the 3D representation, navigation in the virtual world with gestures, the overall user interface, the mini map and the criticality filters. Furthermore, the users' major dislikes were reported which were mostly originating from the problems they faced during their interaction with the system. Finally, a number of suggestions regarding features that users would like to be added into the system were acquired, namely direct access to a list with all the problems, a functionality for directly contacting other people to assign them problems to look into, as well as a "teleportation" functionality for directly navigating to a specific area.

Finally, the UX assessment indicated that participants found the showcased system to be innovative, engaging, and pleasant. Efficiency and dependability also scored a positive result, indicating that participants felt in general that they could solve their tasks with the product without unnecessary effort, as well as that they would feel in control of the interaction. The lowest score was received for learnability, indicating that participants would have concerns as to how easy it will be for a user to get familiar with the product. However, during the usability evaluation experiment the system turned out to score high in learnability. This difference in results is well justified, since the workshop participants had no previous experience in the system, while the system itself addresses regular users, a condition which was anticipated and controlled in the usability evaluation experiment.

10.2. Usability Evaluation of the Smart Museum system

A usability evaluation with end-users has been performed on the final version of the system, divided into two sessions:

- A typical observation experiment has been carried out, involving 21 users, aiming to assess the usability of the system and the user's immersion, followed by an interview.
- A UX assessment questionnaires has been delivered to the 21 users, with the aim to evaluate their overall impression and subjective view regarding their experience from the system.

The two evaluation approaches are complementary and each is aimed at assessing different attributes of the system. More specifically, the observation of users while using the system aimed at revealing potential usability problems, evaluating the effectiveness and efficiency of the system, assessing the interaction techniques and their learnability and retrieving explicit user feedback about likes, dislikes and potential suggestions through a semi-structured interview. However, another important parameter that should be studied for the system is that of the overall experience and users' feelings from their interaction with the system. This was achieved through the questionnaires the users answered after the end of the evaluation process. Literature has indicated that involving 20 users in a usability testing evaluation will find 95% of the problems of the system [131] [Figure 77, Figure 78 and Figure 79].

Figure 77: User standing while interacting with the system

Figure 78: User sitting during the interaction

Figure 79: User moving in space in order to examine the environment details

10.2.1. System setup

Usability testing involved 21 participants who used the system in a laboratory setup, resembling however the envisioned context of use. In more details, the system was deployed on a VR-ready laptop, placed in a quiet room. The laptop used for the experiment had an Intel i7-6700HQ processor @ 2.6 GHz, 32GB of RAM and an NVidia GTX 1070m GPU.

Users wore the Oculus Rift headset on their heads and used their hands to use the Oculus Touch controllers. The appropriate sensors (Oculus sensors, Kinect One sensor) were placed in front of the users in order to be able to track the headset as well as users' position. Users were allowed to sit on a chair (if they preferred to), which had been placed at a convenient position, or to stand in a position across the monitor in order to be inside the field of view of the sensors. Minor amendments were made to the placement of the chair, if needed, to better serve each individual user and the sensors where adjusted to each user's height. The users' surrounding area was clear of items and furniture which could obstruct the users' movements in space.

Participants were recruited with the aim to involve a uniform distribution of users with low, medium, and high expertise in interacting with software systems applied in VR environments. Given that the Information Worlds system does not target first-time users only, but depending to the context of use it can also be used on a regular basis by its target audience, it was important to involve experienced users as well. In total, the participants of the evaluation included:

1. 12 male and 9 female users
2. 5 aged between 20-30, 9 between 30-40, 5 between 40-50, 2 between 50-60
3. 10 users with small experience with VR systems (minimum familiarity/never used any VR system), 7 with medium experience (have used a VR system 2-3 times) and 4 with high experience (more than 4 systems)

Users' demographic information with reference to their gender, age, and expertise in VR systems is described in the figures below.

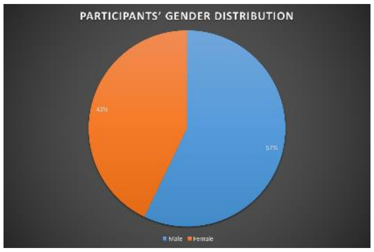


Figure 80 Usability test participants' gender distribution

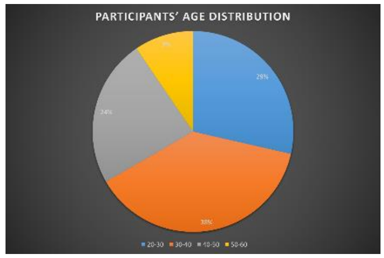


Figure 81 Usability test participants' age distribution

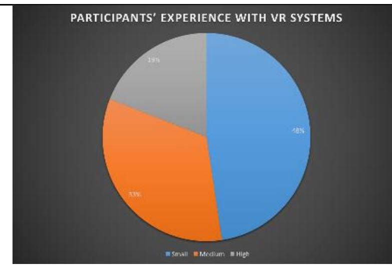


Figure 82 Usability test participants' experience with the motion sensor

The entire evaluation process was approved by FORTH's Ethics Committee [136], [14.7].

10.2.2. Usability testing through observation

The usability testing experiment held four main hypotheses that needed to be confirmed:

H1. The system can be used effectively in the envisioned context of use to serve the needs of interacting with Virtual Reality environments.

H2. Users were immersed in the virtual environment and felt present.

H3. The interaction with the system is intuitive and easy to learn.

H4. The system does not impose physical strain or fatigue.

Taking into account that the system addresses everyday users, and therefore users will be quite familiar with its features and functionality, the experiment comprised two phases:

A. **Acquaintance with the system**. Each participant was individually introduced to the system, explained all the functionality and interaction methods and was allowed to explore it through free interaction. Each acquaintance session lasted for about five to ten minutes.
B. **Usability evaluation**. Each user was asked to interact with the system following specific tasks, which were handed one-by-one. Additional details about the tasks, the process that was followed during the test and the results obtained are provided in the following section. Each usability evaluation session lasted approximately twenty to thirty minutes, with minor differences between users.

10.2.3. Usability evaluation session

During the usability evaluation session, the participants were asked to execute specific tasks while they were observed and notes were kept regarding specific problems, comments, the time on task, and successful execution of the task. Once they completed the test scenario, they were asked about their impressions on the system following a semi-structured interview approach [141]. Finally, they were requested to answer the questionnaires regarding their experience of interacting with the system. This section describes in more detail the tasks that were assigned to the users, the metrics that were recorded, the main contents of the semi-structured interview, the usability evaluation test process as it was followed, and the results and findings obtained.

10.2.3.1. Evaluation Process

The usability evaluation session involved the execution of a series of tasks, in the order given by the evaluator. The tasks revolved around a specific user scenario, according to which the user is a visitor of the FORTH’s ICS Ambient Intelligence (AmI) Facility having a demo tour of the developed systems and finally reaching the Virtual Reality (VR) area, where is introduced to a framework where can reveal information in virtual reality environments, simply by wearing the Oculus headset and dive into the Information Worlds system and starting the virtual tour from the AmI Facility.

10.2.3.2. Tasks

The following points present the tasks that constituted the entire evaluation scenario along with their aims:

- **Task 1:** Put on the VR headset and describe where you are and what you see.
  - Getting familiar with the Virtual Reality headset
  - Smooth absorption into the virtual environments
- **Task 2:** Given that you are interested in Crete, find a media gallery on the central television of the entrance of the Ambient Intelligence facility and explore the content there.
  - Identification of interactive elements
  - Small and medium distance travelling
  - Interaction with the Media Gallery Information Piece Template
  - Ability to locate information within the template
- **Task 3:** John suggests that you use the interactive system which allows to see yourself in front of various landscapes and is located in the big room to the right of the entrance. You are interested in Knossos Palace and you decide to see yourself there.
  - Long distance travelling
  - Location and recognition of specific interactive elements
  - Interaction and manipulation of the BeThereNow Information Piece Template
- **Task 4:** John informs you that there is extra information for the palace in the VR environment. Find the virtual world of Knossos and visit the throne’s room.
  - Usage of Information Worlds switching options
  - Identification and transition to a specific Information World
  - Identification and navigation towards specific Information Things
- **Task 5:** Visit the information world for the museum and find a 3D amphora there.
  - Switching across different Information Worlds
  - Recognition of certain Information Things
- **Task 6:** Find information regarding the big sculpture in the centre of the room (name etc.).
  - Detailed examination of Information Things
  - Information examination about certain elements
- **Task 7:** You are interested in ancient Rome so you decide to go to the next room and find where the ancient Pompeii was on the interactive map on the table.

  - Navigation to other rooms within users' virtual surroundings
  - Recognition of the Augmented Map Information Piece template
  - Ability to locate a certain place within the Augmented Map template
- **Task 8:** Complete your virtual visit by exiting this world. Navigate towards the lit area and describe what you are perceiving in this room.
  - Termination of the visit and switch to the post-visit Information World
  - Identification of the virtual mirror and exploration of the keepsakes generated by the system

It should be noted that all tasks were designed so as to have a clear ending condition (e.g., find a specific information, go to a specific room, or perform a specific interaction) and that all participants were asked to navigate to the same areas and perform the same actions.

Apart from the above tasks, all users had time to investigate the area of the virtual reality environment, visit other rooms and interact with other embedded applications such as Timeline [6.5.2.1] and Wordcloud [6.5.2.6].

10.2.3.3. Metrics

The following metrics were recorded during the usability evaluation session, using appropriate recording sheets [14.2]:

- **Success** in accomplishing the task, marked as (S) for success, (PS) for partial success, and (F) for failure.
- **Time** on task (in seconds) for all the tasks.
- Number of **tries** for all the tasks.

Additionally, handwritten notes were kept for users' comments and any suggestions which were provided by the users during their interaction with the system, as well as regarding the interaction flow, system errors, or other remarks that might lead to useful results.

10.2.3.4. Interview Questions

Following the scenario-based execution of tasks, users were interviewed to elicit their comments regarding the system, following a semi-structured interview approach. Semi-structured interviews are conversations in which the topics of the discussion are known before hand – therefore a preliminary set of questions can be prepared and used to guide the interview – but the conversation is free, and therefore it can be vary between participants [141].

The questions participants were asked were the following:

1. Do you have previous experience with systems in VR environments or the interaction controllers?
2. What did you like the most about the system?
3. What did you like the least about the system?
4. In which area could the system be applied in?
5. Would you prefer already existing tours in the environment, to investigate the area by yourself or a combination?
6. Would you like to save or share the souvenirs? In which way?

7. Would you like the system to be cooperative?
8. Do you have any suggestions for the system?

All the provided answers were recorded by the evaluator, through handwritten notes.

10.2.3.5. Main Experiment

Before coming at the evaluation area, the users were informed by email regarding the process of the evaluation [14.1] as well as the risks [309] that may take if they participate, stemming from the usage of the Virtual Reality headset.

As soon as users arrived at the usability evaluation room, they were welcomed and introduced to the evaluator and facilitator. The evaluator was responsible for steering the session, handing out the tasks one by one to the user, providing any explanations when appropriate, keeping notes and asking questions to the user. The facilitator was a technical person, responsible for setting up the system and assisting in adjusting the user's distance from the sensor if needed, as well as for recording the time required to complete a task, where appropriate and keeping extra notes.

After welcoming the user and after the user was introduced to the system during the acquaintance session, the evaluator proceeded with explaining the purpose of the evaluation and the process that would be followed, as well as the recordings (e.g., time in task, number of tries) that would be made during each task. It was clearly explained to users that it was the system that was being assessed and not the users themselves or their performance, and that they could stop the evaluation for any reason and at any time they wished during the experiment. They were also informed about the presence of a pathologist doctor in the area in order to help in case the participant did not feel well during the process.

Then, participants were handed out two copies of the consent form to sign. Both copies were also signed by the evaluator, and one of them was returned to the participant. In summary, the provided consent form described the system, the purpose of the evaluation and the evaluation process. It also informed participants that their participation was voluntary and can be withdrawn anytime, that they would not receive any reimbursement and that they would not have a direct benefit from the evaluation other than assisting in improving the system. In addition, it described how the participants' personal data are protected and provided contact details the scientific advisor of the evaluation.

Once the consent form had been signed by the participant, tasks were handed one at a time. The evaluator avoided answering questions and prompting the user as to how to proceed with carrying out the task. The only clarifications provided if needed by any of the participants were related to the description of the tasks themselves, in case they were unclear to the user. As each user proceeded with the task execution, the evaluator took notes on user comments, questions, and observations about the interaction that was taking place. Furthermore, the evaluator and the facilitator proceeded to the necessary metrics' recordings.

The interview and debriefing session followed the execution of tasks, allowing users to describe their overall experience with the system. Finally, participants were thanked for their time and effort and were moved to a different room with the help of an assistant to answer the questionnaires and treat themselves with provided finger food.

10.2.3.6. Findings and results

10.2.3.6.1. Tasks Findings

Users turned out to be very successful at accomplishing the tasks they were assigned with, based on the user success rate metric. Success rate is defined as “the percentage of tasks that users complete correctly” [305]. For each task, the user’s success is marked as (S) for success, (PS) for partial success, and (F) for failure. The total success rate is calculated by the formula:

*Success Rate = (TS + (PS * 0,5)) / Number of attempts*

TS is the total number of successful attempts, and PS is the total number of partial successful attempts. More specifically, for the evaluation of the Information Worlds system, the formula is produced as follows:

*Success Rate = (21 + (0*0,5))/21 = 1*

The detailed analysis of users’ success per task is presented in [Figure 83]. Successful task accomplishment is marked in blue, partial successful accomplishment in orange and fail in grey. It can be easily noticed that all the tasks had success by all users, which means 100% success.

Figure 83 Task success diagram for the user observation experiment

As indicated by the chart above, users completed all the tasks successfully. The chart below (Figure 84 and Figure 85) presents the mean time duration required in order to complete the corresponding task. Time distribution variations presented are mainly related to the task requirements, i.e. distance travelled and number of actions required. A slight increase noticed in the time and tries for accomplishing task 4 is related to a minor issue when users tried switching worlds in this specific case (the button containing the Knossos Information world could sometimes be successfully clicked on the second attempt).

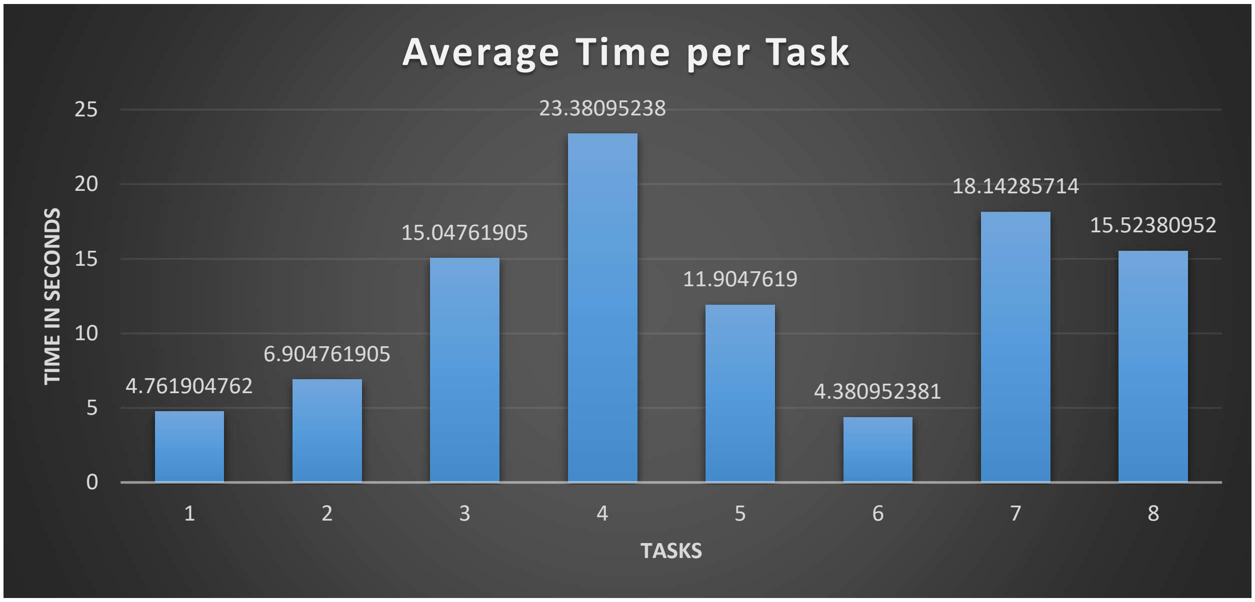


Figure 84: Average duration for users to complete a task

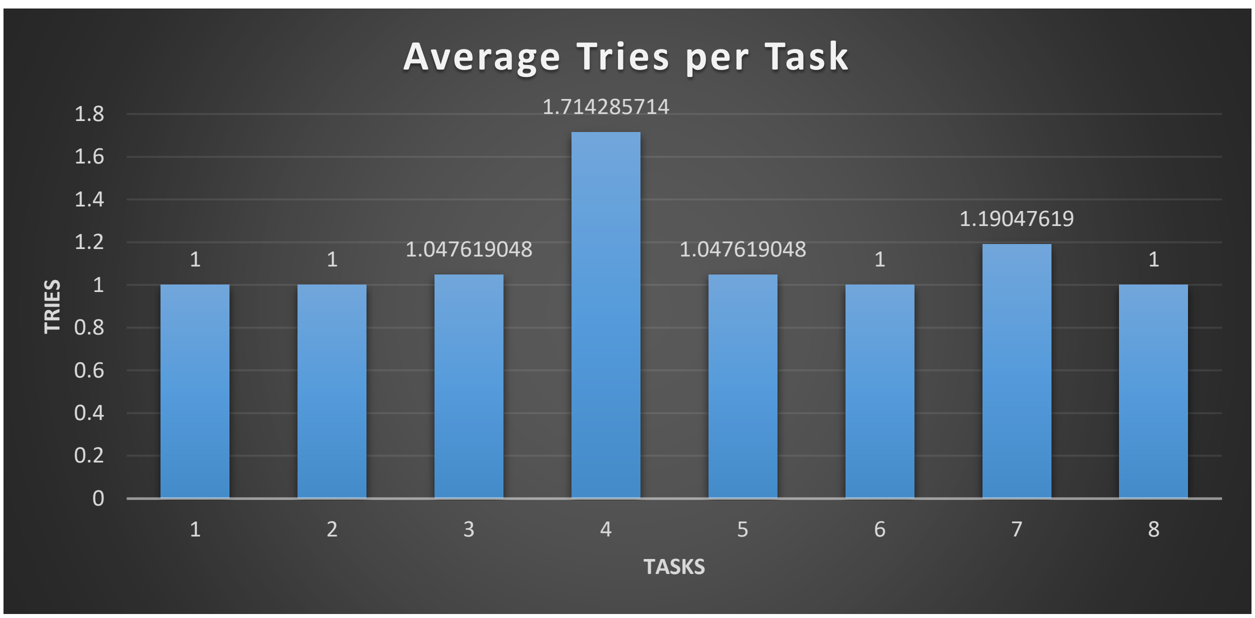


Figure 85: Average number of tries for users to complete a task

10.2.3.6.2. Findings stemming from structured interviews

After the completion of the application assessment, a structured interview took place between the user and the evaluator and the facilitator. During the interview, users were first asked to explain what they enjoyed more as well as negative aspects of the system. The negative aspects usually stemmed either from problems that they faced during their interaction with the system, issues that did not confine them from achieving the task but imposed some difficulty nonetheless or simple aesthetic preferences. Users' reported positive and negative feedback were initially filtered to create one unified set of positive and negative feedback to eliminate data duplication.

Then, the provided comments were combined with the evaluators' observations and were organized in a table making cross-references to the users involved, in order to locate any outliers. Finally, reported dislikes were filtered as to their impact, examining:

- The number of users who reported the issue
- The type of the issue (e.g. personal aesthetics, functionality problem, usability problem, etc.)
- Frequency with which the issue occurs
- The impact of the issue if it occurs, assessing if it will it be easy or difficult for the users to overcome
- The persistence of the problem, assessing whether users can overcome the problem once they know about it or will they repeatedly be bothered by it

In summary, the more appreciated features of the system were reported to be:

1. The **immersion** of being in a different environment.
2. **Interaction** provided - element selection and travelling in the virtual world.
3. The feeling of **control** over the system methods.
4. The information **visualization components** (Media Gallery, BeThereNow, Timeline, Wordcloud etc.).
5. The concept and implementation of **switching worlds seamlessly**.
6. The **teleportation gate**.
7. Teleportation via the "**point & click**" method.

Negative feedback was reported in a more sporadic manner, usually having users report as disliked the features that made it difficult for them to complete the tasks. These negative aspects have been combined with the evaluator's observations and are reported as issues in the following:

1. The visualization of the current **language** was ambiguous: the majority of the users (12 out of 21) thought it was the one virtually viewed in the controller on the language button area, but this one was the next available language in the raw.
2. The Mirror of Thoughts was not clear in terms of what it was representing.
    a. 13 out of 21 users did not immediately perceive the presence of a mirror in the virtual space. This was related to the fact that their reflection in the mirror appeared only when approaching it in the virtual space; also, due to the virtual room being empty without certain visuals elements (e.g. objects or even a floor with a tiled texture instead of a solid colour) did not assist them quickly noticing that the element was a mirror.
    b. 6 out of 21 users did not understand that the words referred to their visit.
    c. 2 out of 21 users did not understand that the framed pictures referred to their visit.
    d. 15 out of 21 users thought they could interact with the provided words/images.
3. Moving using the joystick made them often feel dizzy (motion sickness) – 4 out of 21 users; these users all employed the "point & click" method.
4. Flickering of small letters and images (4 out of 21 users). This issue had to do with the Oculus Rift device display resolution for elements that were placed further away from the users – upon approaching them, the elements became clear.

5. 3 out of 21 users stated that they would like a visual feedback of their hands/body in order to know where they are and have a clearer perception of what their physical hands should look like.
6. 8 out of 21 users stated their preference for controlling the rotation of the WordCloud3D rotation.

Another kind of user feedback had to do with mixed and contradicting optimal preferences. This kind of input was mainly subjective and varied according to each user’s preferences. An indicative example of such feedback involves user distance upon selecting an element: although all users were placed at the same distance towards the item in focus, user feedback was mixed as to what the optimal distance would be – the distance provided was reported as closer than needed, perfect and further away in an equal distribution. To this end, such feedback could not be used to improve the system as no concrete result is elicited. Mixed and contradicting reactions were noticed for users with regard to:

1. Gradual movement in Timeline: upon the selection of a timeline event, users were automatically travelled towards the expanding event in a smooth manner. In this case, this movement was reported as unwanted by 10 users, from which some felt dizzy, others uncomfortable as they were losing the control of themselves and wanted to be able to stop it.
2. Distance at which users were placed from elements: the distance provided was reported as closer than needed, perfect and further away in an equal distribution.
3. Design colours: even though the design colours of the evaluated application were generally accepted, certain elements received mixed reactions, such as the design of Timeline which was grayscale. 7 users enjoyed it, 12 found it okay and 2 did not like the fact that everything was grayscale.

Apart from positive and negative feedback, users were asked to provide their ideas and recommendations in order to improve the system and the resulting user experience. These answers that expressed (both while using the application – think aloud process – and through post-session interviews) were collected by the evaluator and are listed below:

1. **Object manipulation:** 3 users expressed their will to be able to manipulate 3D virtual objects using their controllers in order to be examined from different perspectives. Although this option is implemented and supported by the framework, it was not integrated within the virtual environments in the evaluation scenario.
2. **Help option:** the ability to retrieve assistance on demand was also mentioned so that they would be guided in terms of either providing recommendations for continuing their visit or accomplishing any tasks they have in mind (3 users out of 21).
3. Out of 21 users, 4 of them expressed their will for an improved user experience when **exiting Information Worlds**. According to the users’ rationale, the ending of their visit should be the most impressive part of their user experience and therefore expected a more exciting ending environment.
4. The presence of an **avatar** mapped with their body and moving in correspondence with their actions in order to increase embodiment was suggested by 3 users.
5. **More auditory feedback** was proposed by 3 out of 21 users in order to further improve their user experience and increase the feeling of presence.

6. The display of a **mini-map on demand** was suggested by 2 users so as to know where they are or to choose where to go.

Finally, all users concluded that the system could easily be applied in different domains and contexts of use, such as cultural heritage, games and entertainment, education, training systems, non-accessible places, in tourism and in architecture. Additionally, they stated that all the target groups can benefit from such systems and especially people with disabilities, who cannot easily visit and participate in such experiences in real life.

10.2.3.6.3. Travelling in space findings

As far as travelling is concerned, users were able to complimentarily use two different means for navigating in the virtual environments: using the joystick embedded in the Oculus Touch Controller and teleporting via “point & click”. These distinct methods were both provided to be used both exclusively, i.e. using only the preferred one, or combined and complimentarily, i.e. using both of them and switching between the provided methods according to the specific action they want to make – e.g. “point & click” for long-distance quick travelling and joystick for fine-tuning user position.

1. 8 users (38.2%) used only the “point & click” method. The users preferring this approach chose this option in order to avoid motion sickness, as the joystick made them feel uncomfortable. Moreover, these users felt that this travelling technique was sufficient to accomplish the required tasks and had no need to combine it with the usage of the joystick.
2. 6 users (28.5%) used only the joystick to navigate in the virtual environment. These users were not affected by motion sickness and preferred this method either due to having a gaming background (joystick and keyboard constitute a widespread method of travelling in gaming) or because they felt that their user experience was more fun and gamified.
3. 7 users (33.3%) combined both interaction methods, dynamically switching between them in accordance to their needs. These users could equally interact with both methods and employed the joystick either for fine-tuning or for free-moving in space. Moreover, “point & click” was mainly preferred for visiting specific elements, as this option allowed them to point at their element and directly examining it.

These findings indicate that no specific usage of the provided methods was largely preferred – users chose their means for interacting with the virtual environment according to their subjective preferences. In addition, the choice of navigation means was largely affected by the users’ feeling of control over the system and also involved the factor of gamification, given that the context of use was not a mission-critical application but was experienced from a more relaxed perspective.

Information Worlds also allowed users to switch from the different virtual environments on demand using two different metaphors: using the on-demand displayed curved menu and using the teleportation gates. In total:

- 7 users (33%) used only the gates to navigate between the different environments, consistently looking for them and even moving between the rooms to use the gate despite knowing how to display the available menu. The rationale of this approach involved two factors: firstly, users either felt that these gates acted as their “base” and point of reference for switching through the environment because they had seen them earlier, making them feel confident about their actions. The second factor affecting their actions had to do with the sense of gamification shaped by looking for the element that would allow them to perform an action instead of accomplishing the same result from a menu option.

- 5 users (23.8%) used only the menu to switch between the different Information Worlds and ignored the presence of gates. These users were mainly focusing on reaching the target environment and carrying out the assigned task.
- 9 users (42.8%) employed both the menu and the gates, according to their location: in case they were close to a teleportation gate they would use it for switching worlds, but if not, they would not look for it, but rather employ the menu.

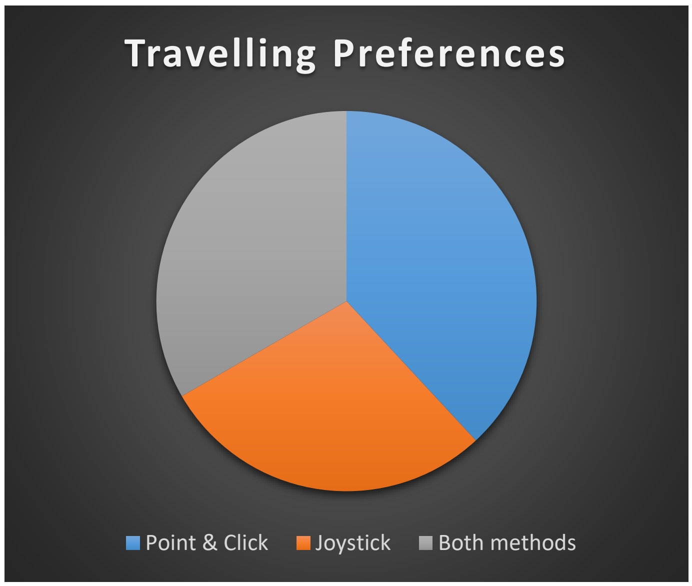


Figure 86: User preferences for travelling in Information Worlds

Despite the fact that gates are not a scalable option for the users to select from a large list of available options (as they occupy large space in the virtual environment and rendering a multitude of gates would clutter the display), the results indicate that they still proved a popular tool, as 76.2% of the users employed them for travelling between the different environments.

10.2.4. Usability and User Experience assessment

In order to assess User Experience, two types of questionnaires were created and filled in by end users. The following sections present the questions asked as well as the findings stemming from the answers provided. The usability questionnaire aimed at evaluating the feelings of presence and immersion, whereas User Experience focuses on capturing the feelings, impressions, and attitudes that arise after using the system.

10.2.4.1. Usability questionnaire

Presence and immersion were the areas of interest to be assessed with the presented questionnaires, as they constitute fundamental aspects of Virtual Reality applications and greatly affect user experience. Despite the fact that presence and immersion are closely related, as they both describe the extent to which the senses are engaged by the mediated environment [384], immersion has more objective characteristics, whereas presence is mainly a subjective metric [373 and 374].

A common issue which needs to be assessed involves the factor of cyber-sickness when using Virtual Reality systems. Cyber-sickness is a type of motion-sickness and refers to the process of users feeling discomfortable when using immersive systems. This is caused by the senses mismatch that the users' bodies receive: while users may receive input of their bodies being in a certain environment (e.g. vision and auditory input) and performing actions such as moving, their bodies in the physical world might not be moving; therefore, users' brains receive contradicting sensory input and react by generating the feeling of uneasiness. Such indicative cases include redirected walking exposures [182] and more passive user experiences such as rollercoasters experienced in Virtual Reality, which are assessed in terms of motion sickness by [100].

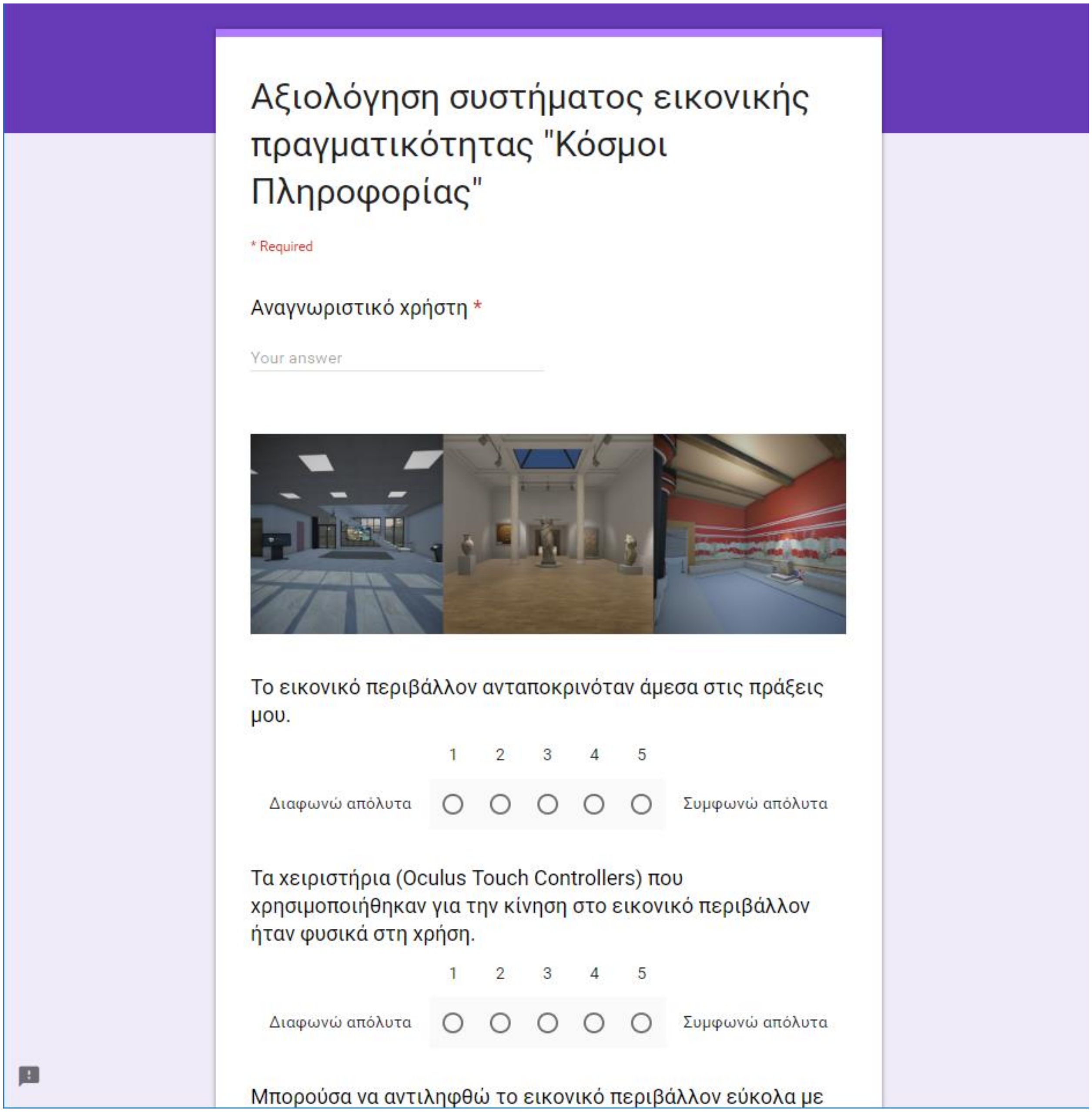
Virtual Reality applications immerse users into environments which are usually unaware of. Especially after prolonged usage and navigation further into the surroundings, a common problem rising is the sense of disorientation [348] and its assessment [49]. To this end, heuristics [306] are employed more recently by [296] in order to measure and assess via questions the users' level of orientation in space and familiarity with their surroundings.

The questionnaire in place is based on the questions presented by Tcha-Tokey et. Al. [399], by integrating a subset of the total questions presented with the accumulation of a few additional ones that were found as useful for the process of this evaluation. The main factors that gather the users' opinions are in general preserved were retrieved through a structured questionnaire and are the following:

1. **Immersion:** refers to the illusion that the virtual environment technology replaces the user's sensory stimuli by the virtual sensory stimuli.
2. **Presence:** the feeling of presence is defined as the experience of being in one place or environment even when physically situated in another [469]. Level of presence [363] is one of the major aims of all Virtual Reality applications as it constitutes an integral part of User Experiences and a driving force of improved User Experience.
3. **Engagement:** refers to the quality of the user experience and emphasizes on the positive interaction aspects and user motivation to use a system [255].
4. **Emotion:** encompasses the different feelings that users experience while using an application, such as joy, satisfaction, anxiety and disappointment. Achievement Emotions Questionnaire (AEQ) is an indicative assessment tool created for the evaluation of emotions during applications usage [329].
5. **Usability, Flow and Skill:** Usability refers to the ease of learning and using a system, while flow refers to the state of sense of control, fun and joy that users experience during interacting with a system. Finally, skill contains the knowledge the user mastered via experience in terms of performing certain activities.
6. **Experience Consequence:** includes all the post experiment symptoms that appear during or after using the Virtual Reality system, such as simulator sickness, headache, etc.
7. **Technology Adoption:** describes user intention to use similar systems in the future

The factor of judgement was excluded from the questionnaire, as it is closely related to the User Experience Questionnaire and constitutes a subset of the entire subjective User Experience questions.

Users were asked to give their answers on a scale from 1 to 5 (1 totally disagree, and 5 totally agree) [14.6]. The questionnaire has been divided in sections each of which has a set of questions that refer to a specific field of user experience. The questionnaire was provided as an anonymous secure online form which users could fill in at their own pace, while also allowing the straightforward answers export (Figure 87 below).


Αξιολόγηση συστήματος εικονικής πραγματικότητας "Κόσμοι Πληροφορίας"

* Required

Αναγνωριστικό χρήστη *

Your answer

Το εικονικό περιβάλλον ανταποκρινόταν άμεσα στις πράξεις μου.

	1	2	3	4	5	
Διαφωνώ απόλυτα	○	○	○	○	○	Συμφωνώ απόλυτα

Τα χειριστήρια (Oculus Touch Controllers) που χρησιμοποιήθηκαν για την κίνηση στο εικονικό περιβάλλον ήταν φυσικά στη χρήση.

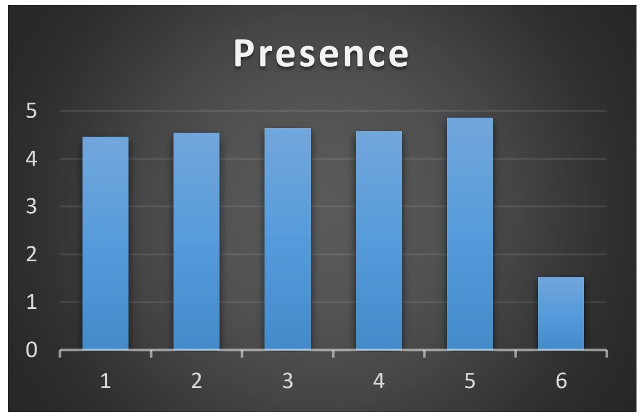
	1	2	3	4	5	
Διαφωνώ απόλυτα	○	○	○	○	○	Συμφωνώ απόλυτα

Μπορούσα να αντιληφθώ το εικονικό περιβάλλον εύκολα με

Figure 87: Aspect of the questionnaire which was filled in by the end users after the evaluation session

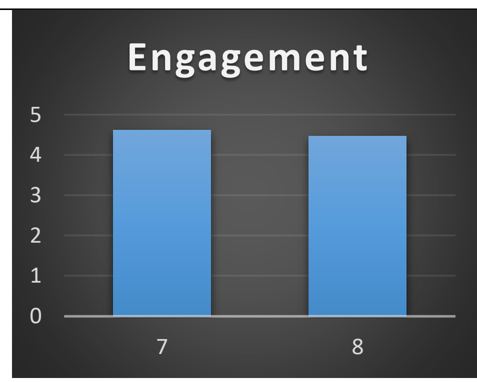
Presence is composed of the following questions and the results are shown on the chart below. As the results indicate, the users had the feeling of presence while using the system and interaction seemed natural. Despite this, still the control mechanism had a small impact on their feeling of being in the virtual environment, as it was considered a little distracting (question 6 – 1.5/5). Figure 79 is an indicative case where one specific user would almost kneel in order to examine the virtual environment and what lies below a virtual table.

1. The virtual environment was responsive to actions that I initiated.
2. The interaction devices (Oculus Touch Controllers) which were used for movement in the virtual environment seemed natural.
3. I was able to actively survey the virtual environment using vision.
4. I was able to examine objects closely/ from multiple viewpoints.
5. I felt proficient in moving and interacting with the virtual environment at the end of the experience.
6. The control mechanism was distracting.



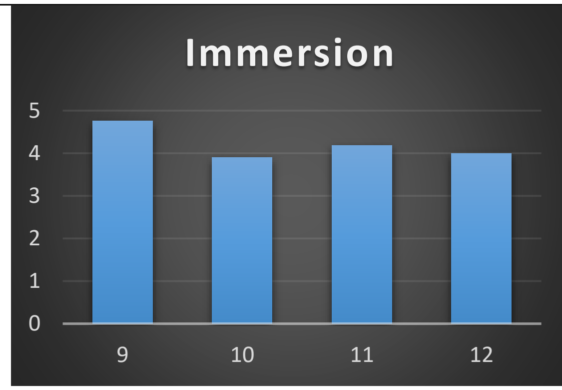
Engagement is composed of the following questions and the results are shown on the chart below. Users were involved and engaged with the system, enjoying moving and interacting with the virtual environment.

7. The visual aspects of the virtual environment involved me.
8. The sense of moving around inside the virtual environment was compelling.



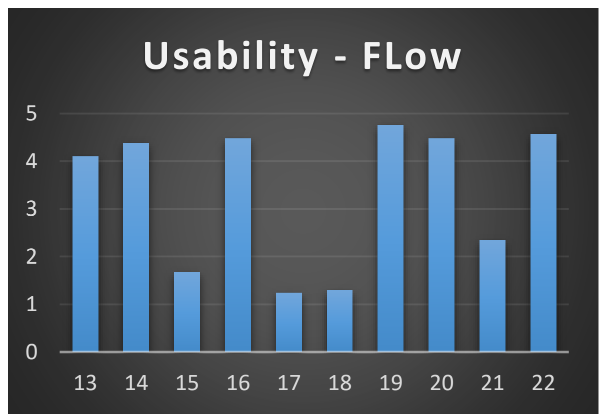
Immersion is composed of the following questions and the results are shown on the chart below. The results regarding immersion are very positive (mean value of 4.21 out of 5), but have still room for improvement. This can be achieved through improving all the graphical elements and 3D geometry with higher resolution/polygon count and further enhancing how photorealistic the environment is. Moreover, immersion could be improved by using wireless headsets and combining it with a moving floor so as to further immerse users into the virtual world by allowing them feel like they are physically moving in space while interacting with the system.

9. I felt stimulated by the virtual environment.
10. I became so involved in the virtual environment that I was not aware of things happening around me.
11. I felt physically fit in the virtual environment.
12. I become so involved in the virtual environment that I lose all track of time.



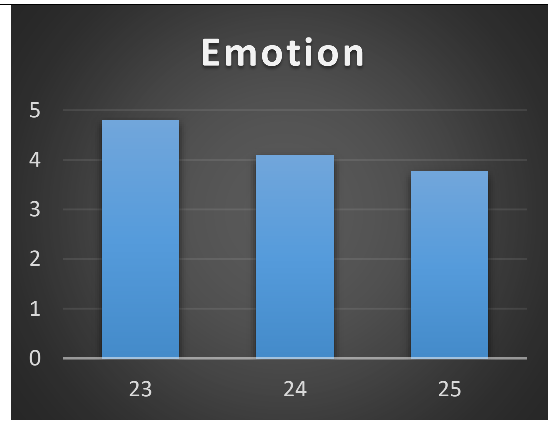
Usability & Flow are composed of the following questions and the results are shown on the chart below. In general, the values are positive (questions 15, 17, 18 have lower values as positives) in terms of user opinion. As indicated by question 21, some users found reading texts within the system problematic in the case the texts were not placed near them, due to the device display resolution.

13. I felt I could perfectly control my actions.
14. I felt I controlled the situation.
15. I thought there was delay between my actions and the expected outcomes
16. The movements were representative of the actions involved.
17. I thought there was too much inconsistency in the virtual environment.
18. I found the interaction devices (Oculus Touch Controllers) very cumbersome to use.
19. I felt confident using the gamepad and/or keyboard to move around the virtual environment.
20. I had the sense of orientation in the virtual environment.
21. I had difficulty reading texts within the system
22. I understood what the symbols near the information represented.



Emotion is composed of the following questions and the results are shown on the chart below. Users enjoyed being in the virtual environments and were generally excited by the user experience.

23. I enjoyed being in this virtual environment.
24. It was so exciting that I could stay in the virtual environment for hours
25. I found my mind wandering while I was in the virtual environment.

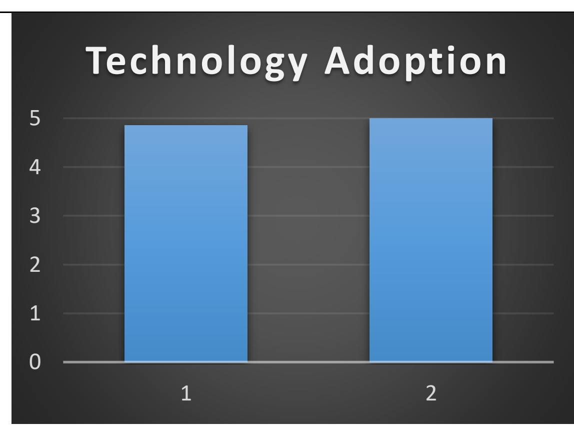


Experience Consequence is composed of the following questions and the results are shown on the chart below. Despite the fact that in general experience consequences are still present (mean value of 1.48/5), it can be stated that this element is not a factor that pushes back technology adoption.

26. I suffered from fatigue during my interaction with the virtual environment.
27. I suffered from eyestrain during my interaction with the virtual environment.
28. I felt an increase of my sweat during my interaction with the virtual environment.
29. I suffered from nausea during my interaction with the virtual environment.
30. I suffered from vertigo during my interaction with the virtual environment.

Technology Adoption is composed of the following questions and the results are shown on the chart below. The results are excellent and indicate the high potential of the technology used for showcasing Cultural Heritage content.

31. If I use again the same virtual environment, my interaction with the environment would be clear and understandable for me.
32. Learning to operate the virtual environment would be easy for me.



10.2.4.2. User Experience Questionnaire

The User Experience Questionnaire (UEQ) [246], also available in 14.4, was used to capture user impressions. This questionnaire allows a quick assessment of the user experience of interactive systems as it supports users to immediately express feelings, impressions, and attitudes that arise after their interaction with a system. It contains the following 6 scales with 26 items:

- Attractiveness: Overall impression of the system. Do users like or dislike it?
- Perspicuity: Is it easy to get familiar with the product? Is it easy to learn how to use the product?
- Efficiency: Can users solve their tasks without unnecessary effort?
- Dependability: Does the user feel in control of the interaction?
- Stimulation: Is it exciting and motivating to use the product?
- Novelty: Is the product innovative and creative? Does it catch the interest of users?

Each item in the questionnaire has the form of a semantic differential, i.e., each item is represented by two terms with opposite meanings, for example: Attractive – Unattractive. The order of the terms is randomized per item, i.e., half of the items of a scale start with the positive term and the other half of the items start with the negative term and a seven-stage scale is used to reduce the well-known central tendency bias for such types of items. So, the items are scaled for -3 to +3, with -3 representing the most negative answer, 0 representing a neutral position, and +3 representing the most positive answer.

Example:

attractive	○	⊗	○	○	○	○	○	unattractive

This response would mean that you rate the application as more attractive than unattractive.

Of the 6 scales, *Attractiveness* is a pure valence dimension, while *Perspicuity*, *Efficiency*, and *Dependability* are pragmatic quality aspects (task and goal-oriented), and *Stimulation* and *Novelty* are hedonic quality aspects (not task or goal-oriented).

10.2.4.2.1. Process

After interacting with the system and the mini-interview with the evaluator, the participants were asked to fill in the questionnaire in a different room at their own pace. The results stemming from the filled in questionnaire are presented in the following section.

10.2.4.2.2. Results

A total of 21 people answered the questionnaire. The results from the questionnaires are depicted in the Tables below. Table 5 and Table 6 respectively show the collective mean averages per scale. Values between -0.8 and 0.8 represent a neutral evaluation of the corresponding scale, values >0.8 represent a positive evaluation and values <0.8 represent a negative evaluation. The range of the scales is between -3 (horribly bad) and +3 (extremely good). As indicated by the results captured, the system had high scores in the attractiveness and hedonic qualities scales as well as the pragmatic ones.

More specifically, the *Attractiveness*, *Stimulation*, and *Novelty* scales all received positive scores from 2.3 to 2.73. These scores are an indication that the participants found the showcased system to be innovative, engaging and pleasant. The pragmatic scales, *Perspicuity*, *Efficiency* also received high scores, 2.57 and

2.44 accordingly (Figure 88). On the other hand, *Dependability* received the lowest score, 1.78. Although this is a positive result, when isolating the subjects from the table below which refer to the *Dependability*, it can be easily concluded that the set which makes the difference and it is the question where users had to classify the system as an "unpredictable-predictable" one (Table 7).

Even though it is impossible to identify the exact rationale of this finding, it can be assumed that users may regarded "unpredictable" to refer to a good surprise and "predictable" having the meaning of being expected. So a possible explanation for this case is that participants decided to vote for the modern, surprising feature instead of the old-fashioned one.

UEQ Scales	
Attractiveness	⇧ 2.730
Perspicuity	⇧ 2.571
Efficiency	⇧ 2.440
Dependability	⇧ 1.786
Stimulation	⇧ 2.536
Novelty	⇧ 2.345

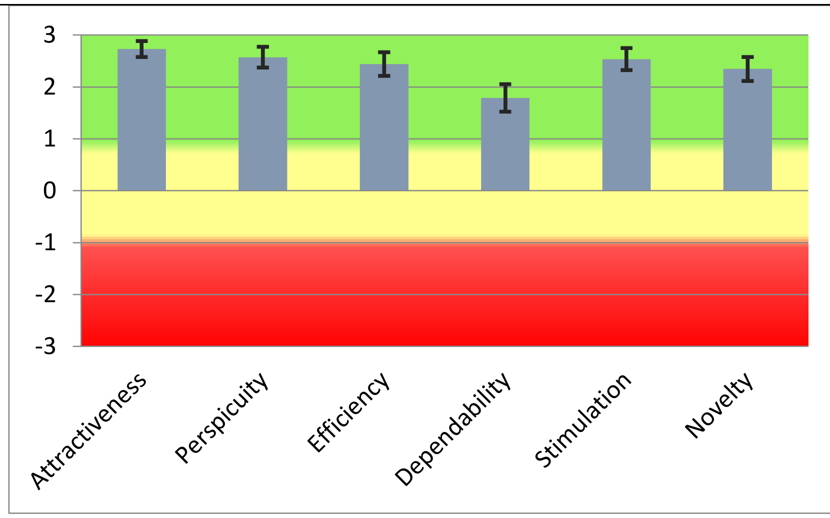


Table 5: UEQ Scales (left) and mean values (right)

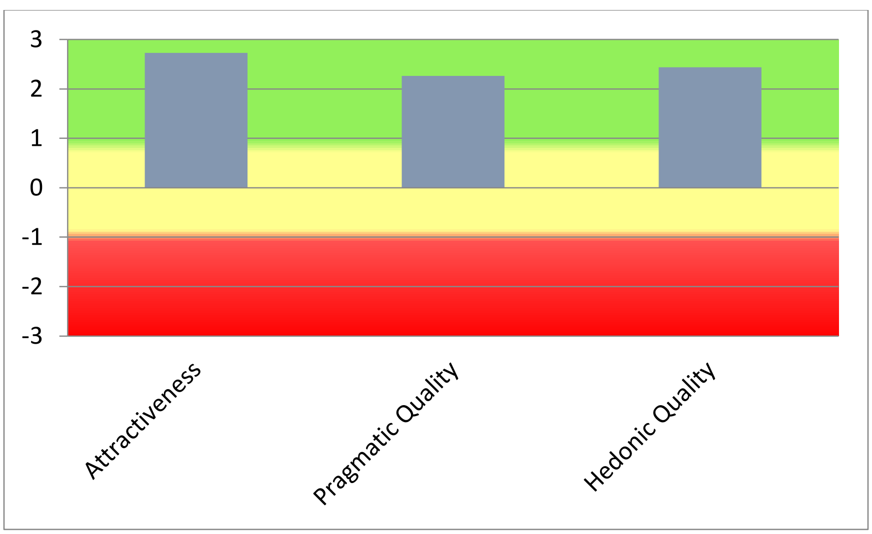


Figure 88: Pragmatic Quality

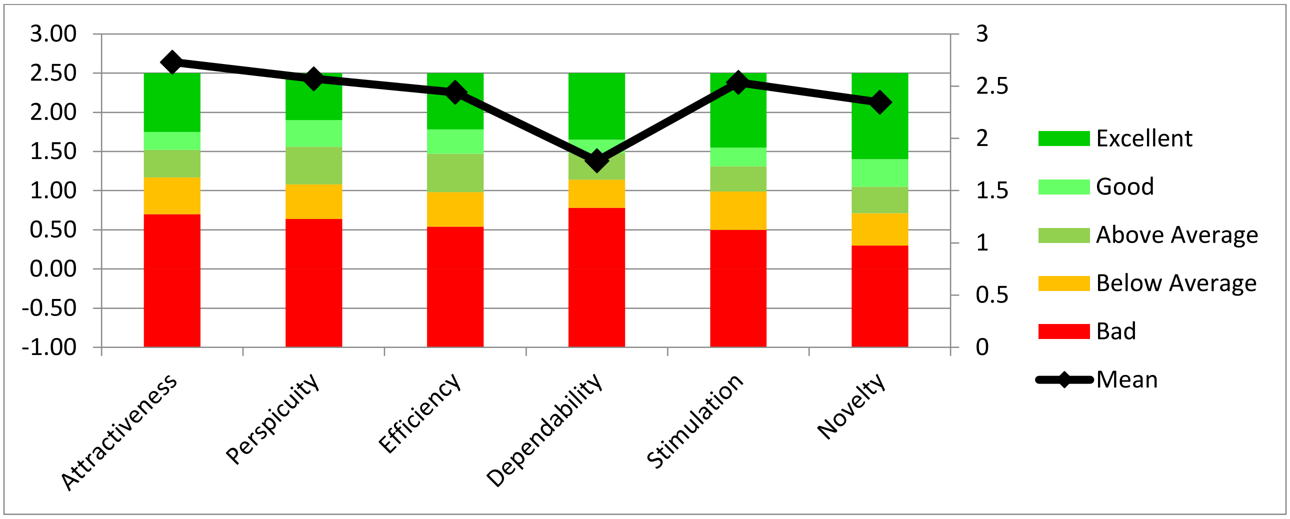


Table 6: The measured scale means are set in relation to existing values from a benchmark data set.

Item	Mean	Variance	Std. Dev.	No.	Left	Right	Scale
1	⇧2.4	0.7	0.8	21	annoying	enjoyable	Attractiveness
2	⇧2.4	0.5	0.7	21	not understandable	understandable	Perspicuity
3	⇧2.3	0.6	0.8	21	creative	dull	Novelty
4	⇧2.8	0.2	0.4	21	easy to learn	difficult to learn	Perspicuity
5	⇧2.4	0.7	0.9	21	valuable	inferior	Stimulation
6	⇧2.4	0.5	0.7	21	boring	exciting	Stimulation
7	⇧2.7	0.3	0.6	21	not interesting	interesting	Stimulation
8	⇨0.1	3.1	1.8	21	unpredictable	predictable	Dependability
9	⇧2.2	0.8	0.9	21	fast	slow	Efficiency
10	⇧2.0	0.8	0.9	21	inventive	conventional	Novelty
11	⇧2.2	0.7	0.8	21	obstructive	supportive	Dependability
12	⇧2.9	0.1	0.4	21	good	bad	Attractiveness
13	⇧2.4	0.5	0.7	21	complicated	easy	Perspicuity
14	⇧2.8	0.2	0.4	21	unlikable	pleasing	Attractiveness
15	⇧2.6	0.4	0.6	21	usual	leading edge	Novelty
16	⇧2.8	0.2	0.4	21	unpleasant	pleasant	Attractiveness
17	⇧2.3	0.6	0.8	21	secure	not secure	Dependability
18	⇧2.6	0.3	0.6	21	motivating	demotivating	Stimulation
19	⇧2.6	0.4	0.6	21	meets expectations	does not meet expectations	Dependability
20	⇧2.3	0.8	0.9	21	inefficient	efficient	Efficiency
21	⇧2.6	0.3	0.6	21	clear	confusing	Perspicuity
22	⇧2.6	0.4	0.6	21	impractical	practical	Efficiency
23	⇧2.7	0.2	0.5	21	organized	cluttered	Efficiency

24	⇧2.8	0.2	0.4	21	attractive	unattractive	Attractiveness	
25	⇧2.8	0.2	0.4	21	friendly	unfriendly	Attractiveness	
26	⇧2.5	0.4	0.6	21	conservative	innovative	Novelty	

Table 7: Results of the UEQ per question. (Measures mean, standard deviation and variance)

10.2.5. Conclusions

This chapter presented the findings of the usability evaluation that took place in order to assess an application built with the framework presented in this dissertation, Information Worlds. The evaluation process followed a two-step approach aiming to assess different aspects of the system:

1. Firstly, a usability evaluation experiment involving 21 users was conducted, in order to evaluate the effectiveness and efficiency of the users while using the system. Moreover, another aspect of the application presented to the end users involved interaction learnability, as well as evaluating whether the system imposes any physical strain on the end users.
2. Secondly, a User Experience evaluation by handling two types of questionnaires. The first questionnaire was aimed to retrieve user feedback classified in five main categories, namely attractiveness, perspicuity, efficiency, dependability, stimulation and novelty. On the other hand, the second questionnaire was formed so as to measure user presence, immersion, emotions, usability, experience consequence and technology adoption of the system. Both questionnaires were retrieved by all the 21 participants.

The analysis of the findings of the evaluation process were presented in the previous sections of this chapter thoroughly. The insights derived from the evaluation experiment can be summarized in the following points:

Analysis of the results of the usability evaluation experiment indicated the following conclusions:

1. High success rates can be achieved even for the most complicated tasks and for any user population in Virtual Reality environments; all users were able to successfully carry out the assigned tasks within the expected time.
2. Having prior experience with VR environments or with the controllers affects user performance. Even though this an expected outcome, this does not contradict with users' ability to efficiently interact with the virtual environment; on the contrary, it indicates that the evaluated system is effective in terms of learnability.
3. The technology used appears to have sufficiently matured and be ready to be adopted across all user ages. This is evident not only on users who had previous experience with Virtual Reality systems but also by new users, especially when taking into consideration the excellent results reported both in the assigned tasks and the technology adoption questions.
4. By consensus, the most important piece of the system is the idea of being in a different world and to feel like you are in it for real (immersion).
5. Navigating from one world to the other proved to be one of the most fascinating features of the system. The entire framework concept was based on the concept of various virtual worlds that are connected with each other; therefore, this finding proves not only that these connections did

not prove to act as a burden in conceiving the concept, but users enjoyed the navigation process and the flexibility they had to freely focus on their virtual world of interest.

6. The usage of the system does not impose physical strain on the users. Virtual reality systems are still maturing and consequently physical strain is still an aspect under investigation, as it does not only affects user experience negatively, but can also be a factor which would override any large-scale adoption potential.
7. Interaction and navigation is easy to learn. Users were capable of moving and interacting even within the training environment almost immediately after the interaction methods they were presented with the basic instructions.
8. High success rates can be achieved for navigating in the virtual world using the interacting controllers across all user groups. Perfect success rates were measured for the tasks assigned by all users, regardless of their age and experience with similar systems. Furthermore, despite the overhead of requiring an interaction device for the interaction process, users were not distracted by the controllers.
9. Users' efficiency in interacting in the virtual world improves over time. Users not only performed their actions better over time, but also felt more confident – this fact was noticed both from their expressions and from their interaction with the system.
10. The system can be applied in various contexts. All users unanimously stated during the structured interviews that they would like to experience the concept of Information Worlds adapted to different contexts, such as the industry, training simulation and education.

Therefore, it can be concluded that the following hypothesis are confirmed:

H1. The system can be used effectively in the envisioned context of use to serve the needs of interacting with VR context aware environments (as indicated from conclusions 1, 5, 7, 8, 9 and 10 above).

H2. Users' immersion with the system is satisfied (conclusions 3 and 4 above).

H3. Interaction is easy to learn (conclusions 2, 5 and 9 above).

H4. The system does not impose physical strain or fatigue over users (conclusion 6 above).

Regarding the fourth hypothesis, H4, that the system does not impose physical strain over users, it is concluded that 95% of the participants would rate their fatigue level as a light fatigue at most. Only 1 out of 21 complained about his hand.

Regarding the second hypothesis, H2, it is also remarkable that 10 out of 21 users after removing the headset at the end of their experience felt disappointed being back to the real world. Only one stated that preferred the real world instead the virtual; on the contrary, all other users were at least satisfied from their experience and enjoyed exploring the virtual environments.

Furthermore, the most appreciated features of the system were identified including the virtual surroundings, navigation in the virtual world using teleport, the immersion of being in a different environment, the control they felt to have and the overall user interface and information visualization.

On the other hand, the usability evaluation revealed some usability issues, three of which were classified as minor, due to their frequency or to device constraints, and two as major usability problems. The two major and most common issues that were identified involved the language button and the virtual mirror placed in the post-visit Information World.

Moreover, a number of suggestions regarding features that users would like to be added into the system were acquired, namely being able to manipulate 3d items, having help option, a more impressive ending of their virtual visit, an avatar mapping with their body/hands, more auditory feedback and a mini-map to know their exact location in the virtual space.

Finally, the user experience assessment indicated that participants found the showcased system to be immersive, innovative, engaging, pleasant, learnable and efficient. Dependability also scored a lower, but positive result, indicating that participants felt in general that they could solve their tasks with the product without unnecessary effort, as well as that they would feel in control of the interaction. As indicated by the results that are analysed as very positive, the evaluated system had excellent values for technology adoption and presence, whereas immersion could still further improve.

11. Potential Impact

This research work aims at having a significant impact on different aspects of information visualization across various domains using Augmented, Virtual and Mixed Reality. In order to achieve this, a generic purpose concept was designed and implemented, contributing scalable information modelling techniques and adopting novel technological means of presentation. The following sections present the outcomes of this work in terms of the potential impact that may have on the domains targeted.

11.1. Facilitating cross-domain Information Visualization

The use cases presented in chapter 9 aimed to outline the framework's potential to efficiently visualize large volumes of information. The illustrated aspects of the design and visualization process illustrate the ability of the framework to offer:

- **Cross-domain application**: dissimilar domains can be efficiently visualized, covering domains such as Big Data, real time environment monitoring, tourism and cultural heritage presentation, semantic information visualization, world simulations and education. Moreover, the framework can be equally used for less demanding domains, such as marketing, advertisement, architecture and healthcare.
- **Scalability of the mental model and architecture:** the framework allows the addition of extra worlds and components on-the-fly.
- **Appropriateness for varying information types:** the framework is able to represent a wide series of information types, ranging from highly interconnected entities to elements whose data change at high velocity.
- **Variety of contexts of use**: applications built with the framework are suitable for usage within different contexts, such as everyday working environments, Cultural Heritage institutions and public spaces in general, education.
- **Promotes access to unavailable physical locations**: provides virtual access for users to experience areas which may be inaccessible due to physical environments restrictions, such as Cultural Heritage sites.
- **Extendibility and scalability:** the employed information categorization and presentation model can be extended straightforwardly, as new components can be developed and incorporated.
- **Customizable Visualizations:** the provided templates can be adjusted to the aesthetic expectations of visualization creators, covering diverse design requirements.
- **Natural multimodal interaction:** users interact with systems developed by the framework using a variety of methods, including touch, gestures and movement in space.
- **Data Sparseness Independent:** as illustrated in the two use cases, the framework is able to visualize information which is located relatively sparsely (museum) or is congested within a room (data center).
- **Real-time content:** Information displayed on applications created with the framework can be changed at runtime, suiting the needs of real-time adaptation to the user's interests.

- **Various data sources:** the framework supports the addition of various input sources, ranging from strictly defined relational and non-relational databases which are accessed over the network to semantic information representation models, such as ontologies.
- **Interactive narratives visualization**: stories and narrations can be structured and presented, assisting Visualization Creators to construct the visualization and users to perceive it. Moreover, users are allowed to choose their own information exploration path.
- **Wide User Group Coverage**: the needs of various user group types are covered by the provided ones, covering expert and novice users.
- **Adaptation to content**: input data can be diverse in terms of nature and have different characteristics (e.g. semantic information using ontologies or large data volume that changes with high velocity).
- **Adaptation to devices**: the resulting applications are automatically configured to suit the needs of the display device used (Augmented Reality, Virtual Reality, large scale displays).
- **Integration within Ambient Intelligence environments**: the framework's architecture aims at facilitating Ambient Intelligence through interoperability with existing systems and services.
- **Personalized Visualization**: information is tailored to the needs of the user's profile, allowing the profile creation either before or during interaction.
- **Support for various display technologies:** the framework visualizes 3D environments targeting Augmented Reality, Virtual Reality and large, high resolution displays.

11.2. Efficient and extensible application creation

The framework facilitates the creation of virtual environments which either augment existing locations or construct an entirely virtual world with high flexibility. To this end, visualization creators can create the virtual surroundings without restrictions, simply choosing from the supplied components to integrate within the final application.

Given that no framework is capable of covering all visualization needs, the modular architecture employed ensures the scalability required in order to be extensible for other visualization components to be integrated straightforwardly. The framework's core components (reused by other elements) are distinguished from the data sources, keeping in turn the elements used for content visualization orthogonal to both the engine's internal implementation and to the final data sources. Therefore, supplementary visualization components can be created and added, while also providing the required elasticity to developers to implement custom variations of the individual components.

Finally, the main framework outcomes are scalable, device-independent and therefore compatible with technology evolution, providing a flexible way to address future challenges. Visualization devices that facilitate Augmented, Virtual and Mixed Reality have the potential not only to provide immersive user experiences and insightful visualizations, but also to boost the economic potential of applications created by frameworks such as the Information Worlds.

11.3. Low-cost application creation and deployment

The presented framework aims to create applications which provide immersive user experience at a reasonable cost. Therefore, the sensory equipment currently used do not exceed in cost the price of 1500 euros for the Virtual Reality applications, while also being compatible with commercially available smartphones that users already own. As a result, the outcomes of this framework can be easily deployed in various settings.

As far as software is concerned, the costs of creating applications is minimized through software component reusability, compliance with knowledge representation sources and device-independence application creation.

11.4. Areas of contribution

This research work aims at having a significant impact on interactive data visualization across a multitude of domains, facilitating efficient and rich in terms of user experience information perception by proposing a scalable model which employs 3D visualization environments. This can be achieved through the various ready-to-use components that allow rapid virtual world creation, while also ensuring compatibility with a multitude of data sources.

In addition, the approach described in this research work aims to assist data experts provide insights to non-expert users by providing a model which is suitable for a plethora of input data types and contributing the necessary tools for enhancing data presentation, improving the visualizations for the citizens. The following domains are representative of the potential utilizations of this research work in various sectors and research fields.

11.4.1. Research outcomes in-the-wild

As far as Big Data visualizations are concerned, the Data Center Infrastructure Management use case was exhibited to the public in a full-day workshop attended by more than 80 administrators and faculty belonging to the sector of public safety.

Mixed reality installations have taken place out in-the-wild through the installation of the BeThereNow! component, adapted to also provide user photographs which can be distributed via email. The deployed applications are installed in airports via the Creative Crete initiative, tourist info-points (in Heraklion and Hersonnisos), temporary exhibitions such as ITB Berlin Travel Show and Cultural Heritage institutions such as the Natural History Museum of Crete and Teloglion Foundation of Art A. U. Th. [Figure 89].

Figure 89: BeThereNow! at Teloglion Foundation of Art A.U.Th. (Thessaloniki-Greece)

A modified version of BeThereNow! was demonstrated during Techn-e-ology 2018 [Figure 90] where the system was installed in a cave setup. In this setup, three projections (each accompanied by a Kinect sensor) surrounded users producing an immersive experience in which users could watch themselves being immersed in different art creations of a specific painter concurrently.

Figure 90: BeThereNow! at Techn-e-ology 2018, Heraklion Crete, Greece

Virtual Reality outcomes of this work related to Cultural Heritage have been showcased in various public events. The Object Manipulator component was demonstrated in 82nd Thessaloniki International Fair 2017 [Figure 91], international conferences including Smart Blue City 2018 and HCII 2017 and University of Crete's Computer Science Department presentation to school students in 2017.

Figure 91: Virtual reality system for promoting Cultural Heritage in 82nd Thessaloniki International Fair 2017

Moreover, this work was also presented other events providing fully functional simulated spaces augmented with interactive information but showcasing the entire concept of Information Worlds. Such examples are in the Human-Computer Interaction International 2018 conference [Figure 94], the 83rd Thessaloniki International Fair 2018 [Figure 93], Researcher's Night 2018 [Figure 92] and University of Crete's Computer Science Department presentation to school students in 2018.

Figure 92: Part of the presented work introduced on Researcher's night 2018 Heraklion, Crete, Greece

Figure 93: Part of the presented work introduced on 83rd Thessaloniki International Fair,2018

Figure 94: Part of the presented work introduced on HCI International 2018 Exhibition on behalf of FORTH - ICS

11.4.2. Cultural Heritage

The Cultural Heritage domain constitutes a fundamental area of application for systems developed using the framework presented in this thesis. The Information Worlds framework is able to facilitate information provision in a range of real and virtual contexts, as it adds value when employed in-situ in institutions, such as museums and archaeological sites, but also facilitates the creation of virtual environments to access areas that would be otherwise inaccessible.

The feeling of immersion and presence is successfully experienced by users trying the systems generated using the framework. Thus, added value is generated and users are engaged in interacting with the created visualizations, facilitating intuitive presentation of complex information in a natural and easily perceivable manner. The framework provides the tools for enhancing the impact of digitized cultural heritage information, thus providing significant and measurable benefits to citizens, as they are able to experience rich multimedia content intuitively. Moreover, complex correlations between historic events can be illustrated efficiently and explained to end users.

Furthermore, the framework has the potential of attracting user attention towards cultural heritage institutions by exploiting new media as a means of enhancing otherwise static information; such an indicative example is the immersive cultural heritage environments using Virtual Reality [114]. Additionally, the presented research work provides alternate ways to experience cultural heritage information through personalized user experiences.

Finally, the provision of means to connect to semantic information in an automated manner facilitates the combination of rich visualizations via Augmented and Virtual Reality with rich data sources. This connection capability is currently able to selectively retrieve information from the provided data sources, but can be straightforwardly adjusted to generate visualizations on-the-fly, providing an entirely new world of interactive visualization exploration via fostering semantic relationships.

11.4.1. Education and Infotainment

Education constitutes another domain of application for the presented research work, as the framework is able to transfer knowledge shaped by visualization experts to the final end users. The presented approach constitutes an interactive solution which visualizes information in a playful manner, allowing them to selectively experience their areas of interest at will. The applications generated from the framework create worlds that encourage the exploration of existing or virtual environments, providing a personalized experience which is shaped partially by the predefined environment but also by user actions. Data is presented in an interactive and pleasant approach which promotes information perception. The applications created using the presented framework create a gamified experience, generating the feeling of presence and stimulating user interest while also presenting content in an appealing way. Such outcomes are evident when on aspects of this framework which are combined with Mixed Reality [120] and Ambient Intelligence [327] infrastructure.

An indicative example of this research work involves rich 3D visualizations which, in the context of archaeological sites, can be employed for the representation of ancient environments, providing reconstructions that illustrate how the existing remains looked like when they were built. To this end, users and especially children can be immersed in virtual surroundings and have a historically accurate (given that it is generated in collaboration with archaeologists and museum curators) visual experience of environments they are unable to see in real life, such as everyday life in ancient cities.

Another fundamental characteristic of this research work is the ability of the framework to communicate messages in the form of narratives. Stories often contain multidimensional information which is perceived in an alternate manner by different user groups. Thus, expert users, such as educators and development experts, are able to define stories that implicitly prescribe ways of thinking, facilitating the tuition of complex processes such as analytical thinking or correlation of events with practical examples. Therefore, when for instance creating a visualization for physics laws, the way that various theorems are entailed can promote constructive thinking and lead to analytical deductions. Additionally, the personalization of each view assists shaping the information in correspondence with the knowledge background of each user group: the way that physics are explained to a young child is totally different from the one used for a grown-up child. Although the concepts remain identical, the explanations of the phenomena must be adapted to the needs and the maturity of the viewer.

11.4.2. Big Data visualizations

Big Data visualizations are currently mainly examined visually from the perspective of analytics via dashboard visualizations. This research work provides a supplementary visualization to foster perception of complex environments without cognitive effort while providing an interaction technique which exploits the 6 degrees of freedom in order to proficiently manipulate navigation in 3D environments.

The presented case study involving infrastructure management in the case of a data center monitoring scenario showcases the potential using Augmented and Virtual Reality visualizations to manage massive data volumes which rapidly change throughout time. Data center rooms consist of a multitude of information about servers densely located with each other. As a result, in addition to performant data retrieval and rendering, flexible visualizations are essential so as to visually present information intuitively and also alert users about raised events in real time. The rich interaction methods provided allow users to intuitively and efficiently manipulate the 3D environment, thus facilitating every day usage in a professional context.

In addition to the data center use case, another domain of application in which the framework can equally operate and apply is Internet of Things (IoT). The IoT domain includes the hardware infrastructure that makes environment sensing feasible, middleware components which receive and store the values provided by the sensors and visualization components which present tools to understand and interpret the values. In a more general consideration, IoT networks can depict components which are interconnected and combined to create ecosystems of smart entities, such as the context of smart cities. IoT visualizations are composed by displaying networked entities with the data they are hosting. In addition to more typical components, such as charts, graphs and maps, virtual and augmented 3D environments can be employed to visualize large data volumes. A contribution of this research work in the domains of Big Data and IoT visualization is the users' first-hand ability to straightforwardly perceive the overview of the ecosystem, even if they are not familiar to its structure. As presented in the context of smart cities [47] and data center infrastructure management [209], Virtual Reality has the potential to contribute to this domain complementarily to any traditional 2D visualizations such as dashboards. Finally, the relationships between the individual entities can be presented in accordance to their physical location in space, but also on a higher abstraction layer, illustrating any potential data associations.

11.4.3. Other areas of application

This research work aims to contribute a generic purpose approach that is capable of matching complex scenarios, correlating diverse and multivariate information in a single model. However, it can also be used as the basis for also presenting simpler forms of information interactively.

Each Information Piece Template can be even used as a standalone application where the components are the showcased features, applying to a multitude of diverse domains. Such an indicative example is the Object Manipulator [6.5.2.5] which can showcase any type of 3D model, allowing users to examine it in great detail in an engaging and photorealistic environment; therefore, domains such as marketing and advertising can directly capitalize on the immersive user experience and natural interaction provided by the end application.

Another sector which can benefit from the presented framework involves the manufacturing and product assembly process [32]. Manufacturing refers to the process of transforming raw materials and information into finished commodities with good value-added for the satisfaction of human needs [302]. It evolves from the design and prototype stages, which is nowadays usually performed in computer-based CAD systems, to ultimately reach production phase. The final production units can be augmented with information, showcasing their various sub-components, explaining fabrication device functionalities and potentially previewing the final products. Augmentation can be facilitated by the presented framework, as it has the ability to present information in a context-sensitive environment. The framework can be applied for every step of the design and manufacturing process, from the initial sketches to real time assistance while in production. The framework can be firstly used for previewing items that compose the final product in the production environment. Furthermore, it can be used for employee training, providing information perception in a virtual or real world, according to circumstances.

The framework can also be employed for the manufacturing of customized components. While the case of mass production of the same item involves the same steps, customized objects require differentiated tasks, which employees may be unaware of. Thus, augmented reality can assist the production by previewing the final items or explaining step details. Moreover, the narratives can be used as a form of tutorials that analytically explain the various steps to accomplish the desired results.

11.5. Lessons learned

The results stemming from this work can also be used by other researchers in the domains of X-Reality, especially regarding the evaluation conducted in chapter 10. These results can be taken into consideration by future efforts that are closely related to this work in order to build upon the approaches that were implemented and assessed by end users.

The conclusions of the evaluation sessions for the Cultural Heritage [10.2.5] and the Big Data [10.1.4] use cases can be summarized as follows:

- The feelings of immersion and presence in virtual environments can be achieved with cinematography techniques and photorealistic rendering
- Small-sized text or text which appears at a great distance from the user should be avoided
- Despite the fact that certain approaches might not be scalable, they can be used as supplementary yet important tools which are embraced by end users (e.g. teleportation gates)
- Users should have the flexibility to switch among different available interaction methods
- Especially in the context of Virtual Reality, users adapt their means of travelling with respect to motion sickness and experience consequences when possible
- Virtual Reality constitutes an excellent approach to facilitate Cultural Heritage information visualization through enhanced user experience
- Virtual Reality can assist Big Data analytics via supplementary immersive visualizations
- Physical strain when using VR applications can be avoided when interaction is accurate and robust
- Gestures are engaging and easy to learn, providing unique user experience; however, they should be avoided in mission critical scenarios.

12. Discussion and next steps

Virtual, Augmented and Mixed Reality bear the potential of presenting information in an unprecedented manner by stimulating the feeling of presence and engagement in visualizations that typically extend on three dimensions. The challenges of visualizing information often referred as Big Data, namely with high volume, variety and velocity, require volatile and performant approaches which are able to depict complex and continuously evolving over time. Similarly, information variety in contexts like Cultural Heritage requires the creation of immersive visualizations which are however efficient in terms of interaction and scalable to support different data sources and content. Despite the certain drawbacks and limitations of VR, AR and MR, they have the potential to assist users in terms of enhanced user experience, improved human perception and reduced cognition effort required.

Despite the fact that the idea of merging real and virtual worlds is rather old, it is only recently that the supported hardware is mature enough to facilitate rich and immersive visualizations which are able to render complex environments in high resolution. Moreover, in addition to the touch screens and handheld controllers, computer vision based tracking has the potential to foster additional input methods allowing multimodal interaction. Many endeavors for creating VR, AR and MR systems have appeared, but were limited in scope or partial in terms of covering diverse data sources. Despite the fact that these systems often share characteristics or even entire components, little effort has been placed towards targeting an all-inclusive approach aiming to unify these seemingly different domains.

This research work aims to contribute a generic and holistic approach for generating applications substituting (Virtual Reality), enhancing (Augmented Reality) or interweaving physical and virtual worlds (Mixed Reality) in an effort to visualize large data volumes that belong to demanding domains such as Big Data or Cultural Heritage. Thus, the presented research work aimed to address the need for a framework that is able to provide:

- **Connection with external individual systems or environments**, such as Ambient Intelligence, necessary to add value to existing systems and present information put into context.
- **A modular architecture** supporting on-the-fly component replacements and additions in order to be flexible and adaptable to changes required by the various contexts.
- **Interoperability with diverse data sources**, including but not limited to ontologies and databases which provide content remotely.
- **A scalable and easily perceivable data model**, capable both to be diverse enough to match different modelling needs but also to be unbounded in terms of component additions. Thus, future extensions which are completely in line with the conceptual data model.
- **Reusable and extensible visualization components** able to present a multitude of information types and semantic characteristics, facilitating user engagement and producing immersive user experience.
- **Exploitation of the advantages offered by VR, AR and MR** in terms of user engagement and employment of 3D environments to assisting the perception of information.

- **State of the art interaction techniques** capable of providing efficient yet natural methods for travelling in the various surroundings, selecting virtual elements and manipulating showcased components.

This thesis has reported on the design and definition of a cross-domain framework providing a conceptual, knowledge representation and interactive visualization model. To this end, an in-depth study was conducted regarding state-of-the-art technologies in order to gain insights into research past steps and future directions. Data types and corresponding visualizations were analyzed, taking into consideration their domain of application, so as to identify the limitations of existing research work and establish the fields where AR and VR technologies can influence user experience and perception. In this direction, the proposed approach is capable of generating rich, interactive visualizations that suit information provided in various formats and originating from diverse sources. This is accomplished through an extendable collection of customizable ready-to-use templates able to present a wide range of information types and volumes. Furthermore, the proposed framework aims to cover a wide range of data volumes, ranging from a handful of entities to big data volumes. In order to illustrate the potential and the validity of the presented approach, a usage scenario of a smart museum is narrated in the cultural heritage knowledge domain. Cultural Heritage constitutes a demanding field of study consisting of highly interconnected entities with rich multimedia information, where entities create environments with sufficient visualization spaces. In addition, a data center monitoring use case is employed to reflect on the suitability of the framework as far as dense, highly evolving data is concerned. These dissimilar scenarios portray the ability of the proposed model to support disparate information and generate efficient visualizations which allow non-expert users perceive the presented information. Finally, the framework facilitates the creation and the interactive narration of stories personalized with respect to each user’s interests and characteristics. Stories are able to depict processes and flows, making them a fundamental tool for experts to exploit knowledge and document narrations about the connections of individual entities.

The excellent results reported in the evaluation performed illustrate the potential of AR, VR and MR in terms of efficiency and technology adoption by end users, but also constitute a motivation for further improving and extending the presented framework.

As far as evaluation is concerned, one of the next steps of this work involves the conduction of evaluation sessions with developers using and extending this framework and visualization creators constructing Information Worlds. In terms of interaction, an interesting assessment in terms of user interaction involves conducting an extensive evaluation study comparing the various interaction methods provided in order to gain interesting assess their advantages and drawbacks. In addition, such a study can provide valuable insights on the domains that would benefit more from each interaction technique, generating guidelines about the optimal approach accordingly.

An important future addition to the framework involves the integration of simultaneous localization and movement (SLAM) mechanisms able to fully support extended Augmented Reality functionalities, such as precise dynamic localization and robust way-finding. This feature will allow surroundings recognition and device localization, providing more accurate results and allowing end users to freely move in space in a more flexible manner.

Furthermore, the framework is capable of providing recommendations of input data a priori linked. Given the capability to remotely serve content in real time, an interesting future addition involves the integration of rule-based reasoning in accordance to users' actions, thus providing a more intelligent mechanism to provide recommendations.

Moreover, future efforts involve building upon user behavior analysis by the professionals who are involved in the creation of the applications using the Information Worlds framework. Thus, they will have feedback on the end users' actions, generating insights on their interests and the way they approach and explore the visualized thematic areas.

The evaluation conducted in the context of this dissertation involved the process of assessing the final applications developed by the framework; thus, the evaluation of the framework itself constitutes another essential step to follow.

Finally, this framework provides a collection several ready-to-use visualization components (i.e. Information Piece Templates) and rendering effects. Despite the fact that this collection covers a wide variety of different visualization cases, future work involves capitalizing on the scalable conceptual and software architecture of the framework to further enrich the available collection and ultimately facilitate the creation of enhanced applications in Virtual, Augmented and Mixed Reality.

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14. Appendix

14.1. Evaluation Consent Form

Έντυπο συγκατάθεσης σε πιλοτική μελέτη του έργου / προγράμματος / συστήματος

Παρακαλούμε να διαβάσετε το παρόν κείμενο προσεκτικά πριν το υπογράψετε

Επιστημονικός Υπεύθυνος / Στοιχεία επικοινωνίας

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Σκοπός της μελέτης και της συλλογής δεδομένων

Σκοπός της παρούσας μελέτης είναι η αξιολόγηση ευχρηστίας, εμπειρίας χρήσης και γενικότερης επίδοσης του συστήματος «Κόσμοι Πληροφορίας»

Τα αποτελέσματα της έρευνας θα χρησιμοποιηθούν στο πλαίσιο εκπόνησης της διδακτορικής διατριβής του κ. Ιωάννη Δρόση, υποψήφιου διδάκτορα του τμήματος Επιστήμης Υπολογιστών του Πανεπιστημίου Κρήτης, ενώ ενδέχεται να δημοσιευθούν μελλοντικά σε επιστημονικά περιοδικά σε ανώνυμη μορφή.

Περιγραφή του ερευνητικού έργου

Η μελέτη αυτή διεξάγεται στο πλαίσιο της διδακτορικής διατριβής του υποψήφιου διδάκτορα κ. Ιωάννη Δρόση, με επιβλέποντα τον Καθηγητή Κωνσταντίνο Στεφανίδη. Η μελέτη αφορά στην αξιολόγηση του συστήματος «Κόσμοι Πληροφορίας», το οποίο είναι σύστημα εικονικής και μεικτής πραγματικότητας για την παρουσίαση πληροφορίας που αφορά πολιτιστική κληρονομιά σε υπαρκτά ή εικονικά περιβάλλοντα μέσω κόσμων και αντικειμένων πληροφορίας. Αναλυτικότερα, στόχος του συστήματος είναι η διαδραστική παρουσίαση πληροφορίας σε τρισδιάστατα περιβάλλοντα μέσω της χρήσης εικονικής και μεικτής πραγματικότητας. Η αλληλεπίδραση με το σύστημα γίνεται μέσω της φορετής συσκευής εικονικής πραγματικότητας Oculus Rift και μέσω ειδικού τηλεχειριστηρίου. Η πληροφορία είναι χωρισμένη σε ξεχωριστούς κόσμους πληροφορίας σε αντιστοιχία με τη σημασιολογική της έννοια. Ο κάθε κόσμος περιλαμβάνει αντικείμενα πληροφορίας, που αντιστοιχούν σε ομάδες δεδομένων με κοινό στοιχείο το ίδιο το αντικείμενο (π.χ. ένα μουσείο αντιστοιχεί σε έναν κόσμο πληροφορίας, ένα άγαλμα μέσα σε ένα μουσείο είναι ένα αντικείμενο πληροφορίας και σχετικές φωτογραφίες αποτελούν τις αντίστοιχες ομάδες δεδομένων). Οι ομάδες δεδομένων παρουσιάζονται στο χρήστη μέσω επιμέρους μικροεφαρμογών οι οποίες εμφανίζονται με φιλικό προς το χρήστη τρόπο.

Κριτήρια επιλογής συμμετεχόντων

Προκειμένου να είναι δυνατή η συμμετοχή σας στη μελέτη θα πρέπει να πληρούνται οι παρακάτω προϋποθέσεις. Συγκεκριμένα, πρέπει:

- να είστε άνω των 18 και κάτω των 60 ετών
- να μην είστε έγκυος
- να μην πάσχετε από ανωμαλίες διοφθαλμικής όρασης
- να μην πάσχετε από ψυχιατρικές διαταραχές
- να μην έχετε παθήσεις του κεντρικού νευρικού συστήματος (π.χ., επιληψία, απώλεια συνείδησης, ιλίγγους, κ.ο.κ.)
- να μην πάσχετε από καρδιακές ή άλλες σοβαρές ιατρικές παθήσεις
- να μη φέρετε βηματοδότη ή άλλη εμφυτευμένη ιατρική συσκευή
- να μην αισθάνεστε κούραση ή υπνηλία
- να μη βρίσκεστε υπό την επήρεια αλκοόλ ή ναρκωτικών ουσιών
- να μην αντιμετωπίζετε πεπτικά προβλήματα
- να μην έχετε συναισθηματική ένταση ή άγχος
- να μην έχετε κρύωμα, γρίπη, κεφαλαλγία, ημικρανία, ή ωταλγία

Διαδικασία συλλογής των προσωπικών δεδομένων

Για τις ανάγκες της μελέτης θα συλλεχθούν στοιχεία ταυτότητας (π.χ. ονοματεπώνυμο, ηλικία, ιδιότητα, φύλο, στοιχεία επικοινωνίας).

Αρχικά, θα σας ζητηθεί να χρησιμοποιήσετε την εφαρμογή «Κόσμοι Πληροφορίας», μέσω σύντομων σεναρίων χρήσης που θα δοθούν από τον αξιολογητή, με σκοπό την εξοικείωσή σας με τον εικονικό κόσμο και τους τρόπους αλληλεπίδρασης σε αυτόν.

Στη συνέχεια, θα σας ζητηθεί να χρησιμοποιήσετε την εφαρμογή «Κόσμοι Πληροφορίας», μέσω μιας σειράς ειδικών σεναρίων χρήσης που θα δοθούν από τον αξιολογητή. Ο σκοπός των εργασιών είναι η μελέτη του συστήματος ως προς την ευκολία χρήσης του, καθώς και ο εντοπισμός τυχόν προβλημάτων, λαθών και αστοχιών του συστήματος, αντιδράσεων και σχολίων που έγιναν κατά την αλληλεπίδραση με αυτό, κτλ. Στο τέλος της αξιολόγησης θα σας δοθεί ένα ερωτηματολόγιο και θα σας ζητηθεί να απαντήσετε σε διάφορες ερωτήσεις σχετικά με την εμπειρία σας κατά την αλληλεπίδραση σας με το σύστημα.

Πιο συγκεκριμένα, τα δεδομένα που θα καταγραφούν κατά την αξιολόγηση είναι τα εξής:

- Σχόλια, αντιδράσεις, και απαντήσεις σε ερωτήσεις κατά τη διάρκεια των εργασιών και στο τέλος της αξιολόγησης σχετικά με την εμπειρία χρήσης και την ευχρηστία του συστήματος.
- Παρατηρήσεις και μετρικές ευχρηστίας από τον αξιολογητή κατά την αλληλεπίδραση σας με το σύστημα (π.χ. επιτυχία εκτέλεσης εργασίας, αριθμός λαθών, χρόνος εκτέλεσης εργασίας, κτλ.).
- Παρατηρήσεις σχετικά τον τρόπο χρήσης του συστήματος εικονικής πραγματικότητας καθώς και για την αλληλεπίδραση με αυτό.
- Οι απαντήσεις σας στο ερωτηματολόγιο αξιολόγησης του συστήματος.

- Ανώνυμα στατιστικά δεδομένα (logs) που καταγράφονται από το σύστημα, τα οποία θα βοηθήσουν στην εξαγωγή γενικότερων συμπερασμάτων για τη χρήση του συστήματος όπως τη συχνότητα χρήσης του, την πρόοδο των χρηστών με την πάροδο του χρόνου κλπ.

Η αξιολόγηση του συστήματος θα διεξαχθεί στο κτίριο Διάχυτης Νοημοσύνης του Ινστιτούτου Πληροφορικής του Ιδρύματος Τεχνολογίας και Έρευνας.

Επεξεργασία δεδομένων / Προστασία της Ιδιωτικότητας

Στο πλαίσιο της μελέτης θα συλλεχθούν και επεξεργαστούν με τη διαδικασία της «ψευδωνυμοποίησης» μόνο όσα προσωπικά δεδομένα είναι απολύτως απαραίτητα για τη διεξαγωγή της σχετικής έρευνας. Η συμμετοχή σας σε αυτή τη μελέτη θα παραμείνει εμπιστευτική και η ταυτότητά σας δεν θα αποθηκευτεί σε καμία περίπτωση μαζί με τις απαντήσεις σας. Τα προσωπικά σας στοιχεία θα λάβουν ένα κωδικό αριθμό και η ψηφιακή λίστα που συνδέει το όνομά σας με αυτόν τον αριθμό, θα φυλάσσεται σε ένα ασφαλές, κλειδωμένο ψηφιακό αρχείο. Όταν χρησιμοποιηθούν τα δεδομένα, το όνομά σας δεν θα παρουσιαστεί σε καμία περίπτωση. Τα στοιχεία των εθελοντών προστατεύονται και διατηρούνται ασφαλή κατά τη διάρκεια εκτέλεσης της μελέτης. Μετά την ολοκλήρωση της μελέτης, η λίστα που συνδέει το όνομά σας με τον κωδικό αριθμό των δεδομένων σας θα διαγραφεί. Η επεξεργασία και η ανάλυση των δεδομένων θα γίνει από τον υπεύθυνο επεξεργασίας της μελέτης. Τα αποτελέσματα της μελέτης ενδέχεται να δημοσιευτούν σε επιστημονικά περιοδικά και συνέδρια σε ανώνυμη μορφή.

Συμμετοχή (οφέλη / κίνητρα)

Η συμμετοχή σας στην παρούσα μελέτη γίνεται σε εθελοντική βάση και δεν προβλέπεται κάποιου είδους χρηματική αποζημίωση για τους συμμετέχοντες-εθελοντές. Το Ινστιτούτο Πληροφορικής–ΙΤΕ ευχαριστεί τους συμμετέχοντες για την αφιλοκερδή συμμετοχή τους.

Άρνηση συμμετοχής ή ανάκληση της συγκατάθεσης

Ως συμμετέχοντες- εθελοντές στη μελέτη είστε ελεύθεροι ανά πάσα στιγμή, και έως το τέλος της παρούσας ερευνητικής δράσης, να αρνηθείτε να συμμετέχετε ή να ανακαλέσετε τη συμμετοχή/συγκατάθεσή σας για τα στοιχεία που θα συλλεχθούν στο πλαίσιο της μελέτης χωρίς αρνητικές για εσάς συνέπειες και χωρίς να απαιτείται να αιτιολογήσετε την απόφασή σας. Στην περίπτωση αυτή τα προσωπικά δεδομένα που σας αφορούν καταστρέφονται.

Μπορείτε να ανακαλέσετε τη συγκατάθεσή σας στη συγκεκριμένη μελέτη οποτεδήποτε, με γραπτή δήλωση στον Επιστημονικό Υπεύθυνο της μελέτης, Καθ. Κωνσταντίνο Στεφανίδη (βλ. στοιχεία επικοινωνίας στην αρχή αυτού του εγγράφου).

Πιθανοί Κίνδυνοι

Κατά την αξιολόγηση θα σας ζητηθεί να φορέσετε την κάσκα εικονικής πραγματικότητας

Oculus Rift (https://www.oculus.com) και να χρησιμοποιήσετε το τηλεχειριστήριο Oculus Touch. Για τη χρήση της συσκευής Oculus Rift και του τηλεχειριστηρίου της θα ακολουθηθούν οι προδιαγραφές και οι οδηγίες χρήσης της όπως αυτές έχουν οριστεί από τον κατασκευαστή.

Πιθανοί κίνδυνοι όπως αυτοί περιγράφονται από τον κατασκευαστή είναι οι εξής:

- Μερικοί άνθρωποι (περίπου 1 στους 4000) μπορεί να έχουν σοβαρή ζάλη, επιληπτικές κρίσεις, συσπάσεις των ματιών ή των μυών ή σκοτοδίνες που προκαλούνται από φωτεινές αναλαμπές ή σχήματα και αυτό μπορεί να συμβεί ενώ παρακολουθούν τηλεόραση, παίζουν βιντεοπαιχνίδια ή βιώνουν εικονική πραγματικότητα, ακόμα και αν δεν είχαν ποτέ τέτοιες επιληπτικές κρίσεις ή σκοτοδίνες στο παρελθόν ή δεν έχουν ιστορικό επιληπτικών κρίσεων ή επιληψίας. Τέτοιες επιληπτικές κρίσεις είναι πιο συχνές σε παιδιά και νέους. Όποιος βιώνει οποιοδήποτε από αυτά τα συμπτώματα πρέπει να διακόψει τη χρήση της κάσκας και να ζητήσει ιατρική συμβουλή.
- Σταματήστε άμεσα τη χρήση της κάσκας αν αισθανθείτε οποιαδήποτε μορφής δυσφορία, όπως: επιληπτικές κρίσεις, απώλεια συνείδησης, καταπόνηση των ματιών, μυϊκές συσπάσεις ή συσπάσεις των ματιών, ακούσιες κινήσεις, αλλοιωμένη, θολή ή διπλή όραση ή άλλες οπτικές ανωμαλίες, ζάλη, αποπροσανατολισμό, μειωμένη ισορροπία, εξασθενημένο συντονισμό χεριών - ματιών, πανικό ή άγχος, υπερβολική εφίδρωση, αυξημένη σιελόρροια, ναυτία, δυσφορία ή πόνο στο κεφάλι ή τα μάτια, υπνηλία, κούραση ή οποιαδήποτε συμπτώματα παρόμοια με την ασθένεια κίνησης - motion sickness.
- Τα συμπτώματα της έκθεσης στην εικονική πραγματικότητα μπορούν να παραμείνουν και να γίνουν πιο εμφανή ώρες μετά τη χρήση. Αυτά τα μετά τη χρήση συμπτώματα μπορεί να περιλαμβάνουν τα παραπάνω συμπτώματα, καθώς και υπερβολική υπνηλία και μειωμένη ικανότητα πολλαπλών εργασιών. Αυτά τα συμπτώματα ενέχουν αυξημένο κίνδυνο τραυματισμού κατά την εκτέλεση συνηθισμένων δραστηριοτήτων στον πραγματικό κόσμο.

Διακόψτε άμεσα τη χρήση της κάσκας και ενημερώστε τον αξιολογητή αν αισθανθείτε οποιοδήποτε από τα προαναφερθέντα συμπτώματα κατά τη διάρκεια της αξιολόγησης.

Κατά τη διάρκεια της μελέτης θα παρευρίσκεται ιατρός Παθολόγος (ο Καθηγητής Παθολογίας και Διευθυντής της αντίστοιχης Κλινικής του ΠΑΓΝΗ, Αχιλλέας Γκίκας ή ιατρός συνεργάτης του). Παρακαλούμε ενημερώστε τον άμεσα σε περίπτωση εμφάνισης οποιουδήποτε από τα προαναφερθέντα συμπτώματα.

Εφαρμοζόμενοι κανονισμοί

Η προστασία των δεδομένων προσωπικού χαρακτήρα και της ιδιωτικής ζωής αποτελεί θεμελιώδες ανθρώπινο δικαίωμα. Ο νόμος παρέχει συγκεκριμένα δικαιώματα στα φυσικά πρόσωπα (τα υποκείμενα των δεδομένων) και θέτει συγκεκριμένες υποχρεώσεις σε όσους τηρούν και επεξεργάζονται τέτοιου είδους δεδομένα (τους υπευθύνους επεξεργασίας). Στην παρούσα μελέτη λαμβάνονται υπόψιν όλοι οι Ευρωπαϊκοί και Ελληνικοί εφαρμόσιμοι νόμοι και Οδηγίες για την προστασία των προσωπικών δεδομένων, όπως προκύπτουν από την εφαρμογή του «Γενικού Κανονισμού Προστασίας Δεδομένων/ General Data Protection Regulation (ΕΕ 679/2016)».

Δικαιώματα

Οι συμμετέχοντες έχουν το δικαίωμα πρόσβασης στα δεδομένα που τους αφορούν και έχουν συλλεγεί στο πλαίσιο και για τους σκοπούς της μελέτης αυτής. Έχουν το δικαίωμα της ενημέρωσης, της πρόσβασης, της διόρθωσης, της διαγραφής («δικαίωμα στη λήθη»), δικαίωμα περιορισμού της επεξεργασίας, δικαίωμα στη φορητότητα των δεδομένων, δικαίωμα εναντίωσης και δικαίωμα υποβολής καταγγελίας στην εποπτική αρχή (Αρχή Προστασίας Δεδομένων Προσωπικού Χαρακτήρα στο email: complaints@dpa.gr).

Για την άσκηση των δικαιωμάτων σας αναφορικά με τη συγκεκριμένη μελέτη, μπορείτε να επικοινωνήσετε με τον Επιστημονικό Υπεύθυνο της μελέτης, Καθ. Κωνσταντίνο Στεφανίδη. Για την περαιτέρω ενημέρωσή σας σχετικά με την πολιτική προστασίας δεδομένων προσωπικού χαρακτήρα του ΙΤΕ μπορείτε να ενημερωθείτε στον ιστότοπο του ΙΤΕ (www.forth.gr) ή να επικοινωνείτε με τον Υπεύθυνο Προστασίας Προσωπικών Δεδομένων ΙΤΕ στο email: dpo@admin.forth.gr.

Δήλωση Συγκατάθεσης

Εγώ, ο/η.. δηλώνω με την παρούσα ότι συμφωνώ να συμμετέχω σε αυτή τη μελέτη, στο πλαίσιο της αξιολόγησης ευχρηστίας, εμπειρίας χρήσης και γενικής επίδοσης του συστήματος.

Έχω λάβει γνώση μέσω του κειμένου ενημέρωσης και έχω κατανοήσει τον σκοπό και τις δραστηριότητες της μελέτης, καθώς και τα δικαιώματά μου.

Δηλώνω ότι πληρώ τις προϋποθέσεις που περιγράφονται παρόν έγγραφο για τη συμμετοχή μου στη μελέτη.

Κατανοώ ότι σε περίπτωση που κατά τη διάρκεια της χρήσης του συστήματος αισθανθώ οποιαδήποτε μορφής δυσφορία που ενδέχεται να οφείλεται στη χρήση της κάσκας εικονικής πραγματικότητας, θα πρέπει να το δηλώσω στον αξιολογητή και στον παρόντα ιατρό Παθολόγο και να διακόψω άμεσα τη χρήση της κάσκας.

Συμμετέχω απολύτως εθελοντικά και έχω κατανοήσει ότι μπορώ να ανακαλέσω [1] οποτεδήποτε/ανά πάσα στιγμή τη συγκατάθεσή μου χωρίς αρνητικές επιπτώσεις για εμένα. Γνωρίζω και έχω κατανοήσει ότι στην περίπτωση αυτή διαγράφονται τα προσωπικά δεδομένα μου.

Δηλώνω την ικανοποίησή μου για την τήρηση των διαβεβαιώσεων για μία υπεύθυνη, συνεπή και συνετή διαχείριση των δεδομένων.

Γνωρίζω και κατανοώ ότι η συμμετοχή μου και τα προσωπικά δεδομένα μου αντιμετωπίζονται και τηρούνται ως εμπιστευτικά στο πλαίσιο της μελέτης.

Γνωρίζω και κατανοώ ότι τα προσωπικά δεδομένα μου θα τηρηθούν σε ένα ασφαλές περιβάλλον και ότι ο υπεύθυνος επεξεργασίας θα λάβει όλα τα αναγκαία και ενδεδειγμένα μέτρα για να προστατεύσει την ασφάλεια, κυρίως την εμπιστευτικότητα και ακεραιότητα, των προσωπικών δεδομένων, σύμφωνα με τη νομοθεσία και τις οδηγίες που θα εκδοθούν.

Ονοματεπώνυμο Συμμετέχοντος	Ονοματεπώνυμο Ερευνητή
....	....
Υπογραφή	Υπογραφή
....	....
Ημερομηνία	Ημερομηνία
....	....

[1] Μπορείτε να ανακαλέσετε τη συγκατάθεσή σας στη συγκεκριμένη μελέτη οποτεδήποτε, με γραπτή δήλωση στον Επιστημονικό Υπεύθυνο της μελέτης, Καθ. Κωνσταντίνο Στεφανίδη, email: cs@ics.forth.gr, τηλ. +30 2810 291741, διεύθυνση: ΙΠ-ΙΤΕ, Ν. Πλαστήρα 100, Βασιλικά Βουτών, 700 13 Ηράκλειο, Κρήτη

14.2. Session page – Tasks and Metrics

USER ID:	GENDER:		AGE:			VR EXPERIENCE:			
	Male □	Female □	20-30	30-40	40-50	50-60	Low □	Medium □	High □

Task 1: Put on the VR headset and describe where you are and what you see.	
Success □ Partial Success □ Fail □	
Time :	
Number of Tries:	
Does not see clearly from the headband ☐	Errors / Comments:
Does not understand where he is ☐	

Task 2: Given that you are interested in Crete, find a media gallery on the central television of the entrance of the Ambient Intelligence facility and explore the content there.	
Success □ Partial Success □ Fail □	
Time :	
Number of Tries:	
Did not understand which entities are interactive ☐	Errors / Comments:
Could not choose them ☐	
Could not navigate a short distance ☐	
Could not go exactly where he wanted ☐	
Can not handle Media Gallery with multiple images ☐	
Can not handle Media Gallery with one image ☐	

Task 3: John suggests that you use the interactive system which allows to see yourself in front of various landscapes and is located in the big room to the right of the entrance. You are interested in Knossos Palace and you decide to see yourself there.
Success □ Partial Success □ Fail □
Time :
Number of Tries:

Unable to navigate over long distances ☐	Errors / Comments:
Unable to recognize the requested system (BeThereNow) ☐	
Cannot scroll to the desired system (BeThereNow) ☐	

Task 4: John informs you that there is extra information for the palace in the VR environment. Find the virtual world of Knossos and visit the throne's room.	
Success ◻ Partial Success ◻ Fail ◻	
Time :	
Number of Tries:	
Did not remember the button ☐	Errors / Comments:
Menu not shown ☐	
Menu is not perceptible ☐	
Worlds do not look very clear ☐	
Did not understand that they could be chosen ☐	
Did not distinguish the throne ☐	

Task 5: Visit the information world for the museum and find a 3D amphora there.	
Success ◻ Partial Success ◻ Fail ◻	
Time :	
Number of Tries:	
Did not remember the button ☐	Errors / Comments:
Menu not shown ☐	
Menu is not perceptible ☐	
Worlds do not look very clear ☐	
Did not understand that they could be chosen ☐	
Unable to recognize amphora ☐	
Unable to select amphora ☐	

Task 6: Find information regarding the big sculpture in the centre of the room (name etc.).	
Success □ Partial Success □ Fail □	
Time :	
Number of Tries:	
Did not think of going to the next room ☐	Errors / Comments:
Could not handle Tag Cloud ☐	
Did not understand that he could choose words ☐	
The descriptions of the words could not be read ☐	

Task 7: You are interested in ancient Rome so you decide to go to the next room and find where the ancient Pompeii was on the interactive map on the table.	
Success □ Partial Success □ Fail □	
Time :	
Number of Tries:	
Did not understand that he had to go to the next room ☐	Errors / Comments:
Could not find the map ☐	
Did not recognize the information ☐	
It was difficult to read information on the map ☐	

Task 8: Complete your virtual visit by exiting this world. Navigate towards the lit area and describe what you are perceiving in this room.	
Success □ Partial Success □ Fail □	
Time :	
Number of Tries:	
Did not recognize the mirror ☐	Errors / Comments:
Did not go to the mirror ☐	
Did not understand what the words represent ☐	

14.3. Interview Questions

User ID:	Interview General Questions
1. Do you have previous experience from virtual reality applications?	
2. Do you have previous experience of interacting with Oculus controls or another way of interacting in a virtual reality environment?	
3. What were the positive elements in the experience of using the system?	
4. Would you like to be a collaborative system?	
5. In which other areas would you like to use the system?	
6. Did you feel confined to the movement due to the cable of the headset?	
7. Would you like to have lists of tours or explore yourself the system or a combination of both?	
8. Would you like to share or store souvenirs? If so how?	
9. What were the negative elements in the experience of using the system?	
10. Do you have any suggestions for improvement of the virtual environment and generally the entire user experience?	

14.4. Post Session Notes

Observer: **User ID:** **Date:** **Time:**	
Interaction and navigation	
Could the user understand how to move in the virtual world? (that is, where to click to move, when to use the joystick)	□ YES □ NO. Because: □ Partially. Because:
How does the user choose to move in general? (with point and click or using the joystick)	□ Point and click □ Joystick
Could the user navigate the virtual environment in order to perform the assigned tasks?	□ YES □ NO. Because: □ Partially. Because:
Could the user have accuracy in his movement?	□ YES □ NO. Because: □ Partially. Because:
Did the user improve on navigation over time?	□ YES □ NO. Because: □ Partially. Because:
Difficult to interact with the system?	□ YES □ NO. Because: □ Partially. Because:
Could the user remember and press the joystick keys to perform the necessary action?	□ YES □ No. Did not remember the button for:

Usability and Flow	
Did the user understand the layout of the system? (I.e. where information will appear, etc.)	□ YES □ NO. Because: □ Partially. Because:
Could the user identify the actions that had to do with the elements of the interface?	□ YES □ NO

Could use the interfaces / menus that appeared in the application?	□ YES □ Difficult to choose 3d items □ Difficult to select 3d items □ Difficult to drag 3d items
Did the user improved on interface elements recognition over time?	□ YES □ NO
The interaction with the controls was:	□ Comfortable □ Unmanageable □ Accurate □ Not accurate □ Natural □ Not natural
The user was confident about his actions when interacting with the system.	□ YES □ NO. Not sure when trying to:

Immersion and presence	
Did the user prefer to be upright or seated?	□ Upright □ Seated
Was he moving in the real space or standing still?	□ Still □ Full body movement □ Head movement
Did the user feel that he was actually in this virtual world? (e.g., the objects around it were being processed)	□ YES □ NO
How would you characterize the user's behavior?	□ confident □ insecure □ curious □ indifferent □ independent □ waiting for guidance □ concentrated □ chaotic □ patient □ impatient □ nervous □ calm □ excited □ impassive □ focused □ disordered Comments:

Was the user's initial reaction / impression of the system consistent throughout the system's use?	□ YES □ NO □ It was more intense at the beginning and declined over time

Emotion	
The user was excited about using the system	□ YES. With which item in particular? □ NO. Because:
Was he concentrated to perform the actions?	□ YES □ NO. Because: □ He was absorbed in the virtual environment / disintegrated him
The user was surprised when using the system	□ YES. With which item in particular? □ NO.

14.5. User Experience Questionnaire (UEQ)

	1	2	3	4	5	6	7		
annoying	○	○	○	○	○	○	○	enjoyable	1
not understandable	○	○	○	○	○	○	○	understandable	2
creative	○	○	○	○	○	○	○	dull	3
easy to learn	○	○	○	○	○	○	○	difficult to learn	4
valuable	○	○	○	○	○	○	○	inferior	5
boring	○	○	○	○	○	○	○	exciting	6
not interesting	○	○	○	○	○	○	○	interesting	7
unpredictable	○	○	○	○	○	○	○	predictable	8
fast	○	○	○	○	○	○	○	slow	9
inventive	○	○	○	○	○	○	○	conventional	10
obstructive	○	○	○	○	○	○	○	supportive	11
good	○	○	○	○	○	○	○	bad	12
complicated	○	○	○	○	○	○	○	easy	13
unlikable	○	○	○	○	○	○	○	pleasing	14
usual	○	○	○	○	○	○	○	leading edge	15
unpleasant	○	○	○	○	○	○	○	pleasant	16
secure	○	○	○	○	○	○	○	not secure	17
motivating	○	○	○	○	○	○	○	demotivating	18
meets expectations	○	○	○	○	○	○	○	does not meet expectations	19
inefficient	○	○	○	○	○	○	○	efficient	20
clear	○	○	○	○	○	○	○	confusing	21
impractical	○	○	○	○	○	○	○	practical	22
organized	○	○	○	○	○	○	○	cluttered	23
attractive	○	○	○	○	○	○	○	unattractive	24
friendly	○	○	○	○	○	○	○	unfriendly	25
conservative	○	○	○	○	○	○	○	innovative	26

14.6. Usability questionnaire

Users rate the system with values from 0 (completely disagree) to 5 (completely agree)	User ID:
1. The virtual environment was responsive to actions that I initiated.	
2. The interaction devices (Oculus Touch Controllers) which were used for movement in the virtual environment seemed natural.	
3. I was able to actively survey the virtual environment using vision.	
4. I was able to examine objects closely/ from multiple viewpoints.	
5. I felt proficient in moving and interacting with the virtual environment at the end of the experience.	
6. The control mechanism was distracting.	
7. The visual aspects of the virtual environment involved me.	
8. The sense of moving around inside the virtual environment was compelling.	
9. I felt stimulated by the virtual environment.	
10. I became so involved in the virtual environment that I was not aware of things happening around me.	
11. I felt physically fit in the virtual environment.	
12. I become so involved in the virtual environment that I lose all track of time.	
13. I felt I could perfectly control my actions.	
14. I felt I controlled the situation.	
15. I thought there was delay between my actions and the expected outcomes	
16. I thought there was too much inconsistency in the virtual environment.	
17. I found the interaction devices (Oculus Touch Controllers) very cumbersome to use.	
18. I felt confident using the gamepad and/or keyboard to move around the virtual environment.	
19. I had the sense of orientation in the virtual environment.	
20. I had difficulty reading text within the system.	
21. I understand what the symbols that are close to each piece of information represent.	
22. I enjoyed being in this virtual environment.	
23. It was so exciting that I could stay in the virtual environment for hours.	
24. I found my mind wandering while I was in the virtual environment.	
25. I suffered from fatigue during my interaction with the virtual environment.	
26. I suffered from eyestrain during my interaction with the virtual environment.	
27. I felt an increase of my sweat during my interaction with the virtual environment.	
28. I suffered from nausea during my interaction with the virtual environment.	
29. I suffered from vertigo during my interaction with the virtual environment.	
30. If I used the same virtual environment again, my interaction with it would be clear and understandable.	
31. Learning the virtual environment would be easy / fast.	

14.7. FORTH Ethics Committee Conclusion

ΑΠΟΣΠΑΣΜΑ ΠΡΑΚΤΙΚΟΥ ΑΠΟΦΑΣΗΣ ΕΗΔΕ ΙΤΕ
Αριθμός 27/28-1-2019

Στο Ηράκλειο, σήμερα 28-1-2019, συνήλθε ηλεκτρονικά και κατ' άρθρα 21-27 Ν.4521/2018, η ΕΗΔΕ του ΙΤΕ (η οποία ορίστηκε και ανασυγκροτήθηκε με την απόφαση που λήφθηκε με το υπ' αριθ. αρ. πρακτ. 380/27-6/20.7.2018 και το πρακτικό του Διοικητικού Συμβουλίου του ΙΤΕ) με θέμα την εξέταση της αίτησης με Αρ. Πρ. Εισ.: 28/26-12-2018 με τίτλο : 'Κόσμοι Πληροφορίας - Σύστημα εικονικής και μικτής πραγματικότητας', με Επιστημονικά Υπεύθυνο/ους τον κ. Κων/νο Στεφανίδη (ΙΤΕ – ΙΠ, Συν. Μέλος ΔΕΠ), - Επιστημονικά Υπεύθυνο της εν λόγω διδακτορικής διατριβής- και τον Υποψήφιο Διδάκτορα, Υπότροφο ΙΤΕ ΙΠ κ. Ιωάννη Δρόση, με το ως άνω θέμα, που πρόκειται να εκτελεσθεί στο ΙΤΕ ΙΠ κατά τα αναφερόμενα στην υπό εξέταση με Αρ. Πρ. Εισ.: 28/26-12-2018 αίτηση.
Κατά την συνεδρίαση παρέστησαν ηλεκτρονικά τα ακόλουθα μέλη της ΕΗΔΕ :

1. Σωτήρης ΙΩΑΝΝΙΔΗΣ, ως Πρόεδρος ΕΗΔΕ ΙΤΕ
2. Σταυρούλα ΤΣΙΝΟΡΕΜΑ, ως Αντιπρόεδρος ΕΗΔΕ ΙΤΕ
3. Αργυρώ ΚΛΙΝΗ
4. Μαρία ΚΛΑΠΑ
5. Κική ΣΙΔΗΡΟΠΟΥΛΟΥ
6. Αικατερίνη ΤΣΑΚΩΝΑ
7. Νικόλαος ΠΟΤΑΜΙΑΝΟΣ

Υπαρχούσης ηλεκτρονικά απαρτίας, χρέη γραμματείας ΕΗΔΕ ανέλαβε η κ. Ευγενία Ταμπακάκη.

Η ΕΗΔΕ διαπίστωσε σήμερα ότι για την αίτηση με Αρ. Πρ. Εισ.: 28/26-12-2018 με τίτλο: 'Κόσμοι Πληροφορίας - Σύστημα εικονικής και μικτής πραγματικότητας', με Επιστημονικά Υπεύθυνο/ους τον κ. Κων/νο Στεφανίδη (ΙΤΕ – ΙΠ, Συν. Μέλος ΔΕΠ), -Επιστημονικά Υπεύθυνο της εν λόγω διδακτορικής διατριβής- και τον Υποψήφιο Διδάκτορα, Υπότροφο ΙΤΕ ΙΠ κ. Ιωάννη Δρόση, έχουν υποβληθεί τα σχετικά έγγραφα που προβλέπει ο Ν.4521/2018 (αρθρ.21-27), αίτηση-ερωτηματολόγιο σύντομη έκθεση του ΕΥ, εισήγηση του Εισηγητή, ΕΥ απαντήσεις/διευκρινήσεις σε ερωτήσεις, έντυπο ενημέρωσης και δήλωση συναίνεσης με ημ/νία μέχρι και 21/1/2019. Ακολούθως ο Πρόεδρος της Επιτροπής αφού όρισε Εισηγητή για αυτήν την αίτηση κατά τα προβλεπόμενα στο άρθρ. 24 παρ.3 Ν.4521/2018, ο οποίος αιτιολογημένα για αυτήν, ενημέρωσε τον πρόεδρο και λοιπά μέλη της ΕΗΔΕ (ηλεκτρονικά) και στη συνέχεια η επιτροπή έλαβε όλα τα σχετικά υπόψιν της και εξέτασε τη σχετική αίτηση.
Σύμφωνα με τα ανωτέρω στοιχεία και τα άρθρα 21-27 του Ν. 4521/2018 η ΕΗΔΕ αποφασίζει σήμερα ότι δύναται αρχικά να προ-εγκρίνει υπό τους ακόλουθους όρους, την αίτηση με Αρ. Πρ. Εισ.: 28/26-12-2018, κατά το μέτρο και έκταση που, ο ερευνητικός φορέας ΙΤΕ Ινστιτούτο ΙΠ, ο/οι ΕΥ & ΕΥ υπότροφος φοιτητής βεβαιώνουν στην ΕΗΔΕ ή/και λοιπά αρμόδια όργανα (πχ ΔΣ ΙΤΕ) ότι θα πληρούν τους ακόλουθους όρους, καθ' όλη τη διάρκεια της έρευνας, και των ερευνητικών εργασιών ως εξής:
(1) Να προβούν σε όλες τις απαιτούμενες ενέργειες/λήψη μέτρων, ώστε να πληρούνται οι υποχρεωτικά απαιτούμενοι εκ του νόμου όροι και προϋποθέσεις νομιμότητας της αιτούμενης έρευνας /εργασίας σε κάθε στάδιο, ακολουθώντας όλα όσα προβλέπονται στην εκάστοτε εν ισχύ και εγκεκριμένη από το ΔΣ του ΙΤΕ Πολιτική προστασίας προσωπικών δεδομένων του ΙΤΕ, και Κανονισμό Ηθικής και Δεοντολογίας της Έρευνας, τον Κανονισμό Λειτουργίας της ΕΗΔΕ ΙΤΕ, και τις εκάστοτε δοθείσες οδηγίες και έντυπα ενημέρωσης και συναίνεσης που έχουν λάβει από τον Υπεύθυνο Προστασίας Δεδομένων (ΥΠΔ) του ΙΤΕ, και ό,τι άλλο τυχόν ορίζονται στο εκάστοτε εν ισχύ νομικό εθνικό και ενωσιακό πλαίσιο δικαίου προστασίας δεδομένων προσωπικού χαρακτήρα, ηθικής και δεοντολογίας της έρευνας και
(2) ιδίως κατά την διάρκεια της έρευνας στο ΙΤΕ ΙΠ όπου διενεργούνται οι ερευνητικές εργασίες με χρήση των αναφερόμενων φορητών συσκευών στους χώρους του ΙΤΕ ΙΠ, να έχουν εξασφαλίσει να παρευρίσκεται και ιατρός ειδικότητας σχετικής με τους κινδύνους και τα πιθανά προβλήματα υγείας που σχετίζονται με την χρήση αυτών καθ' όλη τη διάρκεια αυτών των εργασιών προκειμένου να μπορεί να αντιμετωπίσει τυχόν περιστατικά, κινδύνου υγείας, ασφάλειας, του/των προσώπων που θα συμμετέχουν σε αυτές και
(3) να ενσωματώσουν τον ανωτέρω (2) όρο/πρόβλεψη-αναφορά και στο Έντυπο ενημέρωσης – Δήλωση συναίνεσης που θα διανείμουν στους ενδιαφερόμενους συμμετέχοντες και αυτό το επικαιροποιημένο κατά τα ανωτέρω έντυπο ενημέρωσης-συναίνεσης να το αποστείλουν οι ΕΥ απευθείας στην ΕΗΔΕ πριν την έναρξη πρόσκλησης/προσέλκυσης συμμετεχόντων.

Η παρούσα απόφαση της ΕΗΔΕ σε καμία περίπτωση ΔΕΝ υποκαθιστά την τυχόν απαιτούμενη από άλλη αρμόδια δημόσια υπηρεσία, διοικητικό όργανο ή ανεξάρτητη διοικητική Αρχή, έγκριση ή αδειοδότηση του παρόντος ερευνητικού έργου/εργασίας που τυχόν επιπλέον απαιτείται εκ του νόμου.

Ακριβές απόσπασμα

Ο Πρόεδρος ΕΗΔΕ ΙΤΕ

Σωτήρης ΙΩΑΝΝΙΔΗΣ
Πρόεδρος ΕΗΔΕ ΙΤΕ

SOTIRIOS IOANNIDIS
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Date: 2019.01.31 11:22:59 +02'00'