UNIVERSITY OF CRETE
DEPARTMENT OF COMPUTER SCIENCE
FACULTY OF SCIENCES AND ENGINEERING

Interacting with augmented physical printed matter in Ambient Intelligence environments

“The InPrinted Framework”

by

Georgios Margetis

PhD Dissertation
Presented in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy

Heraklion, October 2017

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Dedicated to the three Graces of my life,

my wife Stavroula and

my two daughters

Ioanna and Nikolia

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Abstract

Keywords: Interactive printed matter, interactive paper, natural interaction, ambient intelligence, augmented paper, UX evaluation.

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Interacting with augmented physical printed matter in Ambient Intelligence environments

Indisputably, paper constitutes a fundamental means for information sharing among people throughout the centuries. Although many believe that paper will be eliminated by the emerging technologies and will stop being an integral part of our everyday life, it can be easily proven that this will not become a reality, at least for the forthcoming years. On the other hand, the idea of augmenting physical paper with technology and digital information has led to the birth of many research efforts in this direction, beginning from the last decade of the previous century. Since then, numerous approaches have been proposed, aiming to benefit from users' familiarity with paper and the natural interaction fostered by the paper's affordances. All these approaches have the potential to be widely accepted and applied in everyday life, due to the fundamental properties of paper: it is inexpensive, lightweight and can be easily found anywhere.

On the other hand the rise of smart environments and ubiquitous computing provides the opportunity for the creation of new interaction paradigms in the digital world, which resemble those used in everyday activities of the physical world. Furthermore, the opportunity of pervasive access to digital information that approaches such as Ambient Technology can offer to the users increases the potential of engaging everyday objects, like printed matter, in digital interaction.

However, there is still a lack of generic and systematic approaches to support the augmentation and interaction with printed matter in the context of intelligent environments.

This PhD thesis pursues to define and elaborate a generic framework supporting printed matter augmentation and user interaction with Ambient Intelligence (AmI) technologies in Smart Environments. Aiming to fill the identified gap, an **extensible context-aware interaction framework** is presented**,** the **InPrinted framework**, which enables the integration of printed matter into AmI environments by providing:

- natural multimodal interaction with printed matter
- an open reference model for printed matter interaction in AmI environments
- context aware and anticipation mechanisms for printed matter incorporation in AmI environments
- tools and interaction techniques supporting the development of systems and / or applications which offer printed matter augmentation in AmI environments.

As a result, the InPrinted framework can constitute a valuable asset, assisting the easy embedment of interaction with printed matter in AmI environments as well as printed matter augmentation, ensuring high quality and robustness.

For the assessment and evaluation of the proposed framework with end users, four Ambient Intelligence applications have been implemented and assessed, representing indicative examples from different real life activities. The evaluation iterations carried out in the context of this thesis have led to the conclusion that interaction with augmented printed matter has consistently been positively assessed and has been found to be natural by users.

Περίληψη

Λέξεις κλειδιά: Αλληλεπιδραστική έντυπη ύλη, διαδραστικό χαρτί, φυσική αλληλεπίδραση, διάχυτη νοημοσύνη, επαυξημένο χαρτί, αξιολόγηση εμπειρίας χρήστη.

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Αλληλεπίδραση σε περιβάλλοντα Διάχυτης Νοημοσύνης με τη χρήση έντυπης ύλης

Το χαρτί αδιαμφισβήτητα αποτελεί ένα βασικό μέσο μεταφοράς της πληροφορίας μεταξύ των ανθρώπων, δια μέσου των αιώνων. Αν και πολλοί πιστεύουν ότι η χρήση του χαρτιού τελικά θα αντικατασταθεί από τις νέες τεχνολογίες και θα σταματήσει να αποτελεί αναπόσπαστο τμήμα της καθημερινότητας, μπορεί εύκολα να αποδειχθεί ότι κάτι τέτοιο δεν αποτελεί ορατή πραγματικότητα, τουλάχιστον για τα επόμενα χρόνια. Από την άλλη μεριά, η ιδέα της επαύξησης του φυσικού χαρτιού με τεχνολογία και ψηφιακή πληροφορία έχει οδηγήσει σε πολλές ερευνητικές προσπάθειες, οι πρώτες από τοις οποίες ξεκινήσαν από τα τέλη του περασμένου αιώνα. Από τότε, πολυάριθμες προσεγγίσεις προς την κατεύθυνση αυτή έχουν προταθεί, εκμεταλλευόμενες τα οφέλη που προσφέρει το φυσικό χαρτί, όπως είναι η εξοικείωση που έχουν όλοι οι χρήστες με αυτό, καθώς επίσης οι δυνατότητες φυσικής αλληλεπίδρασης που προσφέρονται και ενισχύονται από τις φυσικές ιδιότητες του χαρτιού. Όλες αυτές οι προσεγγίσεις παρουσιάζουν τα απαιτούμενα εχέγγυα για να γίνουν ευρέως αποδεκτές και να εφαρμοστούν στην καθημερινή ζωή, κυρίως λόγω των βασικών ιδιοτήτων του χαρτιού: αποτελεί φθηνό μέσο, είναι ελαφρύ και μπορεί εύκολα να βρεθεί οπουδήποτε.

Από την άλλη μεριά, η εμφάνιση των έξυπνων περιβαλλόντων και της πανταχού παρούσας υπολογιστικής δύναμης (ubiquitous computing) παρέχουν ευκαιρίες για τη

δημιουργία νέων παραδειγμάτων αλληλεπίδρασης στον ψηφιακό κόσμο, τα οποία ομοιάζουν με τη φυσική αλληλεπίδραση που χρησιμοποιείται στις καθημερινές δραστηριότητες στον πραγματικό κόσμο. Επιπλέον, οι δυνατότητες διάχυτης πρόσβασης των χρηστών στην ψηφιακή πληροφορία, που παρέχονται από τα ευφυή περιβάλλοντα, όπως τα Περιβάλλοντα Διάχυτης Νοημοσύνης (ΔΝ), αυξάνουν το ενδεχόμενο της χρήσης καθημερινών φυσικών αντικειμένων όπως η έντυπη ύλη στην ψηφιακή αλληλεπίδραση.

Παρόλα αυτά, ακόμα και σήμερα παρατηρείται η έλλειψη μίας γενικευμένης και συστηματικής προσέγγισης με στόχο την υποστήριξη της τεχνολογικής επαύξησης και αλληλεπίδρασης με την έντυπη ύλη στο πλαίσιο ευφυών περιβαλλόντων.

Η παρούσα εργασία στοχεύει να συμπληρώσει το κενό αυτό, προτείνοντας το InPrinted framework, ένα **ευέλικτο τεχνολογικό πλαίσιο αλληλεπίδρασης με δυνατότητα επίγνωσης-πλαισίου (context awareness)**, το οποίο θα καθιστά δυνατή την αλληλεπίδραση με την έντυπη ύλη σε περιβάλλοντα ΔΝ. Συγκεκριμένα, το προτεινόμενο πλαίσιο υποστηρίζει:

- φυσική πολυτροπική αλληλεπίδραση με έντυπα
- ένα ανοικτό μοντέλο αναφοράς για την αλληλεπίδραση των εντύπων σε περιβάλλοντα ΔΝ
- μηχανισμούς γνώσης, πρόβλεψης και επίγνωσης-πλαισίου για την ενσωμάτωση της έντυπης ύλης σε περιβάλλοντα ΔΝ
- εργαλεία και τεχνικές αλληλεπίδρασης που υποστηρίζουν την ανάπτυξη συστημάτων ή/και εφαρμογών που προσφέρουν τεχνολογική επαύξηση έντυπης ύλης σε περιβάλλοντα ΔΝ.

Ως εκ τούτου, το InPrinted framework μπορεί να αποτελέσει ένα πολύτιμο βοήθημα για την εύκολη ενσωμάτωση της αλληλεπίδρασης με έντυπη ύλη και την ψηφιακή επαύξηση της έντυπης ύλης σε περιβάλλοντα ΔΝ, διασφαλίζοντας την υψηλή ποιότητα και ευρωστία.

Για τη δοκιμή και αξιολόγηση του προτεινόμενου πλαισίου με τελικούς χρήστες, τέσσερις εφαρμογές ΔΝ έχουν επίσης υλοποιηθεί βάσει του πλαισίου αυτού, αντιπροσωπεύοντας ενδεικτικά παραδείγματα από διαφορετικούς τομείς της καθημερινής ζωής. Η επαναληπτική αξιολόγηση που πραγματοποιήθηκε στο πλαίσιο της παρούσας εργασίας, κατέδειξε ότι η αλληλεπίδραση με την έντυπη ύλη εκλήφθηκε απολύτως θετικά ως βασικό μέσο αλληλεπίδρασης και τεχνολογικής, διατηρώντας την φυσική του ιδιότητα ως ένα καθημερινό απλό αντικείμενο που είναι συνυφασμένο με της καθημερινές μας δραστηριότητες.

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Abbreviations

AmI	Ambient Intelligence
HMD	Head Mounted Devices
UX	User Experience
ICT	Information and Communication Technology
IT	Information Technology
OWL	Ontology Web Language
RDF	Resource Description Framework
UM	User Modelling
KMS	Knowledge Management System
HCI	Human-Computer Interaction
iHCI	Implicit Human-Computer Interaction
UI	User Interface
MR	Mixed Reality
DOF	Degrees of Freedom
AR	Augmented Reality
VR	Virtual Reality
GUI	Graphical User Interface
AV	Augmented Virtuality
HMD	Head Mounted Device
I/O	Input / Output
SoA	Service-Oriented Architecture
OCR	Optical Character Recognition
WWFRE	Windows Workflow Foundation Rules Engine

CRUD	Create, Read, Update and Delete
API	Application Protocol Interface
XML	eXtensible Markup Language
PDF	Portable Document Format
SD	Standard Deviation
M	Mean
CI	Confidence Interval
UL	Upper Limit
LL	Lower Limit
SE	Standard Error

1 Introduction

Through the centuries, paper prevailed as the major means for information sharing among people. With the invention of mechanical movable type printing by Gutenberg, a vast burst of information dissemination occurred all over the world, establishing printed matter as an essential part of people's everyday life. Since the early 90's, the idea of digitally augmenting physical paper was intriguing enough to trigger the first research efforts in this direction. Since then, numerous approaches have been proposed, for user interaction based on paper's affordances. All these approaches have the potential to be widely accepted and applied in everyday life, due to a fundamental property of paper: it is inexpensive and can be found anywhere.

In the last decade, due to the radical evolvement of technology and in particular of portable devices, the idea of a paperless world started to seem very appealing. However, as Sellen and Harper discuss in [141], this idea proves to constitute rather a myth than a tangible reality. In contrast to many movements in the past to do away with paper,

paper is still an integral medium in humans' everyday life, because it is better suited than many current technologies for certain tasks.

The importance of using paper as a prime medium for our daily tasks is rooted in its three fundamental affordances:

- Paper is light, flexible and easy to annotate. These characteristics make it the perfect medium to carry pieces of information and annotate them even in difficult environments, such as a construction site or public transportation where tight space, awkward settings and poor lighting conditions may be expected.
- Paper is easy to navigate using tactile input, making it possible to read and navigate at the same time.
- Paper can provide large, inexpensive, high resolution display surfaces either by using large sheets, such as the ones typical in engineering and architecture, or by creating a dynamic display of smaller pieces, as when arranging several document on one's desk.

However, there are obvious disadvantages of using paper, which according to [141] can be categorized as follows:

- *Symbolic*. Paper is a "symbol of the old-fashioned past" and this may become a burden, mainly from a psychological point of view, towards the current technological trends that envisage a high-tech world where technology is ubiquitous.
- *Cost*. The costs of paper documents are problematic after the documents are generated. Printing costs are minimal compared to the start-up fees of new technology, however after a large mass of paper documents has been accrued, storage and maintenance is incredibly costly.
- *Interactional*. Interactional problems with paper, or limitation of the use of paper include: paper must be used locally, can't be remotely accessed; paper occupies physical space, it must be stored; paper requires physical delivery; paper documents are hard to revise or integrate into other documents; and paper documents are static visual displays.

On the other hand, new practices of everyday activities traditionally related to paper (e.g., reading) emerge today, which are totally interlinked with technology [88]. To this end, the need for systematic research in the field of printed matter augmentation with the use of state of the art technologies is prominent.

The recent emergence of Ambient Intelligence (AmI) realizes the vision of a technological environment where the emphasis is on greater user-friendliness, provision of more efficient services, user-empowerment, and support for human interactions. In AmI environments people are surrounded by intelligent intuitive interfaces that are embedded in all kinds of objects, while the environment is capable of recognizing and responding to the presence of different individuals in a seamless, unobtrusive and often invisible way [62]. AmI has profound consequences on the type, content and functionality of the emerging digital products and services, as well as on the way people interact with them, bringing about multiple new requirements.

Although several frameworks have been developed that embed technology in everyday environments, anticipate and address everyday life needs in adaptive and personalized ways and provide natural interaction with the use of physical or smart objects, there are so far no systematic approaches engaging printed matter towards realising such concepts.

This thesis discusses a systematic approach to fill this gap by developing an extensible context-aware interaction framework, namely the Interactive Printed Matter Framework (InPrinted Framework), which enables the integration of printed matter into AmI environments, providing: a) natural interaction with printed matter, b) a reference model for printed matter context-aware and anticipation mechanisms, based on a proposed ontology meta-model, and c) printed matter augmentation.

For the assessment and evaluation of the InPrinted framework with end users, four Ambient Intelligence applications are presented, constituting indicative real life examples. These applications have been evaluated adopting various approaches, such as heuristic evaluation with User Experience (UX) experts, user testing in the laboratory, comparative evaluation through a within subjects user testing experiment, as well as in-situ evaluation of one of these applications installed in a public space. The evaluations have identified specific usability problems of the applications, none of which however referred to interacting with digitally augmented printed matter. Furthermore, according to the in-situ evaluation, interaction with paper can be characterised as easy and natural for users.

The rest of the thesis is organized as follows:

Chapter 2: discusses related work highlighting key aspects of Ambient Intelligence and interactive paper augmentation with technology.

Chapter 3: investigates fundamental issues of the proposed approach, discussing how they can be addressed in an extensible context aware interaction framework. To this end, the addressed target user groups are introduced and illustrated through different personas, while a requirements analysis is provided and highlighted via representative scenarios.

Chapter 4: illustrates the developed ontology meta-model which enables natural interaction with printed matter in AmI environments.

Chapter 5: introduces the InPrinted framework and its components, highlighting their interdependencies and intercommunication, as well as the overall proposed architectural approach.

Chapter 6: introduces the four Ambient Intelligence applications that have been implemented based on the InPrinted framework and have been evaluated by usability experts and end users.

Chapter 7: presents the evaluation methodology followed for the usability assessment of the four applications and discusses the evaluation results.

Chapter 8: discusses the technological potential of the InPrinted framework and showcases a number of in vivo installations that employ AmI applications, which have been implemented using it.

Chapter 9: concludes the thesis, arguing on its contribution to the field of natural interaction with physical objects in smart environments, and discusses future work.

Related work 2

2.1 Ambient Intelligence and smart environments

In recent years, the emergence of Ambient Intelligence (AmI) is driving a transition from traditional human-computer interaction to natural interaction with everyday things. AmI is often claimed to bring a significant potential towards technologically supporting everyday activities. In AmI, technologies are deployed to make computers disappear in the background, while the human user moves into the foreground in complete control of the augmented environment [130]. AmI is a user-centric paradigm, it supports a variety of artificial intelligence methods and behaves pervasively, unobtrusively, and transparently to aid the user.

Aarts and Marzano in [1] discuss the fundamental features that characterize Ambient Intelligence environments. According to their work, Ambient Intelligence environments are characterized as:

1. **Embedded**: many networked devices that are integrated into the environment
2. **Context aware**: that can recognize persons and their situational context
3. **Personalized**: that can be tailored towards their needs

4. **Adaptive**: that can change in response to actions, and
5. **Anticipatory**: that anticipates peoples' desires without conscious mediation.

Following this approach, this section discusses related work organized under the aforementioned attributes of Ambient Intelligence environments.

Technology embedment

The need for technology embedment in real life environments is a dream that has begun to come true in the last decades via the evolution of embedded and cyber-Physical systems. As defined in [89]: "*Embedded systems are information processing systems embedded into enclosing products*". Examples include embedded systems in a variety of everyday life objects such as cars, trains, and planes. However the approach of embedded systems proved to be insufficient for accommodating the needs of linking technology with physical processes due to their real-time constraints, dependability as well as efficiency requirements. In order to fill this emerging gap, Lee in [76] introduced the concept of *Cyber-Physical systems* as "*Integrations of computation with physical processes*". Cyber-Physical systems are anticipated to realize highly demanding requirements, raising the need for a radical shift of computer systems design. Uliery and Doursat in [157] discuss a new approach to computer system design that is more suitable for designing Cyber-Physical systems. According to Uliery's and Doursat's paradigm, the design process of such systems should take into consideration that Cyber-Physical systems cannot be defined a priori, but rather emerge from the interactions between individual machines and people, facilitated by opportunistic ecosystems [34]. Instead of defining the system and its performance requirements in advance, following a top–down hierarchical thinking, the engineer must rather act as a facilitator to support and guide the complex system through its process of 'self-design', which generates organisational structure from the bottom–up interactions among a myriad of elementary components.

Embedment of physical printed matter in AmI environments can be addressed by the design and development of Embedded or Cyber-Physical systems (e.g., [79, 145, 123]), providing thus the necessary functionality for printed matter interaction and content augmentation.

Ubiquitous Computing

The evolution of technology embedment in everyday life has been followed by the prominent technological trend of Ubiquitous Computing. According to the Ubiquitous Computing viewpoint, computers can be interweaved in our everyday life activities, our natural movements, and interactions with our environment [84]. As the computer disappears in the surrounding environments, the objects therein become augmented with Information and Communication Technology (ICT) components (i.e., sensors, actuators, processor, memory, wireless communication modules) and can receive, store, process and transmit information, evolving into digitally augmented real-life objects [67].

In the context of Ubiquitous Computing two types of "disappearance" have been defined [151]:

- *Physical disappearance* is achieved by the miniaturization of computer parts that allows convenient and easy integration into other artefacts, mostly into "close-to-the-body" objects, so that the result can fit in your hand, can be integrated in clothing or even implanted in the body, etc. As a result, features usually associated with a computer are not visible anymore and the interaction happens via the compound artefact in which the computer parts disappeared.
- *Mental disappearance* of computers is achieved by making them "invisible" to the "mental" eye of the users. This can happen by embedding computers or parts of them in the architectural environment (walls, doors) or in furniture (tables, chairs, etc.) or other everyday objects. Then, computers are not perceived as computers anymore – although the artefacts can be quite large – but as adding interactive, communicative, and cooperative aspects to traditional everyday objects (e.g., an interactive wall or an interactive table is a "table", a "wall" that is interactive and not a computer built into a table or the wall).

According to [67], digitally augmented objects in Ubiquitous Computing differ from traditional objects in a number of properties and abilities:

- *Information processing*: The information that an artefact processes can be descriptions of the context of use, data to be used for a task, guidelines on how to perform a new task (i.e., a program), messages to be sent or that have been received from other objects. The result of information processing is a set of services, that is, a set of abilities that appear in the digital space and relate to information; an artefact may offer or request services
- *Interaction with the environment*: artefacts can perceive properties of their context of use (via their embedded sensors, or by communicating with other artefacts) and can also produce responses to these stimuli (via their actuators)
- *Autonomy*: the operation of artefacts depends on electrical power; thus their autonomy depends on the availability of electrical power (which most of the times depends on the capacity of their battery)
- *Collaboration*: artefacts can exchange messages via (usually wireless) communication channels; the content of these messages may range from plain data to complex structures, including programs, database parts etc.

Context-awareness

Context-awareness in AmI environments remains a hot research topic and includes technological semantics such as context modelling, formal context languages that specify interrelationships and events in an environment, as well as infrastructure support for reasoning on contextual information using inference engines.

Schmidt et al. [140] define context awareness as "*knowledge about the user's and IT device's state, including surroundings, situation, and, to a lesser extent, location*", and describe contexts using a three-dimensional space with the following dimensions: *Environment*, *Self* and *Activity*. Dey and Abowd in [28] provide a more pragmatic and system-oriented analysis, introducing context as *any information that can be used to characterize the situation of an entity, providing that an entity can be a person, place,* *or object that is considered relevant to the interaction between a user and an application, including the user and the application themselves*. To this end, *a system is context – aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task*. Dey's and Abowd's context description is, in practice, similar to Schmidt's approach; they define three context dimensions, *Location*, *Identity and Activity*, expanded by an additional one, namely *Time*.

On the other hand, according to Chen and Kotz [19] there are two categories of context – awareness:

- Active context awareness: an application automatically adapts to discovered context, by changing the application's behaviour.
- Passive context awareness: an application presents the new or updated context to an interested user or makes the context persistent for the user to retrieve later.

Strang and Popien [149] discuss and evaluate approaches to context modelling and conclude that the most prominent methods for context modelling are ontology-based. Wang et al. [162] propose an OWL encoded context ontology (CONON) for modelling context in pervasive computing environments and for supporting logic based context reasoning. CONON provides an upper context ontology, using entities related to user, location, activity and computation ontology, which captures general concepts about basic context, and also provides extensibility for adding domain-specific ontology in a hierarchical manner. Chen et al. [20] introduce CoBrA, an agent-based architecture to help agents in pervasive environments to acquire, reason about and share context knowledge. A key component of CoBrA is an explicit context ontology defined using OWL, which models the basic concepts of people, agents, places, and presentation events. Ejigu et al. [37] propose the GCoM model, an ontology-based generic context management model, which facilitates context reasoning by providing structure for contexts, rules and their semantics. The GCoM model consists of three basic components: context ontology, context data and context related rules. Henricksen and Indulska [58] propose a context model that describes context based on several types of facts (e.g., sensed, static and profiled) subject to constraints and quality annotations. Finally, Preuveneers et al. in [115] propose an adaptable and extensible context ontology for creating context-aware computing infrastructures, ranging from small embedded devices to high-end service platforms.

The most generic description frameworks for defining context are the Resource Description Framework (RDF) [12] and the Web Ontology Language (OWL) [92]. Other languages are based on these generic frameworks, providing more specific and narrow descriptions of context. Such languages are, for example, the Context Ontology Language (CoOL) [150], the Composite Capability/Preference Profiles (CC/PP) [71] and the User Agent Profiling Specification (UAProf) [41].

Personalization

Personalization in AmI environments is achieved through User Modelling (UM). UM has traditionally been concerned with analysing a user's interaction with a system and with developing cognitive models that aid in the design of user interfaces and interaction mechanisms. In [73], a historical overview of user modelling systems and approaches is presented from the late 1970s, when user modelling is usually traced back, until 2001, and both academic and commercial approaches are discussed, as well as their main characteristics. Golemati et al. [50] also explore such approaches, highlight important ontology creation issues and introduce a general and extendable ontology for modelling user profiles. There are several approaches to user modelling, however, as highlighted by Razmerita [126], ontology-based modelling has the main advantage of powerful relationships, which enable users to navigate from one concept (and its instances) to another concept (and its instances) easily. A key approach to ontology-based user modelling is OntobUM [127], a generic ontology-based user modelling architecture, applied in the context of a Knowledge Management System (KMS). OntobUM integrates three different ontologies: the user ontology that structures the different characteristics of users and their relationships, the domain ontology that defines the domain and application specific concepts and their relationships, and the log ontology that defines the semantics of the user interaction with the system.

However, with the advent of AmI, recent research efforts in user modelling have focused on models that support intelligent environments to capture and represent information about users and contexts, so as to enable the environment to adapt to both [64, 63]. GUMO [57] is a general user model ontology for the uniform interpretation of distributed user models in intelligent semantic web enriched environments. Basic user dimensions represented in GUMO include ability and proficiency, personality, emotional state, physiological state, mental state, nutrition and facial expression. D-ME [27] is a multi-agent architecture in which users and environments are represented by agents that negotiate tasks execution and generate results according to user in context features. D-ME includes two interacting entities: a D-Me Agent, representing the user, and the Environment, a physical and logical place in which various services are available. User modelling in D-ME includes four main sections: IDENTITY (with identification data such as the user name, sex, id, password, and email), MIND (background knowledge, interests and know-how), BODY (disabilities or preferences in using a body part during interaction) and PERSONALITY (personality traits and habits).

Context – awareness and personalization are the two fundamental ingredients for AmI environments to provide adaptivity and anticipation to the user needs. More precisely, AmI systems can be adaptive and anticipatory only if they are also context – aware and personalizable.

Adaptivity and anticipation

The notion of adaptivity and anticipation of AmI environments should be studied among others in the context of the natural interaction that is provided by such environments. Any AmI system can be considered adaptive and anticipatory if it provides alternative multimodal natural interaction according to the needs and preferences of each individual user. This implies that the system will be able to decide the suitable interaction modalities for every user, based on his/her profile and the current context of use at runtime [110]. In order to provide adaptability and anticipation, an AmI system should incorporate frameworks for context awareness and user modelling, such as those described above.

In particular, the influence of the situation, the context and the environment are fundamental characteristics regarding HCI in adaptive and anticipatory environments, such as AmI environments. To this end, new paradigms have emerged aiming at defining novel ways of interaction. In [139], the authors discuss these new interaction paradigms, introducing the concept of Implicit Human Computer Interaction (iHCI) and providing the three following definitions:

Implicit Human-Computer Interaction (iHCI)

> "*iHCI is the interaction of a human with the environment and with artefacts which is aimed to accomplish a goal. Within this process the system acquires implicit input from the user and may present implicit output to the user.*"

Implicit Input

> "*Implicit input are actions and behaviour of humans, which are done to achieve a goal and are not primarily regarded as interaction with a computer, but captured, recognized and interpret by a computer system as input.*"

Implicit Output

> "*Output of a computer that is not directly related to an explicit input and which is seamlessly integrated with the environment and the task of the user*"

The aforementioned definitions imply that AmI environments are able to perceive users' interaction not in an isolation, but in context, meaning that they are capable to understand the overall situation in which an action takes place. Therefore, the environment can anticipate the goals of the user to some extent and hence it may become possible to provide better support for the task the user is performing.

2.2 Multimodal interaction in AmI environments

The pervasiveness of interaction in AmI environments requires the elaboration of new interaction concepts that extend beyond typical concepts like the desktop metaphor and menu driven interfaces. AmI therefore brings about new interaction techniques, as well as novel uses and multimodal combinations of existing advanced techniques, such as, for example, gaze-based interaction, gestures, and natural language. Interaction is embedded in everyday objects and smart artefacts. The interaction resulting from tangible user interfaces is not mediated and it supports direct engagement of the user with the environment. Consequently, it is considered more intuitive and natural for AmI environments than the current keyboard and mouse-based interaction paradigms.

Interaction in AmI environments inherently relies on multimodal input, implying that it combines various user input modes, such as speech, pen, touch, manual gestures, gaze, head and body movements, as well as more than one output modes, primarily in the form of visual and auditory feedback. In this context, adaptive multimodality is prominent to support natural input in a dynamically changing context-of-use, adaptively offering to users the most appropriate and effective input forms at the current interaction context. Multimodal input is acknowledged for increasing interaction accuracy by reducing uncertainty of information through redundancy.

Intelligent User Interfaces

Intelligent interfaces are becoming increasingly important as users face increasing system complexity and information overload, and at the same time the **user populations become more heterogeneous** (e.g., the typical user is no longer considered a professional in computer science). Such UIs are typically characterized by one or more of the following properties [94]: (a) **multimodal input** (potentially ambiguous, impartial, or imprecise combinations of mixed input such as written text, spoken language, gestures and gaze), (b) **multimodal output** (coordinated presentations of text, speech, graphics, and gestures, which may be presented via conventional displays or animated, life-like agents) and (c) **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.

User profiling is a necessary ingredient for intelligent UIs materialization, in order to provide information regarding the user currently accessing an interactive application. To this end, user profiles initially contain attributes specified either by the user prior to the initiation of interaction or during interaction (based on interaction monitoring). On the other hand, context profiling aims at collecting context attribute values related to [95]: (a) the environment (the physical space the user is located and relationships to other people), (b) the situation the user is in (e.g., emergency situation, someone's birthday, etc.), (c) the activity of the user and its role and (d) the service that the user has access to and/or is using.

User profiling can be classified into three main approaches: (a) **static profiling:** where the complete specification of attributes is defined prior to the implementation of the reasoning engine, (b) **extensible profiling using special purpose languages** and Design Support Tools where the logic is separated from the system performing the adaptation (e.g., DMSL [137]) and (c) **extensible profiling using semantic data modelling** where information representation uses a knowledge base in the form of a web ontology on top of which semantic web rules are used to form the logic (e.g., OWL-DL [122]). An example of the latter case can be considered the User Profile Ontology [121] created in the context of the Cloud4All project [22].

Later approaches [139] aim to provide a continuous user/context profile update and enrichment at runtime, aiming to adjust software UIs at runtime. The UI can be a single device with specific properties or a distributed configurable UI system with various input and output options. In this context, some preliminary adaptation issues include: (a) **UI adaptation for Distributed Settings** (in environments where there is a choice of input and output devices where the context is a key concept for determining the appropriate configuration [13]) and (b) **UI adaptation in a Single Display** (adapting the details in a single user interface at runtime)

Current approaches employ data stemming from user and context profiling in order to provide adaptation toolkits for dynamically generating the interface instance that is more appropriate for the specific user, in the specific context of use. These frameworks in their most advanced implementation consist of a collection of alternative interaction elements mapped to specific user and context parameters. The automatic selection of the appropriate elements is the key for supporting an exponential amount of alternative interface instantiations. An example of such approach is EAGER [32, 33], a development toolkit that allows Web developers to build adaptive applications using facilities similar to those offered by common user frameworks (such as ASP.NET and Java server faces). Another approach aiming to facilitate the implementation of adaptive-aware user interfaces for mobile services is reported in [77]. UI widgets supported by this framework encapsulate all the necessary information and are responsible for requesting and applying the relative decisions. The Toolkit employs a decision-making specification language to allow UI developers to turn hard-coded values of lexical attributes to adapted UI parameters specified in an external preference file. As a result, the UI implementation is entirely relieved from adaptation-related conditionality, as the latter is collected in a separate rule file. Moreover, similar approaches aim to provide, on top of context-aware adaptive UIs, the employment of augmented cognition techniques through the intelligent ICT environment in order to provide more intelligent UI adaptations [68, 112].

Natural Interaction in AmI environments

AmI has broadened the possibilities of users' interaction with computational systems towards new paradigms and metaphors that lead to more natural and intuitive interaction with everyday things [3]. The notion of users' *natural interaction* with the real world in everyday life, has become the prominent objective of all the approaches that have been striving to provide novel interaction techniques for AmI environments. To this end, new interaction paradigms emerged that enable the users to interact through gestures, expressions, movements, etc., to discover their digital world, which surrounds them, by just looking around and manipulating real-world objects in order to have access to digital information [160].

In addition, the emergence of Mixed Reality (MR) has made feasible the integration of digital information into the real environment, enriching and augmenting anything real with the virtual world. Users are able to interact with both these parallel universes (real and virtual worlds) by using real objects in a seamless way [171]. Advancements in computer vision approaches have made this research domain a prevalent contributor for the implementation of the envisaged natural interaction techniques for AmI environments, providing the necessary intermediate layers for interpreting users' interplay with real world to user interaction for the AmI systems. To this end, computer vision mechanisms that provide image acquisition, image processing, object recognition (2D and 3D), scene analysis, and image flow analysis, which can be exploited for humans' and objects' recognition and tracking, have been developed and used in the context of AmI environments [125]. At the same time, ICT components are embedded into everyday objects like furniture, clothing, domestic appliances, toys, etc. [4]. Augmented objects can be used for providing implicit or explicit input to systems while their physical and mental existence as computational devices disappears [151].

2.2.1.1 Gestures

Gestural interaction has become recently one of the prevalent research topics, mainly due to the fact that tangible interfaces constitute mainstream technology nowadays. Many of the research results regarding interaction through gestures fall in the context of AmI environments and natural interaction. Gestures when used in the context of human to human communication are a quick and intuitive way of communication. On the contrary, identifying human gestures in a computerized environment is not an easy task. Research conducted in this field involves the usage of gestures for providing input to augmented desk interface systems using multiple fingertips recognition (identify fingertips and their trajectories and infer gestures based on these trajectories) [120, 100]. In the same context, computer vision is used for identifying hand gestures, facial expressions and body postures [119]. Finally, gaze recognition has been employed for facilitating alternative gesture based input [116, 117, 118].

2.2.1.2 Voice interaction

One of the main aspects of user interaction in AmI environments is the multimodality that such technological ecosystems should provide. Beyond hand and body based interaction, another basic modality is speech. Voice input is the most prominent way of interaction between people and it has been an important research topic in computing. Full automatic recognition and understanding of human languages has not yet been achieved, but modern speech recognition systems are capable of understanding voice commands using a specific grammar syntax and interaction scenarios.

On the other hand, among available voice technologies, text-to-speech systems are considered the most mature. In fact, many multilingual text-to-speech synthesis systems exist, that can convert printed and electronic documents to audio, but further research is needed for structured text, tables and above all graphics to be efficiently transformed into speech. Beyond the text (commonly referred as plain text) which is the carrier of the content, almost all the different types of printed or electronic documents, like newspapers, books, journals and magazines, contain visual and non-visual metadata. Visual information includes text formatting (such as font size, colour and type, as well as typesetting like bold and italics) and simple or complex text structures (e.g., tables, hierarchical lists, scientific formulas, and layout such as columns, borders, and boxes) along with diagrams, drawings, charts, figures, logos and photos. It is interesting to note that text formatting includes domain-specific or context-specific semantics. Non-visual information in documents includes text style, like title, subtitles, header/footer, footnote, captions, etc. Most of the current Text-to-Speech systems do not include effective provision of the semantics and the cognitive aspects of the visual and non-visual document elements. Recently, there has been an effort towards Document-to-Speech synthesis supporting the extraction of the semantics of document metadata [42] and the efficient acoustic representation of both text formatting [169], [75] and tables [147], [148] through modelling the parameters of the synthesised speech signal.

2.2.1.3 Digitally augmented objects

In Ambient Intelligence environments, interaction is expected to be embedded in everyday objects and smart artefacts. As a result, employing physical objects as a means for interaction is an important attribute of natural interaction in AmI environments. Physical objects should be used with caution, making sure to involve objects relevant to the context of use (e.g., a plate on a restaurant table, a book on a reading table, etc.).

The concept of *Tangible User Interfaces* [158], refers exactly to interfaces that use physical artefacts as objects for representation and interaction. The aim is to seamlessly integrate the physical and digital worlds. The physical artefacts are often called tangible, graspable or haptic objects. Such objects couple into digital information and embody the interaction. Moreover, they couple perceptually into the mediated action and represent key elements of the AmI environment.

Tangible user interfaces build on the co-presence of user, object, and environment. They bridge the real/physical world and virtual/digital world [158]. Input and output spaces coincide and the user is part of the interaction space. The shape, colour, orientation, and size of the objects may play a role in the interaction.

Pervasive and interactive displays

A number of touch-based interactive surfaces exist both as research prototypes [129], [152, 165, 54, 52, 43] and as commercial products [97, 30, 144]. Most of these systems use a static planar surface as an interaction surface, because it can be at also used as a desk.

The first approaches towards augmented interactive surfaces [113, 69] concerned the projection of visual content on convenient surfaces in the environment, such as the walls or the floor of a room. Selecting the surfaces a priori, a projector was steered to display upon the surface of choice. Images were pre-warped according to the orientation of the surface, so as to appear undistorted after projection. However, using a more detailed 3D model of the whole scene, projections can appear undistorted at virtually any geometry of surfaces [66].

The counterpart of an interactive display is user input. Earlier approaches used electronic devices to provide input, such as the electronic stylus and touch pad [48]. Other pervasive approaches perceive coarse hand gestures and track an instrumented artefact, a stylus with an infra-red beacon, to decrease obtrusion and increase the workspace size [113, 69]. The recent growth of depth cameras enabled better tracking of hand posture and facilitated tangible interaction upon arbitrary surfaces [55]. Still, pointing devices can be particularly convenient in some tasks, particularly if implemented by an ordinary pen that maintains its common use.

Some approaches in the literature support dynamically moving interaction surfaces that can be manipulated by the user. In such cases, the location and pose of the surface itself can avail valuable information to the user interface. In [146], a coarse estimate of the inclination of a handheld surface (a piece of cardboard) provides input to an interactive game. In [46, 128] a similar surface is used to explore maps, while in [170] a 2 DOF rotating disk is used as an augmented interactive display whose position can be manipulated. Accurate pose estimation as the user manipulates the interactive surface is essential in all the above cases in order to properly project text and images upon it.

Non-visual output

Although blending gestures with visual interfaces is a common practice in Ambient Intelligence environments, there is a substantial need for providing non visual output to potential users. Several considerations lead to this requirement, but mainly the fact that in many cases requiring visual attention from a user is not always the most appropriate solution. Non-visual interfaces are frequently understood to involve tactile, haptic or audio interaction. Work with the visually impaired demonstrates that audio can serve as an effective representation for both visual and conceptual information [8, 10 and 68], and therefore audio can be considered as an effective approach for providing non visual output. In the same context, the significance of audio output has been pointed out through the creation of an audio only feedback system to be employed by users on the move (where employing user attention for visual output is not only less efficient but can also be dangerous) [92]. Towards this direction, since visual output devices may not always be available in an Ambient Intelligence environment, audio as an output channel is considered to be equally important.

2.3 The era of interactive documents

Since the early years of 90's the idea of digitally augmenting physical paper was intriguing enough to trigger the first research efforts in this direction. For example, DigitalDesk [164] and its successor EnhancedDesk [72] performed physical paper augmentation with technology, offering interaction via touch. In 1999, Mackay and Favard in [161] introduced the term "interactive paper", signifying the potential role of digitally augmented paper for the forthcoming technologies.

Since then, more sophisticated AR solutions have been proposed by exploiting the means offered by immersive environments and high quality 3D graphics. For example, MagicBook [16] provides augmentation of physical books with 3D graphics and moving avatars through VR glasses, giving to the reader the sense of living pages. The basic interaction technique in such environments is touch. Pointing and writing in augmented reality environments has also been studied, but the majority of research work is based on proprietary technological artefacts like light pens, pen with pads, haptic devices, etc. ([40], [135]).

Finally, the availability of new digital pens capable of capturing marks made on paper documents has led to the development of various systems exploiting user annotations on physical paper in order to assist the users' reading process. For example, the Anoto system [7] combines a unique pattern printed on each page with a digital pen to capture strokes made on paper. PapierCraft [79], on the other hand, uses pen gestures on paper to support active reading and allow users to carry out a number of actions, such as to copy and paste information from one document to another. Finally, the Paper++ system [83] uses documents overprinted with a non-obtrusive pattern that uniquely encodes the x-y (and page) location on the document; this code can then be interpreted by a specialized pen when it comes in contact with the paper. In such approaches specialized devices (such as the digital pens) are necessary. In order to achieve context-awareness, systems such as Paper++ have to also employ specialized paper besides the digital pen.

Natural interaction with digitally augmented printed matter

As it has already been stated, the preference of users' towards physical printed matter instead of digital paper is due to paper's affordances, but also to its simplicity and naturalness when annotating and writing on it.

A first level of categorization of natural interaction with printed matter can be based on whether the user uses his/her bare hands or other objects (e.g., a stylus) to interact.

In [168] five types of finger based interactions with printed matter are defined:

- *Interactions based on action time*: if, for a short period of time, the user pauses his/her finger on a specific point of the paper, then this maps to a GUI click (select), while a longer pause on the paper indicates a double click (open/play).
- *Interactions based on hand shapes*: this category refers to hand postures that are mapped to specific actions (e.g., hand fist corresponds to stop or abort, a "V" sign stands for zooming).
- *Interactions based on drawing*: virtually drawing simplistic shapes with finger (e.g., a triangle might restore an annotation to initial state, left and right arrows signify the transition from current state forward or backwards respectively).
- *Interactions based on movement*: moving a user's hand in a specific posture corresponds to specific action (e.g., moving hand in the "V" sign upwards stands for zoom in the whole view).
- *Interactions with two hands involved*: for example using the two index fingers together doing a pinch gesture connotes the resize of an annotation projected near the printed matter.

Holman et al. [59] introduce interaction styles that are performed using digitally augmented paper in the 3D space. They define eight interaction styles based on the natural manipulation of paper:

- *Hold*: the users can hold a paper with both their hands raising it to the air, signifying to the system that this is the currently active document.
- *Collocate*: this gesture annotates the system to prioritize the paper that the user holds against others that co-exist in the same space.
- *Collate*: while the user collates papers on a stack the in order to organize them in piles, the system assigns a separate group for each pile, in order to avoid cluttering.
- *Flip*: if the active paper is flipped by the user, then the system changes the content of the paper to the next or previous page.
- *Rub*: this gesture is used in order for the user to transfer content among two papers or among a paper and a computing peripheral.
- *Staple*: in a same way of physically stapling two papers, this gesture is used to link two different viewports into the same document.
- *Point*: a user pointing on a specific area of the paper and then raising up his/her hand is interpreted by the system as a single click gesture. If the user performs this gesture twice sequentially and in a short period of time, then this gesture is considered as a double click.
- *Two-handed Pointing*: with this gesture the user disjoints items on a single paper or across multiple papers.

On the other hand, the use of stylus or other types of pointers for printed matter interaction supports a reduced set of gestures mainly based on handwriting techniques that humans use for annotating on printed matter. In [79] a set of five fundamental types of scope selects are described, inspired by typical marks found on manuscripts, namely **underline**, **margin bar**, **lasso**, **crop marks** and **stitching marks** (across two documents). However, these types of scope selects can be interpreted as a sufficient number of commands for every system that supports them according to context of use. The use of stylus based interaction also incorporates a basic props that hand – based interaction cannot sufficiently compensate, namely **handwriting**. As mentioned in [159], *styli should be used for writing and fingers for drawing*, since the outcome of the performed survey highlighted that in terms of legibility and usability using a stylus was better than using a finger to write.

Printed matter augmentation

According to Milgram's and Kishino's "*Virtuality Continuum*" [98], printed matter augmentation in AmI environments can be considered closer to *Augmented Reality (AR)* rather than to *Augmented Virtuality (AV)*, due to two fundamental reasons: a) printed matter constitutes a basic means of interaction so it cannot be replaced by any virtual alternative and b) the philosophy of AmI is to technologically enhance the real world and not to substitute it with virtual environments.

To this end, various AR approaches emerged for printed matter augmentation. A common way for creating AR environments over printed matter is through the use of portable devices (PDAs, smart phones, tablets, etc.). For example, the gesture-based PACER system [80] supports fine-grained paper document content manipulation through a smartphone with a touch screen and camera. The users can augment a printed document through the smartphone's screen in order to perform actions such as keyword search, browse street view along a route, sweep on a music score to play the corresponding song, copy and email part of the document, etc. PaperPoint [142] enables PowerPoint presentations to be controlled from printed slide handouts on handheld devices through stylus based interaction.

Similar approaches to those that use portable devices for printed matter augmentation are based on Head Mounted Devices (HMD). These approaches offer greater immersion than the aforementioned approaches, but they depend on expensive and cumbersome equipment. Pioneer work towards this direction is MagicBook [16]. The MagicBook system uses a physical book as the main means of interaction. Users look at the pages through an augmented reality display (HMD) and they can observe 3D virtual models appearing out of the pages. The models appear attached to the real page so users can see the augmented reality scene from any perspective, by moving themselves or the book. The virtual content can be any size and is animated, so the augmented reality view is an enhanced version of a traditional 3D pop-up book. A similar approach is discussed in [166], where five educational AR exhibits are presented, based on printed matter containing special markers. In order for the exhibits to provide digital content on top of the printed matter they use the ARToolkit [10], while users need to wear HMDs.

A second category of printed matter augmentation has been introduced by Wellner in [164]. This approach requires a projector and a camera lying over the printed matter. While the user interacts, digital content is projected either on top or laterally to the printed matter. The content that is projected is 2D multimedia info or mini interactive applications (e.g., calculator, map view, slide show, etc.). Live Paper [132] transforms paper sheets into I/O devices. The Live Paper system provides audio and video augmentation, including collaboration with remote users, through video writing and projected annotations. A later approach to augmenting printed books is discussed in [26], where the concept of Projective Augmented Books is proposed. The described system consists of a mobile device with an embedded pico-projector and a digital pen. The mobile device with the pico-projector is used as a reading lamp in order to project dynamic content onto a book printed on digital paper based on Anoto Technology [7]. A digital pen and gestures are used for the user interaction with the printed book. An even more portable system that belongs to this category is PenLight [145]. This system comprises a mobile projector mounted on a digital pen similar to that used in the Live Paper system. In PenLight the projected digital content is relevant to the position of the digital pen, allowing users to visibly correlate information that is stored inside the pen or on any connected resource with the document.

A third category of printed matter augmentation includes approaches that use a companion display to provide the augmented content to the users. For example, Bridging Book [39] is a mixed - media that combines a physical book containing magnets with a touchscreen tablet that incorporates a built-in digital compass. The synchronization between the thumbing of the physical book and the digital content is achieved by placing magnets on the book pages that change the magnetic field strength detected by the digital compass sensor. Each page of the physical book has a corresponding digital set, which includes short animations and interactive elements, context and feedback sounds. Another example is discussed in [74], which offers physical interaction through printed cards on a tabletop setup, where a simple webcam monitors the table's surface and identifies the thrown cards. The system consists of two mini games based on the printed cards shown on the table: a multiple-choice quiz and a geography-related game.

Systems supporting printed matter interaction and augmentation

This sub-section summarizes representative efforts that have been performed over time towards the digital enhancement of printed matter in real-life activities.

2.3.1.1 DigitalDesk

Acting as a real pioneer, P. Wellner pursued to digitally enhance a table top surface to a fully digital desk aiming at combining physical and electronic paper activities at the same time [164]. The goal was not to make the electronic desktop like the physical desk, but "to give the physical desk electronic properties and merge the two desktops into one" [163].

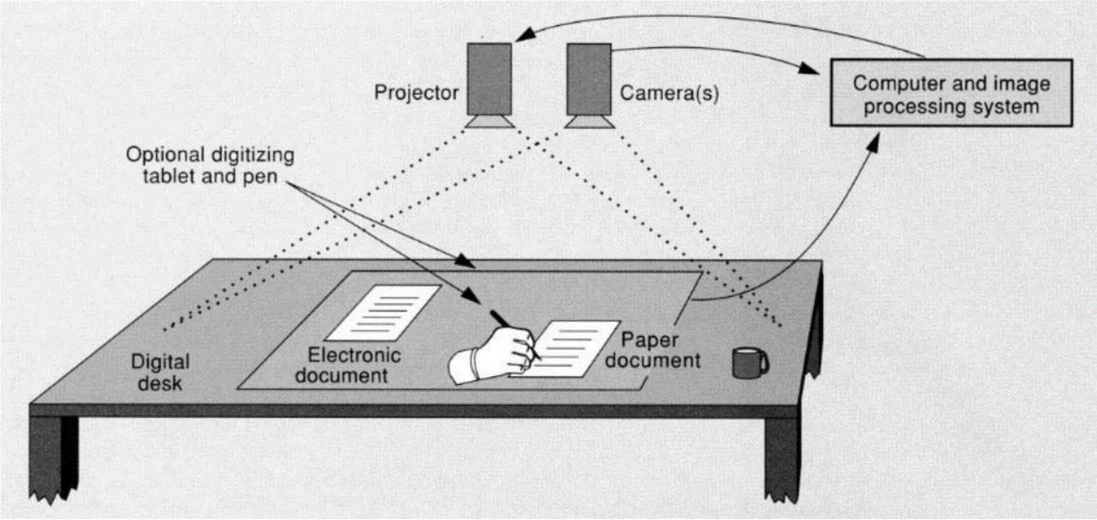


Figure 1. The DigitalDesk setup

Figure 1 depicts the system's setup, which comprised an overhead projector and camera(s) aiming at the surface of a horizontal table top surface. This equipment was connected to a desktop PC. The idea was for DigitalDesk to capture, through its cameras, activities that were happening and items that were placed on the table and provide digital feedback via the projector. The images captured by the cameras were processed by a computer vision system, which led the projector to adapt the content that should display. To interact with the DigitalDesk users could use their fingers to, e.g., move an electronic document, and a pen to, e.g., select text on a paper document.

DigitalDesk provided two applications, namely the Desktop Calculator and the Desktop Translator. The first application enabled the users to select numbers from a printed paper that was lying on the table with the pen. The numbers were automatically transferred to the Digital Calculator that was being projected on the table as well. After the two numbers were transferred to the application, the user could select a mathematical operation in order to combine them. The second application, the Desktop Translator, enabled users to mark words on paper using a pen. The system extracts the root of the word, looks it up in a French-to-English dictionary and displays the definitions in an electronic window projected onto the desk, allowing the user to point to the location where the translation should be placed on the desk.

2.3.1.2 DocuDesk

DocuDesk is another tabletop system that aims to augment physical paper with digital information. Contrary to the aforementioned systems, DocuDesk provides a digital menu next to a physical paper that has been placed on a Wacom Cintiq 21UX pen display, which actually acts as the interactive surface of the system. The displayed menu offers functionality for linking digital content or physical papers with a particular physical paper. The defined links are used to "quickly rehydrate task state when an associated document is placed atop the desk". If an annotated printed document is placed on the top of the surface, the related digital content and links, if any, that have been already stored are displayed automatically by the system.

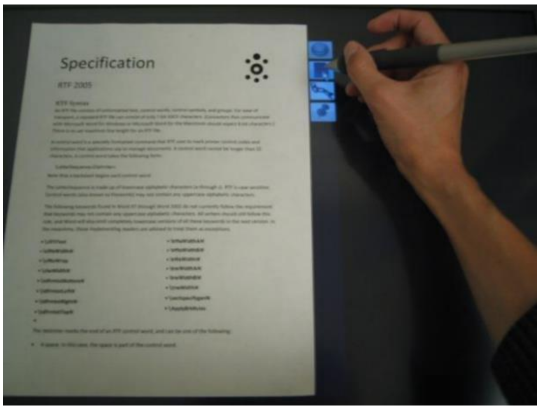


Figure 2. DocuDesk provides a digital menu laterally to the document that is placed on the top of the interactive surface of the system. Through this menu the users can link their digital annotations or other physical papers with the corresponding one.

2.3.1.3 CoScribe

CoScribe constitutes another tabletop system aiming to correlate digital with physical documents. It mainly focusses on providing advanced note taking and annotation techniques in a seamless way for both digital and physical papers. To this end, it enables users to collaboratively annotate, link and tag both printed and digital documents. An interesting feature of the system is the stylus-based interaction with a paper, no matter if digital or physical. To this end, it enables the users to mark or annotate text passages in digital or physical documents with the same device.

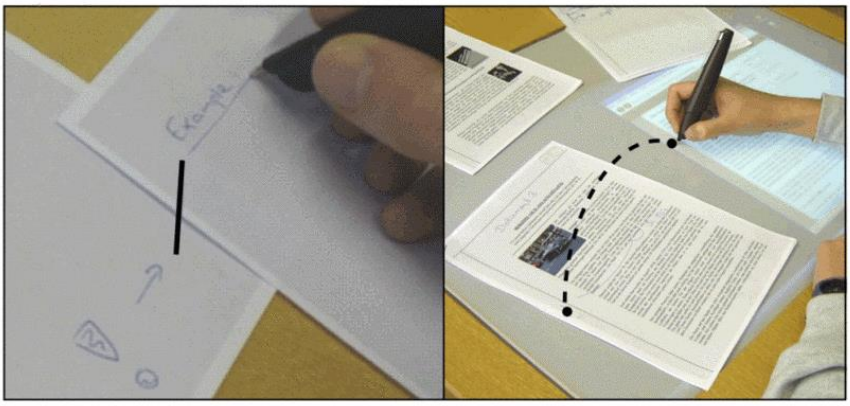


Figure 3. Creating hyperlinks with pen gestures on the CoScribe system. Left: Single-line gesture. Right: Two-part gesture.

2.3.1.4 Fact

Liao et.al introduced the Fact system [81] for eliciting textual information from physical paper in order to provide related digital information. The system consists of a pico-projector and a web camera unit that oversees the physical paper. Interaction is provided to the users through a physical pen. The system allows a user to issue pen gestures on the paper document for selecting fine grained content and applying various digital functions. For example, the user can choose individual words, symbols, figures, and arbitrary regions for keyword search, copy and paste, web search, and remote sharing. The Fact system provides visual feedback upon a user's gesture through projection on the physical paper (see Figure 4). The processing of the extracted information, as well as the provisioning of the results, are displayed either on the physical paper itself or on a nearby computer. Moreover, Fact offers features which support cross-media interaction, such as the possibility to mark text or an image on a physical paper and copy the marked content to a digital document on a laptop. Thereby the link to the original document is kept.

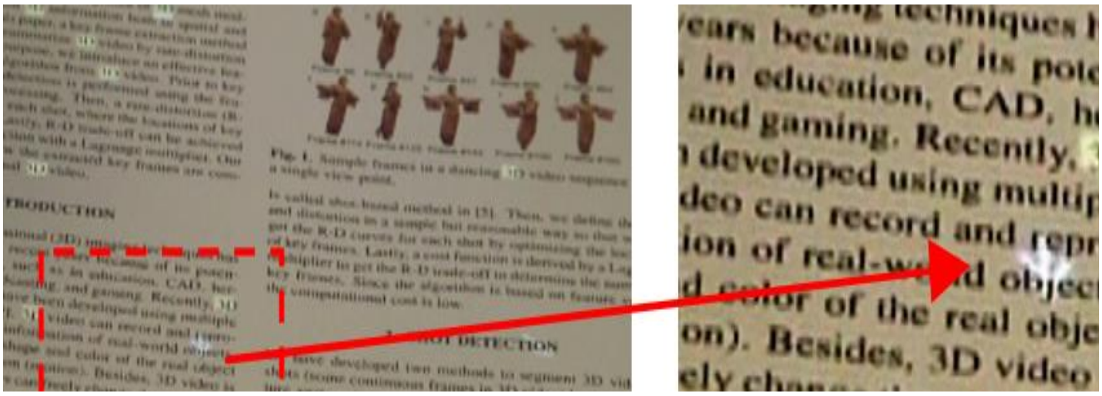


Figure 4. Fact provides visual feedback upon the physical paper. For example, projected arrows indicate the off-projection results that can be acquired by the user through a nearby laptop.

2.3.1.5 LivePaper

The LivePaper system [133] provides digital augmentation to physical papers that have been placed on a desk surface. Digital information is projected onto or laterally to physical paper and the interaction with the system is materialized using pen or touch.

However, this system provides also remote real-time collaborative functionality, thus introducing a new dimension regarding the potential of such approaches. For example, LivePaper allows the users to draw and write on the physical paper, while these annotations are concurrently transferred via the network and re-projected on another similar system. Furthermore, LivePaper provides the possibility to define links between the physical paper and digital information so that they can be related to each other.

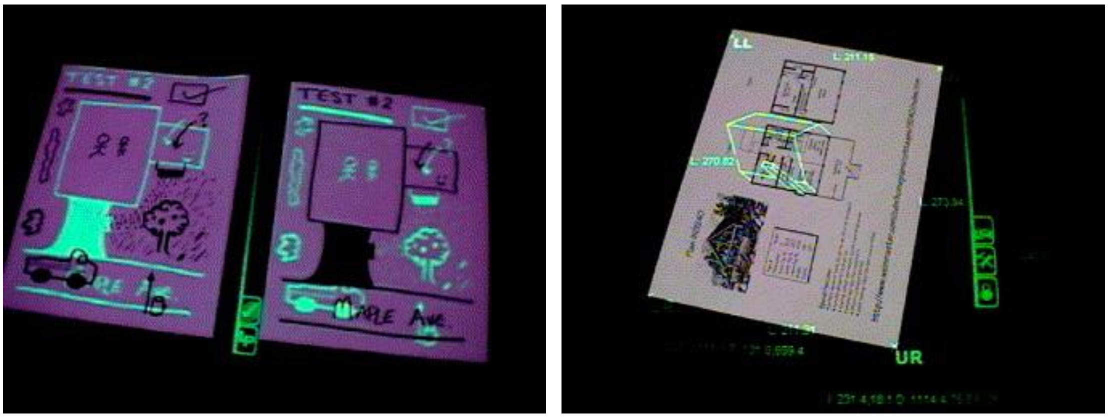


Figure 5. Left: Collaborative drawing and brainstorming application. Right: Architectural application.

2.3.1.6 PaperWindows

This system, introduced by Holman et al. relies on the concept of a number of paper-size flexible displays as an interface to a computer system [59]. These flexible displays would offer a high-resolution view of digital documents through a wireless connection, with flexibility similar to that of paper. The digital augmentation of such surfaces is being done by an overhead projector. PaperWindows doesn't require the physical objects that are used to be placed on a horizontal surface, like other similar systems. The mentioned flexible surfaces, which are used for the materialization of the PaperWindows system, carry similar affordances as physical paper. The position and shape of these flexible displays could be adjusted for various tasks: paper displays can be spread about the desk, organized in stacks, or held close for a detailed view. Direct manipulation takes place with the paper display itself: by selecting and pointing using the fingers, or with a digital pen. Paper displays could also be used globally within the context of a work environment. For example, users can share content by copying a page and physically handing it to another user. The system provides user interaction through pen or touch.

Figure 6. Left: PaperWindows prototype. Right: A paper window is placed on top of a blank page and its content is copied using a rubbing gesture.

2.3.1.7 PapierCraft

This is another system that uses digital paper in order to provide interaction with users. However, as PapierCraft [79] was designed to be used without a nearby computer, commands are executed in batch mode upon synchronization of a digital pen with a server running the system. The research conducted for the system design and implementation mainly focused on a gesture-based interface that allows users to manipulate digital documents directly using their printouts as proxies. Users can annotate a printout or draw command gestures to indicate operations such as copying a document area, pasting an area previously copied, or creating a link. Upon pen synchronization, our infrastructure executes these commands and presents the result in a customized viewer. The interesting part of this system is the classification that has been defined regarding pen-based gestures that can be used as interactive commands during a physical paper reading and annotation process, as well as, the specification of the commands scope that correspond to each gesture.

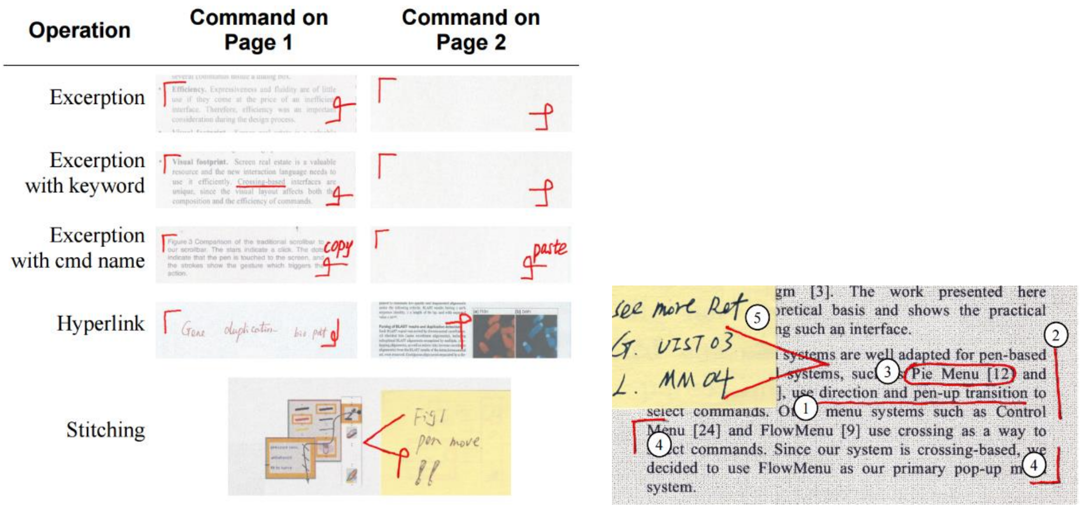


Figure 7. Left: Operations supported by PapierCraft. Right: PapierCraft scopes: (1) underline, (2) margin bar, (3) lasso, (4) crop marks and (5) stitching mark (across two documents)

2.3.1.8 Pictionaire

Pictionaire [56] provides digital augmentation of physical objects aiming to support creative collaboration across physical and digital artefacts. Interaction with the system is supported through stylus and touch, as well as mouse and keyboard. The system provides numerous functionalities, such as capture, retrieval, annotation, and collection of visual material. It also provides hybrid copy & paste operations from digital to physical media and vice versa. The creation of a digital copy of a paper-made sketch can be easily produced via a simple drag-off gesture. The other way round, the creation of a physical copy of a digital artefact, is performed by snapping a digital, projected image on a physical surface like a sketch-book. In addition it is possible to create digital images of physical objects that are placed on the table and project them on the table. Then, if a digital image projected on the table is clicked, the corresponding physical object is highlighted.

Figure 8. The Pictionaire system provides collaborative design across physical and digital artefacts.

2.3.1.9 Projective Augmented Books

This system [26] is based on digital pen and paper technology for supporting interaction with users, as well as a pico-projector for providing visual feedback. The basic principle of the Projective Augmented Books system is that the pico-projector can be used as a reading lamp but also as a means of digital information augmentation on physical paper (see Figure 9). Interestingly, the system doesn't rely to any other computational device for supporting user interaction, but incorporates a printed control-panel that depicts all the functionality supported. The user can trigger any of the supported functionality, through its pen, by clicking the corresponding button on the control-panel. Furthermore, the system enables the user to digitally annotate the physical paper. Using the printed control-panel the user can look up words in a dictionary or translate them, copy content to scrapbooks and share information through email.

Figure 9. Basic concept of the Projective Augmented Books system.

2.3.1.10 WikiTUI

This system provides top-down projection to physical paper towards the provision of digitally augmented information on top or juxtapose the paper. The basic idea of this system is to provide access the digital world through fingertip interactions on books [167]. To this end, small image cues are projected on the physical paper, which can be touched by the user in order for the system to project related information laterally to the paper (see Figure 10). Furthermore, the system offers personalized information in accordance to the user's profile. For example, the information is adapted to the user's language. An interesting functionality of this system is the possibility to access additional information about the contents of a physical book.

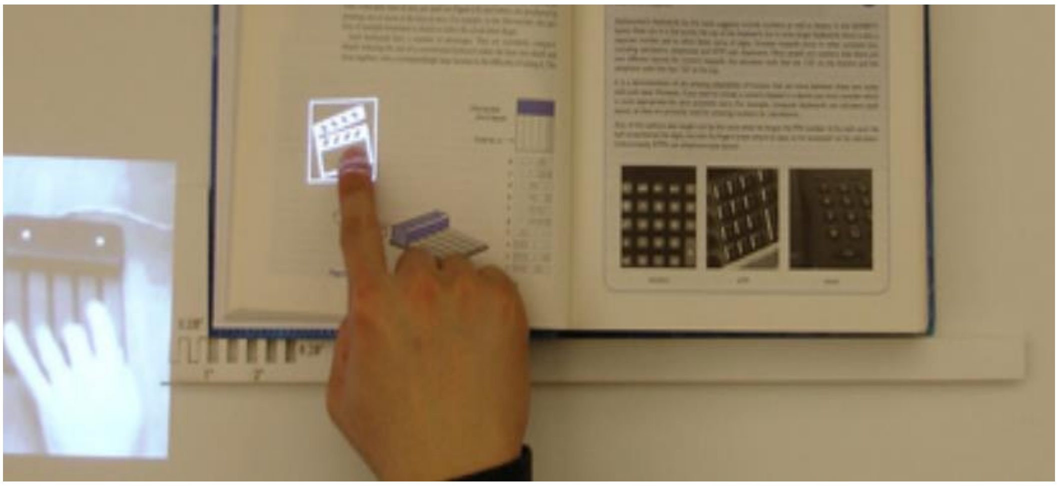


Figure 10. A user moves his fingertip to a projected image cue, which initiates an associated video at the left.

Examples of interactive printed matter in real-life domains

Printed matter is interwoven with every-day life activities. Besides the aforementioned systems that try to address user interaction with physical paper mostly in generic manner, there are several other approaches that try to elaborate on interactive physical paper in specific real-life domains.

For example, in the workplace domain, Integrative Workplace [44] provides a digital desk to support legal work. The system allows the user to search and excerpt content from digital and printed documents that may be spread on the whole desk's surface. It also provides parallel interaction with multiple paper documents. A more specialized example in the workplace domain, is Strip'TIC [60], a system that facilitates air traffic controllers through augmented paper strips. Aliakseyeu et al. [6] introduce a tool for early architectural design in an existing augmented reality system, called the Visual Interaction Platform, aiming at proving that the use of interactive physical paper systems fosters architectural design, based on paper affordances such as freedom, flexibility, abstraction, speed and ease of use.

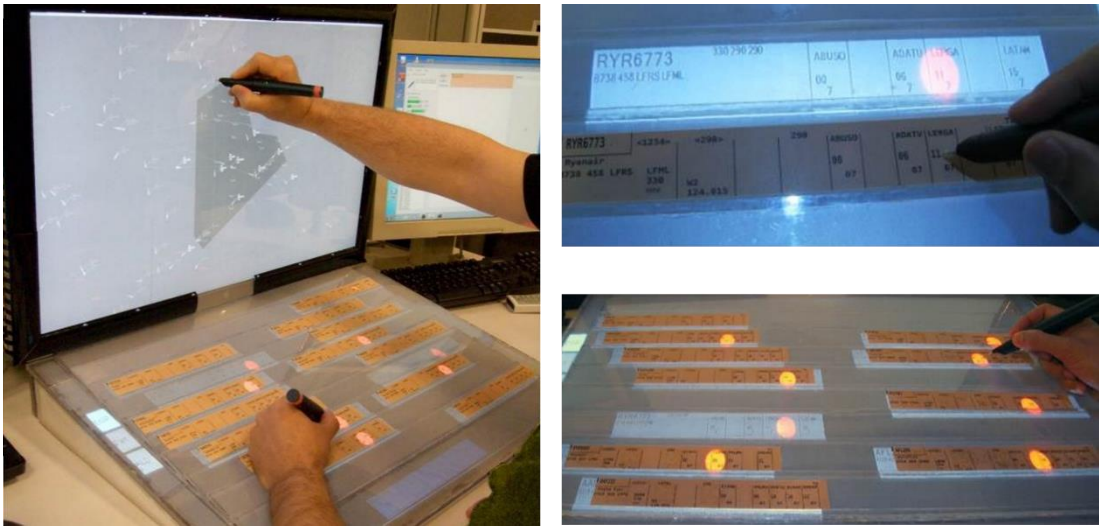


Figure 11. The Strip'TIC system providing computer aided support for air traffic controller through digitally augmented paper strips.

Another real-life domain in which interactive paper can be of great potential is cartography. For example, Reitmayr et.al in [128] present a system to augment printed maps with digital graphical information and user interface components. Similarly, the Paperview system [47] is a multi-user augmented-reality system for supplementing physical printed surfaces (e.g., maps) with digital information, through the use of pieces of plain paper that act as personal, location-aware, interactive screens. Through these paper screens the users can acquire information about areas of interest (such as coins, areas with differences, cities, etc.). Furthermore, the users can also be acquainted with more cartography-oriented functionalities, such as the projection of different map terrain types corresponding to the part of the printed map that the paper screen hovers upon, comparing different version of the map, etc.

Figure 12. PaperView: supplements physical printed surfaces (e.g., maps) with digital information, through the use of pieces of plain paper that act as personal, location-aware, interactive screens.

A creative approach to music composition, relying on the use of physical paper along with end-user programming, is Musink [156]. This system fosters the smooth transition between paper drawings and OpenMusic, a flexible music composition computer tool. Using the Musink system composers are able to add digitally captured notations to traditional music scores, and translate them as parameters for programming in specialized music composition software. Another interesting approach for music composition is the PaperTonnetz system [15], which was designed to assist creative music as opposed to computer-based tools that are specifically intended for composition and which are usually dedicated to the later stages of the creative process.

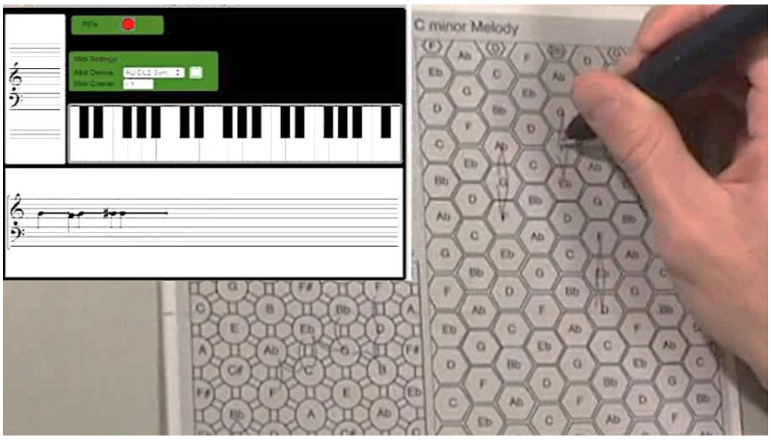


Figure 13. The PaperTonnetz system in practice. The user draws *music paths* using a digital pen and listens to the musical sequence on the computer.

In the health-care domain, Nostos [11] is a system employing interactive paper, which is intended to support clinicians at work, by enabling them to retain mobile paper–based collaborative routines and still benefit from computer technology. The idea is a hybrid system that maintains dual representations (i.e., digital and physical representations) of the same document, folder, and sticker note. Computer augmentation of established routines can be achieved by combining digital paper technology, walk–up displays, headsets, a smart desk, and sensor technology in a distributed software architecture to digitize the ordinary paper forms, folders, and desks.

Figure 14. The NOSTOS prototype.

Finally, in the education domain the notion of interactive paper can be considered as the next step in educational technologies. Although many support the idea of a transition to fully digital paperless education, using devices such as e-paper, e-book readers, or personal laptops for each student in practice printed matter still remains the basic means for learning globally in the world. To this end, the enhancement of physical paper with technology may seem the only viable path for the next years. Various research efforts focus on enhancing the educational process with the use of interactive printed matter. The most representative are discussed in this section.

Mixed reality book [51] enhances with digital 2D or 3D assets already published books, providing this way news means towards edutainment of the readers. The user can interact with the physical book using an AR headset for visualization feedback. A similar approach is the *Augmented Instructions* introduced by Asai et al. in [9]. The main idea of the discussed system was to enrich printed learning materials with additional digital information and instructions using an AR approach. Bonnard et al. in [17] present a table top system with interface elements made of paper that addresses the need of providing a more collaborative process for learning geometry in the classroom.

Figure 15. The “Paper Interfaces for Learning Geometry” system used by students in the classroom.

In [74] Korozi et al. present two educational mini-games that combine learning and AmI technology. Both these games provide physical interaction through printed cards on a tabletop setup.

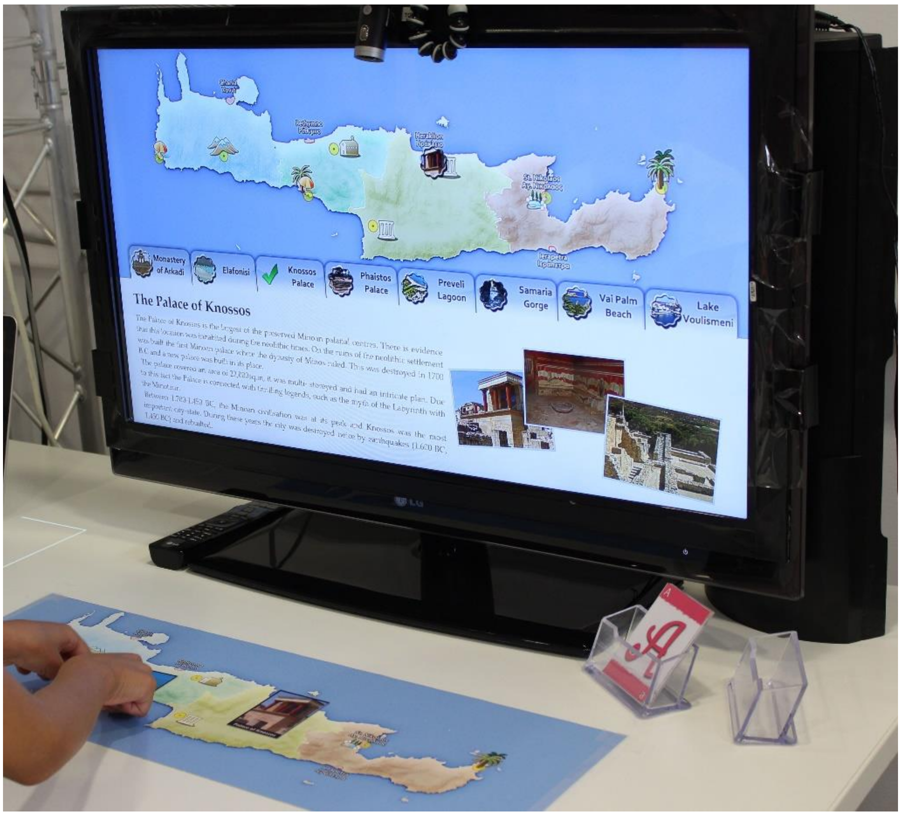


Figure 16. The Ambient Educational Mini-games system.

2.4 Integrating interactive documents in AmI environments

Several interactive printed matter solutions have been realized over time, while the notion of enriching physical paper with technology was conceived in the last years of the previous millennium. In [143], several future technical and non-technical challenges are outlined in terms of device independence, digital ink abstraction, application deployment, visual encoding, interaction design, as well as authoring and publishing. All these new aspects will constitute the objective of future efforts while the idea of interactive printed matter constantly evolves.

On the other hand, the emergence of smart environments, ubiquitous computing, Internet of Things and mainly the notion of Ambient Intelligence, provide nowadays opportunities towards a better integration of interactive printed matter in our everyday living. It is easy for someone to imagine the big potential of employing interactive printed matter systems and approaches in AmI environments maintaining a very common and necessary human practice, such as the use of physical paper, in our real-life. Although the impact of such potential is more than profound, currently there is a lack of approaches aiming at merging these two aspects in an integrated and holistic approach.

Figure 17 depicts a conceptual roadmap of printed matter evolution, as a basic means of static information, towards interactive and context-aware information provision in technologically intelligent environments. A missing link in the evolutionary chain is the absence of a systematic and holistic approach that will merge current printed matter augmentation and interactivity with AmI environments.

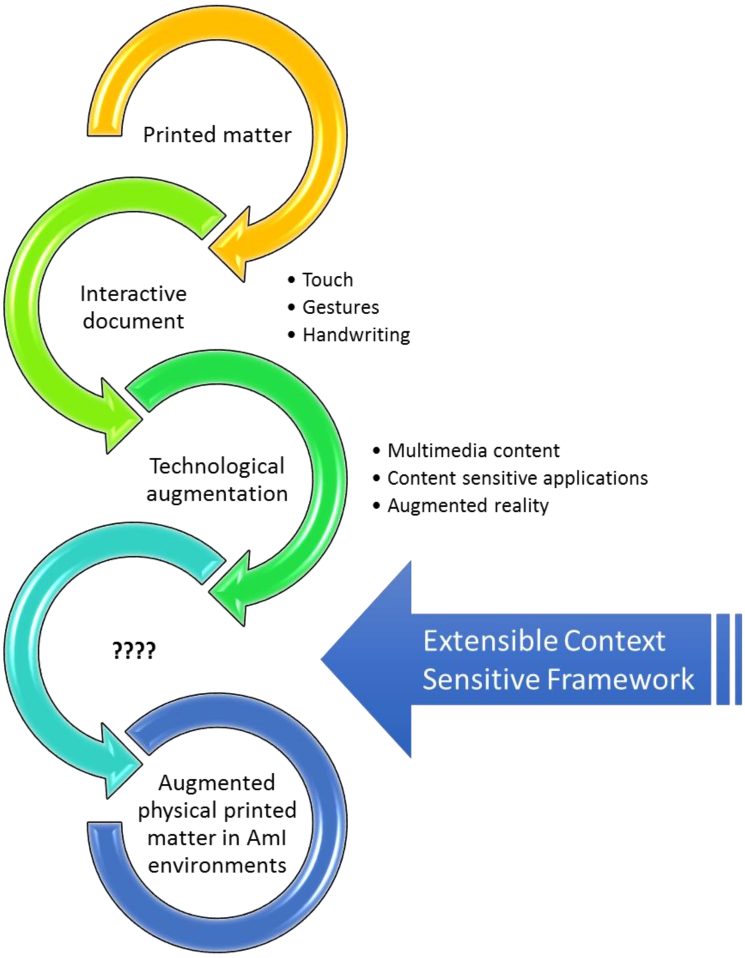


Figure 17. From printed matter to augmented printed matter in AmI environments

Towards this end, a systematic approach is discussed in the context of this PhD thesis, elaborating on the development of an extensible context-aware interaction framework which will enable the integration of printed matter into AmI environments.

This extensible and context sensitive framework captures all the necessary components for facilitating the integration of AmI applications that use printed matter interaction during their whole implementation and deployment lifecycle. The framework has been implemented according to a service-oriented-architecture (SoA) that makes feasible its easy integration into already existing AmI environments. Additionally, an ontology-based model for printed matter interaction modelling in AmI environments has been defined, which can be easily extended in order for the framework to incorporate new means of information acquisition, processing and visualization that may emerge in the future, making it thus fully extensible.

In summary, the InPrinted framework provides:

- open architecture, enabling the integration of new types of technologies for information acquisition and provision,
- independency from the applications' development technologies
- an extensible ontology based reference model for printed matter, context-awareness and anticipation mechanisms,
- implementation of printed matter augmentation mechanisms in the environment
- support for multimodal natural interaction with printed matter in AmI environments.

An important contribution of this thesis is the elaboration of a sustainable and robust mechanism that can be easily integrated in any AmI environment and support natural interaction with and digital augmentation of printed matter. Furthermore, the proposed framework constitutes a stepping stone towards the efficient development of applications that incorporate physical interaction with printed matter in AmI environments, through implementing fundamental mechanisms such as global interaction handling, reasoning and printed matter augmentation. These mechanisms are integrated into the basic AmI infrastructure and can be used as services of the infrastructure. Moreover, ready to use printed matter augmentation components and semantic content analysis tools have also been developed, thus fostering the easy creation of AmI applications.

3 Requirements analysis

This chapter pursues to identify and discuss the requirements of the InPrinted framework in terms of human-computer interaction, technological augmentation and context-awareness.

The next section introduces four *Personas* as representative users, while exemplifying scenarios follow, highlighting requirements that should be addressed regarding users' natural multimodal interaction with the environment, printed matter augmentation and system's context awareness and anticipation.

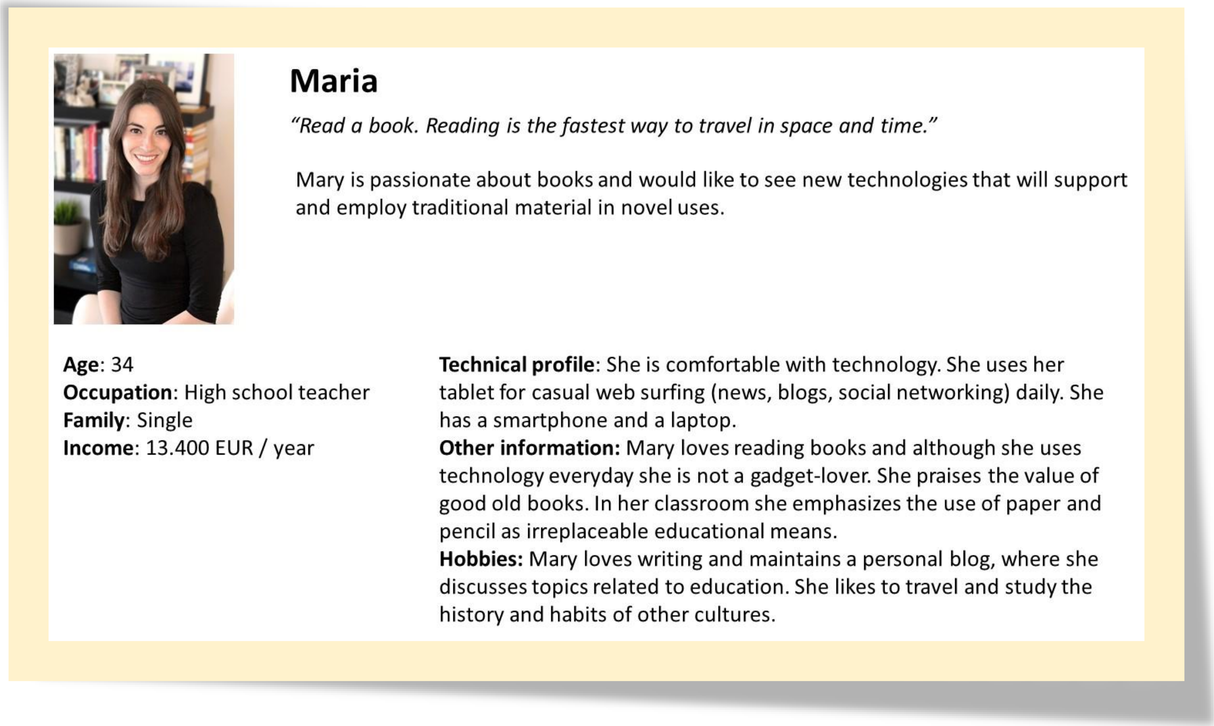
The requirements stemming from the personas and scenarios have been further enhanced through the literature review of relevant systems that has been carried out in the context of this thesis, including published papers, reports, journals, conference proceedings, and books.

3.1 Personas

The concept of "*Persona*" was originally introduced by Cooper [24]. A persona is a precise description of a user's characteristics and what he/she wants to accomplish.

According to Cooper, the construction of a persona needs to be based on sound field research and should/could be presented in text and/or image. A persona is usually generated to help designers understand, describe, focus and clarify user's requirements and behaviour patterns.

Four representative users (Personas) with different demographic characteristics, background and technology expertise were created to assist the generation of scenarios for requirements specification.



Kristen

"Life should be colorful like a nice bouquet of flowers"

Kristen would be interested in technologies that will assist her with her daily activities and health management tasks.

Age: 68
Occupation: Retired florist
Family: Widow
Income: 17.800 EUR / year

Technical profile: Kristen owns a standard mobile phone and a laptop. She loves web surfing to find recipes, read news, and connect with friends through social networking sites.
Other information: Kristen loves cooking not only traditional recipes, but also more sophisticated ones. She suffers from mild headaches, diabetes and arthritis. She has recently become a widow and there are times when she catches herself feeling quite depressed. She has four grand children and enjoys cooking for them and spending time with them, at home or outdoors.
Hobbies: She loves reading, knitting and playing card games. Occasionally she visits the local Community Center for the elderly where she meets friends and participates in the Center's planned activities, such as excursions, errands, etc.

Jason

"Feel the force!"

Jason is an active teenager who dislikes typical studying tasks. He wishes studying and learning could be as fun and adventurous as gaming is. He would like to employ new technologies to make studying and learning more interesting.

Age: 14
Occupation: High school student
Family: Lives with his mother, stepfather and five years old brother.

Technical profile: Jason is very familiar with technology. He owns a smartphone, mp3 player, game console and computer.
Other information: He loves sports and music games, featuring gesture based interaction. When he has no obligations for school, he stands in front of his television, to which his game console is connected, waiving and jumping.
Hobbies: Jason likes listening to music, watching movies, and hanging out with his friends. His favorite movie is Star Trek.

Peter

"Come play!"

Peter is enthusiastic about technology, but he also loves his books, CDs, board and card games.

Age: 5
Occupation: Kindergarten student
Family: Lives with his mother, father, and his fourteen years old brother.

Technical profile: Peter is enthusiastic about technology and a keen learner. He loves to watch his older brother play games in his game console and tries to participate as well. He uses his father's tablet to play games, watch videos and photos.
Other information: He loves reading and watching cartoons with his favourite character, John the giraffe. He loves playing board and card games, listening to music and dancing. His favorite toy is a railway and train set.

3.2 Scenarios

Following the scenario-based design approach [135], six scenarios have been developed in order to describe AmI applications that could be developed and deployed applying the InPrinted framework. These scenarios, based on the aforementioned personas, illustrate printed matter interaction in AmI environments.

Maria @ school

It is a typical Monday morning. Maria arrives at school and directly heads to her classroom, the first of the day. She greets her students, some of whom are still sleepy: "Good morning everyone! Please be seated and let's start. I feel like reading poetry today". Maria sits in her desk, while her students reluctantly take their places. The classroom Maria teaches is a *smart* one: it is equipped with smart teacher and student desks, which collaborate and transparently support all classroom activities. Each desk is equipped with a camera, microphone, headphones and a small screen. As soon as the teacher logs-in to her desk she can see who is absent today (which student seat is empty) and directly contact his/her family. Besides administrative tasks, the desk supports teaching through physical book recognition, hand writing recognition and information augmentation. Maria opens her book at a specific page and her smart desk directly recognizes the page and prompts students through an appropriate message on their screens to also open their books at the same page. Today the class is going to study a poem by Constantine P. Kavafis, titled Ithaca. Maria starts reading the poem: “As you set out for Ithaca hope that your journey is a long one, full of adventure, full of discovery. Laestrygonians and Cyclops, angry Poseidon-don’t be afraid of them …”. Ten minutes later she initiates a discussion on the meaning of the poem. She circles the word Ithaca with her pencil. “Do you know where Ithaca is?”. Her desk opens the article of an encyclopaedia indicating that Ithaca is a Greek island located in the Ionian Sea. She selects to share this information on the classroom’s smart board. “Ok, and what about Ithaca? And who are the Laistrygonians and the Cyclops?”. Nobody seems to know, so Maria underlines in her book the words “Laistrygonians” and “Cyclops” with her pencil. A definition for each word is displayed on her desk and Maria sends both definitions to the smart board for everyone to see…

Maria @ home

Later in the afternoon, Maria is at home preparing the next day’s class. This week she is introducing famous Greek poets to her students, so after Kavafis, she is going to present Odysseas Elytis. She sits at her smart desk, which features a projector and speakers and supports physical paper recognition, as well as touch, gesture-based and pen-based interaction through a stylus. Maria can use a stylus either to write notes on the physical book, or to keep virtual notes on the book or laterally to it on the desk, by using the opposite side of the stylus. She opens her book at the page of the poem “To axion esti”: “Inner Sun of Justice, And you, oh myrtle, glory-bringing myrtle, I implore you; please do not do not forget my country…”. She reads the poem and looks at the accompanying images in the book. Maria finds an interesting photo on the book picturing the poet receiving the Nobel Prize. She would like to create an assignment for her students, who will be asked to write a short essay for the poet’s award. She writes with her stylus the words “Nobel prize” on the page margin. Then she underlines the annotation, indicating that it is a title for organizing relevant material and notes. As a result, the system opens a new box where she can "throw" images, text passages, or type her own text with the help of a virtual keyboard. Maria keeps some notes and then virtually draws with her fingers crop marks on the upper left and bottom right corners of the poet's award photo, indicating thus that she would like to further work on it. The system displays three options: "Find relevant material", "Copy", "Annotate". Maria selects the first option through touch, the system finds relevant images and a gallery of multimedia is displayed on her desk right next to the book. The multimedia gallery features other images related to Elytis, photos from his life, photos from his collages' art book "The room with the pictures" and videos from concerts with songs based on his poems. Maria marks images to be placed in the "Nobel prize" box with a tick gesture. After finishing her work, Maria remembers that she had seen an interesting photo of a collage. With a pinch gesture she selects to view it enlarged. Then, with her stylus she draws its contour, creating a sketch of it. Finally, she selects to send her drawing to her web mail account, in order to upload it later to her blog.

Jason @ school

It is Monday morning and Jason is in Maria's class discussing about the poetry of Constantine P. Kavafis. He is bored and reluctant to participate. However, he begins to become more motivated when the teacher says: "*I have a riddle for you. Can you unravel the mystery of Ithaca?"*. Then, as Maria keeps "throwing" clues on the classroom's smart board he becomes more eager to solve the mystery first. Maria assigns students to teams and leaves them a fifteen minutes to gather information and provide an answer. Jason works with his friends Myriam and Daphne. Each one reads the poem and looks for clues. When a student finds an interesting piece of information, he/she can share it with his team through the collaborative area of their smart desks' screen. The smart desks are equipped with a camera, microphone, headphones and a small screen and they support interaction with physical means (paper and pen), as well as with digital devices (e.g., smartphones). Jason circles the word Ithaca in his book in order to retrieve additional information about it. A results page is displayed in his screen with several results: an encyclopaedia article, a song, a map, and a reference to Homer's

Odyssey. Myriam and Daphne each look up the words Laistrygonians and Cyclops. After a few minutes their shared screen displays three references to Homer's Odyssey, among other things, so they easily guess that Ithaca refers to Odysseus's journey as described by Homer. Through their smart desks they send this information to their teacher, who directly provides them with a printed map, depicting Odysseus's course from Troy to Ithaca. The three children sit together and study the map. They use their smartphone as a lens above the map. Smartphones are a means for digitally augmenting the physical map, since by placing the smartphone over the appropriate map areas they receive multimedia information related to specific hotspots, such as images, music, videos, and text. Jason, Myriam and Daphne follow Odysseus's adventures and watch images of his encounters with mythical creatures: the Laistrygonians, Polyphemus the Cyclops, Circe, the sirens, etc., until they arrive at Odysseus's homeland, Ithaca. The children feel as if they are traveling with the poet's hero and understand that although Odysseus's way was long and adventurous until he reached home, he has learned valuable life lessons through this journey and he has become wiser. They agree that this must have been what Kavafis meant in Ithaca, so they raise their hands to inform their teacher that they solved the riddle.

Kristen @ home

It is Saturday morning, Kristen is at home, sitting on her sofa and reading a magazine. Kristen has lately moved to a modern smart home, equipped with several facilities that among other things help her to manage daily tasks, remind her to take her medicines, assist her in monitoring her health and contact caregivers. Right next to the sofa, she has placed a smart reading lamp. The lamp is equipped with a camera, speakers and a microphone. Kristen flips through the magazine pages when she notices an interesting cake recipe. Her grandson will become six years old in a few days and she has promised him to bake his birthday cake. While she reads for a couple of minutes the recipe, the smart lamp instructs the home infrastructure to ask her: *"Would you like me to add this to your favourite recipes?"*. Kristen responds *"Yes please!"*. Then she points with her finger at the ingredients and the smart lamp announces the relevant options: "Check ingredients", "Enlarge", or "Read aloud". Kristen selects the first option and the lamp checks with the smart refrigerator and the smart cupboards the availability of the recipe's ingredients. The lamp announces to Kristen that there is a lack of milk and asks her whether she wants to order a bottle from the online grocery store. She answers "Yes please" and continues reading her magazine.

A little while later she closes the magazine, but remains sited on the sofa, thinking that it is the first year her grandson will blow the cake candles without his grandfather. The environment notices that she is inactive, the magazine is detected closed in front of her and the health monitoring infrastructure detects that her skin conductivity has increased, which indicates that she is becoming stressed. The environment starts playing music and displaying photos with her grandchildren in the television in front of her. Kristen remembers that she would like to add some more photos to her digital photo gallery and decides to do so right away. She takes a pile of photos and starts placing them one by one below the smart reading lamp. Each photo is transformed to a digital one and the system prompts her to provide a title or annotation and classify it to a specific category or album. While viewing one of the photos, Kristen cannot remember one of the depicted persons. She circles its face with her finger in order to instruct the system to provide information about it, so that she can provide an appropriate photo title. Each new digital photo is presented on Kristen's TV accompanied with its title and category.

A few days later, Kristen is in the kitchen in order to prepare the birthday cake. She places the magazine with the recipe on the smart counter and since it is already in her recipes' list, the system assumes that she is going to prepare this recipe. As a result, it starts reading the recipe, beginning with the ingredients. Kristen gathers the ingredients in front of her, and says "Ok". Then, the smart counter starts reading the recipe steps. Having her hands not clean to touch the magazine, whenever she completes a step, she places her palm above the right-hand side of the open magazine signifying a next gesture. The system reads the next recipe step, and this goes on until Kristen places the cake in the oven. The cake will need to be baked for about one hour, before she can decorate it with her grandsons' favourite character: a funny little giraffe, John.

Kristen on the go

It is Thursday afternoon and Kristen is heading towards the Community Centre for the elderly, for her weekly bridge game. She is in the subway station, when she is handed a leaflet about a children's play with John the giraffe, her grandson's favourite character. The play is scheduled for the next day, but she is not familiar with the address of the theatre. She approaches the "Smart documents table" located at the station, where citizens can use printed documents to receive digital information such as location details. The table features a projector, and can be operated through touch and gestures on the table surface. Kristen places the leaflet on the table and the system provides a set of relevant options (find route, play trailer, book tickets). She selects the first option and the system provides a digital map over which proposed routes are displayed starting from the current subway station and ending to the Theatre. Kristen selects her preferred route and touches the print icon, displayed in the top right corner of the map, she receives her printout and continues her way towards the Community Centre.

Peter @ the library

Peter is visiting the local library with his grandmother Kristen. He loves books and as a result he is a regular visitor of the library in order to borrow books. During the last few months his school teacher has started teaching children in her class how to read and Peter is very excited about this. He and Kristen find a book that aims to support children in their first reading activities. The book contents are organized around phonemes. For instance, the first chapter, *"The cat on the mat"*, introduces the vowel's "a" sound, and the "at" combination. Each book page features an image, accompanied by a short text passage, including words and rhymes using the specific phonemes. What's more, the book is also supported by the smart table of the library and is accompanied by printed cards to support interactive educational games. Peter places the book on the table and the system welcomes him and plays an introductory video displaying its capabilities. Following the video instructions, Peter opens a book page and points with his finger on the text. The system starts reading aloud: "The fat cat sat on the mat". A few minutes later, Peter finishes the first chapter and a suite of card games is initiated to enhance his comprehension. The first game displays words in a nearby screen and asks Peter to throw on the table a card depicting the indicated word. The next game involves comprehension questions that can be answered by selecting the appropriate cards (e.g., “What animal sat on the mat first?”). Finally, a spelling game asks Peter to spell specific words, by placing letter cards on the table in the correct order. Peter with the help of Kristen successfully spells all the words. Kristen finds the software very interesting and asks the library staff if she can buy the same application for her smart lamp, so that Peter can also practice at home.

3.3 Requirements

Following the literature review and a careful analysis of the elaborated scenarios, this section summarizes the requirements that should be met by the InPrinted framework for supporting interaction with printed matter in AmI environments.

Paper based interaction modalities

Table 1 summarizes interaction modalities that should be supported by the InPrinted framework in order to enable printed matter interaction with the AmI environment.

Table 1. Interaction modalities for printed matter interaction

Modality	Description
Hand gestures	This category includes interaction through hand and gestures (e.g., touch, two fingers’ pinch, drawing simplistic shapes)
Stylus based gestures	This category refers to typical marks found on manuscript annotations (e.g., underline, margin bar, crop marks)
Handwriting	Handwriting constitutes a fundamental modality for printed matter interaction and refers to human inscriptions that can be interpreted to meaningful text.

Voice commands	A complementary modality that provides enhanced interaction if used along with printed matter.
Use of smart objects	Technologically enabled components, such as portable devices, are able to provide UI components for printed matter interaction.
Printed matter interaction	Interaction with printed material can be feasible through other printed material (e.g., printed cards thrown on a printed map)

Augmentation of printed matter

Table 2 summarizes augmentation types that should be supported by the InPrinted framework.

Table 2. Augmentation types

Augmentation	Description
Smart objects & Companion displays	Smart objects and companion displays may augment printed matter by enriching it with digital information (e.g., images, videos, animations, text). Examples include smartphones, tablets, smartwatches, etc.
Information overlay	Printed matter can be enhanced with additional information displayed on top of it, or laterally to it through a projector
Audio and voice output	Voice output and audio cues may augment printed material by providing additional information or interaction options
Text to speech	Text to speech technology can be used to convert printed matter to audio, so that it can be used in situations where the user’s visual focus is elsewhere

Context awareness

Context awareness determines how the AmI environment should adapt to best serve the user's needs for every given context, and is affected by the parameters displayed in Table 3.

Table 3. Context awareness parameters

Parameter	Description
User	The specific characteristics of every user may guide context awareness and system adaptations. User characteristics that may affect system decisions include age, education, experience with technology, experience with the specific system, health conditions, emotional condition, etc. For instance: - when an older user interacts with (e.g., points at) a hotspot of a printed matter, the options provided by the system should include "Enlarge" and "Read aloud" - if an inexperienced user interacts with printed matter, the options provided should include the help option
Environment	The physical environment in which the printed matter is used impacts adaptation decisions. Environment characteristics that should be considered include: whether it is a private or public environment, the level of noise of the environment, the presence of other users and their role (e.g., active or passive users of the system), as well as the main goal of the specific environment. For instance: - When a recipe is read in the living room, the system may provide additional information about it and check for missing ingredients. When the recipe is read in the

	kitchen, the system should provide step by step guidance to the user towards actually preparing it. - When a user interacts with a book in a classroom setting, the information retrieved may need to be shared with others (e.g., through the smartboard). On the other hand, when the same interaction occurs in a personal environment, the information retrieved may be used for personal studying purposes, such as to compose an essay.
Content	The actual content of printed matter guides context-related decisions that the system has to make. For instance: - when the user is interacting with a recipe, one of the options that the system should provide should be "Check ingredients" - when the user is interacting with a map, options for finding routes should be readily available - when the content is educational, options related to educational activities should be provided (e.g., if the user is a teacher options and user interface controls supporting assignment creation and delegation should be provided, whereas if the user is a student options for working on an assignment and submitting it should be availed).
Interaction	The supported interaction modalities are an important parameter of context awareness, as the system adapts its functionality and behaviour according to the supported interaction techniques. The combination of different modalities is also important for context-related decisions. For instance, a system that supports voice input and gestures

	will be different from a system that supports handwriting, even when used by the same user in the same environment and featuring the same content.
Augmentation	The augmentation techniques that a system features affect its behaviour and guide adaptation decisions. For example, when a recipe is augmented by using a nearby screen, multimedia information may accompany it. When the same recipe is augmented through text to speech, limited information divided in appropriate chunks should be provided for it.

Printed Matter Model 4

4.1 Introduction

As already discussed in the previous section, the InPrinted framework provides the necessary tools and a software infrastructure for developers to easily integrate their systems in AmI environments. A basic concern in this respect is supporting context-awareness activities, such as acquiring context from various sources (e.g., sensors, databases and agents), performing context interpretation, carrying out dissemination of context to interested parties in a distributed and timely fashion, and providing programming models for constructing of context-aware services, through an appropriate infrastructure [53]. To this end, ontologies are key requirements for building context-aware systems for the following reasons [21]: (i) a common ontology enables knowledge sharing in an open and dynamic distributed systems, (ii) ontologies with well-defined declarative semantics provide a means for intelligent agents to reason about contextual information, and (iii) explicitly represented ontologies allow devices and agents not expressly designed to work together and interoperate, achieving "serendipitous interoperability". As a result, in accordance with the requirements analysis presented in the previous section, a new ontology meta-model scheme has been designed.

For the genericity of the framework's approach, physical paper is considered as a subclass of printed matter. It should be noted that white paper doesn't provide any content and therefore it can be incorporated as soon as anything is written or printed on it. Physical paper can be considered as printed matter as soon as something is written, projected or printed on it.

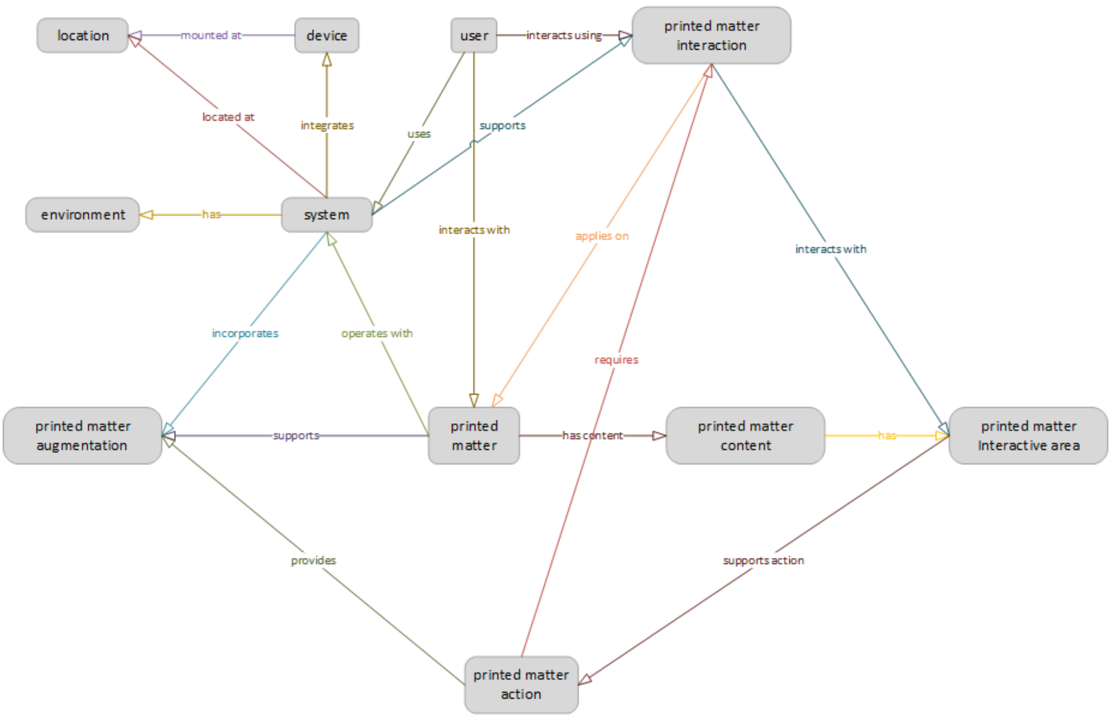


Figure 18. The InPrinted framework's ontology meta-model

Figure 18 depicts the basic entities of the ontology meta-model scheme as well as their inter-relationships. In more details:

- **printed matter** constitutes the generic class that describes the common properties of physical paper or any similar matter that contains handwritten or printed information.

- **printed matter content** is a generic class referring to handwritten or printed information on the matter. This class can be the generalization of the document entity and its subclasses are as defined in [14].
- **printed matter interaction** generalizes the potential ways of users' interaction with printed matter. Direct subclasses are: (a) gestural interaction (e.g., cycling a paper region, making a pinch gesture), (b) handwriting using a stylus object and (c) pointing / clicking either using fingers or stylus objects.
- **printed matter augmentation** is divided in two subclasses (a) intrinsic augmentation that includes all augmentation techniques that apply on the printed matter itself, and (b) extrinsic augmentation that regards augmentation techniques which apply laterally or at a short distance from the printed matter.
- **printed matter interactive area** refers to the types of interactive areas that can be found on printed matter: (a) illustrations, referring to any type of illustrated picture of figure (e.g., images, graphs), (b) text, referring to any handwritten or printed textual information, and (c) input field, referring to any type of printed placeholders that need users' input (e.g., text fields, checkboxes, etc.) and (d) math equations.
- **printed matter action** represents a single action that should be triggered by the InPrinted framework when a specific printed matter interactive area is engaged in a user interaction. The outcome of this action will eventually be interpreted into an individual printed matter augmentation.
- **user** captures users' needs in an AmI environment. It can be extended by user attributes or entities, such as users' profile, or their role and potential tasks that they may perform in the context of an environment.
- **system** a generic class of AmI stystems, ranging from single smart artefacts to sophisticated platforms (i.e., sophisticated systems comprising multiple sensors, running various services and running on heterogeneous hardware).
- **device** refers to any type of device/agent/primitive service (e.g., touch device, users' locator service, etc.) that is employed in an AmI ecosystem. Any device entity can be incorporated in more than one systems.

- **environment** a generic class that defines environmental properties. Directly correlated classes are the location of the systems, the time that users' actions are performed and the environmental conditions in terms of temperature, pressure, humidity, lighting and noise.

The proposed ontology meta-model can be easily extended using existing ones, such as for example [114], providing thus an open ontology scheme that can be used for context awareness in AmI environments.

The implementation of the proposed ontology meta-model in conjunction with a rule-based reasoner constitutes the Context manager module of the InPrinted framework, which is responsible for providing context awareness to the applications using the framework.

4.2 Printed matter model

Printed matter, in the context of the presented approach, is considered as any physical object that carries the physical paper's affordances and can be recognized uniquely based on what has been printed / written / projected on it. For the representation of printed matter the framework's scheme uses "printed matter" and "printed matter content", which are connected through the relationship "has content". Furthermore, the "printed matter entity" is directly correlated to "printed matter augmentation" in order for the InPrinted framework to populate the types of digital augmentations which can be supported by a specific printed matter. Finally, the relation between the "printed matter" and the AmI "system" is also defined, illustrating this way the system (among the available ones) in which a particular printed matter is used. The aforementioned relationships are depicted in Figure 19.

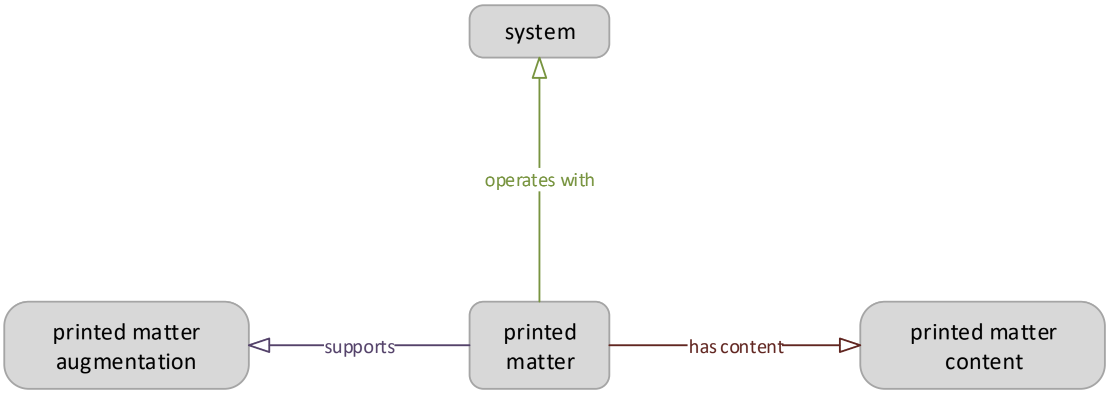


Figure 19. Printed matter model

Table 4 summarizes the properties of the “printed matter” entity of the scheme.

Table 4. Printed matter entity properties

Property name	Description
printedMatterId	A unique id number that is assigned to any new printed matter has been employed in the AmI ecosystem.
printedMatterDimensions	Provides the Width, Height, Depth properties of the printed matter
hasContent	Refers to one or more “printed matter content” entities that constitutes the specific printed matter.
operatesWith	Refers to one or more AmI “systems” that have been employed in the AmI ecosystem. This is a dynamic property that is being updated any time the framework perceives that the specific printed matter is used in the systems of the AmI environment.
supports	Refers to the “printed matter augmentation”

The content of each printed matter is represented by the “printed matter content” entity. For the purposes of the InPrinted framework, this entity captures two dimensions of the printed matter content: (a) the content itself along with its structure and (b) the type of interaction that can be applied on any part of such content.

In order to address the structure of the content that a printed matter potentially may contain, the bibliographic ontology [14] has been incorporated into the framework’s ontology, as a sibling of the “printed matter content” entity. The Bibliographic Ontology describes bibliographic entities. This ontology can be used as a citation ontology, as a document classification ontology, or simply as a way to describe any kind of document. Figure 20 illustrates the hierarchy of the “document” entity of the bibliographic ontology and its siblings as well.

For defining the interactive parts of a printed matter content the relationship “hasInteractiveArea” has been defined between the “printed matter content” and the “printed matter interactive area” entities.

Figure 20. The bibliographic ontology

Table 5 summarizes the properties of the “printed matter content” entity of the scheme.

Table 5. Printed matter content entity properties

Property name	Description
hasInteractiveArea	For each of the interactive parts of the “printed matter content” this relationship is defined for signifying to the framework the type of interaction that should be provided.

4.3 Interaction model

In accordance with the requirements analysis, user interaction with printed matter can be classified into three basic categories: (a) basic, (b) gestures and (c) combined. These types of interaction, as well as their instances, have been modelled in the InPrinted framework’s scheme under the “printed matter interaction” entity. The instances of each category are illustrated in Figure 19 and described in sub-section 5.4 “Interaction manager”.

Any interaction with the printed matter in an AmI environment is triggered by a specific user, either explicitly or implicitly. This notion is captured by the scheme via the “interacts using” relationship which is defined between the “user” and the “printed matter interaction” entity. Additionally, the “interacts with” relationship between the “printed matter interaction” and “printed matter interactive area” entities, outlines a user’s interaction with a specific printed matter. Once the relationships between the user, the printed matter and the interaction that is committed have been defined, then at a second level the type of interaction, as well as the printed matter interactive parts are also defined. In particular, each printed matter content can comprise one or more “printed matter interactive areas” through the definition of the “has” relationship between the “printed matter content” and “printed matter interactive area” entities.

Printed matter interactive areas are categorized into four basic types:

a) **illustration**: referring to any type of printed illustration (e.g., photos, images, figures, charts, drawings, etc.),

b) **text**: includes any textual information that can be used in a printed document, such as document body, captions, references, etc.,

c) **input field**: this type adheres to any part of a printed matter content that requires user's input (e.g., handwritten or typed text, a stylus gesture, drawing, etc.),

d) **math equation**: it includes anything related to a math expression.

Whenever a "printed matter interactive area" is engaged by a user's interaction, then the supported "printed matter actions" are automatically triggered. The relationship that describes this particular connection of the aforementioned entities is the "supportsAction" relationship.

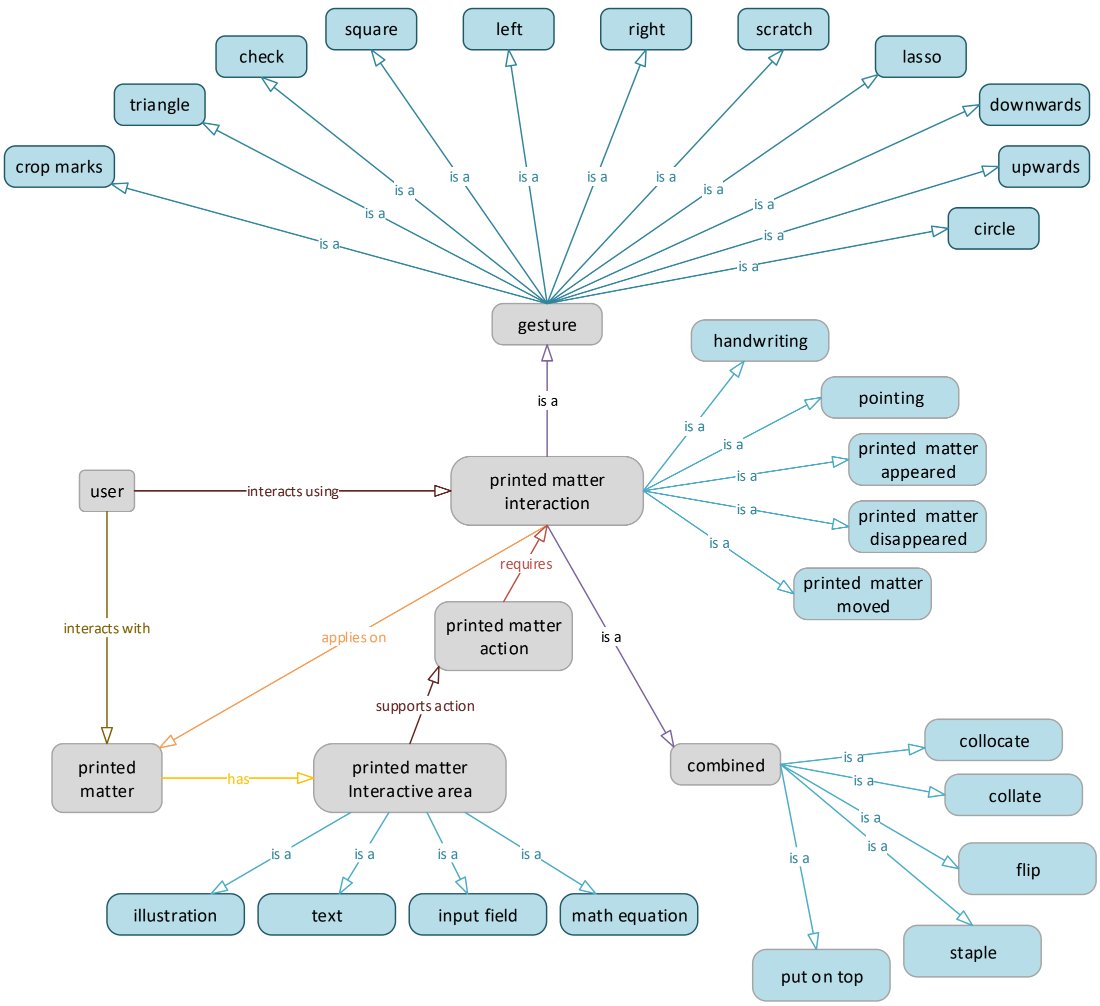


Figure 21. Interaction model

Table 6 summarizes the properties of the "printed matter interaction" entity of the scheme.

Table 6. Printed matter interaction entity properties

Property name	Description
appliesOn	Specifies the set of printed matter that this interaction can be applied on.

Table 7 summarizes the properties of the "printed matter interactive area" entity.

Table 7. Printed matter interactive area entity properties

Property name	Description
interactiveAreaROI	Specifies the interactive area of the printed matter content which accepts user interaction. This area is a JSON formatted string of a points set that outline the contour of the specific area. The X, Y coordinates of each point are the normalized values with respect to the actual printed matter dimensions.
requiresInteraction	Defines the prerequisite "printed matter interactions" in order for the specific area to be triggered.
supportsAction	Specifies the "printed matter actions" that should be triggered every time this area is activated by a user's interaction.

4.4 Printed matter augmentation model

The term augmentation, in the context of the present work, refers to the visualization of any digital information provided by the InPrinted framework as feedback to a user's implicit or explicit interaction. To this end, the printed matter augmentation model incorporates in the framework's scheme all the augmentations that have been defined during the requirements analysis.

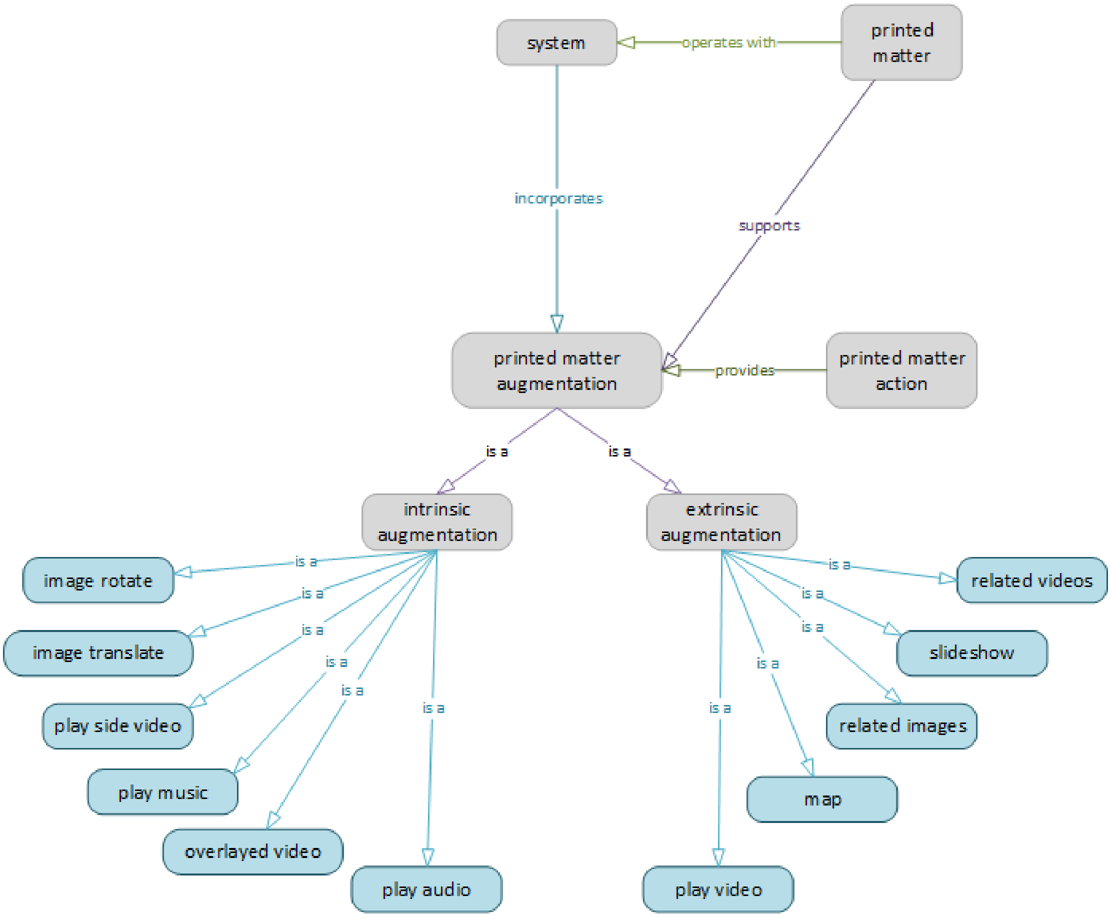


Figure 22. Printed matter augmentation model

As illustrated in Figure 22, printed matter augmentation is classified in two main categories: (a) intrinsic augmentation and (b) extrinsic augmentation. Intrinsic augmentations include all the visualization techniques that can be rendered directly on the printed matter or on a digital representation of it. On the other hand, any visualization which is rendered externally from the corresponding printed matter is considered as extrinsic. This augmentation classification is an important indication for the Context awareness manager in order to decide, during the reasoning process, which AmI systems will eventually render the augmentation.

The entities colored in blue in Figure 22 are the implemented augmentations that the InPrinted framework already supports as they can be materialized by the UI Toolkit that is described in sub-section 5.8 "UI Toolkit".

Each printed matter incorporated in the AmI environment that participates to a user's interaction, is assigned with the system that provides the interaction, through the "operates with" relationship, which is applied between the "printed matter" and the "system" entities of the InPrinted framework's ontology meta-model. It should be noted that each AmI system is capable of providing a number of augmentations. This is declared into the ontology meta-model via the "incorporates" relationship between the "system" and the "printed matter augmentation" entities. A "printed matter augmentation" is triggered during the engagement of a corresponding "printed matter action", which is defined using the "provides" relationship between the latter entities.

Table 8 summarizes the properties of the "printed matter action" entity.

Table 8. Printed matter action entity properties

Property name	Description
requiresInteraction	Specifies the "printed matter interaction" required for performing the action.
providesAugmentation	Defines the "printed matter augmentation" that should be triggered for this action.
interactiveActionExtraInfo	Optional data related to extra information needed for rendering the augmentations (e.g., the audio file path for a "play audio" augmentation)

4.5 User model

A user profile is a set of properties that identify uniquely a user, specifies his/her preferences, state and capabilities. For the purposes of the presented work, a generic model of user profile has been defined aiming to cover a wide range of user categories.

The description of the user is crucial for the proposed approach, since it assists the Context awareness manager to target a specific or event customized service or assistance to the user. Attributes are used to describe the user's characteristics such as identity, reading preferences, preferred interaction modalities, etc.

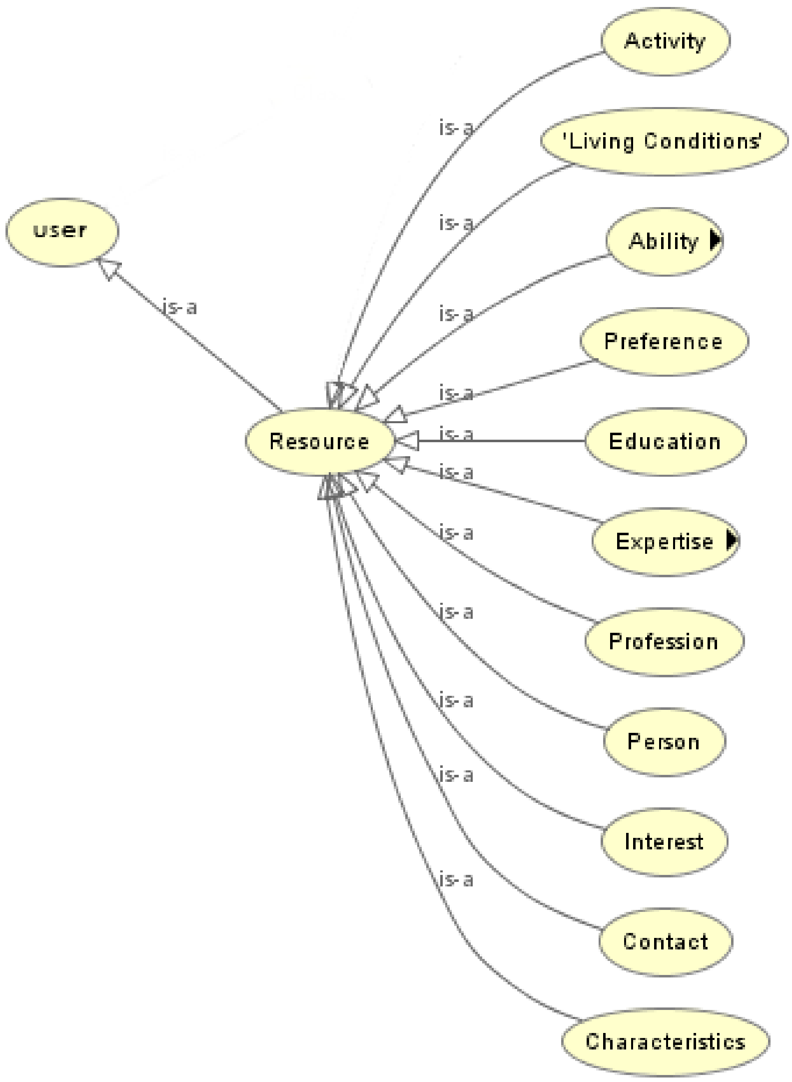


Figure 23. The basic user profile ontology

This user model is based on the user profile ontology introduced in [49] and extended in order to provide extra information regarding users' interaction with printed matter. The aforementioned profile constitutes an extension of the "user" entity of the InPrinted framework's scheme as illustrated in Figure 23.

Table 9 summarizes the properties of the "user" entity.

Table 9. Printed matter user entity properties

Property name	Description
userRepository	Specifies a physical storage means (e.g., a database or a file) where characteristics of the user's interaction with printed matter are stored and retrieved.
interactsUsing	Refers to the "printed matter interactions" that the user is practicing. This is a dynamic property that is being updated any time the framework perceives that the specific user interacts with a "printed matter"
interactsWith	Refers to the "printed matter" the user is interacting with. This is also a dynamic property that is being updated any time the framework perceives that the specific user interacts with a "printed matter"
uses	Refers to the "system" the user is interacting with. Similarly, this is also a dynamic property, which is updated any time the user is performing an interaction on a "system".

4.6 System and environment model

Figure 24 illustrates the system and environment model of the InPrinted framework. The "system" entity represents any AmI system that has been developed based on the InPrinted framework and deployed into a referenced AmI environment. Each system provides a set of its capabilities such as the supported printed matter interactions and augmentations, and exposes the set of “devices” that it integrates. A “device” entity adheres to any existing devices / agents / services that have been installed in the AmI ecosystem and can be used by any “system”. The framework’s devices are classified in two categories:

a) **input devices** that includes any type of services acting as a sensor in the environment and provides primitive information regarding the existence and interaction of a user with the system
b) **output devices**, which refers to the environment “devices” that act as actuators and provide “printed matter augmentations”

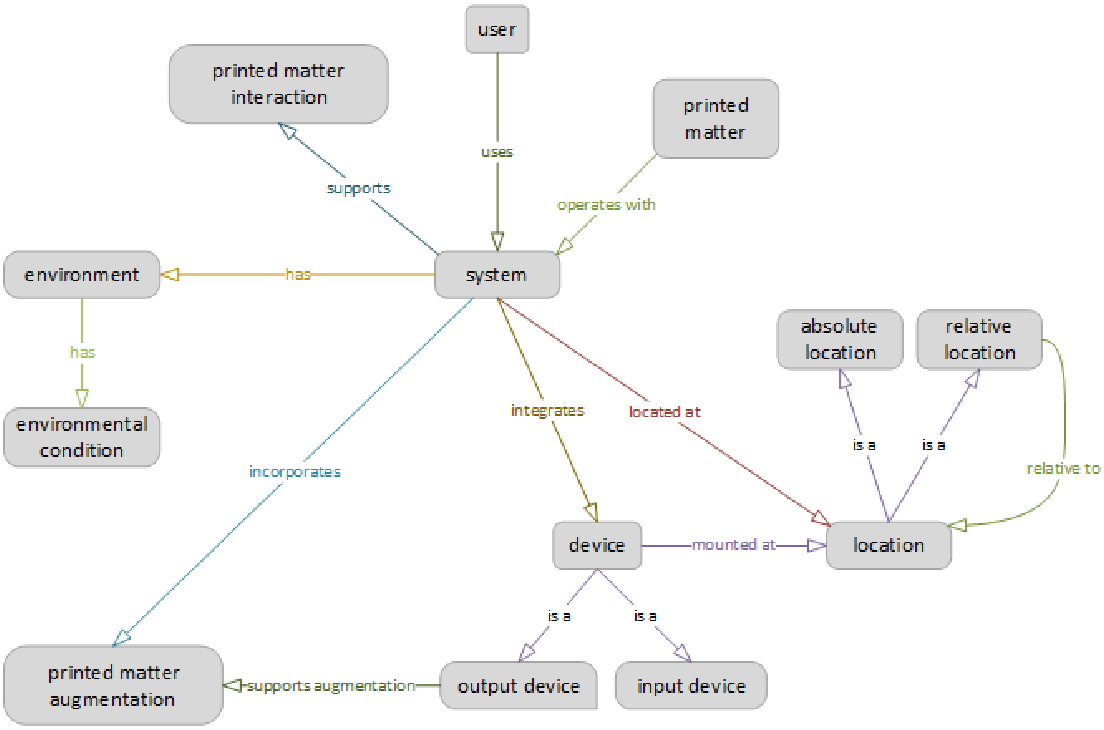


Figure 24. The system and environment model

The environment model is based on the ontology defined in [114]. The “environment” entity provides a number of “environmental conditions”, such as humidity, lighting, noise, pressure and temperature. Furthermore, the notion of “location” is defined in a retrospective hierarchy by introducing the “absolute” and “relative” location entities. Each “device” of the environment is assigned to one “location” through the “located at” relationship. Since a “system” can consist of many “devices” situated in different locations, its location is considered as the union of all the locations of its individual devices.

InPrinted Framework 5

5.1 Overall framework architecture

According to Cook et al. [23], any smart environment can be adequately decomposed in four fundamental layers: physical, communication, information and decision. Each layer performs a different role in the environment, facilitating diverse operations and addressing specific requirements.

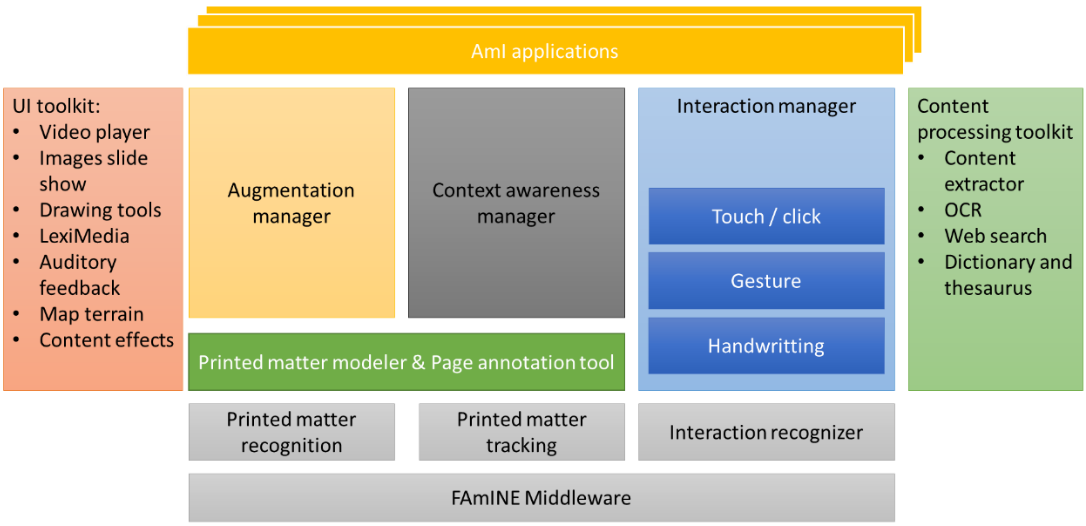


Figure 25. InPrinted framework overall architecture

Figure 25 illustrates the overall architecture of the proposed framework. Beginning bottom-up, the physical layer of the system comprises the hardware accompanied by the necessary software for printed matter recognition and tracking, as well as the supported user interaction techniques. Since the physical layer can consist of heterogeneous and alternative printed matter recognition systems based on different approaches (e.g., computer vision, electronic markers, etc.), the Printed matter modeller provides the digital "alter ego" of the physical subject. Furthermore, the Page annotation tool provides intuitive UIs for printed matter modelling, through which the developers can make available to the system digital information corresponding to the printed matter (e.g., multimedia content, references to internet sources, etc.).

The communication layer is realized by FAmINE [45], a middleware software developed in the context of the FORTH-ICS's AmI Programme and Smart Environments, providing the necessary seamless interoperability of the devices and services that comprise the AmI ecosystem.

The decision layer is implemented by the Context Awareness Manager, a fundamental component of the InPrinted framework, which is responsible for the selection of the appropriate UI components and corresponding content, according to the user's interaction in a specific context of use. The type of interaction is provided by the Interaction manager, which undertakes the task of interpreting users' interactions with printed matter. In order for the Interaction manager to render the supported types of interaction and for the Context Manager to extrapolate the necessary information from the corresponding printed matter, a Content Processing Toolkit has been implemented, including a number of external processes, such as Optical Character Recognition (OCR), information harvesting from various internet sources (e.g., Google search, Wikipedia), and a page content extractor (e.g., extracts text or images from the open pages, etc.)

The information layer consists of the Augmentation manager, which is responsible for the rendering of the available UIs provided by the InPrinted framework for printed matter digital augmentation, adapted to the users' preferences and needs. Moreover, a number of fundamental UI components for printed matter augmentation has been developed and included in the UI Toolkit.

Each of the above mentioned components is printed matter centric, meaning that they address interaction and augmentation requirements for using printed matter. Furthermore, these components implement the necessary functionality for realizing the fundamental properties of AmI environments. For example, the Context awareness manager provides a user / context modelling scheme and ontology-based reasoning enabling personalization, context awareness and anticipation of users' needs. On the other hand, the Augmentation manager facilitates adaptation mechanisms, offering alternative UIs according to the devices where an application is deployed, the profile and preferences of potential users, as well as the type of augmentation supported by an application.

5.2 External H/W and S/W integration with InPrinted

The lower levels depicted in Figure 25 represent Input / Output (I/O) components that may exist in ubiquitous computing environments and are necessary for the acquisition of real world properties (e.g., printed matter localization, recognition) and activities (e.g., user interaction). In order for the InPrinted framework to integrate the large diversity of such I/O components it abstracts them into two main categories:

a) Printed matter recognition and tracking

b) Interaction recognition

For each of these two classes, the InPrinted framework provides communication details and specifications.

Printed matter recognition and tracking

There are several ways to recognize printed matter or physical paper. For example Holman et al. in [59] use special markers for physical paper recognition and tracking. Another approach based on SIFT features for printed matter recognition and localization is discussed in [85]. The diversity of printed matter recognition and tracking is addressed by the InPrinted framework as a separate low-level external layer that intercommunicates with it through a common middleware infrastructure. This approach enables the genericity of the framework decoupling it from the mechanisms that a system uses to perceive the real world (e.g., physical object recognition).

Interaction recognition

Following the same approach as with printed matter recognition and tracking, the interaction recognizer represents the class of all potential printed matter interaction facilitators of an AmI environment. In this respect, the InPrinted framework intercommunicates with interaction facilitators through a common middleware infrastructure.

5.3 Intercommunication and interoperability

The communication layer is realized by *FAmINE,* which provides the necessary intercommunication infrastructure with the available I/O components for printed matter recognition, localization and interaction.

5.4 Interaction manager

The *Interaction manager* undertakes the task of interpreting users' interactions with printed matter. In more details, the interaction manager receives input from the available I/O components of the environment and correlates it with recognized printed matter.

The interaction techniques that are currently supported by the Interaction manager are:

a) **Handwriting**: a user's sequential drawing on a handwriting placeholder (i.e., an empty area of printed matter reserved for handwriting, such as a textbox or a page margin) is interpreted as handwriting. The Interaction manager feeds the user's inscription to a handwriting analysis engine [96] in order to recognize the text. If a text is recognized, then the Interaction manager annotates the Context awareness manager with the text. In the opposite case, the user writing is analysed again and classified as a specific gesture or user's drawing annotation.

b) **Gestures**: Table 10 summarizes the gestures that are currently supported by the InPrinted framework. Similarly to handwriting recognition, if the Interaction manager recognizes a specific gesture (after handwriting analysis), it triggers the Context awareness manager with the recognized gesture.

c) **Touch / click**: user's pointing on a specific area of the printed matter is interpreted as a touch action, while if the user afterwards raises up his/her hand (or the stylus) without sliding in some direction then the Interaction manager perceives this as a click, analogous to a mouse click.

d) **Printed matter direct manipulation**: this category of interaction includes all users' interaction referring to a direct printed matter manipulation. In more details, the interactions that fall in this category are: printed matter appeared in the interaction field of an AmI system, printed matter disappeared, printed matter moved in relation to its previous location, a new content of the printed matter is set active (e.g., a new page of a book is visible to the system after a user has flipped / changed a page of a book).

e) **Combined interaction**: the user can combine two or more pieces of printed matter in order to accomplish more complex tasks (e.g., transfer a picture displayed on a paper that has been placed on an interactive surface to user's image gallery by approaching a printed camera next to it). Table 11 summarizes printed matter combined interactions, which are supported by the Interaction Manager.

Table 10. Supported gestures

Gesture		Usage examples
Triangle		• Basic geometry (e.g., draw specific geometrical shapes) • Play, stop multimedia stream (e.g., video, audio)

Square		
Circle		• Basic geometry (e.g., draw specific geometrical shapes) • Fill-in the gap with multiple choice answers (e.g., circle the correct answer to be filled-in a sentence)
Check		• Confirm for an action (e.g., check with a tick the paragraphs that should be further analysed)
Left Right	 	• Word search (e.g., identify words in a matrix of letters, given a list of their definitions, by striking through the word's letters) • Fast forward or rewind a displayed multimedia stream (e.g., video, audio stream)
Left – Right –Left Right – Left – Right	 	• Word scratch (e.g., signify to the system that the targeted word must be deleted)
Upwards Downwards	 	• Make a margin line sideways to a part of the content in order to start commenting on the selected content • Next or previous image of a displayed slideshow
		• Cut off a part of the content (e.g., digital image acquisition of the selected content)

Lasso Crop marks	 	

Table 11. Supported combined interactions

Interaction	Means of interaction	Description
Collocate	Printed matter or other physical objects	Two or more pieces of printed matter or other physical objects are placed laterally and close to each other.
Collate	Printed matter	Two or more pieces of printed matter are collated as a stack.
Flip	Printed matter	A piece of printed matter is flipped either on its long or its short edges.
Staple	Printed matter	Two pieces of printed matter are stapled

		together applying one's side on the other's side.
Put on top	Physical objects or hands	One or more physical objects or hands are placed on top of a printed matter.

Architecture and workflow

The Interaction Manager functional architecture is presented in Figure 26.

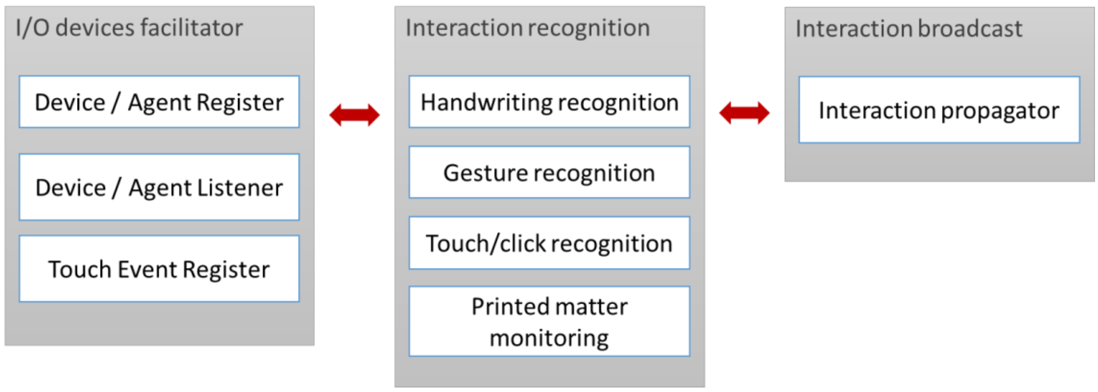


Figure 26. Interaction Manager functional architecture

The main objective of the Interaction Manager is to mediate the recognized interaction provided by the ecosystem's devices and agents to the rest of the framework's components. To this end, the necessary intercommunication with the low level I/O devices and their pertinent agents is facilitated by the ***Device/Agent Register*** and ***Device/Agent Listener*** components. The first is responsible for the discovery of the available device/agents that are installed into the monitoring environment and their real-time status monitoring. The latter component is responsible for the continuous flow of the data provided by the devices and the agents to the Interaction Manager's Interaction and Recognition components. In addition to these components, the ***Touch Event Register*** keeps track of all the incoming touch events (e.g., finger touch, stylus touch, etc.) and correlates them to events' sequences. Whenever an event sequence is ready to be processed, it is dispatched to the Interaction recognition components. The correlation of the incoming events is performed based on the <type, event id, device id> tuple, which is unique for all the events originating from the same interaction. Each touch event sequence includes at least one touch-down event, a number of touch-move events and at least one touch-up event.

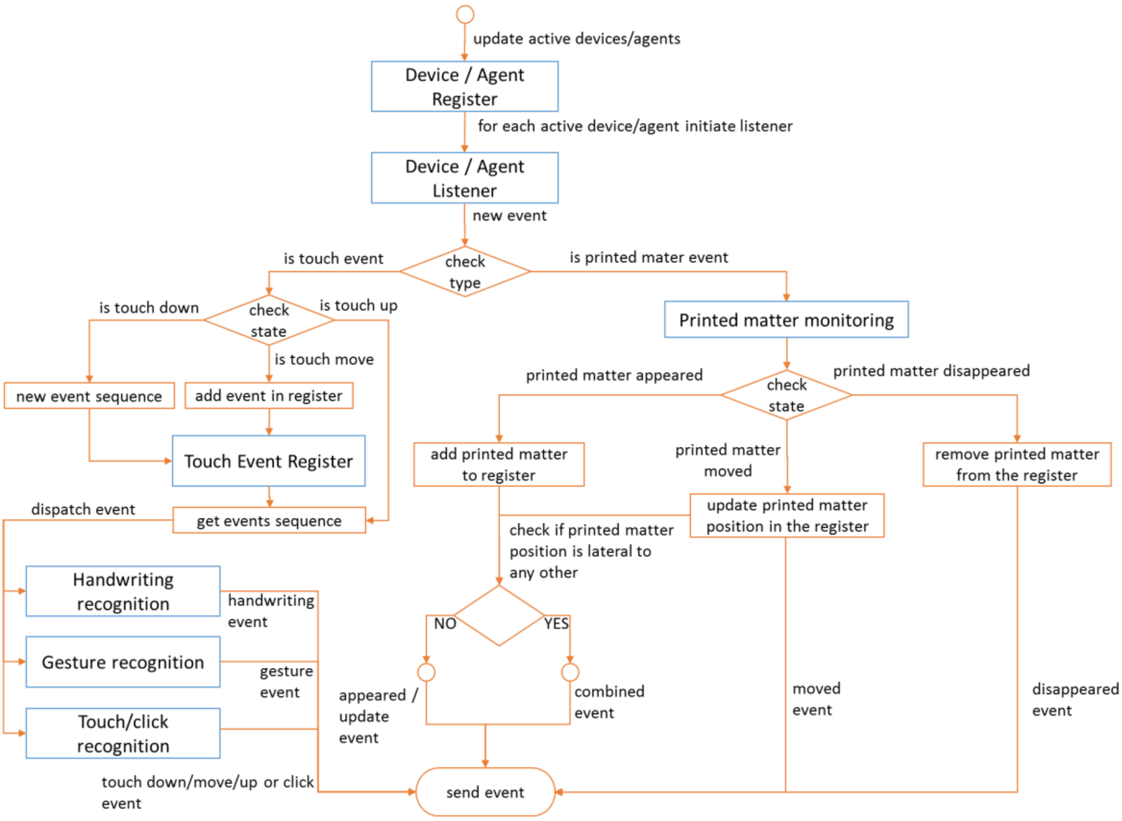
The core of the Interaction Manager architecture lies in the Interaction Recognition components, which are responsible for the timely recognition of users' interactions with the AmI systems that are installed into the environment. Although the Interaction Recognition components provide the interaction semantics to the overall system, they are not aware of who is the user who triggers any recognized interaction or on which system these interactions are performed. This was a deliberate design decision with the aim to decouple the interaction results and semantics from recognition, mainly for performance issues. In more details, the Interaction Manager is responsible for the timely processing of a vast amount of interaction events generated by the AmI environment, demanding high computational power capacity. To this end, any further computation demands for assigning the user and systems with the interaction would result in a big overhead for this module.

The Interaction recognition components are as follows:

- The ***Handwriting recognition*** component processes a number of sequential down/move events provided by the Device/Agent Listener and tries to translate them as a handwriting stroke representing a word of a specific language. It opts to return either the recognized word with an adequate confidence recognizing factor (over 80%) or else, a list of three matching words that correspond to the highest three confidence factors. The Handwriting Recognition component was implemented using the WritePad Handwriting Recognition SDK[1].

[1] https://github.com/phatware/WritePadSDK

- The ***Gesture recognition*** component is responsible for recognizing any gesture based interaction performed on the systems co-existing in an AmI environment. The implementation of this component was based on the Microsoft's Ink Analysis libraries[2] and the supported gestures' set is summarized in Table 10.
- The ***Touch/click recognition*** module monitors the interaction events originating from the installed registered devices aiming at identifying simple touch down – move – up and click (instantly touch down and up) gestures.
- The ***Printed matter monitoring*** component facilitates the recognition of printed matter related interactions, such as printed mater appeared in / disappeared from a system, moved, etc. This functionality is a major ingredient for the subsequent processing of the interaction events by the Context awareness manager, since it allows the direct correlation of all the above mentioned user interactions with specific printed mater.



2 https://msdn.microsoft.com/en-us/library/windows/desktop/ms704040(v=vs.85).aspx

Figure 27. Basic workflow of the Interaction manager

All the Interaction recognition components run in parallel, grouping the incoming events appropriately, keeping the history needed for producing the corresponding interaction results. Figure 27 illustrates the basic workflow of the Interaction Manager.

In more details, during the initialization, the Interaction manager requests from the Context awareness manager a list containing the installed devices / agents in the AmI environment, as well as their current status. This information is kept in the Device/Agent Register component. For each Device/Agent contained in the list, a Device/Agent Listener is activated and starts listening for corresponding interaction events. When an interaction event is received by a listener, depending on the type of the event (touch or printed matter event) the following steps are executed:

(a) Touch event:

- The state of the event is checked in order for the Interaction Manager to find out whether this event initiates a new sequence of interaction events (touch down) or belongs to an already existing one (touch move) or finalizes an interaction events sequence (touch up).
- If the event state is
    - **down,** then a new event sequence is created in the Touch Event Register setting this event as the first of the sequence. Furthermore, the properties of this event are stored as well.
    - **move,** then the event is correlated to an existing registered sequence and stored as the currently last event of the sequence along with its properties
    - **up,** then the Touch Event Register finds the pertinent sequence of the event, adds the event and its properties in the sequence as the last event of it and propagates the sequence for further processing.
- The propagated events sequence is dispatched to the Interaction recognition components that are related to the touch events processing (Handwriting,

Gesture and Touch/click recognition), which start processing the events sequence.

- The processing results, if any, are encapsulated to ***Interaction Events***, which are then broadcasted to the system.

(b) Printed matter event: the event is propagated to the Printed matter monitoring module, which checks the state of the incoming event. According to the event's state, the following actions are performed:

- If the state is *printed matter appeared*, then the event is added to the printed matter monitoring register, along with its properties.
- If the state is *printed matter moved*, then the Printed matter monitoring component updates the properties values of the corresponding printed matter in the register with the ones of the new event.
- After the two previous cases, the system checks if the printed matter pertinent to the event is laterally close to another printed matter that co-exists in the same AmI system. In that case, a printed matter combined event is generated and encapsulated to a new ***Interaction Event***, which is broadcasted to the system. Otherwise, a *printed matter appeared* or *move* event is prepared and broadcasted as an ***Interaction Event*** as well.
- If the state *printed matter disappeared*, then the corresponding record is removed from the registered ones and the event is forwarded as a new ***Interaction Event*** to the system.

Interaction Events are generic events that are broadcasted from the Interaction manger to the rest of the components through the system's middleware. Each Interaction Event consists of a header containing: (i) the interaction type, (ii) the corresponding device/agent and (iii) the region of interest of the event. Optionally, and in accordance with the type of the event, a string array payload can be also included in the event.

Each time the status of a registered device is changed, a "device/agent status update" event is sent by the Context awareness manager and the Device/Agent Register, which is listening for these events, updates the Interaction Manager registry.

5.5 Context awareness manager

The decision layer is implemented by the *Context Awareness Manager*, a fundamental component of the InPrinted framework, which is responsible for the selection of the appropriate UI components and corresponding content, according to the user's interaction in a specific context of use.

The Context awareness manager is based on the ontology of Figure 17. For the implementation of the framework's decision making, a rules-based expert system was used as the core semantic reasoner. Many mature tools, such as Jess [65], Drools [35], and the Windows Workflow Foundation Rules Engine (WWFRE) [61], exist that provide decision-making functionality, which can be based on ontology models. Rules engines ensure a number of advantages, such as improved maintainability, dealing with evolving complexity, flexibility, and reusability [36]. In the context of the InPrinted framework, WWFRE was selected mainly for simplicity in terms of integration (e.g., it provides C# APIs that can be easily incorporated in the framework).

One main feature of the aforementioned technology is its forward chaining capability, which allows atomic rules to be assembled into RuleSets without the definition of, or necessarily even the knowledge of, the dependencies among the rules. However, WWFRE provides the possibility to rules writers to gain more control over the chaining behaviour by limiting the chaining that takes place. This enables the rule modeller to limit the repetitive execution of rules, which may give incorrect results. Furthermore, this approach increases the overall reasoning performance and prevents runaway loops. This level of control is facilitated in WWFRE rules by two properties:

- Chaining Behaviour property on the Ruleset.
- Re-evaluation Behaviour property on each rule.

Both of these values can be set during ruleset design.

Figure 28 illustrates the overall functional architecture of Context awareness manager. In more details, the Context awareness manager consists of three basic components namely (i) Ontology Manager, (ii) Reasoner and (iii) Intercommunication facilitator.

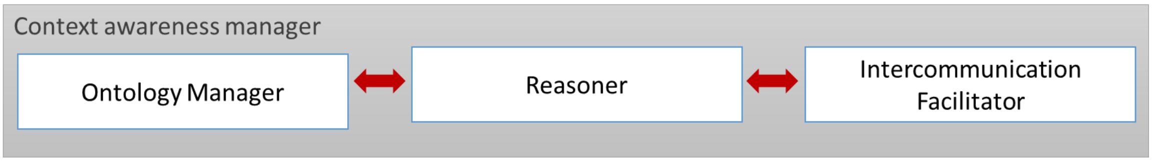


Figure 28. Context awareness manager overall functional architecture

Each component is responsible for realizing specific functionality, which adheres to the context awareness reasoning provided by the framework, as follows:

- The **Ontology Manager**, is the local ontology based repository of the framework which provides the necessary content management functionality, for reading, enriching and modifying the ontology of Figure 18. The implementation of the Ontology Manager is based on the dotNetRDF library [31], which provides basic functionality for reading and writing data in OWL/RDF format, perform SPARQL queries, as well as interoperating with relational databases specifically designed for relational property graphs data management, such as the Virtuoso Universal Server [109]. The Ontology Manager offers a Create, read, update and delete (CRUD) API to the rest of the Context awareness manager's components, transforming the framework's ontology from OWL/RDF to C# objects. In addition, this component provides the transformation of the XML files originating by the Page annotation tool, which is described in section 5.9 to the ontology based model of the framework.
- The **Reasoner** component is responsible for materializing the whole Printed Matter Framework rationale, providing the decision making process which is based on the produced deductions and inferences made by the application of the Ruleset on interaction events triggered in the AmI environment. This process, which is one of the basic mechanisms of the proposed framework, is discussed below.
- The **Intercommunication facilitator** provides the necessary functionality for the communication of the Context awareness manager with the rest of the framework's components. It is actually a client implementation of the FAmINE communication layer, which is responsible for listening to all the interaction events produced by the

Interaction manager and forwarding the reasoning results to the rest of the framework's components. It also provides fundamental information related to the whole ecosystem as it is captured by the framework's ontology model (e.g., provides the list of the available devices operating in the environment).

The reasoning process is triggered every time a new interaction event is generated and propagated by the Interaction Manager. The notion of an interaction event in the context of the reasoning process adheres to the intentional or implicit user's prompt for information acquisition anticipated by the AmI environment. An example of an implicit user interaction can be the fact that a user has opened the page of a printed document for a considerable time period, which signifies to the system her interest for that particular page. The system can then initiate a page content analysis process, aiming at finding relevant content (e.g., from its database or the internet) which may also interest the user.

The major objective of the Reasoner component is to provide the user with the most suitable information by the appropriate AmI system in the most suitable form. In other words, this component aims to select the most appropriate user's environment augmentation for rendering the information that pertains to the user's interaction.

For every new interaction event received by the Context manager, a process based on five priority groups, as illustrated in Figure 29, is commenced. Each priority group corresponds to different Rulesets, yielding intermediate deductions and inferences related to the selection of the most appropriate augmentation that will be rendered by the appropriate system of the AmI environment.

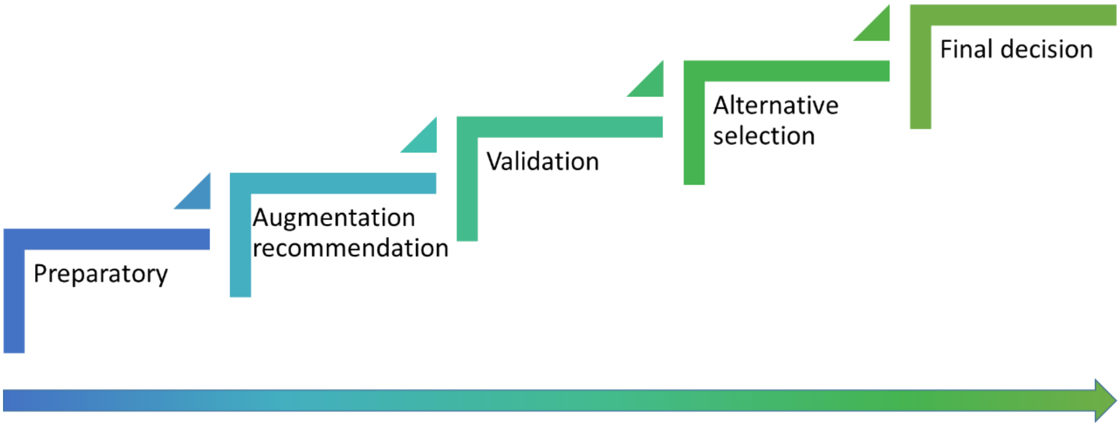


Figure 29. Decision process

The first priority group regards *preparatory rules* that should be applied in order for the system to determine who is the user issuing the event, which is the involved printed matter, which is the originating AmI system from which the event was triggered, and if this event is part of a broader user interaction with the environment. Once the user, the printed matter and the system have been identified, the next priority concerns the selection of the most suitable *augmentations* for providing the information corresponding to the event. In this case, decisions regarding the content that will be visualized are also considered, using – when necessary – the tools of the content processing toolkit (see section 5.6). When a prominent augmentation is selected, then it is validated by the next Rulset, based on the user's preferences, the AmI system's availability and capability of rendering the selected augmentation, as well as the environmental conditions (e.g., a noisy place versus the user's bedroom). If the recommended augmentation meets all the aforementioned prerequisites, then the system selects it as the final augmentation. In case that some of the aforementioned prerequisites are not fulfilled, then the system applies an alternative selection Ruleset, which tries to find alternative ways for providing the corresponding information to the user, either by selecting an alternative nearby system which supports the recommended augmentation or by selecting an alternative augmentation. If one of these happens, then

– due to the Chaining behavior of WWFRE – the Rulesets of priorities two to five are re-evaluated based on the new findings.

5.6 Content processing toolkit

In order for the *Context manager* to extract the necessary information from the corresponding printed matter, a *Content processing toolkit* has been implemented, including a number of external processes such as Optical Character Recognition (OCR), information harvesting from various internet sources (e.g., Google search, Wikipedia), and a page content extractor (e.g., extracts text or images from the open pages, etc.)

For the content extractor and OCR functionality, an independent service has been developed based on the .NET wrapper [1] of the Tesseract open source OCR engine [153]. It accepts as input any digital image of printed matter and tries to retrieve any text in the image, as well as to recognize non text parts of the page, such as photos, figures, etc. After the text of the document has been extracted, the tool proceeds to spell checking using the NHunspell free Spell-Checker for .NET [107] in order to improve the recognized text. The tool returns an xml file containing the recognized text and other printed objects, annotating each of these with the pertinent coordinates in pixels with respect to digital image of the source printed matter.

Additionally, a generic web search tool has also been integrated, aiming at finding web resources (i.e., text, digital images, videos, etc.) related to a set of keywords, provided from the Context awareness manager, originating either from the semantic analysis of a printed matter or from a printed matter extracted area annotated by the user (e.g., using the cropmarks gesture). In the second case, the content extractor and the OCR tool are used for extracting the relevant text from the printed matter. The web search tool accepts as input any arbitrary text, from which it tries to extrapolate meaningful search terms. For doing so, keyword extraction is performed based on word co-occurrence statistical information [93]. The set of the extracted keywords is then inserted as search terms in prevalent search engines, such as the Google search engine or Microsoft Bing. For each of these search engines, the recommended official APIs are used. The results are populated back to the Context awareness manager.

Another tool of the Content processing toolkit is the online dictionary and thesaurus tool, aiming at providing word definitions and other related lexicographic information. In more details, this tool has also been developed as a standalone service accepting words as input. For each of the input words, it returns back lexicographical information based on the Wordnet electronic lexical database [99], such as the word definition, synonyms and antonyms, part of speech (e.g., adjective, noun, verb, adverb), and example sentences explaining the use of the word. The online dictionary and thesaurus interoperates with the rest AmI ecosystem through the FAmINE middleware.

5.7 Augmentation manager

The information layer consists of the *Augmentation manager*, which is responsible for the rendering of the available UIs provided by the InPrinted framework for printed matter digital augmentation, adapted to the users' preferences and needs. In more details, the Augmentation manager provides an API through which every AmI application developed using the framework is able to: (a) listen for augmentation results that stem from the reasoning processing after a user's interaction, (b) acquire assets, in an appropriate format, related to the augmentation result and (c) render this information to an AmI System (using the UI toolkit, which is discussed in section 5.8).

To this end, each application developer is equipped with the necessary tools in order to easily incorporate in the AmI ecosystem any application supporting interaction with augmented printed matter.

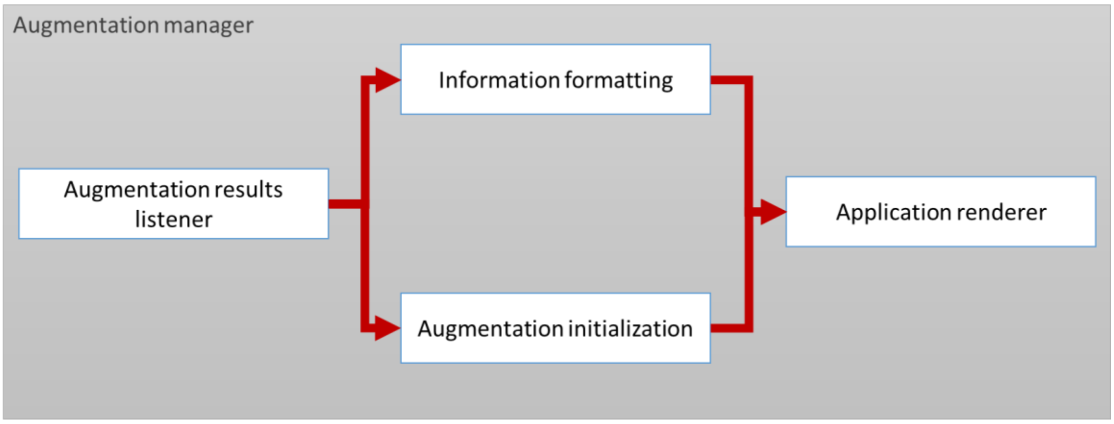


Figure 30. Augmentation manager functional architecture

Figure 30 depicts the overall Augmentation manager architecture, which consists of four basic components that materialize the aforementioned rationale for perceiving, preparing and rendering a digital augmentation in an AmI System.

The **Augmentation results listener** intercommunicates with the Interaction manager and the Context awareness manager, receiving related messages regarding actions that should be handled by the application. Although the majority of the event types that the Augmentation manager handles originate mainly from the Context awareness manager, there are a few event types that can be received directly from the Interaction manager. This fosters the performance of the overall system, since applications can be directly aware of events that don't need further processing, such as printed matter appearance, disappearance or move. Of course, if these types of events affect the overall context of use, then the system should anticipate the user's interaction in a more sophisticated manner (requiring the involvement of the Context awareness manager), in which case additional events can be produced and sent to the Augmentation manager as well.

For example, let's consider the case of an application in the AmI environment that has been placed on a horizontal surface (e.g., a table), and which augments printed matter by continuously highlighting it (as an indicator that the system has recognized it). If a user moves one of the pieces of printed matter existing on the surface, then the application should be aware of this event in order to update its augmentation rendering. This can be directly provided by the Augmentation manager. However, if the user, while moving the piece of printed matter, brings it near to or collates it with another piece of printed matter on the table, then this action should trigger a combined interaction event that should be processed by the Context awareness manager providing a more complex augmentation to be performed (e.g., combine the contents of the two printed matter pieces to provide a merged text).

After a new interaction or reasoning event message has been received, the Augmentation results listener de-serializes it and extrapolates two different types of information: (a) the kind of augmentation which should be rendered and (b) the content of the augmentation.

The **Information formatting** component provides the necessary functionality for appropriately formatting the acquired information for the selected augmentation. It formats any textual information based on predefined templates, it acquires and caches video or audio clips that are available in external repositories, or it produces multimedia information, including any combination of the aforementioned types of content in a solid hypertext content.

The **Augmentation initialization** component is responsible for instantiating and initiating the selected augmentation. In order to do so, it uses a combination of the UI components that are available by the UI toolkit library (see section 5.8), and it encapsulates them in a basic UI container, which is populated to the Application renderer.

The **Application renderer** component acquires input by the Information formatting and Augmentation initialization components and fuses this information to one final digital augmentation that is rendered by the AmI system that the application is running on.

5.8 UI Toolkit

A number of basic UI components for printed matter augmentation have been developed as part of the InPrinted framework.

Video Player

This component provides a simple video player that can be cropped in any shape in order for the framework to support superimposed videos on the printed matter. Figure 31 illustrates a potential use of the Video Player component. A children's book page is augmented with a video clip cropped according to the shape of the page's content on which the video is superimposed, providing thus the illusion that it has become part of the book.

Figure 31. Video player component embedded as part of a children book. (a) The original page of the book. (b) The same page augmented with a relevant video that has the shape of the page part that it substitutes

Images slide show

The image slide show provides an intuitive component, displaying sequentially a number of still images. It supports gestures or simple touch / click for image transition. Figure 32 depicts an example of printed matter augmentation through projection. A user can select to see images related to a specific part of the open page content by touching this particular part. The system projects the Image slide show component laterally to the physical page. The user can browse the available images using the next and previous buttons of the component or by carrying out the next touch gesture.

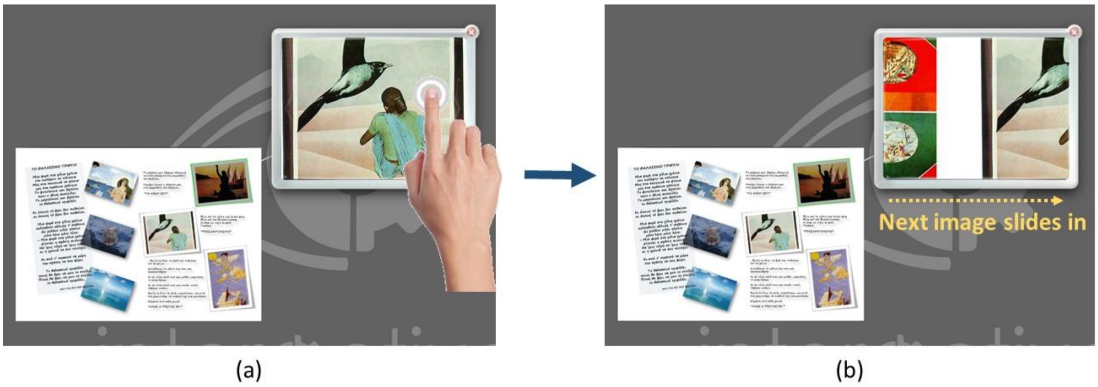


Figure 32. (a) Image slide show component, projected laterally to a physical album page augmenting its content with related images. (b) When a user clicks the "next image button" the component provides a sliding animation displaying the next image.

Drawing tools

This component comprises a set of drawing facilities such as colour palette, ink thickness, undo and clear all actions. The user is able to draw over or next to a printed matter, keep notes, make annotations, etc.

Figure 33. Drawing tools component. The user has already kept notes next to open page and then clicks on the pallet button to choose a different ink colour.

LexiMedia

LexiMedia[3] can be used as a rich dictionary that provides words definitions, thesaurus, etc., but also illustrates related multimedia content (images and video) acquired from

[3] LexiMedia is a composite word consisting of Lexi (which is the Greek term for "word") and Media

the web. As soon as the user indicates the word of interest, a preview of the word information is displayed including up to three definitions for the given word, five representative images and five related videos (Figure 34 a). Additionally, dictionary information can be viewed, including all the definitions available for the word, as well as synonyms and examples for each definition (Figure 34 b). Furthermore, users can view a number of images (Figure 34 c) and videos related to the specified word, which are retrieved by Google. Additional facilities include viewing enlarged images, playing videos, and viewing the visited words history.

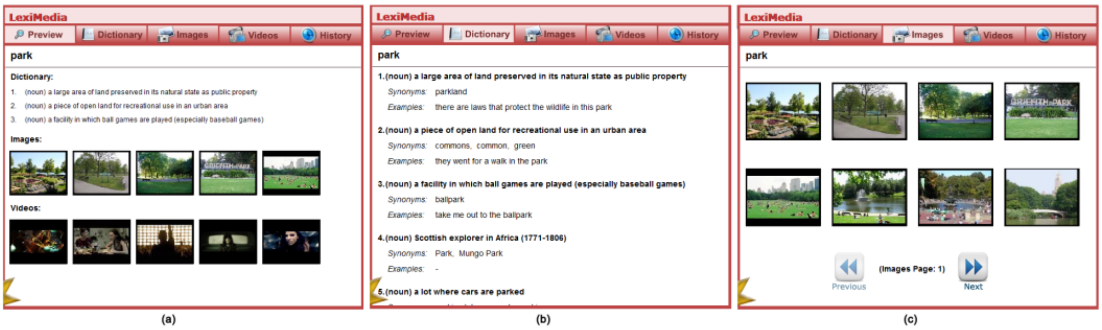


Figure 34. LexiMedia screens: (a) Preview word information (b) Dictionary data and (c) Images related to the current word

Auditory feedback

The InPrinted framework supports printed matter augmentation through audio cues. It incorporates a text-to-speech component as well as an audio player. The audio feedback can be accompanied by visual cues, further enhancing the overall User eXperience (UX). An example is illustrated in Figure 35. The user selects to hear a song related to the content of the open page by clicking on a specific hot spot. While the song is playing, moving musical notes that appear and disappear are displayed on the open page near the active hot spot.

Figure 35. The user touches a hot spot on the page and a song starts playing. Along with the song, appearing and disappearing notes move on the page.

Map terrain

The map terrain component provides an interactive digital map using available online geospatial data (e.g., Google Maps, Open Street Maps, Bing Maps). It supports points of interest annotation, route finder, etc. Figure 36 illustrates the Map terrain component that is projected near the first page of the Foundation for Research and Technology - Hellas (FORTH) leaflet. The user can get geospatial information by touching the title of the leaflet. Subsequently, he/she can interact with the Map terrain getting for example directions how he/she can reach FORTH.

Figure 36. Map terrain component.

Content effects

A set of content effects is supported by the InPrinted framework, facilitating the ability of transforming augmented printed matter to a live document. An example of the provided content effects is illustrated in Figure 37 (b), where the hedgehog image is an active hot-spot. When a user clicks / touches on it, the hedgehog leaves its initial place in the page and starts running out of the screen. A similar example is depicted in Figure 37 (c), where Rickie, one of the three little pigs, introduces itself, when it is clicked / touched by the user, turning its head and saying its name while a textual cue is provided. The text provided also follows an animation path.

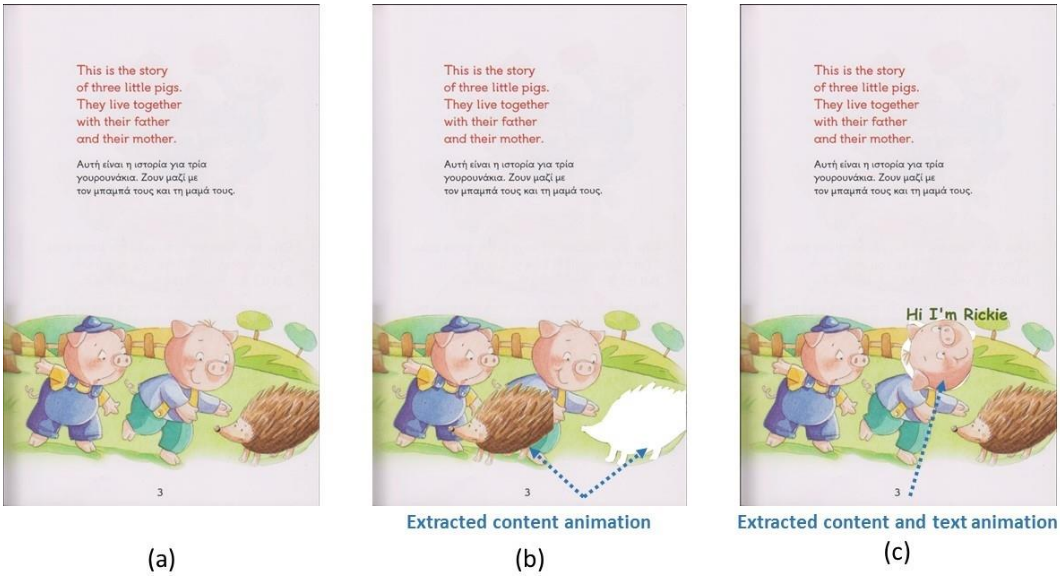


Figure 37. Examples of content effects: (a) The original page (b) Animation of extracted content; a hedgehog moves off its position running out of the page and (c) Animation of extracted content and superimposed text; one of the three little pigs turns its head and introduces itself

5.9 Printed Matter Model

In order for the InPrinted framework to keep structured information about the digital instance of printed matter, the Printed matter modeller has been implemented.

This framework component provides a first classification of printed matter in a XML description stored in a recognition database, including the digital representation of the printed matter and interactive areas (hotspots) accompanied by their properties. Every printed matter item in the recognition database is referenced by a unique id and is accompanied by its digital representation path. This digital representation is necessary for the corresponding printed matter recognition by the framework, but it can also be displayed on any interactive screen near the physical paper or directly on it, using a video projector, enabling therefore the user to interact with hotspots that may be provided.

Every interactive hotspot is declared by a set of coordination points (normalized in order to be independent of the printed matter size), representing the hotspot's bounding path and a set of metadata information regarding the actual content of the hotspot such as the type (e.g., image, textual information, input placeholder), a description and a number of keywords.

The aforementioned information can be edited by the developer or the users themselves through the **Page annotation tool**.

The printed matter model constitutes the basic input for the Context awareness manager to provide appropriate content to the Augmentation manager and to consume interaction events fed by the Interaction manager.

Page annotation tool

Figure 38 portrays the Page annotation tool, an editor for developers and content creators. It supports basic functionality for interactive hot-spots definition on a digital copy of a printed matter, facilitating the classification of actions that will be triggered by the framework on each hot-spot activation by the users.

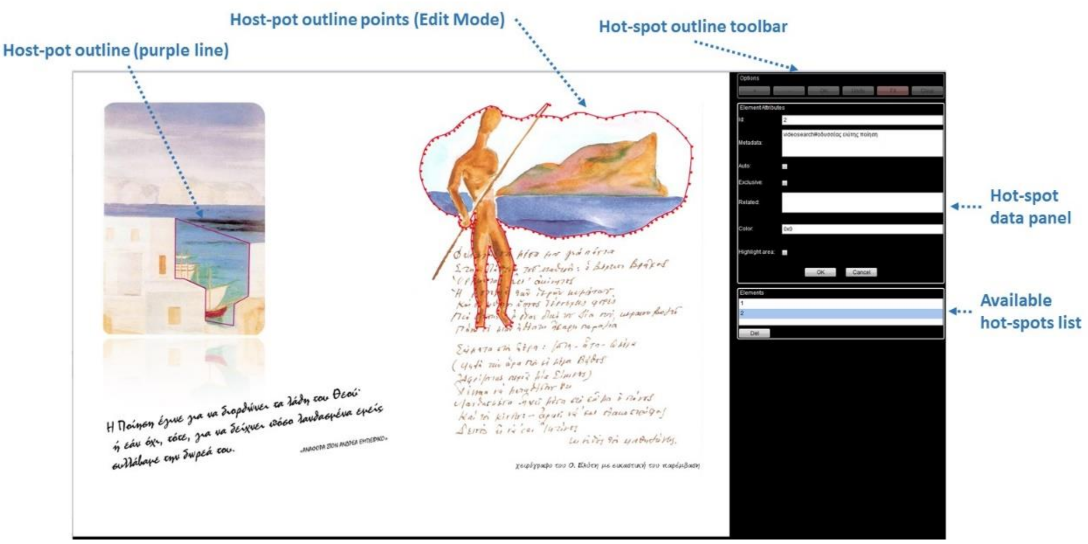


Figure 38. Page annotation tool

The basic components of the Page annotation tool are:

a. **Digital image canvas:** a digital copy of a printed matter is displayed and the users can create and modify the outlines of the provided hotspot for the specific printed matter.
b. **Hot-spot outline toolbar:** provides the necessary functionality for hot-spots area definition on the printed matter, supporting actions such as hot-spot outline path modifications (add a new point or remove a point from the path), undo actions, fit image to the screen and clear outline path.
c. **Host-spot data panel:** consists of a digital form of hot-spot properties that the user should fill in. Each hot-spot consists of:
    - A unique ID that is assigned automatically by the framework the first time the hot-spot is created.
    - Metadata information defining the required actions that the framework should trigger when the hotspot is activated. For example, in Figure 38 for the selected hot-spot, a video search related to poems of a specific author is assigned.
    - Presentation attributes, such as automatic activation of the specific hot-spot when the printed matter is recognized by the framework, hot-spot exclusivity concerning other already triggered hot-spots, the colour of hot-spot's outline, etc.
d. **Available hot-spots list:** summarizes all the available hot-spots for the specific printed matter, allowing the users to select and modify them.

The Page annotation tool exports the aforementioned information for each hot-spot to xml format and populates it in the Context awareness manager.

5.10 Interactive printed matter simulator

This tool simulates an AmI environment that supports interaction with printed matter. It can be considered as an abstract AmI system, which incorporates simulated "devices and services" that produces unprocessed information to the InPrinted framework. The simulator can be used throughout the implementation phase of any new application, enabling the developers to simulate AmI environments to which the application will be embedded, without the need of actually deploying the application in such environments. This is very useful for the first implementation steps, in order to easily and effectively debug a new application.

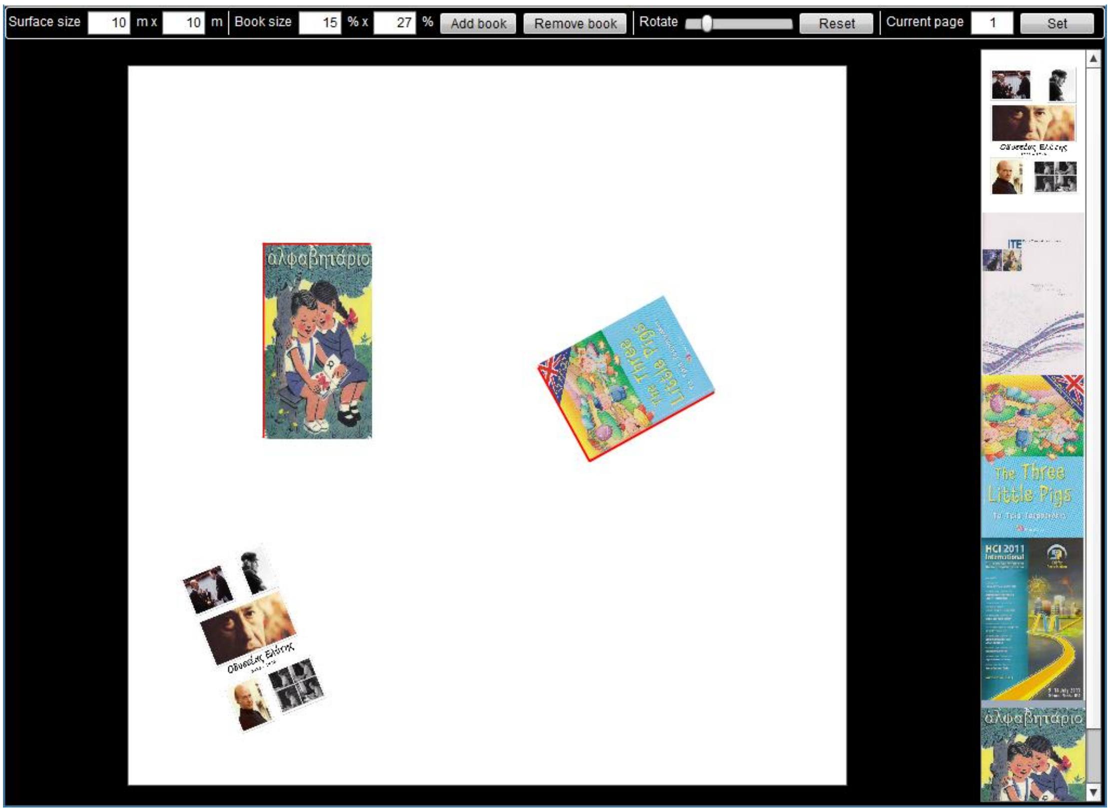


Figure 39. Interactive printed matter emulator.

The available functionalities provided by the simulator are:

- **Registration of** a virtual/simulated AmI system with specific capabilities to the Context awareness manager. The user can define which available devices/services are employed, as well as, physical properties of the system (e.g., surface dimensions in case the system is tabletop).
- Simulation of the **existence, move and disappearance** of multiple printed matter pieces that are collocated in the system.
- Provision of all the available **user interactions** on the existing printed matter.

6 InPrinted applications

This section discusses a number of AmI applications that have been developed and deployed using the InPrinted framework described in the previous sections. All these applications pursue to provide educational assistance to the inhabitants of an AmI environment, mainly focusing on study activities of the users.

6.1 System 1: SESIL

SESIL [87] is an educational system that has been implemented via the InPrinted framework, providing stylus-based interaction in different spatial arrangements, such as large interactive surfaces featuring a display with multi-touch capabilities (i.e., for use in a library or at an exposition) provided that the cameras, needed for pages and stylus recognition and tracking, are positioned appropriately.

SESIL aims at enhancing reading and writing activities on physical books through unobtrusive monitoring of users' gestures and handwriting and the display of information related to the current users' focus of attention. Additionally, SESIL exploits educational metadata on the book's content to decide at run-time the type of additional information and support to be provided in a context-dependent fashion.

In more details, the SESIL system consists of a desk that is overlooked by a set of three high resolution cameras placed above it. A nearby large display runs an educational application that provides content-sensitive information to the users, based on their stylus-based interaction with a school book.

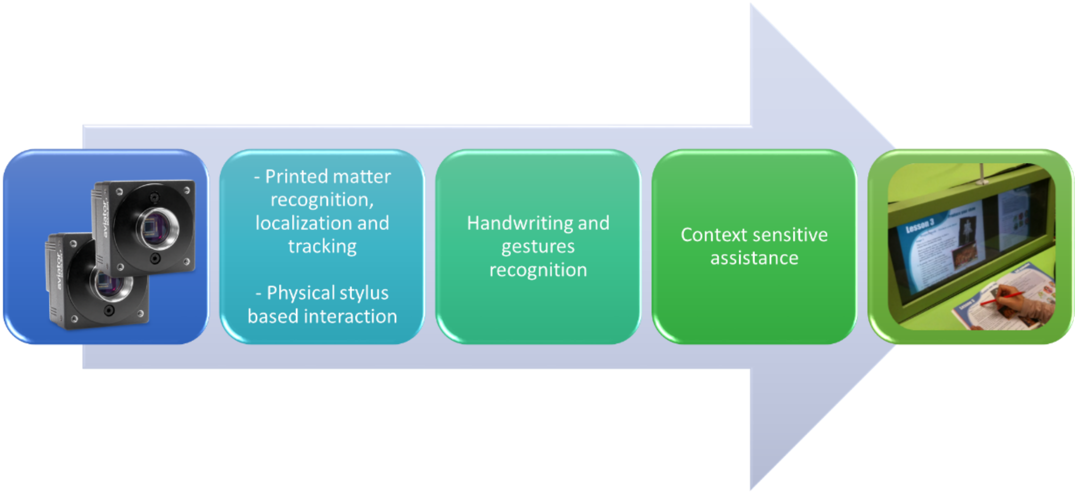


Figure 40. SESIL components chain.

Figure 40 depicts the components chain of SESIL, which is designed to facilitate information flow in real-time, so that system interactivity is served. In more details, the images acquired by one of the three cameras are processed for localizing the book on the table and recognizing the particular page that the book is open at. In parallel, the other two cameras are used for the 3D orientation and location estimation of a stylus, while contact information between the stylus and the book or the desk is also captured. When a user interacts with a specific area of the open pages of the book, SESIL provides context-sensitive assistance to the application running on the nearby display.

Stylus input is additionally used to recognize gestures and handwriting. This module takes as input the pose of the stylus and identifies whether the user is performing a gesture or is writing text. The recognizable gestures are strongly correlated with the natural reading process (e.g., underline text, circle a word, etc.), ensuring that standard studying habits and practices are supported.

Figure 41. While the user changes the page of a book placed on the desk, SESIL recognizes the opened page and displays its digital image on a nearby screen.

The gestures that are recognized and used by SESIL are:

- Basic geometry (e.g., draw specific geometrical shapes)
- Multiple choice (e.g., square, circle or tick the correct answer among a number of available choices)
- Fill-in the gap with multiple choice answers (e.g., circle the correct answer to be filled-in a sentence)
- Word search (e.g., identify words in a matrix of letters, given a list of their definitions, by striking through the word's letters).

In addition, SESIL recognizes and isolates gestures throughout the students' handwriting process, in order to be able to identify specific triggers, such as the deletion of a word that a student has written (identifying the Scratch Out gesture) or the accomplishment of a sentence (identifying the Click/Touch gesture), which means that a student has finished providing input and the system can therefore process it.

In the context of the conducted evaluation, SESIL was installed and integrated in the augmented school desk described in [8], taking advantage of the desk's existing infrastructure and augmenting it with the additional cameras required by SESIL in order to recognize pen gestures and handwriting.

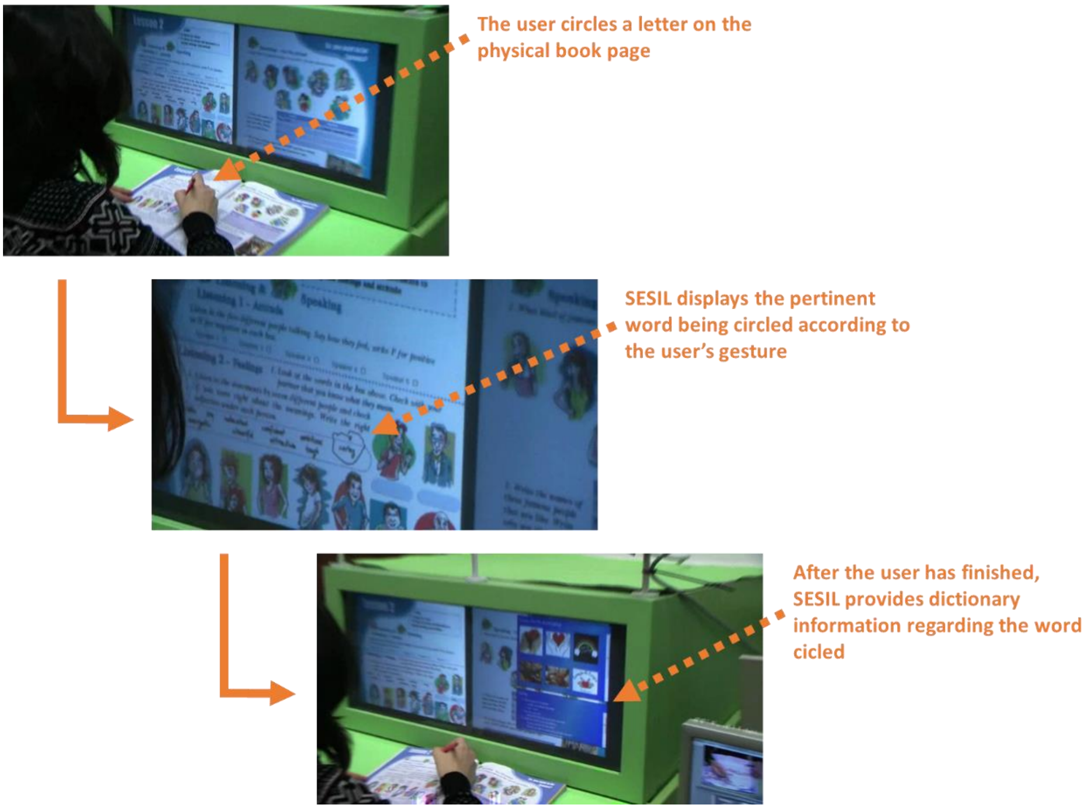


Figure 42. Dictionary and related multimedia provisioning process

For example, Figure 42 illustrates the process a user has to follow in order to get dictionary and related multimedia information regarding a specific word from a book page, which is currently opened. In details, the user signifies this particular action to SESIL by circling a word on the physical book. The system displays what the user is circling on the digital image of the page displayed on a nearby display, providing this way visual feedback to the user. When the user has finished circling the word, then the system displays related dictionary and multimedia information.

Table 12 summarizes the framework modalities in terms of interactions and content augmentation that are supported by the SESIL application.

Table 12. Supported framework I/O modalities of the SESIL application

Supported interactions	• Handwriting
	• Touch / click
	• Gestures:
	    ○ Left, Right (underline a word and ask for dictionary information)
	    ○ Square, Triangle, Check (annotate the correct answer in a multiple choice test)
	    ○ Left-Right-Left or Right-Left-Right (identifies the deletion of a word written by a user)

Supported augmentations	• Provide word definition and related multimedia (LexiMedia) • Handwriting interpretation and visualization • Open page visualization and highlight of the active hotspots

6.2 System 2: The book of Ellie

The “Book of Ellie” [111] is the augmented version of a classic schoolbook for teaching the Greek alphabet to primary school children. The book introduces alphabet letters and their combinations gradually increasing the difficulty level. For each letter or letter combination, relevant images and text involving the specific letter(s) are provided. The short stories for each letter are structured around dialogues and activities of a typical Greek family, with the protagonist being Ellie, one of the four children of the family. In the augmented version of the book, Ellie has become an animated character, constantly available to assist the young learner by reading phrases from the book, asking questions or providing advice.

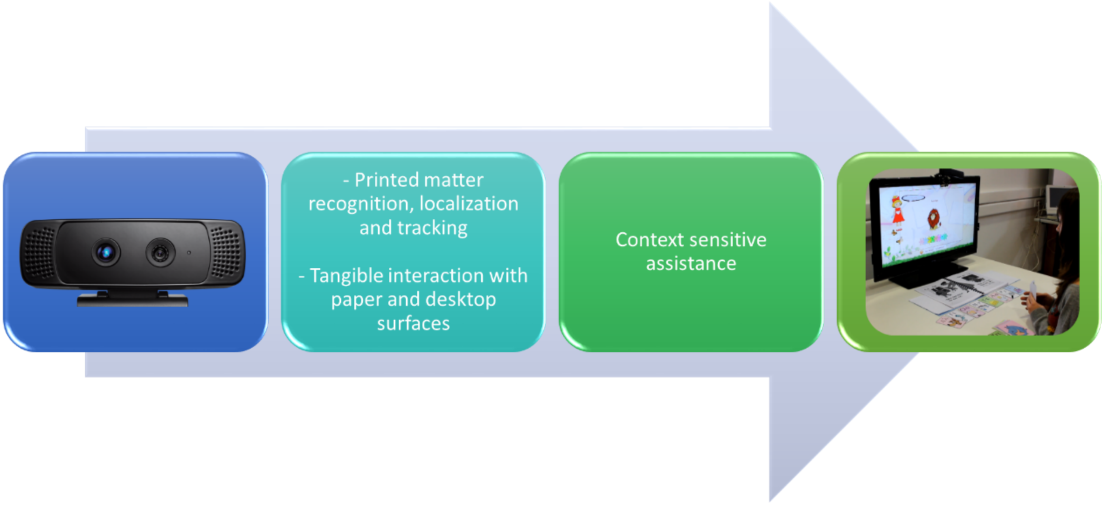


Figure 43. Components chain of The book of Ellie

In terms of setup, the system consists of a television screen (32'') for visual and audio output, an "Asus Xtion Pro" RGBD camera, and a PC running the software. The RGBD camera is used to recognize and localize book pages and cards, as well as detect and localize fingertip contacts on the book and the table. The physical book and paper cards (e.g., depicting letters, simple objects, or animals) are interactive components of the system. The system's main components are depicted in Figure 43.

Furthermore, the system integrates the printed matter recognition and tracking component in order to detect the presence of known books or printed cards on the desktop, recognizes them, and estimates their location and orientation on the desktop coordinate frame.

(a) (b)

Figure 44. (a) Book mode interaction: the user has just pointed at a phrase in the physical book, which is highlighted in the screen as Ellie reads it aloud. (b) Spell-the-word card game

The application supports two learning modes, (a) reading mode and (b) game mode. When the reading mode is enabled, the student can turn the pages of the book as she likes. The system monitors the child's actions and displays the electronic version of the open page to a nearby display. If the child touches a sentence of the physical page, then the virtual character Ellie starts reading this sentence aloud, while it is highlighted on the electronic page that is presented on the display (see Figure 44 left).

Swapping to Game mode (see Figure 44 right), the child is introduced to an educational card game which acts as a recapitulation of the letters that have been taught and a teaching tool for the spelling of some basic words. During the game, the child is presented with twenty-four questions randomly chosen from two categories, asking the child to: (i) select a card with a picture that corresponds to a word which begins with a specific given letter (e.g., Lion for "l") (ii) spell the word represented by a given picture, using cards representing letters (e.g., Lion is spelled by the cards representing the following letters "l", "i", "o", "n").

Mode swapping is achieved by placing special purpose (utility) cards on the desk, one for each mode. The child can activate a mode at any time and resume its interaction from where it was left, i.e., resume reading from the last page that was open or continue answering the last question that was not successfully completed.

An external vision device/agent detects and recognizes the cards that appear on the table at any given time [111]. In addition, it characterizes the spatial arrangement by which the cards are laid out on the table, in order to detect whether they are in a linear spatial arrangement and properly oriented. The orientation of cards is required to be compatible with that of the line. The cards are considered to be properly oriented if their orientation is not more than 20 degrees different than that of the line. In this way, arrangements that include misaligned cards (e.g., upside-down) are not recognized as valid.

Table 22 summarizes the framework modalities in terms of interactions and content augmentation that are supported by The Book of Ellie application.

Table 13. Supported framework I/O modalities of The Book of Ellie application

Supported interactions	• Touch / click (select a paragraph from the physical book page to be read by the Ellie virtual character) • Printed matter placement and orientation feedback (needed for the card game mode)
Supported augmentations	• Text-to-speech (in case that a pre-recorded audio file that corresponds to a book page paragraph doesn't exist, the system provides a text-to-speech interpretation) • Auditory feedback (the system plays a pre-recorded audio file that corresponds to a selected book page paragraph) • Open book page visualization and highlight of the active hotspots

6.3 System 3: Study desk

The Study desk is a newer version of the interactive desk described in [85], aiming to augment physical books with digital information. Figure 45 illustrates the Study desk's components chain.

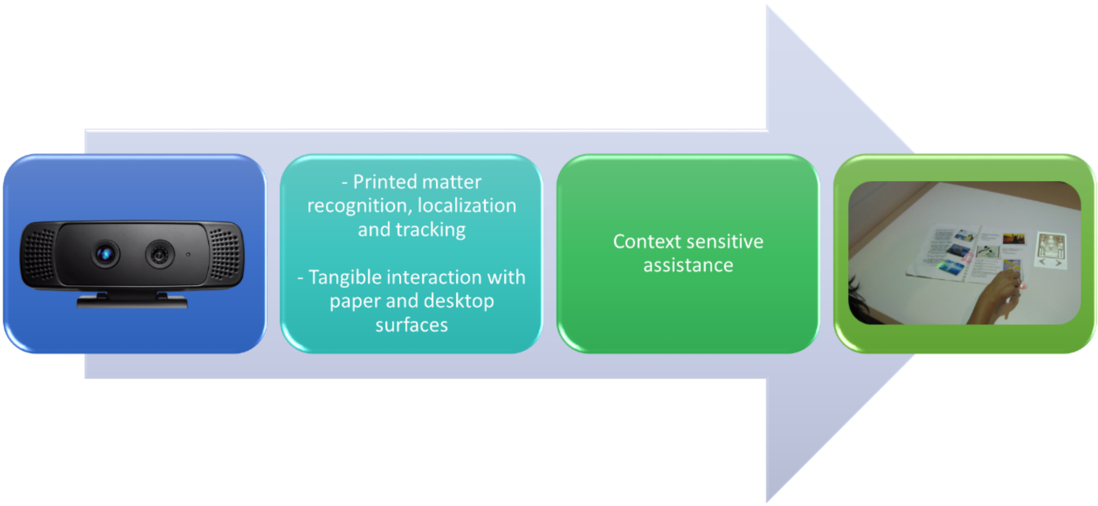


Figure 45. Study desk components chain.

The Study desk consists of a standard definition projector and an ASUS Xtion Pro, both overlooking the surface of a desk. The images acquired by the colour camera of the Xtion are used for printed matter recognition and its localization on the desk surface, while the images acquired by the Xtion's depth camera are used for detecting users' finger touch on the printed matter or the desk.

Study desk provides context-aware multimedia and interactive applications related to the content of the open book page. Such content is dynamically displayed to enrich the contents of the currently open book page, and is aligned, in real-time, with its 2D orientation upon the desk.

The content-sensitive digital content provided can be classified as follows (asset types):

- Images, optionally followed by informative text
- Videos that have been stored in the system

- Images and videos from online web sites (e.g., Google[4] and YouTube[5]) that are being collected at run-time according to the user's interaction
- Map terrains, that provide geo-spatial information related to the content, based on an interactive map

Figure 46. Left: The user clicks on a hotspot and a slide show application opens laterally to the open page playing related videos acquired at real-time from a public image website. Right: The user rotates the book and the content is rendered is updated so that the video keeps its alignment with the book, following its motion.

In more details, every printed page that is included in the system's library has been stored in digital form (PDF) and annotated with "hot-spot areas" that play a role in user-page interaction. When a page hotspot is engaged by the user's interaction, the system evaluates that input and, according to the type of the asset that is represented, selects the appropriate supportive applications and displays them on or near the active book's page. For example, in Figure 46 (left) the user has clicked on a hotspot and an image slideshow related to it is rendered juxtaposed to the open page. If the user rotates and moves the book on the desk, the rendered application follows it, maintaining its alignment with the book (Figure 46 right). However, users can move applications rendered on the desk to a more convenient location by dragging them with their finger.

The rendered images can be controlled using a small set of gestures. For example, if a user wants to see the next image, she can slide her finger from left to right on the table,

[4] http://images.google.com

[5] http://www.youtube.com

while if she wants to see the previous image, she can slide her finger to the opposite direction.

Furthermore, the system provides a note-taking facility. Notes are produced by handwriting on a free area of the table. The user is also able to associate notes with parts of the open page by circling them. Furthermore, she is able to email or post the notes to her Facebook and Twitter account.

Table 14 summarizes the framework modalities in terms of interactions and content augmentation that are supported by the Study desk application.

Table 14. Supported framework I/O modalities of the Study desk application

Supported interactions	• Handwriting (for note-taking) • Touch / click (select a hotspot on the printed matter) • Crop marks gesture (identifies the part of printed matter that corresponds to the notes that a user has just inserted)
Supported augmentations	• Image and video slide collections (related to a selected hotspot) • Drawing tools (keep notes laterally to a piece of printed matter that has been recognized by the system) • Auditory feedback (the system plays pre-recorded audio files that corresponds to a selected hotspot) • Map terrain (give visual geo-spatial information related to the content of the printed matter that has been placed on the system)

6.4 System 4: Study buddy

The aim of Study buddy is to provide an unobtrusive intelligent environment that implements a context aware system, in order to augment the learning procedure. The system is composed of a smart reading lamp and educational software, called LexiMedia, aiming to provide dictionary information, as well as multimedia information for specific words, assisting thus in language learning.

(a) (b)

Figure 47. (a) Study-Buddy setup overview (b) Test-bed setup for the heuristic evaluation

In more details, the reader's desk is equipped with a smart reading lamp that incorporates a small camera and an embedded computer with Wi-Fi connection, as illustrated in Figure 47 (a). The camera of the reading lamp targets to the student's reading area (i.e., the area of the desk where the book is placed). Interaction with the Study buddy system is initiated when a user indicates a word in the book, by using a black pointer (e.g., pen) and carrying out one of the following gestures: pointing at the word, underlining the word or circling the word. From that moment, until the word information is displayed on the user's screen, a number of services are deployed and interoperate, as depicted in Figure 48.

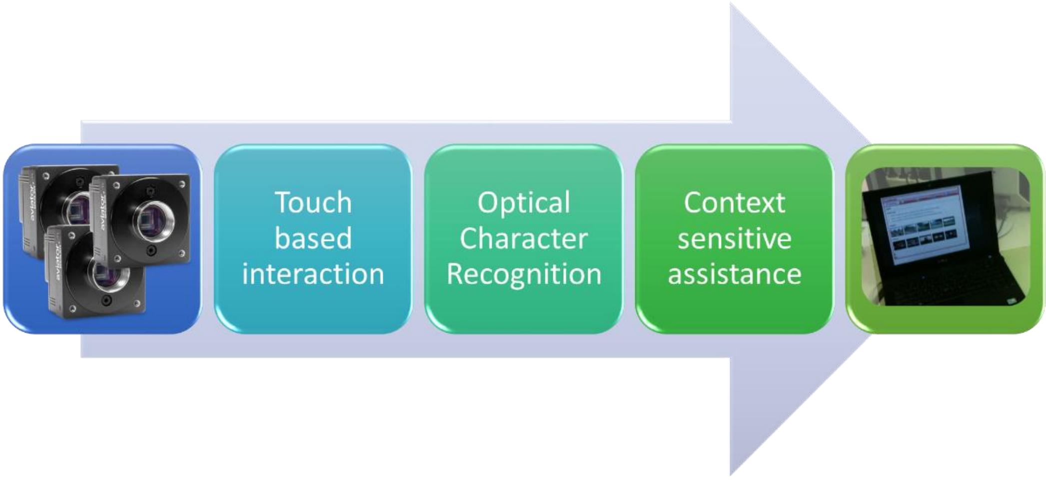


Figure 48. Study buddy components chain

Whenever the smart reading lamp observes that the reader needs help about a word or a phrase, it scans the area trying to recognize the indicated words, using OCR software. Then, it collects useful information about the recognized words, such as related images and words' definition. Finally, it transmits the aforementioned information to a computational device (e.g., tablet, smart phone, etc.) located near the reader, which runs LexiMedia.

Table 15 summarizes the framework modalities in terms of interactions and content augmentation that are supported by the Study buddy application.

Table 15. Supported framework I/O modalities of the Study buddy application

Supported interactions	• Touch / click (selection of a specific word)
Supported augmentations	• Use OCR for word identification • Provide word definition and related multimedia (LexiMedia)

7 Evaluation

Several evaluation iterations have been carried out with the aim to assess interaction with printed matter, as it has been instantiated in the four applications developed with the InPrinted framework. At first, all four systems were evaluated individually, aiming to assess their usability [85, 86, 87, 111], emphasizing however in the context of this thesis in issues pertaining to user's interaction with printed matter and the supported by the framework augmentations. More specifically, all the systems have been evaluated following the heuristic evaluation approach involving User Experience (UX) experts, while the heuristic evaluation of Study desk was followed up by user testing. Study desk was selected to be tested with users as the most inclusive system, incorporating a large number of interaction modalities and augmentations supported by the framework. The heuristic evaluations that have been carried as well as the user testing of Study desk are reported in Sections 7.1 and 7.2, concluding each evaluation report with issues specifically pertaining to the InPrinted framework.

Beyond the individual assessment of each system however, a comparative evaluation has been carried out involving end-users in a within subjects experiment, aiming to not only find specific UX problems for each system, but also to be able to arrive to conclusions regarding the overall UX and users' preferences of various interaction modalities, as they are provided by each system. The procedure and the results of the within subjects testing are reported in Section 7.3.

Finally, a large-scale in-situ evaluation was carried out, aiming to test one of the systems with a larger number of users in order to acquire quantitative results regarding interaction with paper. The evaluation was structured around three main hypotheses regarding interaction with paper, namely that the system is easy to use with minimum guidance, touch-based interaction with the augmented paper is natural, and the overall user experience is positive. Two additional hypothesis were explored regarding the effect of age and computer expertise to the perceived ease of use. The procedure, the results, and the statistical analysis of the in-situ evaluation are described in Section 7.4. This section concludes with a recapitulation of the results throughout the different evaluation iterations (Section 7.5).

7.1 Heuristic evaluation

Heuristic evaluation is an informal usability inspection method [106] and involves having a small number (ideally three to five) usability specialists judge whether each dialogue element in a UI follows established usability principles (the "heuristics"). Involving between three and five evaluators has been found to identify a reasonably high percentage of the usability problems (between 74% and 87%). The output of the process is a list of the identified usability problems in the interface with references to those usability principles that were violated by the design in each case. Once the usability problems have been reported individually by each evaluator, an evaluation facilitator creates an overall report. Then, each evaluator is asked to rate the complete list or problems according to their severity, and an average score is calculated for each problem in order to be able to prioritize their elimination. Severity ratings are as follows:

- 0 – I don't agree this is a usability problem at all
- 1 – aesthetic problem
- 2 – minor usability problem
- 3 – major usability problem
- 4 – usability catastrophe.

SESIL

The heuristic evaluation of SESIL was carried out by four experts. After interacting with the system, the evaluators were asked to fill-in a short questionnaire in order to assess the system's usability, learnability and anticipated user experience.

The heuristic evaluation resulted in 7 usability improvement suggestions, 2 of which were classified as major problems, 3 as minor problems and 2 as aesthetic problems only. Table 16 lists the problems that were identified, classified in categories.

Table 16. List of problems identified through the heuristic evaluation of SESIL

ID	Problem description	Severity
Interaction with the book		
1.	Users might need some time to learn all the supported gestures with printed matter. A quick help functionality to remind them might be helpful.	2.75
2.	The direction of pages' turning in the electronic book version was different than the actual direction on the physical book, when a page was turned from left to right.	0.75
General		
3.	A help functionality is missing.	3
4.	Scrollbars are not very efficient for touch-based interaction on the screen.	1.75

Dictionary application		
5.	The dictionary could be enhanced with further functionality, allowing for example users to add a word to their personal vocabulary.	2.25
Images application		
6.	Images should have a legend.	2.5
7.	The total number of results should be reported.	1.25

The questionnaire given to experts in order to assess the usability and overall anticipated user experience was comprised of thirteen questions, providing pairs of contrasting characterizations for the system, which the experts had to rate on a scale from 1 to 7, were 1 represents the most positive attitude (e.g., pleasant) and 7 the most negative attitude (e.g., unpleasant). The average scores for each pair are shown in Figure 49, where it is evident that SESIL was in general estimated to provide a positive user experience.

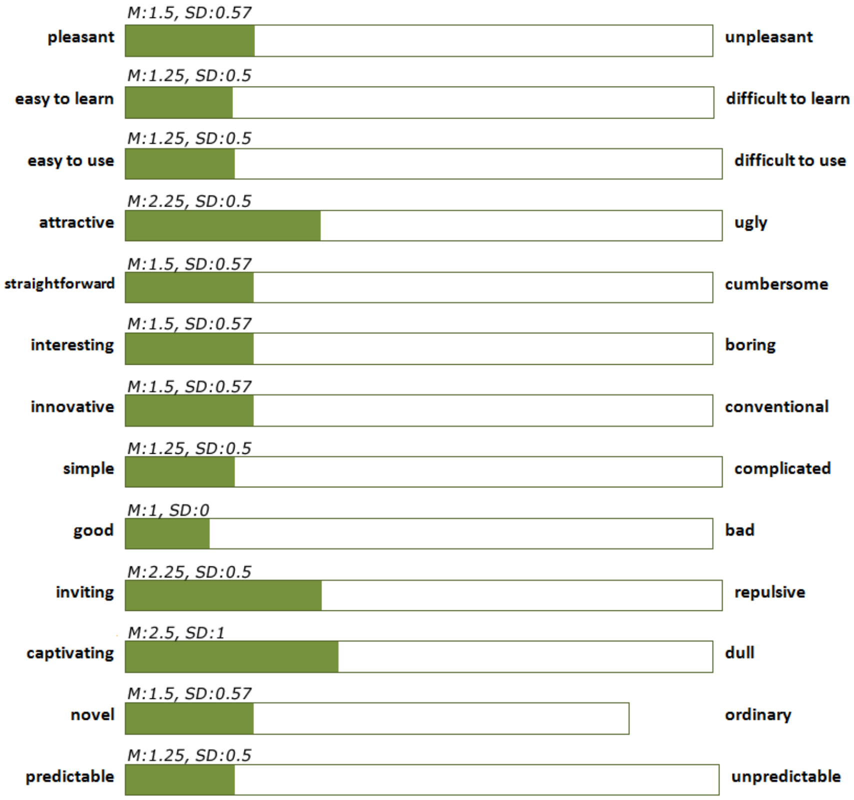


Figure 49. SESIL questionnaire results for expert-based evaluation

Answers were also analysed by grouping them in three categories, namely usability, learnability and user experience. Usability received an average score of 1.25 (SD: 0.28), learnability 1.33 (SD: 0.83) and user experience 1.75 (SD: 0.27). These results can only be used as qualitative measures of an overall UX estimation.

In summary the heuristic evaluation of SESIL pointed out specific usability improvements and an overall positive UX. In terms of interaction with printed matter, the only concern that was pointed out referred to the discoverability of supported gestures for first-time users, an issue which could be addressed with incorporating a help functionality in the system.

The Book of Ellie

Four usability experts participated in the heuristic evaluation of The Book of Ellie system, three of whom had experience regarding the usability of interfaces for children, one due to her engagement with designing and evaluating such interfaces, and two of them as parents of young children, often using IT targeted to children. If double specialists (i.e., usability experts with knowledge regarding the specific type of interfaces) are employed in a heuristic evaluation their error finding performance is even better [102].

The evaluators were explained the purpose of the system, as well as the main interaction concepts, and were left to explore the system by themselves. During each evaluation session two more individuals were present: one facilitator noting down the evaluator's comments, and the chief developer aiming to provide assistance in case of a system error or to explain the functionality of the system if asked.

The evaluators found in total 28 issues that were classified in three categories: General, Book mode, Game mode. The issues identified by each evaluator were aggregated in one report, having duplicates removed. Then, they were rated by each evaluator according to their severity and the average score for each problem was calculated in order to prioritize issues that should be immediately eliminated. The entire list of usability problems found is presented in Table 17.

Table 17. List of problems identified through the heuristic evaluation of The Book of Ellie

ID	Problem description	Severity
General		
1.	A general help system is required.	3
2.	The two buttons describing the current state (reading / play) need to be redesigned: they should be in a fixed position and include images of the cards to allow easy association.	3
3.	A card or other way for exiting the application should be provided.	2.5

4.	Audio feedback from Ellie should be provided when a mode change occurs.	2.25
5.	There is not a clear beginning and ending of the system.	2.25
6.	In long idle times an animation could be invoked (e.g., Ellie dancing, or trying to catch a flying butterfly that appears out of blue) in order to indicate that the system is up & running.	1.25
7.	Playing cards to change mode seems unnatural. Instead they could be placed in a standard position (right or left to the book) and the player could point at the desired choice.	1.25
Book mode		
8.	When several places of the page have been pointed at, all the phrases remain highlighted.	3.25
9.	An option for automatic reading (reading all the text in a page) should be available.	2.5
10.	Interactive (touch-enabled) areas should be highlighted at long idle times, in order to indicate that the child can point at them.	2.25
11.	Phrases should be highlighted in a color different than red.	2.25
12.	When the book closes, options regarding what to do no next should be provided.	2.25
13.	Ellie could be uttering something in all the pages, even in pages without text so that there is continuous feedback.	2
Game mode		
14.	The table area for throwing cards should be somehow marked, since the system recognizes cards which the user may not wish to employ in the current question.	3.5

15.	The game mode activation card uses a question mark as a logo, which may be confused with a help system.	3.25
16.	The algorithm for checking the correctness of the provided answer should be revised, in the case of spell-the-word questions.	3.25
17.	Related to the above, Ellie could be providing hints and feedback during the game play (e.g., how many letters does the word consist of, how many letters have been placed on the table, how many of them are correct, how many of them are in the correct place, etc.).	3
18.	If the next question card is left on the table for a long time, the game should not continuously advance to the next question.	2.75
19.	The puzzle pieces during the spell-the-word game should not be constantly moving.	2.75
20.	An indication of the number of remaining questions (question X out of Y) and/or a progress bar should be available.	2.5
21.	Once a question has been completed, the game should ask the player to clear the table from the cards and then move to the next question.	2.5
22.	If the user quickly changes something, the old and new messages are heard at the same time.	2.5
23.	A previous question card should also be available.	2.5
24.	If image cards are used instead of letter cards (and vice versa) appropriate messages should be provided.	2
25.	When the player provides a correct answer, feedback could be provided in the following order: Ellie confirms, a sound is heard (e.g., bell rings), an animation is played (lion jumps).	1.75

26.	When a letter or image card is played while in book mode, it should act as a change mode card.	1.75
27.	It would be best if the child was first asked to close the book and then play the cards game.	1.5
28.	There are too many cards.	0.75

In total, 7 general issues were found with severity rating ranging from 1.25 to 3, 6 book mode problems with severity from 2 to 3.25, as well as 15 game mode issues with severity ranging from 0.75 to 3.5. An overview of the ratings per category is illustrated in Figure 50.

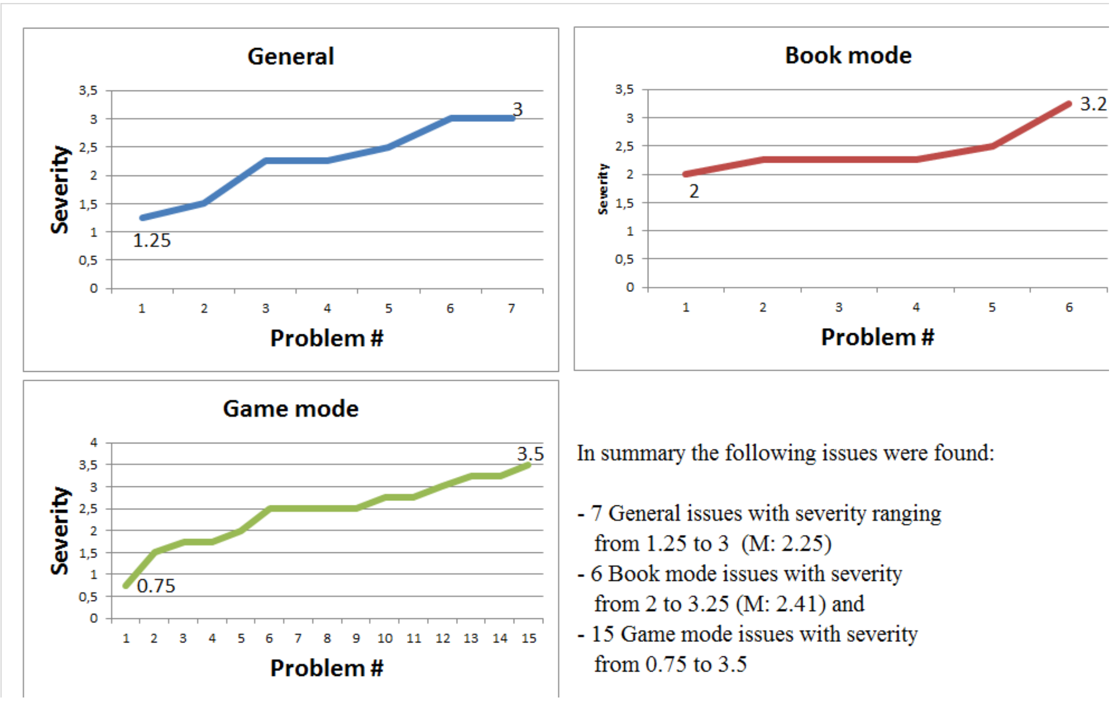


Figure 50. Overview of severity ratings for the usability problems identified through heuristic evaluation for The Book of Ellie

The overall comment of the evaluators was that the system is very interesting and in general well designed for the target audience. One of the most important findings was that a help functionality guiding the child on how to interact with the system is required, since the interaction techniques may be novel to the child. Such guidance could include highlighting interactive book areas at long idle times and providing assistance when actions beyond the expected ones are carried out (e.g., the child closes the book, the child throws on the table a different card than expected, such as a letter card during the find the picture game, etc.).

Furthermore, most of the evaluators agreed that the feedback provided by the system needs to be enhanced by adding audio messages and visual prompts in specific cases, e.g., for changes of the currently active mode, during the game play to indicate the number of remaining questions, as well as in correct and erroneous answers during the cards game. In relation to the last concern, the feedback providing method was suggested to be reconsidered so as to provide messages more promptly, and be enhanced with hints in case the learner has serious difficulties in answering the question.

Overall, the problems that were identified were related as to how specific design decisions were implemented through the framework (e.g., what kind of feedback and when, what amount of help). No concerns regarding the confluence of paper with the augmented reality environment or the interaction with the system were identified.

Study desk

A preliminary evaluation of a fully-functional interactive prototype of the system was carried out by four UX experts. The evaluation yielded seven usability problems, presented in Table 18, five of which were characterized as relatively minor usability problems (severity rating between 1.75-2.5) and two as relatively major (severity rating >2.5).

Table 18. List of problems identified through the heuristic evaluation of Study desk

ID	Problem description	Severity
Interaction with printed matter		

1.	Gestures are difficult to discover the first time.	2.75
2.	Gestures might be difficult to remember for some user groups (e.g., elderly).	2.25
3.	When the physical book is moved on the table, the positioning of digital images projected on the desk is reset, causing confusion to the user.	2
4.	Lights are automatically turned off when the book is open on the desk, even if the user has just turned them on.	2
Multimedia application		
5.	The user is not able to stop music, once it has started playing;	2.75
6.	If users select the corner of a digital media (e.g., images slideshow) they are able to move it, however this feature is not easy to discover;	2.5
7.	When a book image is selected, a different digital image is projected on the desk.	2

From the above, it is evident that no major concerns regarding interaction with printed matter were found, except the evaluators' concern regarding the discoverability of the supported gestures, especially by first time users.

Study Buddy

A heuristic evaluation of the system was carried out involving four UX experts, as soon as a fully functional prototype was completed. The evaluation process aimed at identifying usability problems, focusing on the supported gestures. The evaluation resulted in identifying fourteen usability improvements and problems that should be eliminated before giving the system to actual users, classified in two categories: those that were related to the interaction with the physical book and the ones that pertained to the dictionary application. Problems were rated by each evaluator according to their severity and the average score for each problem was calculated. The findings in order of severity per category are presented in Table 19.

Table 19. List of problems identified through the heuristic evaluation of Study Buddy

ID	Problem description	Severity
Interaction with the book		
1.	It is possible that users would like to look for phrases as well (instead of simple words).	2.75
2.	Additional gestures should be supported for indicating whole phrases, such as for example pointing at the first and the last word of the phrase.	2.5
3.	The response time from the moment the user points at a word until the related information is presented in the nearby screen varies from 2 to 3 seconds. The overall user experience would be further improved if this time could be reduced.	2.5
Dictionary application		
4.	Thumbnails are not interactive in the preview tab.	3.25
5.	Although thumbnails are not interactive in the preview tab, they are in the images and videos tab. This may cause confusion, as they are not visually different.	3.25
6.	Video controls are missing to stop/replay the video.	3.25
7.	When a video is playing and the user indicates another word, the video should be stopped and the new word information should be presented.	2.75

8.	The videos that have been included in the system seem irrelevant for language learning. Replacing them with Wikipedia information might be more useful.	2.5
9.	When viewing an image or a video, it is nice to close it by just touching it, but it could also be possible through a close button.	2
10.	The favorite words ribbon icon is not visible.	1.5
11.	The feedback provided through sound for indicating that the system received the user input (i.e., word to look for) could be further improved with more distinctive and intuitive sounds.	1.25
12.	The word preview should be changed to summary.	1.25
13.	The word definitions should be changed to dictionary.	1.25
14.	The red background with dark red letters for the menu could be changed to something more bright.	1

In regard to interaction with the physical book, according to the evaluators' comments, the most preferred gesture in terms of usability was that of pointing at a word, followed by the underlining gesture. Overall, in terms of interaction with the physical book, two major points were highlighted, namely that several gestures need to be supported to accommodate the various needs for the given context and that response times should be faster in order to keep users engaged and avoid causing impatience to users.

7.2 Study desk user testing

After the Study Desk system had already been evaluated by experts and updated accordingly, an additional evaluation with users was carried out, since even though heuristic evaluation 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 [104]. This evaluation step was observation-based [104] and involved

15 participants. The user group characteristics, in terms of gender, age, technology expertise and usability expertise are reported in Table 20.

Table 20. Study desk usability evaluation participants' characteristics

Gender		Age		Expertise	Technology	Usability
M	40%	*20-30*	26.7%	*Low*	33.3%	33.3%
F	60%	*30-40*	60.0%	*Medium*	40.0%	46.7%
		40-50	13.3%	*High*	26.7%	20.0%

During the test, the participants were welcomed, and introduced to the system and the evaluation goal. Then, they were asked to carry out twelve specific tasks with the system, including to launch and interact with digital content (music, images, and video) related to the physical book, use the light pen to take notes and share them through e-mail. An evaluation observer coordinated the experiment and kept notes with her observations, also recording user comments, errors and help requests. The tasks that users were asked to carry out were as follows:

- T1. Open the book in the first page and identify which parts of the book are interactive

Carry out the following tasks in any page of the book you like:

- T2. Select a music score to listen to
- T3. Stop the music
- T4. Select a video to view
- T5. Select to view some photos
- T6. Move the book on the table

- T7. Create a drawing
- T8. Change the size and the colour of the brush
- T9. Draw something more
- T10. Erase your drawings
- T11. Upload your drawing to your Facebook account
- T12. Clean the desk surface

Task accomplishment was rated as success, partial success (e.g., if the participant made errors or asked for help) and failure [105]. Figure 51 presents an overview of the percentage of users who were successful, partially successful or unsuccessful for each task and the average success percentage for all the tasks. Furthermore, the overall task success rate was calculated by the formula:

$$\textit{Success Rate} = (TS + (PS*0.5))/\textit{Number of attempts}$$

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 Study desk application, the formula is produced as follows:

$$\textit{Success Rate} = (163 + (13*0.5))/180 = 0.94$$

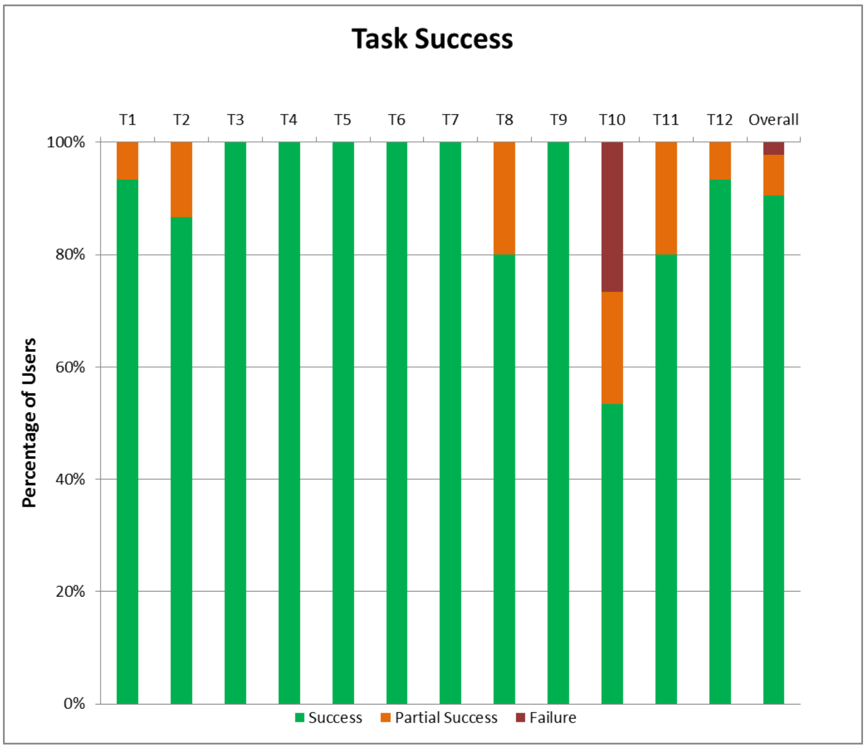


Figure 51. Task success for the study desk user testing

The very high success rate provides evidence of the overall system usability and positive user experience, however in order to identify the specific system areas that needed improvement user errors and help requests were recorded, along with detailed notes by the evaluation observer. In summary, as illustrated in Figure 51, errors and help requests concerned tasks T1, T2, T8, T10, T11, and T12. More specifically, 25 usability problems were identified, as presented in Table 21.

Table 21. Usability problems found through the study desk user testing

General	
1.	A help functionality should be included in the system.
2.	The main menu should be placed at the bottom right corner of the table, to be easily reachable.
Interaction with the book	

3.	If the book is placed in rightmost area of the table, the UI elements located there should move in order to be always visible.
4.	The main menu should collapse when the physical book is placed over it.
Multimedia	
5.	It is not possible to pause and restart a video.
6.	A bar indicating the length of the video, as well as the proportion of it that has been reproduced is missing.
7.	It is not possible to resize the window of a video.
8.	Extended touch opens the same video twice.
9.	The button to stop the music score is not visible.
10.	Videos / music scores are simultaneously reproduced. When a multimedia is selected while another one is active, the first one should stop.
11.	It should be possible to zoom into a photo.
12.	All photos should have a legend.
13.	The total number of videos or photos in the gallery should be provided.
Painting	
14.	The selected size and colour of the brush should be indicated.
15.	A confirmation message should precede any content deletion.
16.	A redo option should also be provided.
17.	An eraser allowing to delete only a part of the drawing should also be provided.
18.	The brush colour could change to indicate the selected painting colour.
Social media sharing	
19.	It should be possible to move the Facebook / Twitter window.

20.	The selected social media channel (Facebook / Twitter) should be indicated.
Icon issues	
21.	The undo icon is not understandable.
22.	The headphones icon is not easy to understand.
23.	The move icon looks like resize and was not easily perceived.
24.	The icon to make the system indicate the interactive areas was not easily perceived.
25.	The Facebook / Twitter icons did not stand out as interactive options.

Following the experiment, the users were asked to complete a subjective evaluation questionnaire, aiming to assess their overall user experience. In more details, the questionnaire involved 12 statements, to which the participants had to specify their agreement on a scale from 1 (strongly disagree) to 5 (strongly agree), as well as two open-ended questions asking participants to identify additional functionality that would be desired and to provide additional comments on the system. Five of the questions were related to the interaction with the system, while the remaining seven questions aimed to assess the user experience and find out whether users would actually use such a system if it was commercially available and for which purposes (e.g., education, entertainment). More specifically, the questions were the following:

1. I liked the interactive table for augmented book reading.
2. I didn't need a lot of practice until I learned how to use the system.
3. The system responded accurately to my actions.
4. The system was awkward to use.
5. The system responded promptly to my actions.
6. The system was tiring to use.
7. I would use such a table, if it was commercially available, for educational purposes.

8. I would use such a table, if it was commercially available, for recreational purposes.
9. A table like this would be useful to young children.
10. A table like this would be useful to anyone.
11. Such a table would make students' studying more effective
12. Such a table would make students' studying more pleasant / enjoyable

In summary, users were very satisfied with the system (M: 4.26, SD: 0.75, 95% CI [4.15, 4.37]), with the interaction (M: 3.97, SD: 0.82, 95% CI [3.79, 4.15]) and with the overall user experience (M: 4.47, SD: 0.63, 95% CI [4.35, 4.59]). Users identified the following functionality that would be desired:

1. Touch-based interaction using just their fingers
2. Redirection to online information sources (e.g., Wikipedia)
3. Text-to-speech functionality for reading aloud selected passages of text
4. Note keeping functionality
5. Addition of games

Finally, the participants were debriefed and a detailed discussion was carried out on the specific tasks found to be troublesome, as well as additional features that would be desired. During the debriefing session, and in accordance with the observer's notes, most of the participants stated that they were unfamiliar with the light pen, which they found somewhat cumbersome. This is also depicted in the satisfaction questionnaire results, where the interaction category scored lower than the user experience category, due to the interaction with the lightpen.

In summary, the system was very usable and satisfying for the users. The evaluation revealed 25 usability problems, all pertaining to the UI of the specific applications embedded in the system. In terms of interaction, it turned out that the device used (lightpen) was cumbersome for the users, and as suggested by users themselves touch-based interaction with their fingers would be preferred. Finally, the need for a help functionality to assist first-time users familiarize with the application was pointed out.

7.3 Within subjects user testing of three systems

With the aim to identify whether the proposed framework is unobtrusive and compare the supported interaction techniques, an additional evaluation experiment involving sixteen participants in a within-subjects setting [103] has been carried out for three of the developed systems, namely SESIL, The book of Ellie and Study Desk. During the experiment, each participant used and evaluated all three systems. The within-subjects test was preferred since it most commonly used in studies aiming to evaluate how easily a participant can learn to use a product (or in our case the various interaction techniques as used in the three systems), employing smaller sample size, and eliminating differences between people that occur in between-subjects testing [4]. In order to address any bias in the results due to carryover effects [4], the order in which participants evaluated the three systems was varied.

Participants

Participants were selected to be familiar with computers, nevertheless their expertise in the use of educational software and multimedia varied. Furthermore, twelve of the participants (75%) were Computer Science students, while the remaining four participants (25%) were recruited as parents of young children who use educational software for their children. It should be noted that the majority of participants were selected to have some experience with educational software and multimedia, since the main evaluation goal was to assess the unobtrusiveness of the system as perceived by the users. Therefore, a comparison of the participants' experience with the proposed system versus standard educational and e-learning software would provide a reliable indicator. Information about the participants' profiles is presented in Table 22.

Table 22. Evaluation participants' characteristics

		Overall	Students	Parents
Gender	Male	50%	41.5%	75%
	Female	50%	58.5%	25%

Educational software expertise	Low	12.5%	16.5%	0%
	Medium	43.75%	33.5%	75%
	High	43.75%	50%	25%

Procedure

An important parameter affecting the evaluation methods that were employed during the experiment was the research question that should be answered in this evaluation. The main evaluation goal was not to identify specific usability issues of the three applications; it was instead to understand how users experience the overall educational procedure with the support of the AR systems, as well as to find out users' satisfaction regarding the supported interaction techniques. Since collecting quantitative data was not a primary concern, the evaluation was carried out by observation [104] of participants' interaction with the systems, taking notes of the errors that were observed and the difficulties met. During the process, the participants were encouraged to express their thoughts aloud [82], thus assisting the observer's note taking process. After using each system, participants were asked to fill-in a short user experience questionnaire, while the evaluation concluded with a semi-structured interview focusing on the participants' view of the systems. The interview aimed at clarifying any interaction issues or usability problems that occurred during the test, and acquire further insights on the users' opinion about the three systems.

During the test, the participants were welcomed and introduced to the systems, their content and the various supported interaction modalities. An important concern which was raised during the evaluation planning and preparation phases was the heterogeneity of the three systems in terms of content and interaction techniques. In more details, both the content and the interaction modalities for each system were selected, so that they would best fit different educational contexts, as displayed in Figure 52. SESIL was designed having in mind a typical classroom activity of reading and exercise-solving. Study desk, on the other hand, targets more exploratory activities where the learner receives information about a topic alone or in collaboration. Finally, The Book of Ellie addresses younger children and edutainment activities, where learning is achieved by play. Design decisions were not revealed to the evaluation participants, in order to elicit their opinion regarding the association of interaction techniques with specific educational contexts and avoid bias.

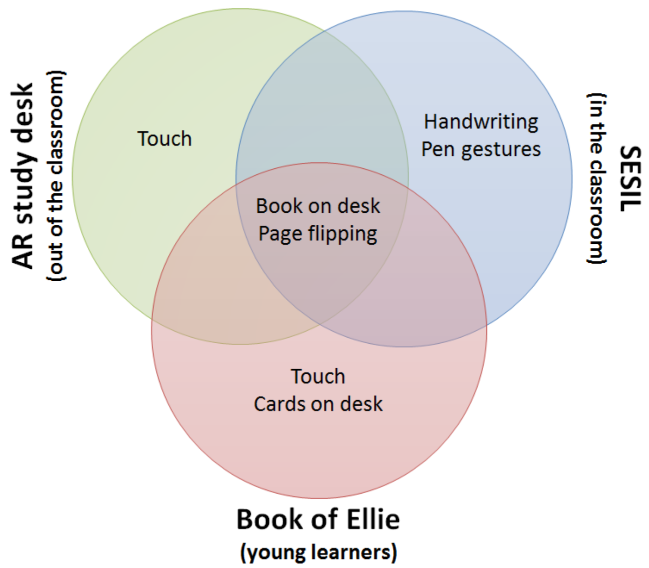


Figure 52. Interaction modalities and educational contexts for each system of the InPrinted framework

Furthermore, aiming at obtaining qualitative data, users were not provided with detailed scenarios structured around specific tasks. However, an indicative scenario highlighting the main system elements that the user should explore was created and used by the evaluation observer to guide the experiment. Scenarios' overviews are provided in Table 23.

Table 23. Scenario overviews

System	Scenario description
SESIL	The user was asked to open the book at the first page of a chapter (thematic unit). Then he/she was instructed to read the content, browse the next couple of pages, and find additional information for specific words that might be of interest. Then, the user was asked to move to the

	chapter's exercises and solve a fill-the-gap exercise with multiple choice answers, as well as to answer an exercise by providing handwritten input.
Study Desk	The user was instructed to select one of the available leaflet books and initiate interaction with the system. Then, he/she was asked to browse through the pages of the book and select three specific points of interest (text passages or images) for which he/she would like to receive additional information.
The Book of Ellie	The user was asked to browse through the book pages, and select text passages or letters of the alphabet of interest. After a short period of interaction with the book, the user was asked to switch to game mode.

The user experience evaluation questionnaire (see APPENDIX I) comprised two sections: a section with statements regarding the users' experience with the system, and a section with pairs of contrasting characterizations for the system. In more details, the participants had to specify their agreement on a scale from 1 (strongly disagree) to 5 (strongly agree) with each of the following seven statements:

1. The system was easy to use.
2. I didn't need a lot of practice until I learned how to use the system.
3. The system was awkward to use.
4. The system disrupted my workflow and disoriented me from my learning goals.
5. Interaction with the pen / by touch / with cards was easy to achieve.
6. Such a system can make studying more effective.
7. Such a system can make studying more pleasant / enjoyable).

In the case of systems employing more than one interaction technique, the relevant question was asked once for each interaction technique.

Furthermore, the system characterizations (Pleasant – Unpleasant, Interesting – Boring, Straightforward – Cumbersome, Predictable – Unpredictable) ranged on a scale from 1 to 7, with 1 representing the most positive attitude (e.g., pleasant) and 7 the most negative (e.g., unpleasant). The participants were asked to provide a rating indicating how they felt about the system they had just interacted with.

Finally, interviews aimed at further investigating the participants' view of the interaction and allowing them to freely express their thoughts. Interviews were structured around the following discussion themes:

1. User's opinion regarding the interaction and the augmented educational experience
2. Learning environments and ages for which each system is more suitable
3. Most liked feature(s) of user's interaction with the system
4. Most disliked feature(s) of user's interaction with the system

The interview discussion followed the laddering technique [131] according to participants' answers in each one of the discussion themes.

Results

Observation during the experiment revealed certain usability problems in the interface or with the interaction techniques, which were further analysed during the interview sessions and are reflected in the participants' ratings in the evaluation questionnaires. However, in certain cases the participants - being impressed by the educational potential of the system and the novelty of the interaction techniques - tended to disregard the usability difficulties they faced and rated the system more positively than expected, based on the hypothesis that they evaluated a system prototype and that the problems will be eliminated in the final system.

In more details, SESIL was the system that was found more difficult to use, mainly due to the interaction techniques employed. Handwriting turned out to be difficult for users, it was not always accurate and it required writing large letters. Furthermore, users faced difficulties with the pen, mainly since they found that they did not know exactly which gestures were supported by the system and they were unsure about what gesture would be appropriate for each task. On the other hand, Study desk was considered more straightforward and easier to predict. Comments regarding Study desk mostly referred to enhancing its functionality with additional embedded applications (such as games). Finally, The Book of Ellie was also considered straightforward, enjoyable and easy to predict. As shown in the diagrams below, both Study desk and The Book of Ellie received similar ratings from the evaluation participants.

Figure 53 displays the average and standard deviation rating for each question of the evaluation questionnaire for all three systems. The results referring to the interaction techniques are presented in Figure 54, where ratings regarding touch in the Study desk and in The Book of Ellie have been aggregated into one result referring to touch in general. Questionnaire results related to users' characterizations of the three systems are presented in Figure 55.

In summary, the two systems employing touch as the main interaction technique were found easier to use and learn, less awkward and obtrusive. Interestingly, however, all three systems were considered as having the potential to make studying more effective and enjoyable. The Book of Ellie was considered as the system that would make studying more effective and enjoyable, mainly since it was more targeted to a specific audience (young children), and thus it was easier for users to appraise its learning potential.

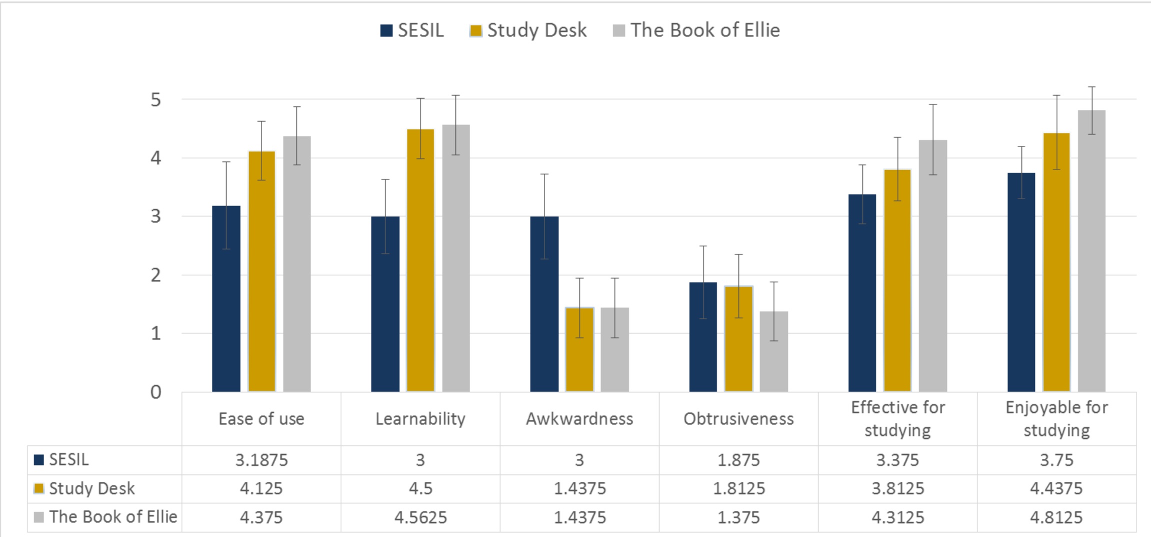
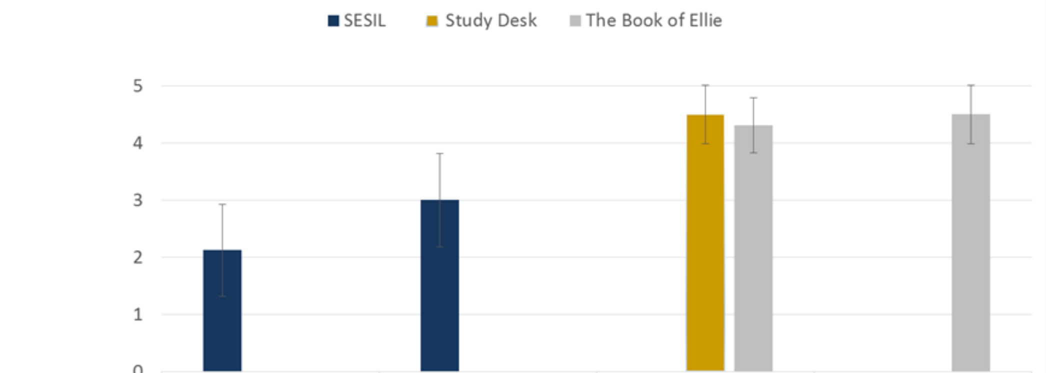


Figure 53. Analysis of the evaluation questionnaire results

Furthermore, results regarding the interaction techniques indicated touch and card-based interaction as easier to use, while several problems and difficulties were encountered with handwriting and pen-based interaction. Note that since not all systems employed all interaction techniques, as illustrated in Figure 52, Figure 54 includes several 0-value bars.



	Handwriting	Pen	Touch	Cards
SESIL	2.125	3	0	0
Study Desk	0	0	4.5	0
The Book of Ellie	0	0	4.3125	4.5

Figure 54. Analysis of the evaluation questionnaire results regarding interaction techniques

In addition, users considered The Book of Ellie as the more pleasant and predictable system, while very close in ratings was the Study desk. On the other hand, although SESIL was considered less pleasant, straightforward and predictable, it is noteworthy that it was rated as the most interesting system.

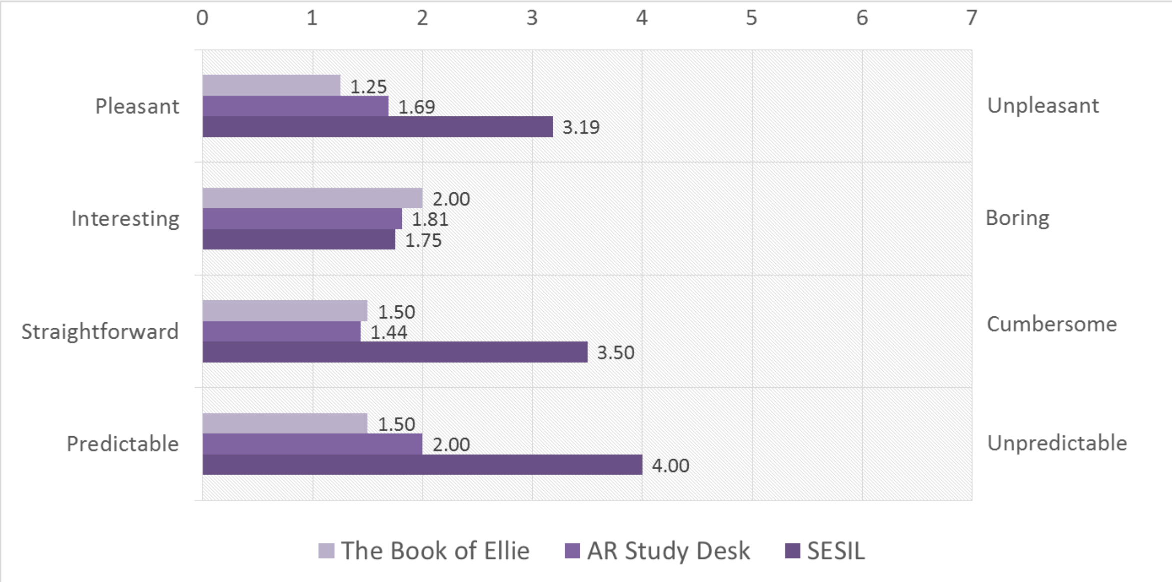


Figure 55. Analysis of the evaluation questionnaire results regarding the systems' characteristics

Users' comments provided during the interview sessions were analysed using affinity diagrams [18]. In summary, the following conclusions relevant to the research questions arose:

- Users' opinion regarding the unobtrusiveness of each system was greatly impacted by the ease of use. As one of the users put it regarding handwriting and SESIL: "struggling to make handwriting work disorients me seriously from my initial goal – solving a simple exercise".
- The majority of users indicated that The Book of Ellie would be more appropriate for young children, while SESIL would be better to address high school students who are more familiar with handwriting. The Study desk was considered to be a system appropriate for all ages and educational contexts, having of course its content and perhaps additional applications updated accordingly.
- Being familiar with touch-based interaction due to the popularity of smart phones and touch-enabled devices, users found this interaction technique as the more natural one. According to a participant's words "I don't have to think about it: I just point with my finger. It's easy and simple."

Finally, a summary of users likes and dislikes about their interaction with each one of the systems is presented in the affinity diagram of Figure 56. Affinity diagrams were also employed in order to find out any important differences in users' comments according to their profile and mainly according to their experience with other educational software, nevertheless important differences and trends were not identified.

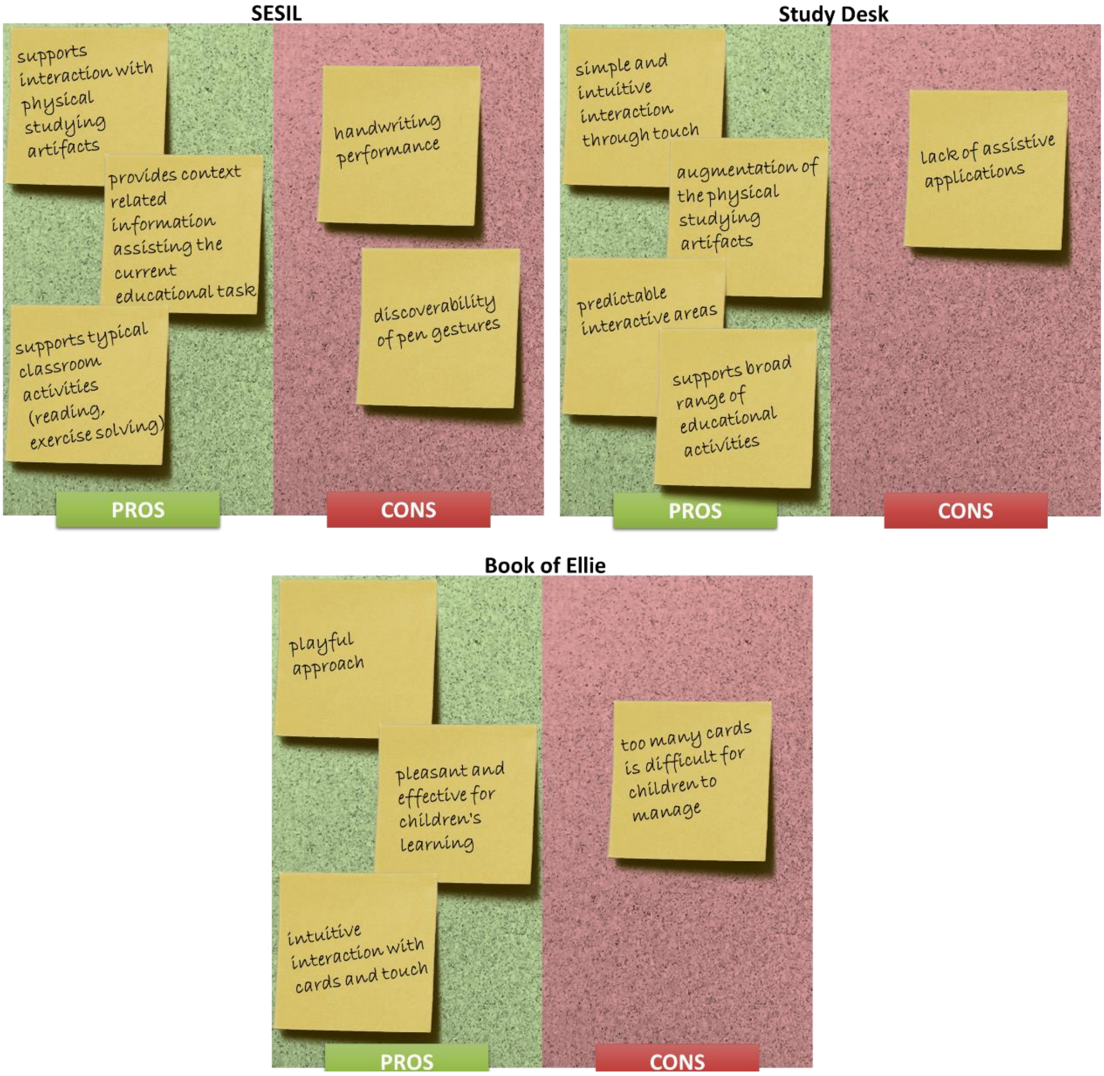


Figure 56. Affinity diagram for users' likes and dislikes for the three systems

7.4 Large-scale in-situ evaluation

The Interactive Maps system, a reduced version of the Study desk system, that has been developed with the InPrinted framework and has been deployed at the Heraklion Municipality InfoPoint, was evaluated in-situ for five days with actual visitors of the

InfoPoint, during its official working hours. Typically, the InfoPoint has in average 80 visitors per day, during the high tourist season (from early spring until late autumn). This evaluation was part of the overall user experience evaluation of the seven interactive systems that have been installed at InfoPoint. The evaluation of Interactive Maps aimed at assessing the overall user experience with the system in terms of interaction with physical paper, and in more details to explore the following hypotheses:

H1. The system is easy to use with minimum guidance.

H2. Touch-based interaction with the augmented paper is natural.

H3. The overall user experience is positive.

H4. The system will be easier to use and more appealing to younger users.

H5. Experienced computer users will find the system more appealing and easier to use.

Methodology

In situ evaluation promises benefits associated with exploring how a system is actually used in its real environment, avoiding contrived situations imposed in laboratory and field testing [38]. For instance, an important benefit of in-situ studies is that they can reveal how the environment itself impacts on the user experience [134]. Although usability evaluations in laboratory settings can identify many usability issues, actual use aspects are less easily revealed in such settings, where participants are asked by an experimenter to follow instructions and perform certain tasks using a prototype system [25]. Comparison of in situ and laboratory evaluation, carrying out evaluations in the exact same way, indicated that more usability problems were identified in situ, while it was only this type of evaluation that revealed problems related to cognitive load and interaction style [101]. An important parameter that may affect the overall evaluations results is users' motivation to use the system in the real world, which is partially determined by users' curiosity and system novelty [108]. Overall, the main value of in-situ (or in-the-wild) evaluations is that they are real and perhaps messy, but more realistic than laboratory evaluations [70].

Despite the high potential of in-situ (or in-the-wild) evaluations, there are several challenges associated, as the high cost involved and the high expectations from such studies regarding the anticipated outcomes [25]. Other considerable challenges include the lack of control, as well as environmental conditions, or social considerations [70]. Furthermore, an important challenge to be addressed is how and what will be recorded. In such situations when it is impossible, yet also not desirable, to capture everything, the key is to use a combination of various methods that reveal both hoped for and unexpected effects of the context of use [134, 136]. It has also been suggested as a best practice in such settings to supplement objective context data with subjective data on participants' context perceptions [136]. Finally, a significant concern for any observation experiment is whether to use any video, photo, or audio recording. Especially in the case of in situ evaluations, it is of uttermost importance to respect social norms and switch to other recording methods, such as note taking, if multimedia recording is considered socially or legally unacceptable [136].

Before determining the exact methodology and tools, it was important to fully understand the context. Therefore, the research team delved deep into the InfoPoint daily routines and visitors' behavior around the interactive systems by observing and documenting points of interest and caution. These observations along with state of the art research in the field dictated the need for an evaluation combining objective and subjective assessments, namely observation, semi-structured interviews with users, semi-structured interviews with employees of the InfoPoint, as well as questionnaires filled-in by the users themselves.

Observations

Although video recording in public spaces is allowed upon approval of the Hellenic Data Protection Authority, given the diversity of cultural backgrounds and social norms of the potential target users, it was decided to not use any multimedia recording, and make thus the recording process less intrusive. In order to compensate the lack of video recording, free note taking was complemented with a structured observation grid, aiming to record the following parameters based on [91]: appeal, learnability, effects of breakdowns, distraction. Additionally the observation grid was further enhanced with parameters related to cultural readiness, flexibility, and interaction behavior as summarized in Table 24 and presented in detail in Appendix II.

Table 24. List of metrics of the observation sheet

Parameter	Metrics
Appeal	User's reaction to the display (e.g., curious, excited, confused, stressed, etc.)
Learnability	Instructions read, understanding how to use the display by oneself, assistance requests, difficulties encountered
Breakdown effects	Technical problems, problems overcome by the user
Attention and distractions	Functionality preferred, distractions
Cultural readiness	Users' comfortability with the display, unexpected / unusual actions
Flexibility	Accomplishment of tasks not originally envisioned
Interaction behavior	User's interaction behavior (e.g., confidence, autonomy, insecurity, impatience, etc.), functionality used

Semi-structured interviews

The semi-structured interviews with users and employees were part of the overall InfoPoint User Experience evaluation and included questions that do not pertain specifically to the Interactive Maps system.

More specifically, interviews with users included the following questions:

- Is it your first time in Crete?
- How did you find about InfoPoint?

- Did you find any useful information or places to visit? (If yes, please explain what and how)
- What did you like most?
- What did you like least?
- Other comments / suggestions / concerns

On the other hand, employees were interviewed using the following questions:

- Can you describe how the interactive systems assist you in your daily work routine at InfoPoint?
- What do users think about these technologies (what comments do you receive for them)?
- Have you observed anything noteworthy as to how users interact with the systems?
- How much time do users spend in the interactive systems?
- Have you observed any user preference towards specific systems?
- Do you guide visitors as to how to use the systems? If yes, how? How often do visitors need guidance?
- Is it easy for you to use the systems?
- Other comments / observations / suggestions

Although the questions are general, only the responses that refer to the specific system are analysed in this section (e.g., if the system was mentioned as one of the most liked/most disliked, or if any specific comment was made for it).

Questionnaires

Users were asked to fill-in a questionnaire to rate their experience. The questionnaire (Annex III) included (i) metrics inspired from [91, 155] provided as bipolar adjective pairs on a 5-point rating scale, and (ii) open-ended comments. The adjective pairs were as follows:

- Attractive / Ugly
- Enjoyable / Boring
- Convenient / Tiresome
- Pleasant / Unpleasant

- Useful / Useless
- Informative / Uninformative
- Satisfactory / Unsatisfactory
- Easy to use / Difficult to use
- Unique / Ordinary.

Procedure and Participants

Visitors were informed of the evaluation and the procedures that would be followed, upon approaching the first interactive system installed at the InfoPoint premises. Those who orally agreed to be observed during their interaction with the systems were given an informed consent form to sign. As the interactive systems are installed adjacently at the InfoPoint, one dedicated observer for every two systems had been a priori assigned for recording user interactions using the observation sheets. Once visitors completed their interaction with the InfoPoint systems and/or with the staff for retrieving information, and before leaving the building they were given the questionnaires to fill-in (one for each system they had interacted with), and were interviewed. Finally, visitors were thanked for their time and contribution towards improving the InfoPoint user experience.

In total, the Interactive Maps system was used by 87 visitors, individually, in pairs or small groups of three or four visitors, resulting in 46 system usages (individual: 15, pairs: 24, small groups: 7). Participant ages ranged from children to seniors, as follows: 5 children (younger than 12 years old), 1 teenager (12-17 years old), 24 youth (17-30 years old), 35 young adults (30-44 years old), 21 adults (44-60 years old), 1 senior (older than 60 years).

The first part of the questionnaire included additional demographic information, namely gender, level of computer skills, frequency of computer use, education level, as well as if their studies or profession is related to tourism or computer science. Table 25 presents the participants' demographic information, as acquired by 31 participants who filled out this questionnaire section.

Table 25. Participants' demographic information

Gender		**Computer skills**	
Male	67.74%	Low	3.23%
Female	32.26%	Intermediate	54.84%
		High	41.94%
Education			
Less than high school	3.23%	**Frequency of computer use**	
High school or equivalent	16.13%	Every day	93.55%
College but no degree	16.13%	Several times a week	3.23%
Associate degree	9.68%	Several times a month	0.00%
Bachelor degree	32.26%	Almost never	3.23%
Graduate degree	22.58%	Never	0.00%
Tourism-related studies or profession		**Computer-related studies or profession**	
Yes	9.68%	Yes	61.29%
No	90.32%	No	38.71%

Results

The initial hypotheses have been explored by combining data recorded in the observation sheets with questionnaire data, as illustrated in Table 26. This section reports the results for each one of the five hypotheses and also provides insights from the qualitative analysis of the free text comments and interviews with visitors and employees.

Table 26. Metrics used to test the hypotheses

H1	**Observation sheet**	Learnability parameters (Instructions read, understanding how to use the display by oneself, assistance requests, difficulties encountered)
	Questionnaire	Easy to use / Difficult to use
H2	**Observation sheet**	Interaction behavior (functionality used) Attention & distractions (functionality preferred) Flexibility (tasks not originally envisioned) Cultural readiness (unexpected /unusual actions)
H3	**Observation sheet**	Appeal (users' reaction to the display) Attention & distractions (distractions) Breakdown effects (technical problems, problems overcome) Cultural readiness (users' comfortability with the display) Interaction behavior (observed users' interaction behavior)
	Questionnaire	Questionnaire results
H4	Statistical analysis of all the results for the different user ages	
H5	Statistical analysis of all the results for the different levels of computer expertise	

H1. The system is easy to use with minimum guidance

In order to study H1, the following observation sheet recordings were used: if the user read the instructions provided by the system, if he understood how to use the display by himself, if he requested assistance and for what, as well as what difficulties did he encounter during system usage. Also participants' questionnaire rating for the easy to use/difficult to use adjectives pair are reported.

Figure 57 illustrates the results recorded in the observation sheets for the aforementioned questions. Error bars in the chart represent 95% confidence intervals calculated with the Adjusted Wald method [78]. The numeric values for metrics of the observation sheet used for testing hypothesis H1, as well as the calculated confidence intervals, are reported in Table 27. A correlation of observation data for the first three questions (see Figure 58) highlighted that out of the 8 participants who read instructions, 7 (87.5%) understood how to use the system by themselves, while only 1 participant (12.5%) had to ask for assistance in order to understand how to use the system.

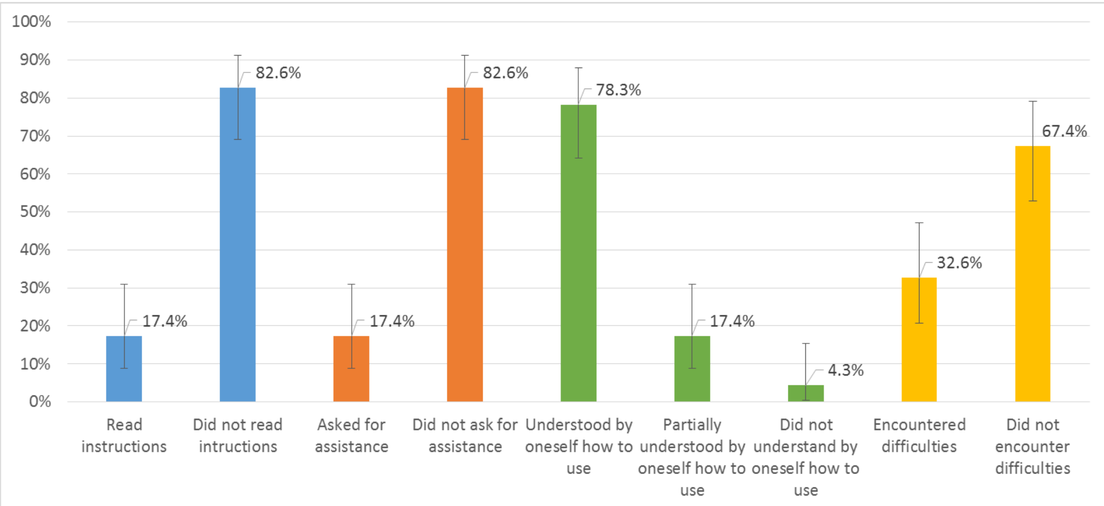


Figure 57. Observation data related to H1

Table 27. Data for observation recordings related to H1

		Proportion	CI[LL]	CI[UL]
Instructions read	**Yes**	17.39%	8.82%	30.99%
	No	82.60%	69.01%	91.18%
	Yes	17.39%	8.82%	30.99%

Asked for assistance	**No**	82.60%	69.01%	91.18%
Understood by oneself how to use	**Yes**	78.26%	64.24%	87.93%
	Partially	17.39%	8.82%	30.99%
	No	4.34%	0.39%	15.34%
Encountered difficulties	**Yes**	32.60%	20.80%	47.10%
	No	67.39%	52.90%	79.20%

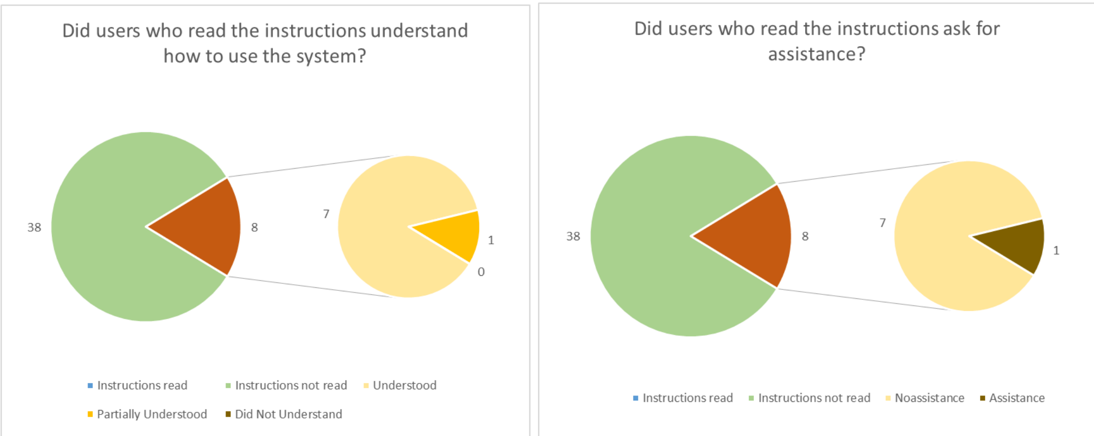


Figure 58. Correlation of data regarding instructions read and [left:] users' understanding of how to use the system, as well as [right]: assistance requests

Further analysis of the difficulties encountered revealed that out of the 15 participants who faced difficulties, 12 (80%) encountered problems related to touch, 4 (26.67%) tried to carry out an unsupported gesture – namely swipe and moving a popup, while 1 (6.67%) faced a problem since the printed map was out of the camera recognition bounds. A qualitative analysis of observers' notes suggested that visitors seemed familiar with touch gestures, perhaps having prior experience with smartphones or tablets. The responsiveness of such devices however is quite more immediate than that of gestures detected through computer vision, a technology which was not visible to participants. As a result, the system did not adhere to their expected response time, leading to repeated touches, which was recorded as difficulty.

Participants' questionnaire responses regarding ease of use resulted in an average score of 1.09, on a scale from -2 (very difficult to use) to 2 (very easy to use), with the 95% confidence interval ranging from 0.69 to 1.5. Further analysis of the answers revealed that only 1 participant rated the system as very difficult to use (3%, CI[UL]: 17%) and only two participants rated it as difficult to use (6.2%, CI[UL]: 21%).

In summary, it can be concluded that we are 95% confident that for the general population at least 64% will understand by themselves and at least 8% will partially understand by themselves how to use the system, while at least 53% will not encounter any difficulties at all. Furthermore, none of the recorded difficulties constitutes a showstopper, further verified by the fact that none of the participants quitted system usage. Finally, the system was rated as overall easy to use, while a very small proportion of participants rated it as difficult of very difficult to use.

H2. Touch-based interaction with the augmented paper is natural

To explore hypothesis H2, the following observation recordings were used: functionality used, functionality preferred, tasks carried out that had not been originally envisioned, and unexpected / unusual actions. As preferred functionality, the observers recorded the system functionality more often used during a session. Figure 59 illustrates the proportion of users who used and preferred each one of the supported system functionalities, while error bars in the chart represent the Confidence Intervals, calculated using the Adjusted Wald method. The corresponding data are available in Table 28.

Table 28. Data regarding functionality used and functionality preferred

	Used			Preferred		
	Proportion	CI[LL]	CI[UL]	Proportion	CI[LL]	CI[UL]
Touch hotspot	95.65%	84.66%	99.61%	86.96%	73.96%	94.26%

Browse gallery	54.35%	40.18%	67.85%	17.39%	8.82%	30.99%
Move map	52.17%	38.14%	65.88%	34.78%	22.63%	49.28%
Read information	45.65%	32.15%	59.82%	13.04%	5.74%	26.04%
Change language	10.87%	4.29%	23.49%	4.35%	0.39%	15.34%
View video	45.65%	32.15%	59.82%	10.87%	4.29%	23.49%

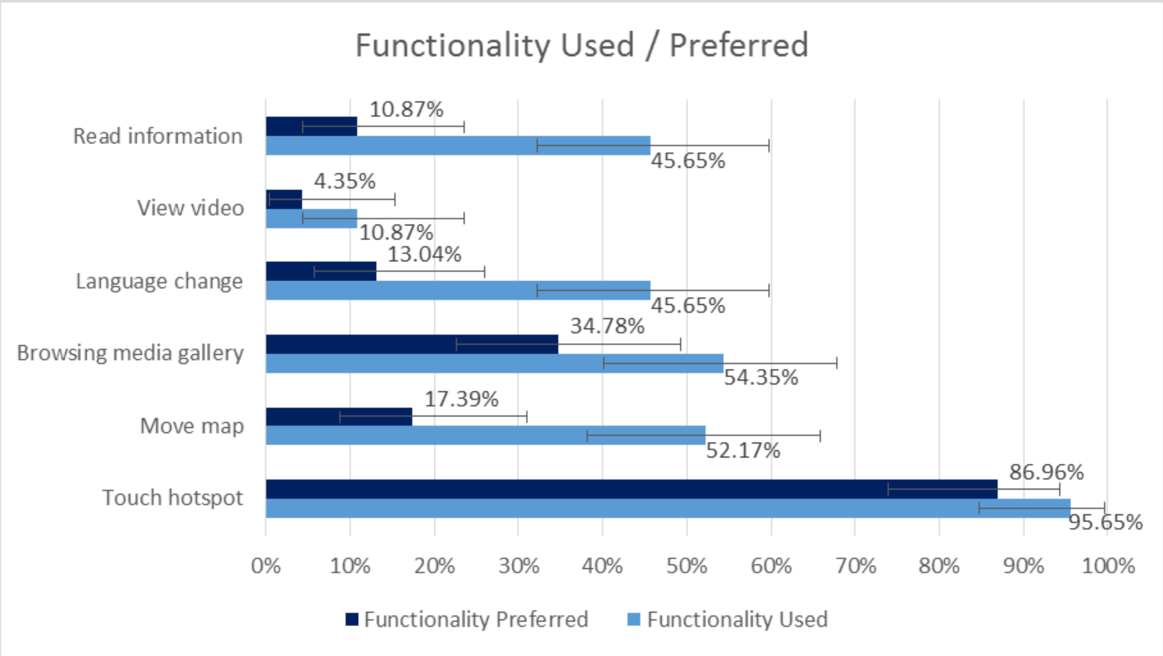


Figure 59. Interactive Maps functionality used and functionality preferred

It can be observed that almost all the participants employed touch to interact with the system, while approximately half of them engaged in additional activities such as moving the physical map on the table, or browsing the gallery of photos. Furthermore, touching hotspots on the printed map and moving the map on the table surface were the mostly preferred actions. Given the high proportion of people who touched the digitally annotated hotspots on the printed map, and that we can be 95% confident that at least 84.6% of the general population would carry out this action with the given system, it is evident that interaction with the system (and in particular touch-based interaction) comes natural to most users.

Regarding tasks carried out that had not been originally envisioned, and unexpected / unusual actions, the following were observed:

- 7 users (36.84%) carried out a swipe gesture to browse the media gallery contents. As observers noted, users seemed in general very familiar with touch gestures and therefore carried out typically employed gestures according to each context. Therefore in a photo gallery, it is usually expected to browse through swiping, a gesture that had not been however incorporated in the specific system implementation.
- 3 users (15.79%) combined the printed map on the table surface with a map they were carrying along, by comparing and keeping notes on their own map
- 3 users (15.79%) took the printed map with them, as they left the InfoKiosk. In fact, this was the envisioned system usage, however as the majority of visitors were not informed of this possibility, it would be impossible to practically "steal" something that did not belong to them.
- 2 users (10.53%) discovered that the system could be operated not only by touching the table surface, but via touchless proximity interaction. Due to the computer vision technology employed to detect fingers, interaction with the system is also possible even at a short distance from the table surface.
- 1 user (5.26%) experimented by turning the map upside down, which caused no breakdown effect, as the system responded to this action by rearranging the highlighted hotspots.

Overall, three types of unforeseen, unexpected or unusual interactions were recorded: (i) interactions expected by users but not supported by the system, (ii) interactions converging the printed and the digital and (iii) innovative interactions to "game the system" and see how well it responds. Although the swipe gesture was not supported, the fact that it was expected confirms that touch-based interactions on digitally augmented paper seemed natural to users. Furthermore, the fact that six users in total extended interaction with the system and complemented it with interaction with the physical paper is a positive indication towards endorsing convergence of the digital and physical world.

H3. The overall user experience is positive.

This hypothesis was explored by studying the observed users' reactions to the display, their interaction behavior and comfortability with the display, as well by analyzing any distractions imposed by the system that might disorient users from achieving their current task at hand, and any major technical problems, as well as their effects. The observation data are further complemented with the analysis of the questionnaires filled-in by the users, as well as specific comments provided through the questionnaires or the interviews.

As illustrated in Figure 60, users' reactions were mainly positive, while the most common reaction was that of curiosity (65.22%). This observation is in-line with research in public displays, which has found that an important motivator for using a real-world system is curiosity [108]. It should be noted that for each user all the exhibited reactions - positive, or negative - as they approached the system were recorded. For instance, a user might approach the system exhibiting curiosity while after approaching he might look confused.

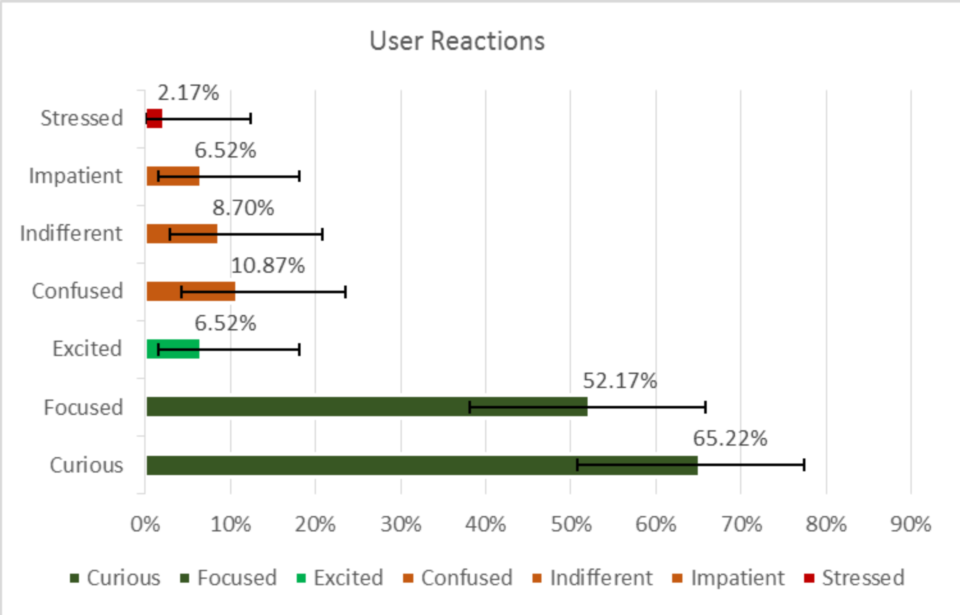


Figure 60. User reactions to the system

The recorded reactions have been further classified into positive and negative according to how they would motivate or demotivate system usage. Analysis of the aggregated data (see Table 29) showed that 79.06% of the users had only positive reactions, 11.62% only negative and 9.3% mixed reactions (both positive and negative). Furthermore, according to the Confidence Intervals, we are 95% certain that at least 64.58% of the wide public will react positively to the system, while at most 24.94% will react negatively.

Table 29. User reactions, classified to positive, neutral and negative

		Proportion	CI[LL]	CI[UL]
Positive	Curious	65.22%	50.72%	77.37%
	Excited	06.52%	01.59%	18.15%
	Focused	52.17%	38.14%	65.88%
Negative	Confused	10.87%	04.29%	23.49%
	Indifferent	08.70%	02.90%	20.86%

	Impatient	06.52%	01.59%	18.15%
	Stressed	02.17%	00.00%	12.38%
Overall reaction	Positive only	79.06%	64.58%	88.79%
	Negative only	11.62%	04.61%	24.94%
	Mixed	09.30%	03.12%	22.16%

Another parameter that has been studied in order to assess the overall user experience is users' interaction behavior. In more details, the observers selected from a predefined list all the perceived behaviors during each session, when the system was used by one or more users simultaneously. The observed behaviors are presented in Figure 61, color coded as follows: green stands for positive behaviors, light green for rather positive, red for negative, and light orange for rather negative. The most often observed positive behaviors were autonomy (39.13%), curiosity (58.7%) and exploratory disposition (47.83%). The most common negative attitudes were impatience (17.39%) and difficulty (13.04%). Difficulties mostly refer to the rather slow responsiveness to touch gestures, as it has been already analyzed in H1, a system behavior which also caused impatience to users, as well as the majority of the negative feelings recorded, namely confusion, frustration, and insecurity. Another important concern expressed by users (vocalizing their thoughts during interaction and/or discussing it with their companions) was that they required more content to be available in the system. As a result, some of the users felt somehow bored, or approached the system with a "killing time" rather than "seek for information" attitude.

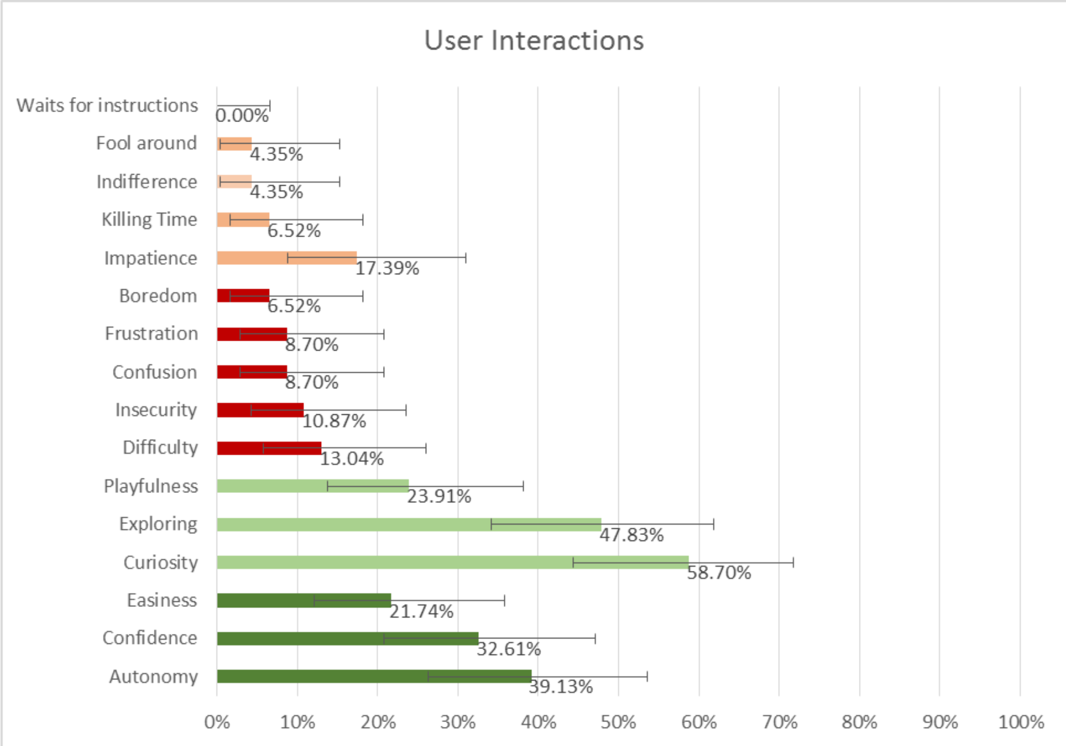


Figure 61. Observed interaction behaviors

Further analysis of the results according to their disposition attempted to identify sessions where only positive, only negative or mixed behaviors were recorded. The results show that only 8.69% of behaviors were in total negative, 63.04% were in total positive and 28.26% were mixed, including both positive and negative attitudes. Mixed behaviors were mainly observed when the system was used by more than one visitors, having for instance one visitor engaged in the interaction and the other uninterested or just fooling around (e.g., children accompanying their parents). Overall, looking into confidence intervals, we are 95% certain that at least 48.57% of the general population will exhibit purely positive attitude in using the specific system, while at most 20.86% may exhibit negative behavior.

Table 30. Interaction behaviors classified to positive, rather positive, rather negative, and negative

		Proportion	CI[LL]	CI[UL]
Positive	Autonomy	39.13%	26.37%	53.57%
	Confidence	32.61%	20.80%	47.10%
	Easiness	21.74%	12.07%	35.76%
Rather positive	Curiosity	58.70%	44.32%	71.73%
	Exploring	47.83%	34.12%	61.86%
	Playfulness	23.91%	13.76%	38.09%
Rather negative	Impatience	17.39%	8.82%	30.99%
	Killing time	6.52%	1.59%	18.15%
	Indifference	4.35%	0.39%	15.34%
	Fool around	4.35%	0.39%	15.34%
	Waits for instructions	0.00%	0.00%	06.65%
Negative	Difficulty	13.04%	5.74%	26.04%
	Insecurity	10.87%	4.29%	23.49%
	Confusion	8.70%	2.90%	20.86%
	Frustration	8.70%	2.90%	20.86%
	Boredom	6.52%	1.59%	18.15%
Overall	Positive only	63.04%	48.57%	75.51%
	Mixed	28.26%	17.22%	42.65%
	Negative only	8.69%	2.90%	20.86%

Another parameter that was studied individually and received the observers' attention was the comfortability of users with the display. The analysis of the results (Table 31) suggested that the majority of users felt comfortable (69.57%) or partially comfortable (10.87%). Furthermore, we can be 95% certain that at least ~60% will feel comfortable or partially comfortable, while at most 33.39% will not feel comfortable.

Table 31. Users' comfortability with the system

	Proportion	CI[LL]	CI[UL]
Comfortable	69.57%	55.11%	81.00%
Partially comfortable	10.87%	04.29%	23.49%
Not comfortable	19.57%	10.43%	33.39%

In terms of distractions two different types were recorded, namely system distractions disorienting the user from the task at hand and external distractions (e.g., by other visitors, adjacent systems installed at the InfoKiosk, etc.). It is important to note that no internal system distractions were recorded. The only distractions that were observed (in total 21.74%, CI[LL]: 12.07%, CI[UL]: 35.76%) occurred due to interruptions by other visitors, or due to looking at adjacent systems. Along the same lines, only two major technical problems were observed. More specifically, one user passed by the system while it was rebooting and as a result he had to wait, while in one case the information card that is displayed upon selecting a hotspot was closed and reopened. Both problems were easily overcome by the users and did not negatively affect the overall user experience.

On the other hand, the analysis of the questionnaires showed an overall positive attitude towards the system. The questionnaire results, which are presented in Figure 62, provide evidence that negative feelings – represented towards the center of the circle - received very few points. Table 32 that presents the proportions of responses for each pair of adjectives also confirms that the majority of attitudes were positive. Finally, further analysis through descriptive statistics is presented in Table 33. By studying the

Lowest Level of Confidence Interval (last column of the table), it is 95% certain that the system will be used with an overall positive attitude by the wide public, as even the lowest CI[LL] scores are larger than 0, which is the score for the neutral attitude.

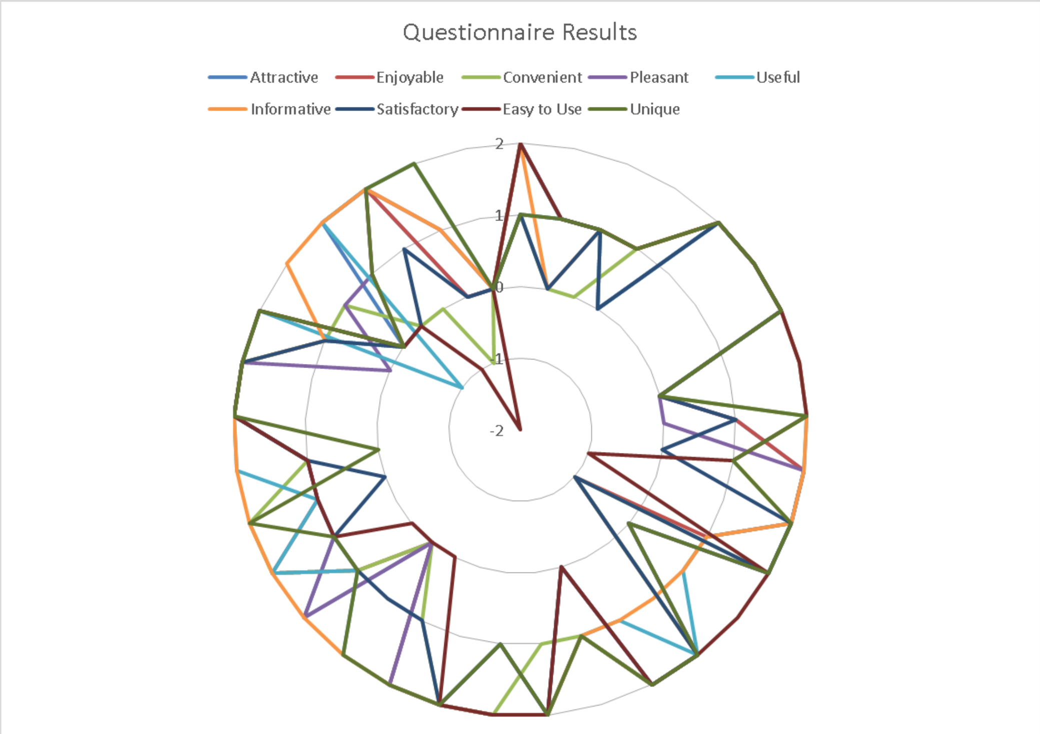


Figure 62. User attitudes towards the system

Table 32. Proportions of users who gave each response

	Very	Somewhat	Neither	Somewhat	Very	
Attractive	51.61%	35.48%	12.90%	0.00%	0.00%	Ugly
Enjoyable	54.83%	32.25%	09.67%	03.22%	0.00%	Boring
Convenient	46.66%	33.33%	13.33%	06.66%	0.00%	Tiresome
Pleasant	56.66%	26.66%	16.66%	0.00%	0.00%	Unpleasant
Useful	68.75%	25.00%	03.12%	03.12%	0.00%	Useless
Informative	68.75%	28.12%	03.12%	0.00%	0.00%	Uninformative
Satisfactory	37.93%	37.93%	20.68%	03.44%	0.00%	Unsatisfactory
Easy to use	50.00%	21.87%	18.75%	06.25%	03.12%	Difficult to use

Unique	58.06%	32.25%	09.67%	0.00%	0.00%	Ordinary

Table 33. Descriptive statistics for questionnaire results

	M	SE	SD	Min	Max	Confidence Level (95%)	CI[LL]
Attractive	1.39	0.13	0.72	0	2	0.26	1.12
Enjoyable	1.39	0.14	0.80	-1	2	0.29	1.09
Convenient	1.20	0.17	0.92	-1	2	0.35	0.85
Pleasant	1.40	0.14	0.77	0	2	0.29	1.11
Useful	1.59	0.13	0.71	-1	2	0.26	1.34
Informative	1.66	0.10	0.55	0	2	0.20	1.46
Satisfactory	1.10	0.16	0.86	-1	2	0.33	0.78
Easy to use	1.09	0.20	1.12	-2	2	0.40	0.69
Unique	1.48	0.12	0.68	0	2	0.25	1.24

In addition, out of the 32 questionnaires, comments were provided in 7 cases. In more details, six users commented that the system needs to improve in terms of responsiveness to touch-based input, while one user also communicated a request for additional content that would further improve the system. These comments are in line with observations, which have identified touch responsiveness as the most important user experience issue of the system.

On the other hand, the results of the semi-structured interviews with users indicated that the Interactive Maps system was often mentioned as one of the users' favorite systems at the InfoPoint (frequency:46.87%, CI[LL]: 30.87%, CI[UL]: 63.55%), while only two users said that it was one of the system they disliked most (frequency: 6.25%, CI[LL]: 0.72%, CI[UL]: 21.16%), one due to its graphic design and the other due to the slow system responsiveness to touch gestures.

Finally, interviews with employees of the InfoPoint also confirmed that the Interactive Maps system is one of the most often preferred by visitors who are interested in retrieving information and not only be entertained, a statement provided by all three InfoPoint employees.

In summary, in the context of studying the overall user experience, the following conclusions have been reached:

- 79.06% of the users had only positive reactions towards the system, 11.62% only negative and 9.3% mixed reactions (both positive and negative). Furthermore, we are 95% certain that at least 64.58% of the wide public will react positively to the system.
- Only 8.69% of interaction behaviors were in total negative, 63.04% were in total positive and 28.26% were mixed, including both positive and negative attitudes. Moreover, we are 95% certain that at least 48.57% of the general population will exhibit purely positive attitude in using the specific system.
- The majority of users felt comfortable (69.57%) or partially comfortable (10.87%) with using the display. In addition, we can be 95% certain that at least ~60% of the wide public will feel comfortable or partially comfortable with the display.
- No internal distractions were observed.
- No major breakdowns were observed. The two technical problems that occurred were easily overcome by the users and did not negatively affect the overall user experience.
- The analysis of the questionnaires showed an overall positive attitude towards the system, while it is 95% that the system will be used with an overall positive attitude by the wide public, as even the lowest possible scores are greater than 0, which the score for neutral attitude.
- The Interactive Maps system was often mentioned as one of the users' favorite systems at InfoPoint (frequency: 46.87%, CI[LL]: 30.87%, CI[UL]: 63.55%),

- Interviews with employees of the InfoPoint also confirmed that the system is one of the most often preferred by visitors who are interested in retrieving information and not only be entertained.

The above indicate not only that in general the user experience with the system is positive, but also that we are 95% confident that the system ensures a generally positive user experience for any user in the wide public. Two major improvements would further strengthen the quality of the system and the interaction, namely enhanced system responsiveness to touch-based gestures, and even richer content.

H4. The system will be easier to use and more appealing to younger users

In order to explore this hypothesis, all observation data were divided according to the recorded user age. In the cases where more than one users used the system, it was observed that most of the users belonged to the same user group, for instance two young adults or two adults exploring the system together. The only exceptions were families with children; however, as interaction with the system was led by the parents and not the children or teenagers of the family, these groups of users were classified under the age group of the parent interacting with the system. This classification resulted in 12 sessions by youth (18-29 years old), 21 sessions by young adults (30-44 years old), 12 sessions by adults (45-60 years old), and 1 session by an older adult (older than 60 years). As the older age group had only one participant, it was excluded from the statistical analysis. Chi-square tests were executed for all the recorded metrics, namely:

- user reactions ($\chi^2(14) = 10.25$, p=0.25)
- user reactions classified into positive, negative and mixed; instructions read ($\chi^2(4) = 6.4$, p=0.82)
- reading instructions ($\chi^2(2) = 0.21$, p=0.1)
- understanding how to use the system by oneself ($\chi^2(4) = 5.25$, p=0.73)
- assistance requests for using the system ($\chi^2(2) = 1.01$, p=0.39)
- encountered difficulties ($\chi^2(2) = 2.73$, p=0.74)
- the specific difficulties that encountered ($\chi^2(6) = 3.59$, p=0.26)

- interaction behaviours ($\chi^2(28) = 38.01$, $p=0.9$)
- interaction behaviours classified as generally positive, mixed, and generally negative ($\chi^2(4) = 5.38$, $p=0.75$)
- functionality used ($\chi^2(10) = 7.36$, $p=0.3$)
- functionality preferred ($\chi^2(10) = 4.42$, $p=0.07$)
- unexpected interactions ($\chi^2(4) = 1.90$, $p=0.24$)
- comfortability with using the display ($\chi^2(4) = 2.32$, $p= 0.32$)

Interestingly, all p values are larger than 0.05, therefore no statistical difference was found for any of the metrics examined between the various age groups.

Respectively, in order to analyze participants' questionnaire answers, they were classified according to the respondent's age. In total, 16 questionnaires were filled in by youth, 8 by young adults, 6 by adults, 1 by an older adult and 1 by a participant who did not provide his/her age. The questionnaire by the older adult, as well as the one of the participant of unknown age were excluded from the statistical analysis. The main effect of age over all the system attributes studied in the questionnaire was explored with one way ANOVA, yielding the following results:

- Attractive / Ugly: $F(2,26)=0.28$, $p=0.75$
- Enjoyable / Boring: $F(2,26)=0.93$, $p=0.4$
- Convenient / Tiresome: $F(2,25)=0.63$, $p=0.53$
- Pleasant / Unpleasant: $F(2,25)=0.11$, $p=0.88$
- Useful / Useless: $F(2,27)=0.14$, $p=0.86$
- Informative / Uninformative: $F(2,27)=1.13$, $p=0.33$
- Satisfactory / Unsatisfactory: $F(2,25)=0.43$, $p=0.65$
- Easy to use / Difficult to use: $F(2,27)=0.54$, $p=0.58$
- Unique / Ordinary: $F(2,26)=0.64$, $p=0.53$

Therefore, the three different user groups did not differ on the reported attitudes towards the system.

Taking into account that no statistical differences were found neither for the observed metrics, nor for the self-reported attitudes, H4 can be rejected. Therefore, it can be concluded that the system is not easier to use or more appealing to younger users; instead it provides an equivalent user experience for all the target age groups studied.

H5. Experienced computer users will find the system more appealing and easier to use.

Experience with computers was recorded through the questionnaires that were filled in by 32 participants, therefore this hypothesis explored only the user attitudes reported in the questionnaires. More specifically, experience with computers was reported through answering the following questions:

(a) Level of computer skills: None, Low, Intermediate, High
(b) Frequency of computer use: Every day, Several times a week, Several times a month, Almost never, Never
(c) Studies / profession related to computer science.

Out of the 32 participants, one did not provide any details at all about his background, therefore his questionnaire responses were excluded from the statistical analysis. The remaining 31 participants reported the following computer skills: Low (1), Intermediate (17), and High (13). It is therefore evident that InfoPoint visitors who approached the systems and were engaged with them are users who feel more confident about their computer skills. This conclusion is further confirmed by the interviews with InfoPoint employees who have stated that

- "There are visitors who perhaps are not so familiar with touch technologies and who prefer to retrieve information from us and get printed material with them, rather than interact with the systems"
- "Often we have to urge visitors to use the systems. Users unfamiliar with technology typically wait to be served by an employee. If the place is too crowded and there is a long line in front of them, then they may start interacting with the systems on their own".

The user sample to be studied exhibited therefore small variations with regard to expertise and skills in computers. Given that only one participant reported low computer skills, his questionnaire responses were excluded from the analysis, as he could not constitute by himself a group to be further statistically analyzed. Additional analysis of responses to questions (b) and (c) highlighted that participants with intermediate and high skills use a computer daily, while some of them had studies or professions related to computer science. As a result, four computer experience levels were determined, as illustrated in Table 34.

Table 34. Participants' computer expertise levels

	Computer skills	Studies / Profession related to computer science	Number of participants
Level 1	High	Yes	13
Level 2	High	No	4
Level 3	Intermediate	Yes	5
Level 4	Intermediate	No	8

The main effect of computer expertise over all the system attributes studied in the questionnaire was explored with one way ANOVA, yielding the following results:

- Attractive / Ugly: $F(3,25)=1.46$, $p=0.24$
- Enjoyable / Boring: $F(3,25)=1.33$, $p=0.28$
- Convenient / Tiresome: $F(3,24)=0.60$, $p=0.61$
- Pleasant / Unpleasant: $F(3,24)=2.18$, $p=0.11$
- Useful / Useless: $F(3,26)=2.89$, $p=0.05$
- Informative / Uninformative: $F(3,26)=0.31$, $p=0.81$
- Satisfactory / Unsatisfactory: $F(3,24)=2.31$, $p=0.10$
- Easy to use / Difficult to use: $F(3,26)=0.86$, $p=0.47$
- Unique / Ordinary: $F(3,25)=1.75$, $p=0.18$

The only parameter to which the analysis suggested an important statistical difference was the system usefulness. Users with intermediate experience and studies or profession related to computer science (Level 3) perceived the system as less useful

(M=0.75, SD=2.25) than the other three categories. A detailed examination of average satisfaction per group for all the studied system attributes revealed a tendency of users with studies or profession related to computer science to provide lower rates. As studies/profession is an objective factor, whereas computer skills is a subjective parameter and was answered by users according to their self-efficacy, an additional classification and analysis of data was performed, according to respondents' objective expertise (studies/profession) in computer science. Therefore, two categories were formed: 19 users with studies or profession unrelated to computer science (level 1) and 12 users with studies or profession related to computer science (level 2). The main effect of computer science relatedness over all the system attributes studied in the questionnaire was explored with one way ANOVA, yielding the following results:

- Attractive / Ugly: $F(1,28)=1.58$, $p=0.21$
- Enjoyable / Boring: $F(1,28)=2.58$, $p=0.11$
- Convenient / Tiresome: $F(1,27)=0.99$, $p=0.32$
- Pleasant / Unpleasant: $F(1,27)=3.22$, $p=0.08$
- Useful / Useless: $F(1,29)=4.62$, $p=0.03$
- Informative / Uninformative: $F(1,29)=0.02$, $p=0.86$
- Satisfactory / Unsatisfactory: $F(1,27)=6.28$, $p=0.01$
- Easy to use / Difficult to use: $F(1,29)=1.05$, $p=0.31$
- Unique / Ordinary: $F(1,28)=5.51$, $p=0.02$

As a result, computer science relatedness had effect on the perceived usefulness, satisfaction, and uniqueness of the system. More specifically, respondents not related to computer science found the system more useful, significantly more satisfactory and quite more unique than respondents related to computer science, as shown in Table 35.

Table 35. Statistically significant effect of computer relatedness to system attributes

System attribute	Studies/Profession related to computer science	Mean	Standard Deviation
Useful	Level 1	1.78	0.17

	Level 2	1.25	0.93
Satisfactory	Level 1	1.41	0.50
	Level 2	0.66	0.78
Unique	Level 1	1.72	0.33
	Level 2	1.16	0.51

Regarding H5, in summary, almost all users who used the system can be considered rather experienced. Therefore, a first conclusion is that in general users who approach the systems are rather confident about their computer efficacy. Further classification and analysis of the different user categories within the sample, revealed that users whose profession or studies were not related to computer science were more impressed by the system, although positive attitude has been recorded for all user categories. Therefore, H5 is not confirmed.

Consolidation of in-situ evaluation results

Overall, the in-situ evaluation of the Interactive Maps system aimed at exploring five hypotheses: its ease of use without guidance, if interaction with the augmented paper is natural to users, if the overall user experience is positive, and whether age and computer expertise affect user satisfaction and (perceived) ease of use. Through exploring the aforementioned hypotheses, the following conclusions were reached:

- We are 95% confident that for the general population at least 64% will understand by themselves and at least 8% will partially understand by themselves how to use the system, while at least 53% will not encounter any difficulties at all.
- We are 95% confident that at least 64.58% of the wide public will react positively to the system
- We are 95% certain that at most 20.86% may exhibit negative behaviour, while interacting with the system. All the negative behaviours that were observed were

due to the fact that the system exhibited low responsiveness in touch gesture. Given that users are used to immediate and prompt responses in their smartphone and tablet devices, some users faced difficulties since they repeatedly touched the surface to select a hotspot and exhibited impatience.

- None of the observed difficulties constitutes a showstopper.
- The system does not cause any distractions and no breakdowns were observed. All difficulties that were encountered by users were rather easily overcome.
- Touch-based interaction comes natural to most potential users of the system.
- We can be 95% confident that at least approximately 60% will feel comfortable or partially comfortable with the system.
- It is 95% certain that users will perceive in general the system positively in terms of its attractiveness, enjoyability, convenience, pleasantness, usefulness, informativeness, satisfaction, ease of use and uniqueness.
- Curiosity was a strong motivator for using the specific system, installed in a public space.
- Users' self-efficacy in computers was a motivator for approaching and using the system.
- The system is not easier to use nor more appealing to younger users, while user age does not affect users' attitude towards the system.
- Users with profession or studies related to computer science were less impressed by the uniqueness and less satisfied with the system and its usefulness, in comparison to users with profession or studies not related to computer science.

In conclusion, both users' questionnaire responses and observations confirm that the system is positively received by the users, especially regarding interaction with paper. In more details, interacting with augmented printed matter was well accepted, easily understood, and natural for the users. The majority of negative attitudes exhibited or rates received was related to the responsiveness of the system to touch gestures, which was expected to be faster and thus caused impatience and/or discomfort to some users.

Limitations of the study

An important consideration refers to the user sample that participated in the study. As the evaluation was an in-situ observation, it was not possible to have a balanced sample in terms of age, gender, education, or computer skills. Nevertheless, a valuable conclusion that was reached due to the in-situ nature of the observation was that such a public system employing innovative technologies is approached more easily by individuals who feel adept at using computers in general.

Although the same individuals participated in the observation, and the questionnaire and mini-interview, due to the flow of visitors in the InfoPoint it was not possible to correlate observations to interviews. In more details, as interaction with the seven InfoPoint systems was spontaneous, each visitor or group of visitors might engage with the systems in a different order, choose not to use some of the systems, and approach the InfoPoint exit - close to where interviews were held - at any point in time. All observation sheets and questionnaires were marked with a unique id, however user #1 at the Interactive Maps system might be different than user #1 of another system or the user who filled in questionnaire #1. However, the results have been used independently, yet in synergy where appropriate, in order to explore the different hypotheses.

Lack of video recordings might result in less data. However, skilled observers were employed for recording interactions, specific structured forms were used, while each observer was responsible for one or two specific systems becoming thus more efficient at recordings. Furthermore, observation sheets were reviewed and processed on a daily basis, when the experiment was still in memory.

7.5 Evaluations' summary

Several evaluation approaches have been employed to assess the four applications that have been developed using the proposed framework, namely:

- heuristic evaluation with UX experts for all the developed applications
- user testing in the laboratory of one selected application, incorporating the majority of interaction modalities and augmentations supported by the framework

- comparative evaluation of three different applications, each encompassing different modalities
- in-situ evaluation of a publicly installed system involving a large number of users.

Through all the evaluation approaches it was evident that users and UX experts agreed on the fact that the systems provide a positive user experience and are well accepted. Furthermore, no specific concerns or usability problems were found regarding augmenting physical paper and interacting with its digital counterpart, or digital augmentations. In fact, users in the laboratory experiment where the think-aloud protocol was applied, identified as a positive attribute of the systems the fact that traditional studying artifacts were augmented and were pleased about the potential benefits this could bring to educational activities.

An interesting finding, consistent throughout all the heuristic evaluation experiments, was the concern of experts regarding the discoverability of the supported gestures, especially by first time users. This result was further confirmed in the user testing that was carried out for Study desk. A help functionality was included in the Interactive Maps system, which was evaluated in-situ, therefore this problem was overcome. Context-sensitive help will be included in future developments of the InPrinted framework.

In terms of interaction modalities, the comparative evaluation revealed that touch and card-based interactions scored higher than pen-based and handwriting interaction regarding their ease of use. The naturalness of touch-based interaction was also confirmed through the in-situ evaluation of the interactive maps system, as most users are already familiar with such interactions due to the wide penetration of smartphones as computational devices. This conclusion does not imply that other interaction modalities should not be supported; rather, it suggests that users can easily expand their knowledge from digital interactions to interactions with augmented paper.

Impact 8

As already discussed, the potential of digitally augmenting printed matter in every-day life is undisputable. For example, as indicated in [154], a survey done of over 1,000 U.S. and 500 U.K. consumers asking their opinions on a variety of issues surrounding paper-based vs. digital media, a sizeable majority of 88% of respondents indicated that they understand, retain and use information better when they read print on paper, compared to 64% or less when reading on electronic devices.

On the other hand, the swift evolution of technology offers new opportunities for improving the quality of our daily life, while access to digital information nowadays is of paramount importance. Panelists at a ‘Knowledge Series’ forum of the Federation of Indian Chambers of Commerce and Industry (Ficci) believe the digital content economy would see exponential growth over the next three to four years [29].

The InPrinted framework aims to provide the stepping stone for bridging the use of such an elementary and fundamental part of our daily life such as printed matter, with the state-of-the-art technology that exists in the AmI environments.

The next sub-sections discuss technological impacts of the work done in the context of the presented PhD thesis.

8.1 Technological impact

One major objective of the presented work was to provide the necessary tools for the easy development and deployment of AmI applications that employ printed matter interaction. Figure 63 illustrates a typical application development lifecycle. The InPrinted framework provides the necessary facilities to AmI applications that aim to use printed matter interaction for supporting their development process throughout their entire lifecycle.

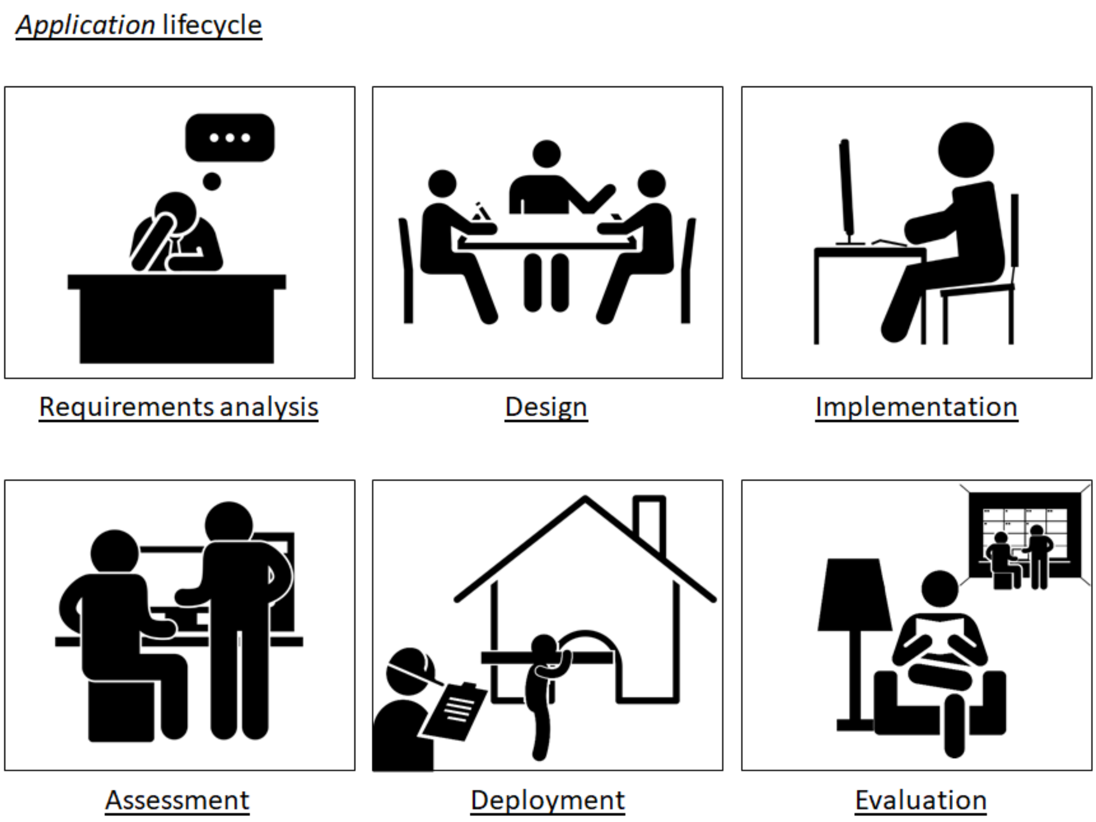


Figure 63. Storyboard of an application development lifecycle.

To showcase this impact, a story line of a fictional application development scenario is presented, highlighting for each step the framework's components that are used.

"*My Personal Chef*" application

The application aims at assisting users to gather recipes of their interest in order to revisit them again later for preparing the corresponding meal. The application will listen to the framework's event about what the users' are reading and will assess the content in order to discover whether any recipes of interest to the user are included or can be inferred.

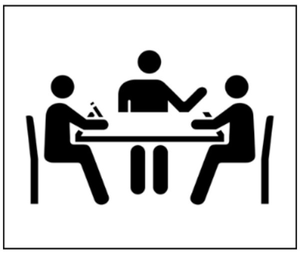
The application will facilitate the storage and acquisition of user's recipes through his/her personal repository, kept in the framework, and will retain basic statistics in order to be able to rank the recipes according to the user's responses.

"My Personal Chef" application can be installed in an AmI environment (e.g., home), which incorporates the interactive printed matter framework.

Table 36 summarizes the potential technological impacts that the InPrinted framework can affect for all the implementation phases of the application.

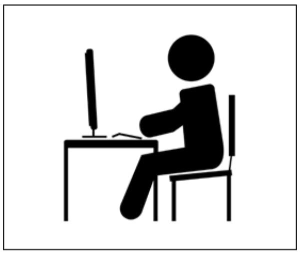
Table 36. Technological impact of the framework for the development phases of an application

Development phase	Technological impact
 Requirements analysis ***Steps*** • User requirements elicitation • Requirements analysis and consolidation • Specification of functional and non-functional requirements	During the requirements analysis phase, the methods that are applied by the expert can be fostered by the **printed matter model** towards a more targeted requirements elicitation and analysis, since the targeted application will eventually be employed in an AmI environment with very specific properties. For example, the functional requirements of the "***My Personal Chef***" application, regarding user interaction, could focus on describing the kind of results that will be expected, leaving to the framework to decide the most appropriate alternatives according to the context of use.

<table>
<tr>
<td>
Design

Steps
• Specify the interfaces of the application
• Describe the final system architecture and setup</td>
<td>Designers can be assisted by the available digital augmentation regarding the provision of information. Furthermore, they can ground the design of user interaction with the printed matter on the classification of the model.

In terms of the application architecture specification, designers can consider to leave any intercommunication, interaction interpretation and content visualization aspects to be handled by the framework and mainly focus on the business logic of the application.

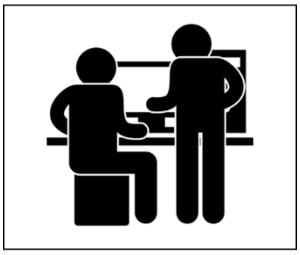
For example, the designers of "***My Personal Chef***" application, can consider that the monitoring of what the user is reading and the acquisition of new content that adheres to the user's interests will be provided directly by the framework. In that case the designers should think how to handle this kind of information from this level and up.</td>
</tr>
<tr>
<td>
Implementation

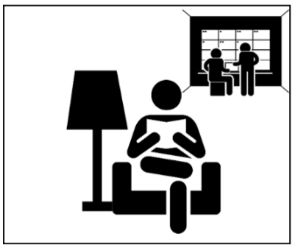
Steps
• Coding of the application components
• Compilation to binaries</td>
<td>During the implementation process programmers can use the already implemented assets of the UI Toolkit.

Furthermore, the implementation will require lesser effort since a large part of the interaction rationale will have already been processed by the framework itself.

The InPrinted framework can be populated with necessary printed matter content related to the application, through the Page annotation tool.

For example, the developers of "***My Personal Chef***" application, can use the "text-to-speech" module for providing output to the users. Regarding the need of the application to monitor and acquire information related to the users' preferences, the developers will only have to add hooks on such events, which are produced</td>
</tr>
</table>

	automatically by the framework, in order to capture and address them.
 Assessment ***Steps*** • Debugging and testing • Quality analysis	During the application assessment phase, the testers can simulate the events that eventually will be produced by the users in the AmI environment, via the framework's simulator. To this end, it will be possible to perform the assessment scenarios without the need of installing the system in the targeted environment.
 Deployment ***Steps*** • (In-vitro) Installation of the systems into the AmI environment in terms of devices/agents and infrastructure and/or installation of the application on the existing systems • Configuration of the application on the corresponding systems	For each targeted AmI environment there is the need of installing once the framework, in order for any AmI application that uses it to be able to work properly.

 Evaluation ***Steps*** • Preparation of the evaluation methodology • Evaluation experiments with end-users	The framework supports all the predefined scenarios of the evaluation process inherently. Furthermore, monitoring services can be easily incorporated for acquiring usage logs and/or the provision of semi-automated insights and statistics.

With regard to implementation, the InPrinted framework ensures the easy embedment of natural interaction with printed matter and printed matter augmentation, minimizing the number of tasks (and therefore the amount of code that needs to be written by software developers). Figure 64 illustrates a high level description of the minimum functionality that should be implemented in order to develop in a traditional way an application embedding interaction with and augmentation of printed matter. These steps should be carried out for each device where the application will run, while it is evident that the outcome will depend on the skills of the developer, as well as the correctness and usability of the interactions and augmentations that will be implemented. On the contrary, the high quality of interaction and augmentation is ensured with the use of the InPrinted framework, while the development effort required is minimized. Figure 65 presents a high level description of the functionality that a developer should implement, in case that they use the InPrinted framework. By comparing the required steps with and without the InPrinted framework, it is apparent that the number decreases substantially in the latter approach, while the code that needs to be written for each step is also minimized. For instance, in order to implement interaction with printed matter, using the InPrinted framework the developer only has to hook to the Interaction

Manager, so as to listen to the events that are sent, a simple and straightforward procedure for any developer. On the contrary, without the framework, for each agent/service that they wish to incorporate, the developer will have to discover and register them, listen to the incoming events and interpret the events to meaningful interaction, a task which requires considerable effort and enumerates many lines of code (increasing for less experienced developers). Similarly, the number of the steps needed to be implemented for decision making and visualization in the context of interaction with printed matter and digital augmentation, is also considerably reduced with the InPrinted framework. For example, the developers need only instantiate the chosen augmentation, by the Context Awareness Manager, using the incorporated Augmentation manager, in order to visualize the generated digital content.

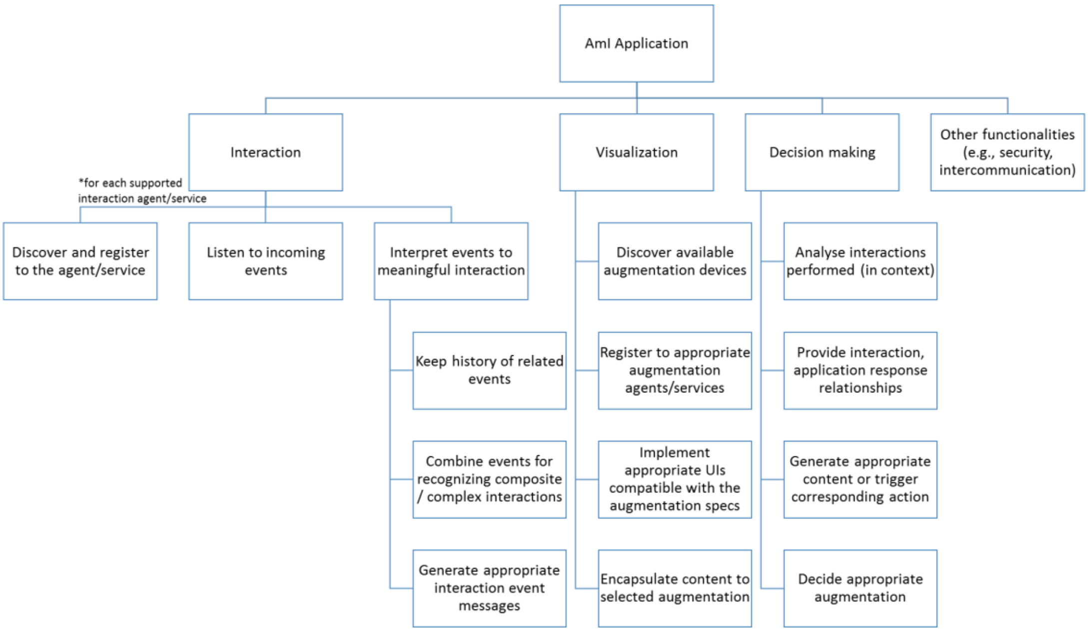


Figure 64. Coding tasks that need to be carried out for every application and each device without the InPrinted framework

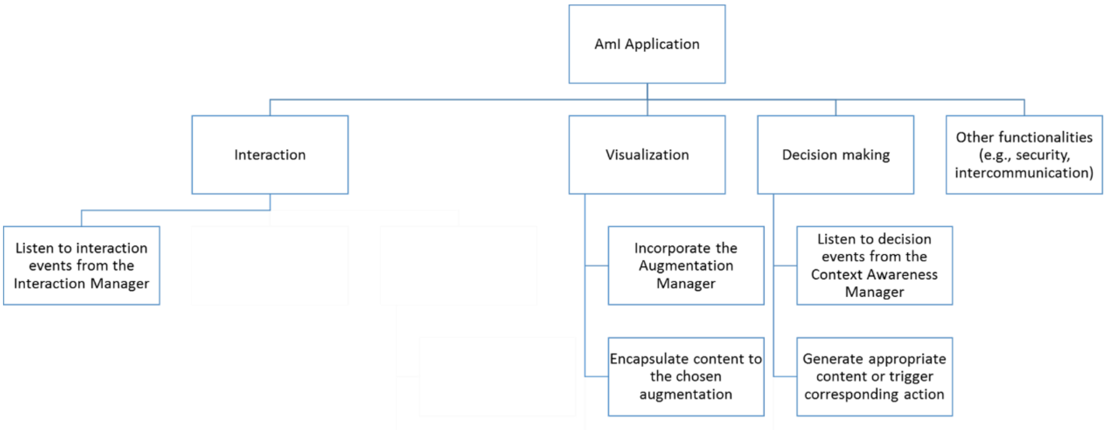


Figure 65. Coding tasks that need to be carried out using the InPrinted framework

8.2 In the wild

Although the diffusion of AmI environments in real life is a near feature vision, the potential of new opportunities emerging by the InPrinted framework can already be acclaimed, since a number of real-life installations of related systems have been deployed in vivo.

Zappeion School for Girls, Constantinople, Turkey

Zappeion is considered as prestigious as the Athenian Arsakeion School. It operated for the first time in 1875 at an old leased building. Since 1885 the school has been in a building near Taksim square, adjacent to the Greek Trinity temple. It was like an educational palace, equipped with modern learning tools and pianos from Paris. It is an asset for Constantinople and remains a live proof of Greek civilization and architecture.

The Book of Ellie system has been installed in the Zappeion School for Girls (Ozel Zapyon Rum Kiz Lisesi). It presents an approach towards augmenting a physical book and enabling interaction through physical cards. The system was customized in cooperation with the World Federation of People from Constantinople and the Centre of Intercultural and Migration Studies of the University of Crete provided the educational content.

Figure 66. A teacher of the Zappeion School for Girls uses The Book of Ellie system for teaching reading to a young pupil.

InfoPoint, Municipality of Heraklion

The InfoPoint of the Municipality of Heraklion is a truly original facility by international standards that promotes what the island has to offer and provides visitors with novel ways to access information–through the use of modern technologies and innovative interactive systems developed by ICS-FORTH. The Interactive Maps system is one of the seven systems that have been installed there. It constitutes an evolution of the Study desk system.

Interactive Maps is a tabletop system, on which visitors may place the printed map of the historical center of Heraklion which is freely distributed at the Info point. The system electronically augments the printed map with multimedia information in several languages and the user is able to interact through touch pointing with the map in order to view further information. The map hotspots that are digitally augmented and have thus become interactive are annotated to assist users in easily identifying them.

Interactive Maps comprises a desk, over which a projector, a high resolution camera and a depth sensor have been installed. The system is integrated into a regular PC. The camera overlooks what is happening on the desk's surface and feeds real time the application with captured images. The application is able to recognize predefined printed maps and track them continuously while they are placed on the desk’s surface. The depth sensor is used in order to provide depth images of objects that are placed over or near the surface. These images are analyzed in order for the system to be able to recognize and eventually track human fingers. Every time a finger touches a map that has been placed on the desk, the application examines if this touch should trigger a hotspot trigger event. In such case, the system searches and acquires digital assets that adhere to the corresponding hotspot of the map. Then these assets are compiled, formatted and displayed laterally to the map nearby the engaged hotspot.

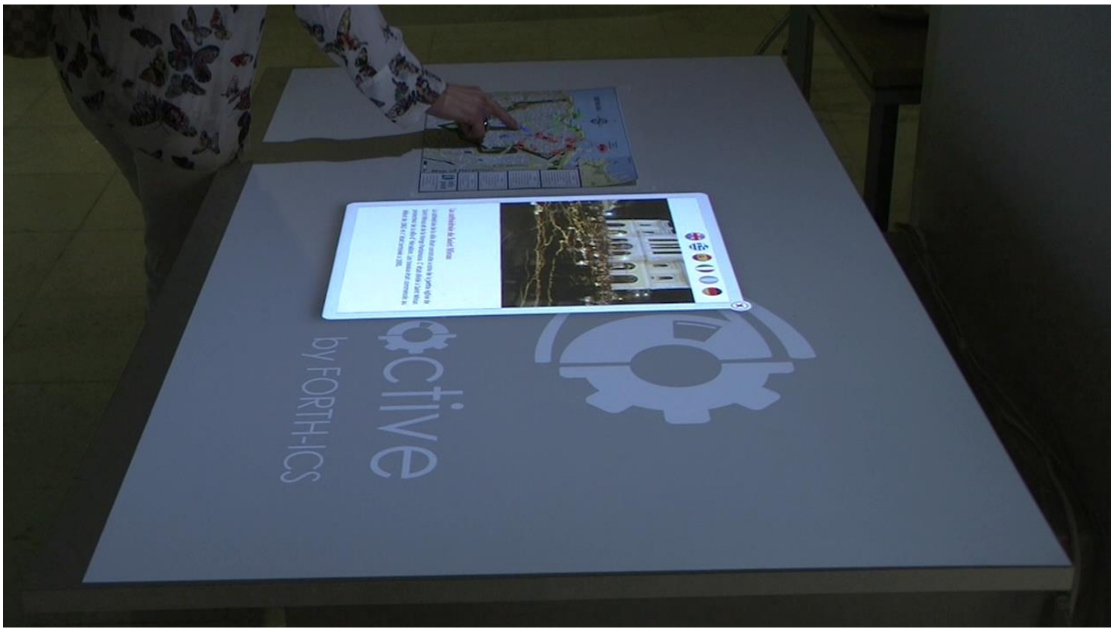


Figure 67. The Interactive Maps system at the InfoPoint of Municipality of Heraklion in Crete.

2014 Taipei International Invention Show & Technomart

INST 2014, Taipei International Invention Show & Technomart was organized by the Taiwan External Trade Development Council (TAITRA). The purpose of INST is:

- To provide a platform for international Intellectual property trade and technology transfer
- To stimulate the internationalization and commercialization of Intellectual property and innovative technology

- To attract greater opportunities regarding to venture capital among international Intellectual property trade and technology transfer
- To demonstrate the innovations among Taiwanese industry, government and academic institutes; to increase the understanding of general public regarding to IP and the innovations
- The ultimate goal is to invite everyone to know Taiwan, come to Taiwan, and invest in Taiwan

FORTH-ICS was invited to participate in the General Secretariat for Research and Technology booth with four of its systems, including Interactive Documents (an evolution of the Study desk system).

All three interactive systems were among the winners of the exhibition's prizes. Interactive Documents received the Gold Medal.

Figure 68. A visitor of the Taipei International Invention Show & Technomart uses the Interactive Documents system.

ITB Berlin Travel Trade Show

Each year the ITB (Internationale Tourismus Börse) welcomes around 10,000 exhibitors from more than 180 countries and regions. Cities, tour operators, booking system developers, airlines, hotels and other businesses concerned with tourism introduce themselves and their services and inspire wanderlust.

On the 5th to 9th of March, 2014, the Interactive Documents system was featured in the Medeat booth which won the second place in the NGOs & Non-Profit Institutions category of the Best Exhibitor Awards organized by the Cologne Business School.

Figure 69. The Interactive Documents system at the Medeat booth in ITB Berlin Travel Trade Show.

2nd International PlayDay on Mother's Day

In the framework of Play & Learn Foreign Languages Tutorial that took place in Heraklion, The Book of Ellie interactive system for children, from 4 years old and older, was demonstrated to the public.

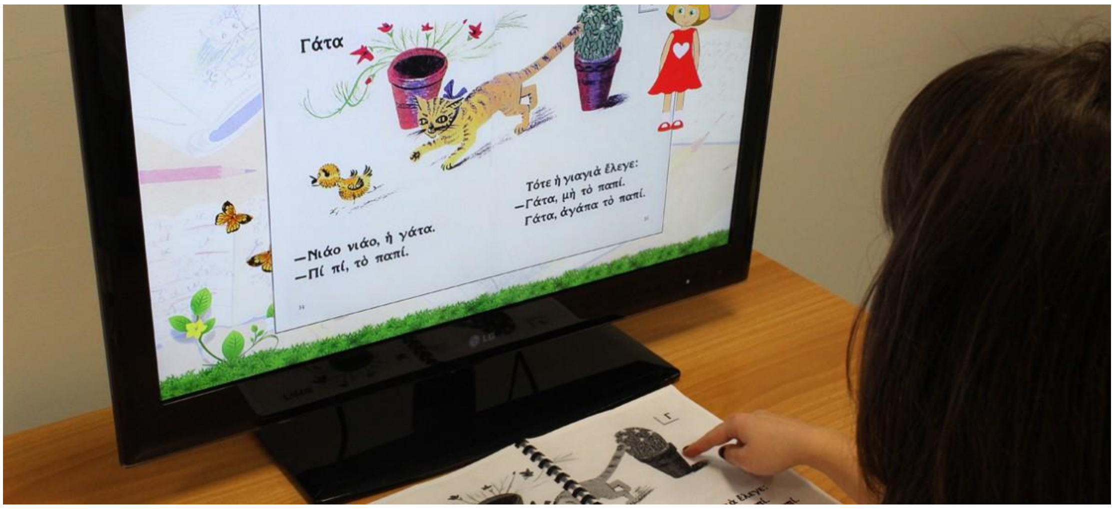


Figure 70. A young girl uses The Book of Ellie system at the 2nd International PlayDay on Mother’s Day.

9 Conclusions

Ambient Intelligence bears the promise of interacting with technology in an unprecedented manner: naturally, seamlessly and transparently. In other words, although technology is a fundamental component of AmI environments, it is interweaved into the environment and as a result users do not strive to interact with technology; instead they carry out daily tasks and activities supported by the technological environment. On the other hand, paper and printed material constitute an everyday asset used for a variety of activities: educational, leisure, informational, recreational, etc. Interacting with physical paper is a fundamental everyday activity that AmI environments should support and embed.

9.1 Contribution

Although, the idea of merging real and virtual worlds using physical paper as a means is rather old, this thesis has pointed out that all the related efforts so far were partial and narrow. On the other hand, the current level of technology is mature enough to combine all the components which are necessary towards a generic and holistic approach. Many endeavors for creating intelligent environments have already appeared, paving the way for many similar but also more sophisticated efforts to come.

To this end, this work has proposed the InPrinted framework for supporting interaction with, and augmentation of, printed matter in Ambient Intelligence environments, providing:

- **natural interaction with printed matter**, a necessary ingredient for its successful acceptance by the users
- an **open reference model for printed matter interaction** in AmI environments, that provides the stepping stone for its easy enhancement and scaling, in order to accommodate any new technologies that may appear in the future and are useful
- **context aware and anticipation mechanisms** for printed matter incorporation in AmI environments, providing thus the necessary environment's intelligence and rationale for anticipating and addressing user needs
- **tools and interaction techniques** supporting the development of systems and / or applications, which offer printed matter augmentation in AmI environments, enabling the easy development and deployment of any systems / applications.

Furthermore, the overall InPrinted framework's architecture addresses issues related to external hardware and software integration, intercommunication and interoperability, interaction management and support of different interaction techniques, augmentation management and support of various augmentation types, as well as context awareness and printed matter modelling. Additionally, the UI components for printed matter augmentation that have been developed in the context of this thesis and integrated in the framework as a UI toolkit provide a basic library that can foster the easy development of new AmI applications.

The adoption of the InPrinted framework for the development of AmI systems and applications ensures robust and high quality systems (independent of the skills and expertise of the software developer), while the development effort is minimized. Developers will only be required to hook to InPrinted framework events and exploit its ready augmentation mechanisms and interaction services.

As a proof of concept, four applications have been implemented, each one supporting different interaction techniques and augmentation types, and addressing different activities. More specifically, the following applications have been developed:

i. SESIL, which consists of a smart desk that is overlooked by a set of three high resolution cameras placed above it, and a nearby large display that runs an educational application providing content-sensitive information to the users, based on their stylus-based interaction with the book. SESIL supports page recognition and interaction through handwriting and pen-based gestures.

ii. The Book of Ellie, which features interaction through touch on a physical book and through printed cards. The book that is currently supported by the system aims at teaching the Greek alphabet to primary school children, and is augmented by additional information and educational games presented in a nearby large screen, as well as by voice output, text to speech and auditory cues.

iii. Study desk, which aims at augmenting printed matter by projecting additional information and multimedia on or laterally to the physical paper which is placed on a horizontal surface. Interaction with the system is supported through touch on the paper and on the digital information presented on the desk

iv. Study Buddy, which features a smart reading lamp that is used to recognize the printed material and to support the user’s interaction with it through pen-based gestures. The lamp is accompanied by a nearby laptop which runs LexiMedia, an educational software application, aiming to provide dictionary information, as well as multimedia information for specific words, assisting thus in language learning activities.

The applications that have been developed have been assessed following a multi-step approach, involving heuristic evaluation with UX experts, user testing in the laboratory using the thinking aloud protocol of the most inclusive application in terms of supported interaction modalities and augmentations, a within-subjects comparative evaluation of three applications employing different interaction modalities, and a large-scale in-situ evaluation of an application installed at a public space. The results of the evaluation point out that interaction with augmented printed matter is natural to users, it ensures a positive UX, while the potential benefits of this technology are well accepted and keenly anticipated.

9.2 Future work

The positive results of the reported evaluation constitute a motivation for further development and evaluation of the InPrinted framework. Although the high value and important contribution of the InPrinted framework has been acknowledged through the applications that have been developed, while the potential of interacting with augmented printed matter has been established through the evaluation iterations, it is necessary that the framework is evaluated by the intended target group, i.e., content creators, developers, etc. in order to acquire quantitative evaluation results.

Moreover, an interesting extension of the framework will be to support the combination of printed matter interaction with other physical / smart objects that may exist in the AmI environment. For instance, in an AmI restaurant, a customer may point at a dish in the printed menu and at the same time a smart plate could display the food a customer is thinking of ordering, provide olfactory cues about how the food will smell, provide nutrition information, or cross-check compatibility with the dietary preferences of the user.

An important future endeavour is the incorporation of novel technologies such as VR glasses / headsets, facilitating the development of innovative applications. For instance, users could open a book page and through their VR headset they could immerse in the story narrated by the book and / or be part of the story through body and mid-air gestures.

Finally, as highlighted by the evaluations that have been carried out, it would be useful for the framework to included context-sensitive help mechanisms, in order to be readily embedded in any application that will employ it, a requirement which will be addressed by future work. Help mechanisms can be embedded in the form of static help, providing guidance regarding the interaction modalities employed and supported augmentations, as well as in the form of dynamic context-sensitive assistance to the user. The latter will employ the reasoning mechanisms of the framework, taking into account the current user, task at hand and specifics of the AmI environment.

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Appendix A List of publications

International journals (Long papers, full-paper reviewed)

- Margetis, G., Zabulis, X., Ntoa, S., Koutlemanis, P., Papadaki, E., Antona , M., & Stephanidis, C. (2015). Enhancing education through natural interaction with physical paper. Universal Access in the Information Society, Special Issue on "User Experience and Access using Augmented and Multimedia Technologies", 14 (3), 427-447.
- Margetis, G., Zabulis, X., Koutlemanis, P., Antona, M., and Stephanidis, C. (2013). Augmented interaction with physical books in an Ambient Intelligence learning environment. Multimedia Tools and Applications, 67 (2), 473-495.

Papers in Proceedings of International Conferences (full-paper reviewed)

- Margetis G., Ntoa S., Antona M., & Stephanidis C. (2017). Interacting with augmented paper maps: a user experience study. In the Proceedings of the 12th Biannual Conference of the Italian SIGCHI Chapter, Cagliari, Italy, September 2017 (CHItaly '17), 9 pages.
- Margetis, G., Antona, M., & Stephanidis, C. (2015). A Framework for Supporting Natural Interaction with Printed Matter in Ambient Intelligence Environments. In the Proceedings of the 5th International Conference on Ambient Computing, Applications, Services and Technologies (AMBIENT 2015), Nice, France, 19-24 July (pp. 72-78). USA: IARIA XPS Press.
- Papadaki, E., Zabulis, X., Ntoa, S., Margetis, G., Koutlemanis, P., Karamaounas, P., & Stephanidis, C. (2013). The book of Ellie: An interactive book for teaching the alphabet to children. In the Proceedings of the 2013 IEEE International Conference on Multimedia and Expo Workshops (ICMEW 2013), San Jose, California, USA, 15-19 July (6 pages). NY, USA: IEEE.
- Margetis, G., Koutlemanis, P., Zabulis, X., Antona, M., & Stephanidis, C. (2011). A Smart Environment for Augmented Learning through Physical Books. In the Proceedings of the IEEE International Conference on Multimedia and Expo (ICME 2011), Barcelona, Spain, 11-15 July 2011.

Papers in Proceedings of international workshops (full-paper reviewed)

- Margetis, M., Ntelidakis, A., Zabulis, X., Ntoa, S., Koutlemanis, P., & Stephanidis, C. (2013). Augmenting physical books towards education enhancement. In the Proceedings of the 1st IEEE Workshop on User-Centred Computer Vision (UCCV 2013), Tampa, FL, USA, 16-18 January (pp. 43-49).

Poster presentations in international conferences (abstract reviewed)

- Margetis, G., Ntoa, S., Bouhli, M., & Stephanidis, C. (2011). Study-Buddy: Improving the Learning Process through Technology-Augmented Studying Environments. In C. Stephanidis (Ed.), HCI International 2011 - Posters' Extended Abstracts (Part II) - Volume 23 of the combined Proceedings of HCI International 2011 (14th International Conference on Human-Computer Interaction), Orlando, FL, USA, 9-14 July, pp. 504-508. Berlin Heidelberg: Communications in Computer and Information Science (CCIS 174, ISBN: 978-3-642-22094-4).

Appendix B Questionnaires for the Comparative UX Evaluation

SESIL User Experience Questionnaire

Please rate how strongly you agree or disagree with each of the following statements by circling the appropriate box.

1. The system was easy to use.

1	2	3	4	5

Strongly disagree Strongly agree

2. I didn't need a lot of practice until I learned how to use the system.

1	2	3	4	5

Strongly disagree Strongly agree

3. The system was awkward to use.

1	2	3	4	5

Strongly disagree Strongly agree

4. The system disrupted my workflow and disoriented me from my learning goals.

1	2	3	4	5

Strongly disagree Strongly agree

5. Interaction through handwriting was easy to achieve.

1	2	3	4	5

Strongly disagree Strongly agree

6. Interaction with the pen was easy to achieve.

1	2	3	4	5

Strongly disagree Strongly agree

7. Such a system can make studying more effective.

1	2	3	4	5

Strongly disagree Strongly agree

8. Such a system can make studying more pleasant / enjoyable

1	2	3	4	5

Strongly disagree Strongly agree

Please indicate how you feel about the system you used

1	2	3	4	5	6	7

Pleasant Unpleasant

1	2	3	4	5	6	7

Interesting Boring

1	2	3	4	5	6	7

Straightforward Cumbersome

1	2	3	4	5	6	7

Predictable Unpredictable

AR Study Desk User Experience Questionnaire

Please rate how strongly you agree or disagree with each of the following statements by circling the appropriate box.

1. The system was easy to use.

1	2	3	4	5

Strongly disagree Strongly agree

2. I didn't need a lot of practice until I learned how to use the system.

1	2	3	4	5

Strongly disagree Strongly agree

3. The system was awkward to use.

1	2	3	4	5

Strongly disagree Strongly agree

4. The system disrupted my workflow and disoriented me from my learning goals.

1	2	3	4	5

Strongly disagree Strongly agree

5. Interaction through touch was easy to achieve.

1	2	3	4	5

Strongly disagree				Strongly agree

6. Such a system can make studying more effective.

1	2	3	4	5
Strongly disagree				Strongly agree

7. Such a system can make studying more pleasant / enjoyable

1	2	3	4	5
Strongly disagree				Strongly agree

Please indicate how you feel about the system you used

1	2	3	4	5	6	7
Pleasant						Unpleasant

1	2	3	4	5	6	7
Interesting						Boring

1	2	3	4	5	6	7
Straightforward						Cumbersome

1	2	3	4	5	6	7
Predictable						Unpredictable

The Book of Ellie User Experience Questionnaire

Please rate how strongly you agree or disagree with each of the following statements by circling the appropriate box.

1. The system was easy to use.

1	2	3	4	5

Strongly disagree — Strongly agree

2. I didn't need a lot of practice until I learned how to use the system.

1	2	3	4	5

Strongly disagree — Strongly agree

3. The system was awkward to use.

1	2	3	4	5

Strongly disagree — Strongly agree

4. The system disrupted my workflow and disoriented me from my learning goals.

1	2	3	4	5

Strongly disagree — Strongly agree

5. Interaction through touch was easy to achieve.

1	2	3	4	5

Strongly disagree Strongly agree

6. Interaction with the cards was easy to achieve.

1	2	3	4	5

Strongly disagree Strongly agree

7. Such a system can make studying more effective.

1	2	3	4	5

Strongly disagree Strongly agree

8. Such a system can make studying more pleasant / enjoyable

1	2	3	4	5

Strongly disagree Strongly agree

Please indicate how you feel about the system you used

1	2	3	4	5	6	7

Pleasant Unpleasant

1	2	3	4	5	6	7

Interesting Boring

1	2	3	4	5	6	7

Straightforward Cumbersome

1	2	3	4	5	6	7

Predictable Unpredictable

Appendix C Interactive Paper In-Siu Observation Sheet

Interactive Maps		Observer:	
Date of observation:		Start time:	
Number of users:	☐ Lone user ☐ Multiple users (Number: ___)		
User age (approx.):	☐ Child (<12)	☐ Teenager (12-17)	☐ Youth (18-29)
	☐ Young Adult (30-44)	☐ Adult (45-60)	☐ Senior(>60)

Appeal

1. What is the user's reaction to the display's functionality? *(check all that apply)*	☐ Curious ☐ Confused ☐ Excited ☐ Stressed ☐ Focused ☐ Impatient Other:

Learnability

2. Did the user read the instructions on how to use the display?	☐ Yes ☐ No
3. Did the understand how to use the display by himself?	☐ Yes ☐ No ☐ Partially
4. Did the user request assistance for using the display? **If yes**, what is the reason?	☐ Yes ☐ No
5. Did the user encounter any difficulties on how to use the display? **If yes** please explain a) what types of difficulties did the user encounter in understanding the functionality of the display; b) if the user overcame those difficulties; c) how the user overcame difficulties encountered	☐ Yes ☐ No

Interaction

6. How does the user interact with interactive maps? *(check all that apply)*	□ Confidence □ Curiosity □ Autonomy □ Easiness □ Playfulness	□ Boredom □ Insecurity □ Impatience □ Confusion □ Stress □ Difficulty □ Waits for instructions □ Frustration
	Other:	
7. Description of behaviour/actions whilst interacting with the system		
8. Interactive maps functionality used	□ Move map □ Touch hotspot □ Browsing media gallery □ Language change □ View video	

Attention

9. Which functionality was preferred by user (used most often?)	□ Move map □ Touch hotspot □ Browsing media gallery □ Language change □ View video
10. Was the user distracted during the interaction?	By what? ____________________ ____________________

Flexibility

11. Did the user manage to complete any tasks not originally envisioned?	□ Yes □ No
12. If yes, which tasks/actions? Describe	

Cultural readiness

13. Did the user feel comfortable using the display?	□ Yes □ No □ Partially
14. Did you notice unexpected movements/actions in user's behavior whilst using the display? Describe	

Effect of Breakdowns

15. Are there any technical problems/failures during the use of interactive maps?	□ Yes □ No
16. In the case of technical problem/failure did the user manage to recover?	□ Yes □ No
17. How did the user recover from technical problem/failure?	

Comments

Other observations/unexpected actions (include any comments you overheard)

___

___

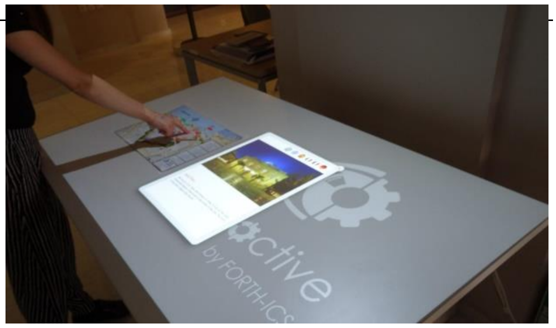
___

___

Duration of interaction (approx.):	□ Short (less than a minute – 2 minutes) □ 2 minutes – 5 minutes □ Long (more than five minutes)
End time:	

Appendix D Interactive Paper User Satisfaction Questionnaire

Interactive documents



Did you use"Interactive maps"?

☐ 1. Yes ☐ 2. No

Following, are pairs of words to assist you in your evaluation. Each pair represents extreme contrasts. Do not spend time thinking about the word-pairs. Try to give a spontaneous response about how you feel. Keep in mind that there is no right or wrong answer. Your personal opinion is what counts! In the table below, check a box between the two opposite values to describe the system "Interactive Maps".

	Very much	Somewhat	Neither	Somewhat	Very much	
Attractive	☐	☐	☐	☐	☐	Ugly
Enjoyable	☐	☐	☐	☐	☐	Boring
Convenient	☐	☐	☐	☐	☐	Tiresome
Pleasant	☐	☐	☐	☐	☐	Unpleasant
Useful	☐	☐	☐	☐	☐	Useless
Informative	☐	☐	☐	☐	☐	Uninformative

Satisfactory	☐	☐	☐	☐	☐	Unsatisfactory
Easy to use	☐	☐	☐	☐	☐	Difficult to use
Unique	☐	☐	☐	☐	☐	Ordinary

Comments: