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Digitally Augmenting Traditional Play Environments

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Abstract

Digitally augmented toys and games are traditional toys or game pieces equipped with sensing technology, computing power and communication capabilities. This allows designers to incorporate novel virtual elements previously only available in video games without compromising the tangible and social benefits of traditional play objects. Through this *digital augmentation*, play environments have the potential to support users by providing them with context-aware information and services and thus to enrich play experiences and facilitate playful learning.

While play environments can benefit from the seamless merging of the virtual and the physical world via such technologies, designing and implementing augmented play environments can be rather onerous. In recent years, research on utilizing pervasive computing technologies for games and toys has focused on demonstrating what is technologically possible. However, this has typically fallen short of addressing the question of how to actually design augmented play objects and environments.

Designers will not only be challenged by the integration of technology into traditional play environments, but also by the typically involved complexity and idiosyncrasies of the particular play scenario at hand. As a result, they must design and implement an infrastructure that will support a variety of potential play objects which inhabit the particular environment. Additionally, the users – many of whom are children – must be provided with adequate interfaces that empower them to configure and adapt the augmented play environment according to their personal preferences and requirements.

This thesis addresses these challenges by examining different play scenarios and investigating how pervasive computing technologies can be used to support players, create more immersive environments and facilitate playful learning. The goal is to provide a framework to help system developers design and implement augmented play environments. To this end, both a process model and a set of design guidelines are proposed for

two very contrasting types of play environments: *toys* and *games*. While the former category is characterized by a high degree of freedom, the latter one is determined by detailed and specific criteria (i.e., rules).

Given these opposite categories, pervasive computing technologies can thus contribute in several ways: in the case of *augmented game environments*, the focus is on supporting players by providing them with context-aware information and relieving them of mundane tasks; *augmented toy environments* in comparison benefit from virtual content that can be added to embellish children's stories and to convey educational content in a playful way.

The main contributions of this thesis are fourfold:

First, we establish the *theoretical groundwork* for the digital augmentation of traditional play environments. For that, we analyze the vast field of existing forms of play, identifying games and toys as the two most distinct and interesting categories and elaborate on how pervasive computing technologies can be utilized to enrich traditional play environments.

Second, the process of *digitally augmenting play environments* is described. The initial part of the process consists of a two-step analysis, a large extent of which focuses on technical challenges developers have to cope with. As a result, we propose a set of design guidelines that can significantly contribute to the success of the digital augmentation process.

Subsequently, we present *two prototypes* – an augmented game environment and an augmented toy environment, to illustrate the practical application of the theoretical framework and demonstrate its feasibility. In concluding discussions we investigate the success of the digital augmentation of each play environment.

Finally, we present the results of a *user study* we conducted to test the augmented toy environment. The goal was to assess our implementation in terms of technical requirements. Additionally, this user study gives insights into how children actually perceive such an environment as well as how suitable it is for storytelling and playful learning.

Zusammenfassung

Moderne Sensor-, Computer- und Kommunikationstechnologien ermöglichen es, traditionelle Spiele und Spielobjekte mit virtuellen Elementen anzureichern, ohne deren physische Form zu verändern oder Einschränkungen bei der sozialen Interaktion zwischen den Spielern hinnehmen zu müssen. Durch eine solche *digitale Erweiterung* können Spielumgebungen geschaffen werden, die den Spielern kontextsensitive Informationen und Dienste anbieten und so den Spass am Spiel erhöhen sowie spielerisches Lernen fördern können.

Obwohl die nahtlose Verknüpfung der virtuellen mit der realen Welt für Spielszenarien sehr vorteilhaft sein kann, gestalten sich Design und technische Umsetzung oftmals schwierig. Forschungsprojekte, die sich mit der Nutzung von *Pervasive-Computing-Technologien* für Spiele und Spielzeug beschäftigen, haben sich bisher vornehmlich auf die Demonstration der technischen Möglichkeiten konzentriert. Der allerdings ebenso wichtigen Frage, wie solche digitalen Erweiterungen adäquat umzusetzen und welche Faktoren dabei zu beachten sind, wurde dabei zunächst wenig Beachtung geschenkt. Dabei kann dieser Aspekt ebenso herausfordernd sein: Entwickler müssen nicht nur Infrastrukturen, die alle möglichen Objekte der Spielwelt umfassen, und Benutzerschnittstellen, die es den Anwendern – meist Kinder – ermöglichen, die Spielumgebungen an ihre persönlichen Anforderungen und Präferenzen anzupassen, entwickeln, sondern auch die jeweiligen Eigenarten der konkreten Spielszenarien berücksichtigen.

Die vorliegende Arbeit setzt sich mit diesen Herausforderungen der digitalen Erweiterung von zwei traditionellen, aber grundsätzlich unterschiedlichen Spielszenarien auseinander: *Spielumgebungen* einerseits und *Spielzeugumgebungen* andererseits. Während *Spiele* oftmals strikten Regeln und anderen Einschränkungen unterliegen, zeichnet sich *Spielzeug* typischerweise durch einen hohen Freiheitsgrad aus. Pervasive-Computing-Technologien können daher in sehr unterschiedlicher Weise unterstützend

eingesetzt werden: Im Falle von *erweiterten Spielumgebungen* liegt der Fokus auf der Unterstützung der Spieler durch die Bereitstellung von relevanten, kontextabhängigen Informationen und durch die Übernahme von eher lästigen und mühsamen Aufgaben. *Erweiterte Spielzeugumgebungen* hingegen können vor allem von virtuellen Inhalten profitieren, die das freie Spielen der Kinder und deren Geschichten anreichern sowie Lerninhalte spielerisch vermitteln können. Das Ziel der vorliegenden Arbeit ist die Bereitstellung eines Rahmenwerkes für Entwickler für den Entwurf und die technische Umsetzung derartiger Umgebungen, insbesondere in Form von Design-Richtlinien für die beiden Spieltypen.

Diese Dissertation umfasst vier Hauptbeiträge:

Zunächst werden die *konzeptionellen Grundlagen* erarbeitet, die für die digitale Erweiterung von traditionellen Spiel(zeug)umgebungen benötigt werden. Dazu wird das breite Gebiet verschiedener Spieltypen – wobei Spielzeug und Spiele die beiden ausgeprägtesten und interessantesten Formen darstellen – analysiert und auf die Anwendung von Pervasive-Computing-Technologien zu deren digitalen Anreicherung eingegangen.

Anschliessend wird der *Prozess der digitalen Erweiterung* von Spiel- und Spielzeugumgebungen erläutert. Am Anfang steht eine zweistufige Analyse, aus der die Anforderungen abgeleitet werden. Darauf folgend werden die technischen Herausforderungen der Entwicklung diskutiert, auf deren Basis dann die Design-Richtlinien abgeleitet werden.

Im nächsten Teil werden *zwei Prototypen* vorgestellt – eine erweiterte Spielumgebung und eine erweiterte Spielzeugumgebung –, die als beispielhafte Anwendungsfälle dienen und illustrieren, wie das konzeptionelle Rahmenwerk praktisch angewendet werden kann. Der jeweilige Umsetzungserfolg wird anhand der Design-Richtlinien diskutiert.

Abschliessend werden die Ergebnisse einer *Benutzerstudie*, die mit der erweiterten Spielzeugumgebung durchgeführt wurde, vorgestellt und diskutiert. Diese Studie stellt nicht nur einen Test der Implementation dar, sondern liefert darüber hinaus wertvolle Erkenntnisse dazu, wie Kinder eine solche Umgebung tatsächlich wahrnehmen und nutzen. Zudem wird diskutiert, wie gut sich eine solche Umgebung zur multimedialen Unterstützung des Spielgeschehens sowie zum spielerischen Lernen eignet.

Acknowledgements

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Contents

1 Introduction

In this chapter, we introduce the field of digitally augmented play environments. We motivate the importance of this research by outlining its benefits and explain where the specific difficulties lie. We summarize the main contributions of this thesis and conclude with an overview of the remaining chapters.

1.1 Motivation

Driven by rapid technological advances and inspired by the vision of digitally enhanced objects and environments, many research projects from the domain of ubiquitous and pervasive computing investigate how information and communication technologies might influence and improve how we live, work and communicate in the future.

Current technological enablers – most notably continuous miniaturization and constantly increasing computational, communicative and sensing power – have already allowed for some ideas to mature beyond the realm of visionary research into practical, mostly industrial applications (e.g., tagging of products for purposes of anti-counterfeiting or more transparent and efficient supply chains). However, pervasive computing technologies are likely to also influence other areas of our everyday lives.

One such emerging field is *play environments*, which has in recent years received growing attention for good reasons: not only is playing as a form of recreational activity the source of a very profitable industry, it is also essential to our well-being and development, being strongly related to how we learn about the world around us. In the modern world there are two main categories of playing: firstly, video and computer games, which are able to provide very realistic and immersive play scenarios but are poor in terms of social and physical stimuli. Secondly, traditional toys and games, which allow for tangible and social interaction but classically do not engulf players in the same exciting way.

Pervasive computing technologies, by technologically enabling a seamless blend of the virtual world and the real world, hold the potential to create completely innovative forms of games and play. Toys and game figures can now be equipped with computing, communicating and sensing capabilities without compromising the tangible and social benefits of traditional play objects. Through this *digital augmentation*, the resulting *augmented play environments* can enhance the players' experience by providing them with germane information, background services and harnessing and incorporating contextual information into the gameplay. Additionally, the integration of virtual elements into the real world enables novel forms of interaction and playful learning.

As appealing as digitally augmented play environments sound, designing and building them is no trivial task as designers must be mindful to not jeopardize the greater goal – increased fun – and end up with the exact opposite of what was originally intended, that is, frustrated users. To this end, designers must not only be concerned with the challenges that inherently arise when integrating technology into traditional play environments (e.g., selection of appropriate hardware or development of the software) but take into consideration the idiosyncrasies of the particular play scenario at hand (e.g., the individual rule system or size and form of play figures).

In addition to this, an augmented play scenario can easily become a complex *smart environment* with numerous smart items: it requires an infrastructure, which is integrated into the play set and is responsible for tracking the objects that bring the play set to life and are added and removed at run-time. This matter is further complicated by considering the users, many of whom are children, alongside their personal preferences. Designers in essence must adjust the user interfaces accordingly and also empower users – who typically have no technical background – to configure the environment.

Thus, the central hypothesis of this thesis is that play environments can benefit from a merging of the virtual and the physical world enabled by pervasive computing technologies. However, to digitally augment traditional play environments, several, mostly technical challenges must be successfully overcome.

This thesis deals with addressing the challenges related to computer science. Nonetheless, by taking into account the interdisciplinary nature of this field, we also consider some aspects from contiguous areas like product and interaction design, electrical engineering or psychology.

As a result, the goals of this thesis are to

- Examine different play environments and investigate how pervasive computing technologies can be used to support players and create more immersive environments,
- Identify and analyze the inherent challenges of these environments,
- Establish a process model to digitally augment traditional play environments,
- Derive generally applicable design guidelines for these environments and
- Develop two prototypes to demonstrate the practical feasibility of the theoretical approach.

To this end, we analyze the diversity of play environments, with the focus being on two classes that mark the ends of the play spectrum: *toy environments* and *game environments*. While the former category is characterized by a high degree of freedom (i.e., pretend play, individual storytelling), the latter one is determined by detailed and specific criteria (i.e., goals, rules, scored points).

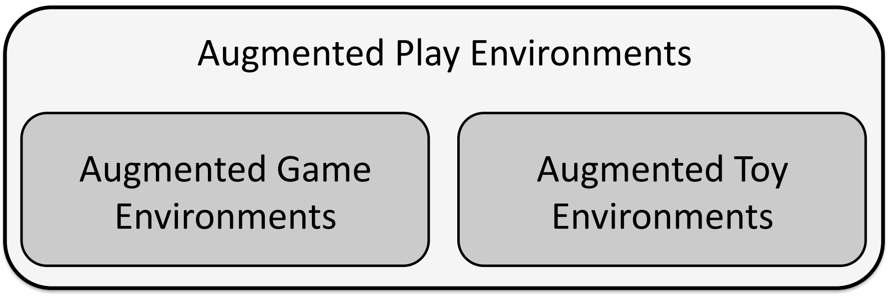


Figure 1.1: The two main forms of augmented play environments.

Given these opposing categories, pervasive computing technologies contribute in several, different ways. While in the case of games, the focus would rather be on supporting the players (e.g., by automatically measuring distances on the game board or by counting points), toys rather benefit from added virtual content (e.g., a toy could tell the children about itself) that can both enrich the children's stories and enable playful learning.

As proof-of-concept, we digitally augmented two traditional play environments, an *augmented game environment* and an *augmented toy environment*, respectively (see Fig. 1.1). The two selected play scenarios we designed and implemented serve to demonstrate three aspects: how the theoretical framework can be practically applied; how challenging such a digital augmentation can be; and how such environments can benefit from the digital augmentation. We will now describe both augmented play environments in more detail.

The Augmented Game Environment

The game environment in this thesis is the popular *miniature war game Warhammer 40K*, a turn-based tabletop game that simulates a battle scenario and typically comprises a comparably large game board (i.e., battlefield) with an assemblage of numerous and varied figures, vehicles, buildings and terrain elements (see Fig. 1.2). Due to the great number of available combat units, weapons, upgrades and other special features, this game can become very complex inasmuch as eventually almost every game figure on the battlefield is unique or has unique qualities and/or equipment.

The game is traditionally played by two or more players, each controlling an army with the declared goal to wipe out adversarial forces. Players can move units, let them engage in battle and exert special powers. The outcome of an attack or situation is usually determined by rolling one or more dice.

The aim of simulating a battle scenario as realistically as possible comes at price: players spend most of the time on necessary but onerous and time-consuming tasks such as keeping data sheets on all their units up-to-date, being cognizant of and applying many rules or incessantly measuring distances and angles between units. Digitally augmenting this play set could thus support players by automatically and constantly scanning the battlefield or by verifying if all actions are in compliance with the rules.

To achieve this, however, the miniature war game has to be digitalized, i.e., the system in the background must have constant access to the localization data of all objects on the field and obtain the results of the dice rolls. The system must furthermore provide players with game-relevant information like current conditions of all units and other rule-based values that might influence strategic and tactical decisions.

Figure 1.2: A typical battlefield in the Warhammer 40K universe with numerous game units (soldiers and vehicles), buildings and landscape elements scattered over a large table. The players stand around the table.

The Augmented Toy Environment

The toy environment we consider is the traditional Playmobil Knight's Castle play set. This medieval play environment contains a number of buildings and locations and, correspondingly, many play figures. Children can move and use the figures and locations without restriction – the emphasis here is on free play and storytelling.

The benefits of augmenting a toy environment differ noticeably from a game environment. By adding audio components as well as visual and tactile feedback to the traditional toy environment, it is possible to create an entertaining and exciting multimedia playground that fosters children's pretend play and offers many possibilities for integrating interactive learning experiences.

However, this requires thorough consideration of what elements are to be augmented and what kinds of virtual contents are to be added. Equally important is *how* this is to be done. The main objective here is to make the digital content that is associated with the play objects available to the

Figure 1.3: The Knight's Castle is a Playmobil play set resembling the medieval world. It consists of many different play figures, buildings and other objects.

children in an unobtrusive and enthralling way. To this end, the system in the background must know where the objects are currently located, use this information to trigger effects or actions dependent on the play situation and process the constant adding and removing of objects.

While an augmented toy environment is not subject to the intricacies of an augmented game environment (i.e., there are no rules), it can become a complex play set nonetheless, which – to make the matter even more complicated – must react in real-time to guarantee immediate feedback to children. Furthermore, children should be given the means to configure the augmented toy environment according to their preferences and requirements, for example, by changing the language of verbal commentaries, recording own sounds and formulating character actions.

These two play environments are presented and analyzed in two subsequent chapters. They demonstrate how the theoretical framework can be practically applied. To this end, each chapter concludes with a detailed discussion about the success of the digital augmentation in terms of achieved goals and met design guidelines.

While prototypes can already provide significant insights, we also wanted to test one augmented play environment under real conditions. We decided to use the augmented toy environment as an extended use case since its design and implementation are subject to stricter technical requirements.

1.2 Contributions

This thesis deals with analyzing and overcoming the challenges that inherently present themselves when creating augmented play environments both from a theoretical and a practical point of view. In particular, the contributions of this thesis are as follows:

- **Theoretical Foundation and Classification**

  This thesis provides an in-depth theoretical foundation of play and games in relation to pervasive computing. To this end, different areas of play, existing theories and approaches towards play and underlying terminology are introduced and discussed. Based on this, we present a taxonomy that helps not only to gain a better understanding of this emerging field of research, but to categorize and discuss related work.

- **A Process Model for Digital Augmentation**

  We then present and discuss a process model that supports the digital augmentation of traditional play environments. The process consists of three phases, a two-step analysis to engineer the requirements, the subsequent design and implementation phase and the evaluation phase. Combined with the design guidelines, this model provides developers with the means to successfully accomplish the task of digital augmentation.

- **Design Guidelines for Augmented Play Environments**

  Additionally, we analyze the characteristics of augmented play environments to gain insights into requirements and challenges of digitally augmenting them. While the focus is on game and toy environments, most aspects are equally applicable to other forms of play as well. Based on the experiences gained during the design and implementation processes of the two prototypes and through a review of current literature, several sets of design guidelines are presented.

These design criteria can serve as general guidelines for the digital augmentation of play environments and can thus be of essential assistance to other designers and developers in this field.

- **Exemplary Prototypes**

  Two prototypes were developed to demonstrate how to practically apply the guidelines and how to overcome inherent challenges: *Warhammer 41K*, the augmented version of the miniature war game Warhammer 40K, and the *Augmented Knight's Castle*, the augmented version of the Playmobil Middle Ages play set. These prototypical blueprints also illustrate the feasibility and benefits of digital augmentation.

  - **Warhammer 41K**

    We developed an infrastructure that not only unobtrusively and unambiguously identifies game objects on the game field, but allows for the automatic determination of location and orientation of these objects with a high degree of accuracy. The system supports players by providing them with information necessary to advance the game in accordance with the rules. Furthermore, we developed an augmented die with the look, feel and form of a regular six-sided die.

  - **Augmented Knight's Castle**

    The Augmented Knight's Castle enhances children's play experience by adding novel elements and effects to the play: the play figures can make sounds and tell stories, mobile devices can be used to display facts and figures about the Middle Ages and children can record their own sounds and associate them with any figure. Moreover, light and smoke effects and background music further add to a compelling play experience. Verbal commentaries also allow for the seamless integration of educational content to facilitate playful learning.

- **User Study**

  A user study was conducted to test the Augmented Knight's Castle. The main objective was to test the success of our digital augmentation under real circumstances. Additionally, this user study also allowed us to gather initial insights into children's perception and usage of such an augmented play set. In particular, the goals of this study were threefold: first, to test technical aspects (e.g., robustness) of the augmented toy environment; second, to investigate whether the augmented version is more engaging and entertaining than the traditional toy environments; third, to find out if the augmented environment actually supports playful learning. Over 100 children participated in this user study whose results should be highly relevant to researchers working on similar projects.

Several aspects of this dissertation have been published in conference and workshop proceedings, journals and books, most notably in [139–151, 183–185].

1.3 Thesis Outline

This thesis addresses the intrinsic challenges of digitally augmenting traditional play environments. We first examine different play scenarios and investigate how pervasive computing technologies can be used to support players and create more immersive environments. We propose a process model and a set of design guidelines for the digital augmentation of play environments. We then present two exemplary prototypes to demonstrate the practical applicability and benefits of digital augmentation. Finally, we discuss the results of a user study we conducted with the augmented toy environment, which can therefore be regarded as an extended use case. In more detail, the thesis is structured as follows (see Fig. 1.4):

Chapter 2 provides the necessary background knowledge for this thesis. We discuss general aspects of pervasive computing in combination with play and games, introduce concepts and terminology and survey related work in the field.

Chapter 3 investigates the requirements and challenges of digitally augmenting traditional play environments. Based on an extensive literature review and our own experience gathered while building and testing our prototypes, we present and discuss design guidelines for the digital augmentation of traditional play environments in general as well as toy and game environments in particular. Additionally, we present a model that

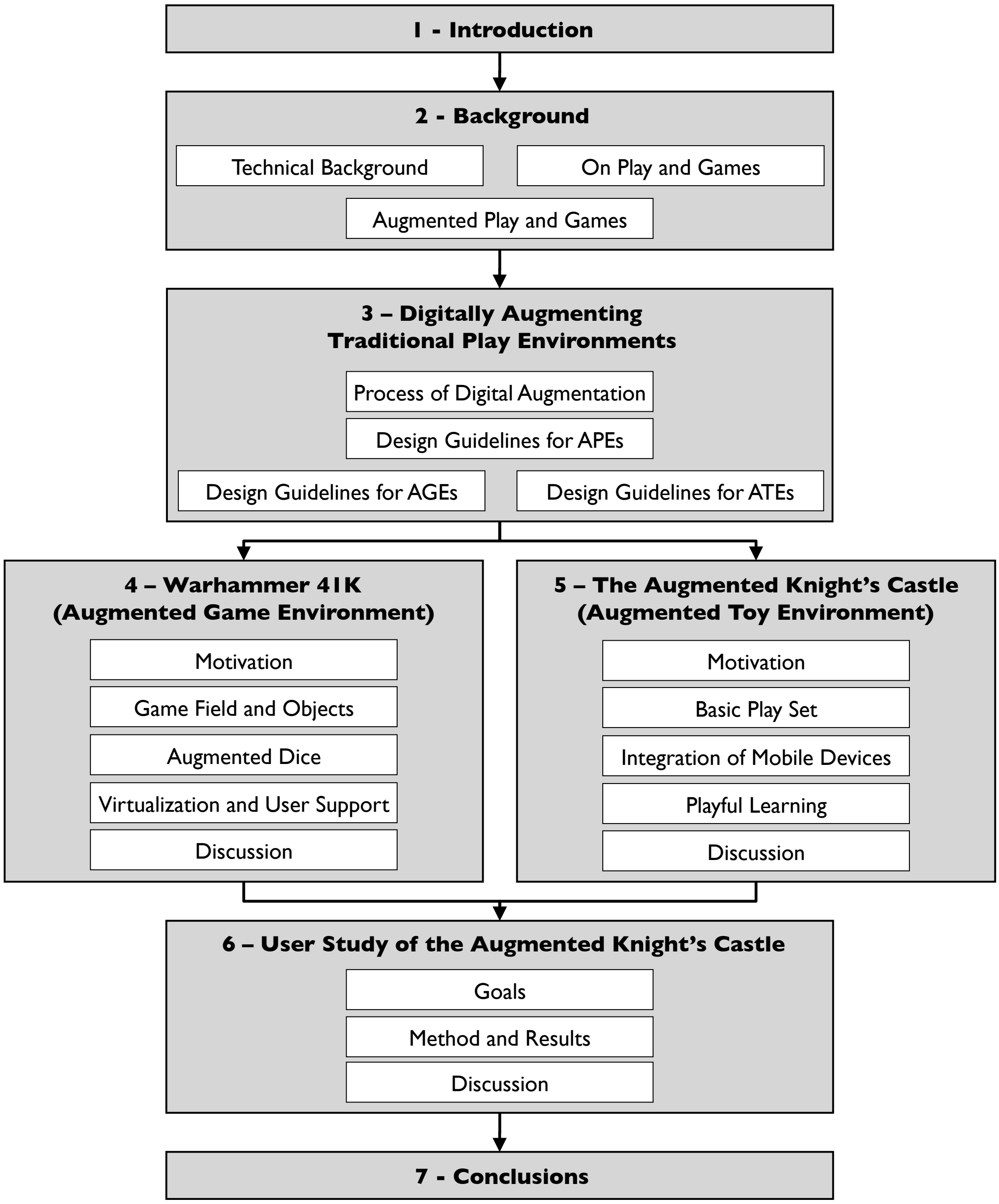


Figure 1.4: Thesis Outline

describes the process of digital augmentation and puts the design guidelines into practice.

Chapters 4 and 5 deal with the two prototypes, the augmented game environment and the augmented toy environment, respectively. These two prototypical blueprints serve to bridge the gap between theory and practice. We present and discuss how these augmented play environments meet practical requirements and design criteria and how we overcame inherent challenges.

Chapter 6 deals with the user study of the Augmented Knight's Castle. This study extends the use case of the augmented toy environment, helping us to understand what the real benefits are and how children actually perceive such an environment.

Chapter 7 concludes this dissertation by summarizing its main contributions, discussing limitations and presenting implications for future work.

2 Background

This chapter provides the background knowledge necessary for the remainder of the thesis. It is organized in three sections (see Fig. 2.1).

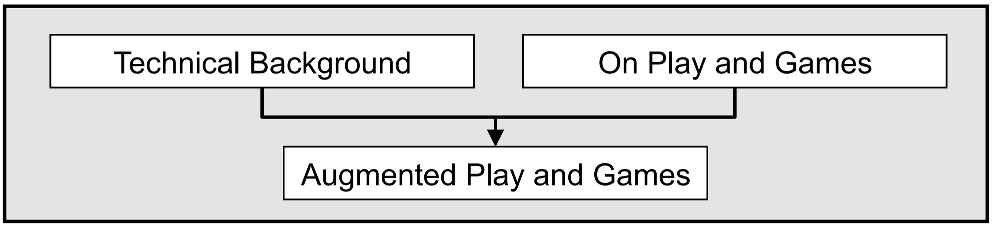


Figure 2.1: The structure of Chapter 2.

First, we introduce the technical developments that expedite *pervasive computing* and *augmented reality*. We then give an overview of current research on the digital augmentation of objects and environments.

Second, we elaborate on the different forms of *play* and introduce a taxonomy, which not only serves to convey a deeper understanding of the nature of play and games, but is useful when discussing related work in the realm of digitally augmented play and games.

Third, we introduce the field of *digitally augmented play and games*, with terminology, definitions, existing approaches and related work.

2.1 Technical Background

In this section we provide the relevant technical background for digitally augmented play environments. It is structured as follows: first, we present the paradigm of ubiquitous and pervasive computing as it is the underlying principle for digitally augmented environments. Second, we discuss the technological enablers for this concept. The last two subsections deal with the digital augmentation of physical objects and environments and the inherent challenges therewith.

2.1.1 The Pervasive Computing Vision

Ubiquitous computing and *pervasive computing* similarly describe a vision of computers where they are integrated into everyday objects and environments to help us with our daily routine.[1]

The term *ubiquitous computing* was first introduced by Mark Weiser in 1991. In his seminal article "The Computer of the 21st Century" he illustrated a future where a myriad of computers would be invisibly integrated into our environments helping people with many aspects of their everyday lives in an unobtrusive manner: "The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it" [359].[2]

Shortly afterwards, the term *pervasive computing* emerged at IBM as a more pragmatic variation of ubiquitous computing. Mattern describes the difference as follows: "While Weiser uses the term 'Ubiquitous Computing' in a rather academic-idealistic way, describing an unobtrusive, human-centric vision of technology, the term 'Pervasive Computing' has been coined by the industry with a slightly different emphasis: this term also centers around the idea of permeating and omnipresent information processing, but with the specific short-term goal of utilizing it in e-commerce scenarios and web-based business processes."[3]

Though the two terms do slightly differ etymologically[4], both are typically used interchangeably nowadays and describe the same paradigm: computers disappear from our conscious attention and work unobtrusively in the background, only to appear again if required. Using computers in this sense would be unconscious and effortless, shifting the focus of our attention to the actual task at hand, not on the computers used.

While this paradigm shift appeared to be rather futuristic when first formulated almost 20 years ago, Weiser's vision has come within our reach. Based on the enormous and rapid technological advances in processing, communication and sensing power in recent years, which also accounts for much of the triumphant success of mobile phones and the Internet,

[1] Over time, further terms such as *ambient intelligence* have also emerged, usually referring to a similar paradigm but focusing on slightly different aspects (e.g., [16, 45, 88, 262]).

[2] These ideas were further elaborated in subsequent articles [360–362].

[3] Translated from [221].

[4] The American Heritage Dictionary of the English Language defines *ubiquitous* as "being or seeming to be everywhere at the same time; omnipresent" whereas *pervasive* means "having the quality or tendency to pervade or permeate" [265].

a world of omnipresent information technology in which computation is seamlessly integrated into the environment seems not only viable, but very probable. We now discuss these technological enablers in more detail.

2.1.2 Technological Enablers

There are today a number of technological drivers that render pervasive computing environments feasible. Mattern, for example, identifies a number of technological trends that enable this paradigm shift, most notably developments in microelectronics, wireless communication technology and sensors [220, 222].

Microelectronics

One of the most prominent and significant drivers is the continuous increase in computing power through miniaturization. As described by "Moore's law" [233], the number of transistors that can be placed on a single integrated circuit doubles roughly every 18-24 months, resulting in an exponential growth of computing power and storage capacity. While this "law" has already been established in the 1960s, it "has held true with astonishing accuracy and consistency" and can be seen as "the driving force behind the continuing technological progress in the field of ubiquitous computing" [43].

Modern available central processing units are capable of billions of operations per second. Additionally, multi-core units have become more and more prevalent, thus multiplying performance per unit. Similarly, storage capacity now exceeds terabytes in the case of hard disk drives and gigabytes in the case of random access memories and flash disks.

Paired with a steadily improving cost-efficiency, this trend has led to a reversal of the human-microchip ratio within less than two decades (see Fig. 2.2) – and if we are to believe statements such as that made by former IBM chairman Gerstner in 1997, describing his idea of the post-PC era as "a billion people interacting with a million e-businesses through a trillion interconnected intelligent devices...", then this is not the end of the road (also cf. [262, 369]).

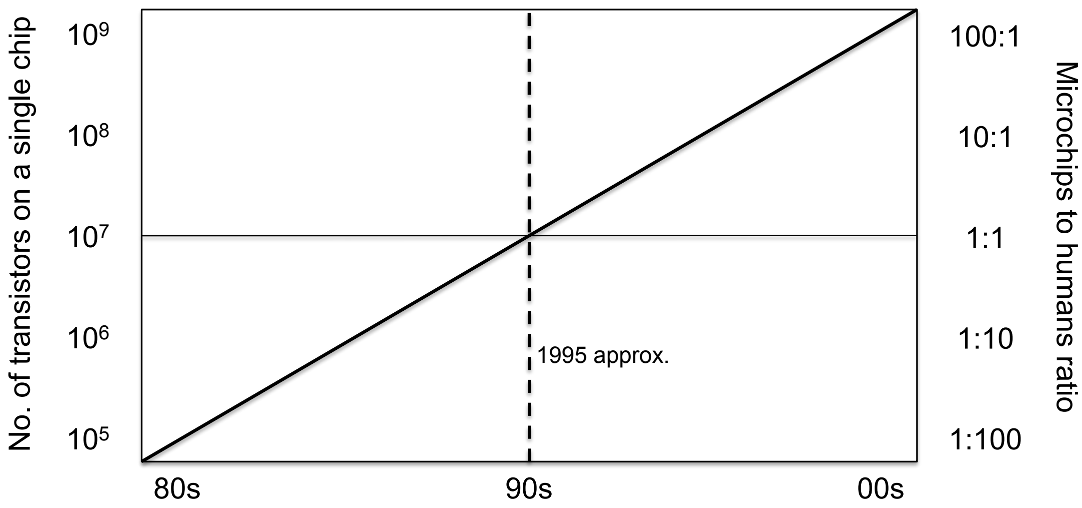


Figure 2.2: The development of microprocessing power in terms of numbers of transistors on a single chip and the ratio of microchips to humans on earth (approximate order of magnitude) (taken and extended from [225]).

Wireless Communication Technology

Wireless communication technologies are another important prerequisite for the vision of pervasive computing. Many applications rely on the capability of exchanging data wirelessly: data synchronization between mobile devices; sensor networks for environmental sensing; automatic track and trace – to only name a few.

Similar to developments in microelectronics, wireless communication technology has advanced tremendously in recent decades, not only with regard to higher bandwidth[5], but also in terms of new standards, covering a broad spectrum of frequencies and, thus, bandwidths and communication distances.

Fig. 2.3 summarizes several predominant wireless communication technologies in accordance with their ranges and data rates. Given the individual characteristics, each technology is suited for particular purposes. GSM and UMTS have been developed for mid- to long-range communication of mobile devices. Wi-Fi features comparably high data rates and has thus become the de-facto standard for local networks. Technologies like Bluetooth or ZigBee are ideal for short-range communication between small devices such as sensor nodes, especially since the hard-

[5]Gilder stated in 1997 that “for the next 30 years, bandwidth is going to be the fastest growing resource and we will use it like we have used the transistor for the past 30 years” [125].

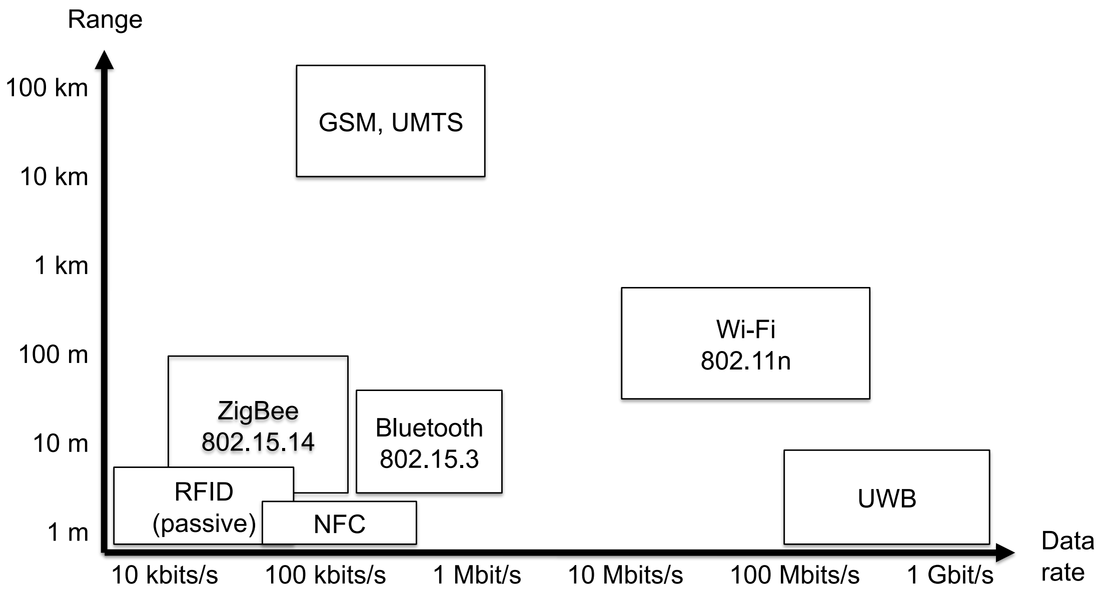


Figure 2.3: Different wireless communication technologies in terms of range and data rate.

ware is comparably inexpensive and energy-efficient. NFC is designed to enable micro-payment and data exchange through the quasi-touching of two devices.

Sensor Technology

Sensors are used for measuring a variety of physical and chemical phenomena and can perceive many aspects of the environment: acceleration, temperature, brightness and humidity for example. Measured values are typically converted to corresponding digital representations and provide the basis for context-awareness: "By sensing context information such as the location and identity of people and objects, context-enabled applications can present context information to users, or modify their behavior according to changes in the environment" [295]. Context[6]-aware computing, even sometimes used synonymously for ubiquitous computing [58], is a prerequisite for the provision of information and services relevant to a given situation [122, 283].

There are a number of sensor boards available that combine several

[6]In the computer science community the widely accepted definition of context by Dey and Abowd is "any information that can be used to characterize the situation of an entity. An entity is 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" [80]. For more information on context in pervasive computing refer to [84] or the PhD theses of Dey [79] and Schmidt [303], respectively.

independent sensors and make them available through wireless transmission, for example, BTnodes[7], Sentilla Minis[8] and Intel Motes[9]. Since these sensor boards typically feature a very small form factor and provide interfaces at software level, they simplify the process of physical integration and rapid prototyping.

Automatic Identification Technology

A further important aspect is the automatic identification of objects. In this respect, radio frequency identification (RFID) technology (e.g., [241, 356]) and visual codes (e.g., [261, 287]) have become the dominant technologies in the realm of pervasive computing scenarios. The underlying principle is the mapping of tagged objects to their *virtual counterparts* by means of an unique ID that is stored on the RFID transponder or is coded in the visual marker. Virtual counterparts are representatives of real-world objects in the virtual world and vice-versa. This mapping allows the "attachment" of all kinds of virtual contents to a physical object: textual information like names and descriptions or multimedia files like sounds, images and videos.

As pointed out in [357], RFID technology has many benefits over other tagging technologies such as barcodes or glyphs:

- Unobtrusiveness (RFID tags are small and can often be integrated invisibly),
- Robustness (RFID tags are quite robust and impervious to environmental influences (e.g., dust)),
- Post-Hoc Augmentation (RFID tags can be easily added post hoc),
- Easily sensed (RFID tags are loosely coupled and do not require physical contact) and
- Aesthetics (RFID tags can often be integrated into an object, thus preserving its natural appearance).

For these reasons, RFID technology has become a widely acknowledged technology for contactless identification and it has already demonstrated its potential in many business applications such as retailing (e.g.,

[7] www.btnode.ethz.ch

[8] www.sentilla.com (formerly known as "Tmotes")

[9] www.intel.com/research/exploratory/motes.htm

[332]), logistics (e.g., [164]), rental industry (e.g., [110]) or asset management (e.g., [186, 193]). Further areas may equally benefit from utilizing RFID technology, for example, healthcare (e.g., [121]) or gaming applications (e.g., [201]).

Further Enablers

In addition to the aforementioned technological enablers, Fleisch et al. list the following facilitators [105]:

- Software support for mobile applications (e.g., JavaME[10] or Jini[11]).
- Energy efficiency: microchips tend to consume less and less energy with the proficiency level remaining constant. At the same time battery technology is continuously improving.
- Actuating elements: new micro-electro-mechanical systems allow for sensing smallest movements and deformations of even tiny objects.
- New materials enable new forms of interaction and pervasive computing applications (e.g., flexible displays based on organic LEDs or light-emitting polymers).
- Global standards: upwardly compatible and extendable standards for information and communication technology are the basis of pervasive computing applications that are to be broadly available.

These enablers demonstrate that the paradigm of pervasive computing does not only depend on classical computer science components, but also on advances in other fields like material sciences.

To sum up, we conclude that recent developments in microelectronics as well as in wireless communication and sensor technologies are the main technological enablers for the vision of pervasive computing. Further salient enablers are automatic identification, global standards and advances in material sciences.

[10] http://java.sun.com/javame/index.jsp
[11] www.jini.org

2.1.3 Digitally Augmented Objects and Environments

Research on the technological enhancement of our surroundings is tightly intertwined with the pervasive computing vision. As a consequence, this field of research has drawn much attention and has yielded a diverse number of scenarios, approaches and projects. We now discuss the digital augmentation of objects and, based on this, proceed to the digital augmentation of environments.

Digital Augmentation of Objects

The aforementioned technological advances enable the digital augmentation of physical artifacts. Therefore, *digital augmentation*, as used in this thesis, can be defined as

> the process of integrating pervasive computing technologies into real-world objects to equip them with sensing, computing, storing and/or communication capabilities.

Digital augmentation enables the adding of a virtual layer to the physical world. This aspect is also referred to as *augmented reality*, a term that was introduced as a counterpart to *virtual reality* [85, 363]. Augmented reality, or *embodied virtuality* as Weiser called it [359], thus refers to the paradigm of bringing the computer into the world (by adding computational power to real-world objects) instead of bringing the world into the computer [289, 299].

This can also be explained by using the mixed reality continuum by Milgram et al. [228] (see Fig. 2.4). The two ends of the continuum are marked by the *real world*, the physical world we live in, and the *virtual world*, an artificially generated, digitized world, respectively. In between these two endpoints is the continuous band called *mixed reality*, simply meaning that elements of both worlds are taken and merged. Depending on how strongly we come to either end of the mixed reality continuum, we have the states of *augmented reality* and *augmented virtuality*.

Resembling the notion of augmented reality, digitally augmenting ordinary artifacts gives means to countless new opportunities and applications: "Smart things can explore their environment, communicate with other smart things and interact with humans, therefore helping users with

Figure 2.4: The mixed reality continuum [228].

their tasks in new, intuitive ways" [44]. The resulting *augmented* or *smart objects*[12] are thus a key enabler for the vision of people unconsciously interacting with physical objects: "People cease to think of themselves as using a technology; instead, they just consider themselves capable of doing whatever the technology enables" [76].

Smart Environments

Smart environments take the idea of digital augmentation one step further and do not only consider individual, independent objects but extend the focus to include whole physical spaces filled with co-existent, possibly interconnected smart objects.

Due to the great number of individual projects with their different foci and the people conducting them, this research has gone by numerous, sometimes interchangeably used names, most prominently *smart environments* (e.g., [11,64]), *intelligent environments* (e.g., [236,258]) and *smart spaces* (e.g., [203, 259]). Subsequently, there are also many definitions (e.g., [11,73,289,299,312]).

This conglomeration of terms and definitions is not very surprising: it demonstrates the variety of disciplines involved, "including pervasive and mobile computing, sensor networks, artificial intelligence, robotics, multimedia computing, middleware and agent-based software" [65].

For the purpose of this thesis and without loss of generality, we will define a *smart* or *augmented environment* as

> a physical environment that has been digitally augmented using pervasive computing technologies to provide users with virtual services and information, which are otherwise not available to them.

[12]Further, yet less prevalent terms are *hybrid objects* or *digital artifacts* [104].

In the past, two areas within the smart spaces research agenda have been of particular interest for applying pervasive computing technologies:[13]

Smart homes This research aims at improving the living conditions at home by providing inhabitants with services to support them with their everyday tasks. Prominent projects are, for example, Microsoft's EasyLiving [49], the Gator Tech Smart House [137], the Adaptive House [235] or the Aware Home [172]. Additionally, there are a number of projects focussing on particular fringe groups such as the elderly or disabled people (e.g., [78, 135, 136]).

Smart offices This research centers around the question as to how our work environments could potentially benefit from pervasive computing technologies (e.g., [190, 319]). Examples of projects in this field are Roomware and iLand developed at Fraunhofer's IPSI [324, 325], IBM's BlueSpace project [182] or the Interactive Workspace project at Stanford [166].

The general goal of smart environments is to simplify our lives, typically through the provision of personalized, context-aware services. This goal inherently raises two questions:

- What are the services and how are they made available to the user?
- How are services configured according to the users' preferences and requirements?

The answers to these questions are neither simple nor generally valid – very much depending upon the scenario, the objectives and constraints within the scenario and upon the chosen technologies. There are, however, two indicators that help us to deal with these questions: the *mode of service provision* and the *mode of configuration*.

Mode of service provision While details of provided services (i.e., *what*) strongly depend on the given scenario, we can identify two main abstract forms of services:

[13]Further areas are, for example, museums (e.g., [96, 131]) or class rooms (e.g., [9]). A good overview is given in [64].

- Services that relieve the user of cumbersome and repeating tasks [124].
- Services that provide the user with currently needed, context-aware information [284].

Equally important is the question of *how* services are made available to the users. Additionally, how does the environment know when to exactly offer the services? Principally speaking, there are two approaches marking the ends of a "spectrum of initiative":

- The services are provided on explicit request (initiative by user).
- The services are automatically provided by the environment (initiative by system).

In the former case, resembling more or less the functionality of classic appliances, the user must manually initiate the service (e.g., John, coming home from work, goes to the computer and puts on some music), while in the latter case the environment, using some form of reasoning engine, initiates the services on behalf of the user (e.g., given the same situation, the system, detecting John's physical condition, automatically turns on appropriate music when John comes home). These two ends of the spectrum can be referred to as *reactive* and *proactive*, respectively.

Mode of configuration In similar fashion, we can analyze how the environment and its services are configured. In the past, there have been two opposing approaches, which mark the end of a "spectrum of configuration":

- The configuration of the system is pre-configured, possibly even immutably hard-coded by the developer.
- The system adapts continuously by recognizing, storing and acting upon patterns of user behavior.

An example of the former case would be a pre-configured office (e.g., the system of Jane's office switches on the ceiling light whenever she enters it), an example of the latter case is an automatically adapting office system (e.g., the system recognizes that for the last three times Jane has immediately switched off the ceiling light after entering the room and switched on the desk light instead; the system will change the configuration accordingly). We can call the former case *hard-coded* and the latter one *adaptive*.

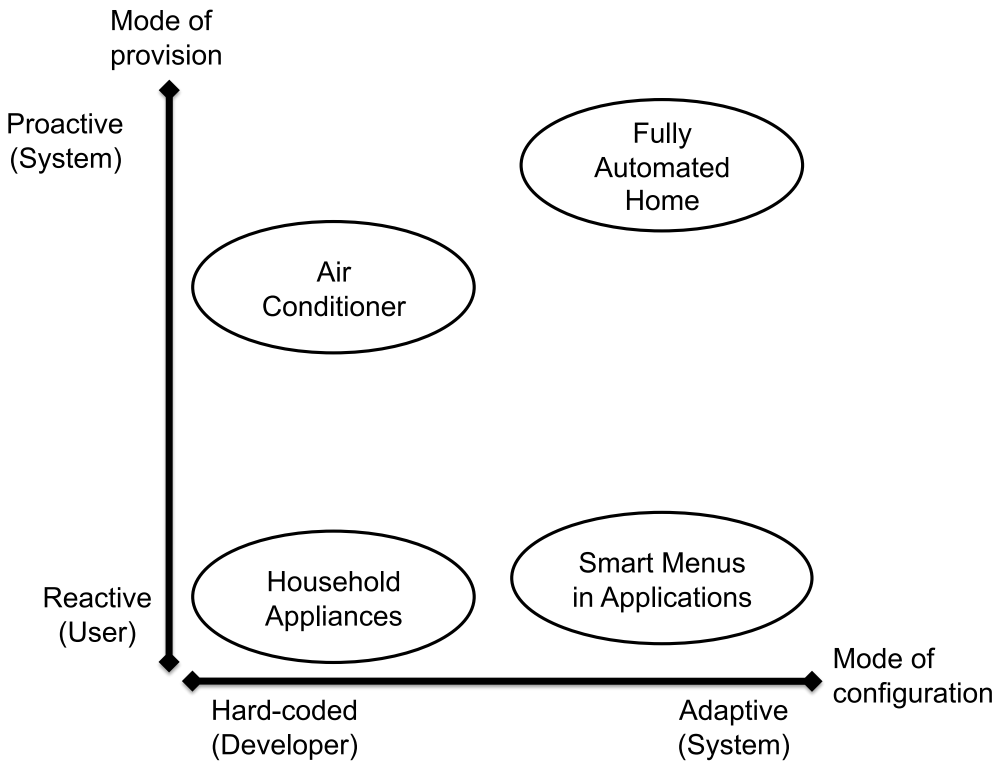


Figure 2.5: The modes of service provision and configuration arranged in a two-dimensional matrix. The mode of service provision ranges from reactive (i.e., the user decides) to proactive (i.e., the system decides for the user). The mode of configuration ranges from hard-coded (i.e., the behavior is pre-configured) to adaptive (i.e., the system adapts the configuration automatically).

These two modes can be arranged in a two-dimensional matrix (see Fig. 2.5). Good examples for the lower-left corner are typical household appliances: a standard dvd player, for example, despite being a high-tech product, is not equipped with any adaptive or proactive capabilities. The upper-right corner, the proactive and adaptive environment, in comparison, represents the "holy grail" of smart environment research, "where omnipresent computing, sensors and other technologies have been developed to the point where they anticipate our needs and act on our behalf" [224].

Both modes are closely related to the question of how smart the environment should actually be and the degree to which users can exert control. This presumably simple question is of major concern when designing smart environments and we will now outline challenges entailed by it.

2.1.4 Challenges of Smart Objects and Environments

Designing and implementing smart environments is generally accompanied by several challenges, though the details certainly depend on the concrete scenario. As discussed before, it is conceivable to have an autonomously and automatically running environment, which infers users' current conditions and makes decisions on their behalf (the aforementioned "holy grail"). However, this vision goes far beyond currently existing systems and the much vaunted field of artificial intelligence so far falls short of realizing this vision. Or, as Greenfield puts it: "We simply don't do *smart* very well yet" [128].

Adwards and Grinter, for example, discuss different levels of intelligence typically found in currently existing systems [90]. They conclude that "all are subject to error, of varying degrees and types"; and, in the end, it is contingent upon the users' capabilities. Mozer comes to the same conclusion and matter-of-factly comments that too often, "operations [...] are initiated not by a smart home, but by smart inhabitants" [237].[14]

Fully automated environments are also often associated with interaction techniques based on speech, video and gesture recognition (e.g., [116]), all of which are still rather error-prone and not feasible in most real-world applications: "Designers have yet to figure out ways of documenting the gestures, voice commands and body positions that will trigger and engage ubicomp systems" [293]. This struggle with the additional ambiguity and complexity of natural interaction is not new, as Nardi already stated back in 1993: "Researchers have been promising for quite some time that very soon... any day now... communicating with computers won't be a problem because we will just talk to them the way we talk to one another" [240].

While a in-depth analysis of current advances in artificial intelligence

[14] We should also keep in mind that history has already taught us some bitter lessons as to the promises of fully automatic robots and environments [223]. Yamazaki even warns that "we have to be careful not to repeat the same mistake that was made with home automation technologies that were booming in the 1970s. That is, [total?] automation should not be a goal of smart home technologies" [370].

would exceed the scope of this thesis, there are two aspects that are relevant to the field of augmented play environments:

- The difficulty of modeling context(-awareness) and predicting what a user truly wants or feels in a given moment.
- The reluctance of users to relinquish control.

We will briefly discuss these issues as they pose major challenges for the design of smart environments.

On the Difficulty of Modeling Context and Predicting User Behavior

The first problem is simply a result of the complexity and ambivalence of the real world: "The physical world is, of course, what might be termed a 'highly analog' environment, presenting a great deal of ambiguity and uncertainty of input" [90].

Salvador and Anderson, based on their findings of an ethnographic case study of how people manage their lives, infer that context is much more subtle, fluid and idiosyncratic than currently existent theories suggest. In [297] they conjecture that "context-aware systems that attempt to know what's happening and to guide a person through certain activities in lieu of their own faculties may be overreaching rational boundaries into that of human lived-experience which is more often than not, not as rational as we might like. It may be not only difficult, but also impossible to provide this level of rational support for any activity except for those in the most constrained and proscribed situations."

With regard to (developing) pervasive computing systems, Rogers states that "it [is] difficult, if not impossible, to try to implement context in any practical sense and from which to make sensible predictions about what someone is feeling, wanting or needing at a given moment. Hence, while it has been possible to develop a range of simple UbiComp systems that can offer relevant information at opportune moments (e.g., reminding and recommending to us things that are considered useful and important) it is proving to be much more difficult to build truly smart systems that can understand or accurately model people's behaviors, moods and intentions" [283]. Other researchers (e.g., [31, 374]) come to the same conclusion.

Three design aspects further complicate the matter.

First, there is the temporal gap between design time and run/use time; i.e., the designer is not only faced with the challenge of modeling context, but must do so in advance. This leads to hypotheses and assumptions as to what might come up in the future (also cf. [161]). Foreseeing and embracing all possible settings might be inconceivable as Newman et al. found: users "will likely want to create particular configurations that no application developer has foreseen" [243].

Second, there is usually a divergence between designers and users (i.e., the system designers are rarely the (future) users of the very same system).[15] This constraint further adds to the aforementioned problem, since the designer has to even make assumptions on what the user might do, enjoy or dislike.

Third, the multitude of potential users can be equally problematic: "Designers of collaborative human-computer systems face the formidable task of writing software for millions of users (at design time) while making it work as if it were designed for each individual user (only known at use time)" [101].

Reluctance of End-Users to Relinquish Control

Consequently and in addition to the question of how smart we *can* design our environments nowadays, it provokes the question of how much smartness we actually *want*. This question cannot be exhaustively answered since it has only recently received attention from the research community. Initial results, however, indicate that people are not too fond of all-knowing environments that act on their behalf (e.g., [224]).[16]

In [275] Randall comes to a similar conclusion. Based on the insights gained through a user study that was concerned with investigating how people might live in a smart home, he states: "Perhaps most interesting [...] was the paradoxical sense in which elaborate control mechanisms could generate a sense of lack of control. By this I mean that control systems were resented if they did not allow users to engage in and complete

[15] This is, for example, discussed by Jacob Nielsen, an acknowledged expert on interface design and usability, in his web article "Bridging the Designer-User Gap" (http://www.useit.com/alertbox/designer-user-differences.html).

[16] Horx describes this tendency quite jestingly: "I don't want my fridge to become intelligent. I want it to be dumb, but function cleverly." This quotation is a translation from the German statement as cited in [221].

the activities they wished to undertake and where designers had simply presumed they could predict what users wished to do."

Spiekermann and Pallas refer to this aspect as "technology paternalism" [318]. They discuss the predicament of people being possibly "subdued to machines' autonomous actions." Based on their findings of a user study, they recommend that "technology should create transparency and explain who is behind the design" and that "there should be a general possibility to overrule 'decisions' made by technology."

This also inherently raises the questions of when and how users should be in control. Exerting power requires the user to know where and how to do this – which can be challenging for pervasive computing systems, where one preeminent criterion is invisibility: "Users may step into a room and unknowingly begin to engage with a ubicomp system – or many systems" [293]. We will discuss this aspect further in Chapter 3.

Summing up, in this section we first introduced the vision of pervasive computing and discussed the technological enablers for it. We then presented the field of digitally augmented objects and environments and discussed the inherent challenges. One particular important issue was the question of how services can be provided and configured in such environments. We pointed out that current advances – most notably in artificial intelligence – do not allow yet for a fully automatic and autonomous operation. Additionally, users seem to be reluctant to give up control and to solely rely on the decisions made by an invisible and obscure background system. On the other hand, if users had to do everything manually, a "smart" system would per definition be rendered obsolete.

We will further pursue this discussion in Chapter 3: with regard to play environments, we will argue for a possible compromise between manual and automatic service provision and configuration.

2.2 On Play and Games

In this section the theoretical background of play and games is presented. First, we briefly discuss why this field is important. Second, we closer examine the field of play and games and differentiate between several forms of playing. Third, a taxonomy is presented, which summarizes the findings and serves as a classification scheme for the related work.

2.2.1 On the Importance of Playing

Playing is an integral and fundamental part of human society. Besides being recreational amusement, playing serves as an important function for the psychological, physiological and social development of children [52, 291, 313] and furthermore fosters creativity [27]. Children at play practice a great variety of skills that they will need for their adult lives: focusing attention, using language through storytelling, reading and writing, manipulating materials in various ways, to name just a few [278,300,314].

Playing is one of the most natural and effective ways of learning, especially for young children: "As they play, children learn to solve problems, get along with other people and control their bodies as they enrich their creativity and develop leadership skills" [2]. Auerbach assents to this by stating that "through observation, mimicry and experimentation, children learn about the world around them and begin to gain mastery of essential skills" [27]. She lists the following benefits that playing might have for children:

- Gain an understanding of the world,
- Act productively with other children and adults,
- Get and hold the attention of others in a suitable way,
- Enhance the ability to concentrate and
- Expand their natural curiosity, help problem solving ability and foster spontaneity.

However, playing is by no means limited to children. Analysis of recently collected data on consumers of computer and video games in the U.S., for example, reveals that less than one third of the players is under 18 years old [5]. The same study discloses that over 24% of all players are over 50 years old and that the average age is 33.

Another aspect is that playing is often a pretext for coming together and enjoying the comfort of socializing and chatting with peers (e.g., bowling or playing cards). Similarly, games of luck strongly appeal to adult players, especially if involving high stakes, for example, in casinos.

These facts are not very surprising given that people nowadays have more free time at their disposal: since the 1970s, annual working hours have significantly dropped in industrial nations, resulting in more leisure time and more money spent on recreational purposes [256, 351].

A current study by Solutions Research Group moreover pointed out that "as consumers use more screens in more places and video becomes ubiquitous on every screen at home and work and on-the-go [...] total hours with video-based entertainment on all platforms is forecasted to expand nearly 35% [from 4.6 hours in 1996 and 6.1 hours in 2008] to about 8 hours on average [in 2013]" [7]. Both trends are also reflected in current sales of both computer / video games and traditional toys.

The video games market, having already surpassed both the global music and movie markets in terms of turnover [347], is growing faster than any other entertainment sector, taking large shares of the entertainment market with rapid strides: Price Waterhouse Cooper's latest annual "Global Entertainment and Media Outlook" states that the global video and computer games market will be worth $68.3 billion dollars by 2012, with an annual growth rate of 10.3% [6]. DFC Intelligence [8], another market research institution, as well as the Entertainment Software Association [5] have brought forward similar estimates.

Traditional toys, though they cannot compete with the strong growth rate of video games, have even higher annual sales than video games: worldwide sales of traditional toys are "expected to drive the market to a value of $108.9 billion by the end of 2010," with the average annual growth rates being about 5% [4]. Apparently, "while computer and video game sales have more than tripled in the past decade, children are still riding bikes, sipping from play tea sets and enjoying some of the same toys their parents did, including building blocks, erector sets, dolls, modeling clay, and jump ropes; simple board games etc."[17]

These numbers clearly indicate how lucrative the markets for toys and games are. And taking into consideration recent products like Sony EyeToy[18] and Nintendo Wii[19], we see the industry's struggle to find new forms of interactive devices – a trend that could be very advantageous for the development of augmented play objects and environments in the near future.

[17] http://www.researchwikis.com/Toys_Marketing_Research

[18] http://www.eyetoy.com

[19] http://www.nintendo.com/wii

2.2.2 Play vs. Games

The terms *game* and *play* are not unambiguously defined as they are understood very differently throughout different cultures. Recreational activities in one country might not be considered recreational or even appropriate in another country and vice-versa. Furthermore, games and play(ing) are very closely related, so close that sometimes it is not possible to distinguish between them (also cf. [177, 296]).

In fact, other languages, like German for example, do not even really differentiate between these terms etymologically: "to play" would be translated with "spielen" (verb) while "a game" would be translated with "ein Spiel" (noun); so the expression "to play a game" would be translated with "ein Spiel spielen", clearly indicating the close linguistic relation between the two words. There are, however, several semantic differences which will be discussed below.[20]

Play

Playing is inherent in human beings. Not only can playing be seen as an expression of joy and recreation, but it also plays an important role in building up and improving important psychomotoric skills and functions. Shwe lists eight different types (or rather, purposes) of play [313]:

- Discovering and exploring play,
- Hands-on active play,
- Problem-solving play,
- Fantasy play,
- Cooperative vs. competitive play,
- Child-directed play,
- Symbolic-representational skills and
- Social play.

But what exactly is playing? Oxford Dictionary [316] defines the noun "play" as "games and other activities engaged in for enjoyment." Similarly, the verb "to play" means to "engage in games or other activities for

[20]The research of play and games is also referred to as *ludology*, which encompasses "different methods with which to study, teach, and even design games" [163].

enjoyment rather than for a serious or practical purpose." It furthermore describes a player's active participation in a game, once more revealing the close relation between game and play.

This definition suffices for the scope of this thesis. We disregard other meanings of play in a sense of acting, sports or art [68, 316]; although it could be interesting to investigate these forms of playing with regard to pervasive computing (for further discussion on the meaning of play refer to [328]). We will now discuss the term "game".

Games

Games can be designed and played for different purposes, including, for example, entertainment, learning or training. In this paper we focus on games designed for entertainment. Analogous to "play", we now discuss several definitions and summarize the important aspects.

According to the definition given in the Oxford Dictionary [316], a game is "a form of competitive activity or sport played according to rules." In contrast to play, game is notably defined by *rules* and a *measurable outcome* (e.g., "scoring units"). It is worth mentioning that there is no real[21] verb "to game", which demonstrates that the emphasis is not on the activity itself, but rather on the event as a whole.

Salen and Zimmermann [296] describe a game as "an activity with some rules engaged in for an outcome" and they further define a game as a "system in which players engage in an artificial conflict, defined by rules, that result in a quantifiable outcome."

Lindley gives a rather ludological definition: a game is "a goal-directed and competitive activity conducted within a framework of agreed rules" [197]. Similarly, Klabbers [176] defines a game as "a contest (play) among adversaries (players) operating under constraints (rules) for an objective (winning, victory or payoff)."

Again, as in the definition before, we see rules, an *artificial conflict* or competition and a measurable outcome as central elements of games. This is also stated by Ellington [91]: "The activity must involve overt competition between individuals or teams, or between the individuals or teams, which are competing against 'nature'."[22]

[21] Oxford dictionary equates "to game" with "to gamble", which Lindley describes as "decisions of gain or loss made by chance within a framework of agreed rules" [197].

[22] "Nature" in this case means that the players can also compete against an artificial opponent.

A game can also be seen as a (social) system that is based on and adheres to (game) rules, which is shown in Fig. 2.6 by Salen and Zimmermann [296]:

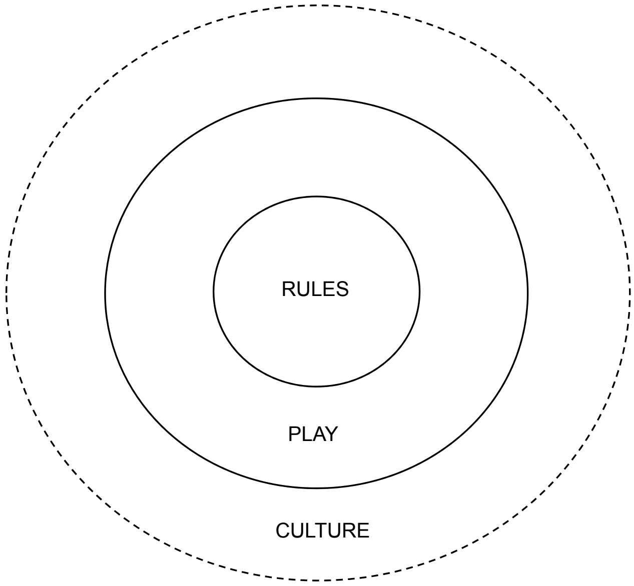


Figure 2.6: The relation between rules, play and culture [296]. They differentiate between three systems: *formal systems*, which are closed and where rules play an important role; *experiential systems*, which can either be open or closed and where the emphasis is on playing (no rules per se); and *contextual systems*, which are open and of cultural nature.

In this context, a game, in contrast to playing, is a "closed formal system" [69] with rules being the central element that converts an open system into a closed one. Walther describes this "boundary" as follows (see Fig. 2.7): "The distinctions that guide the form of play are not enough. In addition, one observes – and responds to – the very criteria of a specific game. At least, one has to be aware of these criteria in order to advance and, preferably, win the game" [355].

Finally, we present Juul's definition of game, which is built on six points [170]:

- Games are rule-based.
- Games have variable, quantifiable outcomes.
- In games, value is assigned to possible outcomes.

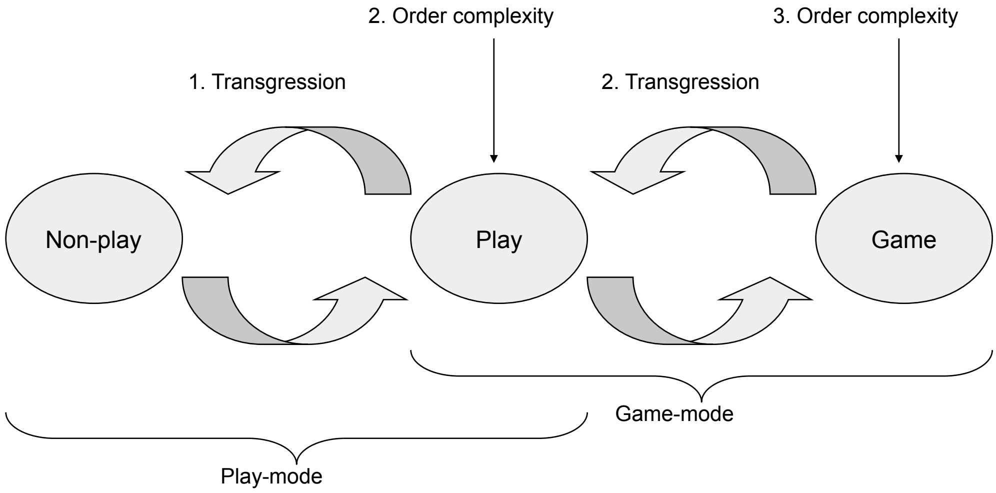


Figure 2.7: Games as a third order complexity [355]. The first transgression means one is either in (play) or out (non-play). The second transgression leads – through the application of rules – from play to game.

- The player invests effort in order to influence the outcome.
- Player is emotionally attached to the outcome.
- It is optional whether a game has real-life consequences.

Having discussed several definitions of game and having collected the central elements of each definition, we will now group equal or similar elements. Tab. 2.1 lists the amalgamated elements of a game besides fun (actually, fun is a result of these factors if implemented well).

Table 2.1: The six elements of a game.

Element	**Synonyms**
Rules	Framework of agreed rules, constraints, rule-based
Competition	Competitive play, artificial conflict, competitive activity, contest among adversaries
Goals	Pursuit of a goal, goal-directed, objective
Outcome	Unit of scoring, quantifiable outcome
Decisions	Manage resources
Emotional Attachment	Value assigned to outcome, effort invested for influencing outcome

2.2.3 Taxonomy of Forms of Entertainment

In addition to the key elements derived from the definitions above, we introduce a taxonomy by Crawford [70] (see Fig. 2.8). It not only helps us to classify different areas of entertainment that can be supported with or augmented by pervasive computing technologies, but it also gives further insight into the nature of games.[23]

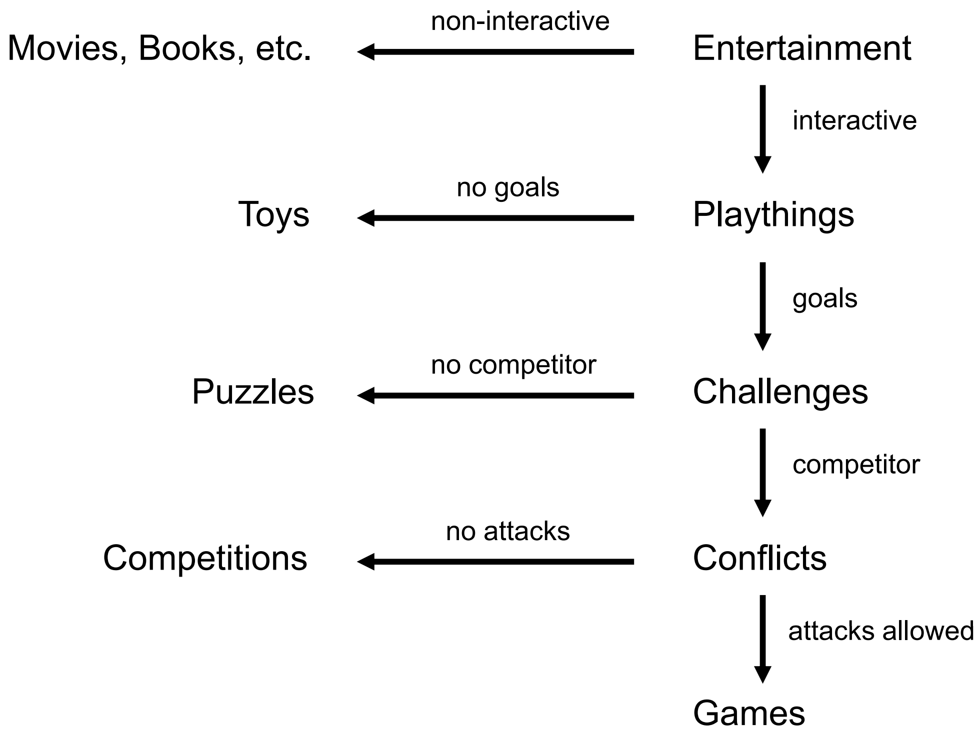


Figure 2.8: Forms of entertainment: Crawford's taxonomy [70].

The initial class is *entertainment*, which can be defined as "the act of diverting, amusing, or causing someone's time to pass agreeably" or "something that diverts, amuses, or occupies the attention agreeably" [351]. Adding the component of *interactivity* to entertainment results in *playthings*, which is a rather vague and indistinct term. Playthings with goals are then called *challenges*, while *toys* are playthings without goals. Challenges in turn are grouped into *puzzles* (a challenge without a competitor) and *conflicts* (where one or more competitors participate). Finally, Crawford differentiates between *competitions* (a challenge with a competitor but without attacks) and *games* (attacks allowed). Summarizing, Crawford defines a game as a form of *interactive entertainment with goals,*

[23]Classifications such as the one presented here are not beyond criticism, especially since play and games strongly reflect and depend on the culture of the region they are played in [373].

competitors and attacks.

With regard to our findings on game elements (cf. Tab. 2.1), one important aspect that is missing in Crawford's definition of games are *rules*. However, we also want to include the narrative component [196, 197], especially *storytelling*[24] and *role-playing games*[25]. To reflect these findings, we extended Crawford's taxonomy accordingly (see Fig. 2.9).

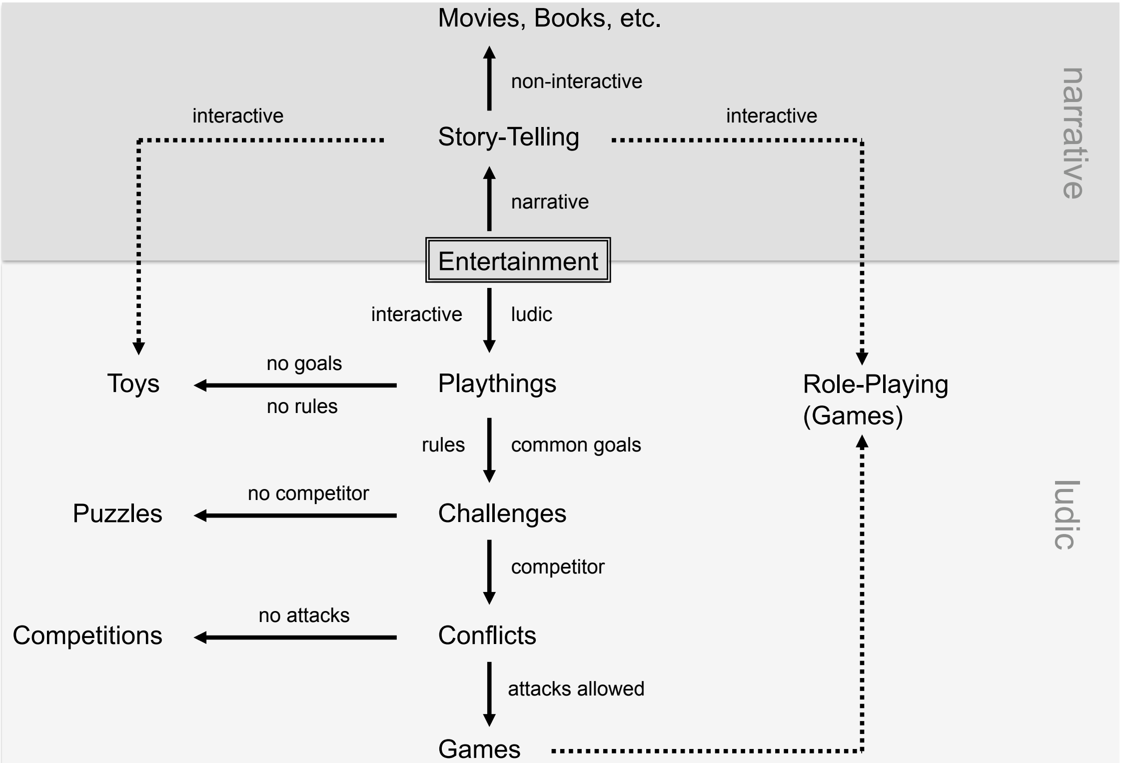


Figure 2.9: The extended version of Crawford's taxonomy. We dichotomized ludic and narrative forms of entertainment and added *rules* to further differentiate free play (i.e., toys) from other, more restricted forms of playing.

In this section we discussed the field of play and games. We summarized several definitions and outlined the differences and characteristics of play and game. These findings were also integrated into an existing taxonomy of different forms of entertainment by Crawford. The resulting classification will be convenient when discussing related work in the field of augmented play and games in the next section.

[24] It is noticeable that there is an ongoing debate on the similarities and differences between narratology (storytelling) and ludology (games) (e.g., [114, 169, 274]).

[25] Role-playing games are usually seen as games, although they satisfy the criteria of games only partially (no common goals, rules are rather flexible, but certainly emotional attachment, etc.).

2.3 Digitally Augmented Play and Games

In this section we combine the two previously introduced fields, pervasive computing and play and games, respectively. First, we discuss the integration of technology into play objects and outline how pervasive computing technologies can be used therefor. Second, we discuss how these technologies can potentially combine the best of two worlds, the physical world and the virtual world. Third, we give an overview of the state of the art and related work in this field. Finally, we introduce *augmented play environments*, which take the idea of digitally augmenting play objects one step further.

2.3.1 Pervasive Computing and Play and Games

Integrating technology into toys is not entirely new as talking dolls can be traced back to the 19th century (for a nice overview see Van Patten's "A Brief History of Talking Dolls – From Bebe Phonographe to Amazing Amanda"[26]). Also, the first computerized board games emerged almost 30 years ago: "A couple of commercial attempts to introduce computerized board games occurred in the 1980ies. Besides numerous clones of chess computers the prime examples are 'Stop Thief' (Parker Brothers 1979) and 'Dark Tower' (Milton Bradley 1981). In the two latter games, computational power was used to randomize events and to hide and reveal information" [201].

Combining pervasive computing technologies with toys or game pieces can thus be regarded as the consequential continuation of merging technology and traditional play and game figures, which, due to tremendous advances in technological progress and miniaturization in recent years, can now be taken to a new level. Augmented toys and games are traditional toys or game pieces that are equipped with computing, sensing, storing and communication capabilities, allowing designers to incorporate novel – almost *magically*[27] appearing – elements into traditional real world objects such as dolls, game figures, puzzles or cards. Not only can

[26] http://collectdolls.about.com/od/dollsbymaterial/a/talkingdolls.htm

[27] Regular physical objects that can suddenly "feel" (sense), "think" (process) and "talk" (communicate) bear a striking resemblance to magical objects in many fantasy books and movies. This has been exploited by several pervasive computing applications in the field of play and games (e.g., [288]). The designer Kuniavsky even proposes *magic* as a general design metaphor that can "help users understand how newfangled ubiquitous computing products can be used" [180].

players be provided with virtual components previously only available in video games, but current sensor technology enables new, context-aware forms of input.

The inherent potential of pervasive computing for the field of entertainment and the field of play and games in particular, has already been recognized (e.g., [202, 283]). Generally, the idea is to utilize pervasive computing technologies to either create a completely novel play format or to augment an already existing traditional play or game (see Fig. 2.10) – although these two categories are not mutually exclusive as mixed forms are also possible.

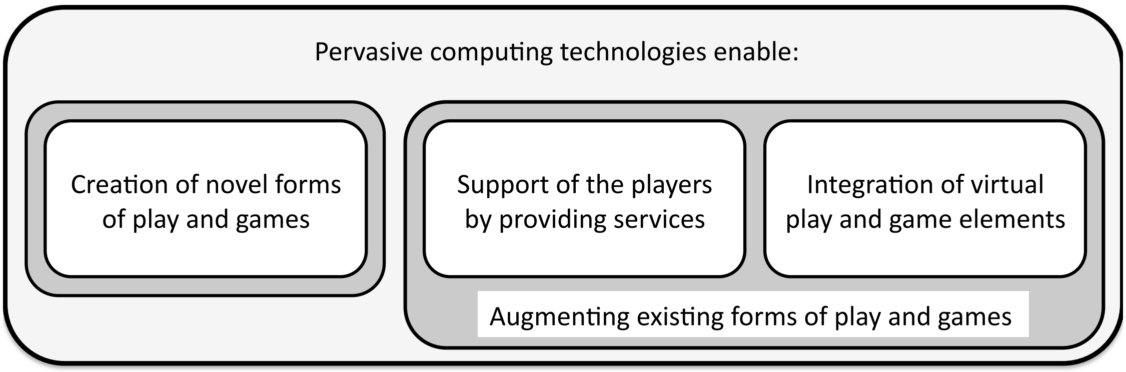


Figure 2.10: Play and games can benefit from pervasive computing technologies in several ways.

A good example for the first category would be location-based games: in these games players move around in a typically constrained area in order to fulfill some kind of task (the successful completion marks the victory of one party and ends the game). They are also equipped with a mobile device that, based on locating technologies such as GPS, will give them information about where they are, where items and other players are located, etc. Players can furthermore send messages and exchange information in accordance with game rules. This form of game has only become possible through modern information and communication technologies.

The second category is that of the digital augmentation of traditional play environments, which is of major relevance in this thesis and centers around two main objectives:

- Pervasive computing technologies can support players by providing them with contextually relevant information and services. By perfectly resembling the vision of pervasive computing, services would run in the background (unnoticeably by players) and only come forth when needed. A good example could be the automatic, constant and unobtrusive measuring of distances between game figures on a game board and then make results available to players.

- Pervasive computing technologies allow for the integration of typically virtual and otherwise impossible new play or game elements. This could be, for instance, a verbal commentary associated with a certain action of a toy to enhance children's storytelling.

These examples demonstrate how play and games can potentially benefit from the utilization of pervasive computing technologies: by combining the best of both worlds, the real world and the virtual world, augmented play and game environments hold the potential to considerably enhance players' experiences, thus striving towards a great symbiotic relationship.

However, creating augmented play *environments* is not just about putting some technology into traditional toys or game pieces, but it is rather the design and implementation of an interactive system that takes both the traditional, technology-less nature of the toy or game figure as well as novel interactive aspects of the newly accessible virtual environment into account.

2.3.2 Combining the Best of Two Worlds

Traditional forms of play and games have been the source of relaxation, enjoyment and learning for thousands of years, featuring many aspects that are important to our well-being and social life. Coming together in order to chat, compete, banter and laugh plays a significant role in human culture. Another important factor is the haptic and spatial experience that comes with moving markers, sorting cards or manipulating game pieces.

Computer and video games typically fall short of supporting these benefits of traditional playing: players sit isolated in front of a screen without being physically and socially challenged; they are absorbed into virtual worlds and detach themselves from the real world for many hours. This improved game immersion is probably both the biggest advantage and disadvantage of video games, depending on your perspective. Many criticize video games for inherently neglecting the social aspect of gaming, as even team-based computer games reduce player interaction to voice or even text messages.

Marchant describes this quite aptly: “Much like talking on the phone, instead of in person, engaging someone personally over an internet [sic] connection, as opposed to a tactile experience in person, the electronic cannot capture the essence of what it means to be human and relational. There is something inherently social and natural in board games which is missing from electronic games. The ironic effect of video games is the world it creates causes a world of isolation and it causes us to wonder what we can do to get back those relationships which are lost in the playing of the game” [216].

Intense video gaming is also often linked to psychological disorders, especially increased violent behavior or loss of reality [20, 115, 123], although this controversial debate is still ongoing [129]. Critics further argue that prolonged exposure to video games can cause obesity [350], addiction[28] and result in decreased school performance [123] as well as diminished “prosocial behavior” [20].

Yet with all their drawbacks, computer and video games continue to appeal to both younger and older players alike, which is mostly on account of the infinite possibilities offered by virtual worlds: in computer or video games, the worlds created and played in are often fantastically designed and presented to the player, creating an immersive environment that usually holds the user captive for some time – players can explore places far away, long lost or that are not even reachable yet to humans in the real world; there is no constraint regarding time and space. Moreover, due to the interactive nature of video games, gameplay itself can offer equally intricate designs, providing mental challenges that can constantly adapt to the players’ skills.

It would seem that traditional forms of play and game on the one hand and video and computer games on the other hand have very different – if not opposite – strengths with regard to four dimensions that primarily contribute to players’ experiences and thus to their enjoyment: physical, mental and social experiences as well as immersion into the game or play. We briefly describe these dimensions in more detail.

[28]To counteract addiction to video and computer games, rehabilitation programs have been established, e.g., Smith & Jones Addiction Consultants in Amsterdam (www.smithandjones.nl/en/home.html). For more information on Internet and gaming addiction see [227].

Physical experience

The physical dimension describes the sensation experienced by players when (inter)acting with tangible objects and real persons in the physical realm. The physical experience can certainly be best realized in the physical reality while in virtual reality there are only limited possibilities for bringing the sensation of tangible user interfaces to the players.

Mental Experience

The mental experience is stimulated by mental challenges such as riddles. Providing players with such challenges and experiences is possible in both realities. In virtual reality, however, there are more powerful conceptual possibilities as riddles or tasks can be adjusted to the players' capabilities and thus allow for optimal challenges and experiences.

Social Experience

"Play does not just come from the game itself but the way that players interact" [296]. Social experience reflects the interaction and communication with other players. This is a very important aspect that has received a lot of attention lately since computer games have been criticized as not supporting or even possibly diminishing the social skills of the players: coming physically together for playing provides more social stimuli than doing the same virtually (e.g., [60, 206]).

Immersion

Finally, there is the immersive dimension, referring to the immersion of the players into a game. This aspect is rather difficult to realize and evaluate, but contributes much, maybe even the most, to the enjoyment induced by game or play. According to Bates, immersion is "what happens when you make the moment-to-moment experience so compelling that the player is drawn completely into the game and the real world disappears" [30].

In [249], Nilsen et al. propose a similar categorization. They call the fourth dimension, *emotional*, which at closer examination coincides with what we call *immersion*: "The emotional aspect of games is perhaps the most difficult to understand. It concerns the way a game affects a player emotionally, by the sympathies they develop with game characters or players and the emotions brought forth by immersion in the game world." This dimension is indeed hard to grasp and evaluate. Measuring immersion or emotional attachment cannot be covered by regular evaluative tools such as questionnaires alone (also cf. [94]). It in fact requires the integration of other scientific disciplines such as neuroscience and biology and would exceed the scope of this thesis.[29]

Virtual reality games, in contrast to traditional games in the physical world, usually contribute more strongly to the players' immersion in the game. It is our opinion, however, that augmented play or games are able to potentially contribute even stronger, since they are not limited to audio-visual output and users are not limited to being in front of a screen: these games "are situated and played in a real environment, much in the same sense as traditional games, their gameplay is augmented [...] by computational services, to enhance and leverage the overall gaming experience" [39].

Summing up, with regard to the four dimensions of player experience, augmented games and play hold the potential to exploit the advantages of both worlds: the social and physical stimuli of the real world and the mental experience and higher immersion provided by virtual games and play. Apparently, combining these two worlds – the real world and the virtual world – yields a powerful and presumably very beneficial symbiosis, which can enhance the players' experiences and thus contribute to the overall goal, that is *fun*.[30]

[29] *Flow theory*, for example, put forth by Csikszentmihalyi [71], describes the phenomenon of a person being fully immersed in an activity, which includes the loss of the feeling of self-consciousness. In that *flow state*, the limbic and the cortical system are in full harmony; it complies with the cardiac coherence, the optimal synchronization of heart beat, respiration and blood pressure. *Affective computing* [264] tries to capture and utilize users' emotions and physical conditions for different applications, including games, which is subsequently called "affective gaming". Regardless of some interesting prototypes (e.g., [36, 330]), some of which even use electroencephalography (EEG) as input (e.g., [152, 248]), this field of research is still in its infancy.

[30] For more information on the theoretical aspects of fun we refer to [177, 189].

2.3.3 On Pervasive (Computing) Games

Due to the very fast growth of this rather young research field, a great number of different terms have emerged in its wake, with *pervasive games*, *ubiquitous games* and *augmented games* being the most prominent. Unfortunately, these terms are often used interchangeably and inconsistently, with no common agreement on their exact definition. On the one hand, "pervasive games" simply refers to games that can be played pervasively, i.e., physically everywhere. On the other hand, the term "pervasive games" has come to comprise games that are based on pervasive computing technologies, i.e., short for "pervasive computing games". In most contexts, they indicate the usage of modern information and communication technologies in one way or the other, but this is not always the case.[31]

McGonial, for example, distinguishes between three categories [226]:

- Ubicomp games: research prototypes that advance the scientific agenda of ubiquitous computing through game design.
- Pervasive games: performance-based interventions that use game imagery to disrupt the normative conventions of public spaces and private technologies.
- Ubiquitous games: commercial entertainment projects that replicate the interactive affordances of video and computer games in the real world.

With this categorization McGonial clearly contradicts the definition of *pervasive games* given by Magerkurth et al., who see it as a new genre that is "no longer confined to the virtual domain of the computer, but integrate the physical and social aspects of the real world" [205] – which would be rather *ubicomp games* according to McGonigal.

According to Walther, *pervasive games* is an umbrella term that also encloses *ubiquitous games*, which in [355] he describes as games that use "the computational and communications infrastructure embedded within our everyday lives." He further states that "pervasive gaming implies the construction and enacting of augmented and/or embedded game worlds that reside on the threshold between tangible and immaterial space, which

[31] In [201], for example, *pervasive gaming* refers to a game that "is played continuously even if intertwined with daily activities such as working or sleeping." These types of games are also known as *alternate reality games* or *life-action games*, surrealistic games that use the real world as a platform and often involve multiple media elements [126, 267].

may further include adaptronics, embedded software and information systems in order to facilitate a 'natural' environment for game play that ensures the explicitness of computational procedures in a post-screen setting" [354].

These different views – among many other (e.g., [288, 322]) – reflect well on the existing nomenclature and definition problem in this area.[32] Additionally, used terminology does not reflect the differences between play/toys and games as outlined in the previous section.

Table 2.2: Three types of reality against different forms of playing.

	Physical Reality	**Augmented Reality**	**Virtual Reality**
Toys	Barbie Dolls, Lego	Augmented Toys (see Chapter 5)	Tamagotchi
Puzzles	Jigsaw Puzzles	Augmented Puzzles (e.g., [42, 254])	Solitaire
Competition	Running	Augmented Competitions (e.g., [255])	Formula 1 (Racing)
Games	Chess, Monopoly, Hide & Seek	Augmented Games (see below and Chapter 4)	Warcraft, Counterstrike
Role-Playing Games	Paper-and-pencil RPG	Augmented RPG (e.g., [167, 232])	World of Warcraft

In section 2.2.3, we introduced, discussed and extended the taxonomy given by Crawford (see Fig. 2.9), which encompasses different forms of *interactive entertainment*. Combining this taxonomy with the three forms of reality where interaction can take place, namely *physical reality*, *virtual reality* and *augmented reality*, respectively, yields a matrix as displayed in Tab. 2.2.

The columns "physical reality" and "virtual reality" contain examples of existing toys, puzzles, etc. for illustrational purposes. Correspondingly, the column "augmented reality" lists related work. Related work

[32] Although certainly interesting from an etymological point of view, this semantic discussion exceeds the scope of this thesis. For further discussion about this topic see, e.g., [247, 353].

for *augmented toys* and *augmented (tabletop) games* is discussed in more detail in Chapters 4 and 5, respectively.

While all forms of augmented reality entertainment have received growing attention lately, games have drawn the major part, mostly because of the diversity of existent game forms. In this respect, we can further subdivide augmented games to reflect the richness of different game forms made possible through pervasive computing technologies, with the most prominent types being:[33]

- **Augmented tabletop games**. This game form typically requires a flat surface with the players gathered around it. There are four subcategories:
  - Miniature war games,
  - Board games,
  - Card games and
  - Dice games.

  We will analyze this category further in Chapter 4 in the context of related work for our augmented game environment.
- **Location-based games**. With this game form, the game field is typically a restricted geographical area (e.g., a city) where people run around with location-aware mobile devices. Prominent examples are Pirates [38], Can You See Me Now [33] and Uncle Roy Is All Around You [106]. As discussed before, this game form is a good example of games enabled by pervasive computing in the first place (cf. Fig. 2.10).
- **Projection-based augmented reality games**. This game form is concerned with the use of live video imagery, which is digitally processed and augmented by additional computer-generated graphics to superimpose graphical information over the real-world [97, 174]. This can be achieved using either a head-mounted display, a handheld device or a projector. Well-known examples of gaming applications are False Prophets [214], Tankwar [250], Hybrid AR Worms [249] and Battleboard 3D [19]. Further examples are described in [257, 273, 345].

[33] Other categorizations are also conceivable, e.g., [205, 355].

There are also mixed forms: Human Pacman [59] or Epidemic Menace [199], for instance, are both hybrid forms of location-based and a projection-based augmented reality games.

Having presented and examined different forms of augmented play and games, we now introduce *augmented play environments*, which expand the focus of digital augmentation to entire play environments.

2.3.4 Augmented Play Environments

As discussed above, augmented toys and augmented games are traditional toys or games that are equipped with sensing technology, computing power and communication capabilities, allowing designers to incorporate novel gaming elements previously available only in virtual worlds into traditional real-world play objects. *Augmented play environments* take this idea even one step further: instead of concentrating on individual objects only, the goal is to create a complete environment filled with numerous objects that can possibly interact with each other and jointly form an enchanted play set.

While in the past many projects focused on demonstrating the possibilities enabled by these new technologies and describing potentially great applications that *could* be built therewith, they do not reflect the complexity that augmented play environments as a whole implicate.[34] Augmented play environments are inherently more complex and challenging than single augmented toy or game pieces. Game conception and artifact design for augmented play environments is thus a very challenging task, as designers have to take a much wider range of issues into account. These are discussed in Chapter 3.

We define an augmented play environment as a

> physical-traditional play environment that is digitally augmented using pervasive computing technologies in order to enhance the players' experience by providing them with novel virtual elements and/or services.

[34]This observation holds true for smart environments in general: in the past, "projects have typically focused on basic system integration – interconnecting sensors, actuators, computers, and other devices in the environment" [137].

In this thesis, we particularly focus on two types of augmented play environments that mark the ends of the play spectrum, as discussed in the previous section: *augmented game environments* and *augmented toy environments* (see Fig 2.11).

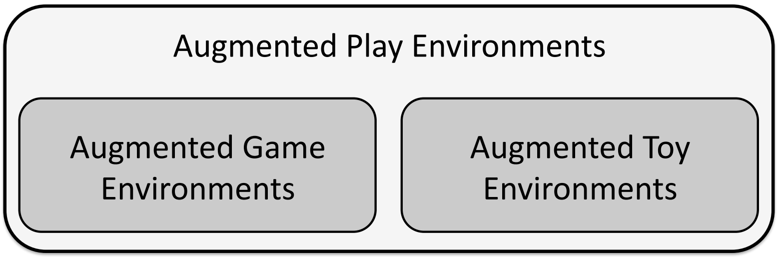


Figure 2.11: The two main forms of augmented play environments.

Augmented game environments are existing real-world games whose components are digitally augmented to support players by offering them in-situ and context-aware information and services, which can improve their play experience by allowing them to focus more on social interaction and the game itself. Augmented toy environments consist of digitally augmented toys and other play objects which can enhance the play and learning of children by integrating virtual, context-sensitive content associated with the toys and objects.

We will further elaborate on these two forms of augmented play environments in Chapters 4 and 5.

2.4 Summary

In this chapter we provided the theoretical background of augmented play environments. We first introduced the vision of pervasive computing and the technological enablers, as well as the concept and challenges of smart environments. Second, we examined definitions and characteristics of different forms of play and classified them. Third, we presented the field of augmented play and games and motivated the application of pervasive computing technologies: embedding such technologies into traditional play or game artifacts enables physical objects to harness contextual information and to be seamlessly connected to any virtual content, which offers many interesting possibilities.

We discussed existing approaches and projects and concluded this chapter with an introduction of augmented play environments, which take the idea of integrating technology into play objects one step further. Based on the theoretical analysis of different forms of playing, we then identified two main forms, augmented toy environments and augmented game environments, on which we will focus in the thesis.

3 On Digitally Augmenting Traditional Play Environments

In this chapter we discuss the challenges that inherently arise when digitally augmenting traditional play environments. This chapter is organized in four sections (see Fig. 3.1):

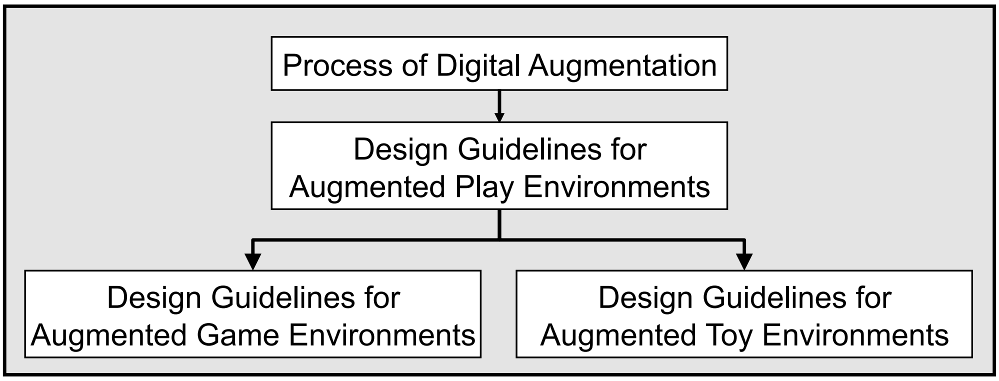


Figure 3.1: The structure of Chapter 3.

First, we present a process model for digital augmentation, which consists of four steps: a two-step analysis of the play environment subsequently followed by design, implementation and evaluation phases.

Second, we then discuss requirements of augmented play environments, which can become serious challenges during the design and implementation phase. The goal of this section is to derive design guidelines to support the process of digital augmentation.

Finally, in addition to the design guidelines for generic play environments, we examine and derive further design guidelines for the two main categories, game and toy environments.

3.1 The Process of Digitally Augmenting Play Environments

In this section we discuss and address the inherent challenges of digitally augmenting traditional play environments.

Developing an encompassing pervasive computing system for a real-world environment can be a difficult and daunting task. As Wellner et al. already found 15 years ago: "Computer-augmented environments raise many issues, both technical and social. They may require a complex, distributed infrastructure, precise alignment between the real and electronic worlds, novel input and output devices" [364].

(Augmented) play environments share most of the characteristics and challenges of more prominent forms of smart environments like smart homes or offices. There are, however, several differences, among which *fun* is the most prominent and important one. When people play, they tend to behave differently: they are not concerned with formal duties, tasks and roles. In a working environment, for example, clear goals and tasks, existing hierarchies and detailed work routines usually define how people interact and behave. Playing (a game) is the opposite as the focus is on relaxation and enjoyment.

Bates matter-of-factly notes that "at any instant while he's playing [...], the player has the option to turn it off and do something else. [...] You have to hold his attention constantly and entertain him from moment to moment" [30]. This seemingly trivial argument entails a number of serious consequences: not only must the environment be operating perfectly, but using it should contribute to the players' enjoyment or at least not diminish it. In other words, designers must be specially concerned with developing a platform that is not only reliable and robust, but also usable and engaging.[1]

To help designers with this demanding task, we now present and discuss a process model, which is mostly based on common software development models.[2] Combined with the design guidelines presented hereafter, it should provide developers with a framework to successfully approach the digital augmentation of play environments.

[1]This especially holds true for children. As Boyle fittingly remarks, "children... may have more fun with pots, pans, and a wooden spoon than the latest hot toy or game" (interview in [230]).

[2]That is, the "waterfall model", the "iterative model" and the "continuous design" practice [311].

In principle, the goal is to answer the following two questions:

- *What* parts of the play environment should be digitally augmented?
- *How* can these parts be digitally augmented and what aspects must be taken into consideration throughout?

To properly answer these questions, the play environment must be thoroughly analyzed. Analyzing play environments can be very challenging. As Koster points out, "games (both video and traditional) are tricky to study because they are so multidimensional. [...] The design and production of games involves aspects of cognitive psychology, computer science, environmental design and storytelling just to name a few" (foreword in [177]). Analyzing toys can be even trickier due the absence of the rules and patterns that games usually feature.

Therefore, designers must be clear about the *goals*, *characteristics* and *requirements* of the play environments and its digital augmentation. This includes addressing questions such as the following: who are the actual users of the augmented play environment? What are the concrete goals of the digital augmentation? What tasks and activities are to be supported? How are users supposed to interact with the system? How can they adjust the environment according to their preferences and requirements?

To this end, we propose a two-step analysis: first, we analyze the play environment to derive both its characteristics as well as the goals of the digital augmentation. This initial scrutiny is followed by a requirements analysis, which concentrates on translating the rather abstractly formulated goals and characteristics into technical service and constraint statements. Based on these findings, the design and implementation of the augmented play environment can then commence. Finally, the evaluation of the system completes the digital augmentation process. Fig. 3.2 summarizes these steps.

We now discuss the four phases of the process model in more detail.

3.1.1 Analysis of the Play Environment

The analysis serves two purposes: first, to gain a better understanding of the play environment and its users, patterns and idiosyncrasies (i.e., the *characteristics*); second, to provide insights into how users should

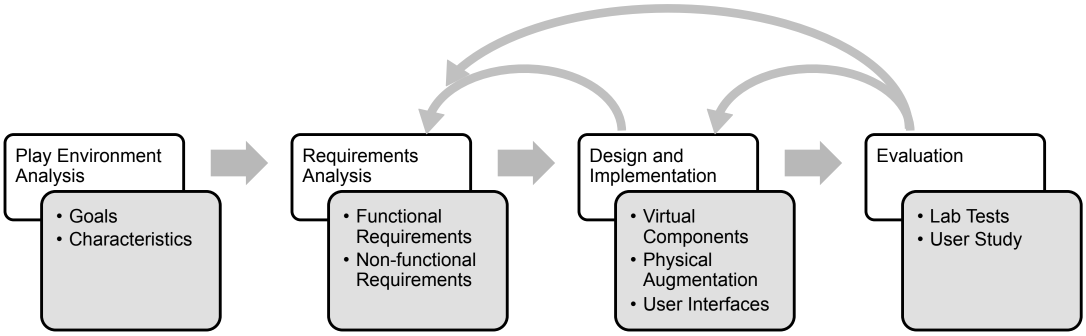


Figure 3.2: The process model of digitally augmenting traditional play environments. The model consists of four consecutive steps. The backward arrows indicate feedback loops.

actually benefit from digitally augmenting this play environment (i.e., the *goals*).

Characteristics

Characteristics are a set of properties and features that distinctively describe a play environment. Examples are age range, number of players, spatial organization and rules. Two very important characteristics that should always be considered are the players and the intrinsic boundaries of the play environment. We will briefly discuss them now.

Target User Groups In contrast to other smart environments, which are typically inhabited by well-behaved adult users (e.g., smart offices), users of augmented play environments can also be teenagers or children. Each user group has individual physiological, mental and sociological characteristics and requirements; and, as Markopoulos and Bekker state, “design should be driven by knowledge of the target users” [217].

Gordon from Electronic Arts accordingly differentiates between three major target groups for play and games (interview in [230]):

- Preadolescents,
- Teenagers and
- Adults.

In addition to this, Acuff and Reiher argue that children pass through several phases in their childhood, which must also be taken into consideration [13]:[3]

- The dependency/exploratory stage (birth-2 years),
- The emerging-autonomy stage (ages 3-7),
- The rule/role stage (ages 8-12) and
- Early and late adolescence (ages 13 and up).

When developing for children, design of play objects and user interfaces must be done with solicitous diligence, virtual content must be appropriate and the process itself must be driven by a clear goal in mind, especially for (playful) learning [92, 331]. While there has been growing attention to children as special users [48, 86], there are still no general approaches or frameworks for the design of interactive pervasive computing systems for this target group.

In addition to the main target user group, play environments might also involve additional user groups:

- Passive users: while the environment is actively used by one user group, it is possible that other users are involved passively (e.g., as spectators).
- Parents and educators: given that physical objects can be enriched with virtual content, children's parents or educators might be interested in influencing what kind of content is available, especially with regard to educational and potentially critical content.
- Content and service providers: depending on the augmented play environment and its infrastructure, third parties could potentially create and offer new content or services.

Boundaries An equally important aspect concerns boundaries[4] and structures of a play environment: what are the possible dimensions of the play environment? Can they be extended at any time? By all players? Can the players add and remove play objects at will?

[3]There are also other theories concerning the different stages of development of children, e.g., Vygotsky's social-cultural approach, which concentrates more on symbology in play [352].

[4]This is also referred to as the "magic circle", a term coined by Huizinga [155], describing the play or game world as a "temporary world within the ordinary world, dedicated to the performance of an act apart" (also cf. [246, 296]).

Depending on the concrete game or play set, there are typically boundaries, not only spatial, but also in form and content (also cf. [69]). We can consequently identify four dimensions of relevance:

- **Space**

  Can the play field be changed (e.g., extended)? Any time? How is the play field structured (i.e., are there discrete fields or is the play field continuous)? Is it important to know the precise position of objects? Is the relative distance between two objects relevant?

- **Objects**

  Can play objects be added and removed at will? Any time? Do they belong to one or more players? Can the ownership be changed? Can an object have different conditions? How can they be changed?

- **Players**

  Who are the players? Are they allowed to join or leave an ongoing session at will? At any time? Can players be replaced by fellow players?

- **Time**

  Is there a time constraint for a single play session? Are there turns for each player? How is a session organized? Is it important to record certain aspects? Is time relevant for a specific action?

Chess, for example, is highly restricted with regard to the first three dimensions (the game board and the game pieces are predetermined and their function exactly specified; the game is played by two players) and there might be even a time limit (e.g., chess tournaments). In contrast to chess, playing with wooden bricks is neither spatially nor temporally constrained and there are neither rules on how they must be used nor on how many people are allowed to play at any given time.

Further Characteristics Each play environment has typically many individual characteristics and deriving all of them can be laborious. As a rule-of-thumb, we recommend to focus on those characteristics relevant for digital augmentation (as many as necessary, as few as possible). Usually, a good first step is to analyze the play environment in terms of rules.

This, however, is not always possible or sufficient, mainly for two reasons: first, some play scenarios like toy environments, for example, do not have formal rules that can be analyzed; second, there might be further issues involved that are not explicitly mentioned in the handbook (e.g., how the players are supposed to keep score). Therefore, other means are occasionally required to find features, patterns and idiosyncrasies.

To elicit these, it is advisable to observe players using the play environment and ask them about it. Consolvo et al. propose four different techniques for this purpose [63]: contextual field research, lag sequential analysis, intensive interviewing and usability testing.

Other approaches or combinations thereof are also conceivable. Schmidt et al., for example, use a multi-techniques investigation, combining the methods of contextual inquiry [37], cultural probes [118], technology probes [156], scenarios-based participatory design (i.e., sketching and designing "a specfic persona focused technology the users would like to have") and interviews in a qualitative research approach [305].

Principally, involving the user, be it actively or passively, should provide the designer with valuable insights into how players perceive and use the play environment and what criteria are important to them.

Goals

Based on a deeper understanding of how the play or game is organized and actually played (i.e., its *characteristics*), we can shift the focus to enriching it with virtual information and services (i.e., the *goals* of the digital augmentation). Relevant questions are, for example: how can players be supported? What tasks can players be possibly relieved of? Could it be beneficial to add virtual elements?

The goals outline what kinds of additional virtual information and services are to be added and how players will benefit from these. The goals should be perspicuous, coherent and feasible. Examples are automatically counting scores for the players (i.e., replace paper-based manual score counting) or in situ displaying context-relevant information. Additionally, the goals should be formulated rather abstractly (i.e., without a particular technology in mind) to not potentially limit creativity.

Barton and Pierce point out that "very often our scenarios are motivated primarily by new possibilities created by technology" [29]. Thackara takes this even one step further: "We know how to make amazing things, technically [...]. Our dilemma is this: we do not know what needs these new technologies are supposed to meet. In fact, we don't even think about that question, the why" [336].

Though a "technology-inspired" approach can also be successful [286], the goals should be formulated in a rather "gameplay-oriented" way, that is, the designer should primarily focus on the *what* and *why*, not the *how*. A good example for a goal would be to "relieve the players of manual score-keeping" without indicating how this should or could be done.

The goals and the previously examined characteristics are the prerequisites for the requirements analysis, which is discussed next.

3.1.2 Requirements Analysis

Based on a declared set of goals and characteristics, the requirements analysis aims at identifying *functional* and *non-functional requirements*. Basically, we have to convert the previously gathered non-technical descriptions into technical specifications. "Requirements define the expected services of the system (service statements) and constraints that the system must obey (constraint requirements). The service statements constitute the system's functional requirements. [...] The constraint statements constitute the system's non-functional requirements" [204].[5]

This means that the goals must be translated into functional requirements (or service statements), based on which more concrete steps can be deduced from. If, for example, a goal is to "relieve the players of manual score-keeping", then a corresponding functional requirement could be "to introduce a system that keeps the score of the game; the game rules state that there are three conditions resulting in a change of the score: A, B and C; to capture these conditions, the system must be aware of the following contextual settings of the game: ..." and so on.

While functional requirements depend on the concrete play environment and the goals of its digital augmentation, non-functional requirements (or constraint statements) are more generally applicable as they refer to augmented objects and the augmentation process itself (i.e., the *how*, not the *what* or *why*). While not all are equally relevant for all play scenarios, there are a number of quite typical non-functional requirements

[5]More detailed information can be found, e.g., in the IEEE standard glossary of software engineering terminology [1].

known from software engineering [3,160,280], many of which can be applied here as well, both for hardware and software development:

- Performance (response time, throughput, capacity),
- Usability (easy to learn, fun to use),
- Efficiency (minimum load on resources),
- Reliability (availability, rate of failure, mean-time to failure),
- Correctness (correct implementation of functional requirements),
- Robustness (reasonable response to unexpected and unspecified circumstances),
- Scalability (adding of further objects or modules scales),
- Cost (acquisition and maintenance costs),
- Maintainability (rectification of errors and problems) and
- Understandability (user understands what can be done and how).

These requirements play a major role in every pervasive computing system but they are especially critical in augmented play environments. Since the ultimate goal is to have fun, systems featuring thorny usability, poor performance or even malfunctions can instantly jeopardize the players' experience. A computer game that still has bugs or performance problems; a talking doll that only reacts every other time when its belly is pressed; a robot that is too complicated to configure and use – all these examples demonstrate insufficiently realized non-functional requirements.

While all non-functional requirements are rather important in the context of play and games, one can be deemed to be exceptionally crucial: *usability* strongly contributes to the level of enjoyment or frustration. It is argued that usability is not only characterized by learnability, efficiency, memorability and satisfaction [245], but also by fun [40], emotion [252,264] and aesthetics [22]. Usability in human-computer interaction (HCI) even seems to be more or less equivalent to the concept of "playability" as it is used in the gaming industry [168,371].

In addition to the non-functional requirements, digitally augmenting traditional play environments also necessitates developers to be mindful of further aspects, which will be discussed in the next section in the form of design guidelines.

3.1.3 Design and Implementation

The two-step analysis described in the previous section should ideally yield a list[6] of functional and non-functional requirements, based on which we can now focus on the design and implementation of the actual system and the digital augmentation process. There are three major categories: the *physical augmentation* of the play objects; the *virtual components and infrastructure* (i.e., the background system); and the *user interfaces* for interaction with and configuration of the play environment.

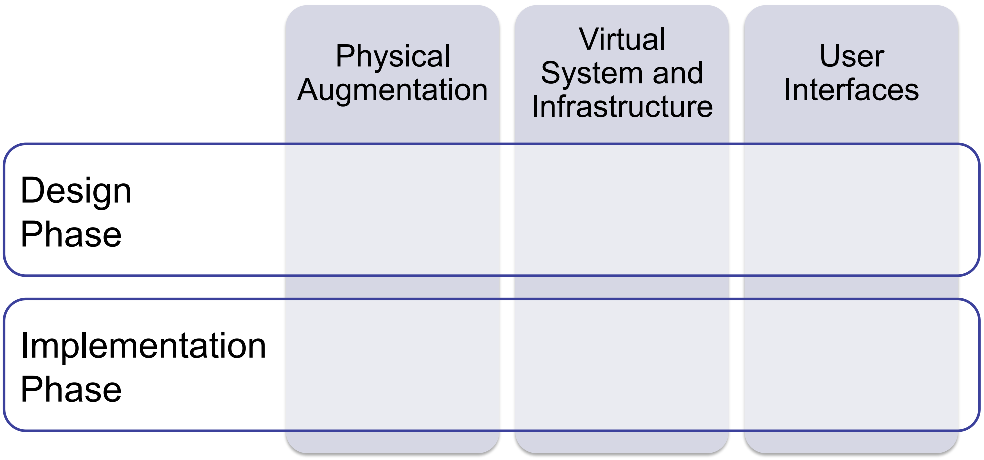


Figure 3.3: Overview of the design and implementation phases of the digital augmentation process. There three main areas: the augmentation of physical artifacts, the virtual background system and the user interfaces.

These three areas each have a *design* (i.e., conceptual approach) and *implementation* (i.e., technical realization) phase (see Fig. 3.3). This thesis mostly focuses on the design phase. Coming up with generally applicable guidelines for the implementation phase is not feasible: either the implementation is very straightforward and does not need to be explained in detail (e.g., integrating an RFID transponder into a physical object using glue) or the implementation depends too much on the concrete play scenario and the design decisions, rendering any general suggestions obsolete

[6]It might be useful to prioritize the functional and non-functional requirements as some aspects may contradict each another.

(e.g., the user interface must be integrated into a "play rug" on which the augmented wooden bricks are to be used).

We now discuss the three different areas for the design phase as indicated in Fig. 3.3.

Augmentation of Physical Artifacts

Although there is extensive research on augmented objects and environments, there is not much literature on *how* the augmentation should actually be done. One of the few existent approaches is presented by Schmidt and van Laerhoven [306]:

1. Identify the contexts that matter and check if context matters at all (In a first step the usage of the artifact that should become smarter is analyzed).
2. Find the appropriate sensors (with regard to the variables identified in step 1).
3. Build and assess a prototypical sensing device.
4. Determine recognition and abstraction technologies (an algorithm is selected that recognizes the contexts with maximal certainty and is also suitable for the usage of the artifact).
5. Integration of cue processing and the context abstraction (the sensing technology and processing methods are integrated in a prototypical artifact in which the reaction of the artifact is immediate).
6. Build applications (build applications on top of the artifact that use the context knowledge).

While this approach gives some useful insights, some important aspects are missing: first, it refers to single, independent objects only (i.e., it does not adhere to environments); second, the focus is on integrating sensor technology (i.e., other forms of technical enhancements are not addressed); third, there are no hints on what the augmented object should look like (i.e., how the technology is to be integrated).

We therefore suggest the following six-step cycle of digital augmentation (see Fig. 3.4), which follows generally established processes of interaction design (e.g., [66, 310]).

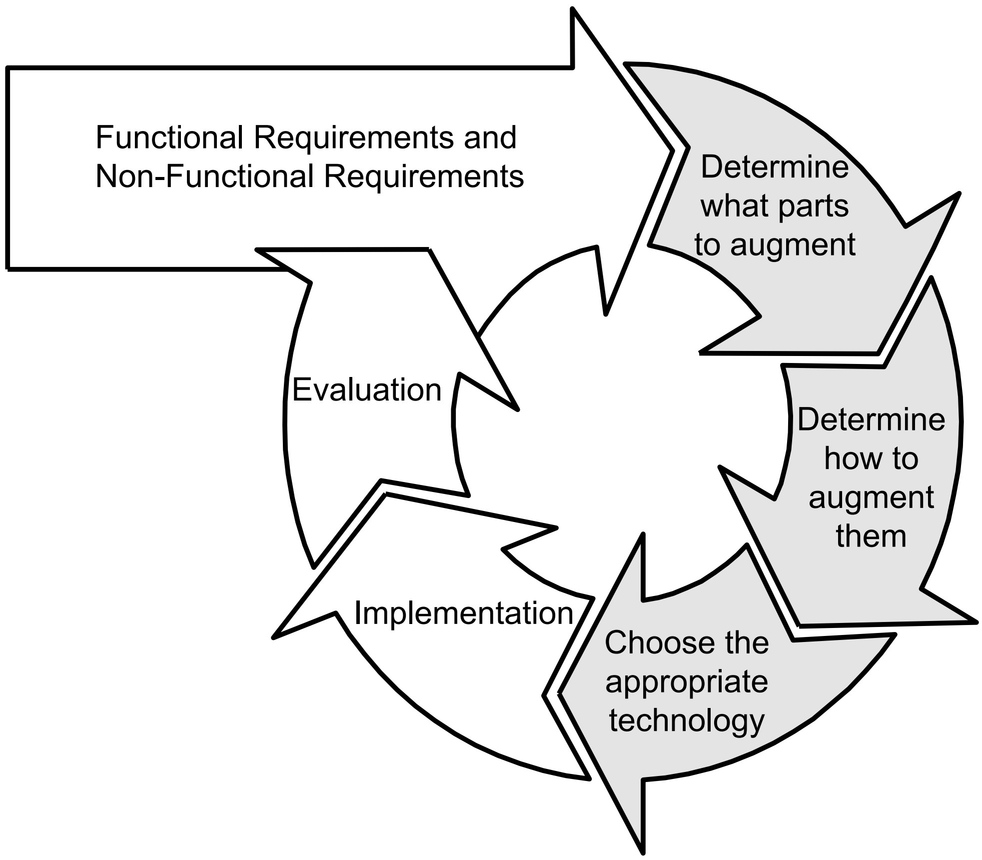


Figure 3.4: Overview of the physical augmentation cycle. The grey arrows indicate that this step is part of the design phase.

Based on the functional and non-functional requirements, the actual augmented play environment can be designed. Here, *design* means determining *what parts* should be augmented and *how* this should be done. In particular:

1. Determine the parts that are to be digitally augmented. This part also includes assessing effectiveness, efficiency and (economical) feasibility of augmentation.
   a) Where should additional interfaces be placed?
   b) Which objects are suitable for augmentation?
2. Determine how to augment the parts with regard to the design guidelines (see Section 3.2).
3. Choose appropriate technologies that contribute to the goals while meeting the guidelines.

In the implementation phase the focus is on realizing these three steps. Typically, a prototype must be subjected to several iterations of design, implementation and evaluation, and it might also be required to adapt the requirements according to lessons learned.

There are principally two types of physical entities that can be digitally augmented:

- The play set or infrastructure (e.g., a game board) and
- The play objects (e.g., game figures).

As far as the process of digitally augmenting physical artifacts is generally concerned, there are no differences between these two types. But some characteristics, especially the form factor, can significantly influence the choice of technology: play figures, for example, are often rather small and might thus rule out certain approaches and technologies from the beginning. We will discuss relevant aspects in the next section.

Design of Background Systems and User Interfaces

The pervasive computing system supporting the play scenario is the heart of the augmented environment. Both front-end (i.e., user interfaces) and back-end (i.e., the software components, the communication infrastructure, the virtualization of the play or game, etc.) play an equally important role. As pointed out before, using the augmented play environment should be fun and users should be enabled to adjust it to their personal requirements and preferences. The keywords are thus *empowerment* and *engagement*, which are discussed below.

Empowerment The system should *empower* players to control and configure the environment ad libitum. Control is one of the most natural and important desires of human beings [239]: "We want sensor-driven pervasive technologies to empower people with information that helps them make decisions, but we do not want to strip people of their sense of control over their environment. Losing a sense of control has been shown to be psychologically and physically debilitating. There are technical and human-computer interface advantages of creating systems that attempt to empower users with information at 'teachable moments' rather than automating decision-making using 'smart' or 'intelligent' control" [157].

This was also one of the major findings of a formative multi-method evaluation on future gaming systems we conducted earlier [281]. Although automation was widely appreciated in order to minimize the installation effort for game devices and players, the majority of participants feared that too much automation might lead to a loss of control. Similarly, Fischer stated already ten years ago that even for the artificial intelligence community the true goal might not be the replacement of human beings, but their empowerment [100].[7]

Engagement Control or empowerment, however, is only one aspect of user involvement. The second and equally important aspect is *engagement*. "Smart spaces must allow people to perform familiar activities in a way that is unobtrusive and provides some value-added capabilities (easier, faster, more efficient, greater functionality). At the same time, smart environments are expected to enable people to do tasks that are not currently possible or not currently conceived" [11].

Rogers even suggests an "alternative agenda which focuses on designing UbiComp technologies for engaging user experiences" [283]. According to her, this includes "a significant shift from proactive computing to proactive people", "engaged living" rather than "calm living", "bounded (as opposed to pervasive) technologies" and having "people rather than computers [...] take the initiative to be constructive, creative and, ultimately, in control of their interactions with the world – in novel and extensive ways".

Intille similarly posits that researchers should "aim to create technology that requires human effort in ways that keep life mentally and physically stimulating" [157]. This has also been the conclusion of a three year user study on smart homes, where the authors then postulate for "assistive technologies, where humans themselves take actions with the help of technology" [224]. The emphasis should rather be on supporting users to make (better) decisions, not have decisions made for them.

As discussed above and in Chapter 2, autonomous, procative systems are problematic for two reasons: first, current technological advances, es-

[7] For the sake of completeness we should mention that other researchers argue *for* automated environments. Sloman, for example, denoted managing pervasive computing as a "nightmare" and he is of the opinion that "humans will [only] be in the way". According to him, "adaptive self-management is the only answer" and we ultimately must "remove human[s] from the loop" [315].

pecially in artificial intelligence, are not yet capable of inferring all possible scenarios or states they might be confronted with in a smart environment; second, users are reluctant to cede control to a system, which they neither see (as it is supposed to run unobtrusively in the background) nor understand (as it can be very complex, especially for laymen). On the other hand, if everything must be manually initiated and configured by the user, the smart environment is certainly not "smart".

Seeing this problem from the domain of play and games, we believe that striking a balance between user involvement and system activity might yield better results in terms of user satisfaction (see Fig. 3.5).

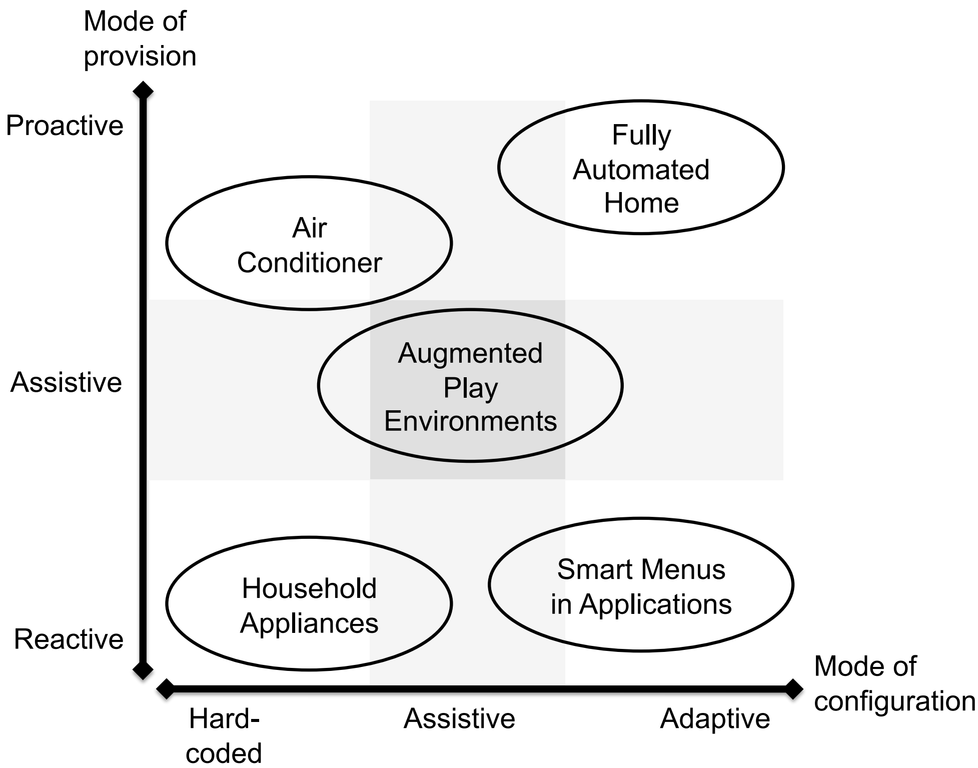


Figure 3.5: The amended version of the modes of service provision and configuration (cf. Fig. 2.5). *Assistive* in the mode of service means "engaging the user" and in the mode of configuration "empowering the user".

The major difference between assistive and proactive is not as much a matter of different methods and technologies, but rather of different goals and design criteria: while proactive environments automatically and autonomically make decisions using learning and reasoning techniques, assistive environments should provide users with appropriate and individualized services and information so that they can focus on the task at hand.

Besides, context modeling, which is the basis for a proactive approach, seems to be exceptionally difficult and impractical in play environments: a child can use a brick as a car in one moment, and decide to use it as a plane in the next; in games like "Settlers from Catan", the players have numerous options and their decisions rather depend on personal preferences than logical conclusions; in toy environments, children can move the objects freely and at any given time. In contrast to office or home scenarios, play is based on fantasy, free decision-making and exploring one's options, making it difficult to derive general patterns.

Thus, the goal should be to leave the players in control (empowerment) and support them with information and services that further enrich their play experience (engagement).

3.1.4 On Evaluating Augmented Play Environments

Evaluating a system is an important part of the development cycle. The goal is to assess if all functional and non-functional requirements are satisfactorily met. This helps designers to find and solve problems, to improve the system and to integrate user feedback. However, it has been recognized that user studies in the field of augmented or pervasive play and games is very resource-intensive [242]. Involving users and testing a system under real circumstances is not easy and requires careful planning of the evaluation.

While evaluating desktop applications, for example, can already be challenging, matters are much more complicated when is comes to testing pervasive computing systems: "Ubiquitous computing raises major challenges for system software researchers, mainly because of the heterogeneity and volatility that characterizes it. The set of participating users, hardware and software in ubiquitous computing environments is highly dynamic and unpredictable" [53], making such systems "difficult to evaluate, particularly at the early stages of design" [340].

In general, there are a number of potential challenges that might arise when evaluating pervasive computing environments. We will briefly list and discuss them now.

Evaluation in the Field Complex systems like augmented environments cannot be genuinely evaluated in a controlled setting like a laboratory. Abowd et al. state that "deeper evaluation results cannot be obtained through controlled studies in traditional, contained, usability laboratory" [10] and Trevor and Hilbert add that "these systems are embedded in a variety of complex real world environments that cannot be easily modeled (as required by theoretical analyses), simulated, measured or controlled (as required by laboratory experiments)" [339].

In other words, evaluations should take place in the field, preferably in places where the system is supposed to be deployed to create bona fide testing circumstances: "What is needed is real use in an authentic setting" [63]. This requirement, however, makes an already hard task even harder because "even in the lab, it is hard to conduct a controlled a Ubicomp evaluation, because Ubicomp applications are generally designed to be integrated into complex applications and tasks. The infrastructure needed to conduct a study may constitute a Ubicomp environment in its own right" [55].

Evaluating the Complete System Evaluation of an ubiquitous computing system usually requires that the complete system is finished and up and running. This entails two aspects: firstly, *all* components must be functional (i.e., the developer cannot test single components detached from anything else without risking the neglect of interdependencies). Secondly, they must be in a fully developed stage (i.e., they must be as errorless as possible).

Both aspects result in a time-consuming and intensive development process: "In the absence of evaluation techniques that do not depend on complete, working systems, developers currently must put significant effort into an application before testing it" [55].

Data Gathering The data gathering should be largely unobtrusive to prevent people from changing their behavior due to the observations [340]. This can cause a dilemma as the goal is to derive as much data as possible without the users knowing about it. The data gathering is further complicated as "everyday life environments typically have multiple interruptions and pose challenges to recording data without getting in the participant's way" [242].

The next question is if the gathered data should be quantitive or qualitative: "While quantitative analysis is well suited to evaluating a ubiquitous system's technical components, qualitative methods might be more appropriate when evaluating how a system integrates with everyday activities" [242]. Mankoff and Carter similarly argue that "an effective evaluation of deployed Ubicomp technology should combine qualitative and quantitative methods" [340]. Qualitative analysis, however, is usually time-consuming and laborious as it is difficult to automatize.

No Evaluation Standards Despite the growing attention that this field has received in recent years[8], there are still no agreed upon standards, methodologies and frameworks for evaluating pervasive computing systems. Connelly et al. see one problem in the complexity and diversity of such systems: "A one-size-fits-all approach to evaluating ubiquitous systems is unrealistic. The variety of contributing factors – from scale to context, to the nature of user interaction – implies the need for a tailored approach" [242]. They continue: "Other disciplines often rely on standardized tasks, methods or test data sets. These don't (yet) exist for ubiquitous systems. Moreover, defining them will be quite difficult because of the context's potential impact on system behavior."

Arnstein et al. come to a similar conclusion: "Ubiquitous computing presents a challenging evaluation problem because we must do without many of the standard assumptions allowed in pure HCI evaluations" [26].

Interdisciplinary Research Though building pervasive computing systems mostly falls into the domain of computer science, the evaluation often involves other disciplines: "an interdisciplinary evaluation appears to be the best way to gain a holistic understanding and cover all relevant factors of a ubiquitous system, its performance and its environmental impact" [242]. This requires the system developer to work together with researchers from other research fields, which can be interesting but also challenging.

Technical Issues While building a system is in itself a major challenge [55], this phase is not truly completed when it comes to testing, on the contrary: upon system deployment unanticipated problems might

[8] Mostly in terms of workshops (e.g., "Reality Testing: HCI Challenges in Nontraditional Environments" at the CHI 2006, "Technology has Escaped from the Zoo: Studying Usability in the Wild" at Interact 2007 and "Ubiquitous Systems Evaluation" at UbiComp 2008).

come up, requiring in situ and possibly real time fixing of hard- and software [56].

Having discussed a number or prominent challenges of evaluating pervasive computing systems in general, we now discuss two additional aspects that must be taken into account when evaluating augmented play environments.

Children as Users While most pervasive computing systems are typically designed for adult users, the target user group of augmented play environment are often children. Evaluating such systems can thus be very difficult as children recurrently display unpredictable – possibly even abrasive and violent – behavior, which might not be anticipated and accounted for from a system's point of view. It is also likely that researchers have access to only a small number of participants, necessitating other techniques like child-based personas as proposed by Antle [25].

Furthermore, it is problematic to tell children to imagine or disregard certain things as it is possible with adult users (e.g., "We haven't implemented this part yet, but imagine that the required information will be displayed over here...").[9]

For these reasons, the system should rather resemble a marketable product than a patchy prototype. The system must be very reliable and robust and should be designed in such a way that the risk of injuries are minimal (e.g., no sharp edges, electric cables or hazardous materials). This requires developers to put even more effort in designing, building and pre-testing the augmented play environment as well as to early integrate children in design and evaluation processes (e.g., [86, 171, 217]).

It's about Fun Unlike working or many other environments, augmented play environments are a form of entertainment and must thus be fun to use. Therefore, interacting with the environment should be enjoyable; otherwise the results of the evaluation might be biased (e.g., the users – especially children – might not be able to sincerely comment on technical aspects if the system was boring). One salient ingredient are the aforementioned non-functional requirements.

[9] This also renders evaluation techniques such as paper prototyping [56] mostly inadequate.

Summing up, evaluating pervasive computing systems in general and augmented play environments in particular can be very challenging and requires careful planning and execution. In Chapter 6, we will present and discuss experiences and insights we gained through a user study we conducted with the Augmented Knight's Castle.

In this section, we presented and discussed the process of digitally augmenting traditional play environments. The first phase is a two-step analysis, that aims at obtaining characteristics of a play environment and goals of its digital augmentation, which can then be translated into functional and non-functional requirements. Based on these sets of requirements, the augmented play set is then designed and implemented. This involves three aspects: the *physical augmentation* of play infrastructures and objects, the *background system* including the virtualization of the play or game and, lastly, the *user interfaces*. This phase is followed by an evaluation of the developed system. The process model furthermore comprises feedback loops since lessons learned in the design, implementation or evaluation phases might necessitate adjustments or changes in previous phases.

3.2 Design Guidelines for the Digital Augmentation

In this section we present design guidelines for the three areas involved, that is the physical augmentation, the virtualization of the play environment and the development of the corresponding background system as well as the user interfaces. The design guidelines provide fellow researchers and designers with hints and recommendations regarding important aspects and intrinsic challenges of the digital augmentation of traditional play environments.

3.2.1 Design Guidelines for the Physical Augmentation

As pointed out before, a fundamental part of the pervasive computing vision is the embedding of technology into physical objects and environments [220], preferably in such a way that it figuratively disappears [359].

This notion leads us to the first set of design guidelines for augmenting play objects and environments:

- Provide added value through technology: enhancing traditional toys with technology should not be a goal in itself, but offer clear benefits. Wren and Reynolds [368] suggest adding "as little as possible, but as much as necessary." Rogers et al. [286] point out that technology should closely follow the specific activities that are to be supported or realized (e.g., looking for or identifying something; using something to cause an effect; viewing or listening to something; collecting things).
- Strive for robustness in the presence of failures: the play environment should still be functional if the technology is switched off or malfunctions; i.e., the technology should not become such a critical part of the environment that technology failures render it useless.
- Technology should stay in the background: the augmentation should not lead players to focus on the added features only. Technology should neither diminish traditional play nor limit the players' imagination. Note that users might change their behavior after they have gotten used to the technology. Rogers et al. point out that "if we want to promote seamless continuity between the physical and the virtual, while at the same provoking wonder, then we may need to design an interactive environment where novelty is appropriately embedded in familiarity" [286].
- Design for implicit interactions [302] and prevent distraction from the toy or game itself. The integrated technology should be unobtrusive or even completely invisible, allowing players to focus on playing with the traditional play object instead of using novel features and interfaces.

As a principle, designers should not focus on pursuing the technology-driven approach, but rather aim at maximizing the benefits from the users' perspective to inhibit that "every interaction form and function is dictated by the platform, devices and software architecture. This often leads to systems that do not harness the true potential of interpersonal interaction. The problem can be explained by two factors. First, technologically oriented development is usually governed by the restrictions and conventions of contemporary systems. Secondly, the limitations of user interfaces, especially in the mobile context, are often said to cause the downscale in interactional degrees-of-freedom" [215].

Equally important is an iterative development process with extensive testing. This is to avoid systems that are too difficult to use or that do not meet certain essential deployment criteria (e.g., robustness or safety), especially in case of initial prototypes of novel games or toys: as they "are extremely time-critical and unlike applications software, [they] require high fidelity prototypes – a slow primitive prototype [...] cannot faithfully represent the gameplay of the real game and its usefulness is questionable at best" [371].

In addition to that, embedding technology into toys requires the designer to expect (and be able to cope with) contingencies: technology, particularly if novel, tends to behave in unanticipated ways or can be used in an unforeseeable fashion. In our experience, this problem is difficult to overcome, especially when designing play environments for children at young age. We recommend fast prototyping (the first draft is usually based on own ideas and personal experiences) with early testing followed by iterations of extension and improvement, each time incorporating user feedback (also cf. [62, 260, 307]).

Lastly, there are three further criteria to be considered. First, as denoted before, considerable attention must be paid to safety, especially when designing for children: designers should be aware of potential health risks (e.g., radiation, electricity or poisonous material) and act accordingly.

Second, the actual operation of the system should be as maintenance-free as possible: players should not be burdened with maintaining the technology, including tasks like recharge of batteries. We will further discuss this aspect in the next subsection.

Third, the number of additional user interfaces should be minimized. Ideally, to avoid shifting the players' focus to screens and other methods of input (e.g., keyboards or mice), play objects should remain the major (tangible) user interface [158, 159]. If the digital augmentation, however, requires additional interfaces to provide information and services, these interfaces should be as unobtrusive as possible to not disrupt the original gameplay. If possible, they should be designed in such a way that they encourage and support collaboration, thus contributing to the players' social experience.

The design guidelines for the physical augmentation are summarized in Tab. 3.1.

Table 3.1: Design guidelines for physical augmentation.

1. The technological enhancement should have an added value (do not use technology just for its own sake).
2. Use and integrate technology according to the maxim "as little as possible, as much as necessary".
3. Technology integration should be done in a way that is unobtrusive, if not completely invisible.
4. The focus should remain on the play or game and social interaction, not on the technology. The technology should always stay in the background.
5. The game or toy should still be playable (in the "traditional" way) even if the technology is switched off or malfunctioning.
6. The operation of the integrated technology should be as maintenance-free as possible.
7. The supported actions and tasks need to be clearly specified. The technology should closely follow activities contingent upon the specific play environment.
8. The technology must be safe if used in highly exuberant play environments (e.g., play objects are thrown or played with vividly) and/or by children (e.g., children might put objects in their mouth). Be considerably vigilant for electricity, sharp edges and poisonous materials.
9. Design and implementation should be tightly coupled as (new) technology can behave unexpectedly and counterproductively. Development should follow an iterative process, including rapid prototyping and testing.

3.2.2 Design Guidelines for the Background System

The previous subsection dealt with the digital augmentation of physical artifacts. In this subsection we discuss issues that arise when combining these individual objects to an augmented play environment. The aspects can have a significant influence on the design of the background system, mainly the communication infrastructure and the virtual model of the play environment.

There is some research on potential challenges of pervasive computing systems. Wright and Steventon, for instance, enumerate architecture and interfaces, complexity and scale, communication systems, human interfaces, accessibility, security, privacy and trust [369]. Similarly, Bull et al., focussing more on technical challenges, list configuration, device composition, resource reservation, user identity, user interfaces, information spaces, storage, security, privacy and trust as potential issues that must be addressed [51]. Similar findings are cited in [21, 132, 349].

While most challenges and requirements apply to the domain of augmented toy and games as well, some technical issues such as security management, storage and resource reservation, or societal issues such as security, privacy and trust are relatively irrelevant to this domain. On the other hand, developers might encounter new challenges that are inherent to play environments and have thus not been addressed yet.

We will now discuss four vital things, which, in addition to the rather generic technical aspects mentioned above, can pose major challenges during the digital augmentation process and must thus be properly addressed: complexity, high dynamics, maintenance and end-user configuration of play environments.

Complexity

The virtualization necessitates the understanding and modelling of play environment and all its play objects, which can be difficult and laborious, especially in complex environments. The system must support all objects of this particular play environment, including future objects (e.g., a newly published play figure). The system might also be required to facilitate adding and removing objects at run-time and maybe even in real time. Consequently, the underlying model must be flexible and extensible.

The highly individual characteristics and idiosyncrasies of existing play and game environments render the development of a universal system unfeasible: chess, a train set or Scrabble, for instance, are very dissimilar. To encompass them all, a very generic object management and communication system would be required, which would yield unsatisfactory results in terms of performance and efficiency.

Costabile et al. warn that "the temptation is to develop very general systems, thus falling in the Turing Tar Pit, in which 'everything is possible but nothing of interest is easy' " [67].

Additionally, a generic infrastructure generates overhead and can be significantly slower than a custom-tailored one.[10] This might not be acceptable as time lags can frustrate or even confuse users – especially children – as they cannot establish a mental model of cause and effect [285]. This issue is further complicated when the play environment allows for numerous, simultaneous interactions.

Designers should thus focus on a concrete, bounded scenario: "Instead of embedding pervasive computing everywhere in the environment," we should design pervasive computing scenarios "to serve specific purposes and be situated in particular places" [283].

High Dynamics

Closely related to the complexity are the high dynamics of smart environments: "Ubiquitous computing environments are intrinsically highly dynamic in nature, since they are designed to respond to changes in the physical environment and to changing user intentions" [258]. Cahill et al. similarly state that "the set of participating users, hardware and software in ubiquitous computing environment is highly dynamic and unpredictable" [53].

Especially in play environments, players might constantly join and leave and play objects might be added and removed frequently. If the digital augmentation furthermore enables them to integrate personal technical devices (e.g., cell phones), the system must support this mobility. This also includes considering the different interaction characteristics and af-

[10]When building the first version of the Augmented Knight's Castle, for example, we initially used Fosstrak (www.fosstrak.org), an open source RFID software platform, for tracking the play figures on the play field. Although this platform is powerful, it was simply too slow for our purpose and we had to replace it with a custom-tailored, less powerful, but faster solution (cf. Chapter 5).

fordances of each device to make effective use of the various – mostly output – options (e.g., if a video is to be played, pick the device with the best playback options) [198].

Additionally, the environment must not only support heterogeneity of devices [195], but also facilitate impromptu interoperability, which is “not just the simple ability to interconnect, but the ability to do so with little or no advance planning or implementation” [90]. The virtual model must thus comprise all objects relevant to this particular play environment and allow for their fast and effortless adding and removal at run-time, possibly even in real time.

The play environment also needs to be adaptable during run-time regarding their modeled rules and play mechanics. This relates to the notion of *house rules* that allow participants of the play or game to change certain play mechanics as a result of their own play history. The “run-time adaptability” of traditional tabletop games, for example, is one of the reasons for their continuing success despite the technical superiority of computer entertainment.

In addition to players, objects, rules and devices, the information flow can also be highly dynamic. Some play environments necessitate the distinction between private and public information when dealing with multiple users (e.g., tabletop games like “Scotland Yard” or most role-playing games rely on restricted information flow). It might thus be necessary to introduce different degrees of private, shared and public information (also cf. [341]) in the social space that can then be utilized by the gaming application to foster cooperation and competition between participants.

Finally, designers must be attentive to simultaneous interactions and shared interfaces. Augmented play environments typically feature a high degree of interaction with the environment and its objects (e.g., two players moving their markers or play figures simultaneously). This problem is also confirmed by Randall [275]: “We’ve already discovered we find ourselves all trying to control the same thing at the same time. [The control systems] don’t tell you that someone else is trying to do the same thing.”

Maintenance

The maintenance of smart environments gives cause for concern [50, 268, 275], mainly for two reasons: first, end-users neither have adequate technical knowledge nor the desire to acquire it. For this reason, users should preferably not be bothered with any maintenance tasks as even exchanging batteries can be perceived as being annoying (especially if such tasks are signaled by the system slowing down or completely ceasing to operate). Second, the *invisible* integration of technology paired with growing complexity and intricacy further complicates the matter (i.e., how are users supposed to maintain something they do not see nor understand?).

Designers must consider these aspects when designing augmented play environments to avoid or at least minimize anything that could be perceived as being burdensome and annoying.

End-user Configuration

Users should be in control of the environment, empowered to make adjustments according to their personal preferences and requirements: "Apart from being dependable from a technology-based point of view, a complex and highly dynamic system must remain manageable and controllable" [43].

Despite the effort spent on researching smart environments (see Section 2.1), few groups have addressed the challenging issue of managing technologically enhanced environments, even though it is agreed that this aspect is of prime importance [348,349].[11] As O'Sullivan and Wade [259] point out, smart environments must become easily manageable and usable by ordinary people, without any special technical knowledge and skills, in order to reach mass-market potential and guarantee the long-term success of such spaces. Hague et al. even state that the "critical question for the acceptance of ubiquitous computing" is, whether [users] "will ever be able to configure and customize interaction between [the] appliances" [130].

Configuration is especially fundamental when it comes to play environments, where a high degree of control and autonomy must be guaranteed. Existing approaches are unsuitable as they have different foci, either in terms of the field of application (e.g., smart living rooms or smart work environments, with often well-defined tasks and well-behaved users) or insufficient vertical integration (i.e., focus is on low level communication and connection only [277], disregarding higher levels).

[11] The Defence Advanced Research Projects Agency (DARPA) has "singled out the (network) management problem inherent in managing Smart Spaces/embedded systems as the most important challenge facing telecommunications service managers for the next decade" (as cited, for example, in [124]).

Managing[12] smart environments can be a taunting and difficult task, given the countless heterogeneous smart objects potentially interacting with each other. The problem is that "almost any device beyond the complexity of a simple switch requires configuration or some form of user set-up" [51]. The situation is further complicated if the configuration must be done by the users as only they know the exact context the system will be running in [90].

Therefore, augmented environments require easy-to-use and custom-tailored management interfaces (also see next subsection) and run-time support. Designers, adults and children should be able to add and remove objects as well as to set and modify roles of individual play pieces without interrupting game flow. The challenge is to find the right mixture of empowering users to create "their own environment" and making this task as easy – and enjoyable – as possible. This includes offering "undo" options to reverse previous decisions and configurations (e.g., [310]).

Similarly, the environment should allow for the seamless and easy integration of personal devices. Users should be able to bring their own devices (e.g., different mobile phone models) and make use of them. This should involve basically no integration overhead: users should not be bothered with details such as IP address spaces or protocols [309].

There are already some approaches towards end-user configuration of pervasive computing environments, but they are typically GUI-based (e.g., [243, 342]). It would be preferable, however, if the players could do this without explicit interfaces and in the environment itself (e.g., tangible user interfaces). We will discuss this further in the next subsection.

Tab. 3.2 summarizes all aspects of this subsection.

3.2.3 Design Guidelines for User Interfaces

User interfaces are of considerable importance in augmented play environments: they should empower users to interact with the environment without compromising the social and tangible benefits of the traditional play environment. Ideally, "hardware and software should be seamlessly integrated and target the very specific needs of an end-user. Complex

[12] We do not mean "management" in the sense of middleware or device management as discussed, e.g., in [187], but in the sense of configuration and personalization of the play environment, which is also called "tailorability" [212, 337].

Table 3.2: Design guidelines for the system (virtualization).

1. The virtual model must include all current and future objects. To cope with inherent complexity, it should be designed “as open as necessary, but as closed as possible”.
2. The system must support the high dynamics: players and play objects might come and go, requiring run-time, possibly even real time support. This might also concern the flow of information.
3. The system must be able to cope with multiple simultaneous interactions.
4. Personal, mobile devices might be added (e.g., for displaying information or configuration purposes). The system should thus support impromptu (inter-)operability and strive for device compatibility and consistency of content.
5. Keep interactions with the system to a minimum (the focus should remain on the social interactions and the play or game itself). But when players are required to interact with it, engage them: make it quick, easy and fun – and never impair gameplay or social interaction.
6. Empower the user: the players should always be in control of the play environment. This includes possibilities to create, change and ignore rules, possibly an undo function.
7. The performance of the system is crucial. Feedback should always be immediate, correct and comprehensible (also see design guidelines for user interfaces).
8. Minimize system maintenance: users are typically technical laymen and such tasks might be perceived as burdensome and annoying.

technology is hidden behind a friendly user-interface” [132]. In other words, user interfaces have a shielding function [43]: they should thus only offer options that are necessary or useful in any given moment. This also ensures that the players' attention is on the play or game itself.

Ideally, a UI in augmented play environments should be simple, intuitive and in situ; it should be a seamless part of the (tangible) play set and enable users to efficiently activate services or configure the environment. We now discuss these aspects in more detail.

Implicit and Explicit Interaction

One particular challenge is the question of how users are supposed to interact with and receive information and services from computers that have completely vanished from their periphery: "With traditional devices the human-computer interaction is explicit. [...] the user explicitly instructs the computer what to do. This concept of explicit interaction contrasts with the vision of invisible or disappearing computing, since a system does not become visible until explicit interaction occurs" [306].

There are two ways to make information and services available to users: either by directly interacting with the object or environment (see Fig. 3.6 (a)) or by using a mediator (see Fig. 3.6 (b)). Or, for a more coherent terminology, users indirectly interact with the system through object manipulation (implicit interaction) and directly using explicit user interfaces.

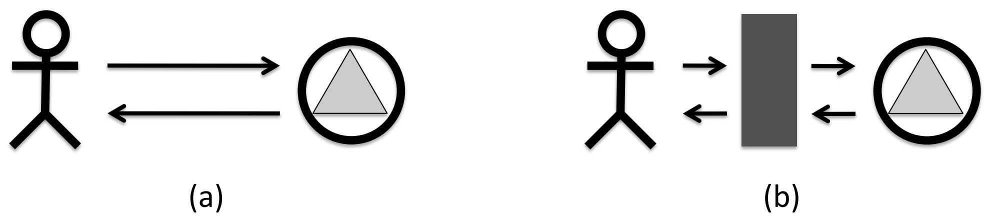


Figure 3.6: Direct interaction between user and augmented object (a) and mediated interaction (b).

Interacting with invisible computers calls for novel interfaces and interaction paradigms that transcend classical user interfaces. In augmented play environments the use of additional explicit interfaces should be minimal to not disrupt the gameplay, the rich social interaction and the physical look-and-feel of the environment and its objects.

Simplicity, Efficiency and Intuitiveness

Independent of the UI type (i.e., tangible, graphical, etc.), the interface should always be as simple, efficient and intuitive as possible.

Simplicity refers to the quality or condition of being simple or plain. The emphasis is on making things as simple as possible, but not simpler.[13] Simplicity is very important when enriching physical objects with additional functionalities to not overwhelm the users; even more so in augmented play environments where the emphasis is on enjoyment and the users are often children.

Efficiency means that users should be able to achieve what they want to do fast and with minimal effort. If the interface is too intricate to use, users will simply become reluctant to use it. Randall illustrates this nicely for a smart home: "Things must be simpler to do than in a normal house... I don't want to work through a menu just to turn off the lights" [275]. He also notes that "it should never take longer than it did before."

Intuitiveness indicates that the user interface is easy to use and understand. Users must be able to easily and quickly develop a mental model of the system that is correct or at least works [251]. This aspect of "understandability" in the realm of smart environments [338] is very crucial: "The obstacle to understanding new interfaces is high. Technology will be adopted only if the perceived return outweighs the effort required to understand the new technology" [237]. Thus, user interfaces should be intuitive and unambiguously[14] usable.

These three criteria, especially the last one, are all the more important when designing interfaces for children because children do not have the mental capabilities, experiences and patience of adults. While children have been recognized as a special user group in the field of HCI,[15] research in this area is still very sparse [217]. It seems, however, that a "combination of simple feedback and control lead children to widely explore and discover a responsive environment" [98]. To this end, developers should thus integrate the children early in the design process for design and evaluation purposes.

[13] This is also known as the "Occam's razor" or the "Keep It Simple, Stupid" (KISS) principle.

[14] Some researchers, however, also proposed to explicitly exploit ambiguity for design purposes [34, 119].

[15] There is, for example, a sub-field of HCI called child-computer interaction (CCI), e.g., [218] focusing on more general (e.g., psychological and social) issues of how children interact with computers.

Interaction Design

Another significant aspect is *in situ interaction* (i.e., the interaction is tied to the object) or *situated action* [327]. "Situated action emphasizes the improvisational aspects of human behavior and demphasises a priori plan that the person simply executes... Ubicomp's efforts informed by a situation action also emphasize improvisational behavior and would not require or anticipate, the user to follow a predefined script" [10].

This concept has received growing attention in recent years and many researchers have stressed its importance. McCullough, for example, postulates that "we need to advance from the science of the computer-human interface into a culture of situated interaction design" [225]. Winograd equally challenges designers to move from *interface* design to *interaction* design: "design thinking as a whole has to focus on the interaction" [367]. Thackara even sees interaction design as the solution for many pervasive computing challenges [336].

These statements indicate that it is not just about designing interfaces but rather finding and using interaction patterns. This guarantees a smooth integration into the gameplay. Notwithstanding, the user-system interaction should be kept to a minimum so that the focus always remains on the play or game itself and the associated social experience. Therefore, the maxim should be to only engage the user if necessary; but if you do, aim at creating meaningful and enthralling interaction situations that contribute to users' enjoyment.

End-User Programming

The system should empower players to adjust and change almost everything. This will endow them with a feeling of power and control. However, as debated before, developers must be careful to not overwhelm users with countless configuration options but concentrate on providing the most essential and often used ones as easily and quickly as possible (similar to modern application GUIs, which offer shortcuts to often used functions, but keep other functions in the back (menu)).

Bellotti and Edwards state that "effective control is not simply about whether the user is intimately involved in execution (with constant user intervention and monitoring); it is more a matter of how easily the user attains the desired outcome (by whatever means). The degree to which user involvement is required, and the point in the interaction at which that involvement will be required, will depend on how much can be determined a priori about a particular action, its likely context and its intent" [31].

Users typically do not possess the knowledge and experience to configure complex smart environments and there are usually no administrators or technical experts around for this job [338]. In other words, it is up to the end-user to configure the environment according to their preferences and requirements only with the means provided by the user interface itself [243], which becomes considerably more challenging when children are the target user group. Developers must thus understand end-users and their capabilities to simplify the configuration process as much as possible, which includes addressing the question of *how* the configuration should be done.

The matters of *how* and *what* users are supposed to configure or create something is often referred to as *end-user programming* (EUP). The goal of EUP "is that users are able to customize and adapt the software systems in use to their particular needs at hand, so that they can perform their work more efficiently and effectively" [269]. A good example for this intuitive and natural form of EUP is *programming-by-example*[16] [240]. Principally, the idea is to "show the system the required functional behaviour by demonstrating the required physical actions within the environment" [61].

EUP not only allows users to configure augmented objects and environments ("entity manipulation" [373]), but furthermore enables them to create their own content, which for all intents and purposes, supports the "from consumers to producers" paradigm[17] [100]. It would seem that this form of configuration can be very intuitive and powerful, especially for young children, as they cannot cope with abstractionism yet.

Thus, if possible and feasible, designers should use the programming-by-example paradigm. Additionally, UIs should always be designed in such a way that configuration tasks are not a burden but, on the contrary, fun – and maybe even part of the play or game.

[16]Other prevalent terms are *programming-by-demonstration* [72, 81] or, more recently coined, *pervasive interactive programming* [61].

[17]This is also one of the key characteristics of *Web 2.0*, which has unprecedentedly demonstrated the importance and potential of EUP [14].

Tangible User Interfaces

Physical objects with integrated technology to control and interact with computers are called tangible user interfaces (TUIs), a sub-field of human-computer interaction. Tangible user interfaces – also sometimes referred to as palpable [18], graspable [103], physical [127], embodied [102] or haptic [200] interfaces – "augment the real physical world by coupling digital information to everyday physical objects and environments", taking "advantage of natural physical affordances to achieve a heightened legibility and seamlessness of interaction between people and information" [346].

Augmented play objects can be seen as a specific form of TUIs. While haptic feedback can be very advantageous in general [133], providing it in play and game environments can be especially beneficial [95]. TUIs might also form higher level interfaces to augmented play objects, providing access to configuration and management options not directly related to gameplay.

Although there has been a considerate amount of research on TUIs in recent years, Stringer et al. note that "tangible thinking", which refers to the "dynamic structure in the real-world space, is still at its infancy" [326] and experiences and guidelines for graphical user interfaces (GUIs) are often not applicable to TUIs. We thus discuss several guidelines for TUI design and their applicability to augmented toy environments.

Terrenghi lists several important features to keep in mind when designing TUIs [333]:

- Allow for three-dimensional space manipulation (if possible) to enable different kinds of actions and feedback from those actions.
- Use of spatially multiplexed input to interact with virtual objects.
- Continuity of action and richness of manipulation vocabulary in input, as distinct from discrete actions or gestures afforded by mouse and keyboard.
- Direct spatial mapping between input and output so that an action produces feedback at the point where input is sensed.
- Rich multimodal feedback (not limited to visual and audio feedback), such as it is possible in the physical world.

- Physical constraints, which affects users' mental model of the possible manipulations with an artifact.

Similarly, Shaer et al. present essential aspects of TUIs [308]:

- Multiple behaviors: when specifying the behavior of a certain physical object, the designer is required to take into consideration the mutual impact of physical objects.
- Multiple actions: in contrast to GUIs where there are six fundamental interaction tasks (cf. [111]), in a three-dimensional space of the physical world there are numerous activities that can be performed with or upon, any physical object (e.g., squeeze, stroke, toss, push, tap, pat, etc.). Hence, the designer is charged with selecting and defining the meaningful actions.
- No standard I/O: for example, measuring movement of an object may be implemented using magnet sensors, RFID or computer vision. Though identical in purpose, each technology currently requires a different set of physical devices, instructions and code.
- Continuous interaction: TUIs support a combination of discrete and continuous interaction. When users continuously interact with physical objects, they perceive that their motions are directly mapped to changes in the digital information. However, existing event-based models for designing interactive systems currently fail to capture continuous interaction explicitly (cf. [162]). Thus, TUI software developers are often required to deal with continuous interaction in considerably ad-hoc, low-level programming approaches.
- Distributed interaction: in a TUI there is no single point of interaction, as multiple users can simultaneously interact with multiple physical objects (also cf. [85]). In addition, the same action in a given interaction may be distributed across multiple physical objects. Existing models for designing interactive systems usually handle multiple input devices by serializing all input into one common stream. However, in TUIs this method is less appropriate, since the input is logically parallel and the users' perception is that two or more dialogues are taking place simultaneously.

Antle proposes the "child tangible interaction" (CTI) framework for the design of tangible (not necessarily technologically enhanced) systems for children [24]:

- Space for action: unlike traditional desktop systems which utilize an indirect controller (e.g., mouse), tangible systems afford opportunities to capitalize on children's developing repertoire of physical actions and spatial abilities for direct system input and control.
- Perceptual mapping refers to the mapping between the perceptual properties (often appearance) of the physical and digital aspects of the system (relationship between how things appear and how they respond). Thus, designed affordances need to consider the age-appropriate perceptual, cognitive and motor abilities and limitations of children (also cf. [334]).
- Behavioral mapping is the mapping between the input behavior and output effect of the physical and digital aspects of the system. Design requires consideration of children's understanding of how things behave.
- Semantic mapping refers to the mapping between the information carried in the physical and digital aspects of the system. Design requires consideration of children's understanding of what things mean in various representational forms.
- Space for friends: tangible and spatial computer-mediated systems have both the space and the affordance for multiple users.

Lastly, it is recommendable to develop TUIs using an iterative design approach. Based on earlier work by Norman [253] and Soloway et al. [317], Stringer et al. come to the conclusion "that TUIs are particularly well-suited to a process of frequent, incremental and iterative design. This is because many of the most important aspects of a TUI – those around integration with the physical context of use – can be tested using low-tech prototypes which can be built quickly and cheaply" [326]. TUIs are a form of HCI after all and "much of the structure of this interaction derives from the technology" [54].

Tables 3.3 and 3.4 summarize the design guidelines for user interfaces in general and additional aspects for tangible user interfaces, respectively.

Table 3.3: Design guidelines for user interfaces in general.

1. The interface should always be as simple, efficient and intuitive as possible. This includes striving for "lightweight" interaction (i.e., users should not have to think much about it) and hiding the complexity of the system (i.e., only offer currently relevant options).
2. It is about fun: interactions should always be enchanting: only engage the user if necessary, but if you do, let the user enjoy it. Provide rich multimodal feedback.
3. Strive for in situ interaction / situated action: the interaction (e.g., configuration) happens right in the play or game, not somewhere outside.
4. Allow for distributed interaction and shareable interfaces.
5. User interfaces and the interaction therewith should be seamlessly integrated into the play environment and fit its theme and flow.
6. Secondary user interfaces should be minimized (ideally, the play objects themselves are the interface).
7. If possible, use the programming-by-example paradigm for configuration issues.
8. Design and implementation should be tightly coupled and users should be included early on in the process. Development should follow an iterative process, including rapid prototyping and testing.

In this section we examined important aspects and problems of digitally augmenting traditional play environments. The discussed issues – partly based on literature, partly on our own experience – should sensitize developers to the idiosyncrasies and challenges of the digital augmentation process. To promote practical usage, we established sets of design guidelines for each involved area: the physical augmentation, the virtualization

Table 3.4: Additional aspects for tangible user interfaces.

1. Exploit the (three-dimensional) space when designing (meaningful) interactions; make use of the inherent richness of tangible interaction.
2. Enable continuous and seamless interaction through multiple possibilities of interaction and manipulation.
3. Spatially map input and output.
4. The physical appearance should be consistent and meet the players' (especially children's) perceptual abilities and mental models (i.e., how things behave and how they are used), also called "affordances": physical properties that invite action and interaction [251].
5. Design the play object (and environment) with an indisputable and consistent semantic mapping.
6. Take into consideration the physical restrictions of the object as well as manipulation constraints.

of the game (flow) and corresponding system development and the user interfaces, respectively.

In the next sections, we will extend these design guidelines with regard to toy and game environments, the two most prominent forms of play environments.

3.3 Design Guidelines for Augmented Game Environments

In addition to the aforementioned design guidelines for generic play environments, we now discuss several game-specific aspects.

As discussed in Chapter 2, games are characterized by rules, competition, goals, quantifiable outcome, decisions and emotional attachment. Games are hence structured and usually contextually, spatially and temporally closed. Therefore, the emphasis is not on adding new features and virtual elements to the game – although it remains a valid option, of course –, but rather on supporting players with context-aware information and services to improve their play experiences. Designers must, however, be careful to not bring the technology to the fore: the focus should always be on the game and the social interaction. Especially video games often address this aspect only insufficiently.

A first approach is Jegers' model of *pervasive game flow* [165], which extends the *game flow* model by Sweetser and Wyeth [329]. Game flow consists of eight elements, which partly overlap with the six elements of games introduced by us before. Jegers then describes how these elements should be supported in pervasive games[18] (see Tab. 3.5). A truly compelling gaming experience must support all these aspects.

In addition to this approach, we can use our definitions and classifications to analyze what designers should keep in mind to maximize the players' entertainment and enjoyment. To this end, we analyze how pervasive computing technologies can be utilized to support the six elements of a game (see Tab. 3.6).

In addition to these rather high level design guidelines, we can list four recommendations that have proven helpful when virtualizing *game flow* (also see Chapter 4):

- We noticed that "pure" object-oriented approaches did not lend themselves well to implementing messy rule books – we were usually more successful with a combination of object-oriented modelling / programming and scripting languages (this approach is also common with computer and video games).
- Another very promising approach, depending on the game, is to model the game using *flow diagrams*, which can then be easily translated into state machines and be realized using scripting languages.
- Since rule virtualization requires that the system is able to track the physical movements of all game objects, we can also utilize this information to allow players to review and analyse a played game (i.e., record all game moves). This also allows players to stop and

[18]The term "pervasive games" in this context refers to all kinds of games that make use of pervasive and mobile computing technologies (cf. Subsection 2.3.3).

Table 3.5: Excerpt from the pervasive gameflow model [165].

Element	**Criteria (PG = pervasive games)**
Concentration	PG should support players in the process of switching between in-game tasks and surrounding factors.
Challenge	PG should stimulate and support players in their own creation of game scenarios and pacing. PG should help players in keeping a balance in the creation of paths and developments in the game world, but not put too much control or constraints on the pacing and challenge evolving.
Player Skills	PG should let the game be very flexible and enable players' skills to be developed in a pace set by the players.
Control	PG should enable players to easily pick up the game play in a constantly ongoing game and quickly get a picture of the current status in the game world.
Clear Goals	PG should support players in forming and communicating their own intermediate goals.
Immersion	PG should support a seamless transition between different everyday contexts and not imply or require player actions that might result in a violation of normal social norms in everyday contexts. PG should enable players to shift focus between the virtual and physical parts of the game without losing too much of the feeling of immersion.
Social Interaction	PG should support and enable possibilities for game oriented, meaningful and purposeful social interaction within the gaming system. PG should incorporate triggers and structures (e.g., quests and events, factions, guilds or gangs) that motivate players to communicate and interact socially.

resume a game anytime. "Many board games take longer than the typical two or three hour period of a single session. Thus, persis-

Table 3.6: Six game elements supported by pervasive computing.

Element	Support through Pervasive Computing
Rules	Unobtrusively but continuously monitor the game, observe the rules and always be aware of the current game state. The game state must be accessible to players at all times and violations of rules should be immediately reported in an adequate way.
Competition	Provide players with the means to smoothly engage in a fair competition.
Goals	See (see Tab. 3.5)
(Quantifiable) Outcome	Always keep score of the game. It must be possible for players to always inquire the current score.
Decisions	Allow players to make decisions anytime. For this reason, it would be desirable to collect data and observe players' decisions in an unobtrusive way. Also, important in this context is immediate feedback by suitable means.
Emotional Attachment	Provide players with a compelling experience that seamlessly combines (well-chosen) several different media ("cross-media entertainment"), multimodal devices, etc. to stimulate physical, intellectual and social experiences and challenges as well as immersion into the game.

tency becomes an issue which includes recording game events and possibly the creation of a corresponding game history" [210]. Explicit *session management* must thus be regarded early in the design process and should not be taken lightly.

- Clearly, an iterative design and implementation process helps with the gradual synchronization of virtual rules with their "printed" counterparts.

Summing up, in this section we discussed additional design aspects for game environments. Game environments differ from other play environments insomuch as they feature six specific characteristics, that is rules, quantifiable outcome, competition, goals, decisions and emotional attachment to the outcome. The digital augmentation should regard them.

3.4 Design Guidelines for Augmented Toy Environments

Toys, in contrast to games, are usually combined and used in a totally unrestricted and free manner. This can render the digital augmentation even more difficult as toy environments usually do not feature distinct patterns or "game flows". Another important differentiation is that toys are primarily used by children. Therefore, safety precautions should be applied.

On the other hand, with toys, designers can freely add new virtual elements to enrich the play experience. While games are contextually closed and rules dictate how play objects are to be used, this constraint does not exist with toys.

We now discuss a couple of additional criteria that only apply to toys. We first look at design criteria for traditional toys: not only are these guidelines equally applicable to augmented toys, but they can moreover be inspirational as they might point at potentially augmentable aspects. We additionally present several guidelines for educational contents and playful learning.

Designing Toys Toys often resemble objects used in the adult world (e.g., a car or tools such as a hammer) and children imitate their usage by what they have been taught or perceived themselves. "Toys [...] have an exciting role in helping children to become mature, confident and imaginative adults" [2]. Thus, children should be able to easily perceive and understand the inherent role or function of each play object based on its physical appearance.

Judy Ellis from the Toy Design Program at the Fashion Institute of Technology states that "a really great toy invites discovery, enhances a child's play environment, and is fun, educational, and age appropriate" [194]. Furthermore, she points out that designers "must address both artistic and practical matters and learn to be mindful of financial, safety, and creative concerns."

The “Let’s Play!” projects at the University of Buffalo formulated a number of universal design guidelines for toys [279]:

- The toy must be appealing: the design should communicate all necessary information effectively and appeal to children’s sensory abilities.
- It should be clear how to play with the toy: a simple design with well-defined access areas that offer consistent responses makes a toy easy to use, regardless of the children’s experiences.
- The toy is adjustable for a range of users: for example, children can use the toy in a variety of positions (sitting, standing, playing on the floor, etc.) or the output is varied and adjustable. Furthermore, the toy appeals to children at varying ages, developmental levels and abilities.
- The toy supports the child’s development: toys should encourage imagination and social play, stimulate physical or mental activity, and promote the discovery of new ways to play.

Hengeveld et al. [138], in studying the design of adaptive and interactive toys for very young handicapped children, came up with similar guidelines for designing complex interactive products, contrasting them in particular to the design of computer- and video-based games:

- Social Interaction: interactive toys should stimulate interpersonal interactions.
- Tangibility: by stimulating multiple senses and skills, affording both actions and play, interactive real-world toys offer more room for social, personal and active interaction, as well as a slower pace and more involvement.
- Challenge: in order for children to learn, they need to be motivated. Challenge is a key element of motivation. Toys should engage the child by stimulating it to reach for the “boundaries of its skills”. Interactions should be appealing, rewarding, engaging and fun.
- Adaptivity: toys that adapt to the individual child optimize the learning setting and avoid frustration. Supporting such adaptability requires advanced technologies, such as embedded intelligence, wireless networking, and interactive, adaptive narratives.

- Design: products should "resonate with young children" and in their specific case appeal to both challenged and able-bodied children.

Based on our experiences when building and testing the Augmented Knight's Castle (see Chapters 5 and 6), we can add the following guidelines that, by and large, confirm common sense:

- Toys must be very reliable and durable. This specifically applies to augmented toys that contain highly sophisticated (and often delicate) technology. We noticed that some children played quite vehemently and strained our play set severely.
- Designers should respect children's intelligence by creating adaptive and age appropriate toys. This includes avoiding the design of toys that are inconsistent with the real world (e.g., a toy dog that says "Hello" [113]).

Educational Aspects While learning based on computer or video games has already been widely investigated (e.g., [120,271]), the potential of learning in mixed reality environments has not been largely explored yet. However, most aspects of conventional learning environments also apply here. Schaller, for example, by extending previous work by Malone and Lepper [213], identifies six key aspects of successful learning systems [301]:

- Challenge: clear, fixed goals that are relevant for the learner can offer motivating challenges. Feedback on performance should be frequent, unambiguous and supportive. Lastly, the activity should promote feelings of competence for the person involved.
- Curiosity: Schaller describes two different forms of curiosity – sensory curiosity and cognitive curiosity. Audio and visual effects, particularly in computer games, may enhance sensory curiosity. Cognitive curiosity is aroused when learners are surprised or intrigued by paradoxes or incompleteness.
- Control: learners prefer feelings of self-determination and control. The ingredients of contingency, choice and power contribute to the control feature of the learning experience.

- Fantasy: learner's emotions and thinking processes form the basis for fantasies, which should appeal not only to emotional needs but also provide relevant metaphors or analogies.
- Iteration: iterations support the learning process by encouraging experimentation, hypothesis testing and synthesis.
- Reflection: ideally, reflection should happen during iterations, as players test new hypotheses and synthesize the outcomes with their existing understanding.

Based on our experiences, we outline additional six criteria.

- Customization of educational content: parents and educators should be able to adjust educational content. Additionally, children should be empowered to select from available educational content to give them a feeling of autonomy and control.
- Multiple challenges and possibilities: a learning environment should offer multiple challenges that users can choose from. If possible, there should be multiple possibilities to solve challenges and riddles.
- Integrate context: a toy should never be seen as a sole play object but should be put in context. This also helps to understand the conveyed educational content.
- Reward learning: do not enforce learning but make it voluntary and fun. To ensure progress, it is recommendable to reward learning. A child could, for example, solve a number of riddles to advance in a story.
- Support learning in teams: if possible, the environment should support learning in teams. This not only supports social interaction, but fosters the learning experience.
- Above all, learning should be fun: "One wonders [...] why learning is so damn boring to so many people. It's almost certainly because the method of transmission is wrong. We praise good teachers by saying that they 'make learning fun' " [177].

Summing up, in this section we discussed additional design aspects for toy environments. Toy environments feature free play and it is often difficult to formally describe their play patterns. For this reason, we looked into designing single toy pieces and listed several well established design criteria that, in addition to the design guidelines for generic play environments, should help designers to digitally augment them. Besides, we elaborated on designing toys for (playful) learning and summarized a number of aspects that should be taken into consideration during the process of digital augmentation.

3.5 Summary

In this chapter we discussed the digital augmentation of traditional play environments. We presented and discussed a model for the process of digital augmentation, which consists of three major steps: a two-step analysis (i.e., the analysis of the play environment and the subsequent requirements analysis), the system design and implementation and the evaluation of the resulting digitally augmented play environment.

We primarily concentrated on the design phase and discussed challenges and important aspects thereof. This resulted in several sets of design guidelines for the three involved parts of the system architecture: the augmentation of the physical play infrastructure and objects, the virtualization of the play or game and the corresponding development of the gaming application and, lastly, the design of user interfaces.

We then extended the general design guidelines and took into consideration further aspects that were unique to the two main forms of play environments, toy environments and game environments, respectively.

4 Warhammer 41K

In this chapter we present *Warhammer 41K* (W41K), an augmented version of the popular miniature war game *Warhammer 40K* (W40K). This game is an excellent candidate for digital augmentation as it perspicuously demonstrates both potential benefits and inherent challenges. This game is very complex and features distinct requirements: not only does a typical game session comprise numerous units with individual characteristics that are subject to constant changes – requiring the players to keep track of a large number of unit sheets –, but it is essential to locate the game objects on the battlefield within the range of millimeters, which has to be done manually using rulers and protractors. In addition to this, the game consists of myriad rules, necessitating frequent consultation of rule books and data tables. For the element of chance, one or more six-sided dice are being rolled.

This chapter is structured as follows (see Fig. 4.1):

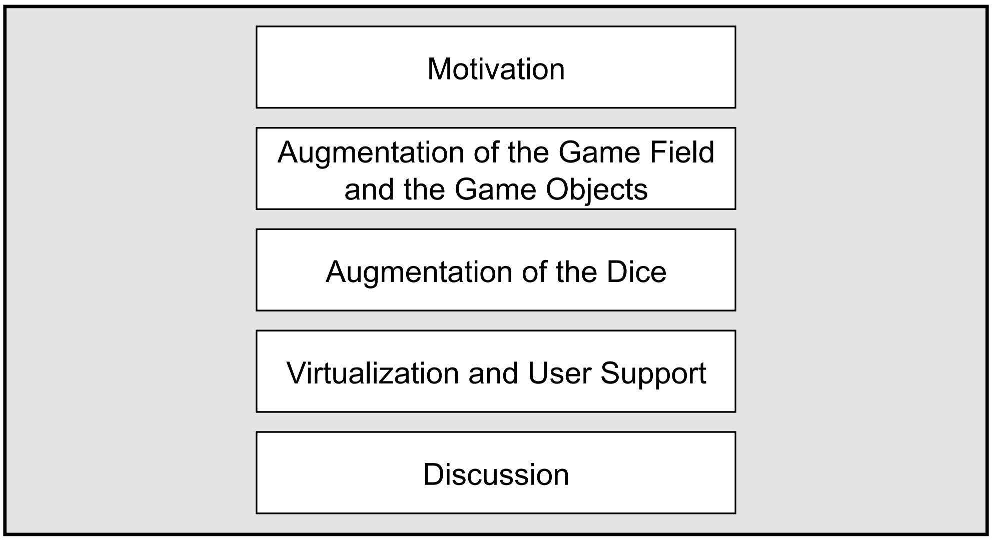


Figure 4.1: The structure of Chapter 4.

first, we introduce the miniature war game Warhammer 40K. We then motivate the digital augmentation of this game and specify the functional and non-functional requirements. Second, we describe the physical augmentation of the game field and the game objects (excluding the dice) and how we managed to develop a system that automatically and unobtrusively determines the position and orientation of game objects. Third, we report on the digital augmentation of traditional dice, realizing the seamless integration of the element of chance into the game flow. Fourth, we present the *virtualization* of the game (i.e., the virtual representation of the game with its objects, rules and flow) and how the users are supported with context-relevant information based on the data gathered by the digitally augmented physical infrastructure. Finally, we assess to what extent our digital augmentation meets the previously stated requirements and how well it complies with the design guidelines discussed in Chapter 3.

4.1 Motivation

In this section we first introduce Warhammer 40K. We then go into the motivation and goals of the digital augmentation of this game. Last, we discuss related work of augmented tabletop games.

4.1.1 Augmenting Warhammer 40K

About Warhammer 40K

Warhammer 40.000™(W40K) by Games Workshop[1] is a very popular *miniature war game*, in which two or more players engage their armies of combat units in battle, usually with the goal of eliminating the adversarial forces. The players are gathered around a battlefield (i.e., a customized tabletop with decorative elements resembling a battlefield scenario) and command their forces by physically moving the miniature war figures[2] (see Fig. 4.2).

The game is round-based and each round consists of three phases: moving, ranged combat (i.e., shooting) and close combat. Each round can easily take up to 10-20 minutes as, on the one hand, the players first carefully examine the current situation and their options before making their tactical decisions and, on the other hand, the execution of the individual

[1] www.games-workshop.com

[2] Miniature war games originated in the beginning of the 19th century, when Baron von Reisswitz developed so-called “Kriegsspiele” (war games) to train the strategic skills of Prussian officers [192].

Figure 4.2: A typical battlefield in the Warhammer 40K universe with numerous game units (soldiers and vehicles), buildings and landscape elements scattered over a large table. The players stand around the table.

phases is rather time-consuming (e.g., all units must be physically moved, distances be measured, etc.).

The game requires an element of chance, which is realized by using six-sided dice. Having decided which unit and how to attack, players must roll one or more dice and the result determines the success of the attack. Depending on the attacking and the defending units, it is not uncommon to roll tens of dice at once. In addition to that, a typical combat phase requires the players to roll the dice several times (e.g., to determine if the attacking unit hits the target, if damage is inflicted, if the defender's armor is penetrated, etc.).

There are two categories of army units that we need to distinguish (see Fig. 4.3): the first category consists of foot soldiers, meaning a single figure representing a single soldier or a figure of equivalent size and "firepower". The second category includes bigger combat units like tanks. Besides higher firepower, weapons ranges and movement distances, the main difference is that these units can usually only fire at targets within their field of vision, while foot soldiers are allowed to shoot at any target

Figure 4.3: A group of miniature war figures and a tank in the background.

around them.

To identify the characteristics and requirements of W40K, we thoroughly scrutinized the rules and played the game ourselves several times. We then observed and informally interviewed seasoned W40K players to verify our initial analysis. This also helped us to elicit further aspects that are not part of the formal rules but nonetheless contribute to the game experience. The key characteristics are summarized in Tab. 4.1, the functional and non-functional requirements in Tables 4.2 and 4.3.

Motivation and Goals of the Digital Augmentation

W40K can easily become very complex and involves several burdensome tasks for the players.

First, W40K comprises countless different units with individual characteristics and special skills (e.g., health points, selected armor and weapons), as well as many rules and corresponding exceptions.[3] Crawford matter-of-factly states that war games "are easily the most complex and demanding of all games available to the public. Their rule books read like contracts for corporate mergers and their playing times often exceed three

[3] In this paper, we focus on the fourth edition (cf. http://en.wikipedia.org/wiki/Warhammer_40,000).

Table 4.1: Characteristics of W40K.

Characteristics • Age Range: 12+ • Number of Players: two or more. During a session, no new players may enter the match. • The goal of the game is usually to eliminate adversarial forces (other scenarios are also possible, e.g., to capture a certain item or conquer a specific building). • An army consists of dozens of individual figures that inhabit the game field. Typical army sizes encompass between 20 and 60 figures, though armies with over 100 figures are not unheard of. • The game field is spatially restricted but continuous (i.e., there is no raster of discrete homogenous fields); the size and layout of the battlefield is determined before the match and may not be changed after it has commenced. • The game is turn-based; each turn can take several minutes, a complete game several hours. There is no time constraint regarding the length of a turn or a game. • The players can constantly add new units to their armies and thus to the game. This is only possible in-between games. Typically, no play objects (i.e., units) can be added during an ongoing match. After each turn, destroyed units are removed from the battlefield.

hours. Wargames have therefore proven to be very difficult to implement on the computer" [69]. Players thus spend much time on reading, both before and during the game and need to continually keep their units' data sheets up-to-date.

Second, warfare in such games very much depends on the exact location and orientation of game pieces, in order to properly assess the visibility of enemies (i.e., line-of-sight) or the range and effect of weapons. To get this information, the players must manually measure the distances using rulers (see Fig. 4.4) and apply templates for attacks that inflict damage within a certain area (see Fig. 4.5).

Figure 4.4: A player measures the distance between two units on the battlefield using a ruler.

Third, vehicles usually have a limited viewing or targeting angle (e.g., a turret on a tank can attack units within a field of vision of 180 degrees based on the current orientation of the tank). This not only necessitates knowing where a vehicle is currently located, but also how it is oriented. So far, players determine the angles manually with protractors.

Figure 4.5: A blast template for determining the blast radius of a grenade (left) and a template to simulate the affected area of a flamethrower (right).

These tasks can be time-consuming and perceived as rather annoying since they have to be executed countless times. Thus, the idea is to relieve players of such mundane tasks and allow them to focus more on strategic decisions and the social interaction with other players – which is one of the main reasons of coming together in the first place. To this end, we aim at supporting the players by providing context-relevant information and simplifying the execution of their moves. This support, however, should not compromise the traditional *look-and-feel* of the battlefield, the units or the dice.

Additionally, there are official W40K tournaments, in which many players engage each other in several consecutive battle matches. In these official games, the players often debate over issues like distances, line-of-sights and interpretation of rules. Informal discussions with tournament players revealed that it would be very beneficial to have an impartial instance that can be consulted in the case of doubt or unclarity. Interviewed players also explained that they sometimes maintain written records of the games, mostly for group discussion afterwards and for possibly adjusting and improving their strategies based on lessons learned.

Overview of the Functional and Non-Functional Requirements

Given these descriptions and issues, we identify five elements of W40K that should be part of the digital augmentation process:

- The game field and game objects: to automatically determine the position and orientation of units.
- The dice: to automatically recognize rolled results and to forward them to the background system.
- The rule system: to automatically check the validity of the players' decisions and to give them the information they require to reach a decision.
- Game session management: to enable players to stop and resume an ongoing game at any time. Additionally, the course of the game is stored for later replay.
- The data sheets: to keep up-to-date information on all units of the current game session and make them available to the players.

There are, however, several issues to be taken into consideration during the implementation:

- The integrated technology must be as invisible and unobtrusive as possible: on the one hand, the focus of the game should remain on the social interaction and the sensation from touching and moving the game objects; on the other hand, the players typically spend many hours on assembling, modeling and painting the game objects – anything that would physically alter their appearance would thus be deemed unacceptable.

- W40K uses a continuous surface (in contrast to discrete game fields), which makes locating objects much more difficult.
- Small scale miniatures: a typical W40K army consists of individual 28mm scale (approximately 1:72) miniature figures. This makes it very difficult to integrate complex technologies.
- The rule-observing system should stay in the background and only appear if appropriate. Players indicated that many disputes can be solved rather fast and through consensus. If this, however, is not the case, the players should have fast access to the impartial "system judge".
- The rule system is rather complex and consists of many exceptions.
- The number and types of available figures is subject to constant change and growth. In other words, it must be possible to easily add newly released figures to the game (not to an ongoing game though).

Tables 4.2 and 4.3 summarize the the functional and non-functional requirements, respectively.

The technical realization of functional requirements are discussed in three subsequent sections following this introductory section. Before we present the digital augmentation of W40K, though, we first discuss the related work.

4.1.2 Related Work

To our knowledge, there is currently no research on digitally augmenting miniature war games that we could compare our work to. We hence extend the focus of our discussion to other forms of electronically enhanced tabletop games. Though none of the discussed games equals W40K in terms of complexity and extendibility, they nonetheless provide a good insight into what research has been conducted in this area. In this sec-

Table 4.2: Functional requirements of W41K.

• Support players by automatically determining the position and orientation of game objects on the game field. • Support players by observing the actions taken and checking if they are in accordance with the rules. • Support players by providing them with up-to-date information about all game objects (i.e., units). • Enable players to stop and resume the game at any time and store all made moves for later replay. • Automatically determine and forward the results of dice rolls.

tion we discuss related work of augmented game environments in general, while related work relevant to technical realization is discussed in more depth in the corresponding sections.

Floerkemeier and Mattern give an example of augmenting an existing card playing game [109]. By equipping a regular card deck with RFID technology, the players can be supported through automatically counting points or by helping novice players to remember the rules (see Fig. 4.6 left). Similar to our project, the focus is on supporting the players easily and unobtrusively. A card game, however, does by far not feature the complexity of a game like Warhammer 40K: the number of play objects (i.e., cards) is completely restricted, these objects do not change their state during the game, there are considerably less rules and the game field is comparably simple (five areas where cards can be placed).

Magerkurth et al. developed STARS [210,211], a tabletop gaming platform[4] based on the InteracTable[5], a touch-sensitive plasma display (see Fig. 4.6 right). The system also enables the identification of game objects as well as their position and orientation using visual recognition. Hence, this system requires the installation and calibration of the video equipment and the game objects must feature significantly distinctive shapes in

[4]Based on this platform, they implemented games like "STARS Monopoly" or "KnightMage" [210].
[5]The InteracTable is a part of the Roomware project [270].

Table 4.3: Non-functional requirements of W41K.

- The integrated technology should be completely unobtrusive. The game should still be playable if the technology is switched off or malfunctioning.
- The focus should always be on the ongoing game and the surrounding social interaction. Thus, interfaces should remain in the background until required: players should have continuous access to game-related information in situ and on demand. Equally, interfaces should provide them with means to make decisions anytime.
- While all non-functional requirements known from software engineering are important, distinguished attention should be paid to reliability, efficiency and usability: players should be supported easily and efficiently, the augmentation should improve their play experience and not diminish it. In this respect, the environment should also be as maintenance-free as possible.
- Players must always be in control of the environment: they should be able to get all information, modify play objects and bend or change rules – just as the traditional non-augmented version enables them to. The system must thus offer the means to add, remove and manipulate play objects as well as to adjust the infrastructure.
- The number and types of available figures is subject to constant change and growth. Players must be enabled to easily add and remove game figures.

order to avoid erroneous detection. The system has moreover not been tested with decorative elements (i.e., it only operates on a flat table), which might reduce the visual recognition capabilities.

The same criticism applies to TARBoard, "a tangible augmented reality system designed for table-top game environments" presented by Lee et al. [191]. The system allows video-based tracking of tangible objects on

Figure 4.6: Smart playing cards [109] (left) and the STARS platform [209] (right).

a glass table. TARBoard shares the common problems of video analysis: the camera must get a clear picture of the scenery at all times and possibly requires video equipment calibration (see Fig. 4.7). Furthermore, video analysis requires much computational power and can be error-prone if a game set consisting of tens or hundreds of small, similar-looking or even identical figures.

Figure 4.7: The TARBoard installation [191].

In [343, 344] Tse et al. show how to exploit a multi-user touch tabletop and speech recognition as input modes for gaming applications (see Fig. 4.8). They use the Mitsubishi DiamondTouch technology [82], which is based on capacitive coupling through the human body. The multi-touch surface also requires a projector for displaying. Though the system works quite well, it suffers from the drawbacks of using a projector (i.e., it must be mounted and calibrated and is not unobtrusive) and requires players to have a constant physical connection to transmitter and receiver.

Figure 4.8: Using the Diamond Touch technology for games [343].

Another category of augmented tabletop applications are games that employ head-mounted or similar devices [28, 174] to project a virtual layer over the real world. These games overlay the real world with virtually projected objects (see Fig. 4.9). Most prominent representatives are Tankwar [250], Hybrid AR Worms [249] and Battleboard 3D [19]. Further examples are presented in [257, 273, 345].

Figure 4.9: The augmented reality tabletop game Tankwar [250].

Although this hybrid approach will probably play a major role in the gaming industry in the future, there are three disadvantages: first, since the game is mostly, if not totally, simulated, the players do not experience the physical sensation that comes from using tangible user interfaces. Second, the social component is not as strong as in traditional tabletop games since players rather focus on projected virtual objects and effects. Third, the players are required to wear devices that create the virtual world, which results in diminished physical stimuli and social interaction, even if these devices become handier and smaller.

4.2 Physical Augmentation of Game Field and Objects

In this section, we present how we digitally augmented the physical game pieces. The goals were twofold: to make each game object uniquely identifiable and to determine the position and orientation of the game objects on the battlefield. To this end, we decided to employ RFID technology. The reasons for and the benefits of this approach are discussed now.

4.2.1 Using RFID to Identify and Track Objects

To provide the players with the aforementioned services (i.e., the functional requirements), it is essential to automatically determine where each unit is located. To this end, we need an infrastructure that enables the automatic and unobtrusive identification and tracking of game objects. The positioning information must be very accurate (within the range of millimeters). This information will then be processed and adequately made available through user interfaces (see Section 4.4).

We chose passive RFID technology to digitally augment the game objects since this technology has several advantages for this setting:

- The technology can be hidden and, thus, works unobtrusively (small footprint of the RFID tags, both in size and weight; the antennas can be smoothly integrated into the environment) (see Fig. 4.10).
- The objects are almost maintenance-free (except for exchanging damaged RFID tags).
- The players do not have to calibrate the equipment.
- Each game object is uniquely and unambiguously identifiable.
- Costs are low by comparison (standard RFID equipment is continuously falling in price).
- No line-of-sight is required.

In the context of a miniature war game, this particularly means that the objects can be moved freely on the surface, even if there are decorative elements.

Figure 4.10: The RFID transponders used (top left) and the (small) RFID antenna we used (top right). In the middle there are two tagged game figures and at the bottom a large vehicle with two transponders.

The calculation can be done by a computer with average computational power, which means that the computer employed can be rather small and thus also be integrated into the environment. In addition to the unambiguous identification, we can scan many figures simultaneously. Since the antennas induce three-dimensional fields, it is also possible to have game elements on the table that make the game map uneven or even represent "hovering" units (see Fig. 4.11 left) or taller buildings (e.g., hills, houses, etc.; see Fig. 4.11 center and right).

Figure 4.11: Objects not directly on the ground make it difficult for some position recognition techniques to work (left). Landscape elements (centre) do not work with sensing techniques that require a flat surface and/or line-of-sight. Video recognition does not work with many objects that look very similar, i.e., objects that do not have distinctive shapes (right).

The main disadvantage of RFID technology, however, is that it was simply not meant to be used for the precise locating of objects, but solely for identification. Additionally, RFID technology is rather sensitive and its performance depends on several factors. Among the most critical are (also cf. [99, 107, 108]):

- Magnetic, metallic or liquid components in range,
- Form factors of tags and reader and
- Power (field strength) of the reader.

Despite these difficulties, we managed to develop an RFID-based infrastructure that is capable of automatically determining where game objects are located within a few millimeters. Before we present our approach, we discuss related work.

4.2.2 Related Work

Smart Shelves

The idea of employing RFID technology for detecting tagged objects on surfaces such as shelves or tables has been investigated for many years now (e.g., the smart shelf project at TecO[6] [75]) and has reached a certain level of maturity. In retailing, for example, there are already existing solutions available that keep track of goods placed on shelves in real-time (e.g., [17, 323] or Metro Future Store[7]).

There are two central assumptions in such scenarios: first, for these applications it suffices to have one antenna to cover an area and read all goods within read range; second, all objects are single-tagged (i.e., equipped with one single RFID for identification). The main purpose of this research is the higher transparency and optimization of replenishment and storage management in retail stores. Determining the exact position and orientation of the goods, however, is irrelevant.

Multi-tagged Objects

Although some research on multi-tagging has been conducted in the past, there is little or no overlap with our approach or goals. Bolotnyy and Robins investigate multi-tag systems and their benefits in [47]. They define three types of multi-tagging:

- Redundant Tags (two or more independent tags carrying identical information),
- Dual-Tags (two tags connected to each other and having one or two antennas; they can be further subdivided depending whether memory is in some way shared or not) and
- N-Tags (n tags connected to each other and having one or more antennas).

Their goal is the improvement of availability, reliability and durability of RFID systems, especially in security-related applications. Our approach differs from this classification since we employ n tags per object, but each tag has a unique ID and they are not connected to each other.

[6] www.teco.edu/projects/smartshelf/

[7] www.future-store.org

The approach of equipping objects with more than one tag has also been applied in [238]: they use multi-tagging to determine the direction in which a person is going. The usage of multiple tags in this case, however, is simply for the purpose of redundancy (i.e., guaranteeing that a person is tracked with a high probability).

Bohn und Mattern [46] use multiple tags, but instead of having fixed readers in the environment scanning moving objects, the environment is tagged with numerous tags and objects are equipped with mobile readers, thus, reversing the traditional concept of employing readers and tags.

Locating Objects Using RFID Technology

Typical RFID-based applications only require the tag ID. For these applications it is typically irrelevant where the tag or the object is actually positioned. There are, however, other applications that must not only be aware of a given object in read range, but furthermore know its exact location. In addition to that, it might also be interesting (or sometimes even necessary) to know how the object is oriented in a two- or three-dimensional space, i.e., which direction a particular part of the object is pointed towards.

There are a few existing approaches using RFID technology for locating objects. Wilson et al. present a technique based on passive RFID technology to locate stationary objects and estimate the speed of mobile objects [366]. Their focus, however, is on larger objects and the accuracy of their measurements is in the range of tens of centimeters, which is by far not precise enough for tabletop games. Similarly, Ni et al. propose a system based on active RFID technology [244]. They are able to locate objects in a three-dimensional space within the range of one cubic meter, rendering this approach equally unsuitable for our application.

Other Positioning and Orientation Technologies

There are other technologies to determine the position and orientation of an object in two- or three-dimensional spaces. These are briefly summarized.

Ultra-wideband (UWB) technology is capable of tracking an object in a three-dimensional space within tens of centimeters (e.g., Ubisense[8]).

[8] www.ubisense.net

Though this level of preciseness might be good enough for other applications, it does not meet the requirement of our application. Furthermore, this technology requires installing and calibrating a (rather expensive) sensor infrastructure. Besides, UWB tags are too big for small game pieces.

Another possible technology is ultrasound (e.g., [83, 298]). Systems such as Active Bat[9] [358] allow the pinpointing of an object within approximately three centimeters, which makes this system one of the most accurate currently available on the market. The bats are slightly smaller than UWB tags, but nonetheless still too big and thus not suitable for our purpose. Last but not least, the costs of an ultrasound infrastructure are also very high.

Krohn et al. present a relative location system that also utilizes ultrasound [134,179]. Their approach, however, does not require an infrastructure, but uses single devices equipped with transmitters that can determine the position and orientation autonomously. The decisive advantage of this approach (i.e., autonomy of devices, no infrastructure) is obviously also the biggest disadvantage: the devices are relatively big and require both an energy source and maintenance.

Schmidt et al. present a load sensing system that allows locating objects on a table [304]. However, using this system does not work in our scenario for two reasons: on the one hand, the objects are too lightweight for the table to sense them (e.g., plastic figures); on the other hand, the surface might not be totally flat, i.e., it might be covered with several decoration components on which the objects are placed.

Decorative elements and buildings also foil the employment of infrared technology (e.g., in [214]), since the line-of-sight between an object and the sensor might be interrupted (also see Fig. 4.11).

The last locating technique is video recognition. This approach, as discussed before, requires the attachment and calibration of a video camera, making this approach comparatively obtrusive. Furthermore, video analysis can be rather error-prone, depending on the concrete video data to be analyzed: a game set consisting of tens or hundreds of small, similar-looking figures is a serious challenge.

Apparently, there is no perfect technology for locating small, lightweight and poorly distinguishable objects on a tabletop that is both unobtrusive

[9] www.cl.cam.ac.uk/Research/DTG/research/wiki/BatSystem

and precise enough. The findings are summarized in Tab. 4.4.

It seems that RFID technology would be ideal for the reasons outlined before, but it is not very suitable for accurately locating objects. There have been a few approaches to locating game figures using RFID technology (e.g., [263]); in these cases, however, the game field typically consists of discrete fields – as opposed to one continuous game field –, which simplifies the locating process tremendously (i.e., each discrete field is equipped with one antenna).

Table 4.4: Overview of the disadvantages of locating techniques for objects on tabletop surfaces.

Technology / Approach	**Disadvantages**
Ultra-wideband (UWB)	• Not precise enough • Fixed infrastructure • Rather big tags • Tags require batteries • Requires calibration • Expensive
Ultrasound (infrastructure)	• Fixed infrastructure • Tags too big • Tags require batteries • Very expensive
Ultrasound (no infrastructure)	• Tags too big • Tags require batteries
Load sensing	• Cannot identify objects • Not sensitive enough for lightweight objects • Requires totally even surface
Infrared technology	• Requires line-of-sight
Visual recognition	• Cannot identify similar-looking or identical objects • Requires calibration • Requires computing power
Touch technology	• Requires calibration • Expensive • With some technologies, the detection is based on capacitive coupling (through the human body)

We managed to develop an RFID-based system that is capable of tracking objects within a few millimeters on a continuous game field. To get there, however, we had to experiment quite a bit with RFID technology. We briefly report on our initial approach, which yielded an accuracy of a few centimeters. While this is a comparably fair result for locating objects in general, it is not precise enough for tabletop games like W40K. We thus had to come up with another approach, which is presented and discussed subsequently.

4.2.3 First Approach: Antenna Grid

Our initial idea was to increase the number of antennas in order to exploit the information gained from the overlapping read ranges of the antennas. The general principle is shown in Fig. 4.12. The circles around the antennas symbolize their read range given a specific tag (the read range inter alia varies with the tag model and was determined empirically by measuring the field strength at different distances from the antenna). This modified version of the "cell-of-origin" approach allowed us to determine the position of a tag as follows: the entire scanning area was represented as a virtual grid consisting of individual 1x1mm blocks. When an antenna reads a given tag, the grid increases an internal counter for each virtual block (the small white squares in Fig. 4.12) that is in range of this particular antenna. After completing the read cycles, the tag is most likely in (one of) the virtual blocks with the highest counters.

In Fig. 4.12, the dark area in the center marks the area where the tag, represented by the small black square, must be located. It is not possible to determine where exactly it is within this area. Therefore, the goal is to minimize this "area of uncertainty", which depends on both number and size of the read range circles (i.e., the antennas) and the arrangement of the antennas.

To counter some technical deficiencies of the currently available equipment and the general problem of interference that RFID technology has to cope with (e.g., tags might be read only intermittently or not at all, environmental interference such as metallic objects or people, etc.), we varied the hardware configuration and experimented with the following components:

- The arrangement of the antennas,
- The RFID antenna model,
- The RFID tag model and
- The read range of the employed reader.

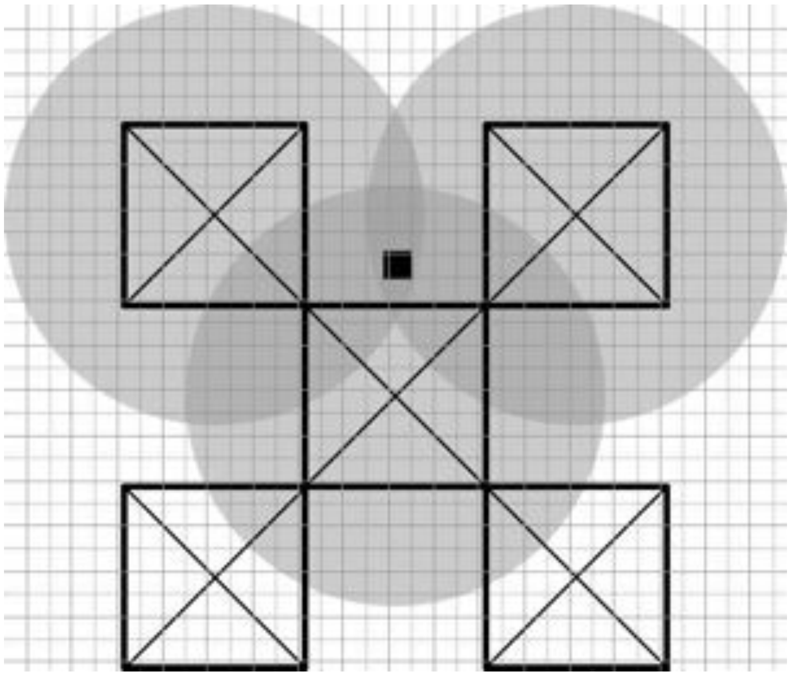


Figure 4.12: Multi-antenna approach using multiple antennas organized in a chessboard pattern (big squares with thick black lines) to determine the position of a tag (small black square) by measuring the overlapping areas of the read ranges (grey circles). The small white squares represent the virtual grid.

An automated test environment was used to investigate how the variation of these components influences the accuracy of the readings, using two antenna models (FEIG[10] ID ISC.ANT 100/100 and FEIG ID ISC.ANT 40/30) and small square-shaped RFID tags (Ario 370-S SM[11]) with an edge length of 1.5cm (see Fig. 4.10). After measuring the range in which each tag could be read by the reader, eight antennas were arranged in a chessboard pattern (see Fig. 4.13) and a number of objects were tagged with several RFID tags and placed onto the field.

A single reader (FEIG ID ISC.MR 101-A) was connected to the antennas via a multiplexer (FEIG ISC.ANT.MUX 8), which sequentially energized the individual antennas to return the tags currently in read range. After several read cycles (one read cycle took approximately 2-3 seconds), which helped to avoid erroneous read data, our system determined the highest probability for each scanned tag on the board. Based on this data and the known shape and size of each object, the estimated position and

[10]www.feig.de

[11]www.tagsysrfid.com

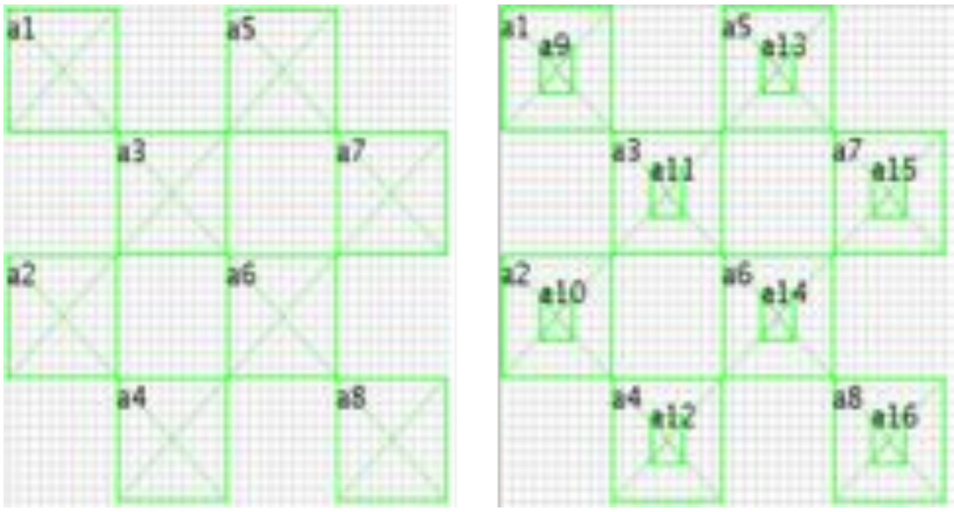


Figure 4.13: The two different antenna arrangements. The arrangement on the left consists of eight 10x10cm antennas, while the one on the right uses eight additional antennas that are considerably smaller (3x4cm) and placed on top of the bigger antennas.

orientation of the game figures was then calculated and displayed.

Table 4.5: The mean deviation of the position of the multi-tagged object after 50 test reads for each antenna setting. The values are listed in millimeters (e.g., a value of 33.86mm means the estimated position of the object is off by 3.4cm compared to the actual position).

Setting	**X-Axis**	**Y-Axis**
Antenna grid with 8 big antennas (10x10cm)	33.86mm	37.85mm
Antenna grid with 8 big (10x10cm) and 8 small antennas (3x4cm)	35.34mm	41.56mm

The results showed that the best estimates of the scanned tags were within a deviation of 3-4cm (see Tab. 4.5), rendering this approach insufficient for applications like miniature war games that require a resolution of less than one centimeter.

4.2.4 Second Approach: Moveable Antenna

While the initial approach showed that it is principally possible to use off-the-shelf RFID hardware for determining the position of objects, increasing the accuracy of a multi-antenna approach is difficult: in order to improve results, the antennas must be smaller and/or arranged more closely. Both options, however, are not practically feasible. On the one hand, placing the antennas more closely together contradicts a natural feature of RF fields: if the antennas are too close together, the field induced by one antenna will be inexorably extended by the coils in the adjacent antennas (i.e., an antenna might then discover a tag that is actually near the coil of another antenna). Using smaller antennas, on the other hand, would not only require a lot more antennas (and thus also more readers and multiplexers to power them) to cover an area of the same size, but also limit overall detection rates due to the much smaller read ranges of the individual antennas.

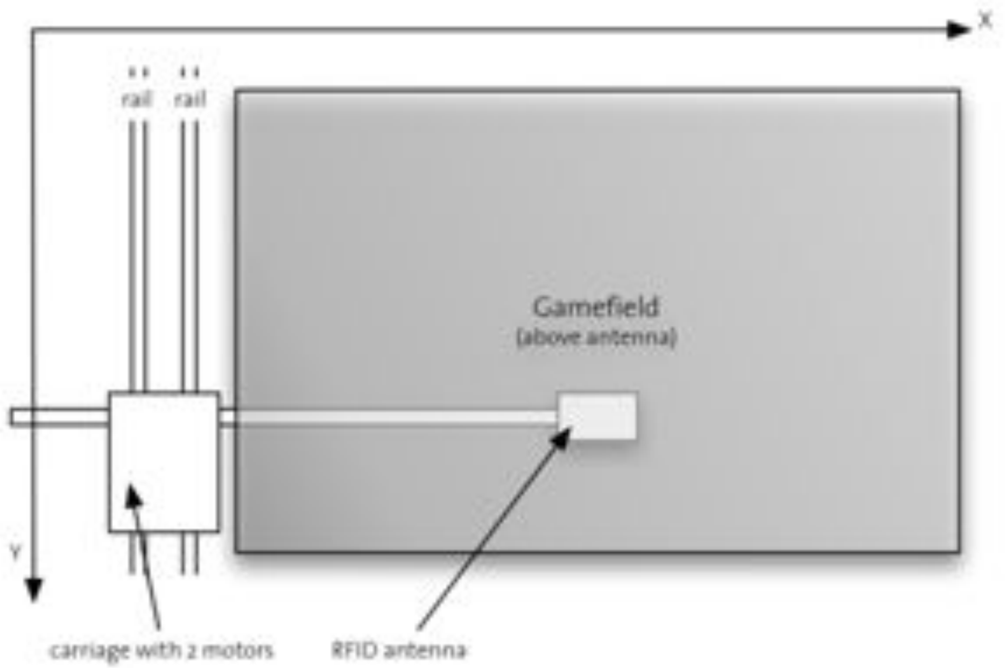


Figure 4.14: A sketch of the revised approach: one RFID antenna is moved across the game field.

Despite the fair but for our application nonetheless insufficient accuracy, we decided to continue using RFID technology for its many advantages. We thus tried a different approach: instead of using many antennas in an arrangement, we used only one moveable antenna that would scan the entire area, continuously reading transponders in range while being moved underneath the tabletop surface (see Fig. 4.14).

The read tags, combined with the current location of the antenna, could then be used for locating the individual RFID tags. In contrast to the

Figure 4.15: The robot moves the carriage with the antenna (indicated by the white arrow) using an orthogonal track system.

multi-antenna approach, this solution has the obvious drawback of requiring more time to cover the same area. However, since tabletop games like W40K do not require real-time locating, a certain period of scan time might be perfectly acceptable.

Figure 4.16: The NXT control unit (left) and the test environment with the robot (right). On the cardboard surface are two test objects with RFID transponders attached to each of their corners.

Using a LEGO MindStorms NXT robotic set, we constructed a test environment in which a robot-controlled carriage attached to an orthogonally arranged track system moves an RFID antenna (again FEIG ID ISC.ANT 40/30) underneath the game field (see Figures 4.15 and 4.16). The size of our test area was 40x40cm. The carriage moves in a "zigzag" fashion across the area (i.e., it moves along the x-axis to the end of the surface, advances 1cm on the y-axis, moves back along the x-axis and so on; also see Fig. 4.20).

Since the carriage was moved by a cogwheel on a cogged track (see Fig. 4.15), it was not possible to directly indicate the speed in a distance-time relation (e.g., in cm/s) but only in degrees determined by the rotation of the motor. The motor could be controlled in ten steps (10-100% of the maximal power output), resulting in different velocities of the carriage (see Fig. 4.17).

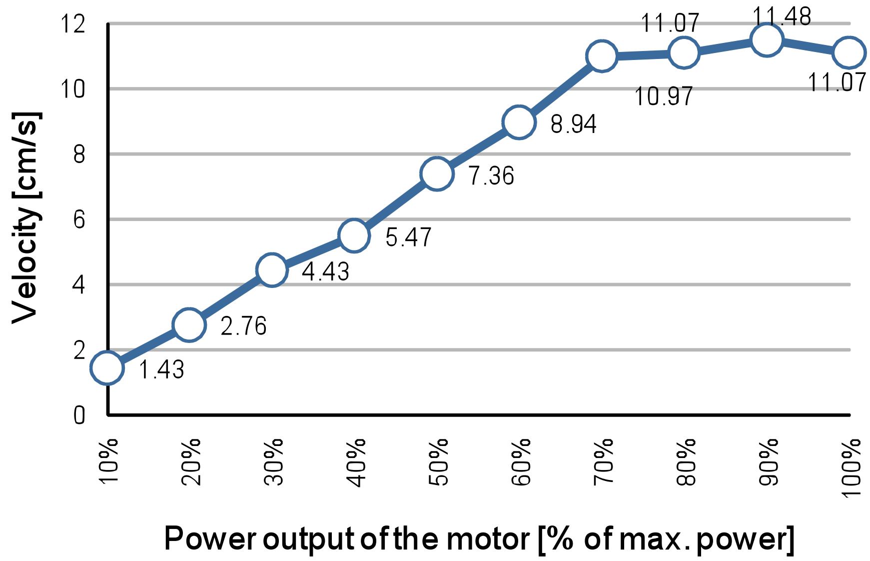


Figure 4.17: The velocity of the carriage in dependence on the power output of the motor.

Another important factor was the number of possible read cycles per second. This factor severely depends on the number of tags being read in one cycle, as each cycle is not completed until tags in read range have been identified. Tab. 4.6 summarizes the required time per read cycle against the number of read tags.

The different velocities of the carriage combined with the fact that we could energize the antenna at a rate of 4-5Hz (given an average read cycle time of 200-250ms), determined the number of possible measurements against the motor output (see Fig. 4.18).

We began our test series by placing two RFID transponders at designated X/Y coordinates (in centimeters) on the test surface: they were positioned at 20/10 and 30/30, respectively, with the lower left corner being the point of origin. Starting from the zero-point, the carriage would then

Table 4.6: The time required for one read cycle against the number of tags in read range. The values are based on a test series of ten measurements for each number of tags. The measured time varies as it depends on the number of collisions during the reading of the tag IDs (for more details on tag collisions, see [107]).

Number of tags in read range	**Required time** $[ms]$ **Range**	**Average**
0 Tag	136-161	154
1 Tag	173-200	189
2 Tags	177-201	195
4 Tags	188-211	205
6 Tags	229-251	244
8 Tags	439-461	455

run over the whole area with a velocity of ca. 4.4$^{cm}/_{s}$ (this initial value was chosen to guarantee approximately one read cycle per cm). We ran the test series five times. Tab. 4.7 summarizes the results.

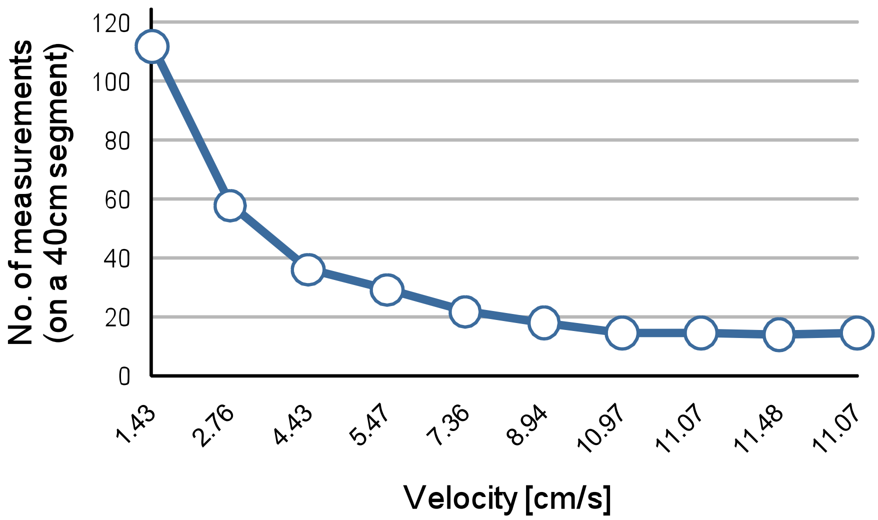


Figure 4.18: The number of possible measurements in relation to the velocity.

The average deviation was 1-2mm. The measurements were extremely accurate, exceeding our expectations by far: our system could in most cases exactly pinpoint the transponders.

It is worth noticing that the deviation on the y-axis was constant in each case, but there is a simple explanation for this: while the antenna con-

Table 4.7: Results for the 20/10 coordinates (left) and the 30/30 coordinates (right) at a velocity of 4.4 cm/s. All values in centimeters.

	Measurements of 20/10		**Measurements of 30/30**	
	x	y	x	y
1	20.1	9.8	30.0	29.9
2	20.0	9.8	30.1	29.9
3	20.0	9.8	30.0	29.9
4	20.1	9.8	30.0	29.9
5	20.1	9.8	30.2	29.9

stantly moved along the x-axis (which elucidated the varying x-values), the y-axis was physically held in place and thus its deviation was invariable (also cf. Fig. 4.14).

Unfortunately, regardless of this almost perfect accuracy, there was a severe downside: each test round took approximately 13 minutes (ca. 20 seconds for scanning the x-axis at a velocity of 4.4 cm/s – including the time required for moving the carriage back and aligning it with the y-axis – multiplied by 40 rows; see Fig. 4.20 (a)). The obvious way to counter this was to increase the speed. The problem, however, was that increasing the speed of the carriage yielded less accuracy due to fewer measurements (see Fig. 4.18). We hence had to find a trade-off between accuracy and scan time.

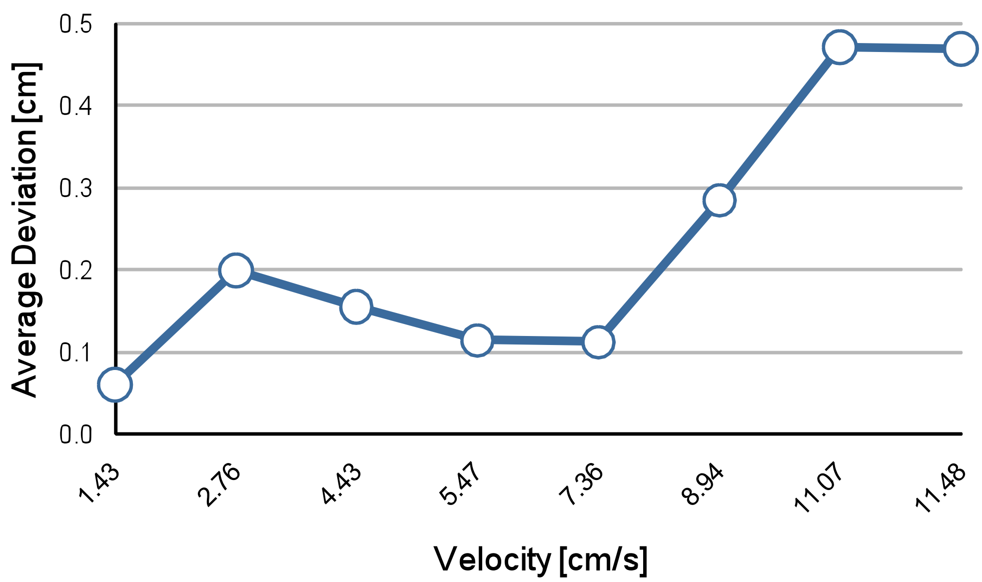


Figure 4.19: The average deviation against the velocity.

To this end, we repeated the previous test series with different velocities and calculated the mean deviation for each velocity. The results are summarized in Fig. 4.19. In general, slower speeds yielded better accuracy, which is not surprising. The error increased with higher speeds and reached some 5 millimeters at velocities of around $11\,\mathrm{cm}/\mathrm{s}$. The minor exceptions at velocities of $2.76\,\mathrm{cm}/\mathrm{s}$ and $4.43\,\mathrm{cm}/\mathrm{s}$ seemed to result from a natural oscillation of the motor when rotating at lower frequencies. The trade-off seemed to be at a velocity of $7.36\,\mathrm{cm}/\mathrm{s}$, which corresponded to a power output of 50%.

Moving the carriage at the trade-off speed of $7.36\,\mathrm{cm}/\mathrm{s}$ along the x-axis and at full speed on its way back reduced the time required to approximately 9 minutes – which even without real-time requirements might render this approach infeasible. Therefore, our main objective was to further – preferably considerably – decrease the time required for scanning the area. We came up with three possible approaches:

- Using a faster and less oscillating carriage to move the RFID antenna. This option, however, was not further pursued.
- Moving the carriage at high speed until a tag is read; the carriage would then slow down to enable a more thorough scan of this area and increase the speed again afterwards (see Fig. 4.20 (c) and (d) as well as Tab. 4.8).
- Reducing the scan area by splitting it into smaller segments with each segment being equipped with its own antenna (see Fig. 4.21).

Varying the speed of the carriage seemed an obvious approach: moving the carriage at high speed ($11\,\mathrm{cm}/\mathrm{s}$) and only slow it down (e.g., to $7.36\,\mathrm{cm}/\mathrm{s}$) when tags are detected (otherwise there are no objects and time can be saved; see Fig. 4.20 (c)). If we moreover consider the read range of the RFID antenna, we can also skip one or more rows on the y-axis and only scan them if an RFID transponder is detected (see Fig. 4.20 (d)). This approach certainly depends on the number of tags on the surface: the more tags there are, the less is gained by this approach. Generally, the scan time can be decreased by an average of 30-60%, resulting in a total scan time of approximately 4 minutes for a 40x40cm area. Moving the carriage at higher speed, however, again diminishes accuracy (see Tab. 4.8).

The second idea, that is splitting the area into smaller, individually scanned segments can also significantly contribute to decreasing the scan

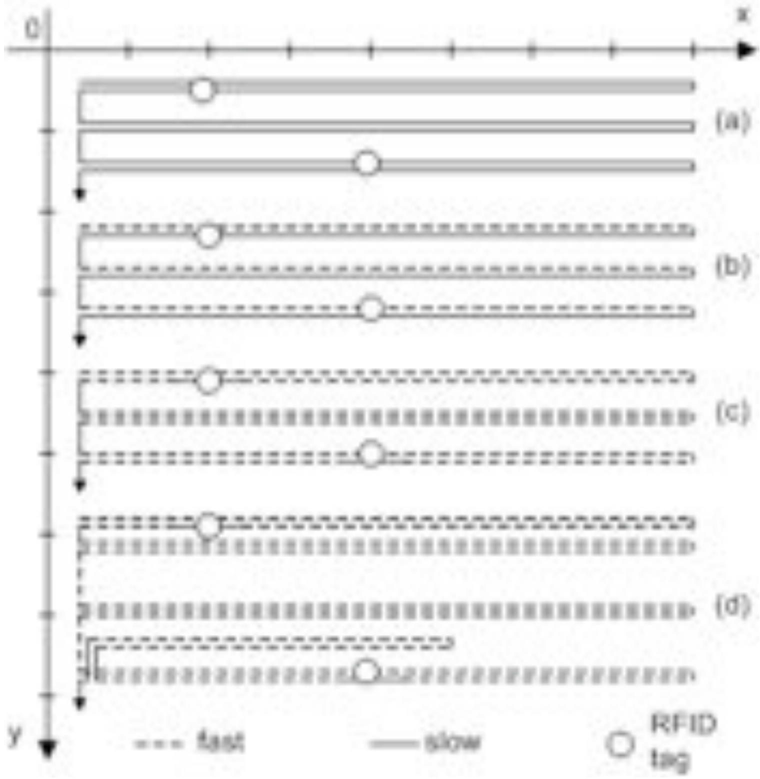


Figure 4.20: Moving the carriage at different velocities and in different ways (sorted by required scan time – high (worst) to low (best)). The modi (a)-(c) vary in speed, but scan every row along the y-axis. The last modus (d) omits several rows and only re-scans them if a tag is read in one of the adjacent rows.

Table 4.8: Modifications for the 40x40 centimeters field.

Modification	**Time required** [min]	**Deviation** [mm]
Variant a	11	2
Variant b	9	3
Variant c	7	3
Variant d (slower)	6	2
Variant d (faster)	4	4

time. If we reduced the area to 20x20cm, the time required would decrease by approximately 75%. This, on the other hand, would entail a correlative increase in terms of antennas (see Fig. 4.21). While this approach can decrease the time significantly, it does not scale indefinitely. The size is naturally constrained by the read ranges of the antennas: as pointed out before, if the antennas are too close together, the field induced by one antenna will be inexorably extended by the coils in the adjacent antennas.

Thus, the segments must be big enough to have sufficient space between all antennas: it is recommendable to not shrink the segments smaller than 10x10 centimeters – at least, with an antenna of 3x4 centimeters.

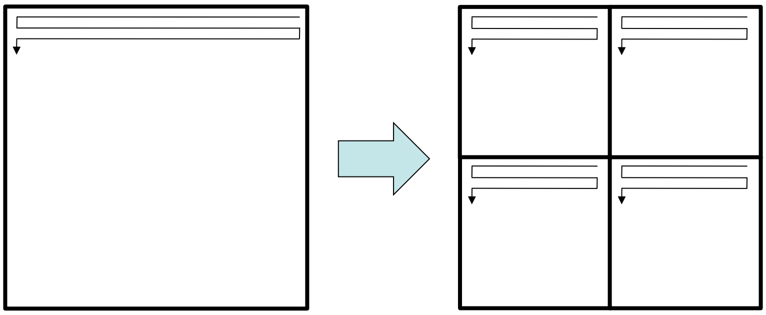


Figure 4.21: Splitting a larger segment into smaller ones to decrease the scan time. The factor of decrease directly correlates with the number of antennas.

These two approaches combined can significantly decrease the scan time: using 20x20cm segments and the "smart" carriage movement (see Fig. 4.20 (d)), the average scan time was approximately one minute, which is more than enough for W40K and probably many other tabletop games. To even further minimize the scan time, we would have to optimize the hardware itself (i.e., the first of the three aforementioned approaches).

4.3 Physically Augmenting Traditional Dice

In this section we present how we digitally augmented traditional dice to seamlessly integrate them into our gaming application. Similar to the game infrastructure and objects, the augmentation of the dice should support users in an unobtrusive fashion, i.e., the dice should be enhanced in such a way that players ideally do not even notice this modification.

Based on this general requirement, we infer three main goals for augmented dice:

- Rolling augmented dice must feel the same as rolling traditional dice.
- Augmented dice must still be usable in the "old-fashioned" way if the technology is switched off.

- The detection system must be hidden and unobtrusive.

As before, we chose RFID technology to achieve this. Before we present the technical realization, we discuss existing approaches and related work and outline why RFID technology is a very suitable means.

4.3.1 Possible Approaches and Related Work

There are several possibilities for implementing an augmented die, i.e., automatically detecting the result of a roll. Since we focus on digitally augmenting physical dice, approaches that rely on a virtual realization of dice (i.e., an application or device simply displaying a result, e.g., [207]) are not an option as they would not sustain the traditional *look-and-feel*.

Eriksson et al. [93] present an overview of different approaches on how to realize an automatic recognition of the eyes of a rolled die. They can be categorized as follows:

- A *visual approach* could use a photo scanner as a (see-through) dice table, with a piezoelectric or electrets microphone on the glass. The microphone would then detect when dice have been rolled and initiate the scanning process. Image recognition could identify the sides of the dice facing down and infer the corresponding values on top. Instead of a scanner, a camera could also be used. To aid in image recognition, the individual dots or numbers on each side of a die could be painted with a UV- or IR-reflecting color.

- An *internal sensors approach* would integrate a small processor, an accelerometer or small low-power ball switches, a transmitter and a power source into the die. The accelerometer would be used to detect when the die has been rolled and read its orientation. The transmitter would then be awakened from sleep mode and send the detected orientation to a receiver. Power would come from batteries or alternatively from harvesting the motion of the die. Instead of using accelerometers, direct contact to a metallic surface could be detected and, depending on different resistors connected to each side, the current side facing the table be identified.

- In the *external sensors approach*, Eriksson et al. suggest to use RFID tags on each side of the die and roll it on a reader antenna. In order to prevent the readout of the tag on top, an interfering metallic core is to be introduced in the center of the die.

The main advantage of visual recognition and internal sensors is, if properly designed and implemented, perfect recognition rates. Acceleration sensors, for example, are very accurate nowadays and allow for recognition rates of 100% in the case of six-sided dice (e.g., [178, 335]).

Rekimoto and Sciammarella present ToolStone, a small cube-like input device with the size of 2.5x4x5cm that uses integrated coils to determine orientation and position of the device [276]. This approach is very interesting since it does not require an internal power source. The necessary energy is provided by a WACOM tablet[12] emitting magneto-electric signals (the coils with a specific resonance parameter respond to this signal). Similar to RFID technology, such a WACOM tablet could be well integrated into the environment.

Table 4.9: Advantages and disadvantages of different approaches for building augmented dice.

Criterion	**Visual approach**	**Internal sensors**	**External sensors**
Size of rolling area	limited	unlimited	limited
Maintenance of die	n/a	batteries, damaged hardware	n/a
Configuration and/or calibration required	yes	possibly	n/a
Robustness of die	very high	low	high
Size of die	small	large	small
Costs of one die	very low	high	low

However, internal sensors are ineligible for several reasons: they are rather big and not consistent with the *look-and-feel* of traditional dice; they require constant maintenance (e.g., exchanging the batteries) and possibly calibration; and they are rather frail and expensive.

The second approach, visual recognition, is also capable of perfect recognition rates using a high-resolution camera or scanner and image recognition software. This approach furthermore has the advantage that

[12] www.wacom.com

the dice do not need to be modified (except, maybe, for some reflective coating of the dots). However, visual recognition is also not suitable since the system is comparably obtrusive (i.e., either a camera above the dice ground or an integrated scanner with a glass surface is required) and typically requires calibration.

This leaves external sensors: their only drawback, which is also shared by visual recognition, is the potentially limited size of the dicing ground. We thus considered the advantages to outweigh this one limitation and decided to explore the use of external sensors in our system.

Tab. 4.9 summarizes the advantages and disadvantages of each approach.

4.3.2 Using RFID for Dice Rolls

Using RFID technology for realizing augmented dice has a number of advantages compared to other technologies, which becomes apparent when examining the requirements of augmented dice as discussed above: first, rolling an augmented die must feel the same as rolling a traditional die; second, an augmented die should still be usable in the "old-fashioned" way if the technology is switched off or inoperable; third, the detection system that automatically reads the rolled result should be hidden and operate unobtrusively; fourth, the system should moreover be easy to use, i.e., the user should not be burdened with configuration, calibration or maintenance tasks.

The basic idea of using RFID technology for determining the die side currently facing upwards is quite intelligible: we add RFID tags to each side of a traditional six-sided die (D6) and embed an RFID antenna in the table surface. By detecting the tag that comes to rest on the antenna, we know the side that is facing down and can thus infer the side of the die that is currently facing up. This information can then be fed into the game system, where it might be displayed on a screen or actually trigger a specific action.

The problem, though, is that RFID technology was not designed for this: as discussed before, the main purpose is to detect and identify items in read range of an antenna. In our case, however, we do not want to read any tags except for one – the one at the bottom of the die.

One option would be to dynamically lower the reader field strength until a single tag remains (hopefully the one at the bottom), another to measure the individual field strength reflected from each tag and assume that the strongest signal comes from the bottom tag. Unfortunately, RFID readers that support these options are rather bulky and very expensive, rendering their usage suboptimal for entertainment appliances.

We thus investigated if we could adjust the RFID equipment in such a way that only a single tag would be read. This is discussed now.

4.3.3 Technical Realization

Initial Approach

To ensure that only a single tag would be read, we initially investigated the use of metallic shielding on the inside of the die to limit the signal strength from all tags but the bottom one. Tags were mounted on the inside and insulated via spacers from an inner aluminum-lined shielding cube (see Figures 4.22 and 4.23). The evaluation of this approach – we rolled the dice over 3700 times –, however, yielded only 80% recognition rate even under ideal conditions.

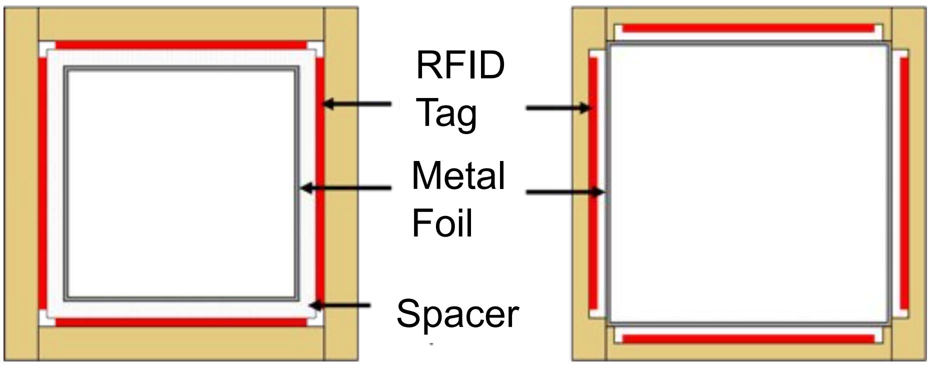


Figure 4.22: Overview of the initial approach: the RFID tags are attached to the inner sides of the die hull. To ensure that only the bottom tag is recognized, metallic shielding is introduced. The left die additionally features a spacer between tag and metal foil.

In most cases, the antenna recognized more than one tag, making it difficult to infer with certainty which side was being read. As the tags we used were rather big (i.e., 4x4cm and 2x1cm, respectively) and since the read range of an RFID tag is proportional to the size of its antenna coil, we concluded that smaller tags would yield much better results. In addition to that, smaller tags would also allow for a smaller form factor than our initial prototypes (see Fig. 4.23).

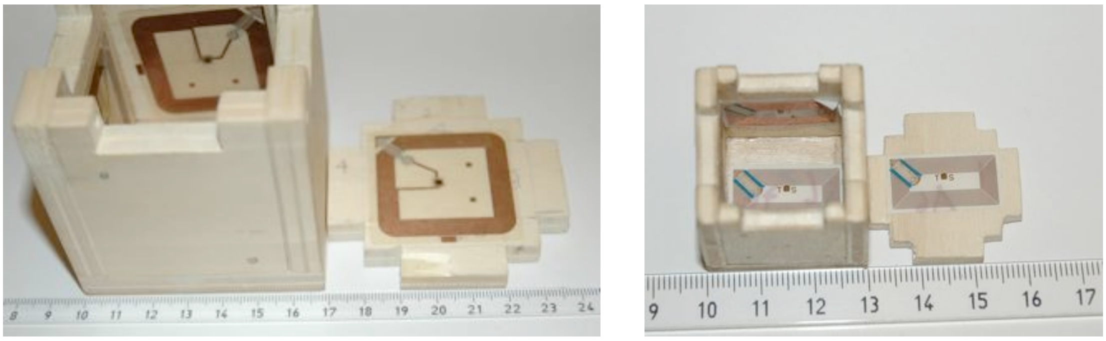


Figure 4.23: The first two prototypes: the big die (left) was equipped with 4x4cm tags, the small one (right) with 2x1cm tags.

Revised Approach

We began work on the next version of our augmented dice using the newly available Ario 370-S SDM tags, which feature a size of only 8.9mm in diameter and very short read ranges. Consequently, we were able to move tags much closer together than before and thus reduce the physical dimensions of the dice. As with our previous version, only standard off-the-shelf HF RFID components were used: a FEIG ID ISC.MR101 mid-range reader, a FEIG ID ISC.ANT100, a 10x10 cm antenna and the aforementioned tags. The basic recognition principle remained unaltered: by ensuring that only the tag at the bottom of the die is detected, we can unambiguously infer which face of the die is on top.

While the read range of the new tags was now much lower, it turned out to be still too high when simply placed directly on the die surface – more than one tag was detected. As before, our idea thus was to reduce the read range with the help of metallic insulators. We successively constructed three 30mm dice, followed by one 16mm die, all made of spruce wood, with each new die generation iteratively evolving from the previous. Each prototype was subject to an extensive test series similar to the one before to evaluate its performance.

In the first 30mm prototype (see Fig. 4.24 left and Tab. 4.10) we inserted aluminum foil cylinders into circular holes of 7mm depth and used wooden spacers to separate the aluminum from the RFID tag. The spacer had a height of 5mm and such a diameter that it would just fit into the drilled hole. A 2mm thin wooden cylinder was put as a cap on the top of each hole to fill the remaining gap. The values were chosen more or less randomly to get a first impression of the behavior. The resulting die performed worse than our previous models: the aluminum cylinders shielded the tags too much, i.e., even the bottom tag would not be detected by the table antenna.

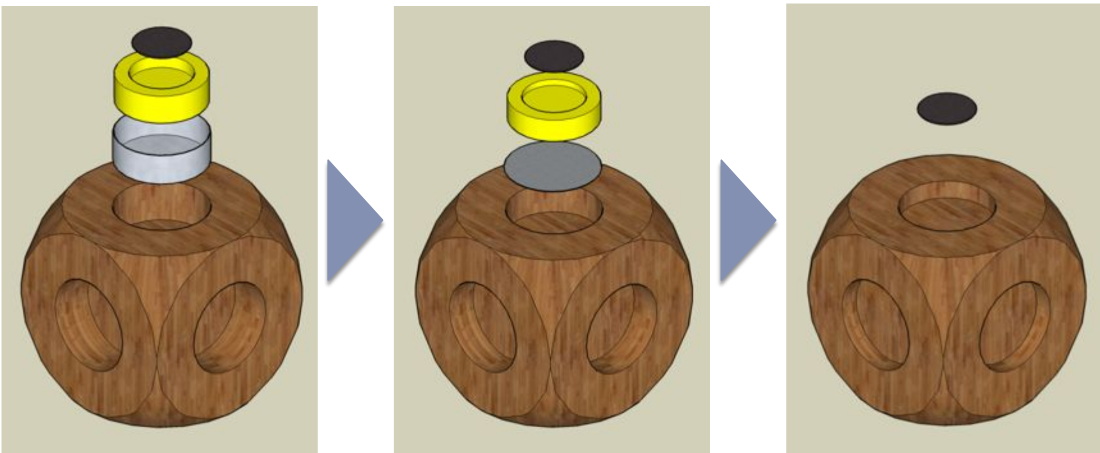


Figure 4.24: The explosion models of the first, second and third versions of the die.

For our second die, we reduced the depth of the holes to 5.5mm and used a circular PVC insulation layer, to reduce the shielding effect (see Fig. 4.24 center). Initial measurements were significantly better, but still far from perfect: while the tag at the bottom was now always recognized, one or two other tags were as well. We thus attempted to increase the distance between the antenna and the die, by raising the tabletop surface slightly above the antenna (see Fig. 4.25 right). After a few tries, we managed to find a solution that turned out to work perfectly: adjusting the antenna-surface-distance to 5mm finally resulted in a recognition rate of 100% according to our test series of several hundred rolls.

Given these results, we wanted to investigate if we could build a die without insulation layers and spacers at all, by only working with the distance between the antenna and the surface. Drilling holes of 3mm depth and 10mm diameter, we directly placed the RFID tags inside and covered them with simple stickers. Using the trial-and-error approach as before, we found the optimal distance to be 14mm, again yielding a 100% recognition rate (the probabilistic correctness of the die was again tested by rolling it several hundred times). Another advantage of this approach is the much simpler construction process as well as the reduction of potential

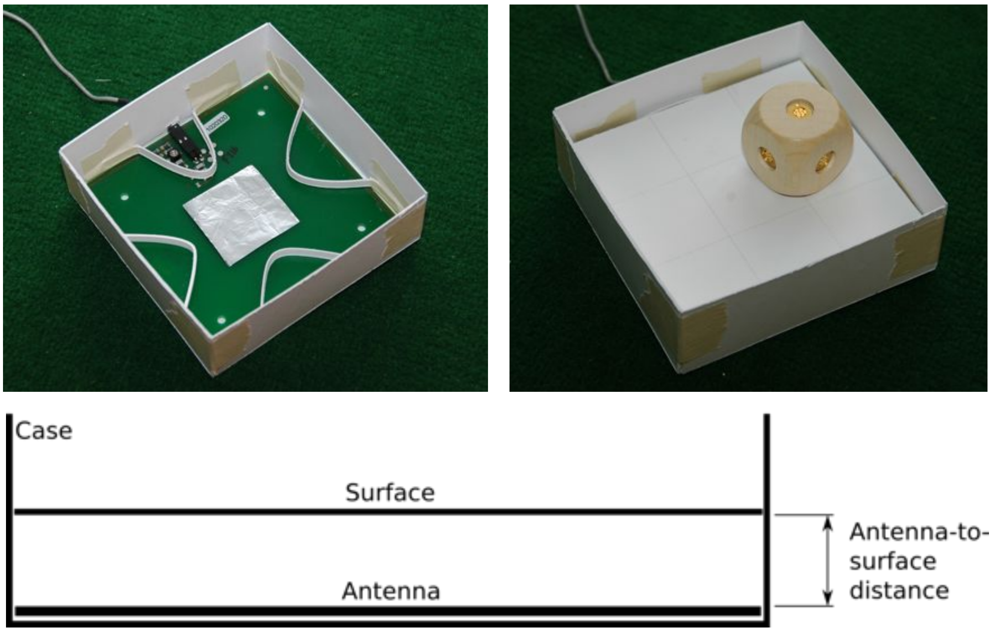


Figure 4.25: The antenna of the dicing ground with a metallic foil in the center (top left), the dicing ground of the 30mm prototype (top right) and the cross-section of the dicing ground construction (bottom).

imbalances due to construction flaws (i.e., preventing that one side has a higher probability of being rolled).

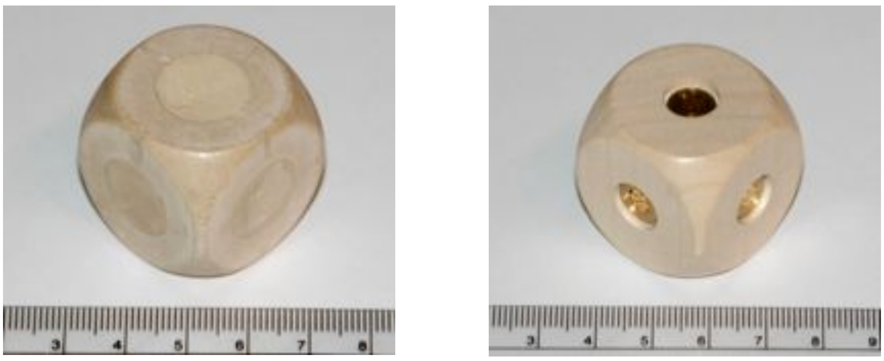


Figure 4.26: The revised 30mm prototypes.

Having achieved perfect recognition rates with the 30mm die, shrinking the die to the more common 16mm size seemed straightforward. However, initial testing with the 16mm die revealed recognition problems at the borders of the surface – the reliable detection of the bottom tag was only possible in the center of the antenna. We realized that since the electromagnetic field at the edge of the antenna runs nearly parallel to the surface, the lower height of the die had moved the side tags into read

Table 4.10: Overview of the different dice characteristics during the iterative development process.

Parameter	**30mm prototypes**			**16mm die**
Hole diameter	15mm	15mm	10mm	10mm
Hole depth	7mm	5.5mm	3mm	2mm
Insulation material	Aluminum foil	Aluminum foil	n/a	n/a
Insulation form	Cylindrical	Cylindrical	n/a	n/a
Spacer material	Wood	PVC	n/a	n/a
Spacer height	5mm	4mm	n/a	n/a
Cap material	Wood	Wood compound	Wood compound	Wood compound
Antenna-to-surface distance	0mm	5mm	14mm	22mm

range again. In many cases, the reduced height even allowed the tag at the top side to be identified. Further increasing the distance between antenna and surface did not help: at a distance of 22mm, no tags were detected near the edges of the antenna anymore, but both the top and the bottom tag were still identified when the die was placed squarely in the antenna center.

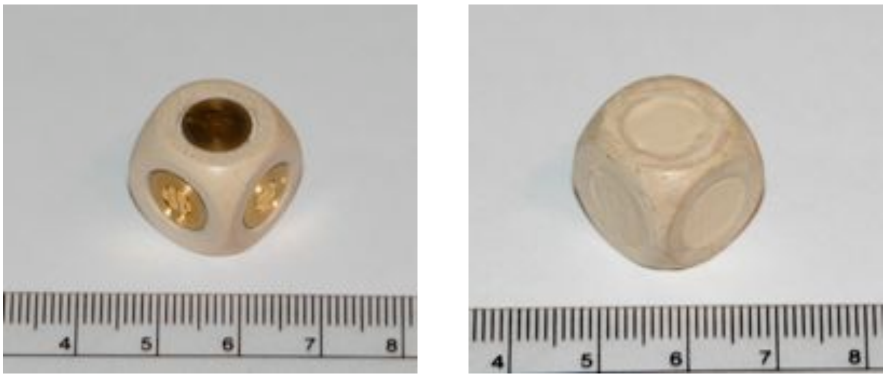


Figure 4.27: The final 16mm prototype shown with the 8.9mm RFID tags disposed (left) and with wooden caps (right).

To help even out the antenna field, we used two approaches: first, in order to weaken the field strength at the center, we placed a 35x35mm aluminum foil as an insulator at the center of the antenna (see Fig. 4.25 left). Second, to avoid the problematic border region, we added a physical barrier that restricted the tabletop surface to 90x90mm (compared to 100x100mm before). These modifications finally yielded a recognition rate of 100% using the 16mm die (see Fig. 4.27), though at the cost of a slightly smaller dicing area.

Summing up, in this section we demonstrated how to design and build augmented dice using RFID technology. After several iterations and modifications we managed to construct an augmented die that features a recognition rate of 100% but maintains the look-and-feel of a traditional off-the-shelf die.

4.4 Gameflow Virtualization and User Support

In this section we present the gaming application itself, which consists of three main parts: the *processing of the data* forwarded by the infrastructures for locating the game objects and determining the results of the dice rolls, the *virtualization of the game flow* and the *user interfaces* (see Fig. 4.28).

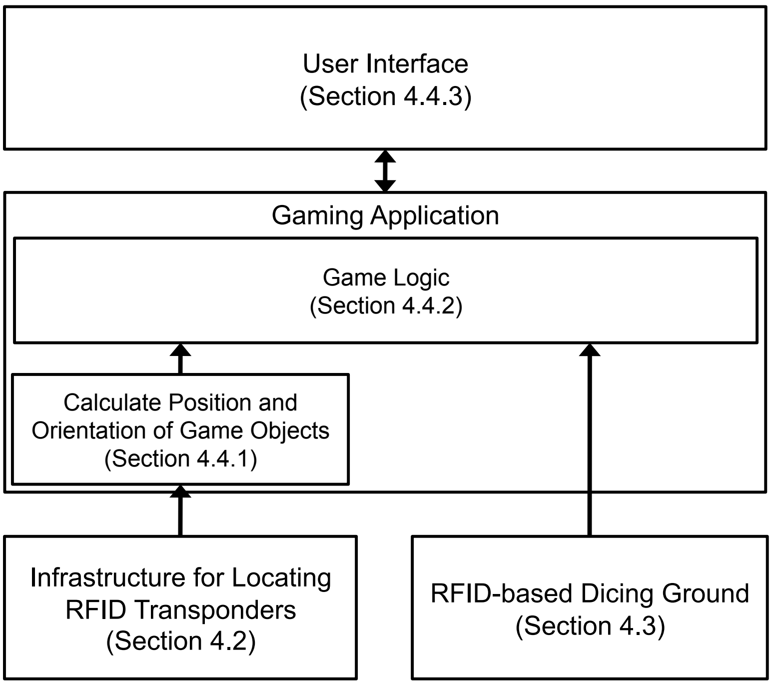


Figure 4.28: Overview of the architecture.

The *gaming application* is the software system running in the background. At its core is the game logic, which is a virtual representation of the actual game and its game flow (see Section 4.4.2). Based on the information forwarded by the RFID-based infrastructure for automatically determining the position of RFID tags on the game field, the position and orientation of (multi-tagged) objects can be calculated (see Section 4.4.1) and fed into the gaming application. The current situation of the game field and the game units is displayed on a screen (see 4.4.3). Players thus receive constantly updated information about the game and can check if their strategic decisions are in accordance with the rules.

We discuss these components now in more detail.

4.4.1 Calculation of Object Position and Orientation

As mentioned before, the position data of the RFID tags is forwarded to our gaming application, which then processes it (i.e., translating the recognized tag IDs into battlefield coordinates of the corresponding game objects). For game units with only one RFID transponder this is straightforward since the transponder position equals the unit position. With multi-tagged objects such as tanks, however, this task is not as simple: we have to find both a position and orientation that fits the detected tag positions as accurately as possible.

For each multi-tagged game object, the system knows the relative position of the tags on the object after an initial registration step. During actual gameplay, the system calculates the center of gravity for the set of recognized tag positions and aligns it with the center of gravity of the registered model (see Fig. 4.29). The system then measures the angles between the center of gravity and all tag positions and averages over all angles. The resulting angle indicates the orientation of the game object.

This algorithm worked extremely well in all our test scenarios: given the very low deviation of the location of individual tags, we can also precisely determine the orientation of objects. The average deviation of a square-shaped object with four RFID tags attached to the corners was approximately 1-2 degrees. Apparently, the more tags attached to outer edges and corners of an object, the better the position and orientation estimates. Tab. 4.11 shows the results of two of our test objects.

Once we had the positions and orientations of all game objects on the

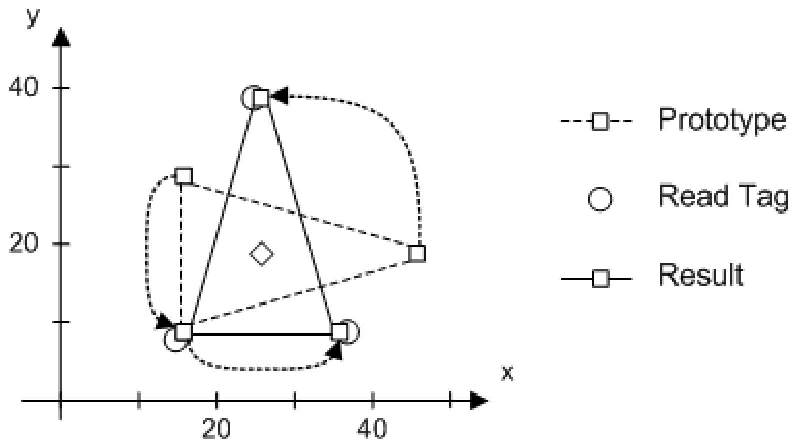


Figure 4.29: Determining the position and orientation of multi-tagged objects: The center of gravity for the unit and the detected RFID tags are placed on top of each other. The average of the angles between the center and the individual tags yields the required rotation of the object.

Table 4.11: The mean deviation of the position and the orientation of two of the test objects.

Object	**Deviation of position** [mm]	**Deviation of orientation** [degree]
Single tag	2	–
Triangle (3 tags)	1.5	1.25
Square (4 tags)	0.5	1

battlefield – in addition to the army units we also had the virtual representations of all static objects such as buildings – we could then verify if moves and attacks were valid. Thereunto, three things are to be inspected:

1. The distances:
   a) Is this unit allowed to move to this point?
   b) Is the target in range of the unit's weapons?
2. The field of vision (only vehicles):
   a) Is the target within the field of vision of the weapon? (Most weapons mounted on vehicles have a field of vision of 180°.)
3. Is the target in the line-of-sight of the aggressor?

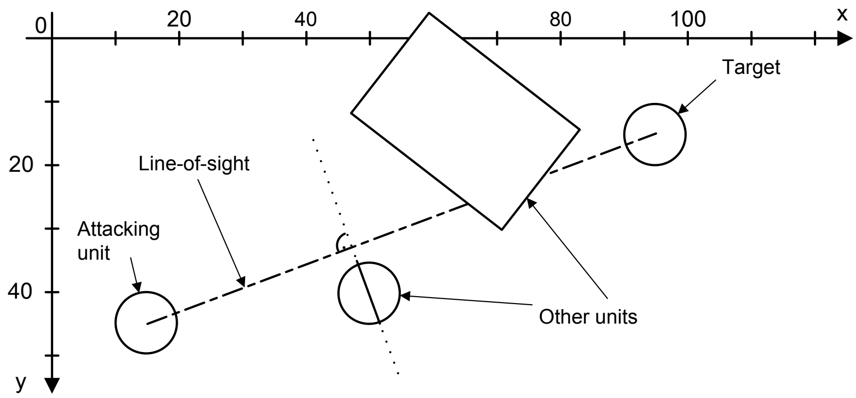


Figure 4.30: Determining the line-of-sight between objects.

Since all objects can be modeled as circles (i.e., foot soldiers) or sets of lines (i.e., vehicles, buildings and terrain sections), checking these three constraints can be reduced to calculating the intersection of two lines. The small figures are placed on round bases (see Fig. 4.10 middle); in this case we take the line that is orthogonal to the line-of-sight and goes through the center of the round base: since we know the diameter of the base, we can determine if the base of the target figure is within the line-of-sight of the attacker. Large vehicles often require the calculation of several intersections due to their typically distinct shapes. Their shapes are stored in XML files (see Fig. 4.31).

This information is then forwarded to the players to provide them with the current state of the game (field) and help them with making their decisions.

4.4.2 Virtualization of the Gameflow

W40K consists of three main phases, that is movement, shooting and close combat. To properly assess if all rules are satisfied, we virtualized these phases and the game objects with their individual characteristics (e.g., strength, range, weapons, etc.). The game phases can be represented in flow diagrams, which give a good overview of how the game is structured and serve as the basis for the classes.

Fig. 4.33 displays the diagrams covering the main game flow of W40K and Fig. 4.34 displays the shooting phase. These diagrams can easily become very intricate due to the complexity of W40K. The two diagrams of the shooting phase do not cover all possible exceptions and rules –

```xml
<model name="Tank␣1" short="Tank1" type="vehicle">
    <points>35</points> <!-- Value in combat -->

    <template>
        <node ref="top">  <x>250</x> <y>0</y>    </node>
        <node ref="left"> <x>-250</x><y>-150</y></node>
        <node ref="right"><x>-250</x><y>150</y> </node>
        <node ref="tlo">  <x>250</x> <y>-130</y></node>
        <node ref="tlu">  <x>230</x> <y>-150</y></node>
        <node ref="tro">  <x>250</x> <y>130</y> </node>
        <node ref="tru">  <x>230</x> <y>150</y> </node>
        <node ref="tru">  <x>230</x> <y>150</y> </node>
        <node ref="wr1">  <x>50</x>  <y>150</y> </node>
        <node ref="wr2">  <x>50</x>  <y>200</y> </node>
        <node ref="wr3">  <x>-25</x> <y>200</y> </node>
        <node ref="wr4">  <x>-50</x> <y>150</y> </node>
        <node ref="wl1">  <x>50</x>  <y>-150</y></node>
        <node ref="wl2">  <x>50</x>  <y>-200</y></node>
        <node ref="wl3">  <x>-25</x> <y>-200</y></node>
        <node ref="wl4">  <x>-50</x> <y>-150</y></node>
        <node ref="wl">   <x>25</x>  <y>-175</y></node>
        <node ref="wr">   <x>25</x>  <y>175</y> </node>
        <node ref="wm">   <x>50</x>  <y>0</y>    </node>
    </template>

    <outline>
        <point ref="tlu"/>  <point ref="tlo"/>
        <point ref="tro"/>  <point ref="tru"/>
        <point ref="wr1"/>  <point ref="wr2"/>
        <point ref="wr3"/>  <point ref="wr4"/>
        <point ref="right"/><point ref="left"/>
        <point ref="wl4"/>  <point ref="wl3"/>
        <point ref="wl2"/>  <point ref="wl1"/>
    </outline>

    <skills>
        <WS>3</WS>  <!-- Weapon Skill -->
        <BS>3</BS>  <!-- Ballistic Skill -->
        <S>3</S>    <!-- Strength -->
        <T>3</T>    <!-- Toughness -->
        <W>1</W>    <!-- Wounds -->
        <I>4</I>    <!-- Initiative -->
        <A>1</A>    <!-- Attacks -->
        <Ld>5</Ld>  <!-- Leadership -->
        <Sv>6+</Sv> <!-- Save -->
    </skills>
    <weapons>
        <weapon ref="wm" angle="0;50">Ion Cannon</weapon>
        <weapon ref="wl" angle="40;40">Ion Cannon</weapon>
        <weapon ref="wr" angle="320;40">Ion Cannon</weapon>
    </weapons>
</model>
```

Figure 4.31: An example of an XML file describing a vehicle. The shape outline is required for determining if this unit is in line-of-sight of another unit or blocking another unit's view.

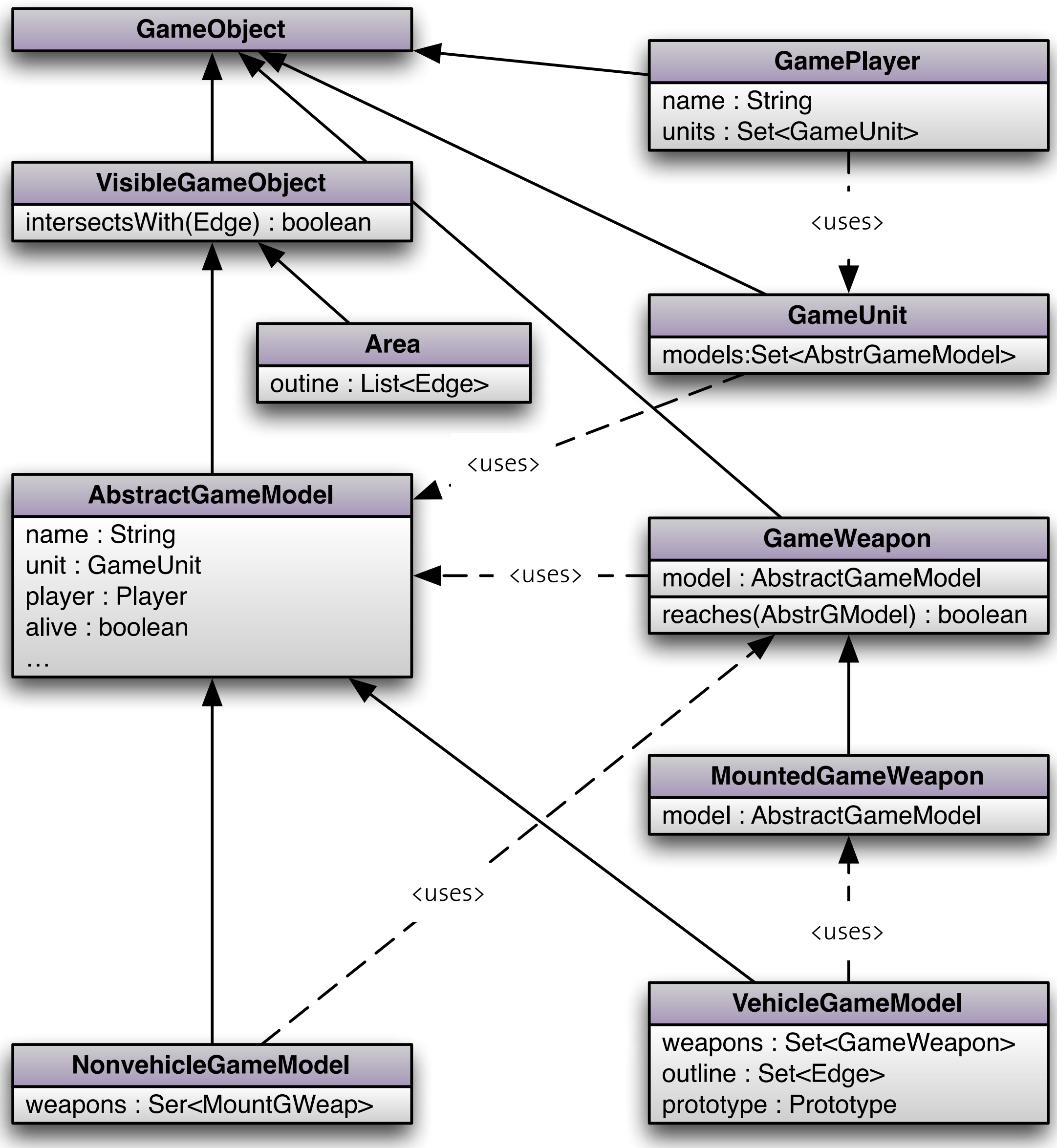


Figure 4.32: The class diagram of the game objects.

including them would have rendered the diagrams rather confusing and hard to understand.

Based on the flow diagrams, the gaming application is aware of the current game state and can now forward relevant information to the players and verify their moves without their having to manually measure distances, angles, etc. and cross-reference them with the individual and current capabilities of the involved units (e.g., health points, fallback condition, PSI support by special units, etc.): the players can simply make their moves and will be informed if and why a move is not valid.

The individual characteristics of each unit are stored in XML files (see Fig. 4.31) and loaded at the beginning of a game session. Every game

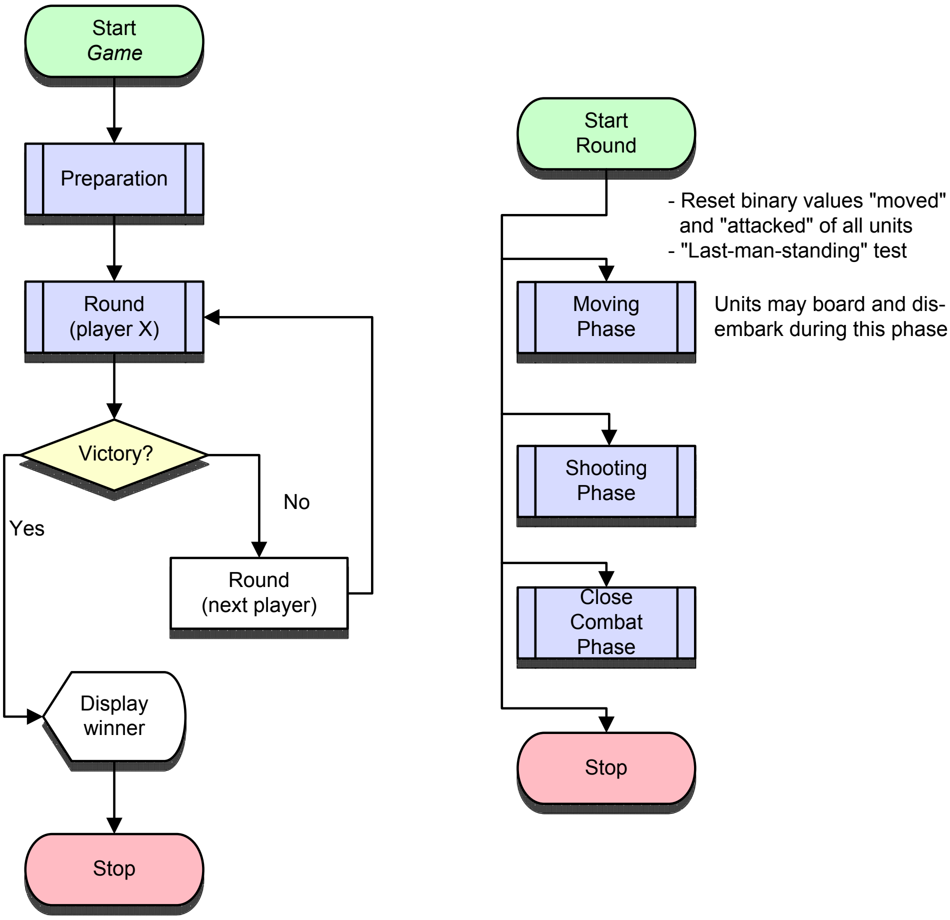


Figure 4.33: The flow diagram describing the “high level” game flow.

object is then represented by its own class during the game (see Fig. 4.32), even weapons and other minor objects as they can also change their state during the game (e.g., weapons mounted on vehicles can be destroyed). During the game, the virtual data sheets are constantly updated.

4.4.3 User Interfaces

To provide the players with the current state of the game (field) and help them with making their decisions, a screen will perpetually display the current condition of the battlefield, including buildings and terrain sections (see Fig. 4.35 (top)). The idea is to draw a virtual game field that represents the physical game field as accurately as possible. Each game object has its virtual, and thus graphical, counterpart. The emphasis is, however, on functionality, not on graphical effects (i.e., the screen should give the players a good and easy overview of the current game state).

By simply moving the mouse cursor over a unit, a player can receive all

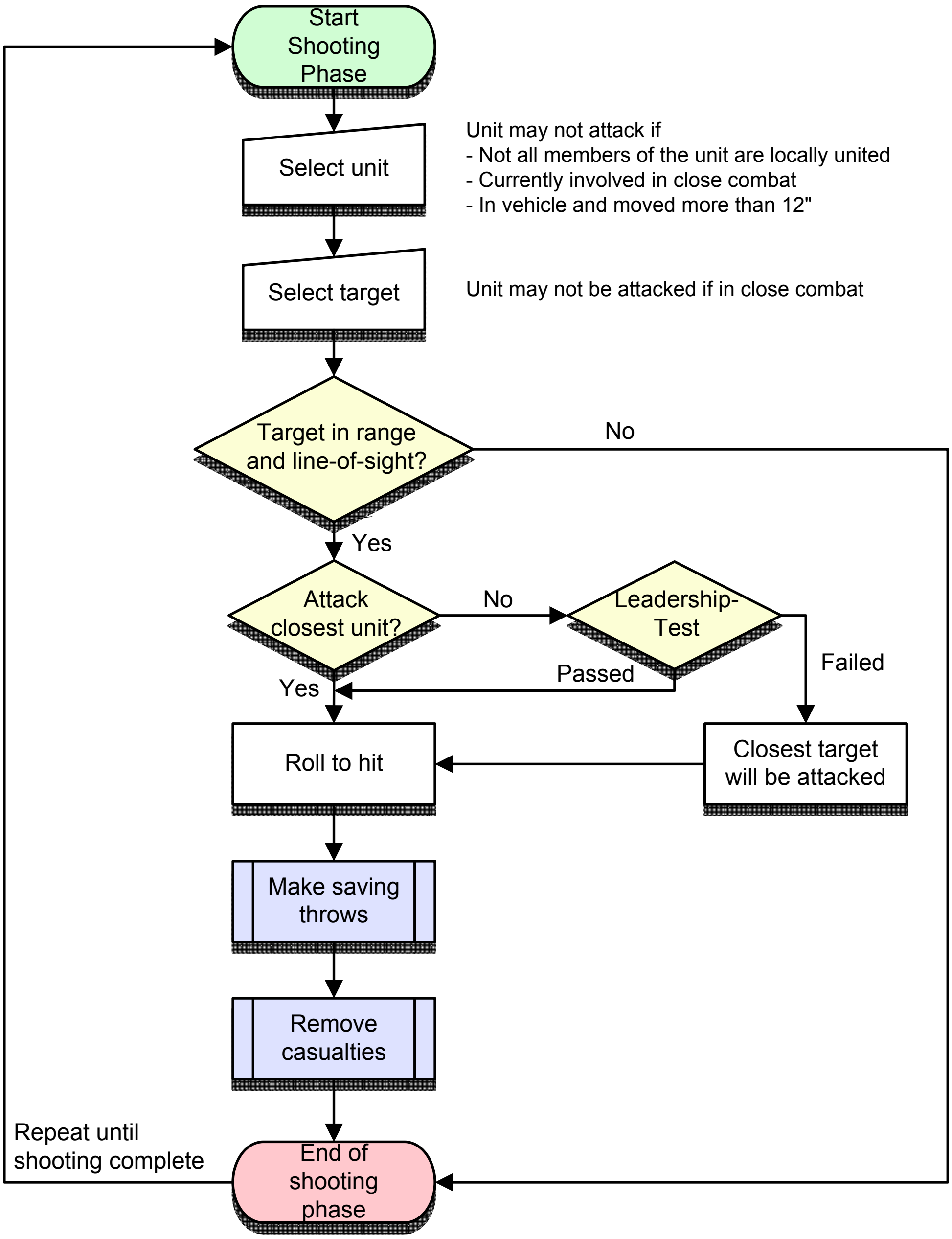


Figure 4.34: The flow diagram of the shooting phase of W40K.

relevant and up-to-date information[13] (see Fig. 4.35 (middle)). Similarly, the screen will notify the players whose turn it is and which moves are possible: if a move is not allowed, the otherwise black "lines of movement" are highlighted in red (see Fig. 4.35 (bottom)).

The system is capable of displaying all game phases and indicating all possible rule violations – similar to a computer game. The players can however also choose to ignore the "guide" or even disregard indications

[13]In fact, the general idea is to take the concept of virtualization even one step further by representing each game object (i.e., the army units) on the Web [175].

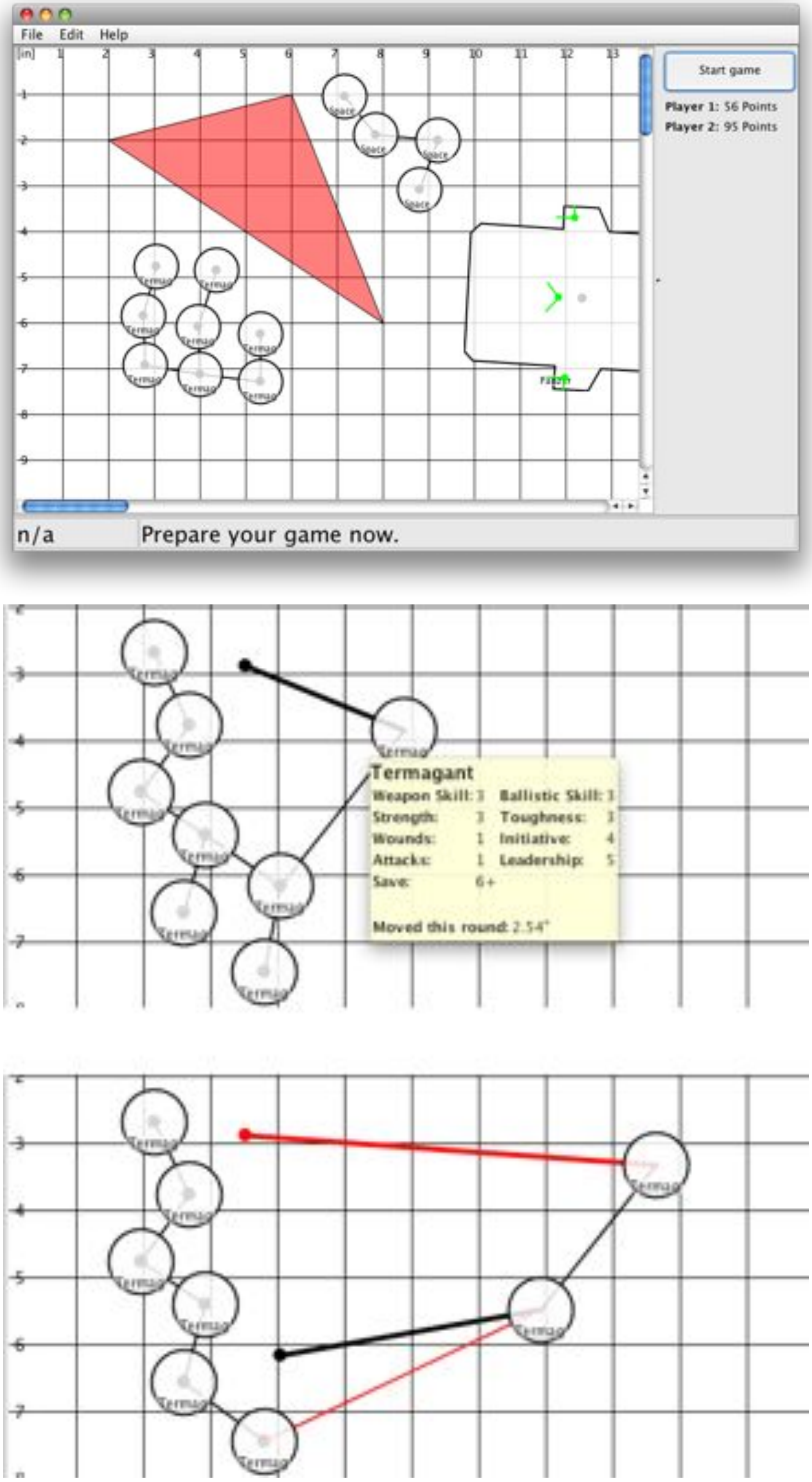


Figure 4.35: Top: recognized game objects ("rough" terrain (red triangle), a tank (right) and two commandos (circles)). Middle: display of additional information about individual units. Bottom: notification if planned moves are invalid.

of rule violation and only use the screen to get an overview of the current game situation when desired. This ensures that the players are always in control of what they are doing and the environment, which is an important prerequisite for fun (cf. Section 3.1.3).

4.5 Discussion

In this section we discuss how well W41K actually meets the requirements and design guidelines. We also include a summary of what could be improved in the future.

4.5.1 Meeting the Functional Requirements

We initially established five functional requirements for the digital augmentation of W40K (cf. Tab. 4.2):

- Automatically determine the position and orientation of units on the battlefield.
- Automatically recognize rolled results and forward them to the background system.
- Automatically check the validity of the players' decisions and give them the information they require to reach a decision.
- Keep up-to-date data sheets on all units of the current game session and make them available to the players.
- Enable players to stop and resume an ongoing game at any time and to store the course of the game for later replay.

Our prototype W41K certainly meets the first four requirements: we digitally augmented the game field and objects using RFID technology to uniquely identify them. We developed an infrastructure that is capable of locating single RFID tags within a few millimeters, which enables determining the precise position and orientation of game units on the battlefield. By integrating RFID tags into traditional off-the-shelf dice, we were able to automatically recognize and forward the results of dice rolls. The virtualization of the game (i.e., objects, rules and flow) facilitates the validation of rule (in-)consistencies and the provision of game information. An up-to-date overview of the battlefield situation displayed on a screen hence allows for au courant decisions.

The last functional requirement remains unfinished for the time being: while our (theoretical) model of the game makes allowance for a session and history management (i.e., each move can be saved), it has not been technically realized yet.

4.5.2 Meeting the Design Guidelines

Physical Augmentation

W41K meets most of the design guidelines presented in Tab. 3.1 rather well. Technology is used sparsely (i.e., play objects are only equipped with RFID tags) and its integration clearly provides an added value (i.e., players are provided with up-to-date information and relieved of laborious tasks like manual measurements), thus meeting criteria 1 and 2.

The guidelines 3, 5 and 6 are inherently met by the chosen technology (passive RFID technology) – also demonstrating how important the choice of the technology can be. RFID technology moreover guarantees that the technology remains in the background (criterion 4): players only see the screen displaying the current state of the battlefield. Additionally, the seamless integration features a certain degree of safety (guideline 8): the tags can be fully incorporated into the game objects and the infrastructure is hidden under the table, thus ensuring that players do not come in direct contact with the technology.

Since the digital augmentation follows the game flow (i.e., the options and interactions provided are based on the current state of the game), the technology is tightly coupled with the activities of the game (criterion 7).

To realize the physical augmentation, we iteratively developed and improved the prototype to meet the required criteria: each component was subject to at least three iterations as discussed in the corresponding sections. The design and implementation processes were realized in accordance with the augmentation cycle (see Section 3.1). Nonetheless, the last guideline was only partially met: W41K has not been tested in field (i.e., under real circumstances) yet (also cf. Section 3.1 and Chapter 6).

Virtualization of the Game and System Development

In Tab. 3.2 we summarized the design guidelines for the virtualization of the play environment and the development of the corresponding software system.

The first three design guidelines are met by W41K. The virtual model of the game supports all current and potential future objects (guideline 1): we use a generic object scheme and store the object data in easily readable and interpretable XML files. However, if the game and its rules underwent major changes, the model would be subject to compliant alterations or adjustments (i.e., although the object model is quite flexible, it is coherent with the current version of the game and thus not universally generic).

We support the high dynamics of the game as players can easily add and remove objects before a game session – once a session has commenced, players and objects cannot be changed anymore –, which meets the second criterion. The third guideline is also met since interaction primarily happens directly on the game field.

The fourth design guideline is of no concern in W41K as all information is displayed on one screen. There are two reasons for this: first, W40K does not make use of private information or secrets – all information is public. Second, while it would be possible (and at times even more convenient) to use personal devices for displaying information (e.g., the current state of one's own army units), having one shared screen is more beneficial in terms of fostering social interaction.

Criteria 5 and 7 are also met, at least partially. As the focus remains on the traditional play set and the interaction between players, interaction with the system is minimal: players occasionally glancing at the screen for information should not disrupt the original play experience. The provided feedback is very accurate and saves time in terms of looking up rules or object information. However, the system does not comprise real-time update, which is certainly a drawback and should be improved in future versions.

The idea of W41K is not to simply replace a rule book with a computer screen but allow players to focus on strategic decisions and social aspects by relieving them of cumbersome chores and providing them with relevant and up-to-date information about all game objects – if *desired*. To this end, players can do two things: on the one hand, provided interfaces allow players to add and change rules. On the other hand, players can decide to disregard rule violations indicated by the system to sustain players' prospective desire to bend the rules [89]. This satisfies guideline 6.

The last guideline is to minimize maintenance tasks. In W41K users are not burdened with any such tasks – except for occasionally replacing broken RFID tags –, which certainly contributes to the overall enjoyment.

User Interface

In Tables 3.3 and 3.4 we summarized the design guidelines for UIs and TUIs, respectively. We discuss the general UI guidelines first, which are of relevance to the physical artifacts and the screen-based interface. The TUI guidelines, which only apply to the physical artifacts (i.e., the game field and objects), are discussed subsequently.

W41K basically features two user interfaces: on the one hand, the physical game field and objects and, on the other hand, the screen displaying the current situation on the battlefield. Both user interfaces are very simple and easy to use (criterion 1). Given that the game objects themselves are the input devices, the interaction is in situ, seamless and also fun (assuming that moving the figures is fun in the first place). Additionally, the game field allows for multiple, simultaneous and distributed interactions. We can thus conclude that the design guidelines 2, 3, 4 and 5 are met.

The screen is an additional user interface, which is not ideal (criterion 6). It would be favorable to integrate the output channel directly into the physical play set, although it might be difficult to resemble the easy, fast and powerful output options of a screen in tangible objects.

Guideline 7 is of no concern in W41K as configuration issues are limited to changing rules and object data: while programming-by-example is theoretically possible (e.g., create a new rule by playing an according scenario), it might raise serious problems regarding semantics. Furthermore, simply editing rules using a GUI is much faster and more efficient.

For the development of both, the physical game environment and the screen-based interface, we went through several iterations, all of which including heavy testing (criterion 8). As pointed out before, W41K has not been tested in the field however.

The TUI design guidelines are equally well met. Guidelines 1, 2, 4 and 5 are inherently realized by using the game objects as input devices. Criterion 6 was of considerable importance to us from the beginning: given the very small form factor of the game figures as well as the value attached to them by the players (players typically spend hours on assembling and painting figures, which are moreover quite expensive), we had to completely disguise the technology – which we successfully accomplished with W41K.

The remaining criterion 3 is the only one completely violated: our output device (computer screen) is neither spatially nor semantically mapped with the input (game figures). This is also closely intertwined with criterion 6 (s.a.) and addressing this issue should certainly be of prime concern in the future.

Game-Specific Design Guidelines

In Tables 3.5 and 3.6 we summarized criteria regarding how pervasive computing can or should specifically support a game. We discuss them now.

The elements "concentration", "challenge" and "player skills" are not truly of relevance here (see Tab. 3.5). Similarly, the element "clear goals" is irrelevant as there is usually only one clearly expressed goal (i.e., eliminate the adversarial forces).

The other elements are largely supported by W41K: the players are certainly in control of the augmented game environment as they can freely add and change both objects and rules. Additionally, they are provided with constant feedback. The elements of "immersion" and "social interaction" are also supported as the players are relieved of laborious and distracting tasks and can thus fully concentrate on the social interaction and the game itself.

The same applies to the six elements of a game (see Tab. 3.6).

W41K supports the players by unobtrusively and continuously observing the game and possible rule infringements. The shared screen facilitates discreet and fair competition between the players: discreet, because the screen is a modest but effective means to keep players apprised of the current game situation – and thus, of the competition; and fair since all players have equal access to information. This inherently includes measuring, storing and displaying the score of the game.

The interface provided also allows the players to make decisions anytime. Since W41K is aware of the current game state, it can even, if desired, guide the players through the game phases, that is movements, ranged and close combat.

The last element, “emotional attachment” is difficult to assess: while we feel that W41K is potentially more compelling and immersive than its non-augmented counterpart, we cannot substantiate this claim without an extensive user study.

To sum up, we conclude that W41K meets both the non-functional requirements and design guidelines rather well. The game could, however, benefit from a better mapping of in- and output. This aspect, among a few others, is discussed now in terms of future work.

4.5.3 Future Work

Our prototype serves as a fair example of how an augmented game environment might look, i.e., data is collected unobtrusively and neither the battlefield nor the game objects are perceptibly modified. While initial trials showed that the prototype works very well, we found several aspects that could be improved in subsequent design iterations.

Integrate Output into the Physical Play Set

As revealed in the discussion, one of the major issues is the replacement of the screen-based display of information with a more naturally integrated interface (cf. section 4.3). One idea would be using a projector to display the information directly on the game field. While a projector potentially violates the fourth design criterion (see Tab. 3), it might on the other hand provide for additional effects (i.e., visualizing explosions and exchange of gunfire) – this trade-off is certainly worth exploring.

Reducing the Scan Time

Further reducing the time required for scanning the battlefield, which is approximately one minute at the moment, is crucial if this approach is to be used for other gaming applications as well. This is, however, not possible without replacing the hardware.

First of all, we could replace the custom-built LEGO robot with a high performance robot arm to move the antenna. This would certainly lead to a more robust hardware installation and should also allow for much faster scans. The faster movement of the antenna, however, also entails less read cycles as RFID antennas can only be energized at certain frequencies. To cope with the faster movement, we would thus have to replace parts of the RFID hardware as well. As discussed before, this can be tricky as the devil is in the detail.

Increasing the Dice Ground

Right now, we can read five to six dice at once, but the game sometimes needs over 20 dice rolled simultaneously.

While our current setup correctly identifies 100% of all rolls in our test, it comes at the expense of a carefully constructed "tabletop surface." Increasing this area will most likely involve another careful round of tuning. Previous investigations into bigger (off-the-shelf) antennas, as well as into the use of antenna arrays, showed that the created field is often too heterogeneous. Additionally, due to the nature of RF, our setup is sensitive to the immediate environment, especially the table it is placed on. A solution could be to include a shielding construction around the whole dicing ground, but this would come at the price of increased size and a more expensive construction.

Admittedly, using RFID for constructing augmented dice is a "hack," as this technology was never designed for precise tag locating. The high sensitivity of the RF field requires an unwieldy trial-and-error process. Furthermore, we have yet to confirm whether our dice are capable of being rolled several thousand times without compromising the perfect recognition rate, which would be the prerequisite for real-world applications.

Nonetheless, in our opinion, the benefits of using RFID technology for external detection outweigh its disadvantages: an RFID-based solution is maintenance-free and the detection devices can be invisibly integrated into the environment (e.g., a game board). The continuously decreasing costs of standard RFID equipment, as used in this project, further strengthen this assumption.

Further Points

We also mentioned the following two points, which we will not further elaborate on here:

- Session management and game history (see above).

- Conducting an extensive user study: the prototype has not been tested under real circumstances.

Improving these aspects should further contribute to creating a truly compelling augmented game environment.

4.6 Summary

In this chapter we presented Warhammer 41K, a digitally augmented version of the traditional miniature war game Warhammer 40K. We first introduced W40K and outlined its characteristics, based on which we discussed the motivation and goals of digitally augmenting this game.

Following the process model, we then physically augmented game infrastructure and objects. This was described in two subsequent sections: first, the augmentation of the game field and the game units and, second, the augmentation of the six-sided dice. In both cases, we employed RFID technology, which has several advantages for this application, namely the unobtrusive integration and operation, the unique identification of objects and very low calibration and maintenance requirements. As a result, we are able to automatically and very accurately determine the location of RFID tags on the game field as well as the results of dice rolls.

This data is forwarded to the gaming application, which processes it and calculates the position and orientation of the game units. Combined with the game logic, which includes the rules and the flow of the game, this information can be utilized twofold: on the one hand, to take the burden of manual measurement and calculation off the players and, on the other hand, to provide them with context-relevant information in situ (i.e., current states of all units and the battlefield). This allows the players to focus on the social interaction (i.e., banter with fellow players) and on the game itself (i.e., on the strategic decisions). It can also be used as an impartial authority for tournaments.

Finally, we discussed the application of the design guidelines as well as the success of the design and implementation with regard to the functional and non-functional requirements. This example of a digitally augmented game environment provides for many insights into how the process model and the design guidelines can be practically applied.

Miniature war games are an excellent example of how players can potentially benefit from a digital augmentation. Given their demanding nature in terms of complexity and intricacy, it seems that if we are able to use the proposed framework of digital augmentation for this game form, it should be a fortiori applicable to almost all other categories of (tabletop) games.

5 The Augmented Knight's Castle

In this chapter we present the *Augmented Knight's Castle*, an augmented version of the traditional Playmobil[1] medieval play set for children. Digitally augmenting this play environment would not only enable us to integrate multimedia effects to let the play set come alive, but furthermore facilitate playful learning as figures could inform, tell or teach children about the Middle Ages.

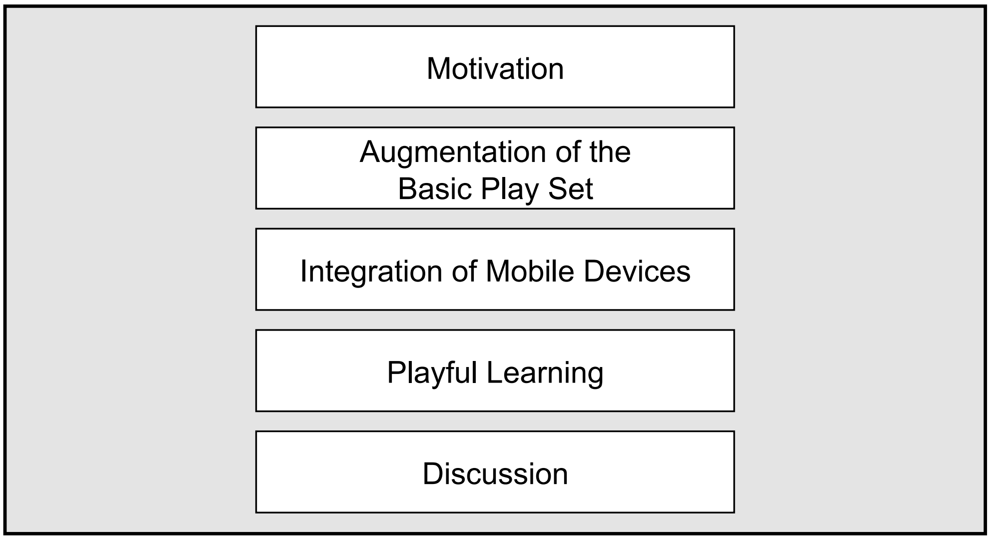


Figure 5.1: The structure of Chapter 5.

This chapter is structured as follows (see Fig. 5.1): first, we motivate the digital augmentation of this toy environment, specify the functional and non-functional requirements and discuss related work. Second, we describe the digital augmentation of the basic play set. In this section we also we discuss how children can configure the environment and create their own content using seamlessly integrated interfaces.

[1]www.playmobil.com

Third, we present how mobile devices can be integrated into the play set and discuss the advantages and disadvantages of different approaches. Fourth, we elaborate on how such an augmented toy environment can be used to convey educational content in a playful way. This section also illustrates tools for parents and educators to configure the environment with respect to learning scenarios. Finally, we discuss the extent to which our digital augmentation meets the previously stated requirements and how well these comply with the design guidelines discussed in Chapter 3.

5.1 Motivation

In this section we first introduce the *Knight's Castle* (KC), a traditional toy environment for children. We then establish the motivation and goals for the digital augmentation of this play set. Last, we discuss related work.

Figure 5.2: The (Augmented) Knight's Castle play scenario.

5.1.1 Augmenting the Knight's Castle

About the Knight's Castle

The Playmobil Knight's Castle is a medieval play scenario with many different buildings, objects and figures (see Fig. 5.2). We chose this play set since it is a rather realistic representation of the Middle Ages and it hence provides many anchor points for play and learning scenarios (e.g., medieval life, music, clothing, alchemy, knighthood, chivalry, heraldry or knights tournaments).

The requirements and challenges of this toy environment are quite different from a game like W40K as the focus is on free play (i.e., there are no rules) and storytelling. As there are no rule books or fixed play patterns, the only option for identifying the characteristics of the KC and for understanding how children actually play with it, is therefore through observation.

We therefore conducted a preliminary user study at an elementary school in Switzerland. Over 30 children between 7 and 9 years old participated. In groups of 2-4 they played with the KC for approximately 30 minutes (see Fig. 5.3). We carefully observed each play session and interviewed the children afterwards. We asked them about their stories, what they liked and disliked or what kind of scenarios they would play.

Figure 5.3: Children playing with the traditional Playmobil play set during the pre-study in a Swiss elementary school.

This user study served two major purposes: on the one hand, observing the children play with the KC allowed us to derive general characteristics (see Tab. 5.1). On the other hand, it gave us an opportunity to see and understand what children actually like and what parts of the play set could be digitally augmented.

Table 5.1: Characteristics of the KC.

Characteristics
• Age range: 6-12 (it seemed that younger children did not fully comprehend the physical appearance of the play objects (e.g., a figure would be interpreted used very diversely), while children at the age of around 13 would no longer be interested due to their entering adolescence). • Number of players: unlimited. During a play session, players may join or leave the play. • There are no generally valid goals, rules or restrictions. • The play field is not spatially restricted and subject to constant changes. There is no raster of discrete homogeneous fields. • There are no time constraints whatsoever (i.e., no turns and a play session can be endless). The (re-)action is real time. • The play set consists of many play objects. During a play session, players might add new objects. It is theoretically even possible to introduce "semantically foreign" objects (e.g., a teddy bear).

Since it is rather difficult to directly elicit such information from children at elementary school age, we pursued another approach: first, we came up with several ideas regarding what could be digitally augmented. The second step was to integrate children's feedback with respect to our ideas as well as their own ideas. To this end, during our preliminary user study we also encouraged them to explain to us what kind of "great features" they would like to have. In addition to the story-based questions (i.e., what kinds of stories they would tell and play), we would ask them what they thought of play figures that could talk, objects that glow, etc. In other words, we confronted them with our initial ideas with respect to digital augmentation.

Generally, the answers were very positive and all the children said that they would really enjoy such an “enchanted” play set, which is certainly not surprising since children habitually tend to rate new toys or play experiences high (also see Chapter 6). We thus decided that the best course of action would be to digitally augment the play set according to our initial ideas and let then children play with it.

Motivation and Goals of the Digital Augmentation

In contrast to games, toy environments focus on free and pretend play. The ideal entertainment experience would seem to stem from the combination of physical experience, virtual content and the children’s imagination. Stapleton et al. [320, 321] combine these components in their model of “compelling mixed reality” (see Fig. 5.4).

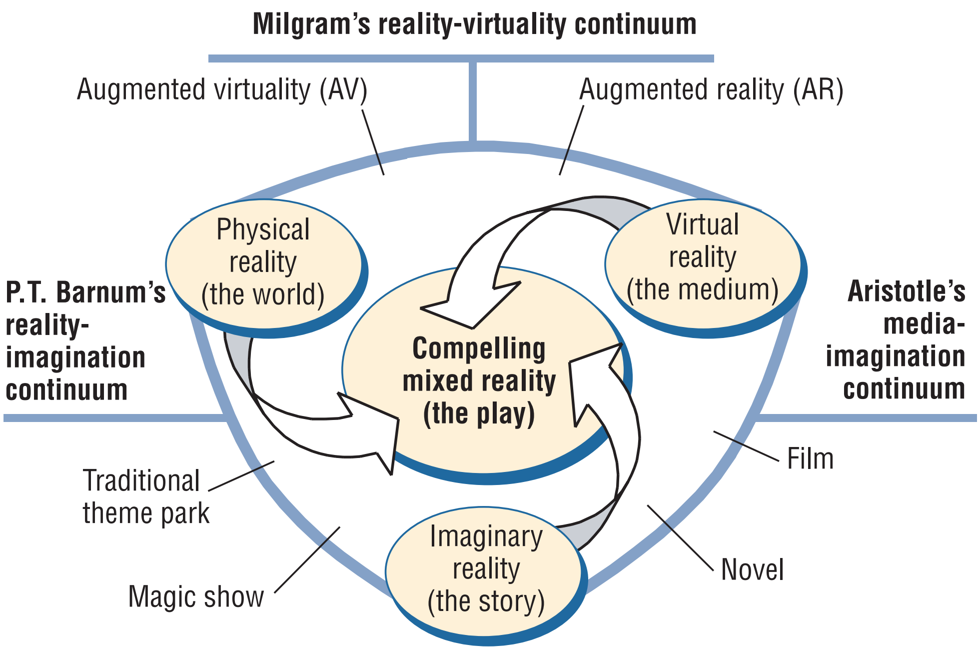


Figure 5.4: The model of compelling mixed reality [321].

The physical reality is the play set including the toy figures and objects children interact with whilst playing. The imaginary reality is the children’s imagination and refers to the stories that unfold in their minds. Traditional toys consist only of these two realities. By adding audial and visual feedback to a traditional play set (i.e., virtual content), we can create an entertaining and exciting multimedia playground that fosters the children’s pretend play and offers attractive possibilities of integrating interactive learning experiences.

Embedding pervasive computing technologies into traditional play artifacts enables physical objects to be seamlessly connected to any virtual content, which offers many possibilities, especially for educational toys [77]. "Technologies can provide a wealth of meaningful new experiences and support children's exploration of their neighborhoods, other cultures and even the universe. [...] Innovative tools can also foster communication, collaboration, storytelling and creativity among children" [87].

Research further suggests the value of features of digital environments for supporting play and learning, e.g., the value of unexpected or unfamiliar events for attracting attention and promoting engagement [272]; the value of tangibles in supporting both exploratory and expressive interaction [219]; and activities that promote diving-in and stepping-out or alternating between immersion and reflection [12].

Other work points out the importance of particular kinds of interaction, which supports narrative construction and storytelling, for example, perspective-taking through the facility for children to take on different roles [219]; recording compositions in an external medium (externalizing) together with a physical structure that provides children with a model of narrative to explore [23]; or a story-listening system to foster storytelling through interaction with stories recorded by other children [57].

Additionally, augmented toy environments can instill moral values [35] and they can also support children with learning difficulties [229] as well as social disorders or mental diseases [173, 234, 372].

Driven by these motivating factors, the major question is what parts are actually to be augmented and what kinds of virtual contents are to be added. This is no trivial task as a play environment like the KC is not contingent on rules or restricted in any other sense: children constantly move and rearrange objects, figures and even buildings; other children might join or leave play sessions; and there are no constraints in terms of time or space. This lack of intrinsic structures, which also became very obvious during the pre-study, makes it difficult to identify routine tasks that could be supported. On the other hand, this absence of definite play patterns grants designers more flexibility regarding the 'what' and 'how' of digital augmentation.

To illustrate how the digital augmentation of a play set like the KC might give rise to a more enthralling play experience, we sketch a play scenario with two children, Tom and Jenny.

The scenery consists of several separated areas of the play set (e.g., as displayed in Fig. 5.2): the formidable castle belonging to the king and his knights, the plain in front of the castle where the inn is situated; the legendary dark forest with the hidden fairy spring and the magic tree; and the mighty dragon tower owned by the dragon knights located behind the dark forest. Tom chooses to play the dragon knights while Jenny commands the king's knights.

A great feast is taking place in the throne room. When Jenny takes the king and the queen to the room, a fanfare and exultation can be heard. Then, as long as king and queen remain in the room, the participants will celebrate and eat frolicsomely. In the meanwhile, the king's knights are preparing the treasure carriage in the inner yard; horses are whinnying, a dog is barking. Idyllic background music is playing.

Jenny takes the king from the room puts him into the inner yard: the celebration stops and an impressive blare of trumpets announces the king's appearance. The draw bridge is lowered with a squeak and the carriage and its escort leave the castle.

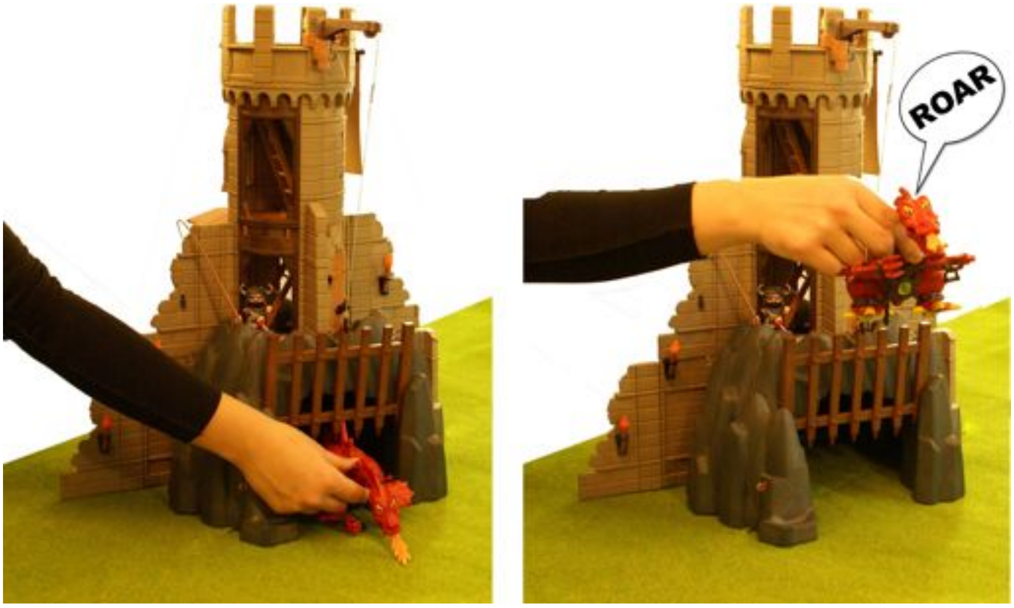


Figure 5.5: The dragon comes out of its dungeon accompanied by a roaring sound.

In the meantime, Tom prepares the dragon knights for an assault on the carriage to capture the treasure. He places several dragon knights in front of the dragon tower: horses neigh and the sounds of knights preparing for battle is heard. Tom sets the red dragon free from its dungeon, which is accompanied by a ground-shaking roaring (see Fig. 5.5). The dragon knights move out to the nearby dark forest, where an owl is howling. Then they encounter the king's knights: the background music becomes more dramatic and clangor of swords and yells of fighting knights can be perceived. Since the king's knights are outnumbered, the fight is swift and they eventually retreat, leaving carriage and treasure behind. The dragon knights bring the treasure back to their dragon tower and start celebrating.

During the confrontation, one of the king's knights has been badly injured and the

Figure 5.6: Receiving the healing potion from the fairy (left) and administering it to the injured king's knight (right).

golden knight sets out to ask the fairy for help. When he approaches the fairy spring, mysterious sounds and music are played. The fairy greets the golden knight and since he brings a gift, she presents him with a magic healing potion (see Fig. 5.6 left). Jenny shakes the bottle to mix the magic potion and the light on top of the bottle starts glowing. She offers the healing potion to the injured knight who acknowledges it with a sigh of relief (see Fig. 5.6 right).

Figure 5.7: The "Point-me-touch-me" paradigm using a smart toy sword (left) and a mobile phone (right).

As illustrated in this brief example, we strove for different forms of interaction between child and play set that trigger, or are part of, playing and learning scenarios:

- One or more toy figures are removed from or placed at a specific location of the play set. For example, the red dragon is removed from the dragon tower making a roaring sound (see Fig. 5.5).
- A child uses a smart toy (i.e., a toy piece that is augmented to detect other figures and perceive the play context, see Fig. 5.7 left and Section 5.3) as a point-and-touch device to select a play object. For

instance, the child uses the magic bottle to administer a healing potion to a figure (see Fig. 5.6 right).

- A mobile phone enabled as a point-and-touch device is used by the child to select objects in the play set. For example, the child points at the alchemist who challenges the child's knowledge with a puzzle, question or riddle (see Fig. 5.7 right).
- A "source of knowledge" can be introduced, which gives the children more information about the play objects and their roles in the Middle Ages. A magic book or mirror, for instance, would tell the children a story or show a video when a figure is placed on or next to it.

In addition to the in situ interfaces, children should also be empowered to configure the play set according to their requirements and preferences. This includes recording their own sounds for the figures and adding and removing play objects, preferably at runtime.

Furthermore, there should be possibilities for parents or educators to pre-configure the environment with regard to play and learning scenarios. The reasons for this are twofold: on the one hand, parents can ensure that children are not exposed to potentially sensitive content (e.g., facts about medieval weapons or wars) and, on the other hand, parents and educators may create or select particular learning scenarios that complement topics currently taught in class (e.g., history lessons about the Middle Ages).

Overview of the Functional and Non-Functional Requirements

Given these descriptions and issues, we identify four aspects to be included in the digital augmentation process:

- The basic play set: to enhance children's play experiences by adding multimedia effects. This necessitates automatically determining the position of the play figures. Based on this position information, the play set triggers certain audial (e.g., sound effects and verbal commentaries) and visual effects (e.g., light and smoke), which let the environment come alive.

- The integration of smart devices: the play set is to be enhanced with additional smart devices to promote further interaction and play options for the children. Two approaches are pursued and compared for this purpose:
  - *Smart toys* are traditional toys with supplementary features endowing them with a “magic” touch (e.g., “magic wand” or “magic bottle”).
  - *Mobile phones* have many capabilities that can be utilized in an augmented toy scenario (e.g., display images or videos).
- Enabling playful learning: an infrastructure is to be designed, which facilitates the integration of educational content. Additionally, user interfaces must be provided for two different user groups:
  - Children: basic audial content can be played using the basic play set. Other forms of multimedia content should be made available using additional user interfaces (e.g., for videos).
  - Parents / educators: provide them with means to create and select content.
- Configuration of the play set: children must always be in control of the environment. They should be able to modify the play set – just like the traditional non-augmented version. The system must thus offer the means to add, remove and manipulate play objects as well as adjust the infrastructure. This must not only be possible at runtime, but preferably in real time and without complex operations.

Several issues are to be taken into consideration during the implementation:

- The integrated technology must be as invisible and unobtrusive as possible: the focus of the play should remain on the social interaction, storytelling and sensation from touching and moving play objects.
- Small scale miniatures: Playmobil figures are usually rather small (typically 7.5cm, scale approximately 1:23). This makes it very difficult to integrate complex technologies.
- The user interfaces must be seamlessly integrated and should not

disrupt the gameplay or the natural appearance of the play set.

- The reaction of the augmented play set should be in real time: if a figure is placed at a location, the response must be immediate in order to be coherent with the children's mental model of cause and effect.
- The augmented toy environment must be extremely reliable: if something does not work properly or as expected, children might have difficulties understanding if this is part of the normal run of events or not. A malfunctioning play set will also discourage them from using it rather quickly.
- The augmented toy environment must be completely safe: the added technology should not endanger children's safety (i.e., prohibit electrocution and other hazards).

Tables 5.2 and 5.3 summarize the the functional and non-functional requirements, respectively.

Table 5.2: Functional requirements of the AKC.

Functional Requirements
• Enhance children's play experiences by adding multimedia effects. • Provide additional devices to promote further interaction and forms of playing. • Provide the children with means to configure the play environment (i.e., add/remove objects at run-time and let them record their own sounds). • Enable the integration of educational content so that children can learn about medieval facts and tales in a playful manner. This requires the provision of adequate user interfaces for both children and parents/educators.

In the four sections following this introductory section, we describe how we realized the functional requirements. Before we present the digital augmentation of the KC, though, we discuss related work.

Table 5.3: Non-functional requirements of the AKC.

Non-functional Requirements
• The integrated technology should be completely unobtrusive. The look-and-feel of the toy environment must not be compromised. • The play set should still be playable if the technology is switched off. • The focus should always be on the ongoing play and the surrounding social interaction. Thus, interfaces should remain in the background and be seamlessly integrated. • While all non-functional requirements known from software engineering are important, distinguished attention should be paid to reliability, efficiency and usability: children should be supported easily and efficiently, the augmentation should improve their play experience, not diminish it. In this respect, the environment should also be as maintenance-free as possible. • The augmented toy environment must be safe.

5.1.2 Related Work

Zowie play sets (i.e., Ellie's Enchanted Garden and Redbeard's Pirate Quest, see Fig. 5.8) are tangible toys with integrated sensors[2] for transmitting the state of movable playing pieces to a computer application [313]. The playing pieces function as a facilitator: the output comes from a computer screen and the pieces are used as a kind of tangible user interface to perform the actions demanded from the storyline or play mode. Based on this setting, several computer-like games are implemented that integrate the real-world play set into their virtual world. The focus on the screen as output device differs from our approach: the major share of children's attention is drawn to the computer screen.

[2]It is not explicitly mentioned what kind of sensing technology is used, only that it consists of a number of patented sensing and recognition technologies that enable tracking the three-dimensional motion and rotation of pieces.

Figure 5.8: The Zowie play sets Ellie's Enchanted Garden (left) and Redbeard's Pirate Quest (right) [313].

Similar to the Zowie play sets, Höök et al. present SenToy, an "affective toy" that controls a synthetic character in a computer game [153]. Using magnetic switches, acceleration sensors and force-sensing resistors, SenToy can recognize movements and several gestures (mostly emotional gestures associated with anger, fear, surprise, sadness and joy). Through this, players can influence the emotions of the characters in the game.

Figure 5.9: The StoryToy animal farm [112].

StoryToy [112] is a toy animal farm with an integrated storytelling environment consisting of an audio replay engine and a tactile user interface based on a sensor network (see Fig. 5.9). It does not require a computer and the objective is to tell stories or play sounds based on the child's interaction with the farm animals. As such, StoryToy is very similar to our basic play set (detection of play figures that trigger audio output). The AKC, however, features additional forms of interaction and effects. We also play background music that can adapt to the actual play situation: this atmospheric but often overlooked aspect [208] further supports immersion into the play.

A slightly different approach was taken with StoryMat [292], a play space where children are able to collaboratively record and listen to their own stories. A child plays with the toys on a soft interactive play mat, thus recording a story, which then can be played back by another child (i.e., it is projected on the mat). In this way, one child's stories can trigger or influence another child's stories. A similar environment for storytelling is StoryRoom [231], where children can author and playback stories by arranging physical toy artifacts with integrated sensors and actuators (see Fig. 5.10).

In our approach we also give the children the possibility to record their own voices and sounds. Nonetheless, both augmented toy environments are dissimilar from the AKC as they center around the idea of creating a story for later replay while the AKC focuses on supporting in situ storytelling by accompanying children's play with sound, light and smoke effects.

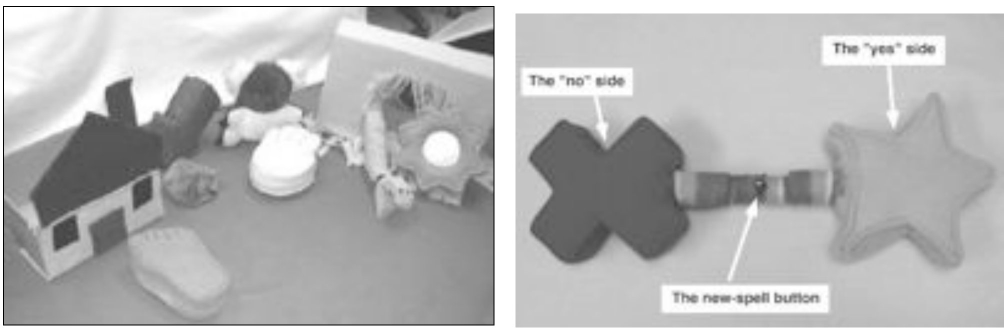


Figure 5.10: StoryRoom [231].

KidsRoom[3] is a perceptually-based, interactive, narrative play space for children [41]. The idea is to equip a room with cameras to identify current activities and projectors to display story-based images on walls and the

[3]KidsRoom is part of the "Toys of Tomorrow" program at MIT Media Lab (http://toys.media.mit.edu).

floor (see Fig. 5.11). This project resembles the AKC only insofar as its focus is also on “action and interaction in the physical, not virtual space” and to get “multiple, collaborating people to simultaneously engage in an interactive experience”. It differs inasmuch as it is not a toy environment but rather an indoor playground for children.

Figure 5.11: KidsRoom [41].

Other approaches are merely GUI-based and do not feature tangible interfaces. “KidPad” [154] and “The Klump” [32], for example, are collaborative storytelling tools that support children creating hyperlinked stories. KidPad has large 2-dimensional zoomable space where graphical objects act as cursors and hold their own state instead of menus or tool palettes. The Klump is a collaborative tool based around an amorphous three-dimensional object (in fact, a textured deformable three-dimensional polygon mesh) that can be stretched, textured and colored and that makes sounds while being manipulated. Both approaches, however, require the children to sit in front of a computer and do not possess the benefits of an augmented environment.

5.2 Augmentation of the Basic Play Set

The Augmented Knight’s Castle as it exists today is the result of continuing improvements and extensions – over the last three years, the basic play set has changed tremendously. In this thesis, we mainly focus on the latest version, but briefly summarize the major iterations.

5.2.1 Major Iterations of the AKC

As with W41K, we used RFID technology to identify and track play objects. The first version of the AKC was quite straightforward: the play set was equipped with eight 10x10cm antennas, each representing an active zone (see Fig. 5.12 (top)).

Figure 5.12: The three versions of the AKC play set.

Since we used a multiplexer for consecutively energizing the eight antennas and the Fosstrak middleware[4], the performance was rather poor

[4]Fosstrak is an open source RFID software platform that implements the EPC Network specifications

(one read cycle took approximately 4-5 seconds). Additionally, the 2x1cm RFID transponders that were simply attached to the feet of the play figures were comparably obtrusive.

By and large, this first prototype did not satisfyingly meet any of the design guidelines and it was far from being usable under real circumstances. However, it served to demonstrate the general modus operandi and allowed us to gather some first experiences. In the next iteration, we improved the AKC in several ways (see Fig. 5.12 (middle)):

- Response time: to decrease the response time, three steps were taken: first, we equipped each active zone with its own RFID reader; second, we substituted the Fosstrak middleware with a custom-built application; third, we used a database to store all data (as opposed to XML files). These alterations yielded an average response time of less than one second, which is good enough for real-world usage (this was also confirmed in our user study, see Chapter 6).
- More and bigger active zones: to increase the size of the sensitive areas, we almost tripled the number of antennas (23 antennas covering nine active zones). The larger areas, for instance the inner yard, were covered with multiple antennas attached to one multiplexer. Our application was optimized to also reduce the time required for one round of multiplexing: inquiring eight antennas now took slightly more than two seconds, which is consequently the worst case for detecting RFID tags on one particular antenna.[5]
- Invisibly incorporation of technology: the antennas were integrated into the play environment as shown in Fig. 5.12 (middle), which enabled an unobtrusive detection of the RFID transponders. To equally disguise the integration of RFID tags into the play objects, we used two tag types of considerably smaller size, circular Tagsys Ario 10-SDM with a diameter of ca. 9mm and square Tagsys Ario 10-SM with an edge length of ca. 13mm (see Fig. 5.16).

While the second prototype was already very close to a working product – this play set was also used for the user study (see Chapter 6) –, there

and it is mainly designed for supporting logistics and supply chain management (www.fosstrak.org).

[5] As discussed in Section 4.2, a reader can poll an antenna or a multiplexer at a rate of approximately 4Hz. If a multiplexer operates eight antennas, the best, average and worst cases are approximately 250ms, 1000ms and 2000ms, respectively.

was still potential for optimizations and extensions:

- Creating a distributed play set where children can move locations around freely, just as they would with the traditional play set.
- Integrating additional effects (e.g., light or smoke effects).
- Add configuration tools for the children to create their own play set (i.e., add and remove objects) and to record their own sounds. The integration of configuration tools should be easy and seamless.

In addition, smaller improvements were realized (e.g., the removal of a play figure would stop the currently played sound – before, a sound file was played until completed). Some of the adjustments were based on findings of the user study (see Section 6.3), others were simply new ideas.

The goal of creating a completely distributed play set required us to start from scratch. We built three separated and autonomously running play elements connected via WiFi (see Fig. 5.12 (bottom)). The elements of the play set can now be moved and arranged freely. Since the third and final version of the AKC is explained in more detail in the following subsections, we will now conclude the major changes of the iterations for the basic play set by summarizing them in Tab. 5.4.

5.2.2 Physical Augmentation of the Play Set

As before, the RFID hardware configuration of the AKC consisted of:

- FEIG ID ISC.MR101-A readers,
- FEIG ID ISC.ANT.MUX multiplexers, which perform time multiplexing with up to eight different antennas each,
- FEIG ID ISC.ANT40/30-A antenna (size 4x3cm) and
- FEIG ID ISC.ANT100/100-A antenna (size 10x10cm).

We defined the following read areas in our play set: the courtyard, the drawbridge, the prison, the throne room, the tower of the king's castle, the area around the fairy spring, the area in front of the dragon tower, the dragon's lair and the top of the dragon tower (see Fig. 5.13).

In Chapter 4 we explained that RFID technology operating in the high frequency spectrum (typically, at 13.56 MHz) features a well-defined read

Table 5.4: Major iterations of the AKC.

<table>
<tr><th>Initial Version</th><th>Second Version</th><th>Third Version</th></tr>
<tr><td>Slow response time</td><td colspan="2">Quasi-real-time response</td></tr>
<tr><td>Eight active zones: one RFID reader, one multiplexer and eight antennas</td><td colspan="2">Nine active zones: nine readers, three multiplexers and 23 antennas</td></tr>
<tr><td colspan="2">Technology is loosely placed under a table</td><td>Everything is secured in place (enables easy transportation)</td></tr>
<tr><td>Storage: XML files</td><td colspan="2">Storage: Database</td></tr>
<tr><td colspan="2">All action rules are hardcoded</td><td>Users can create and configure action rules</td></tr>
<tr><td colspan="2">Integration of additional devices hardcoded</td><td>Web-service-based infrastructure for flexible integration of devices</td></tr>
<tr><td colspan="2">Centralized play set with one computer</td><td>Distributed play set with three autonomous elements connected via WiFi</td></tr>
<tr><td colspan="2">Audio feedback only</td><td>Audio feedback plus light and smoke effects</td></tr>
</table>

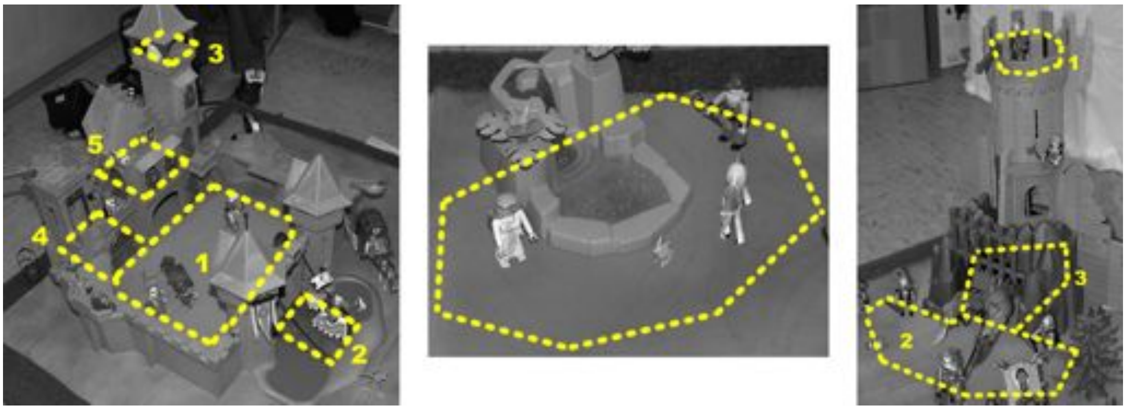


Figure 5.13: The “active zones” of the AKC play set.

range. This enabled us to adjust the size of active zones to the physical layout of the play set: for example, the draw bridge was observed using one 10x10cm antenna, the courtyard of the castle was covered by eight 10x10cm antennas and the tower platforms were each equipped with one 3x4cm antenna.

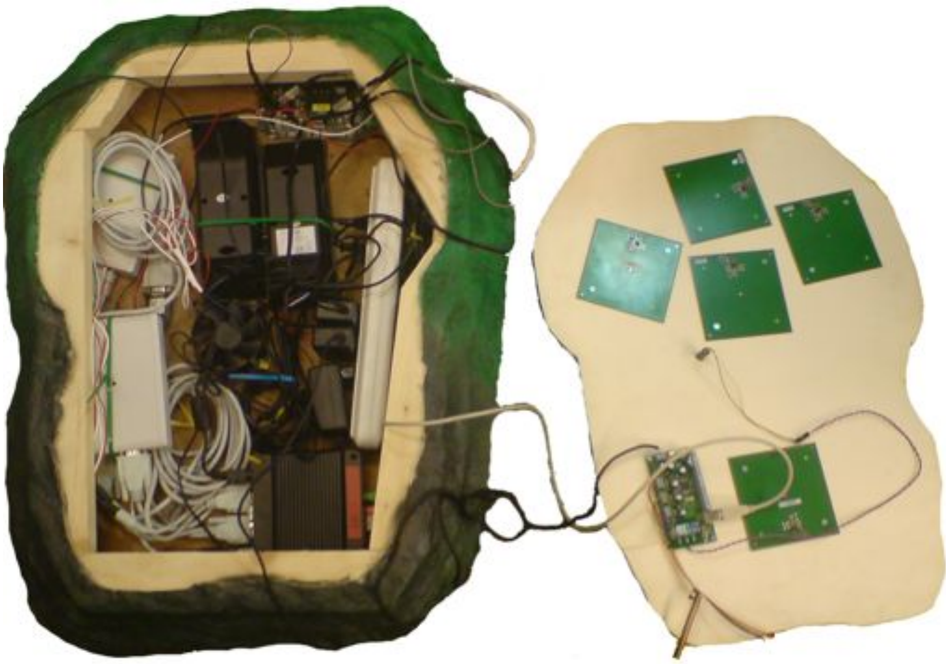


Figure 5.14: The interior of the dragon tower: RFID readers, multiplexer, speakers and computer (left) as well as antennas and effect board (right). Not shown here is an additional antenna that was attached underneath the top of the dragon tower.

The RFID antennas were either attached to the toy buildings or to different types of floor elements to detect the presence of toy pieces in their proximity. Figures 5.14 and 5.16 show how the RFID technology was unobtrusively integrated into the play set.

Additionally, the carriage and the enchanted tree were equipped with BTnodes[6] operating attached Skyetek[7] M1-mini RFID readers with external antennas (see Fig. 5.15).

Figure 5.15: The “Enchanted Tree” (left) with mobile RFID reader (center) and a custom-built antenna (right).

The RFID tags of different sizes were attached to or incorporated into the pieces of the play set to uniquely identify and consequently associate virtual content with them (see Fig. 5.16).

Figure 5.16: The left picture shows a flag with an RFID tag, the right picture shows the king with RFID tags integrated into the back, head and under the feet.

To tackle the problem with tag orientation in antenna fields [108], we tagged most objects with several transponders of different orientation (e.g., back and bottom side of figures) to have at least one of the tags read in an

[6]www.btnode.ethz.ch
[7]www.skyetek.com

antenna field. In other words, in contrast to using multi-tagging for determining the orientation of objects as we did with W41K, here the focus was on maximizing the probability of detecting a figure.

The RFID readers were connected to a NorhTec[8] Micro-Client Sr miniature computer equipped with a 500MHz VIA ULV processor, 512MB RAM, WiFi and three USB and 2 serial ports (see Fig. 5.17 left). This computer does not have a hard disk drive but uses a 4GB compact flash card instead, which makes the system more robust to jolts caused by playing with or moving the play set. An integrated sound card outputs audial feedback through attached speakers.

Figure 5.17: The NorhTec MicroClient Sr computer with a very small form factor (115x115x35 mm) (left) and the effect board (right).

In addition to this, we added an effect board to generate light and smoke effects (see Fig. 5.17 right). This board consists of an Atmel Atmega16 microprocessor, which operates an light-emitting diode (LED) and a smoke generator. The three color channels of the LED can be controlled independently and concurrently, allowing for different effects like smooth changes of colors or stroboscopic patterns. We included two such boards in the AKC play set, one in the dragon tower and one in the fairy well (see Fig. 5.18).

Similar to audial feedback, the light and smoke effects can be associated with events based on the detection of tagged play figures. We now explain how this is done and describe the software and communication infrastructure.

[8] www.norhtec.com

Figure 5.18: Smoke and light effects at the dragon tower (left) and the fairy well (right).

5.2.3 Software and Communication Infrastructure

Communication Infrastructure

The AKC play set consists of three individual locations, castle, dragon tower and fairy well, respectively. The locations run autonomously but are interconnected via WiFi. Additionally, there is one server in the network that runs a database with all information about the play objects. The three locations hence act as clients that detect play figures placed in one of their active zones and forward this information to the server. The server determines what action is to be carried out and sends this information back to the client, which then executes it (e.g., playing a sound file). If the sound file is not yet stored in the client's cache, the file is sent to the client as well. Fig. 5.19 shows the sequence diagram of the communication between client and server.

Using a central server was not so much a design decision as it was driven by one major constraint: the memory capacity of the RFID transponders. Current RFID tags, including the ones used for the AKC, can only store few kilobytes of data. If, however, the capacity was at the magnitude of mega- or even gigabytes, all information could be stored with the play objects directly. The server thus simulates this scenario: instead of storing and retrieving information (e.g., sound files and rules) from the RFID transponders directly, the locations query the server (the unique IDs of the transponders are the look-up keys). In other words, if RFID transpon-

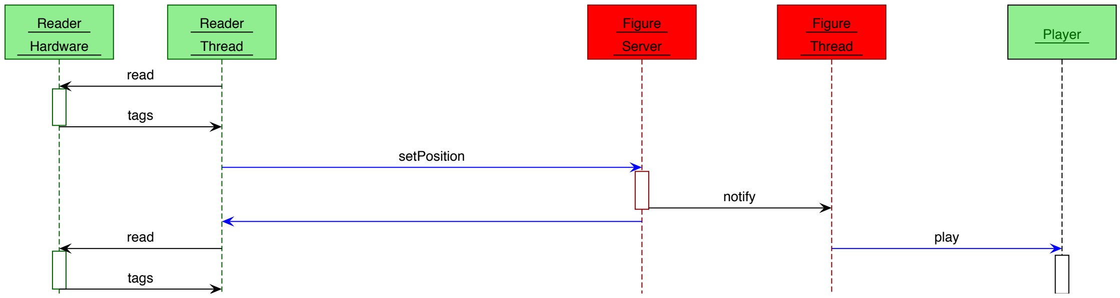


Figure 5.19: The sequence diagram of the communication between client (green; left and right) and server (red; center) when a figure is placed in an active zone.

ders had sufficient memory capacity, we would not require a server: the play set would then only consist of a number of autonomously running locations.

To ensure fast and easy extendability of the play set (i.e., adding new locations) as well as the easy and flexible integration of mobile devices, we decided to use web services for its many benefits in terms of device independence and interoperability.

Play Logic

The play logic determines, based on the current state of the play set, what audio and/or visual effects are executed. Initially, the play logic consisted of state machines stored in XML files, representing chronological play processes. State transitions were triggered by conditions that could be formulated using logical operators and a query language to access the information of the object model. States would then perform actions (e.g., play a sound).

While state machines allow for very powerful scenarios (see Fig. 5.20), they inherently become very complex and are thus incomprehensible to children. Additionally, numerous simultaneously running state machines would be necessary for a pulsating and diverting play set, which might further confuse users.

For these reasons, we decided to replace the state machine concept with a different approach. We chose the *event-condition-action* (ECA) model widely known from database systems [74, 117]. The model is defined as follows:

- Event (E) is a primitive (basic) or composite event.

- Condition (C) is either a boolean expression or a SQL query on the database.
- Action (A) is either a database operation or an arbitrary application program that is executed.

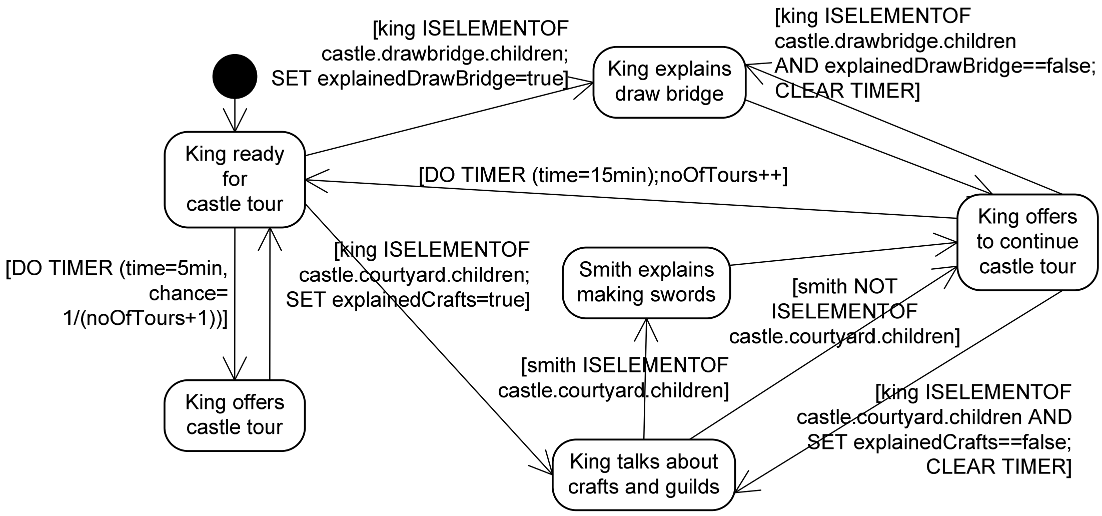


Figure 5.20: An example of a (small) state machine.

Mapped onto our play scenario, this would work as follows: for example, if the queen is placed in the castle tower (event) and the ghost is there (condition), she screams (action). The conditions can be arbitrarily complex, but we were careful about keeping the number of conditions of one ECA rule minimal (typically only one condition). Each play figure can have many ECA rules and each rule has a probability factor. If a particular event is linked with several rules, one is selected randomly with the probability factor taken into account.

All ECA rules are stored in the database together with all information about the AKC play set. The entity-relationship diagram of the AKC is displayed in Fig. 5.21.

5.2.4 Configuration Tools for Children

One important aspect was to empower children to configure the environment with respect to their personal preferences and requirements. In detail, this includes providing them with the means to add new play figures as well as to record their own sounds.

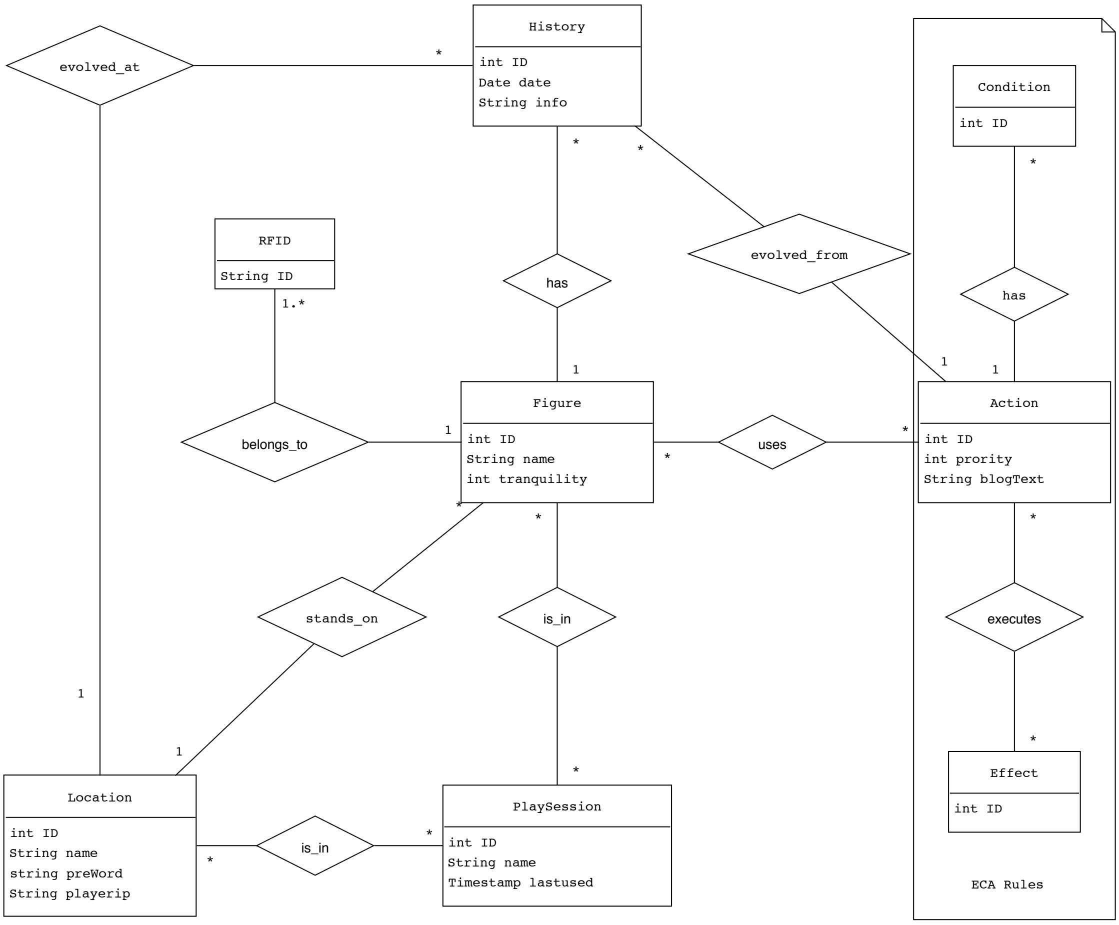


Figure 5.21: The entity-relationship diagram of the AKC.

To this end, we implemented a *magic box*, in which figures can be placed (see Fig. 5.22). A new play figure can simply be added to the play set by putting it in the magic box for several seconds (i.e., the RFID tags are scanned and the figure's information is stored in the database of the play set).[9] After this initialization step, the figure can be used.

The process of recording sounds is equally simple: a child places a play figure in the magic box and just starts saying something or making a sound. Basically, the integrated microphone records as long as a figure is in the magic box. Having removed the play figure, the child simply puts it in one of the active zones and the previously recorded sound is played. This completes the recording process and the ECA rule is added to the database. The next time this play figure is placed at this location, the recorded sound is played (e.g., the queen says "What a great view!" when she is on top of the castle tower). If the same ECA rule is recorded

[9]In the future, either the information is stored on the RFID transponders directly or an online repository is accessed on the fly.

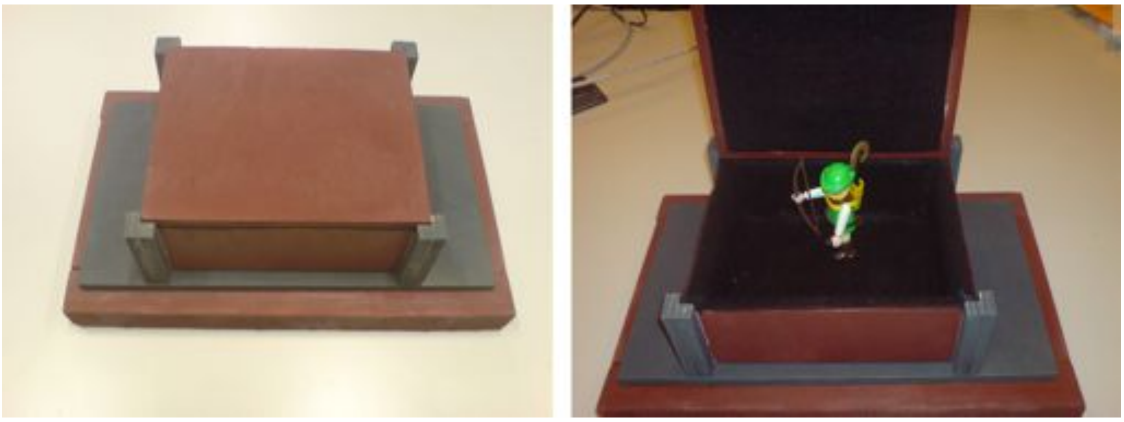


Figure 5.22: The magic box that children can use for recording sounds.

again (i.e., a different sound is recorded for the same selection of figure and location), either of the rules is executed randomly, with the newer rule having a higher priority.

It is also possible to create more complex rules: if a figure is placed in an active zone with other figures already present, the ECA rule would recognize this as additional conditions. In other words, the play figure would only give the recorded audio feedback if the other figures were also there (e.g., the queen says “Eek, a ghost!” when she is on top of the castle tower *and* the ghost is there, too). Additionally, by putting two or more figures in the magic box and placing them at a designated area afterwards, children can simulate dialogues or crowd chatter (e.g., the golden knight and the blacksmith would exchange a few words when meeting in the inner yard of the castle).

Since the AKC infrastructure allows the flexible integration of different end-user devices, it would also be possible to simply use a mobile phone or similar device for this task. This approach, however, can be problematic as the usage of a purely technical device might disrupt the ambience of the play environment. We discuss this next.

5.3 Integration of Mobile Devices

In addition to the augmented play set and the computer-based options for configuration, it is also possible to enrich the children’s play by integrating mobile devices.[10]

[10]Interaction with mobile devices somewhat contradicts the vision of invisible computers working unobtrusively in the background. In the past, this has led to some debates on the relation between pervasive

Figure 5.23: The "Point-me-touch-me" paradigm [266] using a smart toy sword (left) and a mobile phone (right).

We integrated two types of mobile devices, *mobile phones* and *smart toys*. Both approaches potentially enrich children's play experiences as they provide new play options (see Fig. 5.23). We now discuss these two different approaches and subsequently analyze their advantages and disadvantages with respect to augmented toy environments.

5.3.1 Mobile Phones

In recent years, mobile phones have become increasingly powerful and there is already some work as to their role and suitability as "universal devices" (e.g., [282]). In this sense, mobile phones can also be used in our augmented toy environment to provide children with additional services (e.g., display information about a figure or offer small games and quizzes).

To enable the mobile phone as a touch-me device, we equipped a Nokia 6830 with our custom-built RFID reader module based on the BTnode platform similar to the approach as presented in [266]. As shown in Fig. 5.24, the external antenna is attached to the top of the mobile phone to allow the point-and-touch interaction with pieces of the play set.[11] The application on the mobile phone was implemented in C++ for Symbian OS and communicates with the BTnode and the base station via Bluetooth.

Enabled as a touch-me device, pieces of the play set touched by the children can thus be identified. In this respect, a mobile phone can repre-

and mobile computing: Saha and Mukherjee, for example, see mobile computing as a subset of pervasive computing [294], while Roth argues for the opposite [290]. For further discussion we refer to [128, 226].

[11] This admittedly bulky assembly could be replaced with near-field communication (NFC)-enabled mobile phones in the near future.

Figure 5.24: Mobile phone with RFID-reader and external antenna, front (left) and back view (center). The right picture shows its "embodiment" of a magic potion bottle.

sent many roles during a course of play (see Fig. 5.24 right): for instance, it can act as an information device displaying multimedia content related to the piece of the play set that is touched. This role can also be the interface to integrate learning experiences into the play (see Section 5.4). It can also represent a bottle containing a magic potion (e.g., the potion can then be administered to a wounded knight to heal him by touching the figure) or a weapon (e.g., children can touch each other's mobile phones and figures on the play set to initiate a fight between the figures). Certainly, many more roles are conceivable.

5.3.2 Smart Toys

Despite their many functionalities, mobile phones cannot change their look-and-feel, rendering this approach suboptimal in terms of seamless integration into the play set. For this reason, we also considered embedding mobile devices into physical toys, hence called "smart toys".

Similar to the mobile readers of the basic play set, we applied the BTnode platform with connected Skyetek M1-mini RFID readers to different toys to enable them as touch-me devices (see Fig. 5.25). The BTnode sends the IDs of the RFID tags to the base station via a Bluetooth L2CAP connection. The external antenna of the RFID reader is adjusted to the form factor of the toy (e.g., the opening of the bottle or the top part of the magic wand).

To take advantage of the embedded BTnode platform and to allow further forms of interaction, we attached a sensor board to the BTnode that

Figure 5.25: BTnode with RFID reader and sensor board embedded into a toy bottle (left) and a toy wand (right).

included, among others, a triaxial acceleration sensor and a microphone. The acceleration sensor, for instance, enables gesture recognition such as shaking the magic bottle. Simple gestures (e.g., shaking) can be analyzed on the BTnode; for more complex gestures, the data (rather, a data stream) is forwarded to and analyzed on the base station using the Georgia Tech Gesture Toolkit [365]. Additionally, we incorporated vibration modules and LEDs into wand and bottle for haptic and visual effects. At least one toy should be included into the play that allows selecting a figure and display information about it (or play corresponding audio or video). In our case, we chose the magic wand for this.

The toys have to be carefully chosen since the roles they represent are solely communicated by their physical appearance. Subsequently, a smart toy can typically embody one or two roles only, necessitating the integration of new smart toys for new roles and forms of interaction. Additionally, the role of a particular smart toy may not be self-evident. In our aforementioned pre-study, for instance, we would ask children how they would understand and use our magic wand and magic bottle. To this end, we handed them mockups (i.e., the toys had the physical appearance as shown in Fig. 5.25, but without any technology-enabled features) and asked them, what these objects were and how they would use them in their stories. To our surprise, children's perceptions and ideas varied greatly.[12] The different perceptions – which certainly depend on the indi-

[12]The magic bottle, e.g., would be anything from a "magic bottle" with a magic potion (as discussed before) over a "magic lamp" (letting a djinni appear by rubbing it – cf. "Aladdin and the Wonderful Lamp") to a "magic container", in which items can be placed and magically altered.

vidual upbringing and sociocultural background – make it difficult to find toys whose appearance is not liable to misinterpretations (which may also jeopardize the proposed added functionality).

5.3.3 Comparison of the Two Approaches

Both approaches, mobile phones and smart toys, have their respective advantages and disadvantages (see Tables 5.5 and 5.6). Overall, one can say that a mobile phone has many functionalities for a broad spectrum of applications, but it lacks the usability and appearance of a toy. Smart toys, in contrast, support seamless integration and more intuitive use, but they can only represent few roles and all functions have to be custom-built, which requires more time and effort for design and implementation.

Which approach is more appropriate, depends on, for example, prospective functionalities: if videos or images must be displayed, mobile phones are the obvious choice. If the emphasis is on seamless integration, smart toys are better. Another important factor is the age of the children: young children might have difficulties operating a mobile phone and should therefore use smart toys. Older children are more used to mobile phones and usage of technical devices might encourage their engagement in the play since it resembles the user interface of computer or video games.

5.4 Playful Learning

The digital augmentation of a traditional toy environment like the KC can enrich children's play experiences, but it can also enable playful learning: resembling a medieval world, the figures can tell the children about their lives and generally interesting facts about the Middle Ages (e.g., the blacksmith tells about how armors and weapons were forged while the king talks about his tasks and duties).

We developed an infrastructure for the production, modification and integration of educational content for this augmented toy environment. Each play object has a virtual counterpart that can be linked with a variety of educational information, which is then made available in the play environment in an unobtrusive and playful manner. To optimize the integration of learning experiences in children's play, the figures tell facts and tales from their perspective. They also address the children directly, thus

Table 5.5: The advantages and disadvantages of mobile phones.

Pros	Cons
• High deployment of mobile phones in the population, even among children. • No extra device needed. • Multimedia capabilities (audio and visual). • Representation of many roles in the play set (e.g., magic potion, sword, magic wand). • Basic haptic capability (using the vibration alarm). • Can easily be replaced if broken.	• No seamless integration into the play set. • Touch-me paradigm is possibly not as intuitive. • Representation of roles only through multimedia and haptics. • Mobile phone cannot change its look-and-feel. • Software must be installed prior to play. • Additional RFID reader needed (NFC-enabled phones in the future).

stimulating direct interaction (e.g., the bard starts singing every now and then and invites the children to sing along).

Even more complex scenarios are possible: the king explains what it was like to live with his family and court in a castle. As shown in Fig. 5.26, the king invites the child to follow him through different areas and settings of the castle. The king explains for each setting different facts (e.g., defense weaponry, craftsmen and draw bridge) and asks the child to place him at different locations for new information or to leave him at the current location to give more details. Such "castle tours" can either be triggered by the children deliberately or offered by the figures (e.g., after a certain while of inactivity, the king verbally offers to reveal some secrets about the castle).

5.4.1 Providing the Content

Principally, the educational content is provided twofold:

Table 5.6: The advantages and disadvantages of smart toys.

Pros	Cons
• More seamless integration into the play set. • Look-and-feel of the toy represents the role(s) in the play set. • Choice of toy supports intuitive usage of touch-me paradigm. • No installation procedure prior to playing; can be used instantly. • Sensors bring context into the play (e.g., shake magic potion before usage).	• Only limited roles represented by a single toy. • The role or function of the smart toy may not be unambiguously discernible. • Several toys have to be embedded with mobile devices. • Toys are custom-built. • Limited input and output capabilities. • If broken, replacement device must be built (easier with mobile phones).

- *Directly*, using audio feedback (i.e., verbal commentaries by the figures) and
- *Indirectly*, through a mediator such as a cell phone or a screen.

While the verbal commentaries played by the AKC can be used to convey facts about the Middle Ages in a playful way, some educational content may benefit from further multimedia capabilities such as images or videos. As the AKC does not feature any displays – they would counteract the traditional play atmosphere – we support the inclusion of additional devices such as displays or personal digital assistants (PDAs) into the toy environment (also see Section 5.2.3). In particular, we integrated a *magic mirror* (a disguised touch screen) and a *magic loupe* (a PDA) (Section 5.4.3).

One main objective was that the devices should smoothly blend with the play environment and not disrupt the children's play experience. Our magic mirror, for instance, is modeled after its counterpart in "Snow

Figure 5.26: “Castle tour”: the king explains the necessity for and construction of the draw bridge (left) and proceeds to several points of interest inside the castle (right).

White and the Seven Dwarfs,” where it represents an all-knowing source of information. Matching our medieval world and given the respondent function the device is supposed to play, we deemed it a good choice (also cf. [180]).

Additionally, the semantic relation between the physical and virtual realities must be guaranteed to ensure that children easily understand the role or function of a play object and its virtual content. In our play set, the appearance of the physical toy figures is semantically connected to the function such a figure actually had in medieval times.

5.4.2 Infrastructure

The underlying infrastructure features a number of different interfaces to account for the capabilities and idiosyncrasies of different end-user devices, while using a unified representation of the educational content that is independent of the actual feedback channel.

Our main goal was to design a flexible, extendable and easily comprehensible infrastructure for interactive and playful learning in augmented toy environments. To this end, the infrastructure must provide means to easily link educational content to play objects as well as to retrieve this content.

While our main target group are children playing with the play set, there are two further parties involved: first, parents or educators (i.e., school teachers), who supposedly purchase toys and have an interest in knowing what these toys can do. Second, there are content and toy designers, who create educational content modules and subsequently associate them with the play objects. With regard to the augmented toy environment and the individual interests, we can hence derive the following use cases:

1. Children can interact with the AKC and retrieve educational content using the magic mirror or the PDA.
2. Parents / educators can selectively activate educational content for a child. For them, a web-based user interface is provided. They can furthermore review individual interaction histories for each child.
3. Developers can create and modify learning modules and integrate multimedia content using a content management system.

As mentioned above, at the core of the infrastructure are the play objects with associated educational content. The educational content is delivered in *learning modules* with each module representing one topic. Each module is divided into several, consecutive *levels*, which reflect the gradually increasing complexity and difficulty of the content. Each level is associated with *multimedia content* (see Fig. 5.27).

A child can select any level of a module that is unlocked. While most levels are available from the start, a level can have a quiz that must be solved in order to proceed to the next level (unlock); these levels cannot be skipped. This not only ensures a revisable learning progress but is even necessary when a higher level is dependent on the information provided in previous levels. In addition to this, each module might be available in several *languages*. Parents and educators configure what languages should be available and children can switch between these languages simply by pressing a button. The presentation of the same educational content in different languages can help the children with learning foreign languages in a playful manner.

The modules are associated with play objects using *keywords*. To this end, each figure and each learning module has a set of keywords associated with it. The keywords are meant to describe them as precisely as possible. They are assigned by the designers of the figures and the developers of the learning modules, respectively. The keywords can be labeled *sensitive* by the designer if the content is potentially critical (e.g., learning modules about weapons or wars) and also have a *minimum age* attribute.

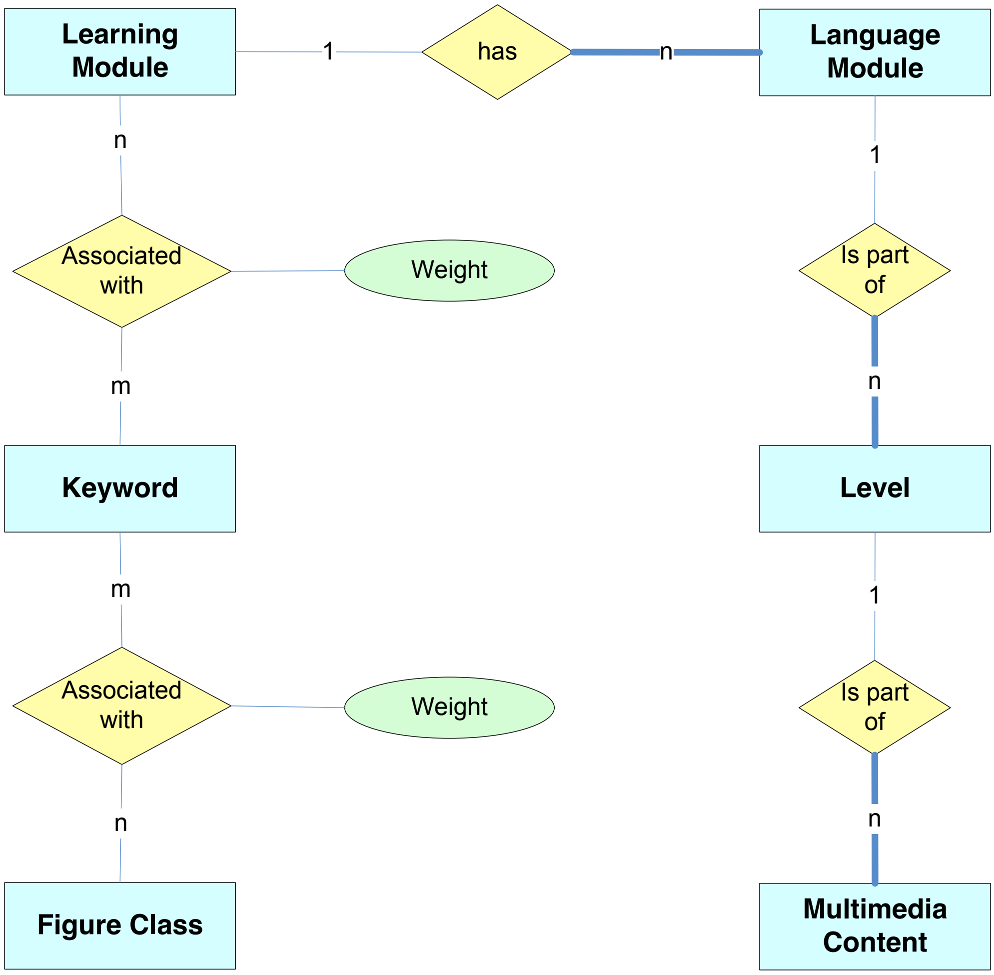


Figure 5.27: This entity-relationship diagram shows how the learning modules are structured and how they are related to figures using keywords.

Additionally, the keywords can be weighed to reflect the relevance of the keyword to this figure or learning module.

A learning module is relevant for a figure, if one or more keywords match. This approach has several advantages compared to fixed associations:

1. There can be many designers of educational content and figures; no synchronization or coordination is required.
2. Newly created learning modules can be easily associated with figures already in existence.
3. The number of learning modules is not limited; for each figure there is a potentially great variety of different modules to pick from.

4. It is even possible to easily link different learning modules, which allows for a more in-depth learning experience.

Educators can pre-configure the selection process by marking keywords for a particular child as *blocked* (i.e., modules that contain at least one blocked keyword are exempt from being displayed) or *preferred* to exclusively select modules for a child (i.e., modules must contain at least one preferred keyword to appear on the list) (see Fig. 5.28). The *block* attribute outweighs the *preferred* attribute: if a learning module contains both, keywords marked as *blocked* and keywords marked as *preferred*, the module is not available.

Conclusively, a learning module is not available for a child if at least one of the following conditions is true:

1. The module is not available in the currently selected language.
2. The minimum age of the module is higher than the child's age.
3. The module contains one or more keywords that are blocked by the parents.

To access a learning module, the child uses one of the available interfaces (in our case the magic mirror or loupe) and scans a play figure (Fig. 5.29 shows the flow diagram of the magic mirror). The device then provides a list of all associated in the order of their relevance. The relevance is determined by the ranking value $\mathcal{R}$ of a module $m \in M$ for any given figure f:

$$m \in M : \mathcal{R}(m, f) = \sum_{k \in K} G(m, k) * G(f, k)$$

with $G(m, k)$ being the weight of the keyword k associated with the module m and $G(f, k)$ being the weight of the keyword assigned to figure f. Accordingly, the maximal ranking value $\mathcal{R}_{MAX}$ for a figure f is

$$f \in F : \mathcal{R}_{MAX} = \max_{m \in M}(\mathcal{R}(m, f))$$

These values indicate how well a module matches a figure. The ranking values are sorted from high to low. In addition to that, a selection value $\mathcal{S}$ is used to select only modules with a ranking value higher than $\mathcal{S}$. In other words, the lower the threshold $\mathcal{S}$, the more modules are being displayed.

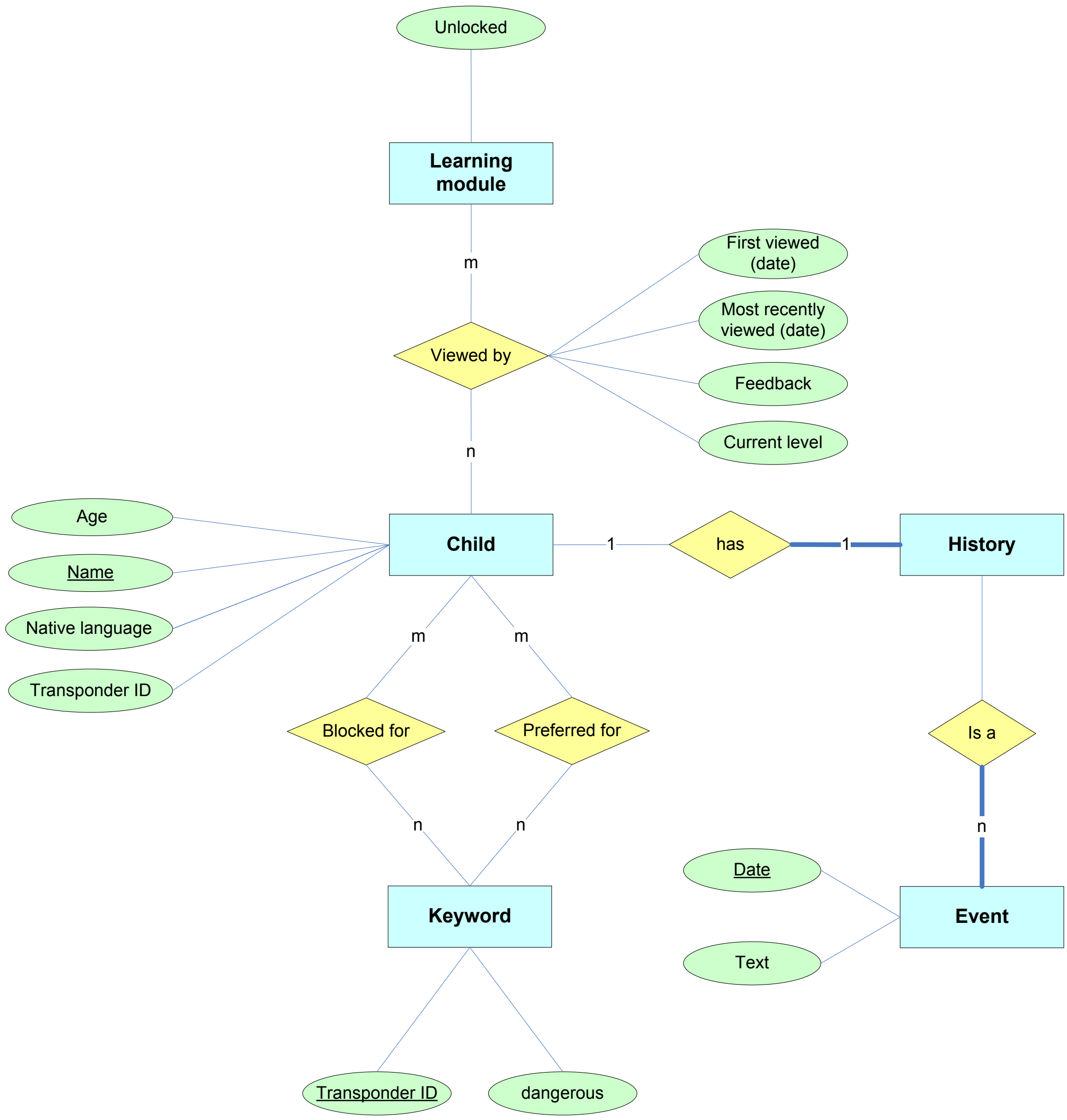


Figure 5.28: This entity-relationship diagram shows the relationship of and between learning modules, keywords, children and their learning history.

The modules are divided into two groups: the first group contains all learning modules with at least one keyword marked as *preferred* and the second group contains the remaining modules. In both groups the learning modules are then sorted by their ranking value. The subsequent merging of both groups (i.e., the second group is appended to the first one) yields the final list of available learning modules for this child sorted by relevance.

To guarantee maximum flexibility, the multimedia content is referenced by a uniform resource locater (URL): on the one hand, the educational content is globally accessible and does not need to be stored locally (i.e., the educational content is always up-to-date) and, on the other hand, the educational content can be provided using numerous different technologies. Additionally, the communication infrastructure is based on web services to ensure flexibility with regard to end-user devices: not all devices are capable of displaying websites and their limited input and output capabilities often necessitate adjusting the provided content.

5.4.3 Configuration Tools for Children

Magic Mirror

The magic mirror consists of a computer with a touchscreen, a webcam and a small wooden pedestal with an embedded RFID antenna. A child can use the magic mirror by simply placing a figure on the pedestal: the mirror will then switch from displaying the child's reflection (using the webcam, see Fig. 5.30) to displaying the learning modules associated with this figure (see Fig. 5.31). In order to recognize individual children, we provide them with a personal magic item (e.g., a brooch, a magic card or a figurine) that they will need to wear or place next to the mirror in order to activate it. Each magic item contains an RFID transponder that identifies the child, thus supporting an individual learning history for each child in order to keep track of his or her progress.

The magic mirror then displays the educational content available for this play figure. Depending on the available content, children can select from a number of different learning modules and retrieve information about the figure as well as facts about the Middle Ages in general. In contrast to the verbal commentaries, the magic mirror is much more powerful in terms of feedback (i.e., text, pictures and videos).

The main advantage, however, is the higher level of interactivity: while the verbal commentaries during the play allow for some interaction with the children, the magic mirror is capable of more sophisticated selection and feedback processes such as quizzes and puzzles.

Magic Loupe

In addition to the magic mirror, a PDA-based solution was implemented (see Fig. 5.32). This approach is mainly motivated by two trends regard-

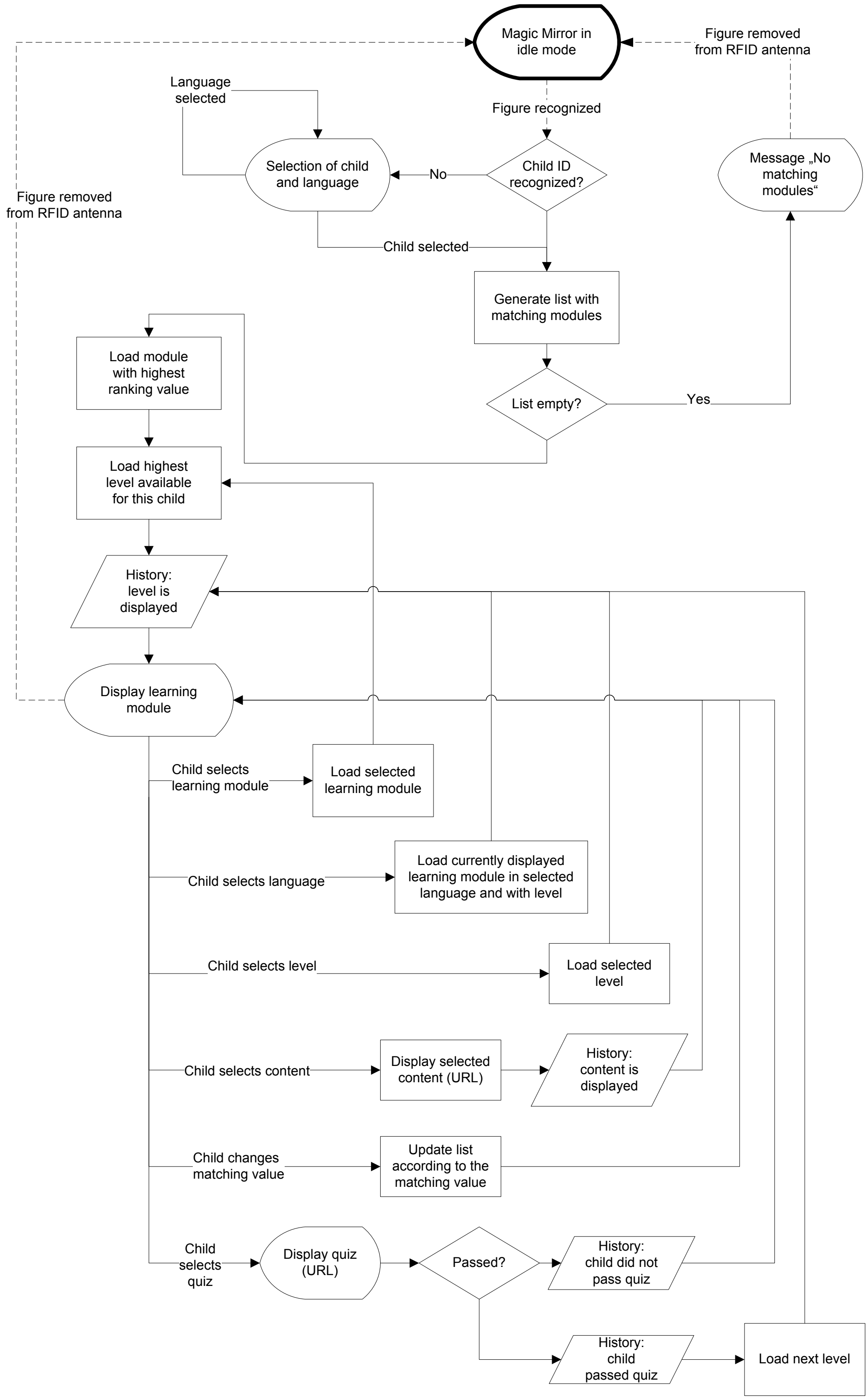


Figure 5.29: The UML flow diagram of the magic mirror.

ing mobile phones and similar devices: first, these devices are steadily becoming more powerful with novel capabilities being added and old ones being improved constantly. Second, the number of children in possession

Figure 5.30: The magic mirror login screen.

of mobile phones is continuously growing, even at elementary school age (also cf. Chapter 6). In other words, small mobile devices must be considered seriously when designing pervasive (computing) environments, even for children.

The PDA, a HP iPAQ hx2400 with integrated WiFi and an attached RFID reader (Socket RSC 6E), can be seen as a pocket magic mirror and principally offers the same functionality as the magic mirror. The problem is that a PDA has limited resources by comparison and a standard browser on the PDA is often not sufficient since the browser usually displays the original website with scroll bars, necessitating a custom-built user interface. We thus implemented our own user interface: the magic

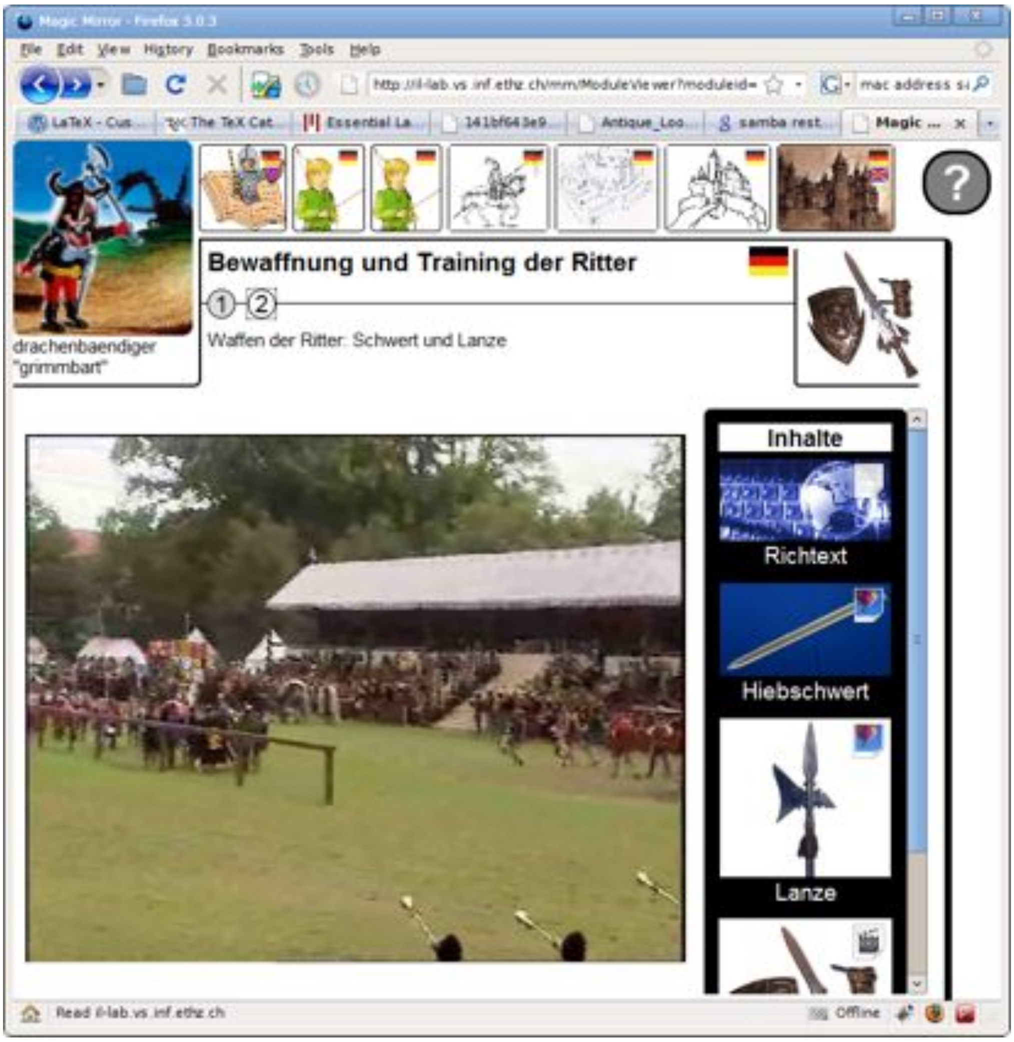


Figure 5.31: A screenshot of the magic mirror. The matching modules are displayed on top.

loupe is now capable of (dis-)playing almost all learning modules – the multimedia content is dynamically adjusted to the I/O capabilities of this device (e.g., images or videos are resized accordingly).

5.4.4 Configuration Tools for Parents and Educators

In addition to children, our main target group, we also considered parents and educators. This user group has very different intentions and prerequisites and there are two major distinctions compared to the user interfaces presented before. First, the interface need not seamlessly blend with the play environment: traditional I/O like mouse, keyboard and computer screen can be used and the interface must not be formated child-friendly –

Figure 5.32: The PDA with the attached RFID reader.

a simple but well-arranged website is sufficient. Second, parents and educators should be enabled to configure *everything*, from adding new play objects over selecting learning modules to blocking sensitive content.

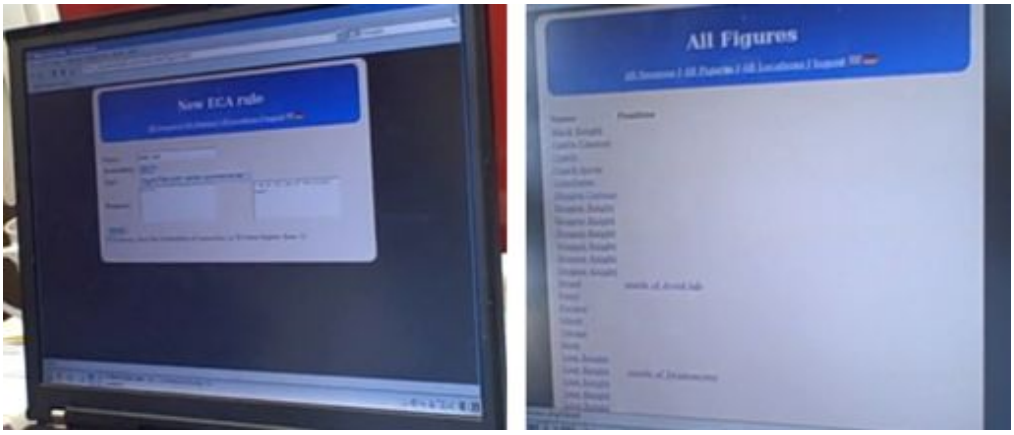


Figure 5.33: The configuration tool for parents and educators.

To this end, we developed a web-based configuration tool (see Fig. 5.33). Using this tool parents and teachers can not only do everything children can do, but they are furthermore enabled to manage play sessions, administer learning modules or create new content.

In general, the configuration tool for parents and educators is powerful and easy-to-use: with a few clicks, new play and learning scenarios can be created and modified or children's learning histories be studied. While this intervention is not essential to the operation of the AKC (i.e., the augmented play set can be easily started and stopped by children without adult support), we think it is necessary to provide them with adequate tools to influence the playing of children, especially in the context of (playful) learning as there is clearly a risk in linking traditional play objects with virtual content, especially if this content can be downloaded from the Internet.

5.5 Discussion

In this section we discuss how well the AKC actually meets the requirements and design guidelines. We also discuss future work.

5.5.1 Meeting the Functional Requirements

We initially established four functional requirements for the digital augmentation of the AKC (cf. Tab. 5.2):

- Support children's play experience by adding multimedia effects.
- Provide additional devices to promote further interaction and forms of playing.
- Provide the children with the means to configure the play environment (e.g., let them record sounds).
- Enable the integration of educational content such that children can learn about medieval facts and tales in a playful manner. This includes the provision of adequate user interfaces for children, parents and/or educators.

The AKC, at least in its latest version, meets all four requirements. The digital augmentation adds multimedia effects to the traditional play set to create a new enthralling play experience for children: using RFID technology, we can track play figures and thus react to the children's play by triggering context-aware effects like verbal commentaries.

With respect to the different aforementioned aspects of mixed reality environments, the AKC play set combines the advantages of physical and virtual realities: it is physical in the sense that the pieces of the play set can be touched, moved, manipulated and rearranged in a variety of ways. It includes the social aspect of traditional toys since children play together sharing the same play set and their stories. The virtual aspects of the toy (e.g., the learning scenarios), which reaches out into the physical through light, smoke and, most importantly, sound effects, allow stimulating the mental and intellectual capabilities in a way traditional toys are not capable of. These effects let the play set come alive and thus deepen children's immersion into the play.

To provoke further interaction, mobile devices that implement the touch-me paradigm to identify play figures are integrated into the play set. Children can use mobile devices to touch pieces of the play set either as part of a learning scenario, a story that unfolds or simply as part of free play.

To this end, we developed several smart toys and added them, together with mobile phones, to the toy environment, which enabled both the integration of novel interaction forms (i.e., the magic bottle and the magic wand) as well as the configuration of the AKC (e.g., the magic box). Furthermore, a communication infrastructure based on web services ensures device-independence and flexibility.

We introduced a keyword-based approach to convey playful learning. The educational content can be delivered in two ways, directly (i.e., the figures tell stories during the play) and indirectly (i.e., the children use the magic mirror or the magic loupe). We presented an infrastructure for linking educational content to the figures, which can then provide information and tell stories to the children. The AKC is thus an example of situated learning [188]: the children learn about the world while playing (here, the Middle Ages).

While our focus is on learning, the infrastructure is by no means limited to educational content: the flexible design allows to potentially integrate all kinds of information. One idea is to map *all* information relevant for an object to it, which also includes, for example, manufacturing and shipping information (e.g., the object could "tell" where and when it was created and how it was transported from its place of origin to the current location).

Though we met all our initial functional requirements, further requirements and ideas came up during the design, implementation and evaluation of the AKC. These aspects are discussed in the subsection on future work below.

5.5.2 Meeting the Design Guidelines

Physical Augmentation

Similar to W41K, the AKC meets most of the design guidelines presented in Tab. 3.1 rather well. Technology is used sparsely (i.e., play objects are only equipped with RFID tags) and its integration clearly provides an added value (i.e., the traditional environment is enriched with multimedia feedback), thus meeting criteria 1 and 2.

The guidelines 3, 5 and 6 are again met by choosing passive RFID technology. This technology can be invisibly integrated and it operates unobtrusively in the background, which also satisfies criterion 4. Additionally, the seamless integration features a certain degree of safety (guideline 8): the tags can be fully incorporated into the play objects and the scanning infrastructure is hidden under the table, thus ensuring that players do not come in direct contact with the technology.

Since the digital augmentation is following the game flow (i.e., the feedback provided is based on the current play situation), the technology is tightly coupled with the activities of the play (criterion 7).

To realize the physical augmentation, we iteratively developed and improved the prototypes to meet the required criteria: the AKC underwent three major iterations and improvements. The design and implementation processes were realized in accordance with the augmentation cycle (see Section 3.1). The AKC was also exhaustively tested in the field, which complies with the last guideline 9.

System Development and Virtualization of the Play Set

In Tab. 3.2 we summarized the design guidelines for the virtualization of the play environment and the development of the corresponding software system.

The AKC meets all design guidelines for system virtualization and development quite well. This is mainly because of the numerous iterations and due to extensive user testing.

The virtual model of the play set supports all current and potential future objects (guideline 1): we use a generic object scheme and the object data, which is stored in a database, is easily accessible through the interfaces provided. The same applies to the “rules” created for each play setting: the ECA rules are also stored in the database and can be easily created, altered and removed.

Similarly, we support the high dynamics of the play scenario as players can easily add and remove objects at runtime, which meets the second criterion. Additionally, children can play and trigger actions concurrently on the play set, allowing for shared as well as simultaneous interaction (criterion 3). Since our infrastructure is based on web services, we support the comparably fast and easy integration of mobile devices as discussed above (criterion 4).

As for the fifth guideline, the focus remains on the traditional play set and the social interaction. Interaction with the system is kept to a minimum and even then the interaction is a seamless part of the play set (e.g., the magic mirror or the magic box). Provided interfaces also enable children to configure the play set in terms of adding and removing objects and locations as well as recording sounds. The AKC also features interfaces for parents and educators as well as content developers. This satisfies design guideline 6.

Criterion 7 is equally met since the AKC in its latest version is highly performable: the augmented play set is not only very reliable and robust but its response time is close to real time, which is a very important asset when dealing with children as users.

The last guideline is to minimize maintenance tasks. In W41K users are not burdened with any such tasks except for occasionally replacing broken RFID tags, which certainly contributes to the overall enjoyment.

User Interface

In Tables 3.3 and 3.4 we summarized the design guidelines for UIs and TUIs. The AKC consists of several interfaces, which can be divided into three types of interfaces: the physical play set itself, the smart toys integrated into the play environment (i.e., magic box, mirror, wand and bottle) and the mobile devices (i.e., the PDA). The AKC meets most of the presented guidelines quite well.

Generally, the focus always remains on the play set, which is the primary interface – interaction with secondary interfaces such as the magic mirror or the PDA are kept to a minimum, only to be used if additional means of I/O are required (e.g., displaying a video on the magic mirror). Given that the play objects are the input devices, the interaction is in situ, seamless and fun. Additionally, the play set allows for multiple, simultaneous and distributed interactions. We can thus conclude that the design guidelines 2-6 are met.

As to how the interfaces are being used, our focus was to create them as simple, efficient and intuitive as possible: children can use the interfaces as part of their play and the interaction with the system always advances the current play or learning scenario (criterion 1). Recording sounds, for example, is done by simply putting a figure in the magic box, delivering a verbal commentary or sound effect and placing the figure in an active zone. This also satisfies guideline 7 ("programming-by-example").

We only partially meet the last design guideline 8, mainly for two reasons: first, not all interfaces we developed meet the design guidelines equally well. For instance, the PDA, though it can be directly used in the play set, is not seamless and input options are not as intuitive – there is certainly leeway for improvements. Second, some interfaces have not yet been tested (also see future work).

As for the TUI design guidelines, the AKC meets them quite well. Guidelines 1 and 3 are apparently met: children can move around freely, most smart toys are mobile and allow for three-dimensional interaction (e.g., gesture recognition with the magic wand) and input and output are spatially mapped (i.e., if a figure is placed at a specific location, audio and/or visual feedback is given in situ). Furthermore, every child can use every toy and simultaneous interaction is supported and even encouraged.

We think that guideline 2 is also realized: children can, for example, learn about a play figure (e.g., the king) by either using the magic wand or loupe (i.e., pointing with the wand at the king triggers a verbal commentary), the magic mirror (i.e., the king is placed in front of the magic mirror and a short text about him is displayed) or by putting the object at a designated location (e.g., putting the king in the tower of the castle also triggers the audio feedback). In this context, the physical appearance of the play objects was chosen and designed in such a way that children immediately understand how to use them (e.g., magic metaphors from fairy tales), thus satisfying criterion 4.

Guideline 5 is implemented by exploiting the inherent semantic mapping based on the physical appearance: the smith can be easily identified as the smith, the troubadour as the troubadour, etc. We also use this benefit for learning purposes: the alchemist, for example, can teach the children about chemistry and physics and furthermore inform about the history and role of natural sciences in the Middle Ages.

Similar to W40K, criterion 6 was of considerable importance: given the safety precautions and the very small form factor of the toy figures, we had to completely disguise the technology, which, except for the still visible RFID tags at the figures' feet (also see future work), we successfully accomplished with the AKC.

Toy-Specific Design Guidelines

In Section 3.4 we discussed additional criteria regarding toy design as well as educational aspects.

Most of the guidelines of the first set are inherently met due to shape and appearance of the toys (as designed by Playmobil). Even after the digital augmentation, the play set and its objects remain physically unaltered, thus satisfying guidelines regarding the appearance and appeal of toys as well as how to play with them. The interactive environment furthermore respects the children's intelligence as the content is age appropriate and consistent with the real world.

The AKC also supports social interaction since children still share the same play set and they can explore the "enchanted" world together. As pointed out before, two of the major objectives during the implementation were reliability and robustness. So far, the AKC has performed extremely well and passed all tests impeccably – even the endurance test in form of an extensive user study (see Chapter 6).

This brings us to the final set of guidelines, which deal with educational aspects of toys. The AKC stimulates sensory and cognitive curiosity by playing sounds and verbal commentaries based on where a child places a particular figure. A figure could furthermore tell a child that if placed at a specific place, it could then explain more about a topic related to this place (e.g., the craftsman could say "if you bring me to the draw bridge, I can tell you how these were built."). This does not only provide challenges and feedback, but also stimulates children's curiosity and fantasy.

Our approach even allows for sequential iterations and reflections: another figure, for example, the commander of the king's knights, could ask a child to place him at the draw bridge, where he will not explain then *how* they were built but *why*, thus bringing a new perspective and new information about the same object into the play. This also satisfies aspects of both learning in context and providing multiple possibilities. Since children can always start and stop educational tours through the medieval world and freely learn about further aspects using the magic mirror or loupe, the aspect of control is also realized.

The AKC additionally features interfaces for parents and educators, allowing them to customize and even create educational content.

There are two aspects, however, that should be improved in the future: rewards for learning progress and support of team-oriented learning. So far, the AKC does reward learning only inasmuch as solved quizzes unlock next levels. But it would also be possible – and desirable – to embed educational content into stories. As for the team support, children can collaboratively learn and solve quizzes, but more team-oriented tasks and riddles would be favorable.

One of the central research questions with regard to pervasive learning is "how can pervasive technologies be used to support new ways of learning about different educational subject matters?" [181]. We think that research such as the presented project brings us closer to answering this question: having play figures talk to children and engage them in interactive learning without compromising the original play setting is certainly a "new way".

The AKC in its basic version (without mediators) definitely complies with these requirements. But even the mediators, the magic mirror and the PDA, respectively, are designed and integrated to not distract children from their original playing but they rather serve as information terminals that can be consulted when desired.

5.5.3 Future Work

Designing and implementing the AKC over the course of three years led to many improvements and lessons learned. While the latest version of the AKC meets all our functional and non-functional requirements, there are a few things whose inclusion or improvement might further contribute to enthralling play and learning experiences. We discuss them now.

More and Bigger Active Zones

To begin with, it would certainly be beneficial to cover the entire play set in terms of activity detection. Currently, the AKC consists of nine active zones that can react to children's play. Needless to say, we decided to first cover the "hot spots" of the play set as indicated by the preliminary user study. While children indeed tend to play at more attractive locations (e.g., the inside the castle), naturally, they also play and place figures at locations in-between areas covered by RFID antennas. Therefore, future work should include extending the active zones or combining them with other technologies to detect play behavior. Given the right technology, this might also help with capturing other play patterns (e.g., children let play figures "hover" or "fly").

Better Integration of RFID Technology

Another aspect with regard to the employed RFID technology is to fully integrate RFID tags into play figures. Our current approach works quite well inasmuch as tags are almost completely hidden. However, one figure is typically equipped with four tags for various reasons discussed before and the read ranges are nonetheless rather limited. Thus, a custom-built antenna that entirely occupies the inner space of a figure – which, by the way, are hollow – should significantly increase the read range as well as the probability of detection.

Improvement of Learning Scenarios

Designing good play and learning scenarios and stories is very demanding and requires didactical and pedagogical knowledge. As Kurti et al. point out, "designing technology support for situated learning is a challenging task, since in many cases technology tends to shift the learning environment to a more computer-based representation moving away from the core ideas of situated learning". They continue: "However, pervasive computing opens new dimensions to avoid this diversion, by providing means to trustfully representation [sic] of learners' contexts by placing them back into the authentic. Pervasive environments provide the possibilities of embedding computational support for the learning activity in the learner's physical and social contexts" [181]. Therefore, we intend to improve the educational content such as the stories and facts about the Middle Ages with the help of pedagogically and didactically trained staff.

Further Evaluation

Lastly, more user studies are to be conducted. While our evaluation of the AKC already provided us with many insights, further investigation is required: to expose our environment to long-term and continuous usage; to develop an even deeper understanding of how children actually perceive and interact with such augmented environments; to find out if and how children use our provided tools to configure the environment (e.g., record sounds); to evaluate the AKC in a formal learning context (e.g., in a school to support teachers); and to find out if such an environment can prompt autistic children to play more collaboratively.

5.6 Summary

In this chapter we presented the Augmented Knight's Castle, an augmented toy environment for storytelling and playful learning. We first introduced and analyzed the traditional, non-augmented play environment – the Playmobil Knight's Castle – both to derive its characteristics and to determine the goals of the digital augmentation.

Following the stipulated goals and guided by the process model presented in Chapter 3, the original play set was supplemented with audial feedback (i.e., background music, sound effects and verbal commentaries) as well as with light and smoke effects. We described how we constructed the basic play set, and how – through the integration of RFID technology – play figures can now be tracked and traced.

Additionally, mobile phones and smart toys were added to the play set to further enrich the children's play and make it more engaging. We showed that both approaches have their respective advantages and disadvantages: while smart toys can be smoothly integrated and are less of an "alien" object, mobile phones typically have more functionalities and can take on many different roles.

We then presented a keyword-based infrastructure for educational content, facilitating the association of multimedia learning modules with play figures. User interfaces were introduced for different user groups, that is children and parents or educators. Drawing on our findings from the previous subsection, we integrated two forms of user interfaces for children to display multimedia learning content: a magic mirror (a disguised computer screen) and a magic loupe (a PDA). Parents and educators were enabled to pre-configure the play environment using a web-based front-end.

Finally, we discussed the application of the design guidelines as well as the success of the design and implementation with regard to the functional and non-functional requirements. This example of a digitally augmented toy environment provides many insights into how our process model and design guidelines can be practically applied.

Equipping traditional play pieces with pervasive computing technologies bears some potential for future play scenarios as they can be easily linked to the digital world: for instance, toys can keep a blog of the play activities they have been involved in, which can then be interpreted as auto-generated diaries. Having a kid's room filled with smart objects that are capable of telling stories and giving information about themselves and "their view of the world" could be an enthralling, interesting and, most importantly, playful way of explaining the world to children.

6 User Study of the Augmented Knight's Castle

In this chapter we report on a user study we conducted in a German elementary school with over 100 children to test the Augmented Knight's Castle (AKC) and to gain first insights into how children perceive and use such an augmented play set.

As discussed in Subsection 3.1.4, evaluating a pervasive computing system is rather laborious, time-consuming and expensive. Therefore, conducting two user studies to analyze both W41K and the AKC, respectively, would have exceeded the scope of this thesis, especially since the focus of this thesis is on the design and implementation phase. Hence, we had to make a decision on which augmented play environment would serve as an extended use case.

We decided to test the AKC for two reasons: first, testing an augmented toy environment is much more difficult to evaluate (due to the younger user group) and requires to perfect the system. Second, putting the AKC to test might yield more interesting results as in this case the digital augmentation can influence children's play behavior (e.g., play patterns, collaboration, etc.). In games these factors remain more or less constant and the focus is rather on optimizing existing game flows and provide additional services.

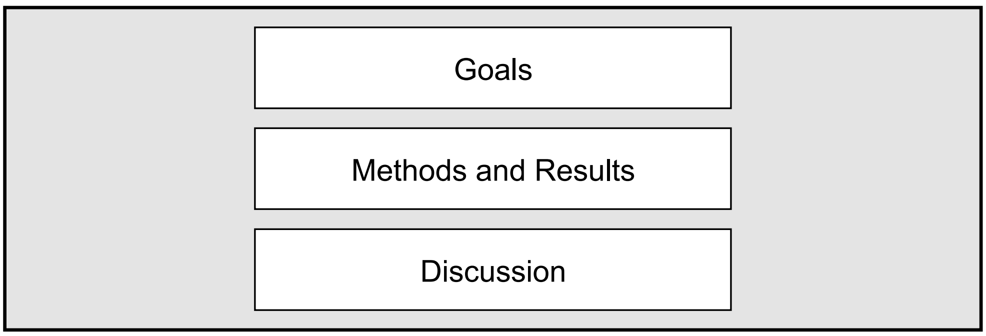


Figure 6.1: The structure of Chapter 6.

This chapter is structured as follows (Fig. 6.1): we first discuss the particular goals of the user study. We then outline the method and the results. Finally, we discuss the results and present the findings.

6.1 Goals

Primarily, we conducted a user study to determine if the digital augmentation of the AKC was successful. Additionally, we intended to investigate the effects of such technology-enhanced environments. To date, little research in technology-augmented environments has undertaken comparative studies with equivalent traditional environments. The AKC, being built from a traditional toy set, offered the opportunity to explore the differential effect of an augmented compared to a non-augmented play environment. Thus, a comparative study was conducted using the AKC and an equivalent traditional (non-augmented) play set to examine possible implications regarding playing, storytelling and playful learning (see Fig. 6.2).

In particular, the goals of the user study were:

- To test the success of the digital augmentation, mainly in terms of robustness and usability.
- To compare the augmented play set with the non-augmented version in terms of children's perceptions of fun.
- To explore the effects of the augmented play set on interactive play and storytelling, for example, to find out whether and how children respond to, use or incorporate the virtual content into their play and stories.
- To explore the value of an augmented play set for conveying educational content.

The user study was conducted with the second version of the AKC. There were several reasons for this: first, one centralized play set is beneficial with regard to transportation and maintenance. Second, the play set must be very robust in terms of its construction as children might climb and stand on it. Third, since we wanted to have a control group, we required a second identical but non-augmented play set; and building one big play set was much less effort than building three locations as described above.

Figure 6.2: The two play sets, the KC (left) and the AKC (right), respectively. Both sets were equipped identically (i.e., they featured the exact same play objects and setup).

We now present the details of the user study and discuss the results and findings, focusing on statistical data collected and data from interviews with children following their play experiences with the AKC and the traditional Knight's Castle (KC).

6.2 Method and Results

In this section we present the methodology of our user study and the results.

6.2.1 Method

Participants

The user study was conducted in an elementary school in Germany. Participants were 103 children, 55 boys and 48 girls, from the first to the

Table 6.1: Overview of the grouping of the children. "Test type" refers to which play set(s) the children played with (i.e., "KC" = played with the KC only, "KC/AKC" shows order of play).

Test type	**No. of groups**	**No. of graders**				
		1st	**2nd**	**3rd**	**4th**	$\sum$
KC	13	6	6	11	10	33
AKC	12	8	8	8	9	33
KC/AKC	8	2	4	5	3	14
AKC/KC	6	6	6	3	8	23
$\sum$	39	22	24	27	30	103

fourth grade (see Tab. 6.1). The children in each class were divided into groups of two or three, resulting in a total of 39 groups. Children were grouped with their classmates to counteract any awkward "getting acquainted" phase and facilitate the children to start playing right away. For our later analysis, we divided children into younger (grades 1 and 2: 6 to 8 years) and older (grades 3 and 4: 9 to 11 years).

Procedure

Each group played either with the non-augmented KC, the AKC or both. The groups that played with both play sets started with the KC and played with the AKC next (KC/AKC) or vice-versa (AKC/KC). Groups were distributed as equally as possible given time constraints by the senior leadership team of the school to fit the children's curricula (see Tab. 6.1). The children played with the KC or AKC for approximately 35 minutes (see Fig. 6.3), followed by group interviews with us (see Fig. 6.4).

The children playing with both play sets would play approximately 20 minutes with each set and then participate in the same interview process. The children were not given any particular instructions – we simply told them to play with the play sets as they would at home. Even the children playing with the AKC were only quickly briefed inasmuch that we demonstrated the modus operandi (i.e., how to trigger the audial feedback) to them once at the beginning.

In the interview session, children were first asked about the kind of stories they had created. This helped us to understand how the children

Figure 6.3: Children playing with the play set.

Figure 6.4: Interviewing the children after the play session.

played, but also enabled the children to overcome any shyness. The children were then asked questions relating to our research focus:

The first set of questions aimed at eliciting the children's feedback on what they thought of the play sets:[1]

1. How much did you like playing with the KC?
   (Answers: rating on a scale from 1 to 5 with 5 being the highest)
2. How much did you like playing with the AKC?
   (Answers: see previous question)
3. If you compare them directly, which play set did you enjoy more?
   (Answers: KC, AKC, same)
4. Which play set was better for your stories?
   (Answers: see previous question)
5. If you could play for another 20 minutes with either set, which one would you choose?
   (Answers: see previous question)
6. Did you like the background music?
   (Answers: yes, no, undecided)
7. Was playing with the AKC more fun than playing with traditional toys (e.g., dolls, miniature cars, Lego, etc.)?
   (Answers: yes, no, same)
8. Was playing with the AKC more fun than playing computer and/or video games?
   (Answers: see previous question)

With the second set of multiple-choice questions we intended to find out if the children paid attention to the integrated educational content of the AKC:

GQ1. What was the most important food in the Middle Ages? (Answers: bread, meat, potatoes)

GQ2. What was the preferred leisure time activity of knights? (Answers: hunting, playing, painting)

GQ3. How much was a sword worth in the Middle Ages? (Answers: 7 cows, 5 pigs, 2 sheep)

NQ1. What was the royal color? (Answers: red, yellow, green)

[1] Not all questions were suitable for all groups. For instance, the children that played only with the AKC were not asked the questions 1, 3, 4 and 5.

The correct answer is shown here as the first alternative in parentheses, but order of answers was randomized for the children. While the answers to the first three questions (‘given’ questions) were provided in the verbal commentaries of the figures in the AKC play set, the answer to the fourth (‘new’ question) was not, providing a control question.

A delayed post-test with the same four questions was administered to 88 of the children two months after their play sessions with the AKC, to determine any longer term effects for learning. To this end, we handed the children a questionnaire with the four questions and the same four answers for each question. The children filled in the questionnaires in their class rooms under supervision of their teachers.

Interviews with the Teachers

We were also interested in the opinions of the seven teachers on both the AKC and the role of playing with different media for children. We presented the system to them and they then completed a questionnaire with the following five questions:

1. How do you like the idea of the AKC in general?
2. Do you consider the AKC to be suitable for conveying informal content to the children (e.g., figures tell about their lives and roles in the Middle Ages?)
3. Do you consider the AKC to be suitable for conveying formal content to the children (e.g., the alchemist could tell them about chemistry or other natural sciences)?
4. How important is it that children at elementary school age work with computers (for gaming and working)?
5. How important that they play with traditional toys?

The teachers could rate their answers each on a scale from 1 to 5, with 1 being the lowest and 5 being the highest rating.

Technical Robustness

To assess the robustness of the system from a technical point of view, we established the following indicators:

1. Critical system crashes (the system in the background stops operating).
2. Critical hardware failures or destruction (one of the employed devices fails during operation or is physically broken).
3. System misbehavior (the system does not behave in the expected manner, e.g., a sound is not played).
4. Hardware malfunction (a device performs in an unexpected way, e.g., the antenna would not read transponders in read range).
5. RFID transponder problems (the transponders integrated into or attached to the figures might be damaged or malfunctioning).

Usability

Similarly, we defined a number of criteria to assess the usability of the AKC (though some of the aspects are highly related to the technical functionality):

1. Are figures always recognized? Are they recognized correctly? What about unsteadiness of tag detection at the outer limits of the antenna fields?
2. A related issue was whether children noticed and/or understood the perimeter of an active zone, as they were not explicitly marked on the surface to ensure that both sets were identical.
3. Do children understand how to trigger sound effects and verbal commentaries? What happens if children trigger several actions simultaneously? Will they be able to understand who or what figure caused what effect?
4. Is the feedback / reaction always immediate?

These four aspects were very important since if only one is not properly addressed, the play experience might be significantly diminished.

6.2.2 Results

Before we invited the children to play with either set, we asked them several questions to gain insights into their typical play habits. To this end, we asked them whether they possessed a cell phone, a video console and/or a personal computer (see Fig. 6.5). We also wanted to assess whether reactions differed depending on how frequently children played with traditional and modern electronic toys (see Figures 6.6 and 6.7).

Possession of Technical Devices

As shown in Fig. 6.5, significantly more of the older children owned a mobile phone than the younger ones, $\chi^2 = 7.0$, $p<.01$ and older children also tended more often than younger to have a video console, $\chi^2 = 3.6$, $p<.06$. There was no difference in computer ownership between the ages.

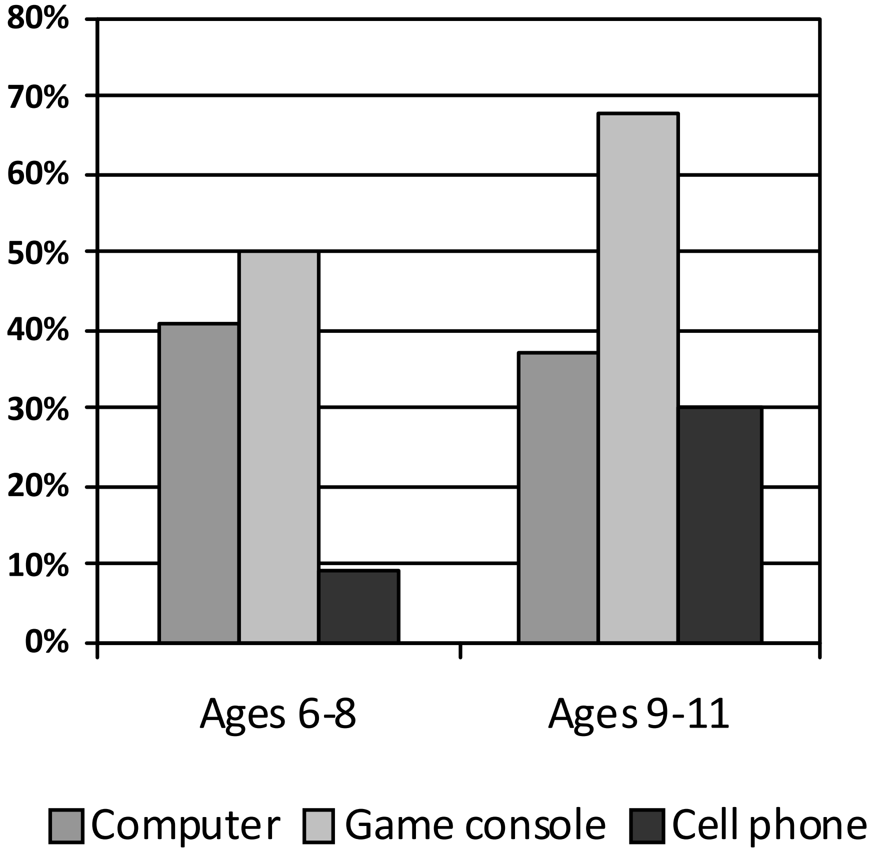


Figure 6.5: Percentage of younger and older children owning either of the three following devices: computers, game consoles and cell phones, respectively.

Children's Play Behavior

Both groups reported playing about the same amount of time with traditional toys, $\chi^2 < 1$, not significant, but the older group was more likely to play video games than the younger, $\chi^2 = 7.4$, $p < .05$ (see Figures 6.6 and 6.7).

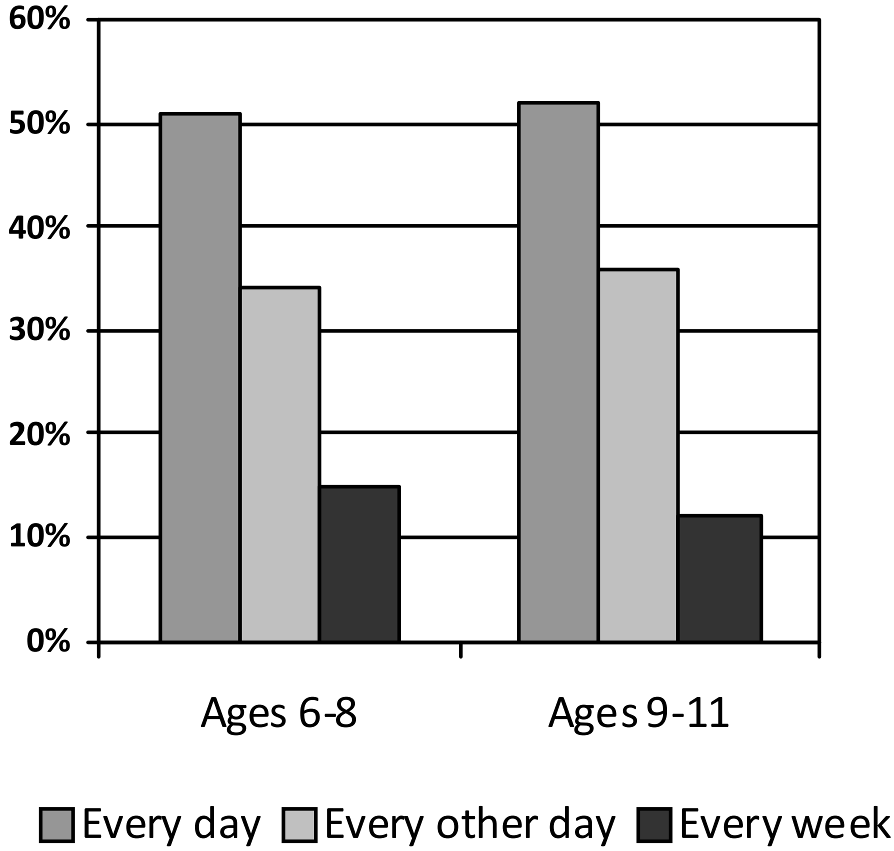


Figure 6.6: Overview of how often the children play with traditional toys.

Children's Rating of the KC and the AKC

Children generally rated both play sets very highly in the individual ratings, with means of 4.4 and 4.6 out of 5 for the KC and AKC, respectively: ratings for each condition are shown in Fig. 6.8. When asked to compare the two play sets directly, 21 of the 37 who played with both sets preferred the AKC, $\chi^2 = 9.78$, $p < .01$, with 6 rating them equal and 10 preferring the KC. There was no significant difference in the frequency of children's preferences between the two sets in supporting storytelling, $\chi^2 = 1.5$, not

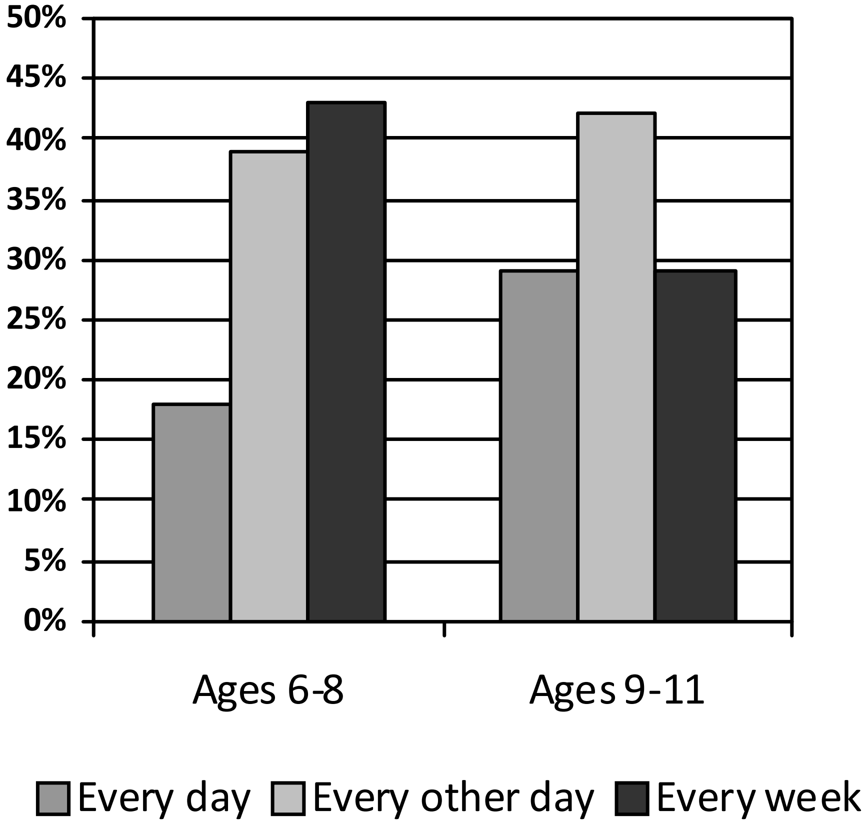


Figure 6.7: Overview of how often the children play computer and video games.

significant.

If children had another 20 minutes to play with either set, which one would they choose? 27 out of 37 (73%) chose the AKC, significantly more than the KC, χ^2 = 7.8, p<.005. Furthermore, 36 out of 37 (97%) liked having background music that fits the medieval scenario.

We also asked the children who played only with the AKC how they liked this form of play compared to traditional toys and computer/video games. 32 out of 33 (97%) said the AKC was more fun than video/computer games and all (33 out of 33) said it was more fun than traditional toys.

Learning

As described above, we asked children two types of question: three related to 'given' information given in the AKC and one related to 'new' information not given, as a check on children's general knowledge of the

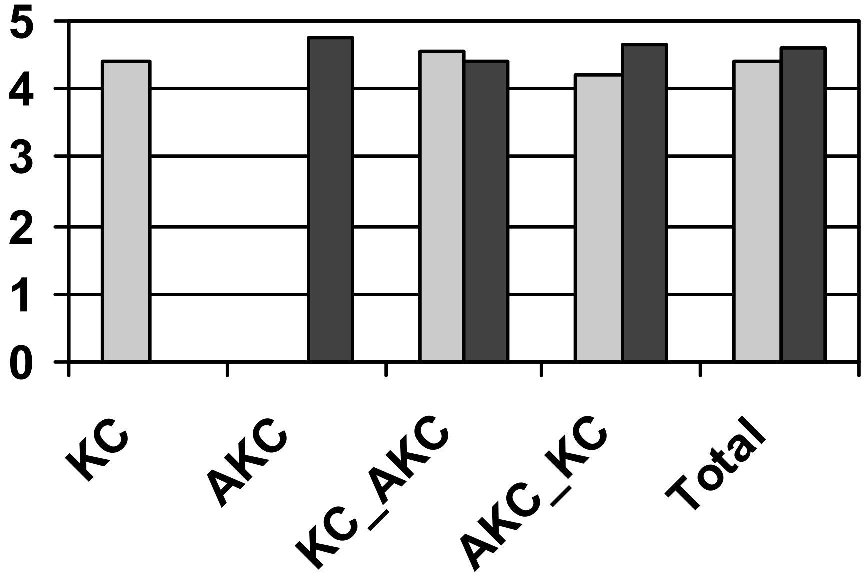
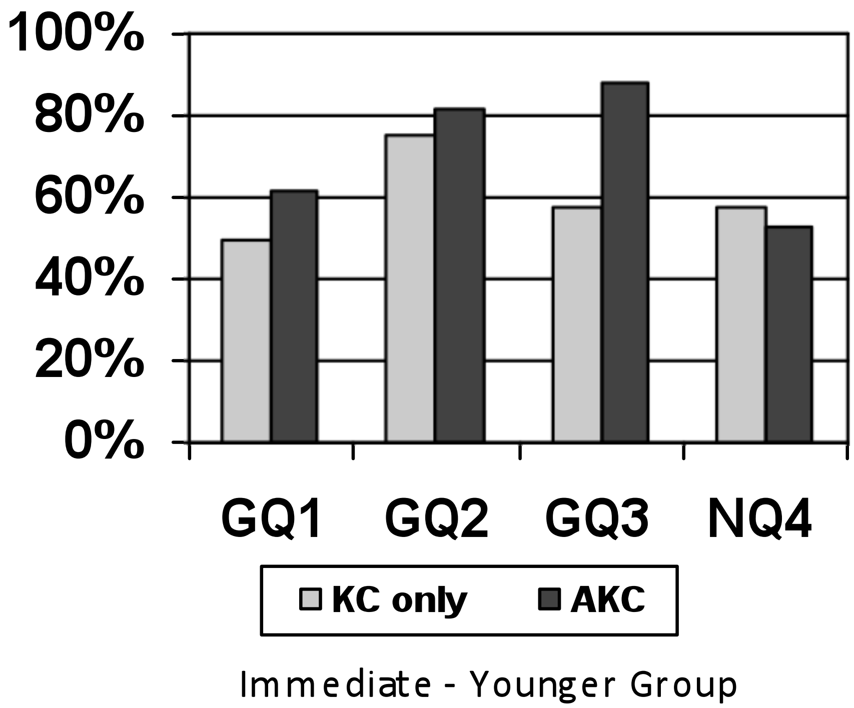


Figure 6.8: Mean ratings of AKC in each play condition (KC = light gray, AKC = dark gray).

Middle Ages. There was an immediate post-test and a delayed test two months later. Percentage of correct responses for the immediate post-test are shown in Fig. 6.9.

Immediate Post-test An analysis of the proportion of correct answers for the given and new information, with age and play condition (which toys the children had played with) as between-subjects variables showed that in general, older children answered questions more correctly, $F(1,95) = 5.38$, $p<.05$, that 'given' questions were answered correctly more often than 'new', $F(1,95) = 8.53$, $p<.01$ and more importantly, there was an interaction between play condition and type of question, $F(3,95) = 2.9$, $p<.05$.

A separate analysis comparing children who played in conditions with the AKC and those with only the KC showed that AKC experience produced better performance than non-AKC on the given questions (overall means of 84% and 54% correct answers, respectively) but not on the new question which had not been covered in the AKC (means of 63% and 64%, respectively). Clearly, children using the AKC benefited from the audio information provided, even though not all actively attended to it.



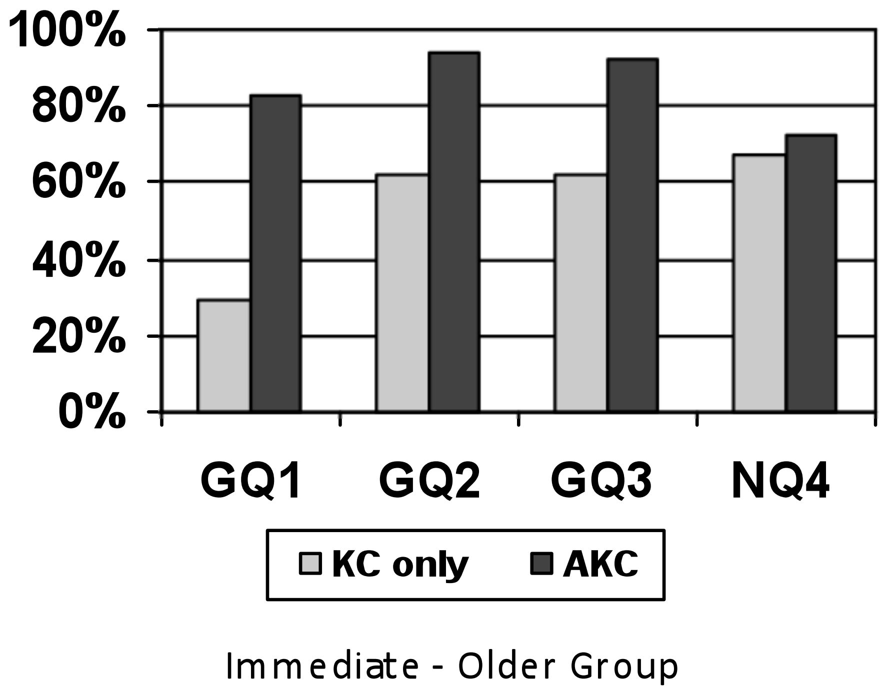


Figure 6.9: Percentage of correct answers for given (G) and new (N) questions for each age group: immediate post-test (KEY: GQ1 = food, GQ2 = leisure, GQ3 = sword, NQ4 = colour).

Delayed Post-test Children were asked the same information questions two months later, as shown in Fig. 6.10. For the given questions, performance was slightly but not significantly lower than the immediate post-test, 69% correct vs. 74%, respectively. An analysis of variance on the given question scores at the delayed test, with age group and testing condition (KC only vs. others) between subjects, showed that children who had played with the AKC still did significantly better than those playing with the KC only, $F(1,83) = 20.98$, $p<.001$, 84% vs. 54%, respectively. In fact, non-AKC children's performance would not be better than guessing.

There was also an interaction between play condition and age group, $F(1,83) = 4.28$, $p<.05$. The difference made by playing with the AKC was greater for the older than for the younger group. For a similar analysis of scores on the new information, there was an effect of testing occasion: performance regardless of age or play condition was higher on the second testing, 64% vs. 80%, $F(1,84) = 6.85$, $p<.01$.

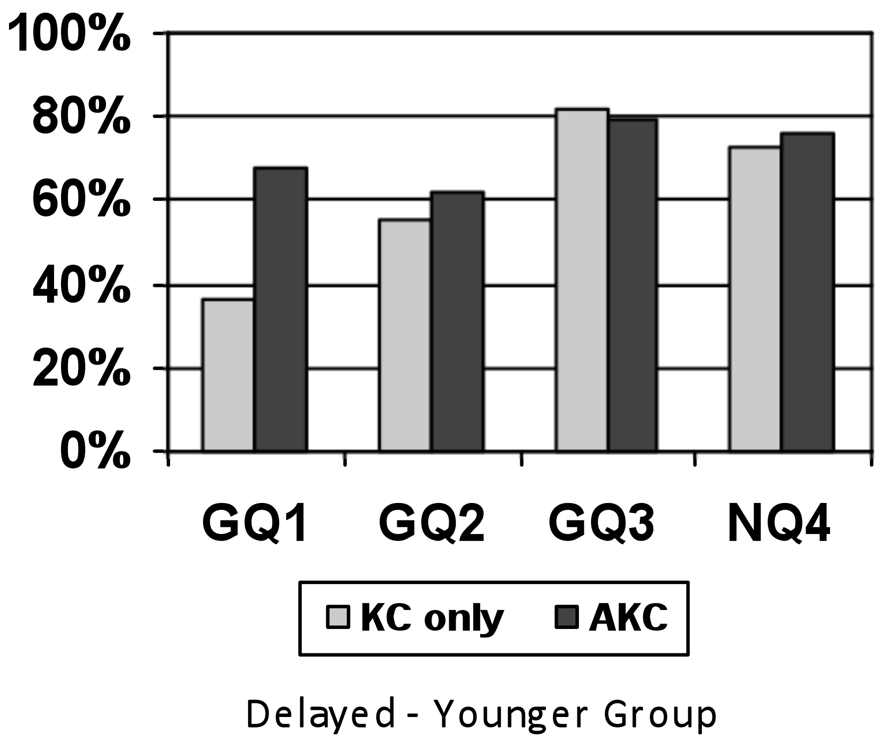
Teachers' Opinions

Teachers' responses are shown in Fig. 6.11. All thought traditional toys were very important (Q5) and that computers were also important but slightly less so (Q4). They rated the AKC generally very highly (Q1), for both informal (Q3) and, to a slightly lesser extent, formal (Q2) learning.

6.3 Discussion

This study is one of the earliest studies in the field that begins to make direct comparisons between digitally augmented and non-augmented equivalent environments. It helps to understand more clearly the differences that technology-enhanced environments have in mediating interaction and to enable a clearer understanding of when and how augmented environments can be best exploited to support play and learning.

A key question is how activity and interaction in the two environments might differ from one another. Based on the quantitative data and qualitative analysis of the children's interview data we discovered a number of interesting findings, which suggest ways in which a digitally-augmented play environment promotes different kinds of activity from an equivalent non-augmented play environment. These findings also show important directions for future work.



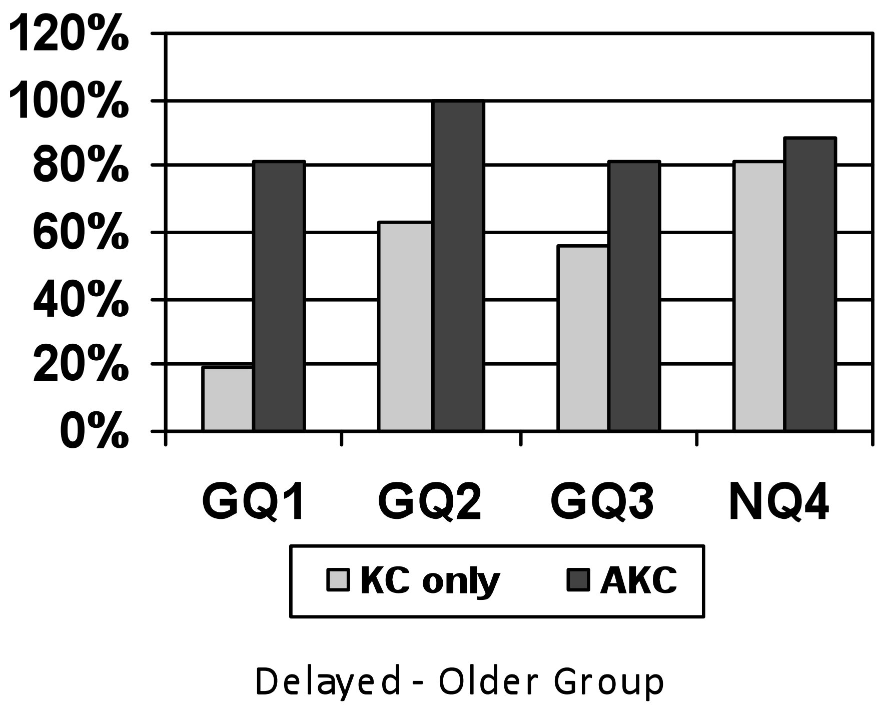


Figure 6.10: Percentage of correct answers for given (G) and new (N) questions for each age group: delayed post-test (KEY: GQ1 = food, GQ2 = leisure, GQ3 = sword, NQ4 = colour).

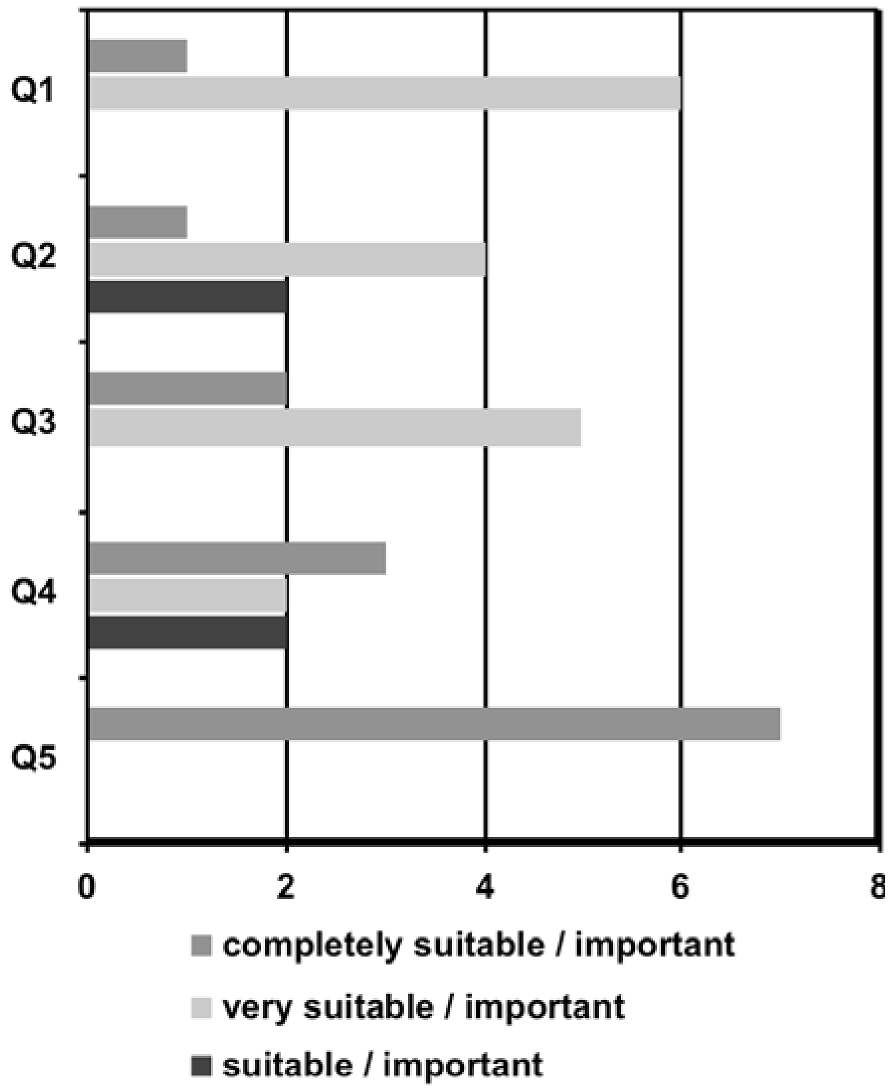


Figure 6.11: Frequency of teacher ratings for each question. Notes: N = 7; see text for questions. Ratings from 1 (completely unsuitable / unimportant) to 5 (completely suitable / important). Ratings of 1 and 2 were never given.

Fun and engagement

The statistical results show no significant difference between children's perception of fun between the two environments for those that played with either the KC or AKC. This is perhaps not surprising as both play environments are very appealing, but nevertheless importantly indicates that both environments are valuable in terms of actively engaging children. However, for those who played with both environments, there was a significant preference for the AKC in terms of fun.

While both the statistical analysis and the children's feedback indicated that they mostly preferred playing with the AKC, we were also interested in finding out whether playing with the AKC would change the way they played. In other words, we wanted to know how children actually reacted to the digital augmentations. Although responses to the digital effects varied, this variation suggests ways in which the digital augmentation influences interaction. Two main groups of augmentation were the talking figures and the background music.

Talking figures Children responded to the talking figures in a variety of ways:

1. Some children just 'cracked up' and laughed.
2. Some children directly replied to the figures' utterance, for example:
   a) 1a: Figure: I'm the golden knight.
   b) 1b: Child: Hello golden knight.
   c) 2a: Figure: I need a new sword, which costs seven cows.
   d) 2b: Child: I don't have seven cows...
   e) 3a: Figure: I was just in the pantry; we have enough bread for the winter.
   f) 3b: Child: Where is the pantry?
3. Some children responded indirectly, for example by saying, "let's take the golden knight".
4. Some children ignored or disregarded it.

One interesting observation that can be made is the choice of perspective-taking in these examples. The verbal responses here take the third-person perspective, whereas frequently in pretend play situations with play figures children take a first-person perspective, pretending to be the figure they are holding themselves. One outcome of the verbal augmentation is that the figures, by talking, take on an identity of their own, prompting the children to take a third person perspective. This may be an indication that the AKC encourages the children to act as producers, taking a more metacognitive and reflective approach to their play (also see [219]).

Augmented toy environments might therefore encourage different forms of play.

Background music Again, children had mixed views about the background music in the AKC, with the majority finding it 'fun' and supporting their imagination, while some children found it distracting. For example:

- L: It was more fun here [AKC] because of the music...
- N: I totally liked the music. That was not so boring. It's more fun.
- M: Without music, you cannot imagine everything so well.
- K: The music was a little bit too distracting... here [KC] there are not sounds all the time. Here you can play as you want to.

However, it was apparent from observation during data collection that children were able to disregard the sound effects and could therefore choose whether or not to use or integrate them into their play. During play with the AKC (as with the KC) children still made their own sounds to accompany their play. Sometimes children would also mimic the sounds pre-recorded by us.

The fact that children are able to disregard sounds / narrative suggests that this kind of augmentation need not be distracting or preventing children from making their own stories:

- M: I didn't really pay attention to the background music...

Thus, children are very positive about the background music and the talking figures in the AKC and identify these as being a key in making the environment fun: they can also choose to disregard them.

Storytelling

Some found storytelling better with the KC whilst others reported it to be better with the AKC. This view was individually-based rather than group. For example, when asked which environment they found better for storytelling, one group of 9-10-year-olds gave an overall mix of responses relating to their story development:

- M: It was more fun here [AKC], actually... because of the sounds...

- V: Here, we focused more on the sounds than on the play.

Question: Which play set was more suitable for your stories?

- V: I find over there [KC]... because you are not distracted by the voices...
- M: I found them equally good.
- N: I found it better here [AKC].

One child felt that with the KC "you could play unhurriedly", while with the AKC they tended to listen to what the figures said, rather than make up their own stories. This is not surprising given the novelty of the environment and the brevity of the sessions. Children's unfamiliarity naturally promotes exploratory activity to find out what is possible, but future work will develop studies to look at the way that children's play might develop over time.

Other data suggests that children sometimes actively used the sounds and commentaries for their own stories / play:

- L: Over there... [AKC] with the sound effects... that was better...
- Lu: We used the sounds and imitated them...

The fact that some felt they were listening rather than playing their own story suggests that this kind of play set may be useful for children who find developing ideas and creating stories problematic and warrants further investigation. One feasible function of the AKC is as a tool to help children develop imaginative play, for instance, for use in children with autism who tend to lack such capacities. The play set could be used to provide support such as sound effects and simple speech on which children might be encouraged to build, in the same way that the design of physical environments can be used to support more social play in this group (e.g., see [372]).

The play set could also be used to support narrative development in young typically-developing children. For example, Marshall et al. describe the PUPPET project, a virtual environment to support playful learning that allows children to interact with virtual characters [219]. The authors note that children could act in four different roles: as audience, actor, script-writer or editor (e.g., recording and pre-recording sounds for characters). As we have shown, the AKC seems to prompt all these types of behavior in children and further development of the environment could be used to support different perspective-taking.

Furthermore, the findings indicate that children, while in general being enthusiastic about sound effects, verbal commentaries and background music, sometimes want to focus on their own storytelling. The AKC addresses this issue well, since the technology is integrated in such a way that is almost completely invisible and the augmentation part can easily be switched off with the press of a button, turning it into a traditional KC.

Learning

Analysis of responses to the test questions showed that, as might be expected, the older children (9-11 years) tended to score higher than the younger group (6-8 years). In addition, the analysis showed an effect of the augmented play set: any group who experienced the AKC did better. Although this is not surprising given the information inequity, it does show that children clearly attend to commentaries and information in the AKC. Interview data of post-play sessions confirmed that children attended to AKC information: some children could repeat commentaries and almost all could reproduce the general essence of the content.

Furthermore, the delayed post-test data showed that children experiencing the AKC continued to have an advantage in their knowledge even two months after their short experience. In combination with the interview data, which clearly indicates that children feel able to ignore or disregard augmented sounds and narrative, this suggests that augmented sound and narrative may have a powerful effect on children's information acquisition.

Emergent findings

One factor that emerged from the children's interviews was their interest in being able to give the figures their own voices. This seemed to be motivated by children's perceptions that they would enjoy recording and making their own sounds, as well as being able to configure the environment themselves. One child suggested how she would like to do this:

- M: It would cool if there were buttons at the figures... for recording, for playing...

Interestingly, when the children were asked what kinds of sound effects and verbal commentaries they would like to record, they picked key figures (e.g., dragon or fairy) and gave as examples the sounds or verbal expressions that were already pre-recorded and integrated into the environment. This may be because of their limited experience with the play environment.

Future work aims to explore the effect of being able to configure the environment on two levels:

1. Usability: understanding the best configuration process to enable young children to configure effectively; and
2. Narrative production and the effectiveness of configuration in supporting expressive interaction [219], given that the ability to think about language removed from context is an important predictor of later literacy [57].

Technology performance

Fortunately, the AKC performed extremely well and the iterative approach (this version was the second major iteration) paid off: during the whole user study we had no problems with the technology whatsoever, including system crashes and hardware failures as well as misbehaviors and malfunctions.

Over the course of the study we only had to replace eleven RFID tags that were destroyed or detached from the figures' feet. This, however, was simply because the tags on the feet were attached to figure body whereas all other tags were integrated inside the figures. Hopefully, in the near future even smaller tags may become available that can be integrated into the legs or the feet of figures, subsequently obliterating the only visible aspect of the integrated technology.

Usability

In general, the system performed very well in terms of response time, which was less than 0.5 seconds with antennas directly attached to a reader and approximately one second in active zones using a multiplexer. In most cases the children would place one figure in an active zone at a time but every now and then, especially at the beginning of a play session, they tried to make several figures talk simultaneously (sometimes on purpose, sometimes accidentally). Once they understood the concept of how to make figures talk, it occurred only rarely.

The only real problem we encountered was the unsteadiness of tags that are at the outer limits of an antenna's read range: a figure would then start saying something not because it was placed at a particular location but because the antenna would not continuously detect the figure and fallaciously treat the re-occurrence of it (i.e., one or more of the figures' incorporated transponders) as being removed and placed there again. This "natural flickering" can only be partially eliminated (e.g., by only considering a figure as being removed if it has not been detected for several read cycles), but cannot be completely annihilated. However, this only happened very occasionally (on average once or twice per play session).

6.4 Summary

In this chapter we presented a user study conducted in an elementary school to test the success of our digital augmentation. This study also allowed us to investigate how augmented toy environments affect the play experience of children and if they can be used to convey educational content.

One emerging aspect was that it could be beneficial if the children could make the figures *stop* talking: in the current scenario, a figure placed on the play set triggers the playing of a sound file which continued until completed. However, if children would be allowed to make the sound file stop playing by removing the same figure, the children would have more control over the play. Additionally, to further extend children's control over the environment, an important extension would be to enable children to record their own sounds and commentaries. Both aspects were realized in the third version of the AKC (see Section 5.2).

The majority of the children really enjoyed playing with the AKC, which was demonstrated not only by the results of the user study, but also by other, more subtle comments received afterwards: for example, children's parents and teachers would occasionally tell us that the children were still talking about the "cool" project in school – even weeks after the study. It would seem that digitally augmenting traditional toy environments benefits and enhances children's playing and storytelling. The results also indicated that the AKC is principally capable of conveying educational content. However, more research and evaluation is required to substantiate these initial findings.

While we already conducted an extensive user study to test the AKC, there are many other aspects worth looking into, for example:

- How do children perceive the AKC over time with repeated play sessions (e.g., is there a change as to how they play and tell stories)?
- How do children use the configuration option, especially the possibility to record their own sounds?
- In how far can augmented play environments support collaborative play among autistic children?

Additionally, since some teachers showed interest in using this augmented play set in the curriculum to support playful learning, e.g., for historical content, a user study should be conducted in a school to focus on the development and use of educational content.

Since September 2008 the latest version of the AKC is at the University of Sussex for further evaluation.

7 Conclusions

In this final chapter we summarize the main points and contributions of this dissertation. Furthermore, we discuss current limitations and possible directions for future work.

7.1 Summary

Digitally augmented traditional play environments attempt to equip real-world toys and games with virtual attributes and functionalities, in order to support play experiences and novel types of play. We believe that the digital augmentation of real-world artifacts can rejuvenate traditional play: not only by increasing its attractiveness when compared to computer and video gaming, but also through innovative features not possible in either traditional games or computer games.

The main goal of this thesis was to provide a framework for supporting developers with the design and implementation process of digitally augmenting traditional play environments. To this end, we scrutinized the field of augmented play environments and addressed the intrinsic challenges. Based on an extensive interdisciplinary literature review and our own experience gained by building two prototypical play scenarios, we established a process model and a set of design guidelines for digitally augmenting traditional play environments.

To explore the challenges, possibilities and limitations of this approach, we digitally augmented two traditional play environments: a miniature war game and a toy environment, respectively. In both cases, the idea was to equip the play infrastructure and objects with pervasive computing technologies to provide players with virtual elements and context-aware information and services.

This gives rise to three benefits: first, game events can be made virtually available in order to enforce game rules and to support novice players; second, traditional play environments can be enhanced with multimedia elements in order to enrich the players' experiences and to stimulate new forms of play; and third, players can be relieved of mundane tasks, allowing them to better focus on game strategy and social interactions.

Facilitated by pervasive computing technologies, this digital augmentation enables designers to incorporate novel elements to enhance the play experience of the players, e.g., by providing digital counters and visual representations of game states or through infusing play with audio cues, light effects, smoke generators and motor-controlled movements of play elements.

RFID technology has proven to be an excellent technological enabler to support the digital augmentation of play artifacts: tags can be easily and unobtrusively incorporated into almost all shapes and sizes, they offer good reliability in terms of detection rates and robustness and they are available at reasonable costs. RFID readers fit most tabletop settings and can even be incorporated into mobile devices. However, RFID systems still need to be carefully selected as the different components (tags, readers and antennas) are highly interdependent and changing one of them often requires extensive re-calibration.

Of equal importance is the suitable integration of system interfaces into the play environment – both to display newly available information and to control extended play aspects. However, any added user interface should neither disturb social interaction nor hinder the natural game flow. The process model and the design guidelines presented in this thesis are thus useful and suitable means to the successful digital augmentation of traditional play environments.

7.2 Contributions and Results

This thesis dealt with analyzing and overcoming the challenges that inherently present themselves when creating augmented play environments both from theoretical and practical points of view. In particular, the thesis consisted of four contributions.

First, we presented an in-depth theoretical foundation of play and games in relation to pervasive computing. We introduced and discussed different areas of play, existing theories and approaches towards play as well as underlying terminology. Additionally, we presented a taxonomy of different forms of playing, based on which we chose our two use cases.

Second, we established a framework to support the digital augmentation of traditional play environments. The framework consists of a four-step process model and several sets of design guidelines, which were based on a review of current related work and on the experiences we gained during the design and implementation process of two prototypes. Especially the design guidelines should endow developers with the means to successfully accomplish the task of digital augmentation.

Third, we developed two prototypes to demonstrate how to practically apply the guidelines and how to overcome inherent challenges: *Warhammer 41K*, the augmented version of a popular miniature war game and the *Augmented Knight's Castle*, the augmented version of the Playmobil medieval play set. These prototypical blueprints illustrated both feasibility and benefits of digital augmentation.

For W41K, we developed an infrastructure that not only unobtrusively and unambiguously identifies game objects on the game field, but allows for the automatic determination of location and orientation of these objects with a high degree of accuracy. The system supports players by providing them with information necessary to advance the game in accordance with the rules. Furthermore, we developed an augmented die with the look and feel and form of a regular six-sided die that allows players to roll in the traditional way.

The AKC enhances children's play experience by adding novel elements and effects to the play: the play figures can make sounds and tell stories, mobile devices can be used to display facts and figures about the Middle Ages and children can record their own sounds and associate them with any figure. Verbal commentaries also allow for the seamless integration of educational content to facilitate playful learning. Additionally, light and smoke effects and background music further add to a compelling play experience. We also provided configuration tools for children and their parents.

Fourth, we conducted a user study with over 100 children to test the digital augmentation of the augmented toy environment. The AKC performed extremely well, demonstrating its technical robustness even under demanding conditions. The study also showed that augmented toy environments can be more engaging and entertaining than traditional ones and they also seem to support playful learning.

Taken together, this thesis should provide fellow designers and developers with helpful insights into and directions for the digital augmentation of traditional play environments.

Additionally, the presented framework should be similarly germane to completely new forms of play and games enabled by pervasive computing technologies (see Chapter 2.3.1) as they share general characteristics. The framework might even be applicable to other, not play-related areas. As pointed out before, augmented play environments are a subfield of smart environments – despite their very specific characteristics and requirements. Since the purpose of augmented play environments is to provide immersive and entertaining experiences, designers are concerned with many challenges simultaneously: not only must the environment be physically, mentally, emotionally and socially engaging, but it must, above all, be fun. If an augmented play object does not work properly, is boring or too complicated to use, it is not fun – and if it is not fun, players will very quickly discontinue using it. Therefore, the digital augmentation must adhere to strict non-functional requirements.

Other smart environments might not have such harsh restrictions. Hence, we should be able to transfer many of the insights gained in the field of augmented play environments to other fields like smart living rooms or work environments, with often well-defined tasks and well-behaved users. These scenarios equal ours inasmuch as the goal is to digitally augment already existing physical infrastructures and objects. The goal is also very similar, that is, providing the users with in-situ services and information or relieving them of cumbersome tasks.

We thus think that the rather strict design guidelines for digitally augmenting play environments might be similarly successfully applicable to other settings. For this reason, researchers and developers might find our findings generally helpful – even for systems designed for adult, professional users. A developer has done a great job, if users enjoy using a system and if even difficult tasks literally become “child’s play”.

7.3 Limitations and Future Work

This thesis covers an interdisciplinary and rather broad domain. Therefore, some limitations had to be made to concentrate on the main challenges. We will discuss these limitations now and outline possible future work.

First, we applied the framework to two use cases only. There are, however, many other forms of play as well as countless games. Although we are of the opinion that our approach also works for other forms of play and games, at least partially, and possibly even for other scenarios like home or work environments, we cannot substantiate this claim without further investigation. In this sense we also do not claim that the design guidelines presented in this thesis are exhaustive or unconditionally applicable.

Second, the design guidelines are qualitative. While this is a first step towards establishing a framework to support designers, it would be desirable if we could 'measure' the success of implementation and provide designers with more detailed feedback as to what parts should be paid more attention to during the next iteration. Coming up with a quantitative framework, however, is very challenging: for example, what would be a sensible and comparable benchmark for measuring "intuitiveness" of a user interface?

Third, in this thesis we mostly focused on RFID technology as the basis for the digital augmentation as it is a suitable means to bridge the physical and virtual world in an invisible or at least unobtrusive manner. While RFID technology has many advantages, other technologies might be equally suitable, depending on the particular scenario. An analysis of how other existing technologies could contribute to the digital augmentation of different play environments would thus be very beneficial.

Fourth, another aspect that we have not covered in this thesis is considering technology as an *active* component. We pursued the notion of where technology is invisibly integrated into objects and the environment and users cease to notice them, allowing their focus to shift from the means (i.e., the technology) to the end (i.e., the actual task at hand). However, the opposite approach, where users actively use and interact with the technology, is also conceivable. Children could, for instance, use RFID tags to assign roles or certain capabilities to play figures by simply attaching them. Similar to the Web 2.0 paradigm, where users are enabled to create applications and content themselves, this approach could lead to completely innovative forms of playing. The emphasis might shift from "fun through engagement and immersion" to "fun through technology-enabled creativity and authoring".[1]

[1]Based on their findings from a user study of their augmented environment for storytelling, Montemayor

Equipping all kinds of play objects with computing, communicating and sensing technologies also raises questions regarding our social, physical and psychological well-being. For example, health risks: there are no clear indicators whether wireless communication and sensing technologies are actually harmful, but there are growing concerns regarding the continuing and increasing radiation involved [15]. Therefore, we should know about possible risks of prolonged exposure to radiation caused by sensors and communication technologies before we start equipping everything around us with them.

Similarly, seeing future play environments as an interconnected network of smart objects that know about us, exchange potentially sensitive information and are connected to the Internet, legal aspects must also be taken into consideration. Bohn et al., for instance, legitimately ask: "Who decides what the smart talking doll tells the children? Could the children become ideologically polarized? There is also the risk that the doll could influence the education and the shaping of the children's opinions, without the parents being fully aware of this. And if the doll starts begging for new clothes from TV advertisements, this could stimulate the children's commercial appetite. If the manufacturer also uses the doll to obtain information on the children's play habits and their other toys, he is in a position to target advertising towards an individual person or household" [43].

Addressing these issues would have exceeded the scope of this thesis. Since our focus was on design and implementation aspects, we completely disregarded aspects related to privacy, security, health, business models or similar areas. Nonetheless, we believe that the progress and success of augmented play environments – and, for that matter, smart environments in general – strongly depend on conscientiously addressing these issues.

With respect to the two prototypes presented, future work should include further improving the systems as described in Sections 4.5 and 5.5, respectively. Evaluation of the systems should receive a large share of the attention since many more insights are to be gained in this rather young field of research.

et al. argue for a compromise: "a balance needs to be struck between visible concrete metaphors for [...] technologies and integrating these technologies into the environment" [231].

7.4 Concluding Remarks

Digitally augmenting traditional play environments equals fun, both figuratively and literally speaking. When work on this thesis first commenced three years ago, all there was, was an idea: what if all toys and play objects could suddenly talk and provide children with information about themselves and their environment?

Driven by this notion of a smart and alive kid's room, we initiated several projects to investigate if such augmented games and toys would indeed be feasible and "cool". It quickly became apparent that enhancing players' experiences by adding a virtual layer to traditional physical play objects and by relieving them of mundane tasks could yield more challenging, interesting and immersive play scenarios.

As digitally augmenting play environments is much more than just slamming some technology into a doll or game board, our goal was then to provide fellow researchers and designers with hints and recommendations for this task. Based on our own experiences and an analysis of recent literature, we established a framework that should appreciably simplify the digital augmentation of traditional play environments.

Certainly, more research has to be conducted in this field, but – hopefully – this is only a matter of time given current technological advances: modern information and communication technologies already allow for a seamless integration of technology and it is possible to create powerful and enthralling augmented play scenarios. Inexpensive, portable LCDs and the proliferation of smart phones and PDAs might soon offer a range of interface modalities to choose from and recent prototypical developments such as flexible organic displays promise to offer even better integration in the future.

Assuming that the trend of constant miniaturization and steadily increasing sensing, communicative and computing power will continue, digitally augmented play and games are likely to enter the commercial market soon – and they could have a similarly significant influence on how people play in the near future like the emergence of computer games in the 1980s.

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Curriculum Vitae

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Education

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