HELSINKI UNIVERSITY OF TECHNOLOGY

Department of Computer Science and Engineering

Software Business and Engineering laboratory

Marjaana Träskbäck

USER REQUIREMENTS AND USABILITY OF MIXED REALITY APPLICATIONS

Licentiate thesis

Supervisor and instructor: Professor Marko Nieminen

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Abstract of licentiate thesis

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The aim of this thesis is to study user requirements and usability of mixed reality applications. The thesis consists of user studies, usability evaluations, literature review, and framework development. The initial mixed reality application's usability framework is based on a literature review and it is further developed according to the results from the user studies and usability evaluations.

The first user studies resulted in context of use analysis (defined users, their tasks, used equipment and environment) and user requirements for the mixed reality applications. Usability studies (heuristic analysis, user tests, expert reviews, and summative evaluations) were conducted iteratively throughout the development process and the results were fed back to the developers for further improving the design.

Mixed reality applications follow some of the traditional usability guidelines (consistency of the user interface) and virtual reality guidelines (the presentation of the virtual objects for the user). In addition to these guidelines mixed reality has specific guidelines. Mixed reality application is highly dependent of the environment of use, which cannot be ignored during the development and it still faces some technological problems, which highly affect usability: for example lack in the accuracy of tracking systems and lags caused by both dynamic and static errors.

Keywords: Usability, human-centred design, mixed reality, user requirements

Lisensiaatintutkimuksen tiivistelmä

TEKNILLINEN KORKEAKOULU

Tietotekniikan osasto

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Tämän lisensiaatintyön tutkimuksen kohteena oli tehostetun todellisuuden tuotteiden käyttäjävaatimukset ja käytettävyys. Työ koostuu kirjallisuustutkimuksesta sekä käytettävyystutkimuksista ja käytettävyysarvioinneista, joissa tutkittiin kolmen tehostetun todellisuuden laitteen käyttäjävaatimuksia ja käytettävyyttä.
Kirjallisuustutkimuksen perusteella kehitettiin alustava kehys tehostetun todellisuuden käytettävyyden ohjeistukselle. Käyttäjätutkimuksien ja käytettävyysarviointien tulokset analysoitiin kehyksen puitteissa, jonka jälkeen kehystä täydennettiin.
Ensimmäisissä tutkimuksissa kartoitettiin käyttökontekstit eli käyttäjät, heidän tehtävänsä, työkalut ja ympäristö, mistä johdettiin käyttäjävaatimukset.
Käyttäjävaatimuksia sovellettiin iteratiivisessa tuotekehityksessä, jonka eri versioille tehtiin käytettävyystestejä käyttäjillä ja ilman. Testien tulokset jaettiin kehittäjille ja niitä käytettiin tuotekehityksen tukena. Kehityksen lopussa suoritettiin loppuarvioinnit, joissa pohdittiin tulevaisuuden kehityssuuntia.
Tehostetun todellisuuden tuotteiden tulee olla perinteisten käytettävyysohjeiden mukaisia (esimerkiksi käyttöliittymän tulee olla yhdenmukainen) ja ne hyötyvät myös virtuaalisen todellisuuden ohjeista (esimerkiksi virtuaalisten kohteiden esittäminen käyttäjälle). Nämä ovat kattavia ohjeistuksia, mutta niiden lisäksi tehostettu todellisuus sisältää erityisominaisuuksia, jotka tulee ottaa huomioon niiden käyttäjävaatimuksissa sekä käytettävyydessä. Tehostetun todellisuuden tuotteet ovat vahvasti sidoksissa käyttökontekstiin eli käyttöympäristöön tulee kiinnittää erityistä huomiota. Tuotteet kärsivät vielä teknologian kehittymättömyydestä, erityisesti erilaiset järjestelmäviiveet ja -virheet sekä paikannuksen puutteet vaikuttavat vahvasti tehostetun todellisuuden tuotteiden käytettävyyteen.

Avainsanat: käytettävyys, käyttäjäkeskeinen suunnittelu, tehostettu todellisuus, käyttäjävaatimukset

Preface

This thesis is conducted on a EU-funded AMIRE (Authoring mixed reality) project during April 2002 to June 2004. I would like to thank all the partners in the project for the interesting research environment and possibility to make research in the field of mixed reality. Thank you, Kalle Huhtala, for the good partnership during the project.

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Espoo, 6th of December 2004

Marjaana Träskbäck

List of abbreviations

2D	Two-dimensional (Chapter 4.2)
3D	Three-dimensional (Chapter 2.1)
AR	Augmented reality (Chapter 2.1)
CoU	Context of use (Chapter 2.2)
DOF	Degree of freedom (Chapter4.3)
EU	European Union (Preface)
GDP	Generalized design property (Chapter 2.7, 4)
GPS	Global positioning system (Chapter 7.3)
HCI	Human-computer interaction (Chapter 4)
HMD	Head mounted display (Chapter 4)
ISO	International Standard Organization (Chapter 2.2)
MR	Mixed reality (Chapter 2.1)
VE	Virtual environment (Chapter 2.1)
VR	Virtual reality (Chapter 2.1)
UI	User interface (Chapter 4.1)
WWW	World Wide Web (Chapter 2.7)

List of publications

This thesis is based on the following academic papers:

I Marjaana Träskbäck, Toni Koskinen, Marko Nieminen (2003). *User-Centred Evaluation Criteria for a Mixed Reality Authoring Application.* Published in Human-Computer Interaction International (HCII2003), Crete, Greece (June 2003).

The author conducted the study in the paper and analyzed the results with the supervision of the two other authors.

II Marjaana Träskbäck, Michael Haller (2004). *Mixed reality training application for an oil refinery: User requirements*. Published in Virtual Reality Continuum and its applications in Industry (VRCAI04), NTU, Singapore (June 2004).

The author conducted the studies in the paper and analyzed the results.

III Marjaana Träskbäck (2004). *Toward a Usable Mixed Reality Authoring Tool: Case study AMIRE*. Published in IEEE Symposium on Visual Languages and Human-Centric Computing Rome, Italy (September 2004).

IV Abawi, D., Los Arcos, J L., Haller, M., Hartmann, W., Huhtala, K., Träskbäck, M. (2004). A mixed Reality Museum Guide: The challenges and its Realization. Published in 10th International Conference on Virtual Systems and Multimedia (VSMM04), Gifu, Japan (November 2004).

The author's part in the paper were usability and evaluation issues. Chapters 2.1 and 4 are mainly written by the author.

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1 Introduction

This licentiate thesis presents research results of mixed reality applications' usability and user requirement studies. The thesis consists of a literature research, six studies (user studies and usability evaluations) and an initial framework construction for building usable mixed reality applications.

1.1 Background

You are visiting the Colosseum in Rome. You see the ancient ruins of what used to be one of the greatest amphitheatres in the world. You hear stories and explanations of the games held in Colosseum and about the gladiators who fought for their lives. Today the arena is torn open and some of the walls are down and you have to imagine most of what happened in there. What if you get a pair of glasses, which help you to see the Colosseum in its glory and what went on there? You can see the gladiators walking around or see them fighting in the arena. You can see the emperor sitting in his booth enjoying his spectacular theatre shows. All this can be projected into your new glasses and you can virtually see the life long time ago. You are aware of the surrounding environment, but you can also see what the history is like. Maybe even smell and touch it. This can be accomplished with mixed reality.

Mixed reality (MR) applications are systems that combine real environments and virtual objects together. The system aligns real and virtual objects with each other in real time and it offers real time interaction (Azuma et al. 2001). In the future these applications are likely to become common in various application fields, like medicine, military, entertainment, industry (Azuma 1997, Azuma et al. 2001) and a more heterogeneous group of users is going to use the applications. The users are changing from developers and researchers to wide variety of consumers. In order to make a successful introduction of MR applications to the consumer markets, more attention needs to be paid to the usability of the applications.

In the survey of augmented reality (AR, see chapter 2.1) (1997) Azuma concludes that augmented reality is ripe for psychophysical and social studies. Performance studies as well as ergonomics and ease of use are important future research issues. In the survey of Recent Advances in Augmented Reality (2001) Azuma et al. call for future work in removing technological and user interface limitations as well as research on social acceptance. In the user interfaces they call for better understanding of how to display data to a user and how the user should interact with the data. According to their survey, most existing research concentrates on low-level perceptual issues, such as properly perceiving depth or how latency affects manipulation tasks. However, AR also introduces many high-level tasks, such as the need to identify what information should be provided, what's the appropriate representation for that data, and how the user should make queries and reports (Azuma et al. 2001).

In the thesis Interactive augmented reality, Vallino (1998) presents ideal characteristics of an augmented reality system. The characteristics concerning the user or the user interface directly are the following:

- *Virtual objects exhibit standard dynamic behavior*. When the user interacts with a virtual object it should move with the same dynamic behavior that an equivalent real object would exhibit.
- *The user has unconstrained motion within the workspace*. The system should allow movement without constraints or limitations. It would be ideal to have no mechanical limitations, blind spots or motion constraints.

1.2 Research problems

According to the above mentioned future research requests, the goal of this research is to gather information of the user requirements and usability issues concerned with mixed reality applications. Based on literature review, an initial framework for mixed reality application's usability is built for developing usable mixed reality applications. The framework guidelines are compared to the results of user studies and usability evaluations conducted with the developed mixed reality applications and the guidelines are refined according to the results.

The aim of the study is to develop a set of guidelines for developing usable mixed reality applications. In this thesis I propose an initial framework for user-centred product development of MR applications from the point of view of two demonstrators from two different domains.

The main research question is following:

- What kind of user requirements need to be considered when developing mixed reality applications for specific domains?

The user requirements are studied in two different application domains: an oil refinery and a museum. In addition, the authoring of mixed reality applications is also considered in order to support easy deployment of mixed reality in by more heterogeneous group of users in different application domains.

1.3 Structure of the thesis

The chapter two in this thesis presents the research and design processes used in this research and the used methods. Chapter three presents related research and chapter four the initial framework. Chapters five and six present the results of the studies: chapter four includes the user requirements and chapter five presents the results of the usability evaluations. Chapter seven analyses the results and collects the results together and chapter eight concludes the results. Chapter nine has some discussion about the study as well as future work.

2 Related research

This chapter describes research areas relevant to this research and defines the terminology used in this thesis. This research is based on previous usability studies in the fields of virtual, mixed and augmented realities as well as multimedia. Usability of virtual reality has been more extensively studied than mixed reality. For example Gabbard (2001) has adopted usability guidelines from virtual reality also for mixed reality.

2.1 Mixed reality

Mixed reality (MR) is a particular subset of virtual reality related technologies that involve the merging of real and virtual worlds somewhere along the "virtuality continuum" (Figure 1), which connects completely real environments to completely virtual ones (Milgram 1994).

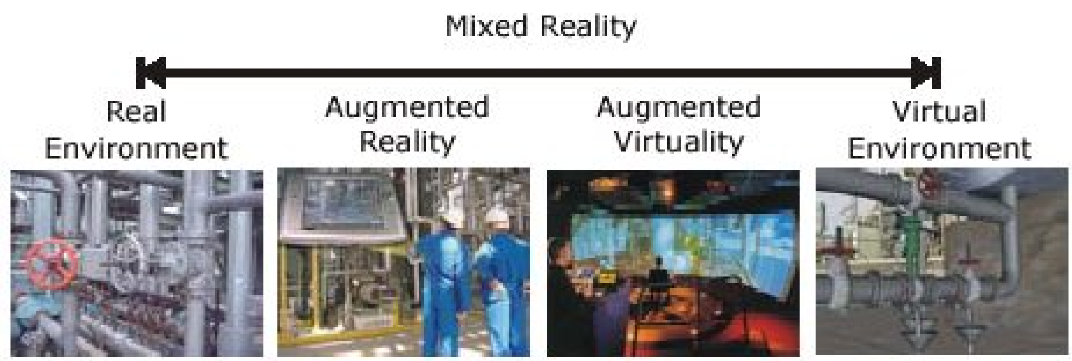

Figure 1 Virtuality continuum (Milgram 1994).

Mixed reality is a concept that includes perception of the reality and virtual reality as well as interaction with them. The user is aware of the surrounding real environment and with the mixed reality application he can experience virtual elements. MR consists of augmented reality (AR) and augmented virtuality (see Figure 1); it is everything between real and virtual environments, excluding the end points of the virtual-reality continuum (the plain real world and virtual environments). The use of augmented reality enhances a user's perception of and interaction with the real world by displaying virtual information that the user cannot directly detect with his own senses (Azuma 2001). In displays, mixed reality occurs when the real world and virtual objects are presented together within a single display (Milgram 1994): in TabletPC with a real-time camera picture (augmented reality, Figure 2) or in an optical (Figure 3) or a video see-through head mounted display (HMD) (augmented virtuality, Figure 4). In this thesis mixed reality always involves a real-time environment, which can be directly seen on a TabletPC through a camera. The two end user applications considered in this thesis are developed for a TabletPC and the authoring tool can be used in a desktop PC and in the TabletPC.

Figure 2. The TabletPC and the camera used in the applications

Figure 3. See-through HMD (Another World)

Figure 4. 5DT Head Mounted Display (Fifth Dimension Technologies)

Mixed reality confronts many technical challenges before it is ready for commercial products. Compared to virtual environments, where the user stays in one place in the real world, in mixed environment the user is encouraged to move around. MR systems require the user to actually be at the place where the task is to take place (Azuma 1997). This means that the system has to support a user who walks around the environment. The system needs to be aware of the user's location and the position of all other objects of interest in the environment (Azuma 2001). The environment is not a controlled one and the scene generator, the display and the tracking system must all be self-contained and capable of surviving in the unprepared environment.

The major challenge for augmented reality systems is how to combine the real world and virtual world into a single augmented environment (Vallino 1998). One of the basic problems currently limiting AR applications is the registration problem. The objects in the real and virtual worlds must be properly aligned with respect to each other, or the illusion that the two worlds coexist will be compromised (Azuma 1997). For many applications accurate registration is critical, for example when surgery is operating on a patient, miss-alignment can be life threatening. Registration errors are difficult to control because of the high accuracy requirements and the numerous sources of error, which can be divided into two types: static and dynamic errors. Static errors are the ones that cause registration errors even when the user's viewpoint and the objects in the environment remain completely still. Static errors have four main sources: optical distortion, errors in the tracking system, mechanical misalignments and incorrect viewing parameters. Dynamic errors have no effect until either the viewpoint or the objects begin moving. Dynamic errors occur from system delays or lags. The end-to-end system delay is defined as the time difference between the moment that the tracking system measures the position and orientation of the viewpoint to the moment when the generated images corresponding to that position and orientation appear in the displays. The biggest problems occur in motion, but are less when the user moves in constant movement. (Azuma 1997)

In addition to registering, focus and contrast are also problems in MR applications (Azuma 1997). Ideally, the virtual should match the real, but for example in the optical HMD case the virtual image is often projected at some fixed projection distance, while the real objects are at varying distances from the user. When the virtual objects are all projected to the same distance, the illusion of one combined world is lost. Contrast in the displayed virtual objects is a problem because of the large dynamic range in real environments and in what the human eye can detect. The problem is not so big when a camera image is augmented with virtual objects on a display, since the virtual object has to match the contrast of the camera picture and not the human-eye. When the virtual object is projected into optical see-through HMD, the contrast should be as accurate as the human eye, a level that the displays cannot reach yet.

Vallino (1998) presents a set of ideal requirements for an augmented reality system, which can be used in comparing the success of different approaches. The ideal requirements for a system of high degree of verisimilitude and utility are following:

- *Constrained cost to allow for broader usage.* To allow augmented reality systems to be deployed in a wide range of applications the cost for the system should be constrained. This leads to a goal of using inexpensive consumer grade video cameras, personal computer processing and lower resolution display technology.
- *Perfect static registration of virtual objects in the augmented view*. When a virtual object has been placed at a location in the real scene it should appear to the user to remain at that same position in 3D space unless an object has interacted with it. If the system cannot meet this goal for all static viewpoints, it will not be possible to meet the following more difficult dynamic registration requirement.
- *Perfect dynamic registration of virtual objects in the augmented view*. Visual updates should be performed at a rate of, at least 15 Hz, and preferably, 30

Hz. Perhaps more importantly, latencies should be minimized. If changes in the rendering of the virtual objects lag behind the user action triggering them the virtual objects will appear to "swim" around in three-dimensional space.

- *Perfect registration of visual and haptic scenes.* This can be phrased as WYSIWYF or "What you see is what you feel." The visual image of a virtual object should match with its haptic counterpart. The user should feel the surface of a virtual object at the same time and in the same place that the augmented view shows the contact.
- *Virtual and real objects are visually indistinguishable.* In addition to photorealistic rendering of the virtual objects—the usual consideration for computer graphics applications—there are additional requirements specific to interactive augmented reality applications. Visual occlusions between virtual and real objects must occur correctly. This is not only for virtual objects occluding real ones, but also for the more difficult case of real objects occluding virtual ones. Lighting in the augmented view must be matched between the real and virtual worlds.
- *Virtual objects exhibit standard dynamic behavior.* When the user interacts with a virtual object it should move with the same dynamic behavior that an equivalent real object would exhibit. This includes correctly rebounding from collisions between virtual objects or between virtual and real objects. To accommodate this characteristic, the system's internal representation of objects should help to compute the graphics rendering of virtual objects and the interactions and dynamics of all objects.
- *The user has unconstrained motion within the workspace.* The system should allow movement without constraints or limitations. It would be ideal to have no mechanical limitations, blind spots or motion constraints.
- *Minimal apriori calibration or run-time setup is required.* To determine the location of the viewer many augmented reality systems require calibration of the video camera viewing the scene. This calibration process is tedious to

perform and will often limit operation to a single focal length. Lenses on standard consumer grade video cameras cannot be zoomed in or out because they do not provide feedback of zoom position. During start-up of the system the user should not have to perform extensive setup such as measurement of the locations of fiducials, or complicated procedures for placing objects into the scene.

The use of these requirements should be tempered somewhat by the particular application under consideration. Some applications will not demand an “ultimate” augmented reality system. To date, no augmented reality system has met all of the performance goals for the ideal system. Comparing these goals against the capabilities of different approaches the reader can determine how close the state-of-the-art comes to achieving all of the performance goals for the ultimate interactive augmented reality system (Vallino 1998).

2.2 Usability

In this study usability is considered as defined in the International Standard ISO 9241-11 (1999):

- *Usability* is the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.
    - *Effectiveness:* The accuracy and completeness with which users achieve specified goals.
    - *Efficiency*: The resources expended in relation to the accuracy and completeness with which users achieve goals.
    - *Satisfaction:* Freedom from discomfort, and positive attitudes to the use of the product.

According to this definition, usability is closely related to the surrounding environment where the product is used, the use context, which can be defined as (ISO9421-11 1999):

- *Context of use:* The users, goals, tasks, equipment (hardware, software and materials), and the physical and social environments in which a product is used.
    - *User:* The person who interacts with the product
    - *Goal:* An intended outcome
    - *Task*: The activities undertaken to achieve a goal

Usability can also be considered as part of product's usefulness, which consists of usability and utility (Nielsen 1993). Utility offers information on what is needed for the functionality of the system to be sufficient and usability offers information how well users can use that functionality.

In this study there are three contexts and three end user groups for the developed applications. First, a graphical mixed reality authoring tool, which is used in an office environment with desktop PC's and occasionally in a visit to a customer site. These users are multimedia designers. Second, oil refinery training tool is aimed to train new process engineers on-site in the oil refinery. And third, a museum visitor guide to deliver information of the museum and the artwork to all the visitors.

2.3 User requirements

User requirement can be any function, constraint, or other property that is required in order to satisfy user needs (Kujala 2002). User requirements are elicited from users and described from the user and customer point of view. These describe how a future product can help users achieve their goals effectively, efficiently, and with satisfaction in their context of use. They include information about those particular user needs that are selected and that are satisfied by the future product.

According to the Human-centred design processes for interactive systems (cf. chapter 3.2) specifying user requirements is essential part of the design process. Active involvement of users provides a valuable source of knowledge about the context of use and how users are likely to work with the future product or system. In order to build user requirements we need to know *user needs*, which refer to problems that hinder users in achieving their goals, or opportunities to improve the likelihood of users' achieving their goals (Kujala 2002). User needs can be gathered from previous documents, like user feedback, help desk reports etc., and also from the users. User observations, questionnaires, interviews and think aloud methods are well suited for the user needs gathering phase (ISO 16982 2002). The collected user needs need to be analyzed and user requirements derived from the needs with appropriate trade-offs identified between the different requirements (ISO 13407 1999). This specification should define the "allocation of function" – the division of system tasks into those performed by humans and those performed by technology. These requirements should be stated in terms that permit subsequent testing and should be confirmed or updated during the life of the project.

In this thesis user needs are gathered with several methods (observations, interviews, questionnaire, user test) described previously. The requirements were collected from the needs and discussed with the users, who rated and made more detailed remarks on the requirements as well as with the developers who also rated the requirements and commented on the possibility to implement them. The list of requirements was then derived according to these results.

2.4 Mixed reality authoring

Authoring can be categorized by the amount of programming it requires from the authors and by the development style, which may or may not be primarily script-based (Davies and Brailsford 1994). Many authoring systems assume that authors will posses a well-developed "programming mentality", and their applications consist of rigidly defined events in logical sequences and hierarchies. In some authoring systems applications are constructed by entering text into an editor and then compiling or interpreting this. Other authoring systems have a graphical interface design editor, but require extensive scripting to describe interactions. Some authoring systems attempt to dispense with a script entirely and use iconic constructs or menu commands for almost all operations.

Currently authoring of MR requires a lot of time and resources. It has to be hard coded and the reusability of existing work is very low. The authoring in such a way is not very cost effective and efficient. Through reuse, adaptation and combination of existing building blocks, components, synergies of previous solutions can be exploited (Dörner et al. 2002). A *component* is a software component in the sense of the component theory (Sametinger 1997). It is a building block of a software system with an explicitly defined interface designed for reusability (Dörner et al. 2002). Authoring considered in this thesis has a graphical user interface, it requires no scripting and it consists of reusable components.

2.5 Mixed reality in museums

The use of mixed reality has good potential for enhancing a museum visit, but it is also a restricting environment. The environmental requirements and museum visitor requirements that restrict the use of MR in museums need to be recognized before the MR applications are developed. Museums differ greatly in the content of the exhibitions as well as in the environment (Träskbäck and Nieminen 2003), but all museum applications have to pay special attention to the restrictions of virtual object enhancing art. Artworks have been designed to be exactly what they are, and the artist’s acceptance is needed for the “virtual enhancement” of their art. The surrounding environment and social context need to be taken into account as well.

Many museums currently take advantage of audio guides as well as printed information. Each piece of art may have an explanation next to it or this can be written in a printed leaflet. Audio guides are used widely to offer more information and saving user from extensive reading. A museum visitor can explore artworks while listening to an audio recording explaining the art in more detail. This applies to single visitors, but for example according to a study by Petrelli et al. (1998) only 5% of visitors in natural history museums in Italy visit the museum alone. To some extent this can be extended to other museums as well. The users would have more use for socially interactive applications, where the experience can be shared with the rest of the group.

In addition to experiencing art, the application could be used to guide the visitor around the museum, as well as to give information on the services the visitor may need. In the study by Petrelli et al. (1999) they found that disorientation is a problem for some visitors. This applies also to the studied museum environment. It is essential that personal discovery is appropriately supported by providing visitors with the suitable amount of information they need, at the right time and place, and in the form that makes it the most acceptable and enjoyable for the visitor. In this chapter some of the general requirements and limitations in a museum environment are discussed followed by ideas of how mixed reality can be used in museums.

A lot of effort has been invested in using new approaches and new technologies for cultural heritage. For example, the EU-funded project Archeoguide (2002) allows the visitors to have personalized 3D information of missing artifacts and reconstructed parts of damaged sites of a Greek temple (Hildebrand et al. 2001, Archeoguide 2002). Another example is given by Villarustica (2002), where the authors present an interactive multimedia walkthrough for museum installations. The most important aspect in this project was to visualize the augmented 3D model in a highly realistic real-time presentation. The project LIFEPLUS (2001), a follow-up of the Archeoguide project, proposes an innovative 3D reconstruction of ancient fresco paintings. In contrast, the project CHARISMATIC (2001) is researching and designing artificial virtual humans, which become an interactive part of the attraction and enjoyment of using a system. In the National Museum of Ethnology in Osaka, Japan, the visitors have already the possibility to have more multimedia information (e.g. movies, pictures etc.) using a Tablet PC. In contrast to the described systems, AMIRE project (2004) implements an in-house museum MR application. Moreover, the abovementioned AR installations focus on a specific domain and are difficult to extend because there are no authoring tools to modify the MR application. AMIRE museum application is constructed modularly, which makes the application easily extendable and maintained.

2.6 Mixed reality in oil refinery

Oil refineries are demanding environments for any kind of activities. Working requires highly trained personnel and safety requirements are high. Training is conducted mainly as a classroom teaching, but requires extensive practical hand-on training with trainers before new employees are qualified to work on their own. The lack of on-site training can be overcome with virtual or mixed reality applications.

Haller et al. (1999) developed an omVR, which is a virtual reality based safety training system in a petroleum refinery. It provides an advanced technique for personnel safety training and allows users to navigate through the training setup and interact with parts of the refinery. By using a head mounted display (HMD) a high degree of immersion is achieved. This was only a simulation program, but could be further developed to be a future training tool. A research team in the Honeywell Technology Center developed personal information processing system (PIPS) solution for the roving industrial field operator (Guerlain et al. 1999). Their PIPS system comprises an RF network to deliver wireless digital information, a wearable computer for delivering web-based information (the hardware is a two-piece system composed of a belt-worn NetPC attached via a curly cable to a handheld unit with a mouse/display device combination), and software applications that provide added value in the field.

Mixed and augmented realities can offer new ways to improve the practical knowledge of the employees on-site. ARVIKA project (2004) studied augmented reality and applied it in such areas as automobile and aeronautical construction and in machine and plant construction. They call for better co-operation between the scientists developing the new technology and the industrial partners in order to achieve application that work in the real environment.

2.7 Previous guidelines and their construction

In 1986 Smith and Mosier (1986) published guidelines for designing user interface software. They collected published and unpublished material from conferences, journals and professionals and discussed the results with their colleagues. They divided the data into six functional areas of user-system interaction and established a broad conceptual structure for dealing with the range of topics that must be considered in user interface design in software development. The functional areas were data entry, data display, sequence control, user guidance, data transmission, and data protection. Smith and Mosier wanted that the generally stated guidelines is offered to designers as a potential resource, rather than imposed as a contractual design standard.

Gabbard and Hix (1999) developed taxonomy for usability characteristics in virtual environments. The goal was to increase awareness of the need for usability engineering of virtual environments (VEs) and to lay a scientific foundation for developing high-impact methods for usability engineering of VEs. They collected information from literature, conferences, World Wide Web searches, investigative research visits to top VE facilities, and interviews of VE researcher and developers. They divided their taxonomy into four main areas: Users and user tasks in VEs, the virtual model, VE user interface input mechanisms and VE user interface presentation components. They don't claim the taxonomy to be exhaustive; it is comprehensive in its coverage of state of the art VE. This was the first trial of building design guidelines for developing user-friendly virtual environments.

In 2001 Gabbard applied and further studied guidelines, which were specifically targeted for augmented reality. Since such guidelines did not exists, Gabbard collected information from various sources: conferences, journals, literature, www, and from users or own experiences from using AR systems. Gabbard adopted the same structure for his guidelines, which he and Hix (1999) used in the taxonomy for VEs. The framework was reviewed for appropriate coverage of the AR usability space.

In 2003 Sutcliffe developed generalized design principles (GDPs) for multimedia and virtual worlds, which specify the usability requirements for design features that may be implemented as graphics, controls, and services in the VE, or information and explanation facilities. Even though he treats the topics separate, he points out that multimedia and virtual reality are really technologies that extended the earlier generation of graphical user interface with a richer set of media, 3D graphics to portray interactive worlds, and more complex interactive devices that advance interaction beyond the limitations of keyboard and the mouse. He grounds his collected design methods for extensive literature review, other taxonomies from different, but related fields and for recommendations and ISO standards.

The guideline framework presented in chapter 4 is based on the VE, AR guidelines by Gabbard and Hix and multimedia and virtual reality by Sutcliffe. These guidelines are considered from the perspective of mixed reality application development. The results from the studies in this thesis are compared and analyzed against the guidelines and the framework is supplemented with new guidelines in the conclusions.

3 Implementation of the studies

The research was conducted according to the research process described in chapter 3.1. and the data was collected according to the human-centred design process for interactive systems (chapter 3.2).

3.1 Research process

The research process is presented in Figure 5. This research started by defining a topic for the research, which is the user requirements and usability of mixed reality applications. The definition of the problem area was to limit the MR applications into single use applications running on a Tablet PC. The literature review and background research was conducted extensively at the beginning of the process and then continued throughout the whole research. The background study was limited into the areas of mixed, augmented and virtual realities, usability, user requirements and some issues of multimedia. After the background study the rest of the research was planned along with the data collection methods and design process. The data collection phase and the methods used are described in chapters 3.2 and 3.3. All along the process academic publications were delivered and presented in academic conferences. These publications are part of this thesis. At the end of the research the collected information was analyzed with affinity diagrams and qualitative data analysis method. At the end of the process the results were reported, which this thesis is part of. The research process was not one-way street, but iterations were done all along the process.

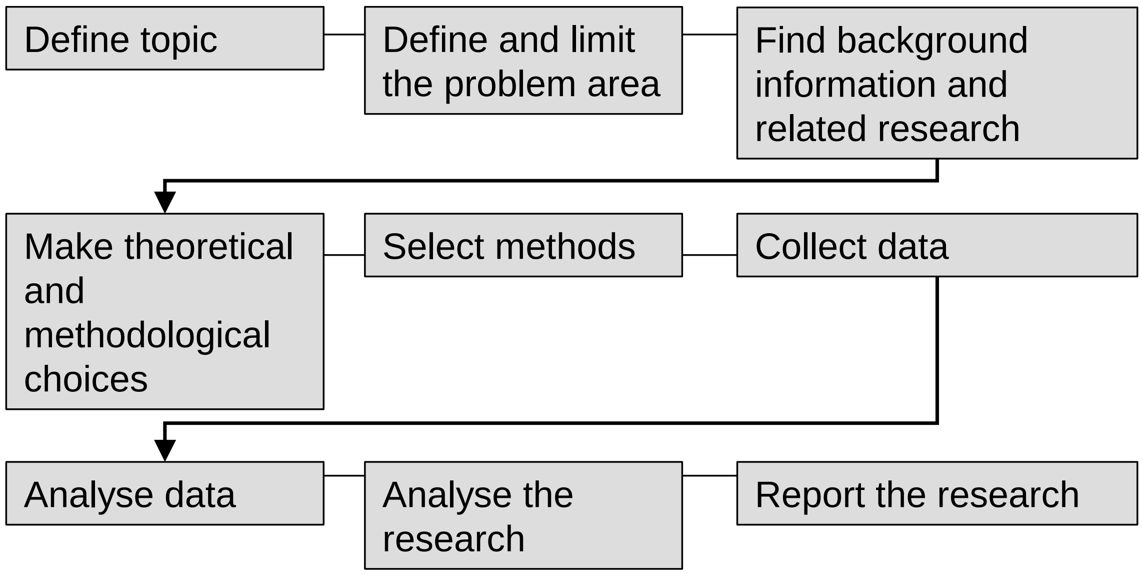

Figure 5 Research process (Metodix 2004, Sajavaara et al. 2003)

3.2 Design process

The data collection was conducted according to the ISO 13407: Human-centred design process for interactive systems (1999), which consists of four phases (Figure 6). Methods used in each phase were following:

1. Specify context of use: (field) observations, (field) interviews, context of use analysis
2. Specify requirements: Requirements derived from the previous results
3. Produce design solutions: Implementation of the results
4. Evaluate designs against requirements: Expert evaluation, user tests in the laboratory and on-site in the field.

First the user requirements were collected and delivered for the developers. Different application versions were iteratively evaluated with expert and user evaluation methods and at the end of the development summative evaluation was conducted.

The methods used in each paper are following:

Paper I: Contextual inquiry (interviews and observations on-site), context of use analysis, requirement meeting

Paper II: Questionnaire, field observation, interviews, context of use analysis, requirement meeting

Paper III: User tests

Paper IV: Context of use analysis, interview, questionnaire, on-site user tests

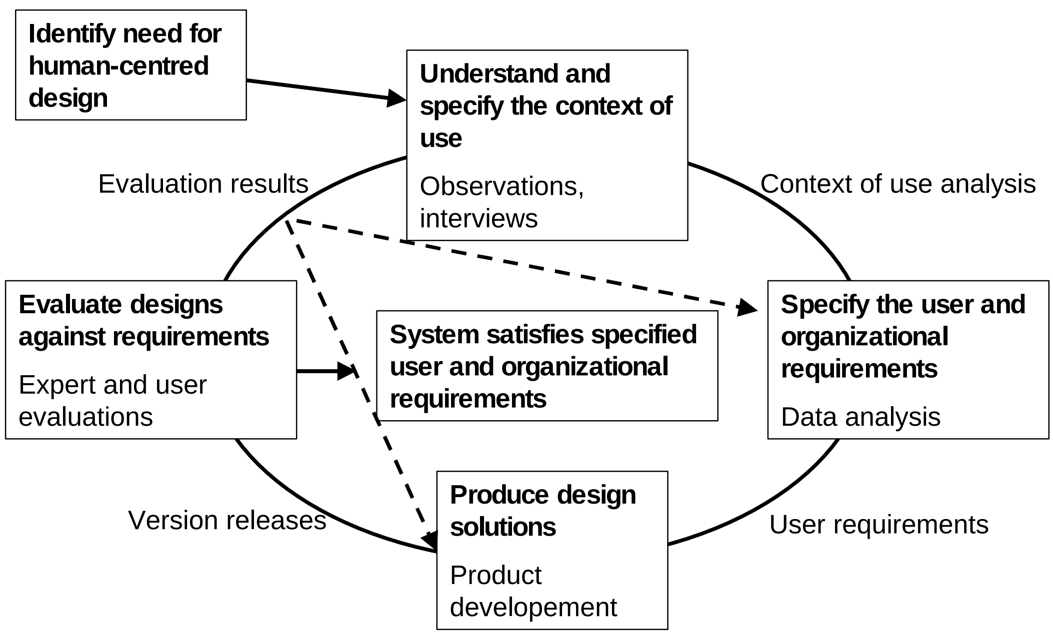

Figure 6 Design process used in the data collection phase (ISO 13407 1999).

The design process emphasizes the involvement of the users in the whole design process from the early phase on as well as iterative process and communication of the different parties involved in the process. The next chapter describes the methods used in this research.

3.3 Methods

3.3.1 Field observation

Field observation of users consists of the collection of information about the behavior and the performance of users in the context of specific tasks during the user's activity, which may be carried out either in real-life situations or laboratories (ISO 16982 2002). Observation method can be used in order to study user's work context and to learn how user conducts work tasks. It is conducted in the user's real environment and involves an investigator, who is viewing the user as he works, inspecting and taking notes and pictures on the activity that occurs (Usability Net 2004). Observation may be either direct, where the investigator is actually present during the task, or indirect, where the task is viewed by some other means such as through use of a video recorder.

Observation allows the observer to view what users actually do in context. Direct observation allows the investigator to focus attention on specific areas of interest. Indirect observation captures activity that would otherwise have gone unrecorded or unnoticed. The method is useful early in user requirements specification for obtaining qualitative data. It is also useful for studying currently executed tasks and processes (Usability Net 2004).

In this research, observation was used to collect data for the context of use analysis. This method was used in the papers I and II. On the first paper the method was similar to contextual inquiry, since it included also interview on-site. Two people observed four employees for about two hours each. The employees were asked some questions about the tasks according to a semi-structured list during the observation. The list was based on the context-of-use definition defined in ISO 9241-11 (1999). The observer recorded the conversations, took notes and pictures during the observation. The second paper included observation of several employees. Two oil refinery employees took the researchers around the refinery explaining the tasks and functions conducted by other employees, which were observed for individual tasks. Notes were taken, but no pictures were allowed in the refinery and the background noise did not allow recording of the conversation. The third paper describes observation, which was also enhanced with an interview. The observation was conducted in the museum where the users were observed on the ways they enjoy the art and how they user the offered audio guide. The researchers also used the audio guide themselves to get first hand experience on it. Notes were taken, but it was prohibited to take any pictures.

3.3.2 Interviews

Interview is a method for discovering facts and opinions held by potential users of the system being designed (UsabilityNet 2004). Because of the one-to-one nature of the interview, what is talked about can address directly the informant's individual concerns. Mistakes and misunderstandings can be quickly identified and cleared up.

Interview was used as a data collection method in all the four papers. On the first paper the interview was conducted with two employee and interviewers at the same time. The goal of the interviews was to gather as much information of the background issues for the context-of-use analysis. This was the basis of the observations done in paper one. The interview started by the interviewees describing the company and its history. The interview continued with throughout analysis of their development process and the tools used in the process. The interview was recorded on an audiotape and analyzed. The second study included an interview of two oil refinery employees, who participated also in the observation prior the interview. The interviewer listed questions in the observation and the interview was started with these questions. The interview continued with the interviewees' explanation of the tasks the developed MR application would be designed for and with explanation of the environmental requirements and restrictions for the equipment. The third study, the museum guide, included interview in order to find out further details for the context-of-use analysis. The interviewee was a museum employee in charge of the development of the new MR museum guide. The interview started with a background information of the museum and its history as well as why they have decided to build a new museum guide. The interview continued with questions based on the context-of-use structure (user, tasks, equipment and environment). This interview was recorded on an audiotape as well as notes were taken.

3.3.3 Questionnaire

Questionnaires are a means of finding out how the software or a product is likely to be used by a specific set of users, and who these users are likely to be. The answers questionnaires provide must be relevant to the issues that are important to the design team. These are traditionally carried out by post, but increasingly, the Internet is used for this purpose.

In these studies questionnaire was used in order to gain important information at the beginning of the study. The end users and their environments were far away from the researcher (in different countries in Europe), so the questionnaire was sent for the participant of the oil refinery and the museum to get background information for the planning of the observations and the interviews. The questionnaires can be found from the attachments. The MR authoring tool users were located in the same country, so a meeting was organized instead of a questionnaire.

Questionnaire was also used in the user testing phase along with user testing method to collect the required user information as well as their opinion of the evaluated demonstrator.

3.3.4 Context of use analysis

Context of use describes the user's relevant characteristics (ISO 9421-11 1999). These can include knowledge, skill, experience, education, training, physical attributes, and motor and sensory capabilities. It may be necessary to define the characteristics of different types of user, for example users having different levels of experience or performing different roles. The context of use includes descriptions of the user, user's tasks, used equipments and social, organizational and technical environments. This information is an essential input to requirements and the planning of other usability methods. It may be collected at an early stage during planning and feasibility, or in more detail as part of the usability requirements (UsabilityNet 2004). Context of use analysis ensures that all factors that relate to use of the system are identified before design work starts and it provides a basis for designing later usability tests.

In this research context of use is analyzed based on the information collected with observations and interviews. All the data is analyzed according to the structure of the context of use by 9421-11 (1999) and reported to the developers in that form.

Context of use analysis were made for the MR authoring tool, oil refinery training tool and for the museum guide. The results are described in the papers I, II and IV accordingly. More on the context of use analysis can be found from AMIRE project reports D8.1 and D8.2 (AMIRE D8.1 2002 and AMIRE D8.2 2002).

3.3.5 Requirements meeting

After the context of use analysis the collected data was analyzed in order to gather needed user requirements. All the gathered requirements were listed and it was send for the users who ranked each requirement in the following scale:

1. Critical, have to be implemented
2. Important, implemented during the project
3. Nice to have
4. Not important

The user representative also clarified and made more detailed comments on the requirements when needed. After the ranking the list was discussed together. The list was then send for the developers, who had possibility to comment of the requirements, especially if a requirement seemed to be impossible to fulfill.

These requirements meetings were important way to communicate the requirements and the evaluation criteria, which are the basis for further evaluation of the developed products. This way the requirements were clear for everybody taking part in the development and it clarified in the early stages the need for user-centred development (UsabilityNet 2004). The set of requirements can be found from AMIRE project reports D8.1 and D8.2 (AMIRE D8.1 2002 and AMIRE D8.2 2002).

3.3.6 Expert evaluation against evaluation criteria

During the development, the authors offered the current application version for the usability expert for evaluation. All the evaluations were based on the evaluation criteria set at the beginning. The first evaluation was done early in the process with specifications and iteratively continued with following prototypes. All the evaluation results were sent for the developer, who commented on the results and future directions were set together with the developer. Most of the evaluations were expert evaluations where usability expert evaluated the design against the evaluation criteria.

3.3.7 Usability evaluations

When the applications were working demonstrators, they were evaluated with users. MR authoring tool was tested in a usability laboratory, since it resembles normal office environment well, which was the environment where it was developed. In the laboratory the recording of the tests has better quality. The usability tests are reported in the paper IV. The tests included six users, who where content providers and they conducted a scenario based usability tests, which was divided into small tasks. After the test they were shortly interviewed and they filled out a short questionnaire. More detailed test setting can be found from AMIRE report D8.3 (2004).

The oil refinery training tool and the museum guide were evaluated with users on-site. The use of the MR applications is highly context sensitive and a laboratory testing would lack many environmental issues. The oil refinery training tool was evaluated with three oil refinery employees. They demonstrator was running on a Compaq TabletPC equipped with a webcam. The users did not have any predetermined scenario, but they were guided for the checkpoints and they were able to use all the offered functionality as they liked. After the evaluation they were interviewed and they filled out a questionnaire. The oil refinery tests were recorded on video as well as screen grabber software was used.

The museum guide was evaluated with five users, who were all employees of the museum. Since the demonstrator was not a final product, we were not able to get users among the visitors. The museum demonstrator had eight checkpoints and the users were guided to each point. They were also able to use all the functionality of the demonstrator as they wanted. Museum tests were recorded on a video and on digital picture. More detailed test settings for the oil refinery and museum can be found from AMIRE D8.4 (2004).

3.3.8 Affinity diagram

Affinity diagramming is used to sort large amounts of data into logical groups. Existing items and/or new items identified by individuals are written on sticky notes, which are sorted into categories as a workshop activity. Affinity diagramming can be used to:

- Analyze findings from field studies
- Identify and group user functions as part of design
- Analyze findings from a usability evaluation

Affinity diagramming is a simple and cost effective technique for soliciting ideas from a group and obtaining consensus on how information should be structured. In this research, affinity diagrams are used for grouping the all the different user requirements from the three domains together. The purposes was to see, if these different domains have some requirement common concerning mixed reality, or are they all dependent on the context where the applications are used.

4 Initial framework for MR application usability guidelines

Mixed reality has been researched mainly from technical point of view (Azuma 1997, Sutcliffe 2003). The technical aspects are really important from usability point of view as well, but in order to make MR application easy to use, there is a lot more to it than technical issues. As mentioned in chapter 2.1 mixed reality still faces important technical challenges, which need to be solved before wide commercial exploitation of mixed reality. Gabbard and Hix have studied usability characteristics specific to virtual (Gabbard and Hix 1997) and mixed reality applications (Gabbard 2001). They developed taxonomy of usability characteristic in virtual environments (VE) for increasing awareness of the need for usability engineering of VEs and to lay a scientific foundation for developing high-impact methods for usability engineering of VEs. The taxonomy's organization has foundation in the Norman's theory of action (Norman 1988) and is divided into four groups presented in Table 1.

Table 1. Groups of the "Taxonomy of usability characteristics in VEs" (Gabbard and Hix 1997).

Group	Usability characteristics of
Users and user tasks in VE	General user and task characteristics and types of tasks in VEs
The virtual model	Generic components typically found in VEs
VE user interface input mechanisms	VE input devices
VE user interface presentation components	VE output devices

Gabbard developed usability design and evaluation guidelines for augmented reality (AR) systems. It is based on literature review and the framework of usability characteristics for VEs. The structure is the same as presented in Table 1.

Sutcliffe has researched multimedia and virtual reality. He notifies that VR has been driven by technology and very little usability research has been undertaken, although the work of Hix stands out as an exception. Multimedia, in contrast, has been driven by forces of technology and more recently by artistic design, so human-computer interaction (HCI) finds itself as a potential arbiter between the technologist who are concerned with bandwidth, graphics, compression algorithms and creative designers who want software tool to empower their abilities to create new forms of digital media. Sutcliffe has studied how usability should be reflected in design with technology and how artistic design can be employed to make interfaces more attractive and usable (Sutcliffe 2003).

Sutcliffe has developed generalized design properties (GDPs), which are generalized usability requirements that can be mapped to more concrete design components that implement them. In some cases the GDPs recommend specific design features, but more usually the general requirements have to be interpreted by the designer in the context of the application. Sutcliffe divides his guidelines into multimedia and VE guidelines even though he explains that the division is false. They are really technologies that extend the earlier generation of graphical user interfaces with a richer set of media, 3D graphics to portray interactive worlds, and more complex interactive devices that advance interaction beyond the limitations of keyboards and the mouse (Sutcliffe 2003). Mixed reality is located in the Milgram's Virtuality continuum between multimedia and virtual reality, so these design guidelines are on a high-degree applicable for mixed reality as well.

These three taxonomies are merged in this thesis in the initial MR framework from point of view of a mixed reality application, where the application used with a TabletPC with attached camera. The organization of the framework is based on the organization developed by Gabbard and Hix (1997). The guidelines with the sign AR are from the taxonomy for augmented reality systems, VE are from the Gabbard and Hix's taxonomy for VEs and GDP if from the Sutcliffe's taxonomy for multimedia and VR. More detailed explanation of each guideline can be found from the original taxonomies.

4.1 Users and user tasks in MR

User-centred evaluation methods are often based on the user performing some kind of task. The task can be specific low-level sub task in a sequence of tasks or a generic task to browse the user interface. User task is explicit examination of user performance and satisfaction, physical device support, and software facilities in support of users' cognitive organization of these tasks, which not only expose critical usability problems, but also promise the most notable improvements when addressed (Gabbard and Hix 1997).

Given the widespread applicability of VEs, their potential user task space is enormous like are the ones of AR and MR. However, a thoughtful approach to understanding a smaller, yet representative, subset of this space may be helpful. Identifying basic task characteristics and elementary VE and MR tasks representing some "common denominator" may be appropriate, since any findings at this level could presumably be applied in a more application-specific or high-level task analysis (Gabbard and Hix 1997).

In this chapter the usability characteristics relating to the user tasks are presented. First some general issues related to the MR users and MR tasks are presented followed by more detailed low-level tasks, which are common for the use of MR applications.

MR users

Like any user group, MR users have varying characteristics like age, sex, level of experience and motivation. These have to be taken into account also when developing MR applications. Mixed reality applications, which often use wearable or at least carry on mobile equipment, the individual size has to be considered more specifically than in desktop environment. The requirements for users' attention have to be carefully designed, so that the user can pay enough attention to the surrounding environment.

- Take into account user experience. (VE, GDP)
- Support users with varying degrees of domain knowledge. (VE)
- Take into account users' technical aptitudes. (VE, GDP)
- Accommodate natural, unforced interaction for user of varied age, gender, stature and size. (VE)
- User control. Undo and backtracking. (GDP)
    - User override of systems initiative. A command is available for the user to regain control. (GDP)
- Adaptability. Interfaces should adapt to the user in several ways. The user and not the computer should be in control, so the interface adapts to the user's speed of work and does not enforce continuous attention (Includes individual user characteristics etc.). (GDP)

MR user tasks

The task execution in the mixed reality application needs to be designed according to the basic guidelines known from previous domains: consistency, clear structure, undo etc. In Virtual reality the tasks can be very complex and there the simplicity and predictability has been found to be important for successful task executions. When we are out in the open environment and the amount of information available for the user is immense, the user should be helped to cope with the information flow with restricting the amount of information presented for the user leaving out all unnecessary information.

- Provide step wise, subtask refinement including the ability to undo. (VE, GDP)
- Compatible. From consistency to state that new designs should be compatible with, and therefore based on, the user's previous experience. (GDP)
- Consistency. Help user learn an interface by making the layout follow a familiar pattern. (GDP)
    - Consistent modality. If speech is used for action, then this mode should be consistent throughout the application. (GDP)
- Structure. Only relevant information is presented to the user, and in a simple manner. (GDP)
- Economy and error correction. Interface design should be economic in the sense that they achieve an operation in the minimum number of steps necessary and save users work whenever possible (shortcuts, defaults, etc.). (GDP)
- Predictability. The interface should always suggest to the user what action is possible. (GDP)
- Organizational and operational metaphors map to the user's mental model, thereby suggesting appropriate action. (GDP)
    - Language and labeling for commands should clearly and concisely reflect meaning (GDP)
- Feature hints. The presence of system services and facilities are signaled during the entry phase of the interface, for example, top-level menus, overview maps, and speech explanation when entering a VE. (GDP)
- Provide awareness-based information for competitive task performance. (VE)
- Support concurrent task execution. (VE)

- Design interaction mechanisms and methods to support user performance of serial tasks and task sequences. (VE, GDP)

Navigation and locomotion

Support for navigation and especially for locomotion is very important in VE and MR applications. When the user is in immersed partly or totally in virtual environments, the build in mechanisms for navigation and locomotion may not apply and the user can be lost in the environment and cannot perform any tasks. The user needs information of the current location, view of the environment as well as clear indications to where they can or should go. This information should be in natural way and should not require too much attention from the user to figure these out during the task execution.

- Support appropriate types of user navigations (VE) and facilitate user acquisition of survey knowledge (e.g. maintain a consistent spatial layout) (AR, GDP)
- Provide information so that users can always answer the questions: Where am I? Where do I want to go? (VE, AR, GDP)
- Ensure that point-to-point animations do not restrict situational awareness. (VE)
- Clear indication of the user's location and state within the task sequence. (GDP)
- User always able to return to known position. (GDP)
- Backtracking to reorient. To help disoriented users, provide backtracking facilities so they can return to areas in the environment with known landmarks. (GDP)
- Waymarks for revisiting favorite locations. Provide bookmarks in information spaces and personalized annotation to mark locations. (GDP)

- Bird's eye view of the overall navigable space. Zoom-out controls show the whole environment or a map of the environment is provided and oriented from the current viewpoint. (GDP)

Object selection

When the real and virtual worlds are combined and the object selection is performed standing up, on the move or other wise challenging positions, it needs to be clear and easy for the user. The selection points have to be clearly presented in large enough size and the selection means need to be fast and accurate enough. For example, if the frame rate is too low, the user can move a cursor too much at a time and miss the selection point. The following issues should be considered when designing object selection for mixed reality application.

- Use direct manipulation for selections based on spatial attributes (e.g. location, orientation, shape) (VE)
- When augmenting landscape and terrain layout, consider organizational principles (GDP). When appropriate, include spatial labels (AR, GDP)
- Strive for high frame rates and low latency to assist users in three-dimensional target acquisition (VE, GDP)
- Object selection point should be made as obvious and accessible as possible (VE, GDP)
    - Tools and interactive features are located to correspond with the user's mental model; for example, drawing instruments are placed next to a virtual paper surface. (GDP)
    - Clear indication of objects and controls that are active in the virtual environment and user interface (UI) are necessary. (GDP)

Object manipulation

In mixed reality applications object manipulation is a very common task, which involves, when possible, all human senses. Object manipulation should follow as much as possible the way humans interact with objects in the real world. Touch and feel of surfaces should be supported as well as smell. In MR applications these are present when concerning the real objects, but the virtual objects should have these characteristics as well. When designing object manipulation it should follow as closely to the real interaction as possible.

- Support accurate depiction of location and orientation of surfaces (VE)
- Support multimodal interaction. Providing multimodal feedback and/or speech plus action modalities increases naturalness, reduces the user's learning burden, and improves task performance. (VE, GDP)
- Support interface query to determine what actions are available for objects. (VE, GDP)
- Indicate appropriate controls and commands for response. (GDP)

4.2 The presentation of virtual objects in the MR application

In the real world we perceive information with all our senses all the time. We see, hear and smell things and we feel, share and experience continuously. We use this information to interpret and create mental images or models of the world around us. There are some issues that we cannot directly perceive with our senses in the real world. User with a mixed reality application can perceive additional elements, which are not present in the real world. We can see objects on top of another or a real world object can be removed from our sight. We can also feel objects that are not really present and hear voices, which are not there. Some of these issues we have had for a long time, for example telephone brings voices for us, which could not otherwise be there, but augmenting our present view with visual objects and feeling remote objects has been made possible in the near history. Phones has been extensively developed to be the small mobile phones they are now, but sensing of other possibilities to augment our world, still needs extensive development.

This chapter includes issues concerning the representation of virtual objects, which are used to enhance the mixed reality environment. The presentation of the virtual objects as well as the setting which it augments need to be considered in order it to be understandable and easy to use for the user.

Virtual surrounding and setting

Making it easy for the user to understand and interpret the virtual objects in the environment they need to be designed based on real world phenomenon. The environment needs to reflect real world behavior and functionality and the virtual objects need to behave like corresponding objects in the real world. Objects need to be overlapped when another object is on front of it. The following issues support the design of the virtual environment.

- Exploit real-world experience, by mapping desired functionality to everyday items. (VE, GDP)
- User relevant settings that suggest user activity and tasks. (VE, GDP)
- Employ rendering techniques that support detailed presentation of setting without introducing lag. (VE)
- Support significant occlusion-based visual cues to the user, by maintaining proper occlusion between real and virtual objects. (AR, GDP)
    - When possible, determine occlusion dynamically, in real-time (i.e. at every graphics frame). (AR, GDP)
- When presenting inherently 2D information, consider employing 2D text and graphics of the sort supported by current window systems. (AR, GDP)

MR system and application information

The term “system information” is used here to refer to information, which is given “on top of” or “in addition to” information presented to establish environment or setting. Equally as important as environmental information, system information provides users with additional system state information such as command interface feedback, navigational aid, and online help (Gabbard and Hix 1997).

- For large environments, include a navigational grid and/or navigational map. (VE, GDP)
- Present domain-specific data in a clear, unobtrusive manner such that the information is tightly coupled to the environment and vice-versa. (VE)
- Physical and spatial fit. Application and its components can fit into the spaces specified, that movement and composition of objects is physically possible, and that people can move in constrained spaces. (GDP)
- Operation can take place under a variety of environmental conditions. Lighting, visibility, noise and so fort. (GDP)

4.3 MR user interface input mechanisms

The dialog between the user and the application is mediated with different input mechanisms. In order to work efficiently this dialog should use commonly known metaphors and natural interaction mechanisms. It should support simple and clear interaction between the user and the application. In order to select correct input mechanism for the developed application the expressiveness and effectiveness need to be considered. Expressiveness means that the input mechanism conveys exactly and only the intended meaning and the effectiveness mean that the input mechanism conveys the intended meaning with felicity (Card et al. 1990).

This chapter discusses issues, which should be considering when selecting an input mechanism for MR application. Selection of the input mechanism for MR application compared to a VE application differs in the needed degrees of freedom (DOF). In VE interaction is more body based and it usually has more degrees of freedom than an MR application. Addition to the user's input mechanism this chapter considers one of the most challenging issues of the MR application, the tracking of the user. The required accuracy of tracking the user, its accuracy, responsiveness, registration etc, is important issue and affects the usability of the whole application.

MR user interface input mechanism in general

The required degrees of freedom (DOF) to be used in the MR application have to be considered for each application. The application should not rely on traditional keyboard and mouse in MR application, but there is often no need for extensive implementation of too many degrees of freedom, if this is not required by the task execution.

- Assess the extent to which degrees of freedom are integrable and separable within the context of representative user tasks. (VE, GDP)
- Eliminate extraneous degrees of freedom by implementing only those dimensions, which users perceive as being related to given tasks. (VE, GDP)
- Address possible effects that prolonged usage with particular input devices may have on user fatigue and task performance. (VE)
- Avoid integrating traditional input devices such as keyboards and mice in combination with 3D, free-space input devices. (VE)
- Operation of commands and controls is within human motor and perceptual abilities, for example selectable areas on an image are sufficiently large so the user can place the cursor on the target without difficulty. (GDP)

Tracking user location and orientation

Tracking is currently one of the biggest problems in MR applications. Tracking is not as accurate as it should be in an outdoor open environment. Inside in a closed area, tracking can be done accurately, but most MR applications are designed for outdoors. The following, mostly technological issues are important to be solved according to the accuracy needed by the task. All these have high implications to the usability of the application.

- When assessing appropriate tracking technology relative to user tasks, one should consider working volume, desired range of motion, accuracy and precision required, and likelihood of tracker occlusion. (AR, GDP)
    - Mechanical tracking technology is well suited for single user applications that require only a limited range of operation, applications where user immobility is not a problem. (VE)
    - Optical tracking technology is well suited for real time applications where occlusion is less likely. (VE)
- Calibration requirements for AR tracking systems should include:
    - Calibration methods which are statistically robust (AR, GDP)
    - A variety of calibration approaches for different circumstances (AR, GDP)
    - Metrology equipment that is sufficiently accurate and convenient to use. (AR, GDP)
    - For testbed AR environments, calibration methods should be subject-specific, i.e. take individual differences into account. (GDP)
- Trackers should be accurate to small fraction of a degree in orientation and a few millimeters in position. (AR)
- Tracking systems should work at long ranges (i.e. support mobile users). (AR, GDP)
- Minimize dynamic errors by (AR, GDP)
    - Reducing system lag
    - Reducing apparent lag
    - Predicting future locations

4.4 MR user interface presentation components

The other side of the interaction between the user and the application is the presentation of the information for the user, which can be done visually, using haptic, audio or any other sense used by human. The presentation means described in this thesis include the visual and aural. Different displays are left outside this framework, since the display technology was selected to be a TabletPC.

Visual feedback – graphical presentation

Presentation of the virtual object visually has to deal with the characteristics of the human eye, which is quite demanding tasks. When designing the MR application, one should consider how important it is to match the object location, contrast, focus etc. to the human eye. In some applications it is not required to locate the object to the correct depth, but in some applications it is very essential. In HMD's it is really important to match contrast and focus to the human eye, but it is not so important in video see through HMD's and in handheld displays. These guidelines should be applied, when appropriate for the developed application.

- Manageable information loading. Messages presented should be delivered across modalities at a pace that is either under the user's control or at a rate that allows for effective assimilation of information without causing fatigue. (GDP)
- Ensure compatibility with user's understanding. Media should be selected that convey the content in a manner compatible with the user's existing knowledge (road signs for hazards, different information on diagrams and graphs) (GDP)
- Information is provided that is appropriate to the user's task (GDP)
- Strive for consistency among the various visual (and other sensory) cues, which are used to infer information about the combined virtual and real world. (AR)

- Feature hints, lists of commands, or functions relevant to the user's task are displayed (GDP)
- Support learning. Active objects should be cued and if necessary explain them to promote learning of the MR environment. Base the layout of the environment on the user's episodic memory. (GDP)
- Thematic congruence. Messages presented in different media should be linked together to form a coherent whole. (GDP)
- Use stereopsis
    - When information is presented in an egocentric view. (VE)
    - When presenting relatively static scenes. (VE)
    - When user tasks are highly spatial. (VE)
- When manipulating objects, the response time delay between user movement and visual feedback should be < 50ms. (VE, GDP)
- Timing and responsiveness of an AR system are crucial elements (e.g. effect user performance). (AR)
- Allow user to optimize the visual display (e.g. support user-controlled illuminance and contrast levels. (AR, GDP)
- Ensure that wearable display is sufficiently comfortable and optically transparent for the user. (AR)
- Minimize static errors by isolating and evaluating
    - Optical distortion (AR, GDP)
    - Errors in the tracking systems (AR, GDP)
    - Mechanical misalignments (AR, GDP)
    - Incorrect viewing parameters (i.e. field of view) (AR, GDP)
- Information is presented in an appropriate modality and location and a message is displayed in an appropriate media. Change in location is displayed on a map or diagram. (GDP)

- Congruent messages in integrated media. The subject matter in different media fits together, for example, picture of a whale and audio of a whale song. (GDP)
- Attention is directed to key information. (GDP)
- Feedback on initiative duration. For example, a timer is displayed to show the remaining duration of the guided tour. (GDP)
- Indication of limits of future action. Feedback should be cooperative and indicate only options available for future action. (GDP)
- Timing and responsiveness of an AR system are crucial elements. (GDP)
- Strive for consistency among the various visual (and other sensory) cues, which are used to infer information about the combined virtual and real world. (GDP)
- Allow users to alter point of view, or viewpoint (VE). Reinforcing messages and viewpoints. A motor vehicle engine is shown using a photograph and as a diagram illustrating its components. (GDP)
- Complementary viewpoints. Similar aspects of the same subject matter should be presented on different media to create an integrated whole (schema and a real picture). (GDP)

Aural feedback – acoustic feedback

Aural feedback has not been used much, since the requirements for the applications prohibit the use. For example the use of audio has been discarded because of social, organizational or safety reasons. The use of audio can be beneficial to be used to draw users attention, but all the environmental issues has to be considered in the design, especially use of headsets that limit the perception of the important audio information from the environment.

- Use headsets for a portable, cost-effective audio system for remote single users. (VE)

These are the guidelines considered throughout this research. During the analysis of the research these guidelines are considered and augmented with the results of the studies.

5 User requirements

This chapter summarizes the user requirements, which can be found from the papers I, II and IV. Each paper is described by presenting the objectives and the main findings.

5.1 User requirements for MR authors (Paper I)

I User-Centred Evaluation Criteria for a Mixed Reality Authoring Application.

Objectives

At the beginning of the research the task was to study the development context of the mixed reality applications and to gather user needs from the target users, which were collected with interviews and field observations. The results were analyzed and user requirements derived for the MR authoring tool. The requirements were used as evaluation criteria in the iterative usability evaluations throughout the project. The goal for collecting the user requirements was to enable the development of usable mixed reality authoring tool for the target user group, the MR authors.

Results

The results of this paper were the user requirements, which were listed following the structure of the context-of-use analysis describing issues related to the user, their tasks, the used equipments and their environment. The target users are familiar with multimedia production and web design. They are familiar with multimedia development software, and the MR authoring tool should follow the common user interface conventions, which are found good and usable and are familiar for the target users. The use of these UI conventions will enable fast learnability of the application.

Multimedia, as well as mixed reality, applications are designed and implemented in customer projects and it is crucial to be able to present the design ideas for the customer. In the customer meetings the developers need to show intermediate previews of their work and the MR tool should support making them. At the beginning of the projects the developers make a customer visit on-site to the application use context where they collect all necessary information and return to their office. For efficient development the rest of the development needs to be made off-site in the developer's environment. The developers are not programmers, so the content creation has to be handled on a high, domain specific level (domain = customer application domain), meaning that the author does not need to touch the source code and program the application for example with C++ or Java. The tool should be compatible with other used tools, since mixed reality is often only one part of the application, which can include text, pictures, HTML, Flash and Java elements etc.

The MR tool is based on components and all the developed applications as well. The component structure entails user requirements itself. MR author must be able to efficiently create and organize an application with existing components (reusability). The components need to have clear specifications and a library structure at a high level of abstraction for finding the components. They should be generic and customizable to fit different requirements and the properties should be easily changeable without touching the source code.

From the organizational standpoint, the authoring tool should not change the MR author's current development, or production, process. The tool should also decrease the time required for the technical development phase of the MR applications and fit to the production cycle of the whole project.

5.2 User requirements for the MR training tool (Paper II)

II Mixed reality training application for an oil refinery: User requirements.

Objectives

This paper describes the user requirements for the oil refinery training tool (Figure 7. Users with the MR training tool for oil refinery). The data was collected with a questionnaire, a field observation and two interviews. The goal of the study was to gather the user requirements, but equally important was to prevail all the project personnel how restrictive and strict this industrial setting can be. I conducted a context-of use analysis and derived user requirements from the data. The requirements were collected for the AMIRE project and were published also in Haller et al. (2003) and Hartmann et al. (2004). The results were supported by studies by Guerlain et al. (1999), Skourup and Stahre (2002) and Gabbard and Hix 2001.

Results

The oil refinery application was for an on-site training, aimed at new employees who are unfamiliar to this particular refinery. They generally have academic process engineering background, but little work experience. They are around 17-25 years and are familiar with computers. Currently training is off-site, on-site being possible rarely only when the refinery has maintenance breaks.

Figure 7. Users with the MR training tool for oil refinery employees

The environment is large area full on pipes, pumps, vessels, reactors etc. and it is really hard to follow the process flow on-site. The refinery area is divided into units, which are logical processes. Each process is operated from a control room and the workers make on-site visits when needed for maintenance or check-up. The height of a column can be several tens of meters high and the operating and maintenance personnel need to climb the plant up and down by stairs or by ladders. When the employees are on-site, they are wearing a safety-dress and often carrying some tools. The new application must be usable with the safety gear on. The new equipment should be easy to carry and it should not hinder the user from climbing up the columns and ladders or from reaching needed parts of the plant. The application has to be easy to learn (maximum of 15 min of training), intuitive and self-explanatory and it should use commonly known metaphors. Its content has to be easily maintained, since the refinery is under constant change.

The used equipment has to been explosion-proof and it cannot act as ignition source. The oil refinery requires that the tracking of the user's real position and orientation is in the accuracy of 1 meter and ±5° and the system has to cover very large outside area (1,6 sq.km).

5.3 User requirements for the MR museum guide (Paper IV)

IV Requirements for using Mixed Reality in Museums.

Objectives

This paper describes the whole development process of a MR museum guide application for the Guggenheim Museum of contemporary art in Bilbao (2004). An authoring-based production process, tailored to the specific requirements of MR is proposed, and its utilization for the realization of the Guggenheim MR museum guide is described. Among the development process, the paper presents the results of a user evaluation of the MR museum guide as well as some user requirements (Figure 8). Some of the user requirements are published in the paper by Träskbäck and Nieminen (2003).

Results

Museum environment is a very restricting and versatile environment. The museum facilities are varying depending on the building, location and contents of the museum. Sometimes filled with small detailed exhibitions in showcases or, in the case of contemporary art, large artworks displayed in unison with the surrounding building. Main part of the environment is the works of art. They are often not owned by the museum and permission is required before any additional mixed reality elements can be used in a museum. The museums change their exhibitions as often as every three months. Use of MR in a museum application need to have easy and fast modification and maintenance possibilities and the use of the application will in this case be restricted to the permanent collection or long-term exhibitions.

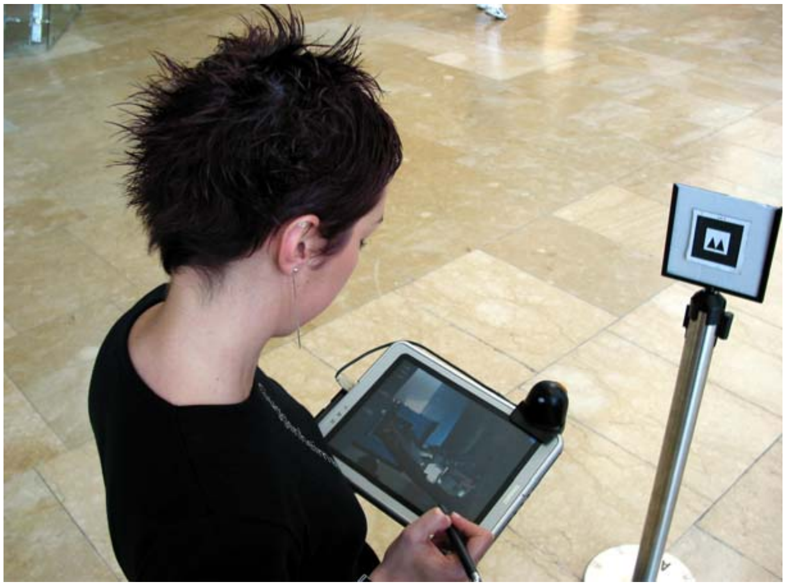

Figure 8. User tests at the museum with the MR museum visitor's guide.

The users of the museum application are wide variety of people. They are from all social groups from children to elderly and from locals to foreigners. This lays high requirements for the used equipment, which has to be lightweight for easy handling and carrying, have a low contact with the body and the appearance should be socially acceptable (no head mounted displays or wearable computing). Also the use of audio is limited to prevent unnecessary disturbance, while physical contact with the works of art is most often forbidden.

When MR applications are developed for a museum context, it is very important to consider the overall big picture. It is important that the used technology does not hinder the visitors' from experiencing the works of art. The MR applications must honor the art and abide by the various constraints. Most of the requirements are the same for all services designed for the general public, but museums have more restrictions related to the use of information of the works of art. They might not have permissions to augment the pieces or they do not wish to alter the original work that the artist has created.

The content in the MR museum guide needs to be easy to use. It should consist of story-like entities with beginning, middle and end. The visitors like to have combined media, for example 3D models and audio. The most interesting content among the test participants were the 3D models and animations. Addition to the content considering the artworks, the application should support the visitor by offering information of the museum services and especially in navigation in the museum and its exhibitions.

6 Usability Evaluations of the MR applications

This chapter presents the usability evaluations of the three applications. First the paper III is presented followed by other usability evaluations conducted as part of this thesis.

6.1 User evaluation of the authoring tool (Paper III)

III Toward a Usable Mixed Reality Authoring Tool: Case study AMIRE.

Objectives

The MR authoring tool (Figure 9) was developed based on the user requirements collected at the beginning of the project. The tool was iteratively evaluated and results fed back to the developers. After several iterations, the authoring tool was ready to be evaluated with actual users. This paper presents the results of a user test.

Results

The usability evaluation was conducted with six users in a usability laboratory. The aim was to find out how well users perform tasks with the developed MR authoring tool and to offer information on how mixed reality authoring user interfaces should be developed.

The users started to browse the user interface and they used previously learned user interface conventions while browsing: tooltips, right-click of a mouse, etc. They were familiar with the windowing system and were willing to work using the camera view, instead of the control windows. Making an application was mainly connecting components together and changing their parameters. Connecting the components was first difficult, since there was no graphical connection editor, but ones they connected two components, the next one was easy for them.

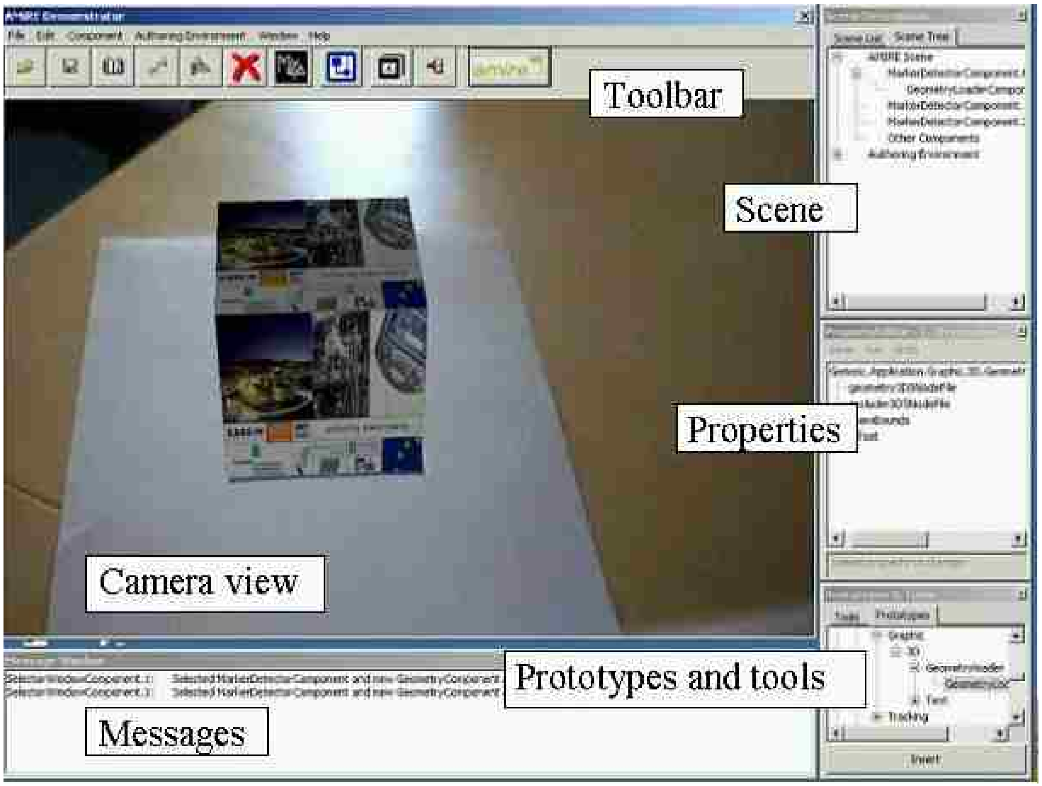

Figure 9. The user interface of the AMIRE authoring tool

The users would rather use drag-and-drop and mouse when working with the components, but it was not possible in the tested version of the tool. The users needed to change the parameters and they had two choices for it; a matrix editor with numbers and sliders and MR tools. All the users selected to use the matrix editor first, since it was more familiar for them. The origin of the changes was not clear, which caused many problems in the repositioning and resizing tasks. From the parameters, the depth was most difficult for the users to perceive and alter due to the 2D screen. The MR tools used the ARToolkit (ARToolkit 2004) markers. These were found problematic, since while moving the marker to the desired location on the table, the users often blocked part of the marker and the component did not respond to the movement. The MR tools were interesting, but the usability of the tools needs to be improved.

According to the users, the evaluated authoring tool (Figure 9) was not easy to use, but it was quite easy to learn. The test results support this fact. The users strongly agree that this tool does not require programming (C++, Java) and that the tool resembles other programming tools that they have used, but it does not resemble Director, Flash or 3DMax, which the users work with.

6.2 User evaluation of the MR training tool

Objectives

The oil refinery training tool (Figure 10) was evaluated with three employee from the oil refinery and they were all wearing their safety-dress (including helmet, safety glasses, heat resistant safety dress) The illumination conditions at the day of the test did not allow testing all stations (checkpoints) in the application. The bright sunlight firstly blinded out the display of the tablet pc and secondly considerably disturbed the tracking functionality. The test included one or two checkpoints where the user used the OMV demonstrator on the TabletPC.

The tests were documented on a video and with screen capture software and no other documentation method was used. The background noise of the oil refinery was so loud that the instructors and users comments were not recorded on an audiotape. Without additional notes the information and comments of the user cannot be retrieved and used in the analysis. These results were not published in any academic media. More detailed information of the test can be found from the public deliverable of D8.4 Final evaluation report (2004).

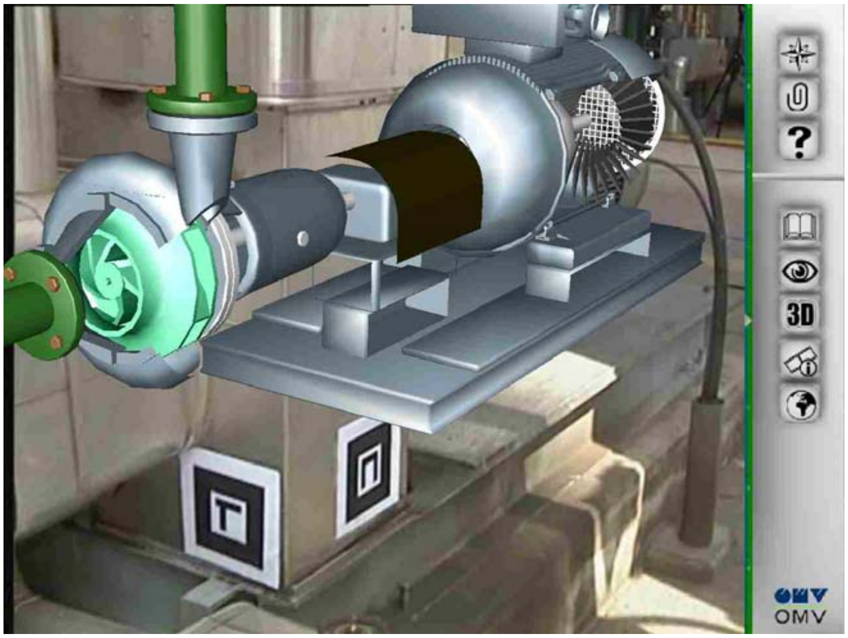

Figure 10. User interface of the oil refinery training tool for the user tests.

Results

The user interface of the demonstrator was easy to learn and understand. The users were able to find all the data by trying all the offered content. Even though the demonstrator did not support intuitive search, the users found needed information by browsing through the information available for them. The user interface was consistent trough out the demonstrator and it was easy to use. This test evaluated a technical demonstrator, so it did not have much content yet. From the limited content the 3D models of the oil refinery equipment were the most interesting ones. The users were able to use the demonstrator equipment, even though they had some little problems in using the pen (pressed too lightly) and at some points the light conditions made it difficult to see anything from the screen.

The used marker-based tracking system (ARToolkit 2004) was not suited for this demonstrator. The users had problems in aligning the camera with the marker and especially in holding the alignment. The positioning of the markers in the real environment was next to the target object. When the users aligned the marker in the middle of the screen, they were not able see much from the augmented target object. The users used significant amount of time for realigning the marker and the target object to the camera view.

6.3 User evaluation of the MR museum guide

Objectives

The museum guide was evaluated with five users working in the museum. The test included 8 checkpoints and the tests were recorded on a video as well as notes and on still images (Figure 11). The screen capture software was not used, since it demanded too much power from the TabletPC and it slowed down the performance of the demonstrator too much. One of the checkpoints also had standing binoculars, which could be used to viewing simultaneously with the TabletPC screen. These results were not published in any academic media. More information can be found from the public deliverable 8.4 Final evaluation report (2004).

Results

The user interface of the museum guide consisted of a control panel on the left and a video picture on the right, which covered most of the screen. First the user pointed the attached camera to a marker, which the software recognized. According to this location information the application presented the corresponding data for the user. The user was able to select different content from the control panel. The panel was difficult to use with right-hand, since the user needed to reach over the screen to the other side, her hand covering the picture. While reaching over it was difficult to maintain the alignment of the camera to the marker and the marker was often lost, which was followed by the lost of the control panel. The user interface was not consistent, which confused the users several times. For example the audio information had three different ways of working: automatically, audio control buttons at the control bar as well as buttons at the bottom of the picture area. All the functions available for the user should work consistently throughout the application. The users also need a clear exit from all the functions.

Figure 11. User using the MR museum guide in the museum balcony during the user test. The test instructor (middle) guides the user to do predefined tasks and the test is recorded on videotape.

The content included text, pictures, video, audio and 3D information. The audio is well suited for a guide, since the user can simultaneously look other content or the art itself. Videos were considered informative, but pictures were not, since the pictures in the guide did not really present much new information. The 3D models of the building were considered really interesting, since the user was now able to see the building from outside while standing inside and listening the audio of the building. Simultaneous content was really important. The users liked to listen to audio, while looking at the pictures, video or the 3D models. The users also liked to have audio to go with the textual information. This will help the user to concentrate on the text better.

The tracking system used in the guide was a marker-based system (ARToolkit 2004), which required the application to recognize a marker in the video picture. The marker needed to be recognized all the time and the alignment of the camera to the marker was difficult for the users to keep. This lead to the content being on and off, which was confusing for the user. The users were guided to use the freeze function of the guide in order to freeze the video picture. This way the user was able to support the TabletPC close to their body, while browsing the content and listening the audio. They did not need to focus on the alignment, but they also lost the main issue of mixed reality application, the location specific information. The tracking system should be changed for the final museum guide.

The TabletPC was scary for the users, since they were afraid of dropping or breaking it while carrying around and using it with a pen. It was also too heavy to be carried around, especially without any strap around it. Overall feeling of the guide was positive among the users, even though it was not a final product, but a demonstrator. The users were happy to get new kind of information, especially visual information.

7 Analysis: Evaluation results against the framework

In this analysis, the results of the studies in this thesis are compared to the framework described in chapter 4. Each part of the framework is discussed based on the results of the studies of MR training tool, MR museum visitor guide, mixed reality authoring tool.

7.1 Users and user tasks in MR

MR users

The studies started with a context of use analysis for all the developed applications and user groups were defined. The authoring tool and training application were designed for a quite homogenous group of users, but the museum guide had very wide user group. When developing MR applications, the users' characteristics and experience with the domain and technology has to be considered, since they have high impact on the design and used technology. The equipment used in the demonstrators (training tool and museum guide) was a TabletPC. In the museum case, the equipment was too heavy to carry along for a long time even for young visitors, so it is impossible to be used by the elderly visitors and in both of the cases it was difficult to align the camera to the markers and hold it still.

The applications used common user interface conventions from MS Windows. The authoring tool had this in the user requirements and the two demonstrators used them by default. The users were familiar with these and in the parts where the application did not follow them users were confused and asked for consistency for MS Windows. Users considered the equipment to be a computer and they were happy to see common user interaction elements and familiar way of interacting with the application. The users were able to use the audio, video and 3D animations from the control buttons, but sometimes the controls were difficult to use or they even disappeared from the screen for a while and the users had problems in gaining control over them. The controls should be located in the same place and be visible for the user all the time.

In the MR applications there is more need for new interaction methods. The use of touch, sound and gestures are applicable for MR applications in general. The equipment used in these applications had to be off-the-self products and a Compaq TabletPC with a touch screen was chosen for the project.

MR user tasks

The user interface needs to be consistent. The common user interface conventions need to function the same way and the user interface needs to be consistent through out the application. When the user interface did not follow consistency, the users were easily lost and it took some time before they recovered. The application structure needs to be simple and consistent.

The demonstrators did not offer undo, which caused little problems. Only little, because the application hierarchy was very low and it was easy and always possible to return to the top of the application. For each checkpoint, the museum guide offered only buttons for the available content in the control bar and this was understood well by the users. If a checkpoint did not have a video, it did not present a button for accessing it. At the same time the appearing buttons suggested the user easily what kind of content is available for them. The oil refinery demonstrator presented all the content buttons all the time, but the inactive ones were presented in grey. The users understood this as well and did not have problems with the control buttons. Placing the content buttons in a certain order in the application supported serial task sequence and most of the users browsed the content in the given order. At the end of the evaluation in the few last checkpoints, the users browsed only the most interesting content and not all of it. Both demonstrators lacked in presenting an overview map, but this was a resource issue and the maps were not developed in the project.

The authoring application acted as an MR application, especially when used on-site in the actual environment. The authoring tool was consistent with other content production tools, which helped the users to build the MR applications. It supported basic undo, copy and paste functions consistent way and the main information was displayed clearly for the user. The authoring tool had problems in the structure and predictability, since the tool did not suggest well available functions and how the functions should be used. These came up clearly in the user tests as needed improvements. Concurrent task execution also has a lot to be improved, especially in the connection of the components. The order of the connections as well as way to connect them is very important for the functionality of the new application and the usability of these tools should be improved significantly.

Navigation and locomotion

The developed demonstrators had low immersion. The users are aware of the surrounding environment and used the demonstrators only when they are still. This was caused by the use of visual tracking system, which the application needed to recognize. In order to examine the content of the application the visual marker needed to be visible and the user had to stand on front of it all the time. The exception was the freeze button, which froze the current camera view and the user was able to move. This reduced the context sensitivity of the application.

The oil refinery and museum environments are both complex and the users requested for navigational aid. They wanted to know where they are and where is something that interests them. The bird's eye view would be helpful for the users as well as navigation guidance from their current place to the chosen place.

Object selection

A touch screen with the TabletPC pen was used for object selection in all of these applications (authoring tool, when used with TabletPC, with desktop computer a keyboard and a mouse is available). The use of the pen was found familiar, but it took some time to get used to it. Most of the users pressed the pen to the screen too lightly, so that it was not detected. When the users dared to press harder, they did not have problems with it. Users did not have problems in selecting functions. In the museum application the control bar was located to the left side of the application, which caused some difficulties for the right-hand users. They needed to reach over to the other side and they often lost the visual marker from the camera during this operation, which cased the content buttons to disappear. Technological issues like low frame rate and low latency did not cause problems in these demonstrators, since they did not include a lot of content yet. During the museum evaluations, the screen grabber recording software was not used, because it slowed down the application's performance too much and it would have affected the use of the application by making it slower.

The selection points were easily visible for the users, since the design was according to commonly used metaphors and visual cues. In the training tool, all content buttons were visible all the time, but the active ones looked different than the inactive ones and the users understood the cues well. In the authoring tool, object selection was done with a mouse, when the application was used in desktop environment and with the pen and touch screen, when on-site.

Object manipulation

In the authoring application the visual markers can be used for object manipulation. By moving the markers, the virtual object was rotated, scaled or positioned in 3D space. This was useful when the virtual object's positions were calibrated on-site, even though required two people.

The demonstrators were used with touch screen and a pen, so they didn't have much possibility to manipulate the objects. The 3D models could be rotated, but only by pressing a rotation button, and the layers of the machinery in the oil refinery could be inspected by reducing or increasing the layers. This was done by + and – buttons. The demonstrators used audio and visual senses, but touch and smell were not explored yet.

7.2 The presentation of virtual objects in the MR application

MR applications augment reality with virtual information and in these cases the augmentation is presented with visual virtual objects.

Virtual surrounding and setting

The virtual object has to exploit real-world experience and behave like its counterparts in the real world. The oil refinery demonstrator presented the equipment from inside in different layers and its functionality. These virtual object's appearance and functionality has to comply with the actual equipment. When the appearance of the virtual object is the same than the real world equipment, it is easier to understand. By emphasising some components with colouring, the user can understand the equipment better. The animations of the equipment's functionality need to present what actually would happen, since all differences to the real world can cause misinterpretations, leading to false use of the equipment during actual process. This can cause severe problems in real life. The physical and spatial fit is really important, when the equipment is introduced and its functions are demonstrated with animations. The floating substance needs to float from the correct pipe into the equipment and out to the correct direction. The refinery is full of pipes and it is really important to point to the correct pipe in the environment. The environmental conditions laid important requirements for the application and end user device. Large and noisy outdoor environment with high security restrictions limited the use of audio and head mounted display in the MR application. The demonstrator's own functionality was presented with 2D text and graphics, since this information is inherently 2D and does not require 3D.

In the museum case the virtual objects were more like additional information and offering more interaction with the artwork. In this case the virtual object were not presenting exactly reality, which cannot be seen otherwise, but to enhance the museum experience. This way the virtual objects do not need to be according to reality, but the functionality has to be mapped to the real world. For example occlusion needs to be maintained properly and in real time. The museum environment also restricted the use of HMD's for more social reasons and it was more restricting in the use of the visual markers in the premises. The markers were considered to disturb the visitor's experience of the art works and should not be used. The museum is an indoor environment, but they have a lot of natural light, which changes significantly during the day. The marker detection system was sensitive to changing light conditions. The application functionality was presented in 2D, like in the oil refinery demonstrator.

MR system and application information

The system information is additional information of the environment or setting. Both of demonstrators offered the user navigational help and the oil refinery demonstrator offered overview of the area also in a scematic view.

7.3 MR user interface input mechanism

Mixed reality offers more variety of interaction mechanisms, which can use any of the human senses. In both of these demonstrators the use of senses were limited, since audio could not be used as an input mechanism, because noice in the environment or the disturbance it causes to others and eye sight detection as input is not developed enough. The demonstrators used a touch screen with a pen as input mechanism.

MR user interface input mechanism in general

The input mechanism can use six degrees of freedom, but in all the design, it needs to be considered how many degrees are really needed. In an augmented reality application, where the user is fully aware of the real world and the virtual augmentation level is very low, the needed degrees of freedom are only a few. In these cases, where the applications run on a TabletPC, the required degrees of freedom were only two. When HMD's are used, the input mechanism can take use of more degrees of freedom, when for example a hand gestures are used for input.

The use of the TabletPC did not put any strain on the human eyes and the virtual objects were presented on top of a realtime video picture, so there was no fatigue, when using the application. The equipment put more stain on the body, when the users had to carry the equipment around. It was too heavy for most of the users.

Tracking user location and orientation

Tracking the user is not solved yet. In MR applications, users locations and even users direction of sight, should be accurately tracked, if a HMD is used. Indoor tracking is far better now, than tracking of outdoor environments. GPS (global positioning system) tracking could not be used in the oil refinery, which is full of metallic pipes, colunms and equipment. The accuracy was about +- 18m, when user's tracking accuracy should be +- 1m. ARToolkit markers suited quite well for the refinery, since the markers does not bother anyone visually. In the museum the visual markers were not wanted, and there a infrared or other invisible tracking system would have been better. The users had a lot of problems when using the marker detection system. The alignment of the marker and the camera in the TabletPC was really difficult and most used function in both of the applications was the video freeze, which then prohobited the user from having a realtime video. The users often aligned the marker to the middle of the screen, leaving little if any room for the equipment or artwork. In quite many of the checkpoints, some of the content was displayed then outside the display area and the user was unaware of it. The marker detection did not work in long ranges, which caused the user to get closer to the marker, and so the marker took most of the display space.

Tracking requires a lot computational power from the hardware. The tracking should not reduce system or apparent lag, which can be detected by the user. When lags increase, the usability of the application decreases significantly for many application fields.

Calibration of the virtual objects is also a problem. The application is developed mainly off-site with a video capture material from the real site and the application needs to be calibrated on-site. Calibrating the tracking system as well as the virtual objects in the actual 3D space can be timeconsuming. The AMIRE authoring tool offered MR tools for the positioning of the objects. With these tools, the application was possible to calibrate on-site by using the same TabletPC, which was used for the application as well. The authoring tool does not provide a subject-specific calibration or take individual differences into account. The displeyment height of the markers was not best possible for all the users, which should be taken into account in the final museum guide.

7.4 MR user interface presentation components

Visual and aural feedback – graphical and acoustic presentation

MR application presentation components can also use any human sense, like vision, haptics, audio etc. The selection for the used modality is based on the content and its purpose. Both of the studied demonstrators used a TabletPC as presentation equipment, so the presentation modalities were limited to vision and audio. The use of audio was limited, but the demonstrator used it in order to test audio in the user test. When the audio was not connected with the other content, the users asked for it and even with a text, they wanted to hear the audio. They liked to listen and look at the target, not read from the display. Audio was presented with the loudspeakers of the TabletPC and so was heard by others. In the museum application this would be too disturbing and headphones should be used, but this limits the social interaction between the users, which is not desired. In the oil refinery the use of headphones were discarded for safety reasons, and there the environmental noise limits the use of audio in the MR application.

The content needs to be consistent in using different visual elements and user's attention needs to be directed to the key information. In these cases attention was devided with the main video window and the control panel. The users were well aware of the functions available for them. In the museum case there was a problem with disappearing controls, when used moved between content. When a functionality is on, i.e. a voice recording running, the control buttons for it cannot disappear from the screen even though other content, i.e. pictures are selected. Durations were shown for the user with a bar moving from one end of the slider to another one. This was well understood by users. Videos in the museum case did not have this function and users required to have it for the knowledge of the duration as well as if they want to repeat some part of the video.

In the content design it is really important to study which media type is best suited for different content. Pictures and text are often simple, clear and easy to understand for some content and some is best described with an animation. The production of animations is very time and cost consuming, so it should be used only when needed and when it gives additional benefits for the user. The media should be selected that convey the content in a manner compatible with the user's existing knowledge. In the oil refinery, the scematic pictures followed the traditional form from the papers and all the signs and colors for the equipment signs were according to the ones used earlier in the refinery. The scematic view presented the user another way of viewing the real environment from the process point of view. The user interface components followed common user interface conventions, so that they were easy and fast to understand. The user interface in both cases displayed the active and inactive buttons. The refinery application presented inactive buttons in grey and the museum guide removed inactive buttons displaying only the active ones. The refinery followed a common way from the PC's, but the change in the color was not sufficient and most of the users tried to press them anyway. The museum system worked, but it was confusing for the users, that the same content, for example audio, was located in different place in different locations.

Technical issues are very important in the presentation. When manipulating the objects, the response time should be less than 50ms. This was met in both of the demonstrators. Because of this limitation, the museum application was evaluated with users without a screen grabber software. Static errors need to be minimized in order to meet the 50ms limitation.

8 Conclusions

In this thesis I have collected user requirements and usability guidelines for building usable mixed reality applications. The user requirements were collected and usability evaluations conducted with several methods described in chapter 3.3 and the results are presented in chapters 5 and 6 and in the publications. Chapter 7 presented analysis of the results against the framework described in chapter 4. This chapter presents the final conclusions for the research question.

- What kind of user requirements has to be considered when developing mixed reality applications?

Chapter 4 presents user requirements and usability issues for building usable mixed reality applications based on literature. After analyzing the user study and usability evaluation results against the framework, some results were not found in the framework. These results were also important for building usable mixed reality applications, and these additional guidelines are presented in this chapter, enhancing the framework. First I present some general guidelines for mixed reality applications, followed by guidelines specific to the two application domains and the authoring environment.

8.1 General usability issues for MR applications

Mixed reality applications are highly context sensitive applications, which are used in real environment in real time, which high requirements for the applications. When the MR application is developed a context-of-use analysis should be made for the application, in order to find out who are the target users, what are their tasks and in which kind of environment the application is intended to be used and with which kind of equipment. Compared to application without virtual objects or virtual worlds, defining the intended environment from physical, social and organizational view is very important. Virtual worlds are inside a restricted environment, which cannot change much and environmental issues are controllable. Mixed reality applications can face more restrictions than traditional mobile applications, because of its nature to bring the user something additional experiences. This will relate to the issue of security, which can be compromised, if the mixed reality application takes too much of users attention when moving in the environment. In the oil refinery case, for safety reasons the equipment needed to be explosion-proof and the application cannot draw users attention when the employees move. The use of HMD was prohibited from safety reasons as well. In the museum the HMD was also prohibited, but for social reasons. It may not be acceptable to walk around with HMD and interaction with other visitors may also be compromised among their own group.

Environmental issues caused problems with the use of audio in the applications. In the oil refinery case it was not convenient to use audio, because the background noise on-site in the refinery is so loud that the user cannot hear the audio properly. In the museum case audio was prohibited, because it can disturb other visitors. Headphones were not tested in the first user test stage, but should be tested later on.

The equipment requirements were high and the equipment in the market did not meet the requirements. For presenting visual data, display needs to be big and the hardware should be powerful enough to present animations and 3D-objects in the moving real-time picture (tracking!). Still the equipment needed to be small and light-weighted, which is contradictory to the other requirements. In the future the equipment will develop to meet these requirements, and then the use of mixed reality will be easy and pleasurable for the users.

The customer partners required the applications to be quick and easy to produce and to maintain. They wanted to be able to make certain changes to the application content, like updating a text of a picture. In the oil refinery case they wanted to be able to build new additional checkpoints themselves for the application. This was considered in the AMIRE authoring tool, where a version with reduced set of functionality can be delivered with the MR application, so that the customers can make develop their own checkpoints and make changes.

The additional guidelines for the framework are following:

Users and user tasks in MR

- Conduct a context of use (ISO 9421-11) analysis to define user, tasks, environment and equipment. Pay special attention for the environment

MR user interface presentation components

- Consider carefully the use of audio content in the MR application. Consider the disturbance and social restrictions it can cause.

General issues

- Application maintenance needs to be possible for the customer
- Equipment needs to be selected to suit all the possible requirements. Often they are contradictory and decision has to be made with considerations.

8.2 Oil refinery MR application

The oil refinery domain is challenging and full of potential for MR application. The biggest limitation in the development was the environment and more closely the safety requirements. This was emphasized in all the work and it restricted the development of the application. The equipment should also be possible to carry without hands and cannot hinder the user from climbing up ladders and should be possible to use while wearing a safety dress. The equipment could not draw users attention while moving and tracking of the users location and detecting the view of the real time picture needed to be very accurate. This was difficult due to the nature of the environment, which is full of metallic columns and pipes, which cause wireless tracking systems to fail.

The guidelines for developing a MR application for oil refinery should follow also these guidelines:

- Safety. Safety should be considered in all the possible development decisions. This is number one for everything happening in the refinery area.
- Equipment should be possible to be carried without hands and user should be able to climb with it without problems.
- Equipment needs to be explosion proof and cannot act as ignition source.
- The application cannot draw users attention while moving
- No head mounted display for safety reasons (at least not the current ones)
- Tracking needs to be accurate in the environment full with detailed location information. User tracking in the accuracy of 1m and environment in accuracy of centimeters.

8.3 MR museum guide

Museum environment is delicate in another way. There the environment is quiet and pleasant and there should be no disturbances. The application and its use must by no means stand out, disturb or compete with the art exhibition. It cannot disturb the user enjoying the artworks and the use of the MR application cannot cause disturbance in the flow of visitors through the museum.

Developing the content is demanding and restricted highly by copyright issues, which can be owned by the artists themselves, the museum or a third party. Augmenting an artwork needs permission from the owner as well as from the artist and it might be complicated to achieve.

When a museum is offering a mixed reality visitor guide, it should be affordable for the museum to buy in large quantities and for the user to user (affordable rent). The user of a museum includes all consumers and the equipment and application should be usable for all the users.

The guidelines for developing mixed reality museum visitor guide are following:

- Social requirement: The application or its use must by no means stand out, disturb or compete with the current exhibition.
- It should not disturb watching the works of art
- Flow of visitors cannot be disturbed
- Copyright issues. Obtain rights to augment an artwork.
- Equipment usable for all users (weight, size)
- Affordable end user devices for the museum as well as for the visitor.

8.4 Authoring mixed reality

Authoring of mixed reality has been conducted inefficiently by programming from scratch. Now the AMIRE authoring tool offers a component based authoring tool for mixed reality applications, making cost and time effective authoring. With the graphical user interface this is also available for non-programmers. Authoring in such is not part of the usability guidelines for mixed reality, but in AMIRE some of the authoring is conducted with mixed reality tools and it is also important to provide the developers some guidelines for authoring the MR applications.

The MR application development needs to fit to the company's current production process in order to make it possible for the application developers to consider the use of MR in their applications. The author has to be able to create the content for the application, animations, 3D models and other virtual objects off-site. The content source material may be collected on-site, but application and content development

should be possible off-site in the developer's own office. For quick presentation of ideas for the customer, a quick preview has to be possible to make.
When developing the application structure from components the components should be handled on a high level and reusability of the components in different domains is important. The components should be available for the users easily and request for new component should be efficient. Changing parameters should be easy and fast to do without programming.

When the application is built with the MR tools (resizing, positioning, rotating) the origin of the tools need to be visible for the users as well as the reference point of the function. MR tools are usable when calibrating the application on-site when positioning the virtual objects to the real 3D world without keyboard and mouse.

In order to make the development of the MR applications cost and time effective, the following guidelines should be fulfilled:

- The use of the MR toolkit cannot change the current production process unnecessarily.
- Development must be cost effective and time consuming
- Content creation and editing must be possible to do off-site
- Content provision is handled on a high level
- The technology and components should be usable in several domains
- The maintenance of the application must to be easy
- Choosing, asking for new and using (changing the parameters) the components needs to be easy
- Possibility for a preview
- With the MR tools the coordinate axes and origin are visible

9 Discussion

This material for this thesis has been collected during 4/02 – 6/04. First the user requirements were gathered with several data collection methods and a context of use analysis was conducted and delivered to the developers. After several iterations, the development of the authoring tool and the two demonstrators were evaluated and the results were fed back to the developers and the human-centred product development process was used.

9.1 Limitations

During the thesis work I tried to use comprehensive set of methods. The data collection methods were often used with two people, but also with only one, the author of this thesis. This limits some of the results to one perspective. Most of the analysis was done only by the author, which limits the findings, making the results less comprehensive as it could be. The analysis would have benefited from other usability experts' opinions and comments as well as given more comprehensive analysis.

The thesis covered only applications run on a TabletPC and only in two domains addition to the authoring environment. In order to build comprehensive MR usability guidelines other domains should be included in the studies.

9.2 Future work

This thesis offers initial framework for developing usable mixed reality applications. The set of guidelines is in a working process and should be tested and challenged in several more studies and it should be refined.

All the studied applications were run on a TabletPC. The next studies should include more other types of end user devices such as PDA or head mounted displays. These end user devices bring new guidelines specific to the equipment and should be covered in a full list of usability guidelines for mixed reality applications.

After the technological problems are overcome, the MR applications will be ready for more accurate performance measures also from usability point of view and more complex content can be presented for the user. This will bring new issues to study to further improve the usability of the MR applications.

Interesting future research questions for researching usability of mixed reality are following:

- User requirements and usability of head mounted displays (optical and video).
- What is the optimal amount of virtual object presented for the user in different displays (TabletPC, HMD, PDA)?
- How well users understand, which is virtual and which is real? Does it make a difference in the user performance or satisfaction?
- Where mixed reality really brings added value? In a museum, multimedia could be enough, so where MR is really needed?
- Mixed reality in mobile phones. Is it worth developing or can we use multimedia?

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Appendix 1. Summative evaluation results: Authoring tool

1. **The use of the MR toolkit cannot change the current production process unnecessarily**. At least it should not make it more complicated. Production process must be cost effective after the team has learned to use the tools. The toolkit must allow development of reasonably priced MR content mainly in the office. Testing should be possible to be conducted in the office and in the site.

The AMIRE toolkit is a prototype, which was not as fast and efficient to use as commercial products like Macromedia Flash or Director. Changing between different AMIRE versions, installing and testing them took a lot of time off the development of the demonstrator. Also getting familiar with the customer took more time than usually due to limited chances to visit the customer. When the authoring tool is ready the development process does not require essentially more time than traditional multimedia production process.

2. **Content creation and editing must be possible to do off-site** for example Guggenheim museum (2004) content in Helsinki. Site visit is done at the beginning to collect information, but the content creation itself should be possible to do in the office.

Off-site authoring is possible with the help of videos from the real site.

3. **Tool should make cost-effective development possible**. Authoring MR with the AMIRE tool should be faster than authoring MR without it.

The use of the authoring tool can be efficient and certainly more efficient than hard-coded content development. With the authoring tool MR is available for non-programmers as well. Currently efficient use of the authoring tool requires very close cooperation with the component developer.

4. **Creation of a MR-object with the AMIRE MR toolkit should be efficient**. Efficiency increases, if the work can be done in the author’s own office environment and if the customer can test the application on the site.

Some of the development work can be done off-site in the author’s own office efficiently. Testing the demonstrator on-site is not supported yet, since the authoring tool did not have an easy viewer/player of the content yet and it didn’t have proper import/export function. During the project the demonstrator was tested with the whole AMIRE authoring tool installed in a TabletPC.

5. **The maintenance of the application must to be easy.** Off-site maintenance of the application should be possible. Application has to be robust and error resistant.

Some of the maintenance can be done off-site. Adding and changing pictures and text is easy, but 3D-content maintenance is more difficult off-site. Transferring new content to a remote location was complicated to the system in Bilbao, since the AMIRE toolkit did not have proper import/export function.

6. **The technology should be usable in several domains**. Domain refers to the customer application domain, i.e. OMV and Guggenheim.

The components are usable in different products and in different domains. Reusability of the components in different domains depends on how specific it is for one domain.

7. **Content provision is handled on a high, domain specific level**. Author does not need to touch the source code (domain = customer application domain). **The Authoring Tool has to abstract the programming processes** by defining the interfaces and basic behavior of components. The level of programming MR Provider does should be equivalent to writing Flash Action Script in Macromedia Flash. See next criteria.

MR content development is possible for a content provider without programming skills, but it is restricted to the use of basic components and simple architecture. Knowledge of programming or programming mentality is an advantage in using the AMIRE authoring tool. AMIRE authoring tool defines the interfaces and basic behavior of the components well, but the use of the components from the user interface is not very easy.

8. **Choosing a component from the library must be easy**. MR application developers must be able to efficiently create and organize applications with the existing components. They select components from the components library to include them in a new application, allowing them to view the system at a high level of abstraction. Authoring process must ensure that retrieving the MR components needed from the library is easy. The user should be able to find specifications easily from the components.

Currently there are not too many components, so they are all known to persons who have read the documentation. When there are hundreds of components, the ease if finding them depends on how well they are documented and how this documentation is presented. The current GEM library is a good example of a way of documenting also components.

9. **Asking for a new component needs to be easy.** Applications may require some functionality that cannot be supported by the existing components. In order to add this functionality, application author must be able to ask for a new component from a component developer. The application developer must have a way to initialize and co-ordinate the gathering of the components needed for the application

This is very easy if the component developer is in the same team or company. Then the process is exactly the same as with any web programming or multimedia development.
If the component expert is in another company and not familiar with the content developers, the process is naturally a little more complicated and slower.

10. **Using the components needs to be easy.** The developer of a component-based application has to be able to connect the component by using a generic interfaces (API). Insertion of a MR component into the framework and the building up connections between the components needs to be easy.

Using the components is not as easy as it could be. This is partly due to the complex nature of the component thinking itself – some thinking must be done before doing anything. Currently there are several ways of manipulating the components, and working with composed components is difficult. Composed components are needed already with quite small applications.

11. **Changing the parameters of the components needs to be easy**. Components must be able to be customized to fit the particular requirements posed by other components and by the application itself. Authoring process must ensure that editing the properties of the MR components is readily

available. All the component parameters have to be customizable to change without touching the source code.

Changing the parameters is quite easy, but the user interface is not consistent: some parameter settings work differently; there should be some default parameters or ways to restore them. But recommendations and user test feedback has been quite well observed.

12. **The tool should be intuitive to use.** The tool should resemble other commonly used tools and the basic functions should work the same way as other reference application (Macromedia Director / Flash for example). The tool should offer intuitive and easy-to-use metaphors and interfaces to the developer and to a certain extent to the user with less expertise.

The tool resembles little bit of the 3D modeling software (like SoftImage and Max), but it does not resemble Macromedia Director or Flash. It resembles MS Windows environment, but it is not consistent with it. For example the windowing system and tooltips etc. works like in MS Windows.
The concept of mixed reality must be understood by the user before starting to use AMIRE. Macromedia Flash is as difficult to understand, if the user just opens it with no understanding of what it is used for.

13. **Preview.** The MR application should support a way of communicating a demonstrator for the customer on the site – either export content viewer (.EXE like in Macromedia Director – Shockwave export function) or by publishing the content in the web (to be seen with web browser and appropriate plug-ins). Preview functions must not require too complicated client-side software or specialized skills in previewing and commenting the material.

The preview function does not work yet. The authoring tool should have a viewer and import/export function in order to make the transfer of content and previewing easy.

14. **Functions**. The MR toolkit should be consistent with the current tools. The user interfaces of the tools that are currently in use are good (especially Macromedia Flash and Director). The application should adapt to existing solutions and provide them in a uniform way. The following functions should be supported in the tool:

• Undo and Redo	Not implemented
• Paste special	Not implemented
• Copy-paste	Partially (copy name, copy ID)
• Object highlight	Implemented
• Preview tool	Not implemented
• Drag 'n' drop	Partially (inside the Scene window)
• Multilingual content	

Appendix 2. Summative evaluation: MR museum guide

1. General requirement: Museum **visitors' support**, improving the Museum's current visitor information systems with the use of mixed reality techniques.

According to the demonstrator user tests in Guggenheim museum Bilbao, a guide developed from the AMIRE demonstrator can improve the museum's current information systems. The users liked to have the information position based, i.e. the information was based on the current position of the user. Users liked to have a guide that will present visual and audio information at the same time and guide them in real time throughout the museum.

2. General requirement: The demonstrator would provide visitors and tourists with the **details and peculiarities of the works of art** on show. This would allow them to obtain more in-depth information and access related works or objects not available to the public.

The demonstrator offers the visitor information in text, pictures, audio and video. The mixed reality based information was presented with 3D-objects and -models. Because of the copyright issues there was no presentation of other related works of art.

3. General requirement: To view **mixed reality content** about the artwork

In the demonstrator mixed reality was used in guiding the user to pay attention to specific art and in guiding the user through the galleries. Enhancing the artwork with mixed reality was not allowed.

4. General requirement: **Virtual tour guide**.

The demonstrator included video of an exhibition, which followed the desired route of the exhibition.

5. General requirement: **Navigational aid**. Guiding could be included, but the visitors should be able to follow their own path.

The demonstrator presented a planned route through the Jean Dubuffet exhibition. The route was presented with 1) a red line in a map starting from the entrance to the set of galleries, 2) with a video showing the user the way to walk through the exhibition and 3) with mixed reality arrows, which guided the user also inside the galleries. If the user followed their own path they were able to return to the path looking at the map or following the arrows presented on the TabletPC around the gallery.

6. General requirement: MR elements should **not disturb artworks** exhibition in the museum

Since there were no MR elements placed on top of the artwork, the elements do not disturb the experience from the artwork.

7. General requirement**: To help general public**, and the different groups of which it consists, to understand and interpret the works of modern and contemporary art held in the Museum's permanent collection or included in temporary exhibitions.

The demonstrator presented the technical possibilities and different ways of guiding the user and enhancing the experience in the museum. To help the user with the interpretation of the art will be issue of the content. This has to be designed with the museum personnel and other professionals.

8. General requirement: To appreciate the remarkable **architecture** of the museum building itself is also one of the main objectives of the application.

The demonstrator has two checkpoints out of eight that presents the building and architecture of the museum. The content included an audio, a video, pictures and a rotating 3D-model of the museum. Most of the users in the user tests were impressed by the presented information of the museum building.

9. General requirement: **Copyright** restrictions must be considered when showing elements that are property of the museum.

Copyright issues were considered in the development of the demonstrator. For example the mixed reality objects in the demonstrator are not placed on top of the artwork and all the content of the demonstrator has permission of the museum.

10. Social requirement: The application or its use must by **no means stand out, disturb or compete** with the current exhibition.

The demonstrator did not have headphones and the audio disturbed the visitors. This can be corrected with the headphones. Being new to the museum environment, the use of the demonstrator caught positive attention in the museum. When the visitor gets used to the equipment in the museum it will not stand out any more.

11. Social requirement: The Demonstrator must not interrupt the **flow of visitors** in the museum. Viewing each MR exhibit must not take much more time than viewing the artwork without MR.

More detailed study should be conducted with more finished content to evaluate this. With the current demonstrator the user did not stay long in one of the checkpoint. The MR guide can also be built so that each artwork has a story with a beginning and an end guiding the user to spend that planned time with specific artwork.
The concept of mixed reality requires that the visitor and the camera of the terminal can see the artwork. There may often be people who obstruct the view.
The Demonstrator requires the use of markers. If these were permanently installed around the museum, they would disturb the visitor flow.

If the visitors are given more information about artworks, they will also spend more time around them. This is not the fault of the content or MR, but must be understood when such new ways of presenting the artworks are taken into use.

12. Organizational requirements: The museum must also appoint **someone responsible** for the MR application.

No one appointed for this during the AMIRE project.

13. Temporal requirements: Art exhibitions change regularly, and this limits the use of MR currently to the (small) **permanent exhibition.**

Now the demonstrator consisted information of the Snake, the museum building and it guided the user through an exhibition.

14. Temporal requirements: allow normal "**visitor flow**

See criteria 11. The duration of the content can be fixed, if wanted.

15. Temporal requirements: the time of day: the **lighting conditions** vary considerably during daytime. This affects marker-based tracking system

The tracking system is too unstable for the museum context. Another tracking system should be considered for the final museum MR guide.

16. Architectural requirements: **Marker positioning**

If the tracking system is changed there is no marker position problem. One of the users compared the markers to the audio guide signs and thought of them the same.

17. Economical requirements: Exhibit **quick and easy to produce and maintain**

With the improved authoring tool it is possible to change the content of the demonstrator. Producing a new checkpoint will require someone appointed for the task.

18. Economical requirements: **Terminals affordable** in large quantities.

The prize of the TabletPC is getting lower, but currently they are too expensive to buy in large quantities. A PDA or other equipment should also be considered and these are more affordable.

19. Economical requirements: Free or **affordable for most visitors** to use

This is an issue for the museum to decide, when the equipment is decided.

20. Interface requirements: The user interface should be **easy to use** (regarding the test group and typical museum visitors).

The user interface of the demonstrator was evaluated with the museum personnel, which were between the ages 33-35 and used to using computers. The MR guide should also be evaluated with actual users from children to elderly. With few corrections the demonstrator's user interface can be made easy to use. During the test the users did not have any critical error that would have prohibited them to continue with the exhibition.

21. Interface requirements: It should **not disturb** watching the works of art.

The MR guide can be set aside when it is not used and it will not disturb watching the works of art.

22. Interface requirements: It should be possible to use with different visualization devices, or at least to be easily **adapted** to different devices

The demonstrator includes a TabletPC with a camera. Additional binoculars were also used which has inertia tracking instead of the marker-based tracking. The user can see the content of the MR guide through the binoculars or from the TabletPC. The system is also adaptable to other devices, for example PDA.

23. **Interface requirements**: Another set of requirements for the user interface comes from the user group and their expected capabilities of using an MR device.

During the project we had access to only one group of users and uses tests were conducted with that one group. More evaluation should be conducted with different user groups.

24. **Hardware requirements**: The weight, processing power, display and camera properties, sound capabilities and input devices of the terminal must match the needs of enjoying the MR exhibit

The equipment used, a TabletPC is too heavy for a long use. The equipment should be lighter. Screen of the TabletPC was sufficient and users liked it. Processing and electrical power was enough for the use of the demonstrator in the tests (1h). The use of the pen as input was first new to the users, but they learned to use it easily. Camera was enough to get the picture of the exhibition, but it may be one reason for the bad marker detection during the tests.

25. **Marker restrictions** by the museum:
    - Each room may have a maximum of three markers
        - OK for the demonstrator. If the tracking system is changed, no visible markers are possibly needed.
    - The markers should be as small as possible (10*10 cm tested)
        - The tested markers were quite small and the user had to go close (1-2m) to the markers for the tracking system to work.
    - The markers must not steal the visitor’s attention
        - The markers were compared to the audio guide signs and would probably not disturb the visitor. But they must be positioned so that both the artwork and the marker are visible at the same time for the

camera, and the marker often covered the artwork or view partially.

- The markers must not be mixed with e.g. audio guide signs
    - They are so different that that it is unlikely that these will be mixed.
- The markers cannot be attached on the artworks themselves
    - OK, no need for it.
- Marker poles can be used
    - Marker pole was used during the user tests.
- Each marker has its own MR content (modular structure)
    - This is defined by the content design.

Appendix 3. Summative evaluation: Oil refinery training tool

1. The tool must be able to **train employees**.

The OMV demonstrator is a demonstrator for the technology and it does not have content created. Currently it cannot be used to train employees.

2. It must be possible for the **OMV trainers to implement** their own equivalent applications without any help from MR experts. The trainers should be able to add (or change) content of the application, etc. add a new check point; for instance a description of a pump or the inside view of a column (MR object).

The AMIRE authoring tool can be used for a small extent to change information of the demonstrator. Creation of a new checkpoint requires help from an MR expert.

3. **Simple maintenance** of the application by trained OMV employees. Basic programming maintenance should be possible for OMV.

Maintenance, i.e. change of information of a checkpoint is possible for the OMV employees to do without the help from MR expert. Texts and pictures can be changed easily.

4. **High performance of the equipment**. The equipment used must be as fast as a medium performance pc (1700 GHz, 256 DDRam etc.) and very fast in showing graphics, videos and animation.

The equipment used with the demonstrator was a Compaq TC1100 TabletPC. The demonstrator was running in the equipment, but when more complex content is used, the equipment should have better performance.

(Compaq TC1100: Ultra Low Voltage Intel® Pentium® M 1.0GHz processor with 400MHz front side bus and 1Mb cache, Ultra Low Voltage Mobile Intel® Celeron® 800MHz processor with 400MHz front side bus and 512Kb cache Intel 855PM chipset, 256MB DDR 266MHZ (Celeron) or 333MHz (Pentium-M) SDRAM Standard, up to 2GB maximum)

5. The training tool should be **easy to use**. Self-explanatory tool - after a short introduction and a few minutes of training anyone should be able to use it (max. 15 min training time for non-pc users).

The main user interface was easy to use and users found all offered content. The marker based tracking was not easy to use and users had some problems with it. The OMV demonstrator was tested with one or two checkpoint, so the overall use of the demonstrator couldn't be evaluated.

6. The training tool should be **intuitive**. The tool should resemble other commonly used tool and the basic functions should work the same way. The tool should offer intuitive metaphors and interfaces to the developer and to a certain extent to the user with less expertise. Intuitiveness can also be increased with proper feedback, error messages and with a help function (context-sensitive help).

The user interface was intuitive to use ones the user had a marker detected and in most cases the freeze mode on. The users found all available content and did not have trouble browsing through the information. These are preliminary evaluation results due to the amount of content available for testing.

7. The training tool should be **easy to handle, flexible and extensible**. The equipment should be possible to be **used wearing a safety dress**. It should be possible **to carry without hands** (while climbing etc.). Later on the tool should be flexible and extensible to suit the changing needs and more extensive use.

The used equipment is quite heavy for a long time use. It is easy to handle, but currently it does not have any strap for carrying it around.

8. The training tool should have the following qualities
   - Light: Not more than 3 kg TC1100 is 1,8kg
   - Small: Max size of a 17” pc screen 27.4 x 21.6 x 2.0 cm
   - Explosion proof (not necessary for the demo) No
   - Ignition protection: Must prevent ignition sources arising No
   - Resistance to strong magnetic fields No special protection
   - Mobile Yes
   - Able to be used outside Like a laptop
   - Able to be used in a noisy environment With headphones
   - Equipment should be shock resistant. It should not break easily. Like a laptop
   - Splash-proof Like a laptop
   - Robust: like a laptop, no extra qualifications Yes

9. The training tool should **not draw the users attention while moving**. During his/her movement the user’s attention should not be drawn off by the application. The Employee must be able to reach all points in the unit without being hindered when walking or climbing up a ladder or a column.

No carrying strap developed for the equipment yet, so it is carried by hand.

10. **Display** resolution should be adequate to display MR objects and video as well as maps. Display should be easy to wear and it should offer enough display and resolution space to show important information.

Display is good for the videos and MR objects and display area is big (10,4 in).
Display: 10.4-inch TFT XGA with 1024 x 768 resolution (up to 16.7M colors internal), hard tempered sparkle-free glass covering. NOTE: All products have at least 100-degree wide viewing angle. Pentium-M SKUs available with 160 degree wide viewing angle.
Graphics: NVIDIA GeForce 4 Go 420 32Mb (4X AGP)

11. Must provide **several interfaces** to connect cameras or tracking system. The technical people of the project can decide which connections are needed.

Equipment had all needed connection interfaces.

12. The training tool should provide an input and output devices, which are mobile and **easy to handle**.

The equipment can be used via keyboard or with a pen that comes with the equipment. The demonstrator was developed to have a pen interface. This kind of interaction was well adapted with the users in the user tests.

13. **Positioning of the user**. The training application needs to keep track of the user's position and orientation and to get the real position in the accuracy of 1 m / +-20°.

Currently ARToolkit markers are used for the tracking. The tracking system is accurate if the markers are detected, but the detection has some problems. The changing lighting conditions affect the recognition as well as distance. The markers have to be viewed from the distance of 3-6 meters.

14. **Positioning of the refinery objects**. The application should be able to tell the place and function of a valve and other equipment in the accuracy of 1m.

When the markers are detected the MR objects can be placed on top of the real object quite accurately, accuracy in centimeters.

15. **Navigation** should be done by using MR based technologies. It should support the user to find the way to the next checkpoint.

In the demonstrator the navigation was supported with the help of video material.

16. **Training tool functionalities**. The following functionalities should be implemented in the training tool.

- Take a picture of the target and to insert additional information to the picture.
  Implemented
- Freeze; the picture can not change even though the camera moves
  Implemented
- Application offers the user different ways of getting more information about the selected object.
    - (Hyper)text explanation and navigation through the application's (hyper)text pages
      Not implemented
    - Process flow diagram (previously called schematic diagram); it gives the main process streams with all the equipment (also a good tool for orientation from the process point of view)
      Implemented
    - Pictures of the target device
      Implemented
    - Educational movie/video of the target's functionalities or a pipeline path
      Not implemented
    - Animated video clips
      Not implemented
    - Rotating selected MR objects
      Not implemented
    - Magical lens – virtual view inside the device. Reducing the size of the overlaid virtual objects, while the scale of the real image remains the same
      Not implemented
    - Graphics, virtual information from flow, temperature, pressure etc.
      Not implemented
- Must offer 3D capabilities and overlaid 3D geometry
  Implemented
- Offer information of the flow direction in the pipes
  Not implemented
- Follow certain pipe from point A to point B
  Not implemented

- Relation between checkpoints should be displayed in the map as well as in the process flow diagram. The way from point A to point B in the map and in the process connection has big difference.
  Not implemented
- The tool should offer different levels of information
  Implemented
- Audio components should be used rarely and carefully. AMIRE should include audio, but OMV cannot use it much. Audio is an important for mainly all following AMIRE toolkits (like Guggenheim).
  Audio component implemented and it was not used in the OMV demonstrator

17. **Object recognition.** The application has to recognize the needed object. Object recognition component of the application identifies a device of a plant, like a pump or a pipeline.

The marker detection system can recognize the target object and identify it based on the marker. All kind of different object can be recognized with a unique marker.

Publications