A Cognitive Systems Engineering Perspective on the Design of Mixed Reality systems

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ABSTRACT

This paper examines usability issues in Mixed Reality (MR) systems from a Cognitive Systems Engineering (CSE) (Hollnagel & Woods 1983; 2005) perspective with the purpose of finding an alternative approach to usability in MR-systems. A qualitative user study has been performed at a Swedish hospital where professionals have tested an MR prototype providing instruction of the use of advanced medical equipment. The results indicate that the participants in this study do not consider the MR system as a traditional computer based manual, but rather as an interactive personal instructor. The fact that users work *through* the MR system rather than *with* the MR system raises some fundamental design issues regarding usability and the perspective on usability. This suggests that there may be a need to utilize a different approach for usability concerning MR systems, instead of transferring traditional human-computer usability guidelines to the MR domain.

Keywords

Cognitive Systems Engineering, Mixed Reality, Usability

INTRODUCTION

Mixed Reality (MR) is a relatively new area where different forms of technology are used with the intention of supporting users in a variety of situations. Designing new MR systems based on heuristics developed for computer based applications is common practice, but there are few examples of studies on how users actually perceive the system. During user tests in a current project (Gustafsson et al 2005), users were asked about this and none of them actually even mentioned desktop or laptop computers or programs when describing what they were interacting through or with. Words like robot, video game and instructor were used to describe the system, and this of course raises questions of how useful it really is to use desktop computer metaphors and usability criteria when designing MR systems.

This paper aims at discussing usability issues in MR systems from a Cognitive Systems Engineering perspective (Hollnagel & Woods 1983; 2005) with the goal of finding an alternative approach to usability in MR systems. The paper also includes a discussion whether MR systems are to be seen as tools or prosthesis and if this view on the system has any effects on usability issues when it comes to designing for interaction. An observational study of medical personnel working with an MR system is used to exemplify some of the main discussion points.

THE COGNITIVE SYSTEMS ENGINEERING APPROACH

Traditional approaches to usability and human computer interaction often adapt a de-composed view of humans and artefacts. The starting point has been issues of human perception, cognitive abilities and limitations. The idea of the human mind as an information processing unit which receives input and generates output has had great impact on the domain of Human Computer Interaction (HCI). A problem with many of these theories is that they mostly are based on laboratory experiments investigating the internal structures of cognition, and not on actual studies of human cognition in an actual work context (Dekker & Hollnagel 2004).

Another way of using knowledge or assumptions of human cognition was introduced by for example Suchman (situated cognition, 1987) and Hutchins (distributed cognition, 1990; 1995), where the context in which the cognition takes place has an important role. The human is not an isolated creature but is always a part of an environment, and the interaction between the human, the environment and the artefacts s/he is using is equally important for the experience of usability. The human is thus part of a system where cognition is not isolated in the mind but takes place throughout the system. This is also known as 'distributed cognition' (Hutchins 1995; Norman, 1998; Hollan et al 2000). In a similar approach, Cognitive Systems Engineering (CSE, see Hollnagel & Woods 1983; 2005) has introduced the concept of 'Joint Cognitive Systems', which are systems that "can modify its behaviour on the basis of experience so as to achieve specific anti-entropic ends" (Hollnagel & Woods 2005, p 22). The traditional definition of cognition as something only human beings possess is questioned in this approach.

In the joint cognitive systems (JCS) approach it is important to see the system as a whole and not isolate the parts from each other. The JCS can be comprised of a human and a computer, a human, a computer, a telephone and another human and so forth, where the human brings in the 'natural cognition' to the system and artefacts or technological systems may have 'artificial cognition'.

Other approaches to usability and HCI often define the systems involved in a human computer interaction situation by the structure of the system and not as in the CSE approach, by its function; "A joint cognitive system is defined by its *function* (i.e. what it does) rather than by its *structure* (i.e. what it is)" (Hollnagel & Woods 2005).

The use of Artefacts – tools and prosthesis

The main constituents in a JCS are humans and some type of artefact, where Hollnagel and Woods (2005) define an artefact as "something made for a specific purpose". Hutchins (1999) defines *cognitive* artefacts as "physical objects made by humans for the purpose of aiding, enhancing, or improving cognition". An artefact can thus be any man-made object, and depending upon how it is used, it can be seen as a tool or as prosthesis.

A *tool* is something that enhances the users' ability to perform a task or solve problems. A *prosthesis* is an artefact that takes over an already existing function (Hollnagel & Woods 2005). A wheelchair can, for someone with no legs, be seen as prosthesis or a substitute for the lost legs. It can also be considered a tool for getting around faster in the world than by for example crawling or using your arms, which would be the alternative for someone without legs. Another example is the computer which is a very general tool for expanding or enhancing the human capabilities of computation and calculation, or even a tool for memory support and problem solving. But the computer can also be used to not only enhance these human capabilities but also to replace them when needed. A computer used for automating the locks of the university buildings after a certain time at night has replaced the human effort of keeping track of time and at the appropriate time going around locking the doors. The consequences of this view of artefacts as tools or prostheses in relation to MR systems are discussed later in this paper.

MIXED REALITY SYSTEMS

The field of Mixed Reality is a relatively new field in terms of commercially and publicly available applications. As a research field it has existed for almost two decades with applications in diverse domains, such as medicine (Reitinger et al 2005; Gosbee & Ritchie 1997), military applications (Gustafsson et al 2004; 2005), entertainment and infotainment (Stapleton et al 2005; Koyama et al 2003), technical support and industry applications (Navab 2003; Zauner et al 2003; Caudell & Mizell 1992; Friedrich 2004), distance operation (Milgram et al 1997) and geographic applications (King et al 2005; Reitmayr et al 2005).

Milgram and Kishinos (1994) virtual continuum is often used to describe the relation between augmented reality, virtual reality and the stages in between. Mixed Reality is the collective name for all the stages (see figure 1).

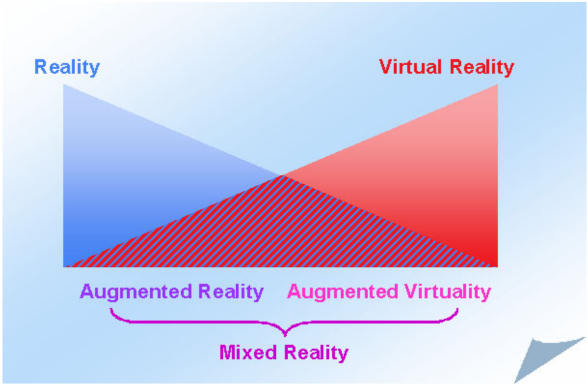

Figure 1: The Virtual Continuum (figure from Gustafsson et al 2003 after Milgram and Kishino, 1994)

Azuma (1997) mentions three criteria that have to be fulfilled for a system to be classified as a Mixed Reality system: they all combine the real and the virtual, they are supposedly interactive in real time (meaning that the user can interact with the system and get response from it without delay), and they are registered and aligned in three dimensions. As an example, motion pictures with advanced 3D effects might have elements of Mixed Reality, but they are not interactive so the do not qualify in the MR category.

The focus in many MR definitions is 'the merging of worlds' but MR is also defined as the technology used to accomplish this merging of real and virtual worlds. There is also a focus on the 'interaction between the system and the user' in MR research (Mansoux et al 2004).

Different Technological Solutions

The different ways of merging real and virtual worlds has impact on how the user and the researcher perceives and uses the system. There are two principally different solutions for merging reality and virtuality in real time today – video see-through and optic see-through (Azuma 1997; Azuma et al 2001; Gustafsson et al 2004; 2005). Optical see through is where the user has a head mounted see through optical display which allows the user to see the real world as if through a glass lens. The virtual information is then overlaid on the see-through display (se figure 2).

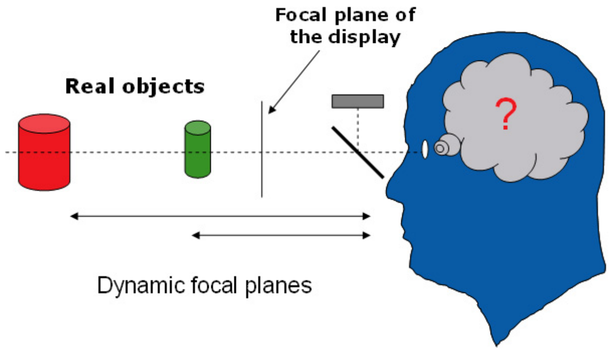

Figure 2: Optic see through MR (Gustafsson et al 2004)

This technique causes some problems since the virtual information has to compete with the surrounding light, which places great demands on the display capabilities (it can be compared with having to work with a computer screen in direct sunlight). There are also some problems with placement of the information in relation to the surroundings since the depth of the display in this constellation is fixed whereas in reality objects are perceived in different focal planes (see figure 2, Gustafsson et al 2004).

A way to overcome the problems with optic see through is by using a camera in front of the users' eyes, and then projecting the camera image on a small display in front of the users' eyes (Azuma 1997; Gustafsson 2004). The virtual images are added to the real image before it is projected which solves the surrounding light problem as well as gives control over where the virtual objects are placed (see figure 3).

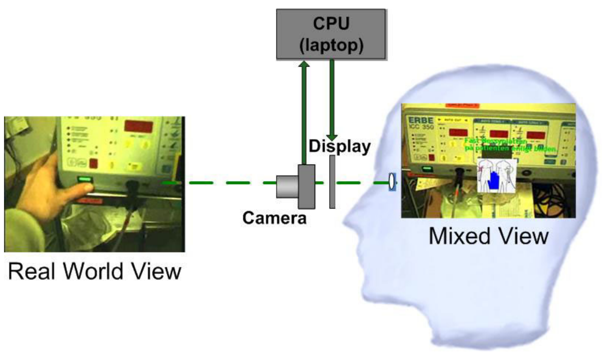

Figure 3: Video see through MR

This in turn puts other demands on the system, as the transferring of the real image suffers from the lag determined by the cameras image update frequency. The lag can have effect on the user experience of the system, such as simulator sickness. To conclude there is a trade-off between the two different solutions and the choice of solution is often determined by the available resources.

USER EXPERIENCES OF AN MR SYSTEM

This section describes the results of a usability study where MR was used for giving instructions on how to start up a medical diathermy apparatus (DA). The study was conducted on site at a university hospital and involved eight users divided into two different groups – four with previous experience of the DA, and four without any previous experience of working with the DA (in the quotes below the respondents are numbered with 1 for inexperienced users, 2 for experienced users, and individual letters for each participant).

The main questions in focus relevant for this paper involved questions of the user experience of the MR system; whether it could be viewed upon as a tool or prosthesis; how the users experienced the interaction; and if traditional usability guidelines are applicable for the design of MR systems.

The system was based on video see through MR and detection of fiducial markers which triggered different instructions. The MR equipment used consisted of a helmet mounted display with a fire wire camera (see figure 4). A num pad was used for the interaction with the user.

Figure 4: A video see through MR system (Gustafsson et al 2005)

The users were recorded on video when using the MR system, and interviews were conducted after the test. It was found that all users but one could solve the task at hand when aided by the instructions given in the MR system. The interviewed responded that they preferred personal instructions from an experienced user, sometimes in combination with short, written instructions, but also that they appreciated the objective instructions given by the MR system. The problems users reported on related both to the instructions given by the MR system and to the MR technology, such as problems with an unstable image etc. Despite the reported problems, the users were positive towards MR systems as a technology and as a tool for instructions in this setting.

The most important aspects regarding the *user experience* of the MR system can be illustrated by some quotes from the interviews where the respondents compared the MR system to other technology:

"A bit like a video game." (2:F)

"It's a bit computer gamey. If you're used to that, I think you can handle this better than if you're not used to it." (2:G)

"I would call it a robot or something like that, like I would image controlling a robot would be like." (2:H)

None of the respondents referred to interacting with or through a computer when asked what the interaction felt like. All of the respondents work with computers on a day to day basis and are accustomed to traditional windows based graphical user interfaces but they saw no similarities with the MR system:

"Well, You don't work like this at all normally. Feels unusual." (1:B)

One respondent even compared the experience to having a personal instructor guiding through the steps:

"It would be if as if someone was standing next to me and pointing and then… but it's easier maybe, at the same time it was just one small step at a time. Not that much at once." (1:D)

The users were also asked about in what situations or for what purpose they think an MR system could be useful, if in any. Two of the respondents mentioned medically invasive procedures such as laparoscopy. Several of the users responded that MR systems could probably be used in any situation where instructions are needed, such as in education or for guiding users on how to use technical equipment:

"Well it's all devices and instructions that you can give, then you can use this system…" (2:G)

"I think education in all hands-on practical elements" (2:E)

"..Of course if you need to guide people, but I can't name anything specific..." (1:A)

"Well… for everything I was about to say, but for many of our technical devices. At the reception or whatever, but I mean also when you're doing laparoscopy…" (1:C)

APPLYING THE CSE APPROACH TO MR SYSTEMS

One term that has been used to describe MR systems is *Intelligence Amplification* which was re-introduced by Brooks (1996, referenced in Azuma 1997). Intelligence amplification means using the computer (or MR system) as a tool to make a task easier for a human to perform. This can be compared to the concept of 'intelligent action', explained by Hollnagel and Woods as behaviour that is "goal oriented, based on symbol manipulation and uses knowledge of the world for guidance" (1983 p 589). This type of intelligent action is what distinguishes a cognitive system from other systems. An MR system uses knowledge of the world to position virtual information; it manipulates symbols and should strive to reach the goals set by the user. Therefore it would be appropriate to define an MR system as a cognitive system, and human user and the MR system as a joint cognitive system (see figure 5 illustrating the JCS in the user study).

Figure 5: The joint cognitive system in the user study. A user interacting with a DA, assisted by the helmet mounted MR system.

As the quotes from the users in the study above illustrate, the MR system can clearly be used for instructions in different situations, and as a tool for aiding the use of complex technical equipment.

Taking the CSE approach, the focus on the interaction between system and human shifts to the common goals and performance of the joint human MR system (Hollnagel & Woods 2005). Instead of looking at the merging of real and virtual, one could look at the goal of completing a task as a joint cognitive system. The task at hand could, as mentioned by the users in the study (2:G, 1:C), be to guide someone through the use of technical devices or during medical procedures. The interaction with the MR system itself is not the goal. Rather, the goal is working *through* the system and not *with* it.

In this section two different aspects of a CSE approach to MR systems are discussed, first the descriptions of MR systems – where the boundaries between system, human and artefacts are drawn, and secondly the use of the MR system as a tool or a prosthesis.

Applying a different aggregation level

The MR description in previous sections of this paper illustrate how MR systems currently are structurally decomposed into separate systems of technology and human users. What happens if you change the aggregation level and define the artefact not based on the technical and structural components of the systems, but on the functions of the system in terms of goals of the use and the experience of the system instead?

The technology can still be used as a base for decomposing the system, at the same time keeping the goal of the system in mind. If the goal in fact is to interact with the surrounding via the MR system, then one could base the decomposition on the interaction technique, instead of individual technological components. This method of decomposing according to purpose or performance of the MR system is illustrated in Mackay (1998). She uses three different starting points for defining the system depending on the main purpose; augmenting the user; augmenting the physical object and; augmenting the environment surrounding the user and the object. In the case of guiding the user through the use of medical equipment, the system could add information to the object, enhancing it, in order to augment the capabilities of the user/ JCS.

In traditional decomposition of systems, the boundaries between the human user and the artefact are based on the assumption that the human ends where the artificial system begins – there is an obvious division between the display and the users' eyes. Even within the artefact the boundary is drawn based on physics – software and hardware. But this does not have to be the case. The boundary could be drawn differently or not drawn at all, allowing the camera and display to be part of the human cognitive system, as an extension of the perceptive abilities of the user. This also coincides with a boundary drawn when defining the system based on functionality (i e what the system component does) instead of structure (e g hardware and software). The function of the camera, and display in combination with the users visual perception is to convey an image or other virtual information to the user, who then can respond to the system or take other actions.

MR systems as artefacts - tools or prosthesis?

In video see through MR the user experiences the world only through the artefact (the MR system, see figure 3 and 5), while the optimal, yet to be developed, optic see through should have more of an 'embodiment relation', in the same way a pair of glasses act as an extension of our eyes.

In a video see through system the system takes on the so called amplifier hermeneutic relation (Hollnagel & Woods 2005), where the artefact is an interpreter and takes care of all communication between the operator and the application. The MR system is not transparent to the user, meaning that all information is filtered through the system - through the camera, the processor, and virtual information being added and then projected on the display, to the user who has no real control over it.

Simply by using the term 'augmenting' reality one can argue that the question of tool or prosthesis is answered - the augmented reality system is there as an enhancement or extension of reality. But is this really the case? Are we not just adding things to reality rather than augmenting things that were there already? One could only conclude that things can not be more than 100% real, so augmenting reality seems an impossible quest. Perhaps *augmented* is a contradictory term in relation to reality, rather the term should imply adding virtual objects to the real surrounding. Some systems may actually just be pointing out things already visible or in other ways perceptible by the system, but a majority of the systems described in current literature (Azuma 1997; Azuma et al 2001) are actually adding things to the visible environment, such as text, images and animations.

In MR systems used for technical support the system in itself could be viewed upon as a tool for retrieving and presenting information, but if it is used for example as a part of distance expert guidance it can be considered an extension of the expert assistant's eyes and arms when giving instructions in the remote operator's field of view.

As stated above, many of the definitions used to describe MR systems rely on the physical boundaries between the parts of the system which illustrates a tool view on the combined MR system. An underlying assumption in this perspective is that the user and the MR system are separate systems where the human system uses the technological system to merge real and virtual worlds, which is the stated goal of the MR systems. The interaction *between* the human and the technology is in focus for the usability analysis. The person in the system is *using* the system to retrieve information or solve problems. By not focusing on the physical boundaries, but instead using a CSE approach, focusing on the common goals of the system, it can be seen as a prosthesis or an extension of the human system capabilities. The interaction with the environment, through the system, becomes the tool for achieving the goals, such as repairing an engine or starting up complicated technical devices.

In conclusion, the MR system can be viewed upon both as a tool and as a prosthesis depending on the context and purpose of using the system. But the question is if this affects the development and the design of the system as it very well should.

DISCUSSION - IMPLICATIONS FOR USABILITY STUDIES IN MIXED REALITY SYSTEMS?

Usability methods used for MR are mainly based on usability methods used for graphical user interfaces in combination with usability for Virtual Reality applications (Gustafsson et al 2005; Träskbäck 2004). However there are some complications with this approach since it is not based on the actual MR system users' experiences. Usability methods such as Cognitive Task Design (Hollnagel 2003) where the design approach is based on observations of how a user completes a task in which the system or artefact is involved, also have to deal with the so called envisioned world problem (Woods 1998). This is when the results of the cognitive task analysis causes design changes in the artefact or the system which in turn changes the use of the artefact and therefore also the base of the results of the cognitive design based on the previous observations. This is certainly an important issue for systems that are constantly redesigned and changed, which most MR systems in research applications are.

The MR system used in the study has been redesigned and rebuilt since the user study, which of course means that usability issues that were in focus for the first study may have changed significantly. The remarks about what the MR system can be compared to, and for what other situations it may be useful can still be valid. However with the new design of the system, the questions may of course yield new responses. Basing usability guidelines etcetera directly and only on system characteristics do not seem appropriate. In the CSE approach the usability discussion focuses on more stabile issues such as the intended goal and functionality of the system.

Another issue of interest for usability studies in MR is the user experience of what the MR system actually is. Designing it based on heuristics developed for computer based applications is common practice, but as noted previously, there are few examples of studies on how users actually perceive the system. During user tests in Gustafsson et al (2005) and the study presented in this paper, users were asked about this and none of them mentioned desktop or laptop computers or programs when describing what they were interaction through or with. This raises questions of how useful it really is to use desktop computer metaphors and usability criteria when designing MR systems.

The usability criteria and heuristics that have been used during the design of new MR systems tend to be general, broad criteria such as the ones Nielsen presented in his list of usability heuristics in 1993. There are very few examples of MR specific usability criteria and from a CSE perspective there may be no need for such criteria. Usability should instead be based on the task and goals of the user in the actual context of use, and not based on the technicalities of the system or previous systems. Different kinds of technologies result in principally different types of artefacts (compare the optic with the video see through MR) although the underlying purpose of the system may remain the same. But the type of artefact affects the interaction techniques and thus also what type of usability method or perspective that should guide the design. Usability criteria, which are solely dependant on the technical solution and/or perceptual issues, should not be allowed to determine the design without taking usability aspects on a higher conceptual level into consideration.

The use of usability or design criteria should depend on how the user perceives the system, as a tool and amplification, or an extension of the user. If the system is used as a tool, as in the study presented in this paper, the usability criteria should be based on the needs of such a system, if the system is used as an extension of the user (similar to the way glasses are used) the design of the virtual information should be influenced by this.

Another aspect is of course if the MR system is to be used during work or if the purpose of the system is to entertain. If it is somewhat forced on the user by it being part of everyday work the system needs to reach efficiency standards that may not be equally important if it is used as a toy or entertainment equipment by the users own free choice. In the latter case the simplicity factor is more important than the efficiency (Hollnagel & Woods 2005).

CONCLUSIONS

MR-systems do not always have clearly defined user groups, however they are most often, like other systems, designed to complete certain tasks in specific applications. The CSE approach to this problem is to focus on higher level issues such as the common goals of a system design, rather than focussing solely on lower level issues such as visual perception and cognitive abilities of the user (Hollnagel & Woods 2005). This makes the CSE approach appropriate for studying usability in MR-systems, since, as in CSE, the task, goals and performance of the user and system are more important than the details of the users' internal processes and interaction with the artefact. Rather, the composition of user and artefact should be studied in relation to the goals of the activity in which they are involved. In the user study, the goal of the MR-user cognitive system was to start up a diathermy apparatus, and this goal was also achieved. The MR system was not experienced as having clear boundaries, i.e., as a separate entity, which the user had to interact with, rather the entity to be interacted with was the diathermy apparatus. This indicates that traditional usability methods may not be very useful when analysing usability of MR systems.

Since the boundary between the MR system and user is unclear, the focus lies on the common goals and purpose of the joint human-MR system and not on the interaction between them. The focus of the usability analysis thus shifts from detailed studies of the interaction between user and MR system towards how well the joint system works together towards the common goal. If the user-MR system achieves the goal, the starting point of usability analysis is quite different than if the system fails to achieve the goal at all. If there is a failure to reach the common goals, the designer of the MR system may have to rethink the design from scratch. If, on the other hand, the joint system actually achieves the goal the redesign can focus on individual aspects of the system and interaction and improve upon these.

Apparently there is some work to be done in the field of usability for MR applications. Applying new approaches and alternative ways of addressing the problem will increase the possibility of designing more user friendly and transparent Mixed Reality systems. The CSE approach is very promising as a way to approach the design of MR systems. First and foremost an MR system being developed must be developed with a specific purpose – a problem to solve, a task to perform - and an identified user group. By using more traditional usability methods such as the cognitive task design approach one can observe the context in which the MR system is supposed to be implemented. Then one can define what the MR system together with the user as a joint cognitive system should be able to perform. This in turn gives clues as to what characteristics and technological solutions in the MR system are more likely to help the joint cognitive system achieve its' goals.

The MR system in some joint cognitive systems will be considered a tool, and therefore should be designed as such, leaving the control of the system open to the user. If the MR system is supposed to be used as a prosthesis, some of the users' control could be transferred to the MR system.

The techno-centred culture in MR research is under transformation and some recent papers emphasize user aspects, both in discussions about interaction techniques and in the choice of technological solutions. However these papers are few and far between and there is still room for a new approach that is not solely based on traditional HCI theories and views of human cognition.

Still, the most important role of MR systems in a professional work situation is that the system supports and amplifies the abilities of the user or human operator. So long as the MR system is part of, and contributes to the overall performance of the Joint Cognitive System, MR shows a lot of promise as a way of interacting with, and through, computers.

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