Proc. of the 25th ACM International Conference on Design of Communication (SIGDOC '07), ACM Press, El Paso, TX, USA, 22-24 October, 34-41, (2007). ISBN: 978-1-59593-588-5.

Design Experiences of Multimodal Mixed Reality Interfaces

Fotis Liarokapis
Coventry University
Faculty of Engineering and Computing
+44 (0)24 7688 7631
F.Liarokapis@coventry.ac.uk

Robert Newman
University of Wolverhampton
School of Computing and IT
+44 (0)1902 321801
R.Newman@wlv.ac.uk

ABSTRACT
This paper presents an overview of the most significant issues when designing mixed reality interfaces including displays, tracking, interface design, interactivity and realism. Multimodal issues regarding visualization and interaction are integrated into a single interface. Three case studies in diverse areas including automotive, archaeology and navigation are presented, illustrating the use of the above issues addressed. Furthermore, the experiences gained and lessons learned are discussed including our plans for future work.

Categories and Subject Descriptors
I.3.0 [**Computer Graphics**]: General. H.5.0 [**Information Interfaces and Presentation**]: General. J.0 [**Computer Applications**]: General.

General Terms: Design, Experimentation, Human Factors

Keywords: Mixed reality, virtual and augmented reality, tangible interfaces, human-computer interaction

1. INTRODUCTION
In recent years mixed reality (MR) has emerged as an area of extreme interest for visualizing and interacting with three-dimensional (3D) information in context, while the cost of building relevant applications has fallen considerable. MR interfaces, interaction techniques and devices are developing at a rapid pace and offer many advantages over traditional windows style interfaces. In 1994, Milgram [1] tried to depict the relationship between virtual and augmented reality (AR) by introducing MR and augmented virtuality (AV). The result of Milgram's classification is the Reality-Virtuality diagram where there is the representation of the real world and the ultimate synthetic environment. MR stretches out in-between these environments and AR expands towards the real world and thus it is less synthetic than AV which expands towards virtual environments.

AR allows for the seamless integration and interaction of digital information with the real environment in real-time performance. Previous research has indicated that AR has a number of proven advantages [2], [3] over other visualization and interaction technologies such as static multimedia and other traditional methods. However, if we blend all technologies together into a single interface it is possible to obtain a really powerful design tool which can be used to implement a wide range of innovative user-centered applications. Besides, multimodal interfaces provide alternative visualization and interaction representations and are becoming increasingly popular.

Shared space approaches, such as collaborative interfaces can be classified in respect to the dimensions of artificiality and transportation [4] where the dimension of artificiality is related to the extent to which a space is either synthetic or it is based on the physical world. The dimension of transportation expresses the degree to which participants and objects can be transferred from a local space into a remote space. AR interfaces can balance this by merging virtual information with the real environment based on the fact that navigation using 3D interfaces helps users to understand better the environment [5].

This paper presents the experiences gained from designing high-level and user-centered MR interfaces which were used to develop applications that could work in practice. It proposes multimodal MR interfaces which are capable of presenting virtual information over the internet in a virtual reality (VR) or an AR environment. Interactions are handled in either a user-centered or a computer-oriented way so that they are performed in a realistic and natural manner. To illustrate the capabilities of MR technologies and the feasibility of the system three potential applications have been designed and implemented including automotive, archaeology and navigation.

2. DESIGN ISSUES
2.1 Displays
Nowadays, see-through displays are lightweight with high-resolution optical devices that enable researchers to implement many applications. However, even today and despite the advances performed during the last years, certain inefficiencies remain such as sufficient brightness resolution, field-of-view and contrast [6]. Before deciding which is the most appropriate display technology for an application many issues must be taken into consideration. The selection depends always on the nature of the application but there are some standard features that all displays easily support such as field-of-view, resolution and pixel spacing. In contrast, there are other features such as comfort, mobility, privacy, opacity and immersiveness, which vary according to the type of display [7].

The most common types of displays used for MR systems include HMDs. The purpose of an HMD is to isolate the user from the real world and then substitute binocular views of the synthetic environment. Most MR systems usually operate using one of the following types of technologies: *video see-through* and *optical see-through*.

Video see-through makes use of video mixing techniques to synthesize computer-generated information with video streams [8]. A characteristic video see-through system consists of a graphics system, one or more video cameras, a monitor and a video combiner. In contrast, optical see-through systems are comprised of a graphics system, a monitor and an optical combiner [6]. There are quite a few applications where the use of HMDs is impractical or unnecessary. An alternative approach is to use other types of displays that can provide robust solutions for situations requiring long term or extensive use of MR visualization. Large area displays is another type of technology that can be integrated in MR systems. These displays are used in three basic configurations [9]: front projection, back projection and conventional monitors. The major advantage of such visualization devices is high resolution and a simple means of collaboration. Nevertheless, they usually have limited range of operation and most of the times high cost since very large displays increase the field-of-view and therefore immerse the user more.

A popular MR display system consists of small area displays whose size ranges between a few centimeters to around 30 cm approximately [9]. This allows small area displays to be portable and thus be suitable for many AR applications that require the user to navigate in indoor or outdoor environments. The major disadvantages of these displays are the limited working area and resolution. In addition, small displays have a similar illumination problem with optical see-through head mounted displays. If the real objects are better lit and brighter than the illumination provided by the monitor, then they disappear from the synthetic image. Notwithstanding, during the last few years the evolution of mobile computing has developed a new series of powerful wearable devices also known as hand-held displays such as mobile phones, Tablet PCs, and Personal Digital Assistants (PDAs).

2.2 Tracking

Tracking in MR is the operation of measuring the position and orientation, known as six degrees-of-freedom (DOF) tracking, of real 3D objects (or humans) that exist in indoor or outdoor environments. This simultaneous measurement of camera's position and orientation (pose) can be performed when objects are static (fixed in space) or dynamic (changeable in space). A typical tracking example is to use sensors to receive positional and orientation information about the physical environment. Sensors can also be employed in conjunction with other input devices such as microphones, cameras, global positioning systems (GPS) and wireless communications. However, tracking systems used for MR environments must satisfy three basic requirements [10]: the tracker must provide high accuracy when calculating the pose; the latency between the graphics system and the tracker must be very low; and the tracker's range of operation must be wide enough to cover the needs of the application. Most of the current input devices, for instance mouse, trackball and graphics tablet, are mostly used for pointing and selecting. In contrast, interactive computer graphics and user interfaces require the user to be able to navigate, select and rotate in three-dimensions.

An alternative way to achieve real-time tracking performance for MR systems is to use computer-vision techniques to estimate the camera pose by detecting either artificial (fiducials) or natural features. Fiducial-based tracking works by placing recognizable markers at carefully measured locations in the scene and make this information available to the tracker for its operation [11]. The nature of the fiducials may vary between different shapes of special markers [12] or active light sources (LEDs) [13]. The method assumes that the markers are always in sight of the camera in order to estimate their location. Marker tracking has a number of advantages over other techniques. Since the last decade, many AR systems have been built based upon tracking markers [12], [13], [14], [15], [16]. They can be designed in such a way where the performance of AR systems is maximized when they can be detected and distinguished from each other. Another benefit is that they can be cost effective and they can be placed arbitrarily on objects. In some cases, the use of marker-based tracking can be complicated due to maintenance issues [17]. The basic limitation of vision-based systems is that the range of operation is limited to small regions that should always have in view at least three known features. On the contrary the natural features detection algorithm is more popular for outdoor environments since it is very difficult to populate them with fiducials.

2.3 Interface Design

An ideal AR system must be able to mix the virtual information with the real in a user friendly way as well as allow users to interact naturally. In some cases, the participants should not realize the difference between the real and the augmented visualization but this is not always the case. Each type of virtual information is designed for specific purposes and as a result produces different outcomes. In some cases of communication meaningful textual explanation can be used much more effectively than auditory description and it is very easy to achieve. On the other hand, pictures and images work better than text, for recalling or explaining diagrammatically a procedure (i.e. 2D digital maps). To describe a sequence of events video seems to be one of the most efficient techniques especially for training purposes. However, a combination of some or all types of information described above can be sometimes beneficial.

2.4 Interactivity

Human-computer interactions are one of the most important issues when designing any real-time system. They have to be performed in a natural way so that inexperienced participants get used quickly to the AR environment. To achieve this, a number of interaction techniques must be used and some of the most characteristic include physical manipulation, interface menu (or GUI) interaction, standard I/O interaction, Touch-Screen interaction and SpaceMouse interaction [18], [19], [20]. Although, some types of interactions are not novel, the originality comes in the way they are used by the participants. Depending on their previous experiences, they can combine two or more types and encounter a novel form of interaction with great flexibility. For example, the most significant combination of human-computer interactions is the use of intuitive methods like tangible manipulations with sophisticated pointing devices. Users can hold in one hand a marker card with a virtual object superimposed (see Figure 2) and on the other hand use the pointing device to perform graphics operations (see Figure 3).

2.5 Realism

Realistic augmentation is an issue of high importance for any AR interface system. The major focus must be given on the realistic augmentation various types of virtual information (3D objects, images, video, text and 3D sound). To increase the realism of the AR scene, computer graphics algorithms must be implemented such as artificial lighting, shading, shadows and reflections. In particular, the precise manipulation of the virtual light sources allow for the generation of real-time hard and soft shadows and reflections. Other effects which can be easily implemented to enhance realism include atmospheric effects and transparency, which is a very important component when augmenting assisted information. Additionally, the simultaneous rendering of virtual humans (known as avatars) and spatial sound can provide a very strong augmentation platform which can further immerse participants and provide solutions to a number of application domains.

3. MULTIMODAL MR INTERFACE

The aim of having a multimodal MR system can be beneficial for a number of complex operations as well as new applications. The novelty of the system is that it allows users to switch rendering modes between three rendering environments including: *AR*, *VR* and *cyber reality*. A high-level architectural diagram illustrating the technologies taking place in the multimodal MR interface is presented in Figure 1.

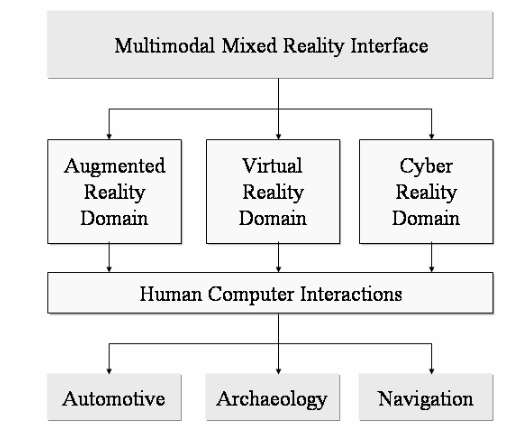

Figure 1. Multimodal MR interface

In the MR interface three different types of visualizations for each exhibition can be realized based on open standards. In the cyber space, users can browse the hierarchy of exhibition spaces and cultural objects by clicking on appropriate icons at the web page. For example, virtual exhibitions can be visualized in a Web browser in a form of 3D galleries. In addition to the Web presentation, users can examine selected cultural objects in the AR environment by the use of the augmented space. The main advantage of the multimodal MR interface is that it allows users to select which is the best rendering mode for visualization of a particular application scenario. The basic idea behind this, is based on the dynamic concepts of a previously implemented interfaces [18], [19], [20] which allows users to transfer 3D information over the internet and superimpose them on a table-top AR environment. In addition, users can make use of the same human computer interaction techniques and apply them to all the derived applications.

In terms of hardware the dynamic MR interface is operational over a range of displays ranging from flat panels, touch screens, projectors and a head-mounted display (Cy-Visor HP4400VP). Besides, using a video splitter (Rextron Video Splitter VSA 18) it is possible to achieve distributed visualization on all above types of displays. Interactions can be performed using standard I/O devices (mouse, keyboard) as well as more sophisticated interaction devices such as a 3D mouse (i.e. SpaceMouse, SpacePilot, SpaceNavigator) the 3 DOF InertiaCube and the 6 DOF Polhemus Patriot. Furthermore, the software libraries that have been employed in the implementation of the proposed interface include the ARToolKit [21], OpenGL, DirectX and VRML. All these technologies have been wrapped around a user friendly interface based on Microsoft Foundation Classes (MFC) and C++ computer graphics classes. A brief overview of the capabilities of each mode is presented in the following sections.

3.1 Augmented Reality Interface

AR interfaces have become popular after Billinghurst et al [21] released ARToolKit which provides computer vision techniques to compute the camera pose (position and orientation) allowing developers to built fast prototype applications. Numerous interfaces have been experimentally proposed based on ARToolKit but although, each interface can serve the needs of a particular application, there is no system capable of handling the scopes of commercial applications. In 2004, Liarokapis et al [18] proposed a generic AR interface that is wrapped around a user friendly interface and it is capable of superimposing four different types of multimedia information (models, text, images and spatial sound) in indoor table-top environments. Based on this framework, the functionality of the system has been extended so it can superimpose video as well as all the previous types of multimedia content. The user can control and customize all types of multimedia augmentation using the interface menu including operations like positioning the augmentation in 3D space, start and stop an augmentation and change its rendering properties (color, size, lighting, material, etc).

3.2 Virtual Reality Interface

VR interfaces exist for more than two decades now, and a lot of research has been performed in issues like realism, immersion and evaluation. However, as far as this research is concerned, there is no VR interface capable of changing modes between real, virtual and augmented spaces. The proposed VR interface is capable of performing advanced visualizations based on the OpenGL, VRML and DirectX APIs together with custom made graphics classes implemented in C++. In terms of rendering, the interface supports both VRML and 3ds file formats. The reason for this is to allow VR delivery over the internet as well as in stand-alone mode. In the latter case, the user can perceive a realistic visualization based on computer graphics algorithms such as interactive lighting [19], ground culling [19], planar shadows [18] and planar reflections. In a remote VR scenario, a Cortona VRML client will be embedded inside a web browser (i.e. Internet Explorer) so the rendering capabilities are dependent of the Cortona's capabilities.

3.3 Cyber Reality Interface

Cyber reality is probably the most common type of interface that can provide fast and powerful delivery of multimedia information anywhere in the world. Access everywhere is the basic aim of cyber reality interfaces and it becomes more and more possible due to the recent advances in telecommunications. Although, this interface is based on simplicity, the combination of a web interface with VR and AR interfaces seems to be the future of MR interfaces. In the cyber interface approach, a web browser has been implemented in C++. This visualization consists of 2D Web pages with embedded 3D VRML models and other multimedia objects (i.e. video animations, pictures and metadata) and can be used remotely over the Internet. The interface can act as a client and it can be configured to connect to web servers that contain multimedia content. Similarly to the web interface proposed in [19], users can browse a server database, which is full of virtual information, and visualize it in the cyber environment. Then the same information can be dynamically transferred into either a VR or an AR space. Although this scenario looks ideal for any type of software system, one of the most important limitations is the effectiveness of the communication between the client and the server due to the bandwidth limitations.

4. MIXED INTERACTIONS

Since users can switch dynamically between different rendering modes, they can also change dynamically human-computer interaction techniques. This allows users to choose the most appropriate mechanism of interaction during for a particular application during run-time. Alternatively, a combination of two or more methods can be employed to achieve more complex operations. The most significant interaction methods that can be supported by the system include: *user-centered* and *computer-centered* interactions [25]. An overview of the capabilities of each method is illustrated in the following sections.

4.1 User-centered Interactions

The first and simplest way of interacting with digital information is through the use of physical marker cards. This vision-tracking approach was proposed and implemented by Billinghurst et al [21] and has been adopted by a number of AR applications successfully. The advantage of marker-based tracking is that it allows the user to manipulate the superimposed information using a tangible interface (in this case the physical marker cards). The user can examine intuitively the superimposed information in 3D space without the need of extra hardware sensors as illustrated in Figure 2 below.

Figure 2. Example of user-centered interaction - natural interaction of a virtual artifact

To increase the level of interaction the marker cards can be also used as means for transferring (or copying) virtual information from one location of the environment to another. This option is used again instead of using alternative hardware sensors. The main disadvantage of marker based manipulation is that the physical cards must always be in line of sight of the camera. In addition, the marker detection algorithm is prone to a number of sources of errors including: *lighting conditions*; *material of the markers*; and *range of operation*. However, they still provide a tracking environment for developing robust and personalized indoor applications.

4.2 Computer-centered Interactions

An alternative way of interacting with virtual information is through the use of computer-based techniques involving both hardware (Figure 6) and software solutions. In terms of hardware solutions, simple (i.e. mouse and keyboard) as well as sophisticated interaction devices can be integrated (i.e. 3D mouse, inertia and magnetic sensors, touch screen, etc). It is important to ensure interoperability with hardware systems (i.e. digital compasses, gyroscopes, accelerometers, etc) that can be used in parallel to enhance the interaction process.

In this work, the Magellan SpaceMouse Plus XT, a USB device that provides both a six DOF mouse as well as a nine button menu interface, was used. All nine menu buttons have been programmed to perform various graphics operations including basic transformations (rotations, translations and scaling) and more complex graphics operations (lighting, clipping, etc). Each button of the device can be programmed to perform any type of operation. In our case five bottoms are used to enable basic transformations (rotation and scaling and translation) and allow the user to perform graphics operations (LOD, lighting, etc), two buttons are used to change camera positions, while the rest are used to provide information about the object (i.e. historical information, multimedia presentation of the 3D object, etc).

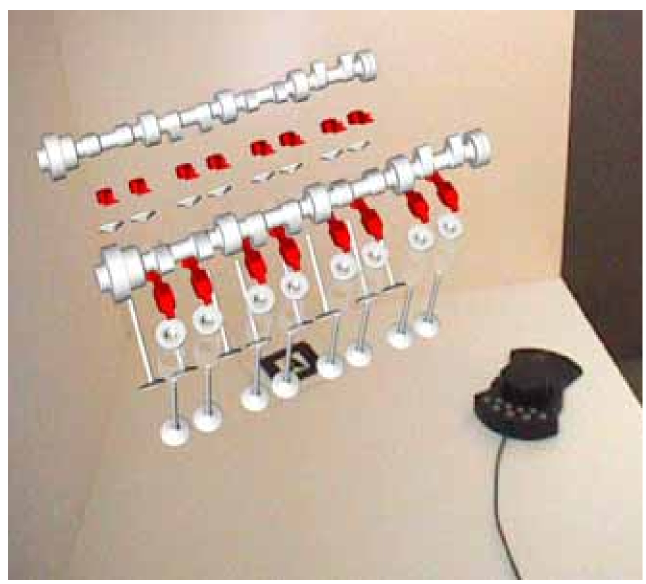

Figure 3. Example of computer-centered interaction – 3D camshaft interaction

Interaction with 3 DOF sensors like the InertiaCube can be performed in a number of ways but in the simplest scenario, it can be used as an orientation device. More advantageous are the 6 DOF sensors such as the Polhemus Patriot that can act as an extra localization device. In any case, users can ‘see’ the digital information in either the virtual or augmented space and by manipulating the sensors in the real environment the virtual information is updated respectively. However, the disadvantage of this technique is that to achieve realistic interactions the speed of moving the sensor must be updated appropriately with the virtual information.

Furthermore, software user-friendly interfaces can be used to manipulate virtual information in a very accurate way. Another advantage of software interfaces is that they can be used in conjunction with standard display devices and touch screens that are commonly used for kiosk interaction in various types of environments (i.e. galleries). Additionally, one of the most impressive features of the interface is that it allows multiple cameras to be connected simultaneously [19]. This makes the interface ideal for MR exhibitions since it is capable of selecting which camera is active and thus selecting the real-time viewpoint of the visualization. On the downside, this technique requires more advanced computer skills and it is not considered ideal for some application scenarios (i.e. museum environments) where user’s age ranges from young children to mature visitors.

5. CASE STUDIES

This section presents three different case studies that illustrate the capabilities of high-level user-centered MR interfaces when applied to everyday applications.

5.1 Automotive Styling

The car industry is very large, possibly the largest manufacturing industry in the world. The impact of the car has been enormous, and arguably it is the product which best represents the twentieth century. Success or failure in the market place can depend on subtle factors of design, and the longer the development process the more difficult it is to get these factors right. Consequently there has been a major squeeze on development times in the motor industry. One of the major approaches that have been used to shorten the time taken to create a new product is concurrent design. The technology and engineering design of vehicles tend to be convergent and there are often great similarities between different manufacturers’ cars.

In these circumstances the appearance design becomes increasingly important. It is the major factor which enables the customer to distinguish between various manufacturers’ models. Vital to the business process of automotive design is the assessment of possible design themes as quickly and thoroughly as possible. Over the last few years computer aided styling has allowed rapid development of very high quality 3-D models, and realistic visualisers which allow some assessment to be made without recourse to the building of an expensive physical model [22]. One of the most time consuming jobs in the construction of a convincing model is the detailing. This can be hastened by 'borrowing' features from a real car. Figure 4 shows such a hybrid model.

Figure 4. MR car – real styling cues mapped onto a computer model

However, such visualizations, while better than sketches and hand renderings in terms of providing an accurate impression of the style, still fall well short of a physical model. Although the virtual model is geometrically accurate, subjective assessments suggest it lacks the 'presence' and 'scale' of a full size physical model. One approach to solving at least some of these problems is to allow the digital model to be viewed in a real environment. In this case, it is hoped, it can gain the presence and scale from that environment. However, styling visualization demands the highest quality display so will stretch the abilities of even top end hardware. Given the investment required to develop automotive designs, however, the need for expensive display systems is hardly a large drawback.

5.2 Museum Exhibition

Museum exhibitions exist for a while now and although a number of experimental systems have been designed by the academic community, most of them can not meet the demands of a wide range of visitors. Museum virtual environments can offer much more than what many current museum web sites offer, i.e. a catalogue of pictures and text in a web browser. Digital artifacts or cultural objects can be presented in a virtual museum exhibition. A virtual museum can consist of many exhibitions representing different museum collections. Additionally, the users can select some cultural objects and observe their digital representations in the context of real artifacts in an AR scene. An example of a complete digital museum gallery which is superimposed on a tabletop environment [23] is depicted in Figure 5.

Figure 5. Virtual museum exhibition of four artifacts

To make the virtual artifact representation as realistic as possible the 3D models were generated photo-realistically and rendered in the MR environment using high level graphics algorithms and techniques. The objective is to make the augmentation look appealing to satisfy the demands of a wide audience. As a result, some of the distinctive detail that exists on the real artifacts such as the reference number is clearly visible on the virtual artifact. Participants of the MR interface can alter some of the visualization properties in real time such as lighting effects, scaling, and dynamic camera switching using the GUI functionality [19]. Moreover, it is possible to examine artifacts in detail using the SpaceMouse as shown in Figure 6.

Figure 6. Virtual artifact manipulation using marker cards and a 3D mouse

In particular, users can translate, rotate, scale, change lighting conditions in real-time performance. To perform one of the above operations the user has to press one of the buttons (the translation button for example) and then use the bar to translate the object in 3D space. Depending on which direction force is applied the object will move respectively. Apart from using the SpaceMouse users can naturally manipulate the augmented information in an intuitive way similarly to section 4.1. The main advantage of the archaeological MR application is that it offers a new type visualization museum focused solution that can be configured for different types of museums. Potential museum visitors can perceive a virtual museum exhibition over the internet, or inside the museum using VR and AR interfaces. Initial evaluation has shown that this interface has the potential to satisfy even the most diverse user requirements.

5.3 Navigation and Geovisualization

Another application on which the multimodal MR interface can be successfully applied is navigation and geovisualization. Advances in mobile technologies have stressed the need of new navigation techniques (i.e. in-car navigation) which can be realized in everyday life by any-one. Current digital techniques used in navigation do not suffice for an effective guidance. The techniques proposed through this application are based on the effective visualization and understanding of interactive maps as well as urban navigation [24]. Interactive maps can consist of landscape features (Figure 7) as well as 3D building virtual reconstruction of areas of towns or even complete cities. More specific, the modeling of the geographical and geo-spatial information is performed based on GIS (i.e. ArcView) and 3D modeling (i.e. 3ds max) software tools and the output information can be stored in VRML and 3ds file formats. However, depending on the geo-spatial location that is going to be modeled, two different techniques have been derived: *vector* and *raster* reconstruction [25]. An example screenshot of a user observing the landscape topology of a 3D map representing the north part of England is shown in Figure 7.

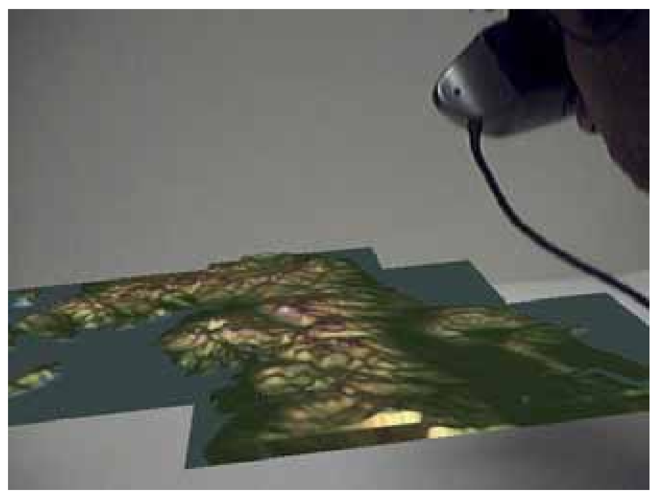

Figure 7. Geovisualization of suburban landscape using an HMD

Moreover, urban navigation is a challenging area of research because it combines both cognitive and perceptual issues. Pedestrians have two options for navigating in the urban environment either using fiducial-based tracking or natural feature detection [20]. The former requires some preparation of the environment prior to the navigation. Fiducial points must be positioned in specific places known as decision points as well as landmarks tasks and that is the main disadvantage of this approach. On the other hand, the main advantage of this approach is that markers provide very robust tracking.

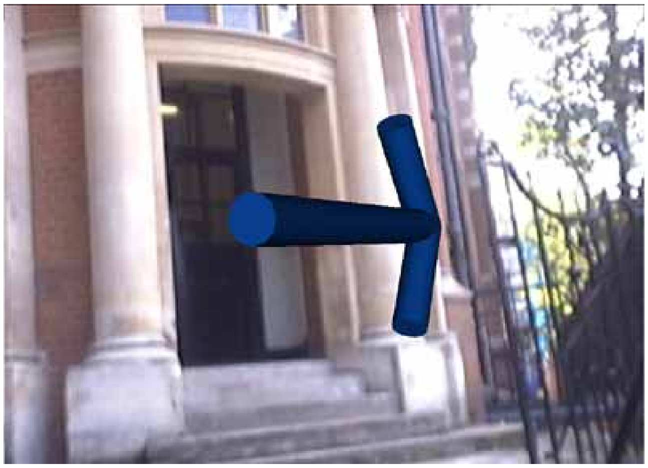

Figure 8. Mobile urban navigation and wayfinding

The alternative way to perform navigation is to detect natural features from the environment (Figure 8). In big cities usually building structures consist of regular sized shapes such as rectangular sized windows and door entrances. Using edge detection and template matching specific building facades can be trained and used instead of the marker cards [20]. This approach has a large range of operation and there is no need to prepare the environment, and thus it can be more easily applied for urban navigation. However, calibration is much harder to achieve especially when dealing with buildings that look very similar and other structures. In both cases, pedestrians must scan the environment for the fiducials or the natural features and as soon as one is detected navigation multimedia information is superimposed onto the user's visualization display.

6. CONCLUSIONS

This paper proposes an innovative framework of a tangible MR interface that contains three rendering modes: an AR; a VR and a cyber reality space. These environments can be used to design effective MR environments. Participants of the system can dynamically switch rendering modes to achieve the best possible visualization. Three prototype applications focused on automotive, archaeology and navigation have been designed and experimentally presented.

6.1 Lessons Learned

The main goal of this work is to explore multimodal MR interfaces when designing innovative applications. We anticipate that the multimodal features allow participants to select the most appropriate medium for visualizing and interacting with virtual information. The capability of dynamic switching between cyber and MR worlds allows remote users to bring VR and AR into their own environment. In addition, participants can change dynamically interaction modes to interact with the virtual information in a user-centered mode as well as through a computer-centered approach. This might be very useful for elderly and disabled people, which have difficulties in doing particular operations or going to specific places.

The MR technologies have been experimentally presented to users and the informal feedback received was very encouraging. The majority of users really liked the idea of using a tangible MR interface for visualizing and interacting with virtual information. In addition, the multimodal capabilities received positive feedback although the AR interface was usually preferred. Some users argued that more virtual content should be digitized and more scenarios should be implemented and stored in a remote database. The main feedback was that the indoor applications worked more robust but the outdoor seems to have a lot of potentials for the future especially with the availability of powerful mobile devices and wireless communications.

6.2 Future Work

Currently, a mobile version of the system is under development so that it can be employed on mobile devices such as PDAs and third-generation cell phones. Although mobile devices are considered to be the future in computing, currently the limitations of the devices (display size, processing power, graphics card and memory) do not permit complex graphics visualization. It will take more time until we see commercial MR applications applied to the above areas or other areas, since a lot of research must be done to improve the visualization and interaction techniques currently used as well as the interface design. Finally, more work needs to be done on evaluating multimodal MR interfaces before a killer application appears.

7. ACKNOWLEDGMENTS

Parts of the work presented in this paper was conducted within the EU IST Framework V programme, Key Action III-Multimedia Content and Tools, Augmented Representation of Cultural Objects (ARCO) project IST-2000-28336 as well as the LOCUS project, funded by EPSRC, through the Location and Timing (KTN) network.

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