Mixed Reality Architecture: Concept, Construction, Use

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Abstract

Mixed Reality Architecture (MRA) dynamically links and overlays physical and virtual spaces. This paper investigates the topology of and the relationships between the components of MRA. As a phenomenon, MRA takes its place in a long history of technologies that have influenced conditions for social interaction as well as the environment we build around us. However, by providing a flexible spatial topology spanning physical and virtual environments it presents new opportunities for social interaction across electronic media. An experimental MRA is described that allowed us to study some of the emerging issues in this field. It provided material for the development of a framework describing virtual and physical spaces, the links between those and the types of mixed reality structure that we can envisage it being possible to design using these elements. We propose that by re-introducing a level of spatiality into communication across physical and virtual environments MRA will support everyday social interaction, and may convert digital communication media from being socially conservative to a more generative form familiar from physical space.

Keywords:

Mixed Reality, Architecture, Space, Topology

Introduction:

Physical architecture traditionally functions as a social object through the way that it acts to structure patterns of co-presence between people. By structuring and controlling co-presence architecture creates the potential for social interaction on which the reproduction of social forms, such as organisational or community structures, and the generation of new forms ultimately depends. In this way architecture acts not only to express, but also actively to shape and reproduce the norms and rules of social interaction of a particular society. Describing this process, Hillier and Hanson (1984) argued that the architecture of the physical built environment, through the way it structures patterns of space, plays a much more active role in society than had been previously suggested. The architecture emerging from this process is available publicly in principle, which makes interaction within it accountable. It is also very stable as any change of the spatial pattern of the built environment tends to be relatively slow, making the interactions structured by it relatively predictable.

However, physical architecture has come under the influence of a number of different technologies whose impact on our need to be co-present has been profound. Pool (1998) details the parallel development of communication and transportation technology that have on the one hand made possible new building forms (for example the development of the skyscraper depended not only on structural and constructional innovation, but the invention of the passenger lift and the telephone) and on the other hand, new urban forms where mass transit systems at the same time as enabling the extension of the city with suburbs have resulted in its segmentation into mono-functional zones. These new architectural forms afford near instant access to non-adjacent parts and, as Virilio points out, the distinction between near and far becomes irrelevant here: the spaces ‘travelled across’ are lost and become invisible (Virilio, 1997). They are compressed and social interaction across two spaces is effectively de-spatialised. However, this can result in the reduction of chance encounters which form an essential part of the economic function of physical architecture (Hillier & Penn, 1992) and of its capacity to foster innovation (Penn, Desyllas & Vaughan, 1999). Spiliopoulou, for instance, has found that communication channels (the phone and email) are used as powerful means of status maintenance in modern organisations where they may be used to deny access by junior staff to senior management and so may act to perpetuate power structures (Spiliopoulou & Penn, 1999). In this sense, although new technologies have had an effect of compression of space, and so an increase in Durkheim’s (1893) ‘density’, there appears to be a concomitant elimination of chance interactions and their unpredictable outcomes. It could be argued perhaps, that where the new technologies serve to reproduce and reinforce existing social structures, space and the chance encounters it offers can serve to generate new social forms.

In this context, it is of considerable interest to investigate how the more recent 'virtual' media can be used to support social interaction. Mixed Reality provides perhaps the greatest potential to enable remote communication and interaction between people and groups in ways that are directly analogous to, and add to, those offered by physical architecture. Mixed Reality joins or overlays physical and virtual environments to varying degrees, using a number of different approaches, technologies and interaction paradigms (Milgram & Kishino, 1994). Our own approach to Mixed Reality involves linking and overlaying multiple physical and virtual spaces that have three spatial dimensions and one temporal dimension (Benford, Greenhalgh, Reynard, Brown & Koleva, 1998) in an attempt to bring together the affordances of modern communication technologies (we are especially thinking about their flexibility), the affordances of physical architecture, as well as human competences in dealing with everyday physical reality as a framework for social interaction. We are therefore considering Mixed Reality from a decidedly architectural perspective and the remainder of the paper will describe this approach as 'Mixed Reality Architecture'.

The paper is presented in three main parts. We will first describe a Mixed Reality Architecture experimental set-up, in which a number of different physical and virtual spaces are linked together into a particular configuration. We use this example to define terminology and raise some of the specific issues that any theoretical discussion of MRA must deal with. Next we propose a simplified framework describing MRA, and discuss the kinds of structures that can be formed when physical and virtual spaces are linked together. Finally we draw some conclusions about possible future work to investigate some of the gaps in understanding highlighted by our framework.

Building and using Mixed Reality Architecture

In a recent pilot study we have started to explore some of the emerging issues in the design, set-up and evaluation of Mixed Reality Architecture. For this pilot study we used a Mixed Reality Boundary (MRB) (Koleva, Benford & Greenhalgh, 1999) and a series of desktop PCs to create a simple MRA consisting of four physical spaces and one virtual space. The MRB appears as a bi-directional window between physical and virtual space. This allows a view into and audio transmission from virtual space, while at the same time providing a video and audio link from virtual space back into physical space. The study was originally set up to evaluate the use of a MRB as support for distributed presentations (Koleva, Schnädelbach, Benford & Greenhalgh, 2001). Its design incorporates a number of features that we will draw on for the development of the framework proposed in this paper.

We aimed to explore whether we could establish mutual awareness between audience members and speakers distributed in different parts of the MRA, as awareness has proven to be a key issue in studies of other systems supporting remote presentations (Jancke, Grudin & Gupta, 2000; Isaacs, Morris & Rodriguez, 1995). To support mutual awareness, a common spatial frame of reference for all the participants was set up in form of the MRA. Two presentations were staged to a distributed physical and virtual audience. A physical audience is one that is physically co-present with the speaker. A virtual audience only has access to the speaker by means of a MRB. One presentation was given by a virtual speaker and one by a physical speaker. Half the audience were located in the same physical space that staged the presentation by the physical speaker. The other half of the audience were located in three separate remote physical spaces. These audience members were embodied in the virtual space as avatars, which they controlled from desktop PCs. Both speakers had visual material to present in the form of slides. Each presentation was followed by a question and answer session. A qualitative analysis of semi-structured interviews and video recordings was used to evaluate the participants' response to the MRA.

The set-up of the study is illustrated in the following figures. Figure 1 shows the MRA from physical space during the presentation by the virtual speaker. The physical audience is situated in front of the MRB with the virtual speaker on the left and virtual audience on the right of the projected screen. The slides presented by the virtual speaker are visible in the middle.

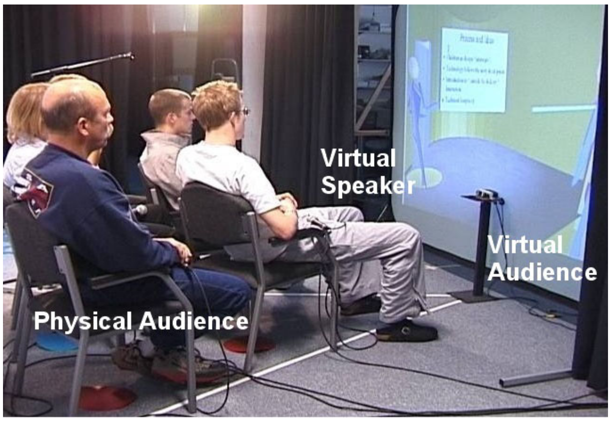

Figure 1: Virtual presentation - Viewpoint of physical audience in local physical space

Figure 2 shows a view from virtual space across the MRB during the same virtual presentation. The virtual audience is situated on the left; the physical audience in the middle via the video texture and the virtual speaker is on the right with the slide screen at the very edge of the screenshot.

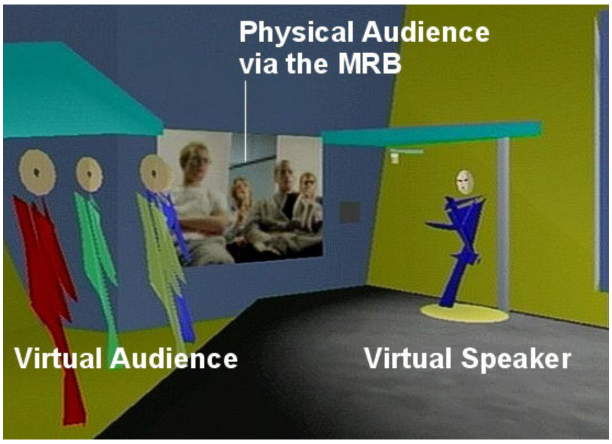

Figure 2: Virtual presentation - Viewpoint of virtual audience located in a remote physical space

For the presentation by the physical speaker, the set-up was adapted to better cater for the changed requirements. In this situation the distributed audience was being addressed from a different direction, namely that of the physical speaker. The audience therefore had to re-orientate. This re-orientation was being guided by changes in the topology of the MRA, which were carried out during and as part of the study. The following two illustrations show the set-up after the changes. Figure 3 shows the physical presenter from physical space. The view contains the physical audience in the foreground, the physical speaker and slides in the background. The virtual audience is situated to the right of the physical audience presented on the same projected interface as before. This is just outside of the frame below.

Figure 3: Physical presentation – Viewpoint of physical audience located in local physical space

Finally, Figure 4 illustrates what the virtual audience saw from within virtual space during the physical presentation. The virtual audience is located in the foreground with the physical audience, speaker and slides visible on the video texture in the background, across the MRB.

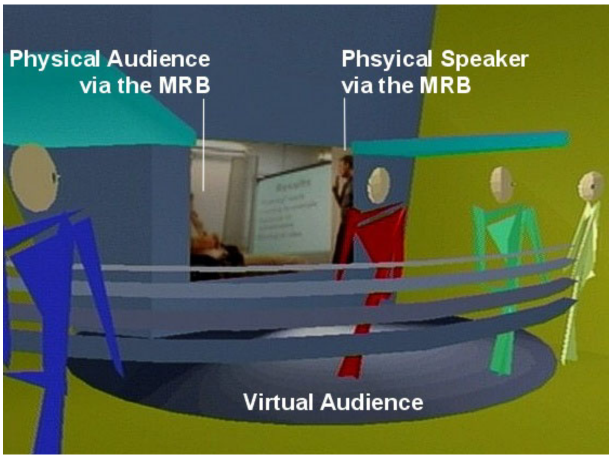

Figure 4: Physical presentation – Viewpoint of virtual audience located in remote physical space

The analysis of interviews and video recordings revealed that a degree of mutual awareness was established between all the participants. However, we found that participants who were co-located in the physical space and experienced the MRB as large projected screen understood the set-up as a more spatially integrated architecture than those who only had access to desktop PCs. Full details of the evaluation and outcome of this study can be found in the paper referenced above, however, there are number of properties of this particular MRA that are interesting for the discussion in this paper and which form the basis for a number of categories describing MRA in general.

Firstly, topological flexibility is a defining property of MRA. The set-up of the pilot study can be described as flexible but static. By providing the facility to move some of the surfaces and furniture objects within physical space and virtual space respectively, we designed the architecture to be adaptable to different speaker locations, while spaces within this particular MRA remained static relative to each other as well as the MRA as a whole. Secondly, access to different parts of its topology is a major issue for any MRA. In our pilot study access across the link between physical and virtual is limited to the senses of sight and hearing, which is a limitation given by the technology of the MRB. However, unlike with many other electronic communication media this access is public, which provides everyone physically and virtually close to the MRB with a similar quality of access to the linked space. The spatial and temporal topology of MRA is also an important consideration. Here, the topology is a discrete arrangement of spaces. These cells are one local physical space, three remote physical spaces (location of desktop computers) and one virtual space. All of these spaces are designed to appear synchronous to each other discounting any unavoidable network delays. Finally, the interaction among participants as influenced by the specific properties of MRA is an important concern. With the design of the layout and the subsequent change of that layout during the study we aimed to influence the behaviour of participants. There were elements designed to afford navigation to suitable viewing positions, while the change of the layout during the experiment was aimed to lead participants to alternative positions better suited for the second presentation.

Through the design, set-up and study of the very simple MRA of our pilot study topological flexibility, access, topology and interaction have emerged as important categories for the description of MRA in general. These provided us with a good starting point for a more systematic exploration of the properties of MRA.

Defining Mixed Reality Architecture

In the remainder of this paper we will describe the kinds of structures we believe can be formed when physical and virtual spaces are linked by presenting an overview of categories that describe the field of possible architectures. This overview is intended as a resource for our own work but also, we hope, as a resource for the development of Mixed Reality systems in general. The categories, inspired by our pilot study but also extended through more theoretical work, are in the following applied to the qualities of physical and virtual 3-dimensional spaces, the qualities of links between a combination of the two and the qualities of the resulting MRA.

Spaces

In this section we are discussing how physical and virtual spaces are conveyed to us, how their flexibility is defined, what type of access we are granted, the limits of experience within them and the relation of society to them.

Conveyer of spaces

Architecture is based on the modulation of the properties of the spaces around us. It expresses those spaces by representing their boundaries with tangible and visible substance. How spaces, whether physical or virtual, are conveyed to us, depends on our perception. Space perception in turn is based on our internal and external senses. Internally, the kinaesthetic sense and the sense of equilibrium provide stimuli about the relationship of our bodies to the space around us and our movement through it. Externally, the senses of sight, hearing, touch, taste and smell deliver data about the boundaries that define spatial cells. The output of our sense organs is then synthesised according to inborn and acquired models.

We would argue that this could hold true for the experience of virtual as well as physical spaces. A thought experiment introduced by Deutsch in *Fabric of Reality* might serve as a starting point here. The author describes an interface capable of rendering virtual environments directly to our nervous system (Deutsch, 1998). In science fiction this has of course been suggested previously, most notably in *Neuromancer* (Gibson, 1984), but here Deutsch uses this type of interface as a vehicle to discuss the possibilities of VR in principle. It would require sensors that measure user's actions directly from their nervous system, output devices that feed back the environment's reactions to the user as nerve impulses and a computer that controls the process and synthesizes environments. Users of such a system could then decide whether they want to experience physical space, predominantly virtual space or a mixture of the two according to their requirements. While well aware that such an interface does not exist at present and making no claims about its future availability, we found the assumption of its existence useful for a discussion of the possibilities of MRA independently of the capabilities of currently available interfaces to virtual space. This is because the limits of what can be experienced in physical and virtual spaces then depend on the capabilities of our sense organs and nervous system, and not the particular interface technology used.

Flexibility of spaces

Physical spaces, or more precisely the physical enclosures of spaces, change over time. Boundaries in nature, for example the sides of a rock gorge, erode slowly; physical buildings are continually re-adapted to new uses (Heath, 2000) and sometimes even moved to new locations (Lighthouse megamove complete, 1999). These changes to physical space are however relatively expensive in terms of time as well as cost. In certain cultures, such as the traditional Japanese house, considerable use is made of spatial adaptation, however, this is not common in most traditions. Therefore it can be argued that the flexibility of physical space is highly limited by the stability and longevity of its enclosures.

In contrast to this virtual spaces can be designed to accommodate rapid changes in extent and position to suit changing requirements. Novak describes 'Liquid Architecture', architecture "designed as much in time as in space, changing interactively as a function of duration, use, and external influence" (Novak 1995, p.45). This architecture is an attempt to overcome conventional, very static architectural concepts by making use of the inherent flexibility of virtual environments.

Virtual environments enable architects to consider not only the movement of people through space but also the movement of spatial elements themselves animated or even animate in relation to time as a vital element of the design. But are virtual environments really as flexible as they seem? In general they are being perceived as allowing users the change of any of their aspects. If not restricted by the architects of the environment, virtual objects can be moved at will to any position and they can be passed through other users as well as other objects. In fact, the lack of appropriate restrictions of this flexibility can lead to problems for users in terms of their ability to interact with each other and the environment (Purbrick, 2001). However, there will always also be limits to the flexibility of any given environment as defined by the underlying computational infrastructure. An infrastructure will allow the change of certain aspects but might prevent or at least make rather difficult the change of others. For example, systems do not typically enable users to change the spatial co-ordinate system of an environment or its system time. In comparison to physical reality though, virtual environments do allow much greater flexibility in their topology and this property will be exploited for the construction of MRA.

Access to space

Our bodies, including all our physical needs (e.g. nutrition, rest) and our sensorium have full access to physical space and our body movement results in movement through space. Indeed, our bodies are what gives us access to the experience of space in the first place, through our sensorium, nervous system and brain (O'Keefe & Nadel, 1978). Furthermore, our bodies as well as our sensorium are spatial themselves, having their own spatial extent and constraints in the same framework. This level of access is afforded to everyone, meaning that people present in the same portion of physical space will perceive almost the same underlying data, while they might well perceive a different mediation of this data.

In contrast, while providing full access for our senses, virtual space does not allow access for our bodies, even when assuming the use of Deutsch's interface described above. Therefore the satisfaction of physical needs might be simulated but cannot be fulfilled and the movement of our limbs does in general not map directly on to the movement in virtual space. Another property of virtual space is that it is possible to tailor the level of access to it so that the experience of it is different for different people, for example, when certain elements of it are only visible to certain groups (Greenhalgh, Purbrick & Snowdon, 2000). Instead of providing public access to all aspects of virtual space, the experience then becomes private and individualised.

Limits to experience

There are also clear limits to our experience of reality, mainly resulting from the limitations of our sense organs. In physical space for example we cannot perceive infrared light or the rotation of the earth. Deutsch points out that this also limits virtual space as only experiences that we can sense can be rendered (Deutsch, 1998). Virtual environments allow the experience of things that are impossible in physical space (e.g. flying) but cannot guarantee the reproduction of internal experiences (e.g. pride) or at all reproduce illogical experiences (e.g. unconsciousness). However virtual space will allow the experience of other's experiences at least to the extent of the relevant sensory data that can be replayed to more than one person.

Social interaction in space

Space is the prerequisite for co-presence unmediated by technology. It provides the framework for physical encounters and social interaction. We establish relationships within space and Hall describes how personal space is then being used to control or regulate these relationships (Hall, 1966). Crucially, social interaction does not take place in an unbounded, abstract spatial expanse but space has a certain structure. The geographical features of an environment determine an overall structure of space. However, more importantly in this context, spatial structure is provided by architecture, both within and outside buildings. As Hillier argues (Hillier & Hanson, 1984), this structure as provided by architecture, within as well as outside buildings, has certain effects on social interaction as it structures movements, encounters and avoidance patterns of otherwise discrete individuals prior to the effect society itself has. This structuring effect can be generative, when it encourages encounters between people, opening up the chance for social interaction between strangers. It can also be conservative, when it limits such encounters, in effect preserving the structure of the already existing social interaction. At the same time, the spatial patterns of architecture are clearly structured by society as they are laid out according to certain rules that differ from one society to another. These patterns as affected by the underlying social rules in turn make the existence of society visible and make its spatial form recognisable.

The smallest unit in this structure is the elementary spatial cell. It can be defined as a space in which people are regarded as being co-present and having a symmetrical relationship to each other in terms of their potential for social interaction. One of the functions of the spatial cell is to establish the two categories of inhabitants and strangers. A cell is owned by its inhabitant who controls its boundary or link to the outside public space, the domain of strangers as well as the domain of encounters between strangers and inhabitants (Hillier & Hanson, 1984). The inhabitant exerts control of the link to public space to maintain the discreteness of the category, to establish the identity of strangers and authorise the crossing of a link turning strangers into visitors.

As mentioned above, physical spatial patterns are relatively stable. Radical shifts in these patterns are generally only caused by revolutionary events (i.e. industrial revolution, wars, natural disasters). This provides society with a more or less stable base to grow from both spatially as well as socially. Access to space is democratic in principle. In practice society restricts access for certain classes of people and physical and mental competence of individuals do have an effect on access. Nevertheless, there are spatial regions (i.e. public space) where all classes of people will encounter each other and where there is potential for social interaction between them.

When analysing virtual spaces it becomes clear that their purpose is to provide a similar kind of spatial framework to that of physical space for electronic communications. The aim is to make use of the affordances of space in support of co-presence and therefore social interaction. Benford, Brown, Reynard and Greenhalgh (1996), in their analysis of spatial approaches to CSCW mention the need to provide peripheral awareness of the actions of others, the realisation that informal interactions as often generated by chance encounters are an important part of co-operation and the benefits of providing users with a sense of place as many online co-operative activities are distributed over a number of sessions. Indeed, often the aim is to directly simulate the properties of physical space and make similar use of it in the virtual environment. For instance, the spatial model of interaction (Benford & Fahlen 1993) imposes rules on the ability of users to communicate with each other that are based on the spatial proximity of their virtual representations.

The spatial topology of virtual environments is often similar to that of general physical space. Activeworlds, a platform for persistent virtual environments, is a good example in this context as it allows users to construct their own virtual buildings. Started on a flat virtual plain in 1995, Alphaworld which is the main environment in the Activeworlds universe has a vast number of buildings that have been placed in what now very much resembles an urban structure. The overall topology seems to result from the wish of users to build close to others and the power of the co-ordinate system as users preferred easy to remember co-ordinates (Schroeder, Huxor & Smith, 2001). However when planned, as in a number of smaller areas where groups of people decided to co-operate, space has been structured with public as well as private areas and Schroeder et al. describe how these areas are used for general socialising and more intimate interaction respectively. Alphaworld grants users certain property rights. They can claim land, build on that land and exert some control over it. But overall control over space, including individually 'owned' land and buildings, ultimately lies with the owner of the computational infrastructure, which is probably a defining feature of all online environments.

We would like to argue that virtual spaces are comparable to physical ones of similar topology in terms of their generative and conservative effects on social interaction. Indeed, movement through virtual space, which is providing the chance for encounters and therefore the potential for social interaction, can be shown to be statistically similar to movement through and equivalent physical space (Conroy, 1998).

Two of the defining properties of virtual space mentioned above however are expected to cause social interaction to be distinct from that within physical space. Firstly, if a truly flexible spatial topology were implemented for virtual space, the society shaped by it would be confronted with a shifting spatial arrangement, rather than a stable basis, which would presumably be difficult to navigate and visualise. To be able to see such a flexible topology as an expression of a society, this society would have to have adopted a rule system quite different from one grounded in much more static physical space. Secondly, as access to virtual space can be tailored to individuals, users cannot necessarily expect a common frame of reference for social interaction, which seems to be contrary to the original goal of the introduction of spatial metaphors into electronic communication.

Mixed Reality Links

Following the description of the qualities of physical and virtual spaces above we will now attempt to outline the properties of the links required to shape these into MRA. A previous analysis of the boundary between physical and virtual (Koleva et al., 1999), but also a fresh look at links within physical and virtual architecture has served as basis for the following account of Mixed

Reality Links. We will discus how those links are conveyed to us, how flexible they are, what type of access we are granted across links, what types of target are possible and how social interaction is affected.

Conveyer of links

At the most basic level, the link between physical and virtual space is created by the set-up of virtual space itself, as there needs to be an interface for the input and modification of the underlying data. Through the mere existence of virtual space the two kinds of space are therefore always linked by technology, while the way this link is conveyed to us is a matter of design. In physical space a link to virtual space might appear as a gap in a virtual wall, creating an opportunity to cross. That wall in turn would have been rendered to our nervous system as a representation of a boundary between physical and virtual space. The gap will then allow parts of our sensorium to traverse and explore the other side. Crossing this link means that our sensorium predominantly perceives stimuli from within virtual space. Once there, a link back across would also be represented to us as a gap in whatever denotes the boundary to physical space. Boundaries and links between physical and virtual are then perceived just like ordinary architectural elements (e.g. walls, doors) and their affordances in terms of their traversability will have to be made clear in design.

Flexibility of links

Mixed Reality Links are highly flexible in terms of quality and mobility. Which spaces are linked to which can be changed and adapted quickly, given the right access control (Benford, 1998). In addition, a link between one particular physical space and a particular virtual space can also move its position, in effect re-connecting the same two spaces in different locations over a period of time (Schnädelbach et al., 2002).

Access across the link

In terms of what access they provide, Mixed Reality Links have very different properties from links between separate physical spaces. Our physical body with its physical needs cannot cross regardless of the type of interface we might be using. Crossing instead means projecting all or part of one's internal and external sensorium to predominantly perceive the space across the link. Different kinds of links will then permit different portions of our sensorium to cross just like the ordinary telephone links two physical spaces by audio only while it does not allow us to see the other space.

This also requires us to take on one or multiple representations in the space on the other side. For virtual space this would be an avatar, which can appear to others just like our physical body or take on a new form and identity. For remote physical spaces a physical proxy would take the role of the avatar (Koleva, Schnädelbach, Benford, Greenhalgh, 2000). What different people experience of a certain link can be tailored finely to an individual, resulting in the link no longer being available publicly. Unlike a door between two physical cells that is visible and usable in principle for everyone, a Mixed Reality Link can be rendered differently for different people, in effect individualising links.

Target of a link

The target of the type of mixed reality link we are discussing here is always another space. When starting from a physical cell, this can be any virtual space in the MRA. From within virtual space, a target can be any physical space in the MRA. Significantly, there is a fundamental difference between the physical cell an individual starts off in and all other physical cells as only the former can be entered fully with our bodies as outlined above. Mixed Reality Links can also be segmented meaning that the target of a particular link can be accessed in more than one way. The segments of a target can then have different properties from each other. As an example one could envisage a Mixed Reality Link that provides two views from physical space into virtual space, one being vertical and the other horizontal to be able to observe different aspects of the other space at the same time, possibly even at different scales. In terms of time, targets of a Mixed Reality Link can be accessed instantly, bar the physical limitations of the hardware used both locally and across the network; but accessing parts of the MRA that are more remote in the topology can require time for virtual travel. In addition to the above, Mixed Reality Links can also transform the target in time when they link to a recorded virtual space for instance (Greenhalgh, Flintham, Purbrick & Benford 2002).

Social interaction

Socially, crossing a Mixed Reality link can be compared to crossing a link between two physical spaces. This typically means a change of status for instance turning a stranger into a visitor. If they have not been 'individualised', links are part of the same spatial framework as any other objects or indeed users and crossing as well as the associated changes in status become visible. An important part of 'civic legibility' (Mitchell, 1996) is re-introduced into networked social interaction as now it becomes possible again to understand who is accessing what.

An individual or an organisation as the 'owners' of a link typically controls the access. They decide who has got access to the link and at what quality, while the amount of control they themselves have be in turn managed by whoever controls the underlying infrastructure. Mixed Reality links could also be used, just like links within physical space, to exert control over the behaviour of people, when certain routes within the MRA are made available or are closed to channel the flow of people.

Mixed Reality Architecture

In the final section of this overview we are aiming to set out the concept of Mixed Reality Architecture as a configuration of physical and virtual spaces joined by Mixed Reality Links. We will discuss MRA in terms of how it is conveyed, how flexible it is, what access we can gain to its parts, what its topology is like and what MRA means for social interaction.

Conveyer of MRA

The quality and dimensions of MRA are conveyed to us by the assemblage of spaces and links described above. Their properties tell us about the qualities of the complete architecture and we perceive these properties with whatever part of our sensorium we have access to in different segments of a MRA. At the same time the architecture takes on properties as a whole that can only be understood by considering more than its separate elements and through movement between its parts.

Flexibility of MRA

The topology of MRA is very flexible. Each link can rapidly adapt to join different cells. A user aiming to adapt the topology to their needs might trigger this change or it might be triggered automatically by certain events. Links can potentially also be generated as well as removed from the MRA very quickly. In addition to the above, parts of the structure can also move position. This is certainly true for virtual space but even an entire physical cell could move (e.g. vehicle). However, MRA as a whole is 'anchored' in some respect from the perspective of each user. The physical space they started off in is always the one they will come back to, given that no physical travel is involved.

Access to MRA

Effectively, people have different degrees of access to different parts of a MRA. Firstly, full bodily access is only given to the cell that was physically entered, while parts or all of our sensorium can reach other areas of the topology. Secondly, depending on the type of link employed, parts of MRA can be experienced only by individuals or certain groups, while other parts are available publicly. On the one hand this is the result of control exerted at each link, effectively barring access completely for particular groups. On the other hand it is caused by the ability to render parts of the virtual structure, spaces as well as links, selectively to individuals or groups only. Both the above will result in an individualised outlook on MRA, in terms of which parts of it are accessible. This might seriously impede the civic legibility of MRA as individuals or groups of individuals might not have a common frame of reference for social interaction even if they are close to each other in the MRA.

Topology of MRA

For all practical purposes physical and virtual spaces can be described as boundless in all of their three spatial dimensions. Conceptually, we regard them therefore as always directly overlaid, while at least one Mixed Reality Link is required to make this apparent to inhabitants of a MRA. Where and how physical and virtual spaces are linked is then a matter of design as already discussed in the section on Mixed Reality Links.

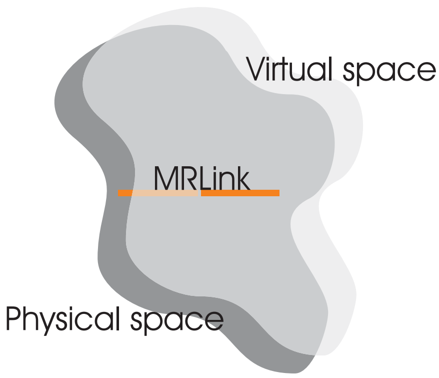

Figure 5: Physical and virtual spaces directly overlaid

One of the most common approaches to Mixed Reality, Augmented Reality (AR), is based on this type of spatial topology (Anabuki, Kabuka, Yamamoto & Tamura, 2000). In AR the topology of physical space is typically applied to virtual space, which makes it similarly inflexible. Indeed, one of the main research challenges in this area is the as exact as possible registration between physical and virtual environments. Links between physical and virtual space are often user-centred

(Head Mounted Displays), therefore mobile and position tracked. On the other hand, physical and virtual space can be designed to appear discrete with different spatial topologies on either side. Mixed Reality Boundaries as used for the pilot study described above are based on this second type of topology. In contrast to AR the MRB is usually space-centred rather than user-centred and therefore available to small groups of people. Through its implementation it appears like a window or door between physical and virtual spaces, giving it an architectural quality.

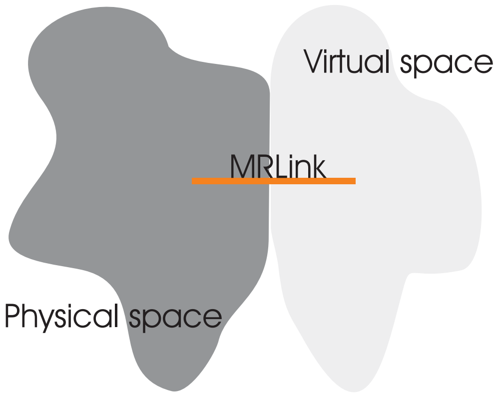

Figure 6: MRB - Physical and virtual spaces are linked but separate

In this context the two approaches above have been introduced to demonstrate the topological extremes possible within Mixed Reality. Significantly, they cannot clearly be separated and indeed are often combined (Schnädelbach, Koleva, Flintham, Fraser, Izadi & Chandler, 2002). Both of these extremes influence the topology of MRA itself, which is based on the premise that physical and virtual spaces are overlaid but segmentation is introduced where required.

As basic building block of MRA and as equivalent of the elementary physical architectural cell we propose the MRA Cell. The MRA Cell is defined as spatial unit consisting of one physical and one virtual spatial cell joined by a Mixed Reality Link. It is designed to simulate co-presence between people on either side of the link and offer them an as symmetrical as possible relationship for social interaction. The MRA Cell can take a number of forms. The simplest implementation could look like the figure below. Other implementations are possible but in this context we have chosen the separation of the two spatial units within each MRA Cell with the aim to allow separate access control to both parts of the MRA Cell. This will be discussed in more detail below. Each inhabitant of a given MRA then owns and controls one MRA Cell. These exist in conjunction with any public MRA Cells that might exist in a MRA and which are controlled by a group of people rather than an individual.

Figure 7: Public and private MRA Cells: Physical and virtual cells joined by Mixed Reality Links (Surrounding topology omitted). Cell boundaries as controlled by inhabitants determine level of privacy

As a result the overall topology of MRA is defined by the properties of the two underlying topologies of physical and virtual spaces as effected by the relative position of MRA Cells within them. Importantly, the physical side of a given MRA Cells can be described as embedded in a static physical topology (unless it is a vehicle), while the virtual side of a MRA Cell can be described as embedded in a flexible virtual topology (unless it is designed to be fixed). The movement of individual MRA Cells within virtual space then allows the dynamic configuration and re-configuration of the topology of MRA and with it to a certain extent that of physical space. The graphic below serves to illustrate that process. On the left Topology 1 of a given MRA is shown, where five static physical cells embedded in physical space are linked to their equivalents in virtual space. On the right the graphic shows Topology 2 of the same MRA where the linked virtual cells have changed position and formed a new virtual topology. As a result the spatial relationships between physical cells have also changed across virtual space.

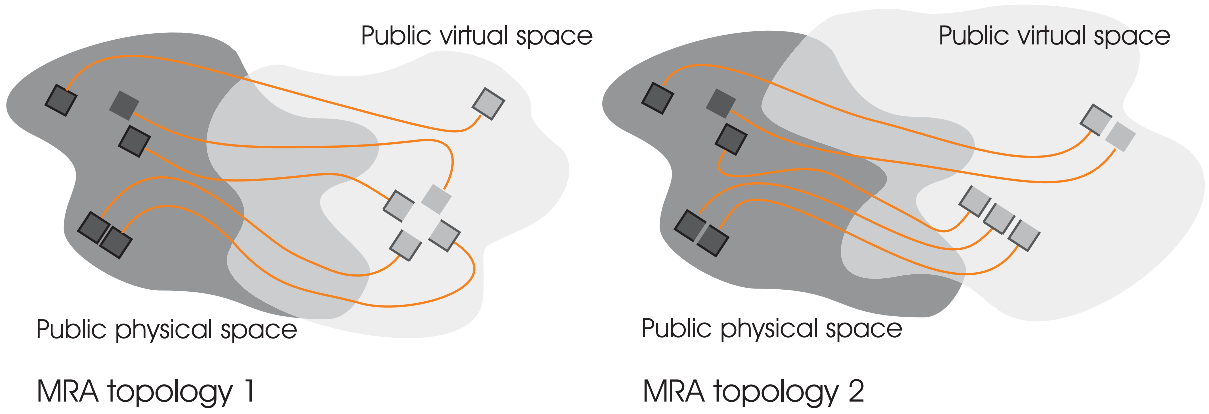

Figure 8: Topology of MRA: Flexibility of virtual topology allows links of physical cells in different configurations. Cell boundaries can be opened, lowered or removed according to requirements

The above is only a simplification of the configurations we are currently considering. There are a number of other aspects that are important like the question of the discreteness of spaces, the spatial expanse of MRA as well as the temporal expanse of MRA.

Social interaction

Each inhabitant owns and therefore controls the access to at least one MRA Cell. There are two types of control. Firstly, inhabitants control the position of their MRA Cell in virtual space, which in turn affects the overall topology of MRA. By moving their MRA Cell they can create spatial configurations according to their requirements. Secondly, inhabitants also control access to their MRA Cell either from public physical space or public virtual space but also across their own MRA Link. This is achieved by controlling the boundaries to a particular Cell. Boundaries can be closed, opened or removed altogether. This is the rationale for the separation of the physical from the virtual spatial unit within a MRA Cell, as now entering one does not necessarily allow access to the other. MRA Cells are designed to allow protection of private property and social interaction from the interference from strangers very much like physical architectural cells. The public spaces surrounding these private MRA Cells are expected to have a similar effect on patterns of encounter between people with the potential for social interaction to those of physical space. However, one of the main differences of the topology to that of physical space is its flexibility. When MRA Cells move the relationship of private to public spaces is changed and it will be an interesting future area of inquiry to see how this flexibility might influence social interaction.

It is quite conceivable that one person or organisation has overall control over a MRA, similar to a company having control over their own intranet. However, if the infrastructure was constructed on the basis of open protocols and standards, each individual piece of MRA could be linked to any other cell, effectively making overall control impossible, very similar to the current structure of the Internet.

Conclusions

In this paper we have outlined the concept of Mixed Reality Architecture. Taking the observations and findings resulting from our initial pilot study as a starting point we have described and discussed the qualities of physical and virtual spaces, links between those and the resulting overall structure of MRA. At present, MRA tends to be set-up as lab experiment but we would like to suggest that there are other motivations that might lead to its wider use. A significant amount of everyday social interaction is already taking place via electronic media. As we have argued those media typically do not provide a spatial framework for that interaction, in effect de-spatialising it. For this reason, unlike physical space, these media do not provide for random social encounters. In turn, this prevention of encounters with the potential for social interaction results in the conservation of pre-existing social structures. We are proposing a concept of MRA with the aim of re-introducing a level of spatiality into communication across physical and virtual environments supporting everyday social interaction but also more specific collaboration tasks that require a spatial context, such as design, rehearsal or some forms of gaming.

We are now planning to investigate the concept further with in-depth studies of a persistent MRA covering a number of physical and virtual spaces. It is clear that we will be facing very real constraints given by the particular interface technologies chosen and this will result in the actual

MRA being different from the idealised framework we have presented in a number of ways. However, we feel that it as it stands provides a useful tool for us and hopefully other researchers in the field for understanding the issues emerging when constructing Architecture that spans the physical and virtual. With our studies we hope to gain experience in the design, construction and use of MRA in general with the aim of evaluating the concepts presented in this paper but also of uncovering new issues. We are particularly interested in how inhabitants assemble MRA topology from the cells they own and how this might be used to set up private and public areas for different uses. We also hope to see what use inhabitants make of the topological flexibility of MRA, as people have no access to this in physical architecture, and how that might influence social interaction. Finally, our aim is to investigate whether MRA, in contrast to other technologies supporting social interaction across space, really can be generative in terms of chance encounters and what types of design best support that aim, or whether the flexibility and possible individualisation of MRA will simply be used to exert more control.

References:

Anabuki, M., Kabuka, H., Yamamoto, H. & Tamura, H. (2000), *Welbo: An Embodied Conversational Agent Living in Mixed Reality Space*, Video proc. CHI 00, The Hague

Benford S., Brown C., Reynard G., and Greenhalgh C. (1996), *Shared spaces: Transportation, artificiality, and spatiality*, Proc. ACM CSCW'96, Boston, pp.77-86

Benford, S., Greenhalgh, C., Reynard, G., Brown, C. & Koleva B. (1998), *Understanding and Constructing Shared Spaces with Mixed Reality Boundaries*, TOCHI, 5 (3), pp.185-223

Benford , S. & Fahlén, L. (1993)*, A Spatial Model for Interaction in Large Virtual Environments*, proceedings ECSCW, pp. 109-124

Conroy, R. A. (1998), *A Method for the Comparison of Pedestrian Movement in Real Environments to Navigation in Virtual, Simulated Environments: Case Example, The Tate Gallery*, presented at UKVRSIG , Exeter

Deutsch D. (1998), *Fabric of Reality*, London, Penguin Books

Durkheim, E., (1893/1984), *The Division of Labour in Society*, Basingstoke, Maxmillan

Greenhalgh, C., Flintham, M., Purbrick, J., and Benford, S., (2002), *Applications of Temporal Links: Recording and Replaying Virtual Environments*, Proc. IEEE VR 2002, Orlando, pp. 101-108

Gibson , W. (1984), *Neuromancer*, New York, Ace Books

Greenhalgh, C., Purbrick, J. & Snowdon, D. (2000), *Inside MASSIVE-3: Flexible Support for Data Consistency and World Structuring*, proceedings CVE 2000, pp.119-128

Hall , E. (1966), *The Hidden Dimension*, New York, Garden City

Heath, T., (2000), *Adaptive Re-use: Commercial to Residential*, Cast*,* Issue 3, pp. 92-95, http://www.nottingham.ac.uk/sbe/cast/dload.html

Hillier, B., Hanson J. (1984), *The social logic of space*, Cambridge, Cambridge University Press

Hillier, B. & Penn, A., (1992) *Is Dense Civilisation Possible?: or the shape of cities in the 21st century*, Applied Energy 43, London, pp. 41-66

Isaacs, E. A., Morris, T. & Rodriguez, T.K. (1995), *A forum for supporting interactive presentations to distributed audiences*, proc. CSCW 95, pp. 405-416

Jancke, G., Grudin, J. & Gupta, A. (2000), *Presenting to Local and Remote Audiences: Design and Use of the TELEP System*, proc. CHI 00, The Hague, pp. 384-391

Koleva, B., Benford, S., Greenhalgh, C. (1999), *The Properties of Mixed Reality Boundaries*, proc. ECSCW 99, pp. 119-138

Koleva B., Schnädelbach H., Benford S., Greenhalgh C. (2001), *Experiencing a Presentation through a Mixed Reality Boundary*, proc. of GROUP 01, pp. 71-80

Koleva, B., Schnädelbach, H., Benford, S. & Greenhalgh, C. (2000), *Traversable Interfaces Between Real and Virtual Worlds*, proc. CHI 00, pp 233-240

Lighthouse megamove complete (1999), retrieved October 25, 2001 from http://news.bbc.co.uk/hi/english/sci/tech/specials/set99/newsid_298000/298123.stm

Milgram, P. & Kishino, F. (1994), *A Taxonomy of Mixed Reality Visual Displays*, IEICE Transactions on Information Systems, Vol E77-D (12), pp. 1321-1329

Mitchell , W. (1996), *City of Bits- Space, Place and the Infobahn*, Cambridge-Massachusetts, London-England, The MIT Press

Novak, M. (1995), *Transmitting Architecture* in Toy, M.(Ed), Architects in Cyberspace, London, Academy Group Ltd, Vol 65, No 11/12, pp. 43-47

O'Keefe, J. & Nadel, L. (1978), *The Hippocampus as a cognitive map*, Oxford, Oxford University Press

Penn A., Desyllas J., Vaughan L.(1999), *The space of innovation: interaction and communication in the work environment*, Environment and Planning B: Planning and Design, 26, pp. 193-218

Pool, I. (1998), *Communications Technology and Land Use*, in Etheridge, L. (Ed.), Politics in Wired Nations, New Brunswick and London, Transaction Publishers, pp. 193-206

Purbrick, J. & Greenhalgh, C., *Collaborative Creation of a Persistent Virtual World,* proceedings Interact 2001

Schroeder, R., Huxor, A., Smith, A., (2001), *Activeworlds: geography and social interaction in virtual reality*, Futures 33, pp.569-587

Schnädelbach, H., Koleva, B., Flintham, M., Fraser, M.,Izadi, S. & Chandler, P. (2002), *The Augurscope: A Mixed Reality Interface for Outdoors*, proc. CHI 02, pp. 1-8

Spiliopoulou, G. & Penn, A., (1999), *Organisations as multi-layer networks: face to face, email and telephone interaction in the workplace*, proc. Second International Space Syntax Symposium, Bartlett, UCL, London, 1999, Vol 1. 13.

Virilio, P. (1997), *The overexposed City* in Leach, N. (Ed.), *Rethinking Architecture*, London, Routledge, pp. 381-390