Moving Office: Inhabiting a Dynamic Building

Holger Schnädelbach* **, Alan Penn**, Phil Steadman**, Steve Benford*, Boriana Koleva*, Tom Rodden*

* Mixed Reality Lab
University of Nottingham
(hms,sdb,bnk,tar@cs.nott.ac.uk)

**Bartlett School of Architecture
University College London
(a.penn, j.p.steadman@ucl.ac.uk)

ABSTRACT

Mixed Reality Architecture (MRA) supports distributed teams in their everyday work activities by linking multiple physical spaces across a shared three-dimensional virtual world. User configurable audio-visual connections give the inhabitants of MRA full control over whom they want to be in contact with and when they make themselves available, as well as over the overall configuration. We report on the design of MRA, its deployment in an office environment and results from a long-term observational study. The study shows that MRA supports the management of awareness, social interaction and privacy well, that the architectural design features are crucial for this process and that the dynamic architectural topology of MRA and social interaction within it are linked in a fundamental way.

Categories and Subject Descriptors

H.5.3 [INFORMATION INTERFACES AND PRESENTATION (e.g., HCI)]: Group and Organization Interfaces --- Computer-supported cooperative work, Synchronous interaction, Evaluation/methodology; H.4.3 [INFORMATION SYSTEMS APPLICATIONS]: Communications Applications --- Computer conferencing, teleconferencing, and videoconferencing

General Terms

Design

Keywords

Architecture, Buildings, Situated Study, Prototyping

1. INTRODUCTION

Organisations today are very flexible in response to the fast-paced environment they operate in. The buildings that house such organisations are frequently called upon to accommodate organisational change, but often prove too rigid [4, 19]. In addition, organisations are often distributed across multiple sites. This can clearly cause problems in terms of communication. It also prevents cross-influences between diverse parts of an organisation, which has been identified as vital, particularly for maintaining an innovative edge [1].

Technological means have long been employed to provide better communication between different organisational parts as a substitution for physical copresence. The invention of the telephone was followed in the 1970's by video telephony, which provided the first two-way audio-visual link between remote physical spaces [7]. Video conferencing then allowed multiple links to be established, while these were typically for formal and arranged meetings [21]. The recognition of the value of unplanned and informal interaction in the workplace then led to the development of media spaces, more persistent audio-visual links designed to support background awareness and focussed interaction. *Portholes* provided awareness information to a group of work colleagues distributed across two sites. The interface presented users with regularly but infrequently updated glances into connected offices and public spaces. Audio messages could be left for others, images could be manually updated and email could be initiated by clicking on one of the images [6]. Dourish et al also describe a long term study of a media space linking two colleagues via audio and video equipment placed on their desks [5]. They emphasise that new types of interactional behaviour emerge over time and that although designed to link people, in fact media spaces have the capacity to link spaces. The linking of three public spaces with a video and audio connection in an office setting is described by Jancke et al [14] who report on difficulties in pushing this type of technology out to a wider set of participants. Privacy issues become much more pressing when compared to installations that connect only a close circle of people, who are well known to each other.

In response to problems that have been reported in the media space work to do with turn taking and gaze direction spatial approaches have been introduced to conferencing applications. For example, the HYDRA [22] and MAJIC [13] systems spatially arranged local views of remote participants. The introduction of live video into collaborative virtual realties had the same aims [11, 17], but also allowed scaling to larger group sizes. Here representations of individuals were augmented with live video streams. As they were embedded in a common virtual environment, they could spatially arrange themselves in a configuration that was appropriate to their needs. Mixed Reality Boundaries (MRB) were a further extension of this work [3]. MRBs provide a two-way video and audio link between physical and virtual space and are implemented as large shared displays. The combination of many MRBs into a structured system has previously been suggested but not studied in any depth [3].

In this context and in addition to the aforementioned use of communication technologies, there have also been numerous proposals for making buildings more dynamic. Price advocated assembling buildings from prefabricated units and giving

inhabitants control over how they are configured [20]. Novak suggested entirely virtual architecture that is animated and reacts to its inhabitants [18]. Osterhuis Associates proposed physical buildings the size of which adapt in relation to the number of people present [23].

For the research presented here we set out to combine the situated nature of the original media space research with the user-controlled configurability found in virtual environments and design principles derived from building architecture. We describe Mixed Reality Architecture (MRA), linking multiple diverse physical spaces across a shared virtual environment. In what follows we describe the design of MRA, including the key concept of the Mixed Reality Architectural Cell. This is followed by an outline of the deployment of MRA in a distributed office environment spanning three campuses in three different cities. Two initial prototyping phases of one and four months respectively were followed by a long-term deployment lasting 18 months. We conclude by presenting the results from our observational study of this deployment.

2. MIXED REALITY ARCHITECTURE

The design of MRA is grounded in architectural theory, where the understanding of the relationship between social life and the physical spatial topology it is embedded in is a key interest. One starting point in this discussion is the elementary architectural cell. It is a fundamental architectural concept and the smallest building block that any architectural structure consists of. One of the functions of the 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, which is the domain of strangers as well as the domain of encounters between strangers and inhabitants. Inhabitants can authorise the crossing of the link to their architectural cell, turning strangers into visitors [12]. Another function of the cell is to establish copresence between two or more people who are present within it at the same time. This is achieved by placing people within the boundaries of the same space. In this context, architectural cells can therefore be defined as spatial units within which people are regarded as copresent and have a symmetrical relationship to each other in terms of their potential for social interaction. Arguably, this can be applied to both physical and virtual architectural spaces.

2.1 Mixed Reality Architectural Cell

As an extension to the above considerations, the concept of Mixed Reality Architectural Cells (MRACells) was developed. MRACells are defined as spatial units, consisting of one physical and one virtual spatial cell, which are permanently joined together by Mixed Reality technology. MRACells form the basic building blocks for the creation of Mixed Reality Architecture. Based on the definition of architectural cells adopted here, they are also designed to support copresence between inhabitants who are physically or virtually present within them. The aim is to maintain a symmetrical as possible relationship between people present within an MRACell.

For the construction of MRACells we used an established technology designed to link physical and virtual spaces: the Mixed Reality Boundary (MRB) [3]. In contrast to previous uses the MRB has been made virtually mobile for Mixed Reality Architecture. A large screen projection provides a view from the physical part into the virtual part of the MRACell. A camera mounted on the screen captures events in physical space and maps them back onto the virtual representation of that same space. There is also a two-way audio connection between physical and virtual spaces making use of noise cancelling microphones. The virtual space has been implemented in MASSIVE3, a computer platform for Collaborative Virtual Environments [10]. Each MRACell runs a client connecting to a central server that coordinates movement updates. Client and server run on standard PC hardware. In physical space MRACells are represented by their actual physical cell (an office for example) with the attached virtual cell being projected on the screen of the MRB. This screen is designed to be as a large as possible in the given space, as previous research has indicated that this influences the degree to which participants can accept virtual space as an extension to their environment [15].

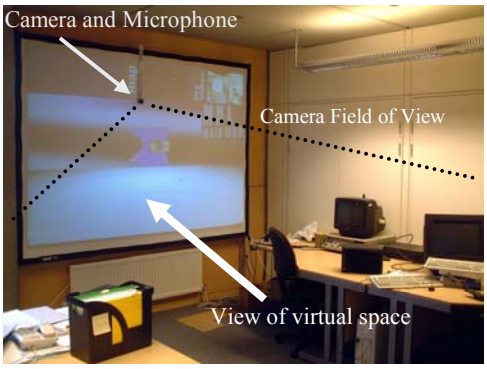


Figure 1MRACell in physical space

Within virtual space virtual and physical cells are both represented with 3D geometry as one element. Live video taken from the physical cell is mapped on to the front of the representation of that physical cell. Live audio captured from the physical microphone is mapped to its virtual position. The audio range is visualised as a circle around the MRACell.

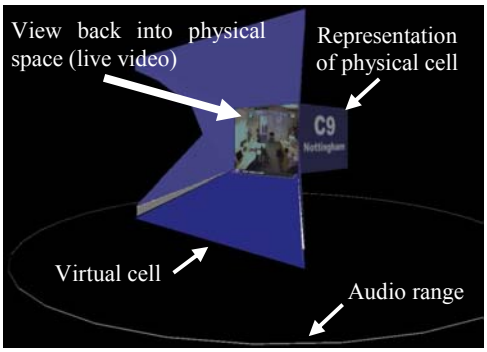


Figure 2 MRACell in virtual space

The shape of the virtual part of the MRACell derives from the field of view of the virtual camera that generates the view projected in physical space. It makes the affordances of the MRACell clear within virtual space, by indicating 'how much' inhabitants can see of the virtual environment and in which direction they are pointing. The design also enforces symmetry of visual awareness, i.e. somebody looks into the physical part of an MRACell from virtual space, they can be seen by its inhabitants on their projection screen.

2.2 Control over access and virtual position

Owners of MRACells have the rights and tools to change the quality of access on two different boundaries. Firstly, there is the physical access to the physical space. This is usually controlled with a door in addition to windows controlling visual access only, just like in any typical room. Secondly, access to the virtual side of the MRACell is controllable through similar architectural elements, effectively creating a virtual door to the virtual cell. For this reason the virtual part of the MRACells has been designed so it can be closed, semi-closed or opened.

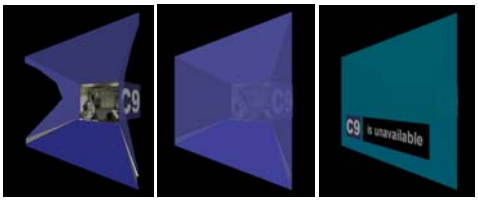


Figure 3 MRACell: Open, Semi-closed and Closed

The semi-closed state acts like a curtain, blurring the view into the physical cell unless one actually steps through, which would be very clearly visible to the person owning that particular MRACell. The closed state blocks the view into the physical space and marks the MRACell as unavailable. Inhabitants toggle between the three states using the buttons on the joystick associated with each of the MRACells. The joystick is also used for navigation within the virtual environment. In addition to moving on the horizontal plane, MRACells can be set to two vertical heights.

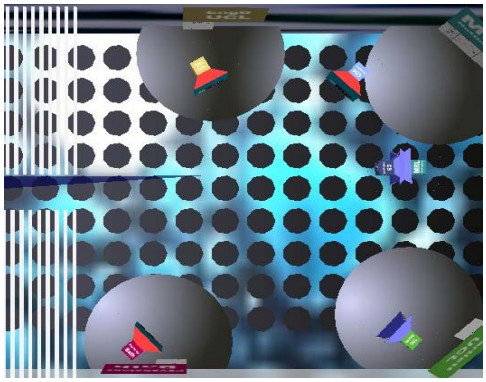


Figure 4 MRA: Map view of virtual space

Using spatialised audio, when two MRACells are virtually close to each other, a live audio connection is opened in an application of the spatial model of interaction [2]. Once the audio ranges (visualised by a circle as shown in Figure 2) of two or more MRACells overlap, audio is transmitted between them. The volume changes according to the distance between the MRACells involved in the interaction. In addition, the video becomes clearer when MRACells get virtually close; simply because it fills more of the available screen space (compare Figure 5 with Figure 6 (left)).

2.3 The interface

The onscreen interface includes a map at the centre top of the screen, which displays the live MRA including all its currently connected MRACells. The video to the right of that displays the view of the inhabitant's own camera. This was added to allow people to position themselves so they were in view and close enough to be seen properly by others. The main part of the interface displays a first person view into the virtual public space of the MRA.

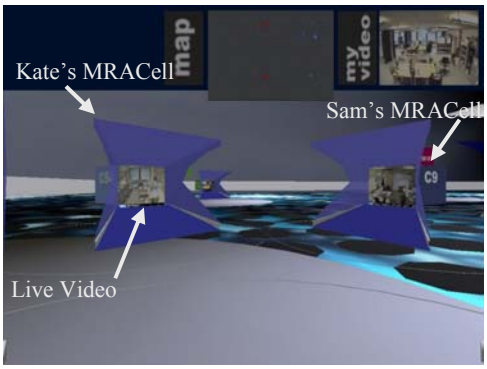


Figure 5 Sarah's view 1

The 3D nature of MRA makes remote social interaction within it legible [16], as a direct result of drawing on principles grounded in (building) architecture. Connections between inhabitants are clearly visible to everyone else, not only on the map but also in the 3D space. Figure 5, showing the view of Sarah into the MRA, can serve as starting point for an example scenario. To speak with Sam in C9 (on the right) Sarah needs to move her MRACell forward, using the joystick, until the two audio ranges (circles on the floor) overlap and the video becomes clear enough, filling a large proportion of the screen (see Figure 6 left). This movement can clearly be observed by Kate in C54 (see Figure 6 right).

Figure 6: Sarah's view 2 into Sam's MRACell (left) and Kate's view (right)

3. DEPLOYMENT OF MRA

The deployment of MRA then followed an iterative prototyping process, in which our goal was to feed back initial results quickly back into the development process [8]. Initially three MRACells were installed in our building on two different floors. This set-up was evaluated for one month A second prototyping stage followed that lasted for three months, for which a fourth MRACell was added on a different floor in our building.

Both phases were evaluated using video recordings, taken through the MRA cameras, in addition to informal interviews. The evaluation provided a valuable early insight into the use of MRA. Social interaction between remote spaces was well supported alongside social interaction continuing to take place in the physical parts of each MRACell. MRA blended in well with other activities and communication technologies. Virtual movement appeared to be an effective means for establishing and controlling links between remote spaces and dealing with privacy issues. The spatialised audio meant that people could stay outside the audio range of others while maintaining visual contact. However, there

were also a number of problems. Initial issues with echo produced by open microphones were overcome with the introduction of echo-cancelling models. Also, at this stage mouse and keyboard were used for navigation and changes in privacy settings. This proved to be ineffective and too slow especially in combination with other interfaces at the workplace (e.g. the phone, desktop PC). The introduction of joysticks allowed inhabitants to navigate while for example picking up the phone. There were other minor changes as well. Overall however, it was felt that MRA was ready for wider and more long-term deployment and analysis.

3.1 Organisations

For our main study, MRA was still set up in our research lab but also with regular collaborators. Without MRA, this collaboration tends to be organised via email, the telephone and of course physical meetings which incurs considerable amounts of travel. Arguably, the above is indicative of many organisations that operate across multiple physical sites.

To gain an understanding of the relationship between patterns of social interaction and the physical locations of collaborators in our environment, a survey was conducted that focussed on informal encounters and social interaction. It was introduced before each of the MRACells had been set up in the various spaces and consisted of two parts. The first part was concerned with existing informal social interaction within the work environments of participants, while the second part investigated social interactions that were not currently taking place, but were deemed desirable for work by participants. Overall 19 people provided full survey answers. Participants were asked to rate up to ten informal encounters that they had experienced on a typical day at their work place. They were also asked to categorise ten people that they considered to have too little informal contact with. In total 175 people were listed and then categorised as being encountered informally at work and 90 people were listed and categorised as being informally encountered too infrequently. The descriptive categories were then concerned with their relative spatial location, the working relationship with them and the type and quality of the existing social interaction.

A full description of the results would go beyond the scope of this paper. However the most relevant outcomes were, may be not surprisingly, that a high proportion of colocated people were not direct work colleagues. Participants who shared their workspace stated that they never worked with around 40% of the people they shared an office with. It was also notable that a high proportion of people who more informal social contact was sought with was physically remote. Well over 50% of the people listed as being met too infrequently were located off site in relation to the respondent. These results show that the type of research setting under investigation here was an ideal test bed for MRA because the spatial set-up only partially mapped the organisational structure. Arguably similar circumstances can be found not only in research settings but in commercial domains where project teams are distributed such as design, architecture and engineering.

3.2 The connected spaces

For the final set-up and study, MRA was expanded to three remote sites. Two main issues helped to guide the placement of MRACells of the original as well as the new MRACells. The main factor was the willingness of its occupants to participate. Secondly, the spaces chosen had to be analysed in terms of their everyday use and possible private and public areas within them had to be identified. This influenced the placement of the Mixed Reality Boundary technology within these spaces. It also affected the choice of camera lens for a suitable field of view, camera placement and orientation. In this context, it was important to check what inhabitants could see from their everyday vantage points and what others might be able to see of them once linked into MRA. What follows, is a description of the six MRACells.

MRL MRACell (a public space) - This is the main meeting room of the Mixed Reality Lab (MRL) at Nottingham, located on the 1st floor of the building. It acts as the main access to the laboratory area and some offices beyond for the rest of the department. Weekly seminars take place here. The office of the project administrator is adjacent to it as is the office of the local system administrator. It is a space that often leads to chance encounters between people during a normal working day.

C9 MRACell (a shared office) - Room C9 is a shared office on the 2nd floor of the northern wing of the building. Sam (all names have been changed) shares this office with a changing group of up to three other people. MRL researchers and students pass by every day resulting in a general awareness of each other.

C54 MRACell (a single-occupancy office) - Room C54 is a single office located on the 2nd floor of the middle wing of the building. Kate, a lecturer in the department, occupies it. Students enter C54 regularly for small group meetings and tutorials.

UCL 1 MRACell (a shared lab space) - The fifth MRACell was installed in a semi-public lab and meeting space at University College London (UCL). It contains a meeting table for the research group as well as the main printer and desk space for around 10 researchers. A small experimental lab is accessible only through this space. As a result of its location and layout, it is a room that often leads to chance encounters between people during a normal working day.

UCL 2 MRACell (a single occupancy office) – This MRACell was installed in 127C, the office of Scott, a lecturer at UCL. Scott's colleagues and students entered 127C regularly to generally catch up and for meetings.

Bath MRACells 4.9 and 1.2a (two single occupancy offices) - Sarah, occupying the fourth local MRACells mentioned for the second prototyping phase, moved to Bath University during the main study. There she occupied two different offices: 4.9 and 1.2a. Both were single occupancy offices. 4.9 was located in a different building to most of Sarah's colleagues and this together with the fact that she was a new colleague, meant that were was relatively little contact. 1.2a was then located much more centrally within the main departmental building.

It is worth outlining the geographical relationship between the six MRACells. The first three were located within the same building. The following two MRACells (UCL 1 + 2) were located in different buildings belonging to the same organisation, which is itself approximately 140 miles from the first organisation The sixth MRACell was located in a third organisation, approximately 150 miles from the first and 120 miles from the second organisation. Clearly, the connected spaces were quite different in character. There were two more public spaces, which were available to quite a large number of people and visitors. There was one shared office with changing occupancy and there were three single occupancy offices.

3.3 Situated observational study

The study of the final situated prototype began in July 2004. The main data collection took place in the following four months. MRA has been operational ever since, interrupted only by Christmas and summer breaks as well as technical issues, such as upgrades to the various networks, for example. At the time of writing this amounted to about 18 months in total. For the study of the final situated prototype, the main method of enquiry was an observational study. Video and audio were recorded via the infrastructure set up for MRA and the six streams were taped on two S-VHS recorders in parallel with the live map. 30 hours of material was indexed and labelled to be able to gain an overview of the material. In addition, using the Record&Replay feature of MASSIVE3 [9], virtual movements, re-orientations and changes of privacy settings were being logged. The playback of these logs then allowed the study of virtual configurations in more detail and from any angle, in contrast to the recorded map, which provided only a single view. From the combination of both sources of material, a series of interactional episodes was documented. These described social interaction in detail, including people's actions in physical and virtual space and the talk between inhabitants across the MRA. There is not enough space here to reproduce the documented episodes, but Figure 7 shows one small excerpt for illustration.

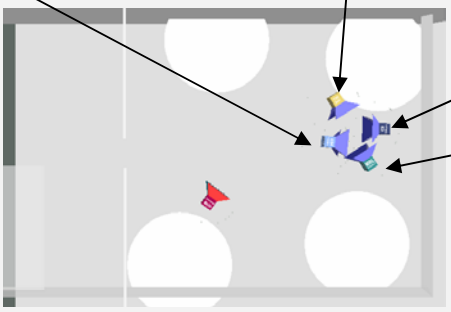
Here, Scott in 127C comes over to talk to people in the C9 MRACell. This episode actively involved four of the six MRACells (one of which being disconnected at this point in time). This excerpt begins with the description of Scott moving his MRACell, followed by a tabular listing of time, rooms and people. A still of each of the video frames is included in the following row. Arrows show the MRACells on the map just below. The lower part includes three lines of conversation, when Scott and Sam greet each other. Actions and events that occurred during conversations appear on the right. Overall, the analysis was then also complemented by keeping in touch with inhabitants of MRA to clarify recorded events and also to collect additional comments.

Scott moves the 127C MRACell slightly closer to the C9 MRACell, but they are still not directly facing each other.

Time	15:34:44			
Room	C54	127C	C9	MRL
People	Kate B	Scott A	Sam H, Gemma A	







Line	Person	Transcript	Actions / Events
10 11 12	Sam H Scott A Sam H	Hello, Scott. Hello. How are you?	Gemma A can be seen taking the C9 phone to her desk in the background

Figure 7 Excerpt of one of the interactional episodes

4. INHABITING MRA

What follows reflects on the use of MRA in our very active and busy research environment. The two earlier prototyping stages gave us confidence that the general approach was sound and that MRA was fully useable on an everyday basis.

The aim now was to understand how people used it as part of their office environment, what they use it for and how it impacted on other people in the organisations. We were also particularly

interested in understanding the relationship between social interaction within MRA and its dynamic architectural topology.

4.1 Purposeful and reactive reconfigurations

There were two overall modes of interaction with the MRA. Inhabitants reconfigured MRA purposefully according to their needs and requirements and this then often triggered others to react to the new situation by reactive reconfigurations. One of the episodes shows Scott reconfiguring MRA to be able to speak to Sam.

Scott approached an existing group of three MRACells with his own 127C MRACell. As there was no virtual space for him to join the group, Sam broke away with the C9 MRACell (see Figure 7). This was on the one hand a purposeful reconfiguration to enable social interaction with Scott, but it was also a reaction to Scott's actions. Kate and Richard reacted to the new situation by pulling their MRACells back from the new group, so they were not disturbed themselves by the audio streaming from these locations. In discussing this point, Kate stated that it was also to provide privacy for the conversation between Sam and Scott that followed.

Beyond this more general point, the material collected for the observational study provides detailed information about people managing awareness, social interaction and privacy. All three will be considered in turn.

4.2 Managing Awareness

Inhabitants were interested to know about the presence and activities of others in the MRA community. Two different episodes provide more concrete examples of how inhabitants made use of this in specific circumstances.

In the first example Gavin made himself aware of what Scott was doing very actively, by moving the MRL MRACell to the 127C MRACell. He then reported back to Sam in the C9 MRACell that Scott appeared to be busy in his office. The fact that Gavin was moving the MRL MRACell was clearly legible to Sam, who interrupted his activity to re-enter a conversation with Gavin.

A second episode included a situation where a meeting between Karl and Sarah had been scheduled for later that morning using the C9 MRACell and the Bath MRACell, respectively. Before it began, Karl explored the MRA environment extensively using the public MRL MRACell. At different points on his route he would have been able to see into the C9 and Bath MRACells, which were intended to be used in the meeting. It appeared that Karl very purposefully made himself aware of the overall state of the environment, the presence of Sarah and the availability of the C9 MRACell, before entering into the meeting. The same episode also shows Sarah strengthening the link between her MRACell and the C9 MRACell in anticipation of the start of the meeting. When Karl entered C9, she was clearly aware of the other space and it was her who started the conversation.

In addition to the observation described above, informal feedback from inhabitants had already indicated that the MRA map was used for the same purpose. It was used to gain information about the overall state of the environmental as well as more specific information about the relationship between different MRACells.

What can be said in summary is that inhabitants made extensive use of MRA's facilities for keeping aware. This extended to being aware of activities in remote physical spaces, to the overall state of the MRA topology as well as the activities within virtual space, for example virtual navigation. Although the above has mainly considered inhabitants' proactive behaviours to reconfigure MRA with the aim of making themselves aware, it is clear that the resulting configuration then allowed them and sometimes others to be more aware passively of the activities within MRA. For example, once one of the MRACells had been moved to be in visual contact with another, both could then be aware of the activities taking place in the other physical space without any further action.

In comparison to many media space approaches as mentioned in the introduction, MRA had a different emphasis. Instead of making everyone aware of everything and everyone else at all times, it allowed its inhabitants to be visually aware of a number of aspects of MRA. As the audio depended on virtual vicinity, it was treated separately from that. In addition, control over awareness was very fine grained as the distances and angles between MRACells could both be modified. There was much more than a simple choice between being connected and not being connected. Overall MRA provided for awareness but made social interaction more occasioned. This is not to say that MRACell did not sometimes remain within audio range for extended periods. When such connections were established, they were then undoubtedly visible to and legible by others, whether that was from within the physical or virtual spatial frameworks. This legibility then directly supported others' decisions in terms of whether to contact a particular person for example. It might also have another effect as Dourish et al have indicated in the context of their media space research. They point out that the visibility of such connections can be read by others as an affirmation of personal and professional relationships[5].

4.3 Managing Social Interaction across MRA

Although awareness was of course an important factor, MRA was designed to allow inhabitants to establish and maintain verbal social interaction across it. The following will consider certain aspects of this interaction.

People often used MRA simply to greet each other. This sometimes took the form of waving but also of calling across. For the former the video textures of at least two MRACells needed to be in view of each other, although this could be in the distance. For the latter, two MRACells needed to be in audio range already, which was also the case for more prolonged conversations. The material recorded showed that conversations ranged widely in terms of topic. Work related and non-work related matters were part of most conversations. Issues like collaborative paper writing, the organisation of conferences and establishment of new projects were discussed, while the latest departmental gossip, activities over the last weekend and holiday plans also featured. Often, future activities were discussed and agreed on. The activities were planned for physical space (i.e. a face-to-face meeting), a different communication channel (i.e. Email) or indeed MRA itself for a later time. One of the recorded episodes can demonstrate this.

When Karl (in the C9 MRACell) and Sarah (in the Bath MRACell) discussed the progress of Karl's PhD during a scheduled meeting over MRA, he brought paper copies of some graphs that detailed results from one of his studies. He referred to these during the conversation and Karl and Sarah then agreed the exchange of these via email for further discussion at

a meeting that they intended to have over MRA at a later stage. However, this second MRA meeting was replaced by a conversation on the phone, during which the graphs that had arrived in the mean time were discussed.

The above shows how different activities (e.g. document exchange, future meetings) were achieved across MRA in tight coupling with other communication channels like Email and the telephone. In addition, what emerged from the study was that there were very different ways of initiating conversations within MRA. These will be considered in turn below.

4.3.1 Arranged Meetings

There were occasions where meetings had been prearranged. One of the examples, already referred to in the previous section, describes such an event.

Karl, Rico and Sarah had agreed to have a PhD tutorial in the MRA. Karl and Rico were not permanent inhabitants of an MRACell and had arranged to use the C9 MRACell instead at a specific time just after the weekly seminar at the MRL, while Sarah was using her Bath MRACell. As Rico was not available, the meeting proceeded without him.

4.3.2 Taking the initiative

Most conversations resulted from one inhabitant taking the initiative to speak to another. Often inhabitants left their MRACells in a place that allowed a view of the environment but was not close enough to another MRACell to allow conversations to take place. This resulted in at least one of the inhabitants having to move their MRACell closer to another, if they wanted to talk to somebody. Once the conversation had ended, the MRA was reconfigured again. Both parties pulled backwards, keeping the other party in view. This appeared to be a result of the interface used: the joystick interface allowed backwards movements just as easily as forwards movements. This also allowed inhabitants to see where the other MRACell was being moved to and whether they had actually left their audio range. However, a side effect was that when pulling backwards, inhabitants often did not see that they might affect the privacy of another MRACell that was behind them, which occasionally triggered a secondary reconfiguration.

4.3.3 Chance encounters

Chance encounters were also relatively frequent. In contrast to the interaction in other online communities, chance encounters did not tend to occur in virtual space, i.e. by navigating virtually with an MRACell. These could occur if two or more MRACells were moved at the same time, and through this movement people navigating their MRACells encountered each other in virtual space. The recorded material does not suggest that this type of chance encounter took place. In this sense the promise of designing MRACells to be mobile architectural interfaces was not entirely fulfilled. It is likely that the relatively low number of MRACells contributed to the fact that chance encounters during reconfiguration were not frequent. In addition, the virtual public space of MRA was not really used for frequent and extensive navigation. While clearly dynamic, it proved to be relatively stable in the sense that configuration often lasted for a number of hours, until someone initiated contact with another MRACell for example. Virtual space was the spatial framework that allowed flexible and legible connections between remote spaces to be established.

Chance encounters in MRA were much more the result of inhabitants or visitors passing physically through an MRACell already connected to another. The following example can illuminate this.

Sam in the C9 MRACell got into contact with Gavin passing through the MRL MRACell. As Gavin entered the MRL foyer, Sam spotted him and initiated a conversation. By walking through the public MRL foyer, Gavin made himself available for contact and this was made use of by Sam. Although Gavin was being interrupted on his way to the main lab space, he did enter into the conversation.

The above interaction was made possible by the previously established configuration of two MRACells, which had been initiated by Sam before anyone was in view in the MRL foyer. The positioning of the C9 MRACell in such a way allowed Sam to be aware of events in the other space and this was then made use of to initiate the interaction. As the two MRACells were virtually close by, the video was clearly visible and audio was being transmitted. For example, it was clearly audible that somebody opened the main door and then entered the room.

This interaction is also noteworthy because a private MRACell (C9) and a public MRACell (MRL) were involved. Relatively few interactions (in comparison to other MRACells) were recorded at the MRL, being mostly a circulation space. During one 3 hour period, 65 instances were counted of someone passing through this space and it was clear that people did not tend to spend much time there, unless it was for one of the scheduled meetings around the meeting table. Also, the MRL did not belong to anyone in particular, which meant that others connected to it across the MRA could not generally know who they might bump into. However, as the above example demonstrated, chance encounters could take place here, although relatively infrequently, as was evident from other data collected.

In summary, chance encounters in MRA were dependent on the pre-existing topology and the fact that people were physically moving through it. This topology might have been the result of a planned reconfiguration, for example when two MRACells were brought close together for a specific purpose and then left there. The topology might also have emerged over a longer period with many individual decisions leading to a configuration that brought at least two MRACells into proximity. When such a topology existed, chance encounters between people could occur, when they passed through the physical part of the connected MRACells. If such a topology did not pre-exist, planned reconfiguration was necessary to establish social interaction. Finally, chance encounters across MRA occurred in parallel to those that took place within the physical parts of the MRA topology, and one could lead to another.

4.4 Managing Privacy

A further reason for reconfigurations and more general interactions with MRA was the need to deal with privacy. As outlined previously, each of the MRACells was embedded in two separate public spatial topologies: virtual public space and physical public space. To maintain control over privacy in their MRACells, inhabitants had to manage access from both of these. In physical space this took place through the opening or closing of doors or window blinds, for example. How this could become a resource even for those accessing a space from its virtual end is

demonstrated in one of the interactional episodes, where Fred and Sarah concluded that Sam must be around as the physical door to the C9 MRACell could be seen open (for security physical doors tend to be locked, when offices are not occupied). There was also access to MRACells via the telephone for example. This could be controlled through the volume of ring tones or the use of answering machines, but this is not the subject of discussion here.

From the outset MRA was designed to allow inhabitants the management of privacy in a very similar fashion to physical space. Privacy was configured in two ways. Firstly the virtual position of an MRACell controlled how much others could see and hear of it, and secondly the state of its privacy settings (open, semi-private or private) controlled the visual access to its physical side in a more deliberate way, and this was designed to be similar to physical building architecture. Both of these were visually available to all others present in virtual space and the recorded material shows that both were used, but to different extents.

4.4.1 Virtual position

There were two overall motivations for MRA to be reconfigured for privacy reasons. Inhabitants changed the MRA topology so as not to be disturbed themselves and they changed it to avoid disturbing others. An example of the first motivation has already been explored in section 4.1. Here Kate and Richard reacted to a conversation starting in their audio range by pulling away with their MRACells. Regarding the second motivation there were a number of occasions where inhabitants avoided disturbing others. Inhabitants increased the distance between their cell and that of others when somebody entered for a meeting, for example. While welcoming the visitor(s) into their physical space, they would often grab the joystick and move to a different part of the environment, resulting in others not being able to overhear their meeting. Inhabitants also sometimes moved away just before making a phone call again resulting in nobody virtually present being able to overhear their conversation. One instance was observed during which two office MRACells were located near the public MRACell in the MRL meeting room. When one of the inhabitants realised that they might disturb the gathering going on in the meeting room they suggested to the other inhabitant that they should relocate to a different part of the MRA. Both MRACells were moved away together by their inhabitants, where the conversation was picked up again at a 'safe' distance.

4.4.2 Privacy settings

The buttons on the joystick allowed each of the MRACells to be set to open, semi-closed and closed (see Figure 5). Of the three states, the semi-closed state was used least frequently. The recorded logs show that none of the MRACells was set to this state for more than 5% of the overall time. Inhabitants seemed to prefer to indicate only that they were in and available or that they were unavailable, whether being present in the (physical part of the MRACell) or not. It might simply have been too awkward to keep switching settings constantly. One inhabitant reported that she found using the keyboard (keys a,b,c) easier to use than the joystick, which meant that she could switch directly between open and closed without going through the intermediate step, which was required with the joystick.

For the remaining two settings, two overall strategies of use could be identified. There were those MRACells that were open for at least 50% of the time. These were the C9, MRL, C54 and Bartlett MRACells. The first two of these were open considerably longer, this was most likely the result of the author controlling the privacy settings on both of these and using them for testing as well as interaction for some of the study period. Regardless of this, these four MRACells were available to others for a substantial proportion of time and their inhabitants appeared to feel comfortable with this. The inhabitants of the 127C and Bath MRACell seemed to employ a different strategy, where they kept their MRACells closed for the majority of the time to make the physical side of their MRACells private. Sarah in particular seemed to open her MRACell for periods of actual verbal social interaction, while keeping it closed during other times.

Setting an MRACell to private not only provided privacy to its inhabitants, but also made them unavailable for others to interact with. Sarah and Scott were only available to others for ~23% and ~32% of the time respectively and this clearly affected how often others could have encountered them. Finally, ignoring what had been set by an inhabitant and transgressing the privacy setting was rare and not regarded as acceptable. This was confirmed by inhabitants in informal interviews but also in one particular interactional episode where one inhabitant complained about another inhabitant simply moving through the virtual door.

4.4.3 Privacy concerns

Concerns about privacy also led to inhabitants and visitors not using MRA in certain instances. There were two areas of concern, one about recording information during the evaluation periods and the second about not wanting to be in camera view at all.

Inhabitants were alerted to the times of recording in advance and their consent was ensured. Visitors were alerted by signs displayed on the entrances to the various spaces and by inhabitants themselves, who were asked to tell visitors about the presence of MRA. However, (at least) one inhabitant was concerned about the information that might be recorded. During one of the recorded examples, Sarah mentioned that she would wait until the recording had stopped, so that she could phone her bank. What Sarah could not have been aware of is that conversations on the phone were not picked up by MRA anyway as the microphone tended to be too far away. Following this, Sarah also asked for parts of a previous interaction to be deleted from the recording, or at least not used in the analysis.

There was also a small number of people who avoided being in camera view, if possible. These were typically visitors to the connected spaces and there were a number of instances were one visitor to Sarah's office would not enter the room when MRA was up and running, asking for meetings to be conducted elsewhere. Equally, one member of staff at the UCL1 MRACell, whose office was located on a different floor from the MRA installation, was very concerned about the installation. One instance was recorded where a person walked through the Bartlett MRACell holding a sheet of A4 paper in front of their face, presumable to conceal their identity. Informal feedback from the people concerned pointed to the fact that these anxieties were at least partly due to the fact that MRA displayed a mirror image of the space it was placed in. This meant that people who entered any of the MRACells would see an image of themselves, which some people were uncomfortable with. At the same time, this feature was clearly very useful to the majority of the inhabitants of MRA. Overall, strong privacy concerns were confined to a small minority of people who came in contact with MRA, and previous

research has reported on similar problems especially for installations in public places (Jancke, et al, 2001). Installations in private and semi-private spaces, for example single offices and small shared offices, are therefore preferable. There, the anxieties of some can be managed on an individual basis by the inhabitant(s), as was observed at the Bath MRACell.

5. ARCHITECTURAL TOPOLOGY

Due to its grounding in Building Architecture but also in response to Dourish et al's finding that media space technologies do not just link individuals [5], one of the core design decisions for MRA was the emphasis on connecting spaces rather than individuals. This was reflected in the design of the interface for the MRACells. It was publicly available for everyone to use. Additionally, the set-up in semi-public spaces reinforced this point. Overall, this resulted in the group of inhabitants being relatively large. The observational study then showed that inhabitants of MRA fell into different categories. Hillier describes inhabitants of physical architectural cell according to their status, which is differentiated by access to and control over space [12]. We have taken this as inspiration for the following categorisation:

Core inhabitants - A core inhabitant was that person for each MRACell who had the most contact with MRA. This was easy to define for the private offices C54, 4.9/1.2a and 127C where Kate, Sarah and Scott were the sole occupants and therefore the main users of the respective MRACell. A core inhabitant also existed for the shared C9 MRACell. The first author was the main user of the MRA technology in C9, although others were also permanently located there.

Permanent inhabitants - A second group consisted of those people whose main work space was in one of the MRACells, but who were not the main users of MRA. This applied to a rather large group of people whose membership changed over time as people moved in and out of the MRA topology. This category also applied to people in the more public spaces. In case of the public Bartlett MRACell, there were nine people located permanently inside the physical part of the MRACell, with a number of others located in the surrounding offices, who did also occasionally make use of MRA. The public MRL MRACell did not have permanent inhabitants and the people in the adjoining offices did not take up using the interface. Neither of the two public MRACells had core inhabitants who used the MRA frequently.

Visitors - The final category comprised all visitors to the MRA topology, simply meaning that their work space was not located in an MRACell. Sometimes visitors were located very close by, as for example next door to one of the MRACells. In this case, they could have gathered some experience with MRA over time. Other visitors might only come into contact with MRA once during a visit to one of the labs and they would not have gained any experience with MRA themselves but instead would have been shown around by others.

5.1 Roles of different groups

These three different groups exerted very different levels of control over the topology of MRA and privacy settings. One of the interactional episodes can serve as an example. It details a series of interactions taking place within MRA that are all the result of Sarah in the Bath MRACell attempting to find Sam, first in the C9 MRACell and then in the MRL MRACell.

During the interaction, the core inhabitant Sarah did most of the reconfiguration of the topology. The core inhabitant Sam and the permanent inhabitant Gemma mostly reacted to the initiative taken by Sarah but also directly influenced the MRA topology themselves by moving the C9 MRACell and the MRL MRACell, respectively. In contrast, the visitors involved in this series of interactions took no direct role in navigation. This applied to Eric coming into C9 to find one of its inhabitants, Marcus observing an interaction in the MRL MRACell, Gerald simply passing through that same cell and Maria being involved in a discussion with Sarah. The visitors' use of MRA was opportunistic and was mostly organised around the pre-existing topological structure as set by inhabitants.

This is not to say that visitors could not reconfigure MRA. The public MRL MRACell for example could be moved with the joystick that was prominently located in front of it. However, the recorded material showed that reconfigurations by visitors were comparatively rare.

In summary, it can be said that core inhabitants of MRA took control of the MRA topology, with permanent inhabitants having some influence as well. Just as core inhabitants would decide whether their office door was open or closed, they would open or close the virtual side of their MRACell, making them and everyone else in the office available for interaction. The fact that an office was available and that the connection to other connected spaces was available was then visible from physical space and from virtual space, which is a direct effect of the design of the Mixed Reality Architectural Cell. In addition to the privacy settings, core inhabitants then also took the main control over where they virtually moved their offices. Clearly there is no equivalent for this in physical buildings, as changing the topology of a building is too slow and costly to be considered as a short-term solution. Overall the topology was an 'unintentional' result of the individual decisions of inhabitants. It emerged but also kept changing over time There was no outside influence to establish 'suitable' configurations. Therefore a decision to move one of the MRACells to a certain virtual position might well block the view of another, which was not even involved in the interaction. However, just like the privacy settings, the current MRA topology was available to see for everyone, whether this was from physical space or from virtual space. Both the above, privacy settings and MRA topology then impacted directly on the possible encounters within MRA, between and among the different groups of people using MRA.

5.2 Topology and social life within MRA

It has already been discussed how social interaction shaped the dynamic topology of MRA. It was also clear that the resulting topology then affected social interaction, one example being chance encounters as introduced in section 4.3.3. In fact we would argue that social interaction within MRA and its dynamic architectural topology were inextricably intertwined.

Inhabitants did not separate interacting across MRA from interacting with others in physical space. Social interaction took place across the whole MRA topology, where it moved relatively seamlessly between physical and virtual spaces and where the topology was continuously adjusted to suit the individual requirements of its inhabitants. This was because the MRA topology itself was embedded within the general physical topology of everyday social interaction that people occupied and

moved through. Social interaction could occur exclusively in physical space, for example in a single MRACell. It could occur across two physical spaces remote from each other, either linked by MRA or by another communication technology like the telephone for example. Multiple interactions could also occur within the virtual space of MRA itself. Inhabitants managed these by separating them in time, in space, or simply by letting them continue in parallel with each other. They appeared to have no problems moving between those activities whether they were local or remote across the MRA or indeed across a different communication technology.

Episodes of social interaction within 'reach' of any one of the MRACells can therefore not really be separated into those that happen within physical space and those that happen in MRA. The above then leads to the understanding that social interaction within MRA and its dynamic architectural topology are linked in a fundamental way: social interaction drives its reconfiguration and the resulting topology in turn influences social interaction.

6. CONCLUSIONS

In this paper we have reported on Mixed Reality Architecture, linking multiple and diverse physical spaces across a shared virtual environment. This novel approach introduced the concept of virtually mobile Mixed Reality Architectural Cells, permanently linking one physical space with one virtual space, which has been inspired by principles found in building architecture. We have outlined aspects of the design and deployment of MRA within a busy office environment. Our long-term observational study has demonstrated that MRA works well and unobtrusively in a real world setting. It supports distributed small to medium-sized teams by allowing them to manage awareness, social interaction and privacy. The architectural elements introduced for this purpose make managing the above smooth but also legible within the extended Mixed Reality space. It has been shown how different groups of inhabitants take on different roles, based on their ownership of spatial cells, in a very similar way to physical buildings. Overall the study demonstrated that the dynamic architectural topology and social life within it are fundamentally interlinked and it is felt that MRA or an approach that is built on similar principles will be applicable in many different domains, where teams are distributed across different sites, such as design, architecture and engineering.

7. ACKNOWLEDGMENTS

We thank the EPSRC for their support through the EQUATOR project [GR-N-15986] and all the inhabitants of MRA.

8. REFERENCES

[1] Allen, T.J. *Managing the flow of technology : technology transfer and the dissemination of technological information within the R&D organization*. MIT Press], [Cambridge, Mass., 1977.

[2] Benford, S. and Fahlén, L., A Spatial Model for Interaction in Large Virtual Environments. *In Proceedings of ECSCW*, (Milano, Italy, 1993), Kluwer, 109-124.

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

[4] Brand, S. *How buildings learn : what happens after they're built*. Viking, London, UK; New York, USA, 1994.

[5] Dourish, P., Adler, A., Bellotti, V. and Henderson, A. Your place or mine? Learning from long-term use of audio-video communication. *CSCW*, *5* (1). 33 - 62.

[6] Dourish, P. and Bly, S., Portholes: Supporting Awareness in a Distributed Work Group. *In Proceedings of CHI*, (Monterrey, USA, 1992), ACM Press, 541-547.

[7] Fish, R.S., Kraut, R.E., Root, R.W. and Rice, R.E. Video as a Technology for Informal Communication *Communications of the ACM*, 1993, 48-61.

[8] Floyd, C. A Systematic Look at Prototyping. in Budde, R. ed. *Approaches to Prototyping*, Springer, New York, USA, 1984, 1-18.

[9] Greenhalgh, C., Purbrick, J., Benford, S., Craven, M., Drozd, A. and Taylor, I., Temporal Links: Recording and Replaying Virtual Environments. *In Proceedings of Multimedia*, (Los Angeles, USA, 2000), ACM Press, 67-74.

[10] Greenhalgh, C., Purbrick, J. and Snowdon, D., Inside MASSIVE-3: Flexible Support for Data Consistency and World Structuring. *In Proceedings of CVE*, (San Francisco, USA, 2000), ACM Press, 119-127.

[11] Han, J. and Smith, B., CU-SeeMe VR immersive desktop teleconferencing. *In Proceedings of Multimedia*, (Boston, USA, 1996), ACM Press, 199 - 207.

[12] Hillier, B. and Hanson, J. *The social logic of space*. Cambridge University Press, Cambridge, UK, 1984.

[13] Ichikawa, Y., Okada, K.-i., Jeong, G., Tanaka, S. and Matsushita, Y., MAJIC Videoconferencing System: Experiments, Evaluation and Improvement. *In Proceedings of ECSCW*, (Stockholm, Sweden, 1995), Kluwer Academic Publishing, Dordrecht, Boston, London, 279-292.

[14] Jancke, G., Venolia, G.D., Grudin, J., Cadiz, J. and Gupta, A., Linking public spaces: technical and social issues. *In Proceedings of CHI*, (Seattle, USA, 2001), ACM Press, 530-537.

[15] Koleva, B., Schnädelbach, H., Benford, S. and Greenhalgh, C., Experiencing a Presentation through a Mixed Reality Boundary. *In Proceedings of Group*, (Boulder, USA, 2001), ACM Press, 71-80.

[16] Mitchell, W. *City of bits : space, place, and the infobahn*. MIT Press, Cambridge [Mass.], USA; London, UK, 1995.

[17] Nakanishi, H., Yoshida, C., Nishimura, T. and Ishida., T., FreeWalk: Supporting Casual Meetings in a Network. *In Proceedings of CSCW*, (Boston, USA, 1996), ACM Press, 308-314.

[18] Novak, M. Transmitting Architecture. in Maggie, T. ed. *Architects in cyberspace*, Academy Editions, London, UK, 1995, 43-47.

[19] Penn, A., Desyllas, J. and Vaughan, L. The space of innovation: interaction and communication in the work environment. *Environment and Planning B*, *26* (2). 193-218.

[20] Price, C. *The Square Book*. Wiley&Sons, Chichester, UK, 2003.

[21] Reynard, G. A Framework for Awareness Driven Video Quality of Service in Collaborative Virtual Environments *Computer Science*, University of Nottingham, Nottingham, UK, 1998, 284.

[22] Sellen, A., Buxton, W. and Arnott, J., Using spatial cues to improve videoconferencing. *In Proceedings of CHI*, (Monterey, USA, 1992), ACM Press, 651 - 652.

[23] Zellner, P. *Hybrid space : new forms in digital architecture*. Thames & Hudson, London, 1999.