MUTUALLY AUGMENTED VIRTUAL ENVIRONMENTS FOR ARCHITECTURAL DESIGN AND COLLABORATION

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Abstract. Augmented Reality (AR) augments real environment by means of virtual objects and Augmented Virtuality (AV) augments virtual environment with the insertion of real entities. Current AR and AV systems exist independently. This paper proposes a novel concept – Mutual Augmentation (MA) where AR and AV co-exist to form a seamlessly integrated mega-space by sharing certain real/virtual entity. This paper presents a systematic framework of exploring MA for supporting collaboration, communication, and coordination in architectural design beyond traditional single real/virtual space. It also opens up a key direction for future research into Collaborative Virtual Environments, AR and AV.

1. Introduction

Over the past decade, there has been a growing research interest and efforts in investigating techniques to combine real and virtual spaces. Various techniques have been investigated including Augmented Reality, Augmented Virtuality, Mixed Reality boundaries, etc. Milgram et al. (1999) presented a Reality-Virtuality (RV) continuum as shown in Figure 1 to describe the distinctions of those techniques. As a more enveloping term, Mixed Reality (MR) could create spatial environments where participants can interact with real and virtual entities in an integrated way (Milgram and Kishino 1994). Mixed Reality may also be shared and enable distributed people across multiple physical and virtual spaces to communicate with one another (Benford et al. 1998).

As a major sub-mode of Mixed Reality, Augmented Reality (AR) overlays virtual information onto a real world scene as if the virtual information is attached to physical objects (see the left example in Figure 2). In contrast, Augmented Virtuality (AV) (Milgram and Kishino 1994) takes a virtual world as its starting point and then embeds representations of real objects within this (see the right example in Figure 2). It is imperative to
clarify the terms “real” and “virtual” entities/spaces. The real entity, either the augmented real environment in AR or augmenting real content in AV, refers to ones which the computer does not possess, or does not attribute meaning (Milgram et al. 1999). Real entity therefore could encompass any kind of sampled image data, and include photographic images (visible or infrared), image of real documents, real-time video, telemetry data, radar, X-ray and ultrasound, as well as laser scanned data (2D and 3D both range and light intensity data). In Augmented Reality, for instance, the real world scene could be either the local environment with the virtual information overlaid via an optical see-through head-mounted display, or a remote video scene augmented with virtual information. Likewise, the real entities in Augmented Virtuality might take the form of textured video views, such as real video views of human’s face on his/her virtual avatar (Nakanishi et al. 1996), or views of remote physical locations (Reynard et al. 1998). Alternatively, telemetry data captured by remote physical sensors should also regarded as real entities, which could be visualized using graphics, text and audio, considering that computer does not hold any knowledge about the data. Likewise, the virtual entity, either the augmented virtual environment in AV or augmenting virtual content in AR, refers to ones which the computer does possess, or does attribute meaning. Virtual environments must consist of virtual entities in order to be rendered, and real environments must be representations of a real world, or region, involving only real entities.

![Diagram](image)

*Figure 1. Definition of Mixed Reality within the context of Reality-Virtuality (RV) continuum (Milgram et al. 1999)*

There are only two illustrations (Augmented Reality and Augmented Virtuality) which purposely emphasise the major distinctions between fundamentally opposing RV mixtures (Milgram et al. 1999), because it is obvious in these two terms whether the primary environment or substratum is real or virtual. There could be many other modes apart from distinct AR and AV along the RV continuum. A thorough observation of AR and AV systems reveals that either AR or AV exists individually. It is possible that the very real environment which is augmented in an AR space could
meanwhile augment another virtual environment to create a resulting AV space. Likewise, the very virtual environment that is augmented in an AV space could augment a real environment and thus create an AR space. Thus, more modes along RV continuum might be possible and feasible. It is therefore argued that a more enveloping term becomes necessary, to encompass all modes between the extremes of the RV continuum. This paper develops a novel concept — Mutual Augmentation (MA) where real and virtual entities mutually augment each other, forming different augmented cells/spaces. In Mutual Augmentation, AR and AV could actually co-exist together to form a seamlessly integrated mega-space by sharing certain real/virtual entity. Mega-space is actually an environment formed by interweaving/inter-augmenting real and virtual spaces together. This concept puts equal weight onto real and virtual environments, considering how each can be accessed from the other. This paper presents a systematic framework of exploring Mutual Augmentation and applying this concept to support collaboration, communication, and coordination of architectural design beyond single real/virtual space.

Figure 2. Examples: (a) Augmented Reality system (Wang et al. 2005); (b) Augmented Virtuality system (Regenbrecht et al. 2004)

The concept of structured MA mega-space also opens up a key direction for future research into collaborative virtual environments (CVEs), AR and AV. This paper seeks to investigate how the concept of Mutual Augmentation could be integrated into the traditional CVEs concepts and development to improve the practice of designing in virtual environments. Next section presents the MA Topology and explains the MA concept through case illustrations in architectural design. The third section presents the fundamental properties of RV interfaces in MA.
2. Recursive Hierarchical Mutual Augmentation Construction

This part investigates the alternatives of spatial topology which spans real and virtual spaces in a structured MA mega-space. Cases in architectural design/collaboration are exemplified and discussed for certain selected topologies.

2.1. HIERARCHICAL TREE

This section introduces the notion of the Mutual Augmentation construction, providing motivation for the subsequent more theoretical treatment. Figure 3 provides a simplified example of what a hierarchical representation of Mutual Augmentation construction might look like. There are two ways of adding spaces: Real (R) and Virtual (V), which could also be added together. MA hierarchical tree construction mainly consists of three legends: real subspace (solid line), virtual subspace (dashed line), and formed space/node (black dot). Each node represents a specific formed mega-space.

The tree hierarchy that is generated by the recursive application of a simple set of Mutual Augmentation rules could yield combinations with properties that strongly reflect their recursive hierarchical construction. Noting that the first mega-space may be conveniently represented by the node of a rooted tree (starting from a void space) as illustrated as “0” in Figure 3. The second level of mega-space is formed by adding subspaces (either real or virtual) onto the above mega-space. Therefore, the rule is set as: the subsequent mega-space at the immediately lower level is formed by superimposing the relevant real and/or virtual subspace onto the mega-space at the immediately higher level. The rule can be applied repeatedly for \( i = 1, 2, 3 \ldots, n \) times starting from a void space “0”, and using the mega-space from a previous node as the starting point for the next node. For example, the mega-space on the bottom of the hierarchy in Figure 3 could be as complicated as VRVRRVVRVVR, which has five real spaces and five virtual spaces interweaved and inter-overlaid and inter-augmented with each other. Not each node inside the tree could be matched to a counterpart of a realistic application scenario in architectural design, but might matter in future as technology advances.

It is possible that the very real space which is augmented in an AR space could meanwhile augment another virtual space to create a resulting AV space. Likewise, the very virtual space that is augmented in an AV space could augment a real space and thus create an AR space. Therefore each intermediate node in the hierarchical tree actually augments its immediately higher-level node and meanwhile is augmented by its immediately lower level node(s). For example, in the case of node “a” (RV) in Figure 3, it augments the node “c” (R) with a virtual subspace represented by a dashed line and are augmented by “g” (RVR) with a real subspace and by “h” (RVV) with a virtual subspace.
The real extreme in the RV continuum in Figure 1 actually could be represented by node “c” (R) in the Figure 3. Likewise, the other extreme which is virtual environment, corresponds to the node “d” (V) in the Figure 3. The AR example (Wang et al. 2005) shown in Figure 2 actually corresponds to the node “a” (RV) in the Figure 3 because a virtual mechanical design is inserted into the designers’ common real working/viewing environment. The AV example (Regenbrecht et al. 2004) in Figure 2, actually fits to the case of node “b” + “e” (VR+VV) on the same level, but under the same previous mega-space because there are two types of subspaces inserted into the base environment “d”: real video image of remote collaborators for node “b” (VR) and virtual car product design for node “e” (VV).

Two segmented spaces in two independent/individual mega-spaces could also metaphorically augment with each other although they are not structurally located along one path in the recursive hierarchical MA construction. A spatially segmented interface links the two spaces through multiple non-adjacent segments (these can themselves be property segmented). For example, the real design documents and experts of a specialty service (real entities in one mega-space) in one project could be borrowed into another project (virtual environment in another mega-space).
by texture-mapping them into the appropriate positions in the virtual design environment with appropriate format (e.g., experts as videoconferencing; real design documents as real images). Theoretically reflected in the recursive hierarchical MA construction in Figure 3, for instance, the virtual space in the node “h” (RVV) could augment the real space in the node “i” (VRR), forming another resulting Augmented Reality mega-space. As explained above, the hierarchical tree representing a recursive MA construction could be much topologically complicated and involve much inter-augmentation among any nodes inside the tree.

In the following subsection, one case is illustrated to demonstrate why this hierarchy is potentially interesting and thus motivates more theoretical investigation. By introducing MA into collaborative virtual environments across real and virtual spaces, the resulting mega-space could support architectural designers’ social interaction and convert digital communication media from being socially conservative to a more generative and familiar form as in real space.

2.2. CASE ILLUSTRATION IN ARCHITECTURAL DESIGN

Based upon Milgram’s exploration of the Reality-Virtuality continuum (Milgram et al. 1999), an MA continuum is formulated from certain nodes identified from Figure 3. The MA continuum spans from a completely real space (mode “c”) and a completely virtual one (mode “d”).

2.2.1. Mutual Augmentation Continuum

A simplified case of MA continuum is illustrated in Figure 4 by allowing only one real and/or one virtual space registered into a predominantly real or virtual substratum space (e.g., mode “a”), to schematically demonstrate a selection of scene composites that could be encountered when one play with combining real and virtual spaces. At a global level, Figure 4 corresponds to the RV continuum along which any number of virtual and real spaces could exist. Furthermore, each mode in this simplified case could find a corresponding counterpart in the hierarchical tree in Figure 5 with the same representation letter. In terms of earlier examples, for instance, the AR example in Figure 2 could be considered to correspond to the mode “a” in Figure 4, in the sense that it has a predominantly real environment as substratum with a few virtual objects superimposed. The AV example in Figure 2, furthermore, would correspond to the mode “b+e”, for analogous reasons.
From Figure 4, it is also shown that real and virtual spaces can “flow” into each other recursively (Milgram et al. 1999). Another important aspect of the schematic representation of Figure 4 is the essentially trajectory nature of the MA continuum. Figure 4 illustrates that there are mainly five interesting trajectories along the transverse between the modes “c” and “d”: two self-trajectories “A” (real-to-real: “c” → “a+f” → “f” → “m” → “c”) and “E” (virtual-to-virtual: “d” → “b+e” → “e” → “n” → “d”), and three in-between trajectories “B” (“c” → “a+f” → “a” → “g+h” → “b” → “i+j” → “c”), “C” (“d” → “b+e” → “b” → “i+j” → “a” → “g+h” → “d”), and “D” (“c” → “a+f” → “a” → “g+h” → “d” → “b+e” → “b” → “i+j” → “c”). As illustrated in the self-trajectory “A” and “E”, we turn the next
doorway into a virtual portal from the mode “b+e”, depicting an adjoining virtual presentation bulletin board. Alternatively, we could turn to a real portal by following the in-between trajectory “B” or “D”. Likewise applies in three trajectories diverging from mode “c” (for trajectory “A”, “C”, and “D”). Clearly, it is possible to continue in this manner, enter completely into the virtual space in the mode “a+f”, and thus traverses the trajectory “C” or “D” to get back to real space “c”. Eventually along the two self- trajectories, if the entire visible image, or view port, consisted of virtual/real objects, one could argue that we had arrived (returned) at the completely virtual/real case of mode “c” and “d” again.

Figure 5. The recursive hierarchy of the case illustration

2.2.2. Case Illustration in the Context of Design
Now, we begin to use a case illustration to verify how the MA concept is applied in the context of architectural design collaboration. In the following we present an analogous case to concretely demonstrate the power of transitions in Figure 4. What we shall do is to illustrate what a journey along the MA continuum might look like, as we travel along some trajectories in Figure 4. The point of departure is mode “d”, which shows a completely virtual residential area to give me an overall sense of the layout of houses that are proposed to be built. It is assumed that I, the actor of the journey, am the chief architect of this area. To continue the journey, we purposely insert a real space (video of a remote house designer attached to a virtual avatar standing in front of a house) and a virtual one (a design information and
documents presentation bulletin) into the virtual residential area, thus forming the mode “b+e”. The virtual space could expand and eventually end up with another completely virtual space back to the mode “e”. If I choose the self-trajectory “E” by stepping into another virtual space, then I will be involved into a virtual presentation board for discussion of issues such as urban planning and environmental regulations or other rules. If I select the in-between trajectory “B or “D”, then I could communicate with the remote house designer whose appearance is displayed as a real-time video appearance texture mapped to the virtual avatar standing in front of a specific house of interests for further inspection as shown in the mode “b”. Thus an AV scene has been created with the virtual space as the registration base for the real entities upon it. As I approach the real portal framed by the video window by zooming in, the composite image becomes proportionately more real and less virtual. Finally, as I advance all the way through the real portal, in the mode “b”, I enter into real environment/real video (mode “i”). It is not the end and as illustrated in Figure 4, if I look in further, it is found that a virtual house is superimposed onto the hand of the designer in the video (mode “j”), thus an AR scene has been created with the real video screen as the registration base for the virtual entities upon it. Next, I could choose from the mode “i+j” to continue talking with the designer only by following the trajectory “D” and then reaching the mode “c”. Alternatively, as I approach the virtual house by zooming in, the composite image becomes proportionately more real and less virtual. Finally, I could advance all the way and “step” into the video and click the door of the virtual house and virtually entering the completely virtual house. For that, I am actually following the trajectory “B” and reach the mode “a” as the next step. Inside the virtual house as illustrated in the mode “g+h”, I encounter two choices again: one is to look at the digital design specification on the virtual display desk (follows trajectory “D” and ends at the mode “d”; be occupied into another virtual space) and the other one is to choose the real wallpaper samples represented by the real photos stored in remote supplier’s repository (follows trajectory “C” and reach the mode “b” again). Real images of wallpapers can be captured in real-time and texture-mapped onto the virtual walls to decorate it with much of the richness of the real world. Theoretically, the story could continue indefinitely along the MA continuum and reach the necessary stop mode.

3. Fundamental Properties in RV Interfaces

The concept of Mutually Augmentation connects distinct real and virtual spaces by creating bi-directional RV interfaces between them. A set of properties associated with RV interfaces in the context of architectural design are identified in this section, based on Mixed Reality boundaries.
The theory by Benford et al. (Benford et al. 1996; Benford et al. 1998; Koleva et al. 1999). In their approach, the real and virtual spaces are not overlaid, but instead are distinct but adjacent. In contrast, the MA approach involves distinct but overlaid real and virtual spaces. These two approaches do share certain common properties with each other. The purpose of identifying these properties is to provide an analytic framework for supporting the design and analysis of RV interfaces and MA mega-spaces for a broad range of cooperative activities in architectural design. Examples of these activities are product/design presentation, distributed design review, design document spaces, design document collaborative editing, etc. Different cooperative activities apparently involve varying requirements for communication, awareness, and even privacy (Benford et al. 1998). These properties are discussed in the context of architectural design below.

3.1. INFORMATION ACROSS RV INTERFACE

There are two major types of sensory information that can pass between the overlaid spaces in MA, which are visual and audio information. Visual quality determines the amount of visual information that is allowed through the interface and depends on the presentation format and level of graphical detail (Benford et al. 1996). For instance, a real remote building site could be transmitted back via computer network and dynamically textured mapped onto the corresponding virtual site in a virtual design environment with high fidelity format as a monitoring video captured by camera, or with low fidelity format as a still image. What audio information is permitted through the interface is determined by the way of rendering the audio information (Benford et al. 1996). For example, audio like project coordinator’s announcement/discussions could be projected to a public system in the virtual design environment so that its effects are amplified to reach all the virtual design team members. Another example is to locate and render the real unprocessed building sound design in a spatially consistent manner to test its functionality in the virtual building. The issue of spatial consistency is a very important one as it affects the level of details to which participants on opposite sides can establish mutual orientation.

3.2. SPATIAL FACTORS OF RV INTERFACES

The spatial factors of RV interfaces include position, orientation, geometry, translation, and rotation. These spatial factors are elaborated in the following subsections.

3.2.1. Position and Orientation

Position and orientation describes the placement of the RV interface within the connected spaces. For example, one RV interface could be vertically located onto a virtual wall so that designers could assess the aesthetic effects
of proposed wallpapers by texture-mapping the real image of wallpaper samples from suppliers. A horizontal location involving projection onto a virtual desk or board could establish the boundary as a shared drawing surface or a platform to review real design documents which are most relevant to the facility the designers are standing in.

3.2.2. Geometry
Geometry determines the contour/shape of RV interfaces. If the display for the RV interface is large enough, the image of real space (real existing surroundings and landscape) might even be presented as a direct and smooth extension of a virtual proposed building. The geometry could also be a door-shaped/looking if this interface intends to lead designers to another virtual room where interior design would be implemented by another design team.

Another important factor of geometry is dimension of the RV interface: 2D, 3D, and even 4D (3D + time). For example, a 3D interface as a bulletin board could be constructed with different facets displaying technical information for different specialty services such as HVAC, safety, mechanical, etc. Time element in 4D refers to when and for how long the interface is in existence. Interfaces may be scheduled to appear at specific times to support the pre-planned nature of many activities (e.g., face-to-face meetings through embedded videoconferencing), and then hide in other times (Koleva et al. 1999). The time element of an interface could therefore be determined by the service nature of the interface. For example, if the interface is devised for remote site surveillance, its time element should be set as long-term duration. If the interface is only designed to serve a specific public meeting, its duration should be aligned with the schedule of the meeting.

3.2.3. Translation and Rotation
Translation and rotation of RV interfaces could also be realized for special purposes. RV interfaces could be static, connecting two fixed spaces. RV interfaces could also be dynamic with users steering through the connected spaces (Benford et al. 1996). For example, the participants could follow a pre-defined trajectory for a tour-like inspection for a building facility.

3.3. INTERFACE TRAVERSABILITY
Traversable interfaces enable users to virtually cross from one space to the other. Traversable interfaces provide a mechanism for people to dynamically relocate themselves along the RV continuum (Koleva et al. 2000) and people located in one space can transverse into connected spaces. Traversable interfaces can allow people to virtually move back and forward through various modes in the MA construction tree, re-positioning them along the
MA continuum, driven by their design task, interest, and focus. For example, at one moment they may be primarily located in the mode “g” in Figure 3, with a view back into the augmented virtual environment in the mode “a”. They may then traverse the interface and find themselves located within the mode “i” in Figure 3, with a view back into the real environment in the mode “b”. MA spaces could be public where every participant can have access to the same pool of resources. MA spaces could also be private where only authorized participants can have access. Certainly participants can actually transverse from a public space through an interface into a private space, and vice versa.

There are various techniques and methods such as immersive displays (e.g., head-mounted display) combined with trackers that allow a designer in one space to enter into another space. The designer might need to change the techniques to interact when he/she is trying to cross the interface. In addition, related collaborators in different spaces might transform their visual representations as one designer is crossing an interface from one space to the other. We now go back to the case depicted in Figure 4 to show how people can virtually transverse between interfaces. I am the designer in the real environment. I am traversing from the space “a” to the space “g+h”. In the space “a”, I see my remote collaborator as a real human through the interface enabled by the telepresence video view. I then “step” into the virtual space “g+h” through the interface technically enabled by the head-mounted display, large projection devices, or even CAVEs (cave automated virtual environments). At the same time, I see my collaborator as virtual avatar that emerges when I enter the virtual space “g+h”.

4. Conclusions

This paper developed a novel concept – Mutual Augmentation (MA) where AR and AV co-exist to form a seamlessly integrated mega-space by sharing certain real/virtual entity. This paper also presented a systematic framework of exploring MA for supporting architectural design beyond traditional single real/virtual space. A case illustration was discussed to explain how the MA concept approach is applied in the context of architectural design collaboration. The case illustration provided an enhanced understanding of how MA-based design environment might be exploited to facilitate the work of architectural practitioners. The MA concept also opens up a key direction for future research into Collaborative Virtual Environments, AR and AV.

References


