Mixed Reality-Based Visualization Interfaces for Architecture, Engineering, and Construction Industry

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Abstract: Varied computing devices and automated sensors will enable new human-computer interface paradigms for interacting with digitally managed project information. The writers therefore propose the development of Mixed Reality (MR)-based computer interfaces, and especially Augmented Reality systems, for the architecture, engineering, and construction industry and describe the technologies and principles for applying such computer interfaces to support all phases of the constructed facility project life cycle. An Augmented Reality computer-aided drawing prototype is described as an experimental platform to study the human factors issues in interacting with Augmented Reality three-dimensional digital design models. Two critical research needs are cited for realizing effective Augmented Reality systems: (1) human factors research for development of visualization tools to enhance design comprehension and support collaborative work, and (2) the development of a technology infrastructure for "augmented" control and inspection interfaces to directly access digital project plan and site information that may be spatially referenced and displayed in the field. Research should be geared to advance knowledge regarding spatial cognition, human–computer interfaces, and computer-mediated human-to-human interactions, and it should address application of MR to all phases of the project life cycle.

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Introduction

The notion of exploiting Virtual Reality (VR) technology for construction planning has gained popularity as desktop computers have supported more sophisticated graphics capabilities. The more typical application is similar to the four-dimensional (4D) type of thinking, visualizing planned construction using desktop PC virtual environments to create graphic simulations of construction processes, perhaps even including equipment operations (Kumi and Retik 1997; Leinonen and Kähkönen 2000; Murray et al. 2000; Naji 2000). Other schemes focus on safety (Maruyama et al. 2000; Hadikusumo and Rowlinson 2002) and Web-based design review and computer supported cooperative work (Fu and East 1999; Campbell 2000). These efforts are motivated by the opportunity to visualize the design model, and in some cases, to dynamically model and simulate project processes taking into account both environment and resources, a powerful tool for planning construction operations.

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New innovations for interacting with project information can be achieved through what is termed as Mixed Reality (MR), a more expansive use of VR-related technologies. Mixed Reality refers to the continuum over which computer-generated content may be blended in varying proportion with an individual's view of a real world scene, and it offers new options for project life cycle interactions both with the virtual design information and with project collaborators. Through the strategic blending of real and virtual and the use of intuitive human–computer interface devices, MR systems can be tailored to enhance information accessibility for decision making in activities such as design review, work planning, work execution and monitoring, and inspection.

This paper provides background on MR, describes a vision for MR applications for the architecture, engineering, and construction (AEC) industry, summarizes AEC-related MR research to date, presents an experimental platform developed for design phase activities, and briefly outlines needed research to establish scientific principles and to extend MR technologies for successful transfer to the AEC industry. The writers seek to stimulate awareness in the industry of the potentials for this computer interfacing technology.

Explanation of Mixed Reality

Milgram's taxonomy for Mixed Reality, as set forth by Milgram and Colquhoun (1999) and extended from earlier work by Milgram et al. (Milgram and Kishino 1994; Milgram et al. 1994) encompasses the continuum of possible combinations of elements from both virtual (computer generated) and real environments, the continuum between fully real and fully virtual. Fig. 1 illustrates this Reality-Virtuality continuum. Closer to the fully real end of

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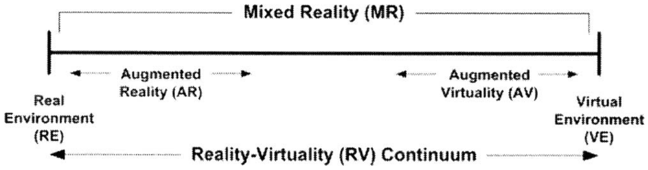

Fig. 1. Identification of Mixed Reality within Reality–Virtuality continuum (data from Milgram and Colquhoun 1999)

the continuum is Augmented Reality (AR), where the image of a predominantly real scene is enhanced with digital content. Toward the other end of the spectrum is Augmented Virtuality, the opposite of AR. By definition, AR is generally more suitable for supporting the performance of real world tasks.

AR is applicable to industrial environments such as construction where the user may need real-time augmentation of his or her knowledge of elements in the present site environment. The power of the AR concept is found in the opportunities for a user to interact in an intuitive, natural manner with only the most important digital information while performing a work task. While VR is suitable for creating visual simulations of the environment and planned construction operations, MR technology, specifically AR, can provide just the critical information, spatially referenced and presented intuitively, to augment an individual's knowledge of the present environment or plan of work. These interfaces have several key attributes that help further illustrate the utility of the MR concept.

Specific MR applications are more thoroughly characterized by Milgram and Colquhoun (1999) in a global (three-axis) continuum. In addition to the RV continuum described above, this framework also addresses the user's frame of reference (viewpoint)—the centricity continuum—and the mapping between that viewpoint and the manipulation of objects in the viewed scene—the congruence continuum. Centricity is defined as the extent to which the human observer's viewpoint is removed from that viewer's nominal viewpoint, the natural point of perspective within the scene. Fig. 2 illustrates the movement along the centricity continuum, from the nominal viewpoint of the crane operator's seat in the cab (egocentric) to a global (3D) view fully separated from the actions within the scene of the performed activity (exocentric). This principle is relevant for establishing awareness for remote observation or teleoperation.

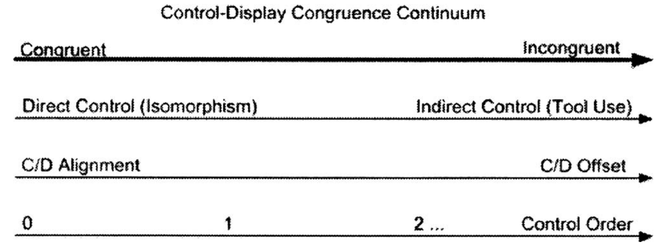

Fig. 3. Parameters in congruence continuum (data from Milgram and Colquhoun 1999)

With regard to the final of the three continua, Fig. 3 illustrates the parameters of congruence between an operator's input actions and the corresponding responses in the operational (display) space. Depending upon the operational circumstances and the technological means provided to the user to interact with the operational environment, there is either a more intuitive (congruent) interaction or a more dissonant (incongruent) interaction that requires some number of mental transformations on the part of the user. Backhoe excavator equipment operators would recognize this parameter in the response of the bucket to control lever motions. This congruence is defined in terms of three factors—directness, alignment, and order—as depicted by the three lower scales in Fig. 3.

The first factor, the directness of control, refers to whether the user's control actions map directly to the operational space that is being viewed or whether some intermediary device or tool (e.g., joystick, mouse, steering wheel, etc.) must be manipulated to influence the environment. The control display (C/D) alignment describes the relative position and/or orientation between the control device and the display space. Control order, a more complex concept, refers to the order of the transfer function between the input commands to the control device and the resulting system response(s). For example, the zero order for a position input would refer to a gain transformation, while a first-order transformation converts the position input command to a rate (integration), and so forth.

The foregoing explanation reveals MR's applicability not only

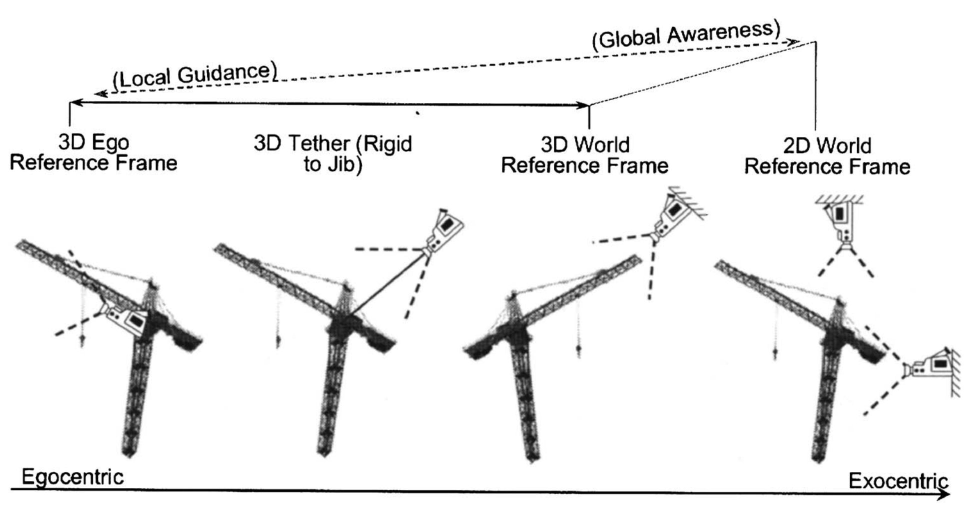

Fig. 2. Changing frame of reference through centricity continuum (modification of data from Milgram and Colquhoun 1999)

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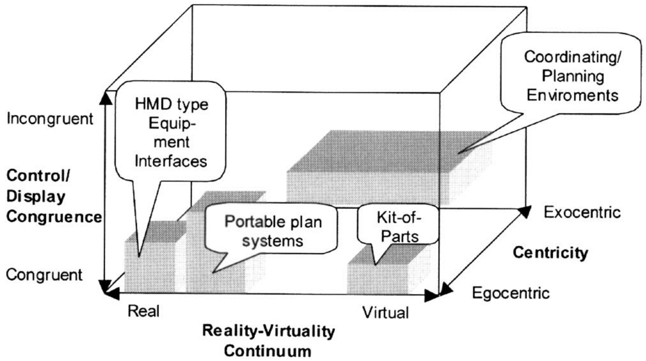

Fig. 4. Approximate locations of interface examples within Mixed Reality global taxonomy

for passive or active viewing and manipulation of digital information (e.g., 3D design models), but also for "augmented" control interfaces to conventional machines, remote viewers, or robotic mechanical systems. For example, an equipment operator equipped with an optical see-through head mounted display (HMD) may have his or her view from the cab of a conventional backhoe excavator augmented with a digital projection of buried utilities registered (aligned) with the real world coordinate system. The proper taxonomic designation of that system would be Augmented Reality with an egocentric perspective, and the control display would be fairly congruent, having a zero order and somewhat aligned conventional backhoe controls, albeit having indirect control via the control levers. On the other hand, safety-critical conditions, such as disaster response, may dictate the need for a remote operator. The control interface might be less egocentric and less congruent. The objective would be to specify an interface that maximizes the user's ability to make decisions and effect corresponding actions in the operational space.

Opportunities for Mixed Reality in Architecture, Engineering, and Construction Industry

AEC projects generate great amounts of data and information that must be accessed by numerous parties, in numerous locations, and under varied conditions. Designers are increasingly under pressure to produce designs according to timelines that require concurrent engineering among separate business entities. Because the construction activity typically takes place in environments remotely located from design and planning functions and the parties involved, construction personnel stand to benefit immensely from the ability to directly access and interact with digitally managed project information without having to use an unwieldy laptop or to return to the office to use a conventional desktop PC. Therefore, the AEC industry constitutes a prime applications arena for exploiting MR technologies.

Technologies Envisioned

Examples of the kinds of MR technology-based systems that can be developed for the AEC industry might include the following:

1. Design platforms which allow a user to "step into" the design space, to build the virtual design in a fashion much like assembling a physical model, or to examine a digital "popup" model of a design concept;
2. Digital planning and coordinating environments which enable remote project partners to collaborate and also enable each of those partners to move seamlessly between map (bird's eye) perspectives and immersive views of the proposed design;
3. Portable AR systems which deliver 3D designs to field construction personnel enabling the user to essentially "build as you see it, where you see it";
4. An extension of the preceding example, inspection support systems which enable comparison of the in-place work to spatially registered 3D images of the design and also enable collaborations with remotely located experts in an interactive interface;
5. Wearable equipment operator control interfaces which enhance decision-making capabilities by adding digitally based information (design details, subsurface data, etc.), in the form of text and/or graphics, to the operator's view of the real work area; or
6. Wearable or handheld aids for workers in disaster response situations which supply database, field sensed, or expert information in a real-time, field-relevant graphical presentation.

The MR systems such as those listed above can be described in terms of the aforementioned three continua. Fig. 4 represents an attempt to globally classify four of the examples, making certain specification assumptions. For example, the equipment operator visual interface is assumed to be a see-through HMD, identifying it as highly congruent. The list above illustrates the broad applicability of the MR concept and technologies. Developing methodologies to specify such systems require both physical and psychological human factors knowledge and integrates advanced technologies to improve delivery of digitally managed project information. A few researchers have already begun to tackle the technical issues for AEC applications.

Noted Architecture, Engineering, and Construction Research Applications

A survey of the literature reveals some notable attempts to demonstrate the efficacy of Augmented Reality technology for the AEC industry. Webster et al. (1996) developed experimental AR systems for the construction, inspection, and renovation of architectural structures, showing users the locations of columns behind finished walls, the location of rebar within the columns, and a structural analysis of the columns. Thomas et al. (1999) developed a mobile AR platform, TINMITH2, which uses a wearable computer system to visualize the architectural features of the design for an outdoor structure using AR in the spatial context of its planned location. Hovestadt and Hovestadt (1999) conceived of implementing AR features to present assembly instructions and building controls for the sixth phase of their ARMILLA building installation model. Kensek et al. (2000) developed a prototype AR and mobile computing system for architecture/facilities management, designed to provide the facility manager with information relating to the various building services elements such as air-conditioning ducts, lighting fixtures, etc. Donath et al. (2001) discussed possible application areas of AR/VR techniques in the revitalization of buildings from the point of view of the user and developed the associated technical requirements. Shen et al. (2001) developed a new video-based, calibration-free AR visual approach for urban planning as an alternative to graphics-intensive VR. Navab et al. (2002) used 2D factory floor plans and the structural properties of industrial pipelines to register 3D models of pipeline retrofits with views of the existing factory

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facility. Roberts et al. (2002) developed a prototype AR system that employs the global positioning system (GPS) and goggles which allow people to "look" into the ground and "see" underground utilities that have been documented in a geographic information system database. Hammad et al. (2002) have been investigating the potential benefits of using wearable computers and AR technology for real-time support of engineers and technicians involved in civil infrastructure field tasks such as a construction, inspection, repair, and maintenance. Finally, the writers have been engaged in the development and experimental study of an AR system to support design activities for mechanical contracting (Dunston et al. 2000; Dunston et al. 2002).

The foregoing examples demonstrate a rational interest in developing AR systems to serve the computer interfacing needs of the AEC industry. Establishing parameters for specifying MR systems for particular industry needs will advance transfer of this technology. The writers therefore refer to Milgram's taxonomy to establish a framework for pursuing the critical research and development.

Building upon Milgram's Taxonomy

Milgram's taxonomy addressed problems of inexact terminologies and unclear conceptual boundaries that appeared to exist among researchers (Milgram and Colquhoun 1999). While the taxonomy is useful in discussions of MR systems as they exist, i.e., for classification, an even more user-based extension of the taxonomy is useful for specification of MR applications and for stimulating valuable applications research. Therefore, the writers seek to extend the original conceptual framework by catering to issues inherent in AEC arenas. Review of the original and related publications reveals several issues for research that can advance technology transfer:

1. Although conceptually defined, there is no consensus on a precise distinction between AR and AV. Milgram and Colquhoun (1999) illustrate that some MR systems are not easily pinpointed in those terms of the RV continuum. Practical definitions for these terms would serve to distinguish the various contexts within which diverse research may be carried out and provide a basis for specifying systems for industrial application;
2. A thorough treatment of centricity ideas presented by Milgram can be found in various reports of Wickens and his colleagues (Faye and Wickens 1995; Wickens 1995; Wickens 1999) who also treat the concept of a continuum as spanning the space between purely egocentric and purely exocentric views. There is no further exploration addressing how such a continuum can be used to facilitate the design of MR systems on the basis of actual task requirements;
3. A viewpoint-related factor which must be taken into account in MR design is the means available to the operator to influence the operational space, primarily whether by manipulating objects within it or by traveling through it. The taxonomy ties the viewpoint parameters together into the C/D congruence continuum (see Fig. 3). However, input and output mechanisms [control (C) refers to input and display (D) to output] may be treated separately for the purpose of selecting corresponding devices. The objective for input should be naturalness of the control metaphor, while the objective for output should be to satisfy a centricity and presence preference. Also, the displays discussed in the taxonomy are predominantly limited to visual displays and there is no study of multisensory interfaces incorporating, for example, aural and haptic sensory feedback;
4. There is no discussion of the selection of media appropriate for the augmenting content (information). The perceptual and cognitive influences of different media representations vary, and each representation should have its own appropriate application domains;
5. There is no insight on the cost implications of a MR system's design. While it is premature to talk definitively about system costs for an immature technology, a drive toward applications development demands a model that at least implies cost.

In light of these noted issues, the writers are building from the foundation of Milgram's taxonomy to incorporate more specific features and to map suitable MR technologies to AEC tasks. The following summary of modifications, to be more fully reported in the future, has been identified to extend the concepts of Milgram's taxonomy:

1. Bisecting the MR continuum: The input and output mechanisms for AV and AR have significant distinctions such that it is useful to bisect the MR continuum into separate AR and AV continua for discussion of interaction mechanisms and definition of related terminologies;
2. Classifying media representations (augmenting content and augmented environment): The type of augmenting content (e.g., text, wireframe, etc.) and augmented environment (e.g., optical see-through, sampled data, etc.) may be classified in terms of certain information visualization issues (e.g., abstract-concrete, cognitive load, computing intensiveness, etc.);
3. Revisiting the control/display continuum: Input and output mechanisms may be categorized in terms of certain criteria (e.g., cognitive load, computing intensiveness, intuitiveness, etc.) to ascertain the most effective of the options available in the use of MR for particular activities.

Position Measurement and Tracking

A critical element of AR systems outside the focus of Milgram's taxonomy is position measurement and tracking. AEC applications would have some demanding requirements for registering the positions of digital information with elements in the operational environment. Developing systems for the construction site will require a special effort to address the peculiar space characteristics of that environment.

The big challenge for AR systems for the construction site is the requirement of accurate and precise, long-range sensors and trackers that report the three-dimensional locations of the user and the surrounding objects in the environment. No tracker is currently suited to provide the high accuracy and precision at long ranges in real time (Azuma 1997). The reader may find details of tracking technologies in surveys by Ferrin (1991) and Meyer et al. (1992). Applewhite (1991) presents a discussion of tracker evaluation by means of a framework for suitability.

There are six current technological approaches as noted from Holloway and Lastra (1995)—magnetic, mechanical, acoustic, inertial, optical, and GPS. Most approaches have critical range, accuracy, or data rate limitations, so more hybrid systems are expected to be developed to compensate for the shortcomings of a single technology by using multiple sensor types to produce robust results (Azuma and Bishop 1994; State et al. 1996; Azuma 1997). Nevertheless, optical systems are viewed as the most

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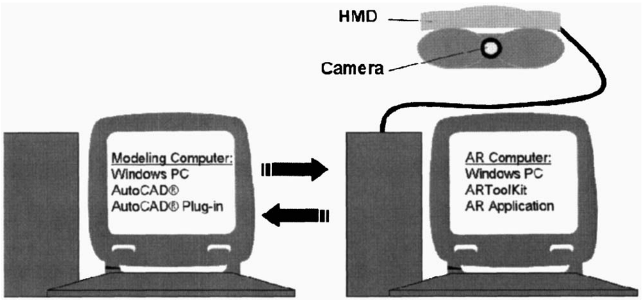

Fig. 5. Components of Augmented Reality computer-aided drawing prototype

promising individual set of technologies for AR when accuracy, precision, and high data rates are desired.

The construction industry already makes use of optical surveying equipment for position measurement, and these technologies should not be neglected in devising a measurement and tracking infrastructure for the construction site. Newer techniques that were designed with tracking of mobile units in mind should be considered. The generic light-based and laser-based real-time position measurement (RtPM) techniques used by Gorham (1999) and Beliveau et al. (1995), respectively, are examples of techniques that might be extended or modified to support the use of AR on the construction site. Besides the position accuracy, range, and update rates, orientation tracking and navigating complex indoor floor plans will be the major challenges.

Augmented Reality Computer-Aided Drawing Experimental Prototype

To begin exploring the usefulness of AR, Dunston et al. (2000; 2002) developed an Augmented Reality computer-aided drawing (AR CAD) prototype. AR CAD is a research platform to establish the foundational scientific principles for applying AR concepts and technologies to design and planning for constructed facilities. The AR CAD concept involves the addition of an AR assistant viewer to standard CAD, thus adding the benefits of a more intuitive and liberal interaction with 3D design models. Mechanical detailing, due to the need to negotiate within limited shared space, was chosen as an initial exploratory application area. Sankar (1997) noted that the first available commercial VR-based design systems were developed by simply transferring CAD technology features into a VR environment, which fell short of exploiting the advantages of VR and failed to recognize strengths in conventional CAD. There is valid reason, therefore, for the drawing environment to be distinct from the conceptual proofing and planning environment, thus the approach of integrating AR with CAD in real time to exploit their combined strengths.

The basic components of AR CAD are depicted in Fig. 5. The actual system is operated on either a single or multiple networked PCs with the desktop monitor and/or a HMD used as the display device. The current system is run on desktop PC(s) with a 1.6 GHz Pentium 4 CPU and a 128 MB INVIDIA GeForce 4 video card. The modeling computer (or component) runs *AutoCAD*® with a specially designed *AutoCAD*® plug-in. The CAD detailer designs the model on this machine and then sends the 3D model information out to the AR computer (or component) using the *AutoCAD*® plug in, which uses a standard network communication code to pass information to the AR computer. The

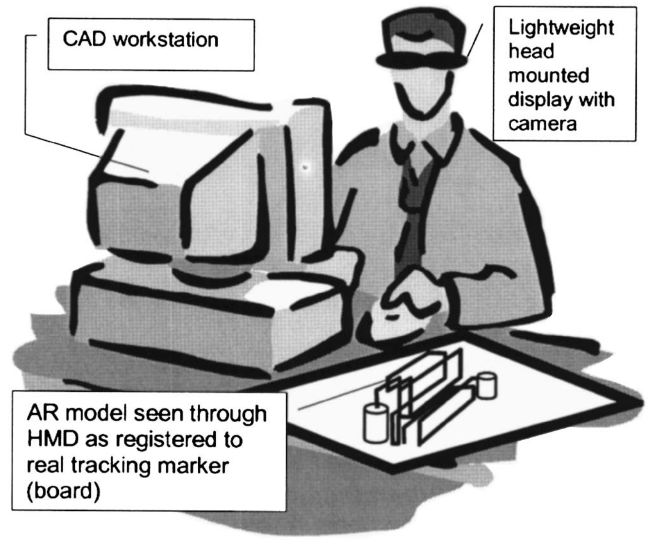

Fig. 6. Initial concept for mechanical detailer's use of Augmented Reality computer-aided drawing

AR computer runs an AR application that allows a user to see virtual 3D models superimposed over a view of the real world by utilizing the *ARToolKit* <http://gitl.washington.edu/artoolkit> computer vision tracking libraries.

Fig. 6 depicts the initial concept of a design detailer using the AR viewer to provide a small scale 3D model for more intutitive inspection during mechanical design detailing, akin to having a small-scale physical model on one's desk (Dunston et al. 2000). The modeling computer equipped with *AutoCAD*® is the data source of the 3D models for virtual rendering. The AR viewer software receives position and orientation data for each element in the design model from the modeling computer and then loads the corresponding simplified VRML model from the database and positions and orients it as in CAD. Although the AR CAD system has been developed using *AutoCAD*® and a proprietary plug in (not essential) developed by a collaborating contractor, any CAD software or appropriate plug-ins may be used with the properly designed protocols.

The AR viewer application is a customized application based on the *ARToolKit* library, the *OpenGL* library, and a database of simplified 3D pipe models in the Virtual Reality modeling language format. The AR application receives the 3D model information (object name, position, orientation) through the network communication from the modeling computer and then instantly creates a 3D virtual model of the design. The system architecture is designed for two-way client–server communication and a video see-through display. The video see-through display is an i-visor DH-4400VPD head mounted display with 1.44 million pixels and dynamic immersive 1.118 m screen as viewed at 2 m. The HMD is connected to the AR computer, and the same augmented scene visible through the HMD can be viewed on the PC monitor as well. Also connected to the AR computer is a Logitech QuickCam Pro 3000 video camera, which is physically attached to the HMD to give the wearer of the HMD a view of the scene which is reasonably close to the natural viewpoint as well as to facilitate position and orientation tracking of a specially designed marker which is mounted on a stiff plate.

The AR modeler (computer) makes use of the video-based Augmented Reality tracking library, *ARToolKit* to accomplish accurate registration by using matrix calculations to tie virtual and

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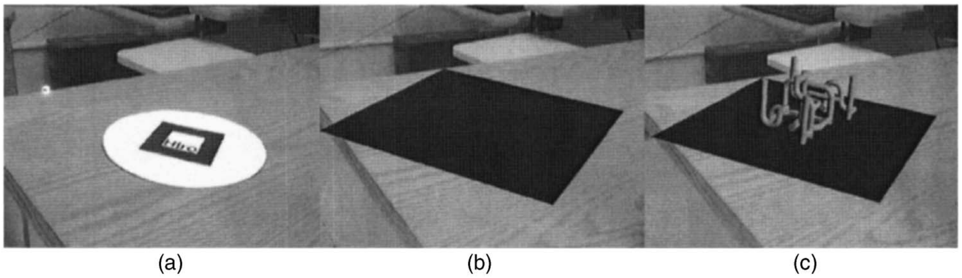

Fig. 7. Illustration of scene compositing sequence used in Augmented Reality computer-aided drawing: (a) video image with tracking marker card; (b) insertion of virtual platform for visual clarity; and (c) insertion of virtual model

real images together via coincident positions and orientations of virtual and real cameras in the reference coordinate frame. The computer performs image processing on the video image from the camera to find a specific image on a specially designed tracking marker. Once the tracking marker is recognized as a match by the computer, the camera's position can be calculated from the tracking marker and the AR software then uses a 4×4 matrix to store the position and orientation data of the real camera relative to the origin (center) of the tracking marker. This tracked viewing pose can define the position of the virtual camera, which is referenced to overlay 3D graphics onto the real world scene. The AR software uses the 4×4 matrix to set the virtual camera to the same position and view as the real camera. Under the virtual camera, AR software then uses the OpenGL graphics library and database to render all the virtual models aligned with the real tracking marker. The resultant composite image is fed back into the HMD for the user to see a view of the real world with accurately and precisely overlaid 3D virtual models. Fig. 7 shows the sequence of scene composition with the initial video captured scene with a real tracking marker card, the same scene with a virtual platform over the marker, and the final composite scene with the model inserted relative to the marker.

This tracking technique enables the user to easily view the model from any perspective above the card. Whenever the spatial relationship between the tracking marker and the camera is changed, the virtual camera's position is recalculated and updated, ensuring that the virtual camera is consistently and perfectly overlapped with the real camera. Manipulation of the card or movement of the camera controls motion around the model with only the restriction that the marker image stay within the camera view. The user is thus enabled to haptically manipulate his or her view of the selected virtual model. Fig. 8 illustrates how the model view may be changed in this natural manner. Alternatively, the user can physically walk or otherwise move around the marker and have the experience of navigating around the virtual model.

AR CAD appears to be unique in terms of its real-time integration of CAD with an AR mode. Currently available software can only perform an off-line conversion of a CAD file to the VRML format, viewable with a separate application or browser plug in. The current AR CAD approach requires a database of standard parts, limiting the types of designs that can be created, so a more flexible approach of translation and optimization of polygons is being explored.

This description of AR CAD illustrates the fundamental elements of a MR system—a virtual information/object source, a display device, an interface mechanism, and a tracking and registration technology. The same generic components would be necessary for using MR on a construction site to visualize features of the facility that have yet to be constructed. In this more challenging environment, other technology options must be considered and developed for realizing some of these basic functions. Much of the MR research focuses on developing such alternative technical solutions for different environments. Research for the AEC industry should emphasize user issues that can support technology transfer.

Research Needs

In light of the potential for MR applications, there are two primary development themes that should be pursued: (1) the creation of efficient and intuitive design and planning environments that exploit MR advantages for digital content manipulation and human-to-human interactions, and (2) the creation of interface systems that support the augmentation of knowledge in job site

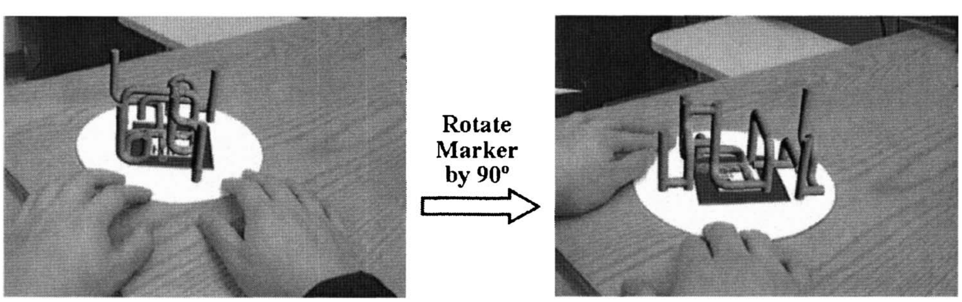

Fig. 8. Demonstration of haptic manipulation of virtual design model

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planning, operations, and inspection through direct access to spatially referenced and displayed digital information. These themes must be realized through both core technology and human factors research. MR technology research will continue to progress through researchers seeking to create more convenient portable devices and to develop systems which can serve users in a broader variety of challenging environments. Adoption of MR systems by any specific profession or industry requires evidence that MR systems can enhance performance of key work tasks. The critical aspect in affirming the benefit of MR systems is to establish that practitioners can be more efficient and yet safe in performing their work while interacting with both the digital information presented via the system and with the work task environment.

AR CAD merely constitutes an initial effort to explore MR's benefits in the design phase of the project life cycle. Research addressing the representation and interaction with digitally maintained information will help establish the science that supports the development of MR systems by integrating knowledge from fields that address human factors (physiological and cognitive parameters), information visualization, and information technology (hardware, software, communications). Knowledge from both human–computer and computer-mediated human-to-human interactions should be applied. The great challenge is to generically validate the benefits that can be derived from system features.

Spatial cognition, a human factor that may be defined as the way in which individuals comprehend and function in reference to space relationships, is the critical concept in understanding the value of MR modeling for design comprehension and communication. Navigation and perspective changing are key aspects to explore. The processes which occur in spatial cognition are complex and not fully understood, but differences in performance in various display environments can be measured through well-planned controlled experimentation (Sholl 1995; Tversky et al. 1999; Oxman 2000; Wang 2002). In experiments structured to isolate spatial cognition benefit, performance may be indicated by the time it takes to complete a task, the time measurement being a surrogate measure for cognition cost. Such experiments must be conducted to address feature validation and to provide solid explanations for more generalized performance advantages.

Another key challenge is to effectively exploit information visualization knowledge. Some visualization research indicates that the spatial relationship between pieces of information affects speed in identifying desired information, recall of information, and planning performance (Billinghurst et al. 1998; Billinghurst and Starner 1999; Liston et al. 2000). Research on this topic will have significant bearing upon computer support for collaborative engineering. There is a need for controlled user experiments for measuring performance improvements in this area.

Applying MR technology to AEC tasks requires gaining an understanding of the intuitive modes of interaction which best support individual and collaborative thinking and matching those modes to appropriate display devices and interaction tools. Carnegie Mellon Univ. researchers have been studying issues of how current wearable computing technology can enable remote workers to collaborate with remote professionals and access critical field task related information (Seigel and Bauer 1997; Bauer and Siegel 1998). In order to establish value-adding MR-based tools for the AEC industry, researchers and practitioners must be involved in experiments to test portable computing devices, remote communications, and design model manipulation tools. The portable systems may incorporate different kinds of displays and portable computers. Wireless communications will also come into play to make a system feasible.

There is a common notion that newer generations entering the workforce will be more geared to computer based control systems, especially inasmuch as they resemble the computer games with which they are intimately familiar. These new workers are expected to be preconditioned and thus more proficient in using such tools to perform tasks. By default, user resistance would be minimized. While this is a logical conclusion and some anecdotal evidence may exist to support it, it remains to be proven, and the impact of gaming technology should be examined to determine whether performance is indeed enhanced by catering to this trend.

Conclusions

This paper has described the fundamental concepts in Mixed Reality technology and asserts that Augmented Reality, a subset of this technology, may be developed and applied broadly as a means to interface with computers to access and manipulate AEC project designs and related information. Technology transfer can be advanced by extending the concepts of Milgram's taxonomy to facilitate specification of MR system features for particular AEC tasks. Supporting research should address the human factors aspects involved in interacting with the MR interface together with the environment of the work task. AR CAD, an experimental Augmented Reality computer-aided drawing prototype was introduced and is being developed as a platform to study some of the human factors issues associated with perception of 3D virtual models and collaborative work scenarios such as design review. However, other technology platforms to support remote field collaborations and information accessing should be developed, and the human factors aspects of both technology usage and information visualization must be studied.

The needed research is interdisciplinary, addressing AEC industry needs in planning, design, construction, and maintenance, and exploiting such user oriented knowledge domains as computer graphics, psychology, ergonomics, collaborative/concurrent engineering, and computer supported cooperative work. Such research will contribute to the knowledge base for AEC visualization and information management, establishing a new class of technology tools and extending our current understanding of human–computer interactions and computer-mediated human-to-human interactions.

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