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Comparative Effectiveness of Mixed Reality Based Virtual Environments in Collaborative Design

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***Abstract*—This paper presents two Mixed Reality (MR) environments that provide alternative mediums that allow groups of people to share the same work and communications space in face-to-face and remote manners. Two experiments were executed to test the capabilities of the two MR systems in realistic environment and collaborative tasks against prevalent methods. Results indicated that the two MR systems significantly reduced the performance time for the collaborative design error detection task. Results also indicated less mental effort for the MR systems, suggesting that some of the mental interpretation for the error detection task is offloaded to the MR systems.**

***Keywords*—Augmented Reality, Virtual Reality, Mixed Reality Interactive system, collaborative design**

I. INTRODUCTION

As it is an inherently resource-intensive and time-intensive activity, a design review may only occur a few times during the design process, so errors may yet persist to the construction phase of a project. Computer supported collaborative work (CSCW), an approach that uses the computer as a medium for human collaboration, is becoming a reality among partners in the building design [1][2]. Discussing ideas in a collaboration meeting need not be limited to the conventional 2D or 3D paper-based medium. To be successful, this type of cooperation often requires new visualization and collaboration platforms. A Collaborative Virtual Environments (CVEs) is one alternative solution.

Mixed Reality (MR), a powerful user interface paradigm for enhancing a user's perception by incorporating computer-generated information into a real world environment, is an attractive solution to this problem. With MR, the user interacts with the real world in a natural way while simultaneously using the computer to explore relevant information interacting with computer-generated virtual objects. More importantly, in a face-to-face scenario, the users can see each other's facial expressions, gestures and body language, increasing the communication bandwidth [10]. Schmalsteig et al. [11] identified five key advantages of collaborative MR environments: virtuality, augmentation, cooperation, independence, and individuality. A Mixed Reality-based collaborative virtual environment (MRCVE) embeds computer-based tools in users' real environments and enables users to experience natural collaborative work in a shared space that is populated with both real and virtual objects. This paper presents two Mixed Reality environments for collaborative applications that provide an alternative medium for allowing groups of people to share the same work and communications space. The first one is an MR-based face-to-face system, which is actually a table-top MR system for supporting face-to-face collaboration for mechanical design review. There are a number of researchers who have already developed table-top MR systems for supporting face-to-face collaboration outside AEC arenas [11] [12] [13] [14] and this system is specifically for collaborative review in mechanical design. As a distributed version of the first system, the second one is an MR-based virtual space system for remote design review collaboration. The difference of the MR-based virtual space system from previous similar applications is that it combines VNC (virtual network computing) technology with the desktop MR system and is dedicated for mechanical design review collaboration. This paper conducted two separate experiments that tested the capabilities of the two MR systems in a realistic collaborative task (detection of design errors) as compared with the prevalent paper-based drawing review method and a commercial remote design collaboration system (NavisWorks Roamer).

II. MR-BASED COLLABORATIVE VIRTUAL ENVIRONMENT PROTOTYPES

This section presents two MR systems: face-to-face (collocated) and virtual space (remote) systems. Both of them are essentially derived from the same MR platform. Figure 1 depicts the generic system architecture of the two MR systems. For details of the hardware and software configuration, readers are referred to Wang [19].

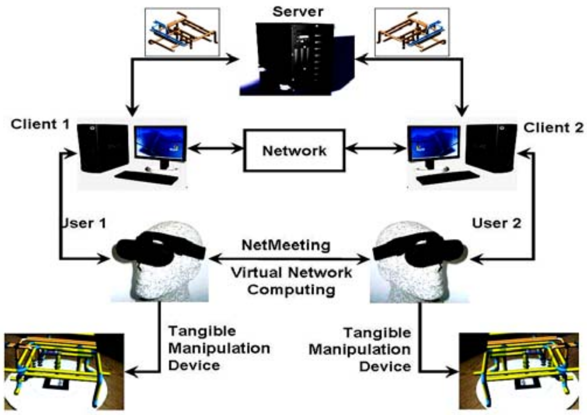

Figure 1. System Architecture of MRCVE

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A. *MR-Based Face-to-Face System*

The basic components or devices consist of the following: (1) Central Server: a computer configured with a CAD application and able to control what information is sent to each remote and distributed client; (2) Client Computer: a networked desktop terminal computer located in a respective design party's working area; (3) Head Mounted Display (HMD) with Video Camera Attachment: a wearable ARvision-stereoscopic HMD with a color video camera (real environment sensor) attached; (4) Multiple Markers: a set of spatial registration fiducials (note black squares in left panel of Figure 2); and (5) Tangible Interfaces by Arbitrary Real Objects: a small-size real cube, in this instance, with a virtual ball overlaid on it (see right panel of Figure 2). Client computers are configured with the same customized MR software, which may receive data packets for graphics objects. Because a real-time groupware system requires short response time, its data state should be replicated at each client's site and the task of rendering graphics is performed at the client-end so that many potentially expensive operations and interactions can be performed locally3D objects are projected into the common collaboration environment of the users as displayed by the HMD which is connected to a networked desktop computer. Large scale virtual design may require too great a distance between the spatial registration marker and the camera since the tracking range for one marker is limited. Multiple-marker technology enables the user can to easily obtain a stable bird's-eye-view of a large scale virtual design without losing the line of sight with at least one of the small markers. Tangible interaction techniques are also incorporated in the form of the tracking marker and a tracker ball used for MR registration. . By using the tracker ball, the user can track his/her hand's position relative to the viewed virtual model by knowledge of the spatial relationship between virtual model and tracker ball. This tool remedies a visual depth mismatch between the virtual model and the user's real hand.

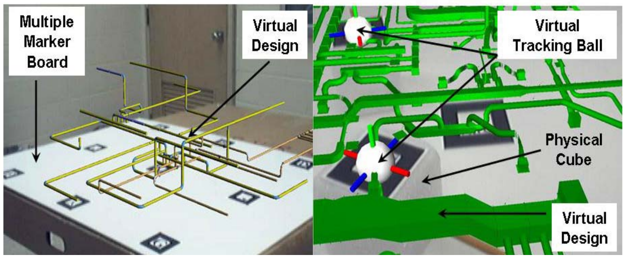

Figure 2. Illustration of Multiple Marker View (left) and Virtual Tracking Ball (right)

B. *MR-Based Virtual Space System*

The basic setup and system architecture is similar to the MR collocated system except that the users of the system are geographically distributed and a single marker instead of multiple markers is used for tracking and interaction. The tracking marker, and the workstation keyboard and mouse are used in the user interface for manipulation of virtual objects. Commercial Netmeeting software is used for audio communication only.

When communicating the model to others over the network and transferring attention back and forth between discussion with other people and observation of one's own 3D models, the user must periodically share the perspective and focus with the other collaborator in order to ensure consensus on their decisions. Such consensus can enable collaborator A to keep track of the series of actions taken by collaborator B from the latter's viewpoint. For example, collaborator B asks A to navigate to a target by passing three walls in front and then turning 60 degrees left and then passing another five walls forward in a virtual environment. Collaborator A might be confused by such verbal instruction and might fail to reach the target. An effective collaboration is difficult to achieve. Effective perspective sharing through certain groupware software can reduce such cognitive effort that is required otherwise. Therefore, the system incorporates virtual network computing (VNC) technology [20] to provide such group communication services in a distributed environment. VNC technology makes it possible to view and fully-interact with one computer from any other computer or mobile device anywhere on the Internet. The VNC protocol can operate over any reliable transport such as TCP/IP.

III. EXPERIMEMTAL METHODLOGY

The benefits of the MR systems should stem predominantly from the enhanced and shared spatial comprehension of the design model, and improved mental interpretation that would stem from the unique capability to manipulate the 3D model. However, certain drawbacks inherent in the MR systems may outweigh such benefits. Therefore, two experiments were devised for evaluating the two MR systems respectively and separately.

A. *Hypothesis, Subjects, Measurement, and Experimental Procedure*

The hypothesis asserts: When compared to their benchmark (3D paper-based drawing media or NavisWorks Roamer), the MR-based system (collocated or remote) will significantly reduce the amount of time to complete an error detection task. Sixteen (12 men, 4 women) graduate student participants were recruited for the study (8 groups with 2 in each group). Participants in the design review were to view and browse the design independently. The measurements of task performance were taken. Each team consisted of two collaborators. The experimental procedure has been identified as follows:

- Training session: Before the start of the actual experiment, all the subjects must familiarize themselves with the methods (MR systems and their benchmark). They were assigned enough time to practice how to use the different platforms.

- Design error education: In order to finish the design error identification tasks in the experiment, the novice subjects needed to know what kinds of errors they should expect. The subjects were therefore educated regarding the design error patterns.

- Real experiment: Two testing models were presented sequentially to each group in the format of either the MR scene or paper drawing. In both treatments in both experiments, the goal of subject groups was to collaboratively identify the design errors based on their knowledge of the given error patterns. The subjects were to complete the task in a collaborative manner by locating three errors specified and the total time spent was then measured and documented for each group.

B. *Statistical Design*

A four-group, two period crossover design was used as the experiment statistical design to incorporate factors of treatment difference, model difference, and treatment sequence. Two methods and two models (C and c) lead to 4 different combinations as shown in Table 1. This scheme considered the learning curve effects of the two consecutive trials (two combinations) for each subject. Replication ensured that each duct model was applied to MR in half the trials and their benchmark method in the other half. On the basis of the considerations of these effects, the initial statistical model was developed as shown in Equation 1.

$$Y = M_{(n)} + T_{(g)} + P_{(j)} + \varepsilon \qquad (1)$$

- Y = the time of completing the task for the gth duct model by the nth method in the kth sequence which is administered at the jth period.
- M = the direct fixed effect of the nth method (n=1, MR; n=2, paper drawing/NavisWorks Roamer) in the kth sequence which is administered at the jth period.
- T = the direct fixed effect of the gth duct model (g=1, P1; g=2, P2) in the kth sequence which is administered at the jth period.
- P = the fixed effect of the jth period. (j = 1,2)
- $\varepsilon = N(0,\sigma)$, random fluctuations which are independent and normally distributed with mean 0 and variance σ.

TABLE 1: INCOMPLETE BLOCK DESIGN (SINGLE REPLICATION OF FOUR GROUP – TWO PERIOD CROSSOVER DESIGN)

Group 1			**Group 2**		
Period	*Method*	*Pipe Model*	*Period*	*Method*	*Pipe Model*
I	MR	P1	*I*	MR	P2
II	Benchmark	P2	*II*	Benchmark	P1
Group 3			**Group 4**		
Period	*Method*	*Pipe Model*	*Period*	*Method*	*Pipe Model*
I	Benchmark	P2	*I*	Benchmark	P1
II	MR	P1	*II*	MR	P2

IV. ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

This section describes the findings of the two experiments in relationship to the stated hypothesis. It discusses the implications of the results on the theoretical model, and provides further insight into the influence of the MR systems on human perception and performance in collaborative work.

Figures 3 and 5 show the original raw data of the performance time for 4 combinations "MRCVE+P1", "MRCVE+P2", "Paper/Roamer+P1", "Paper/Roamer+P2" (P1 and P2 refer to models C and c, respectively). Even though the times measured for the benchmark treatments varied considerably, almost all of the times for those treatments exceed those for the MRCVE treatments, which means that regardless of the model, all of the subject pairs took less time using MRCVE than when using the paper drawing or NavisWorks Roamer. The graph in Figure 4 shows a much shorter mean time of completion (00:05:24) for the collocated MR system than for the 3D drawing on paper (00:15:09). The graph in Figure 6 shows that the remote MR system had much shorter mean time of completion (8.5 mins.) than NavisWorks Roamer (25.6 mins.). Hypothesis 1 of both experiments is well supported because the MR system did appear to provide an advantage in time of completion compared with the paper-based method or NavisWorks Roamer.

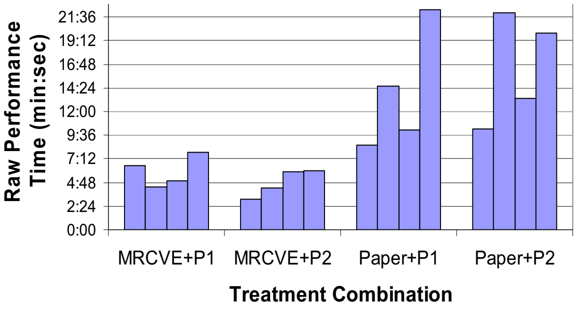

Figure 3. Actual Time Plot for Experiment 1 Treatment Combinations

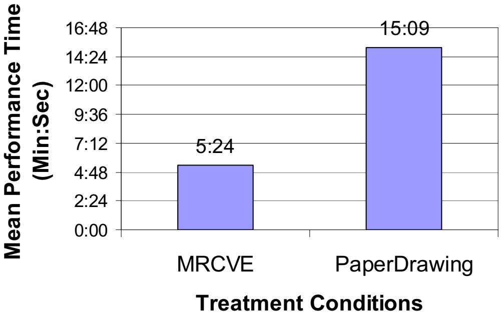

Figure 4. Plot of Average Performance Time in Experiment 1

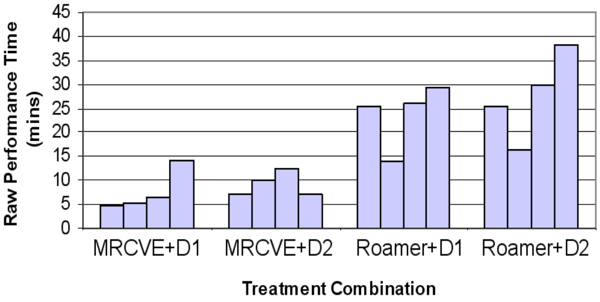

Figure 5. Actual Time Plot for Experiment 2 Treatment Combinations

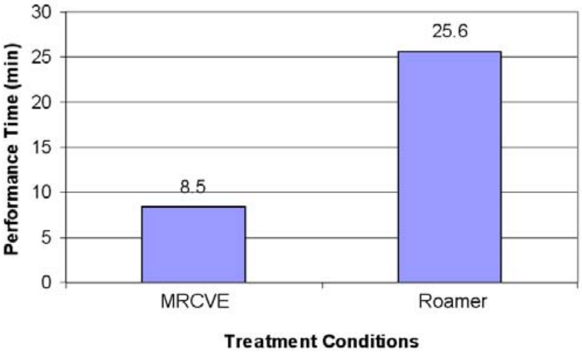

Figure 6. Plot of Average Performance Time in Experiment 2

A one-way analysis of variance (ANOVA) was performed on the performance time data for the error detection task, based on the statistical model. The p-values of factors T (duct model) and P (period), for both experiments are all larger than 0.05. So the effects of factors T and P can be considered insignificant. The insignificant difference between the two designs (factor T) in turn confirms the earlier assumption that the two designs used in the experiment present similar complexity and difficulty for detecting design errors. There is no significant difference in the sequence of presenting the two methods to the subjects, which means no apparent effect from a learning curve is detected. On the contrary, the p-values of the factor M (Method) for both experiments are less than 0.05, indicating that differences between methods (collocated MR system v.s. paper-based method; remote MR system v.s. NavisWorks Roamer) are significant. The interaction of the method applied and duct model used can be represented by factor M*T. The associated p-values of 0.4465 for experiment 1 and 0.7351 for experiment 2 show that the interaction is not present. After deleting the insignificant factors, the statistical model becomes:

$$Y = M_{(n)} + \varepsilon \qquad (2)$$

An F-test, a statistical test in which the test statistic has an F-distribution if the null hypothesis is true, was applied to the model Equation 1 to further validate the simplification. An F-value 0.052 (p-value = 0.95) for experiment 1 and 0.547 (p-value = 0.59) for experiment 2 demonstrated the insignificance of this simplification. Thus, the simplification of model 1 to model (equation) 2 was statistically supported.

The t-test is a statistical test for differences between an observed average value and a predetermined standard or between two observed average values. A t-test was further applied to the model 2 and yielded an estimated performance difference for the two methods for both experiments (9.75 mins. with p-value = 0.0003 for experiment 1; 17.2 mins. with p-value less than 0.0001 for experiment 2). Therefore, the MR collocated system reduced the performance time for the design error detection task by 64% (9.75min/15.15min). The remote MR system reduced the performance time for the collaborative design error detection task by 67% (17.2min/25.6min). From the final model, the conclusion can be drawn that the methods (M) used have a linear relationship with the performance time (Y). For either duct model following either experimental sequence, the MR systems always helped consume less time to finish the design error detection task than the paper drawing/NavisWorks Roamer according to this linear relationship between Y and M used. For practical purposes, we may say that the mean time for the MR system is always less than that for the paper drawing/NavisWorks Roamer, and this statement is true for all kinds of designs.

The total performance time includes the time spent in mental processing as a significant percentage (perception of the specific stimulus — suspected error in the sub-model and entire design model, the cognitive effort to remember the learned error patterns, and the comparison of the stimulus and the patterns). The increased 3D visual perception, spatial cognition, and spatial layout of the design offloaded the required mental processing to the collocated MR system and thus enabled the subjects to complete the task in shorter time. Also, for inspecting the details of the design model, the collocated MR system enabled the users to move their viewpoint to a more advantageous position (closer to the point of interest, with the target directly in front of them) to complete the task more quickly. Observation revealed this practice in a large number of subjects. The subjects had learned the layout of the 3D design space and were perhaps more confident in performing the error detection task without further efforts to interpret the occlusion and depth cues among the objects because they reviewed the design model in a 3D, as opposed to "21/2D" (3D drawing on the 2D paper), manner. This could be another factor that contributed to the shorter performance time with the collocated MR system.

As discussed above, there were statistically significant advantages in time of completion with the MR remote system compared with NavisWorks Roamer. Such an advantage could be explained from two aspects: collaboration mode, and changing viewing centricity. The lack of intuitiveness of collaboration and the frequent loss of orientation could be interpreted as the inefficiency margin of NavisWorks Roamer against the remote MR system in the subjects' spatial orientation activity. They are explored as follows.

(1) Effects of collaborative mode on performance: The remote MR system did yield the advantage of reduced performance time as expected. By sharing the same viewpoint continuously and synchronously between two remote collaborators via the VNC platform, one collaborator could maintain the same changing of viewpoints and frame of reference along with the other collaborator who was leading the discussion and in

charge of navigating the model. On the contrary, the subject using NavisWorks Roamer had to find the suspected error, redline it, save the viewpoint, and then send the information to the other subject. The other subject then received the file and loaded the saved viewpoint for review. Therefore, the subject had to execute additional mental transformation to adapt to the newest static viewpoint saved by the other subject to establish the discussion context. Task performance in the remote MR system was enhanced by reducing the frequency of electronic exchanges of the static red-lining notations and saved viewpoint. However, the possible advantage from the remote MR system of sharing the same discussion context may have been offset to some degree by the resolution limitations from the camera and HMD and bandwidth limitations.

(2) Effects of centricity changing on performance: another concern is the user's easy loss of spatial orientation in using NavisWorks Roamer. It provides the users with the model-centric (bird's eye or exo-centric) view and camera-centric (ego-centric) view. As the subjects tried to switch between these two views through the viewing functions (e.g., zoom out), they had to mentally transform the view in their mind to accommodate the change of these two reference frames [22]. Therefore it was often observed and reported that the subjects became lost or disoriented, especially after using the interactive viewing techniques to switch between these two views. This disorientation and necessary visual re-accommodation created an additional mental burden to the cognitive attention switching. Some subjects using NavisWorks Roamer reported that they felt frustrated because it was hard to even know the previous viewpoint of the design and additional time was required to learn the model again from the new perspective. In contrast, much fewer cases of frustration were reported from the users of the MR remote system since the system provided a smooth and natural way to transit back and forth between viewing centricities. The subjects using the MR remote system could offload the centricity transformation task to the intuitive viewing mechanism of the remote MR system. When the subjects leaned back to enable the camera mounted on the HMD to capture the complete design, an exo-centric view was created. For inspecting the details of the design model, the remote MR system enabled the users to move their viewpoint to a more advantageous position (closer, directly in front of the target) to complete the inspection task more quickly. When the subjects approached a target closely enough, an essentially ego-centric view was created. The extra time spent in using Roamer to accommodate the switch of reference frames was certainly mostly cognitive overhead. Therefore, the frequent loss of orientation could be interpreted as the inefficiency margin of Roamer against the remote MR system in the subjects' spatial orientation activity.

V. CONCLUSIONS

This paper introduced a Mixed Reality-based face-to-face system for collocated collaboration and a Mixed Reality-based virtual space system for remote collaboration, with explanations of system architectures. This paper focused on the experimental validations of these two Mixed Reality-based collaborative virtual environments, elaborating on the complete methodology, experimental design, and interpretation of results. Results showed that in the MR-based face-to-face system, inserting a 3D design into users' real collaborative workspace reduced the performance time for the design error detection task by 64%. Results also showed that the MR-based virtual space system reduced the performance time for the design error detection task by 67%. The two experiments are the first step to validate the effectiveness of the MR tools over the prevalent design review methods.

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