AN EVALUATION OF IMMERSIVE VIRTUAL REALITY SYSTEMS FOR DESIGN REVIEWS

Fadi Castronovo, Dragana Nikolic, Yifan Liu & John Messner

Department of Architectural Engineering, The Pennsylvania State University, University Park, PA16802

ABSTRACT: *With the growth of building information modeling (BIM) approaches to facility design, architectural, engineering, and construction (AEC) industry has been shifting to the use of three-dimensional (3D) virtual facility mockups during design. Studies have shown that 3D models when displayed in an immersive projection display environment allow users to interact with the virtual environment at full scale, and review the designed space in a more intuitive manner. Virtual environments and VR systems however, can vary greatly in levels of immersion and user experience they offer. Thus, for a novice user choosing an appropriate and effective system for specific tasks can be daunting. To understand the benefits of specific VR systems for facility design, this research presents results from conducting design reviews in two immersive display systems. The first system was a fully immersive 5-wall CAVE^{TM} environment, while the second was a semi-immersive 3 screen display system. For each design review, the user experience of a reviewing team was documented and analyzed through targeted questionnaires. The large screens, field of view, level of immersion and the overall value of both systems for design reviews were rated consistently high. Furthermore, based on the comments provided by the project team, the fully-immersive system was found to be more appropriate for smaller groups that desire a higher level of immersion. Additionally, the semi-immersive system with a larger footprint was found to be more suitable for larger groups for various use cases. These results aim to guide future users to make an informed decision when selecting an appropriate immersive display system.*

KEYWORDS: *virtual construction, virtual reality, design review, immersive projection*

1. THE DESIGN REVIEW PROCESS

In architecture, engineering, and construction (AEC) the review of a proposed design is an essential step. Facility design progresses from early conceptual and schematic design to later design development and construction. Each design stage serves to share and communicate project information to provide feedback and check for inaccuracies, or other types of conflicts (East, 1998). How the project information is represented can have a significant effect on understanding the design and providing meaningful feedback.

The design process starts with problem recognition and problem definition in the early conceptualizing stages (Yessios, 1987). The final physical form evolves from numerous iterations of the proposed design solution. During the entire design process and throughout stages, designers use representations to externalize their ideas about the function and the aesthetics of the designed object. The design process is represented at different stages with varying levels of information. When defining the problem in the early stages of the design, designers use more symbolic and abstract representations such as diagrams or schemes. During later stages, as design evolves, representations of the designed object become more detailed and illustrative of its intended physical appearance. Design activities inherent in this design process can also be categorized as *generative* – generating partial solutions and *evaluative* – evaluating proposed solutions (Coyne and Subrahmanian, 1993). In architecture and engineering design, emphasis is placed on the evaluation of the proposed solution. The design solution is evaluated to detect any possible failure with respect to program, function of spaces or overall performance. This process is known as a design review. It is necessary to understand the design in order to evaluate and critique it. Throughout the process, representations are used as a tool for understanding both the design problem and its solution. External representations such as drawings, or scale models as well as internal representations in the form of mental images play an important role in the design process. Representations enable an understanding of the proposed design solution and allow for a meaningful critique (Kalisperis et al., 2002). A valuable external representation is therefore one that requires less translation of the information and allows ideas to be communicated and thus evaluated more easily. By overcoming the cognitive limitations, an appropriate representation becomes a powerful aid in enhancing the reasoning and creative process (Rice, 2003).

Citation: Castronovo, F., Nikolic, D., Liu, Y. & Messner, J. I. (2013). An evaluation of immersive virtual reality systems for design reviews. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Currently, the most prominent method of conducting design reviews is through the use of 2 dimensional (2D) Computer Aided Design (CAD) digital or paper drawings. Previous research suggests that traditional representational mediums such as drawings or scale models are limiting because of the additional effort needed in visualizing space and movement through it (Khemlani et al., 1997). This is mainly due to the fact that the user has to extrapolate the scale of the model to one's own scale. This scale difference limits the ability to experience the space as it is intended and the experience itself can differ immensely from the real scale models (Henry and Furness, 1993). Shiratuddin (2009), and Fu and East (1999) describe the design review process in three steps. In the first step, the reviewer analyzes the drawings and specifications of the design. In the following step, based on rules of thumb and practice standards, the reviewer annotates the drawings' mistakes and omissions. Lastly, the reviewer sends the marked drawings back to the designer, who then integrates the proposed changes. The review process of drawings is conducted through the use of light tables, checklists, and physical mockups. According to Staub-French & Fischer (2001), the overlay process of light tables is highly inefficient and time-consuming. Meanwhile, the electronic or physical checklists process relies on the crosschecking of drawings. This process has also proven to be highly inefficient (Nigro, 1992). Additionally, physical mockups can be developed for the review of the design. However, physical mockups can have a high cost and long construction time (Shiratuddin, 2009). Three-dimensional (3D) computer models have largely replaced the physical scale models allowing easier modifications to the design. The use of building information modeling (BIM) software has showed its value in the visualization of design information (Leicht et al., 2009). The growing adoption of BIM tools is mainly related to the user's ability to directly interact with the 3D model (Tse et al., 2005). However, many of the BIM software focus on supporting the facility design process, and not necessarily on supporting the design review process (Shiratuddin and Thabet, 2011).

2. IMMERSIVE VIRTUAL REALITY FOR DESIGN REVIEW

One method to improve the information representation is through the development of virtual prototypes that can be experienced in virtual reality (VR) environments. Virtual reality is commonly referred to as a computer-generated environment that offers a viewer a convincing illusion and a sensation of being inside an artificial world that exists only in the computer. VR is thus often referred to as *immersion technology*, though the extent of immersion may vary based on the system characteristics and context of virtual model. Immersion refers to a level of sensory fidelity which depends on measurable system attributes such as field of view (FOV); display size; stereoscopy; display resolution; head-tracking; or input devices among other (Slater and Wilbur, 1997; Bowman and McMahan, 2007). Although immersion is a multidimensional construct, based on the presence of specific system components, broad categorization of VR system types include non-immersive systems such as desktop computer systems; *semi-immersive* with large, multiple screens or monitors that provide a medium to high level of immersion; and *fully immersive* systems such as head-mounted displays (HMD) or CAVE™ systems with three or four walls, a projected floor, and possibly even a projected ceiling which significantly or fully cover the users' field of view.

What sets virtual reality apart from other traditional media is the capability to present spatial information in a more engaging manner, allowing for interaction with designed spaces at a human scale. While stereoscopy is one of the defining features of immersive VR systems, large screen size and wide field of view are critical in allowing for more spatial information and alleviating the scale problems characteristic of traditional media. Content-wise, texture, lights, shadows and objects contribute to the overall VR experience and also act as depth cues affecting the perception of spaces. These VR attributes can further augment the richness of information and possibly enhance the visualization process. For its potential to support experiential learning, movement through space and time, and interaction with the design, VR is being increasingly used in architecture, engineering and construction. In the evaluative stages of the design review process, these VR attributes can contribute to understanding specific design features such as scale, dimensions, or layout; complementing existing forms of representation. Virtual reality enables a more qualitative representation of spaces from the users' perspective by using 3D spatial information full scale, and creating the illusion of depth and immersion.

Virtual prototypes have become increasingly used in many areas in the last decades (Kumar et al., 2011). In architecture and construction, virtual prototypes have shown value for their ability to present both small-scale and large-scale three-dimensional spatial information. Compared to standard approaches to building physical mockups and its low cost compared to traditional design reviews, especially physical mockups. Benefits in conducting design reviews using virtual prototypes have been demonstrated in a case study for a courtroom design (Maldovan and Messner, 2006) and in the design review process of operating and patient rooms (Dunston et al., 2007). Kumar (2011) has shown the benefits of interactive virtual prototypes in design reviews of healthcare facilities. Successful applications of virtual reality have been demonstrated in visualizing construction schedules for nuclear power plants (Whisker et al., 2003) as well as in a growing industrial use in the construction contracting, engineering consulting and development (Whyte, 2003). However, most users lack experience in using immersive virtual environments for design reviews due to availability of such facilities. Depending on the user group and their experience, selecting an appropriate immersive display system can be challenging. Shiratuddin et al. (2004) compared all three types of systems for their suitability in decision making tasks in construction. Specifically, using both summative and formative evaluation techniques, the systems were compared by their visual quality, physical comfort, level of realism, ease of navigation, and way-finding. Four-screen (3 walls and a floor) cube-like display was consistently rated higher compared to non-immersive (monitor) and fully immersive HMD, for its higher level of realism, field of view (270^{o}), sense of scale, and overall suitability for design/planning and decision-making tasks. Features such as stereoscopy, large screen, and wide field of view with varying level of detail have demonstrated to effect the level of presence and spatial understanding of the designed space in architecture (Nikolic, 2007; Zikic, 2007).

While immersive systems with large screens and wide fields of view contribute to a higher sense of presence and realism, they are typically associated with higher costs and a learning curve for the end user in both developing the content and using the system. The question is then whether the system provides specific benefits to the task to justify the expense and the complexity of the system. Understanding the advantages and tradeoffs between different system configurations can help potential users make an informed decision when choosing an appropriate system.

3. A COMPARISON OF IMMERSIVE SYSTEMS FOR DESIGN REVIEWS

The research team conducted a study to evaluate the similarities and differences between performing a design review in a semi-immersive display environment and a fully immersive display environment. To contribute to a better understanding of suitability of specific VR features for conducting design reviews, the research team compared a design review process in two types of immersive systems with large screens and wide field of view – an open footprint semi-immersive lab partially surrounding the user (Figure 1) and a 5-screen, fully-immersive lab with four projected walls and a floor fully surrounding the user (Figure 2).

Fig. 1: Semi-immersive display system housed in the ICon lab at Penn State

Fig. 2: Fully-immersive display system (image courtesy of ARL)

3.1 The Display Systems' Characteristics

To compare the systems the research team used in-house facilities located at the Pennsylvania State University. The *semi-immersive* display system, housed in the Immersive Construction Laboratory (ICon Lab) in the Architectural Engineering Department, has an open footprint space with three stereo-enabled 8 foot by 6 foot rear-projected screens joined at 135 degree angles. Each of the displays has a resolution of 1600 x1200, for a total system resolution of 4800 x1200. The display also features a user tracking system with an Xbox tracked controller which was used for the design review activity. Head tracking, however, was disabled during the design review to maintain a consistent viewpoint for all the participants.

The *fully immersive* display system located in the Synthetic Environment Applications Laboratory (SEA Lab) housed in the Applied Research Laboratory (ARL) has a 5-sided CAVE^{TM}-type immersive projection display system providing a 360-degree view. Each of the screens is 10 feet by 9 feet with a floor footprint of 10 feet by 10 feet. The display system also features user tracking with head tracked glasses and tracked navigation with an Xbox controller. Both display systems allow users to collaboratively interact with large 3D models and simulations in real-time.

3.2 The Design Review Procedure

The two labs hosted the team of nine participants including two future facility occupants, four owner's representatives, two architects, and a construction manager to review the design of a new building to house an academic department on a large university campus. The new four-story 72,000-square-foot building will contain offices, classrooms, meeting rooms, and a full height atrium. Particular attention in the design review was given to the 4 story atrium because of its interior architectural wooden cladding panel system. To prepare the virtual mockup for the design review, the 3D model developed by the project architects was imported by the research team into the Presagis Vega Prime^{TM} 3D visualization software through Autodesk 3D Studio Max (Figures 3 and 4). Once the model was imported, surrounding buildings and topography were added. Also, as requested by the review team, an interactive feature was added to the virtual mockup to allow changing the material appearance of the wooden panels located in the atrium (Figure 4).

The first design review was conducted in the fully-immersive (SEA) lab, where the project team reviewed the design by walking through the model, reviewing specific areas, and changing the textures in the atrium. The second design review followed in the semi-immersive (ICon) lab using the same walkthrough procedure of the same model. The walkthrough sequence, navigation, and the review process were kept consistent between the two labs. Following the design reviews, a total of three surveys were administered. Feedback was collected using both open-ended questions and 5-point Likert scale items ranging from strongly disagree to strongly agree. Figure 5 illustrates the sequence of the design review conducted by the project team.

Fig. 3: Virtual mockup – exterior view

Fig. 4: Atrium view with the wooden cladding

Fig. 5: Design Review Procedure

The first and the second survey administered at the conclusion of the design reviews in the fully- and the semi-immersive environment respectively, aimed to evaluate the effectiveness of the systems' attributes such as large screens, field of view, stereoscopy and level of immersion for the design review. The users were asked to rate their sense of presence in the virtual model; the sense of movement through the space; and the appropriateness of the scale of the model and its objects. Additionally, participants were asked to rate the usefulness of the ability to change the model textures. For each of the surveys, a total of 9 data points were collected. The last, third survey, administered after the second design review asked users to compare and rate the appropriateness of the two systems for different tasks such as design/construction/coordination reviews and different user groups. The first section aimed to directly compare the effectiveness and usability of the systems' immersive features. Participants were asked to rate how useful the 360^{o} field of view of the fully immersive system was compared to the 135^{o} field of view of the semi immersive system. The second section asked participants to rate the appropriateness of the two systems for future specific use cases such as small and large groups of users, operational staff, project teams, and contractors. Specifically, participants were asked to evaluate the two system types' suitability for the following types of reviews – design reviews with a small or large group of users, project team, and operational staff; construction reviews with a small or large group of contractors and project team; and coordination, clash, and trade meetings with a small or large group of contractors and project team.

4. RESULTS AND DISCUSSION

The results indicate very little variance in the overall highly rated effectiveness of the two systems, although the small sample size does not warrant significant statistical conclusions. The average ratings of the two systems indicate that the fully-immersive system slightly outperformed the semi-immersive system in providing a higher sense of presence and compelling sense of movement though the model (Figure 6). On the other hand, the semi-immersive environment was rated slightly higher for its higher screen resolution and the effectiveness of changing of the textures (Figures 6 and 7). While the large screen size was equally, highly rated in both systems, the team found the objects to be somewhat more properly sized in the semi-immersive environment, possibly due to the limitation of tracking only one person's viewpoint in the CAVE™. Overall, the data from the first two surveys indicate very little difference in the effectiveness of the two display systems for reviewing the design.

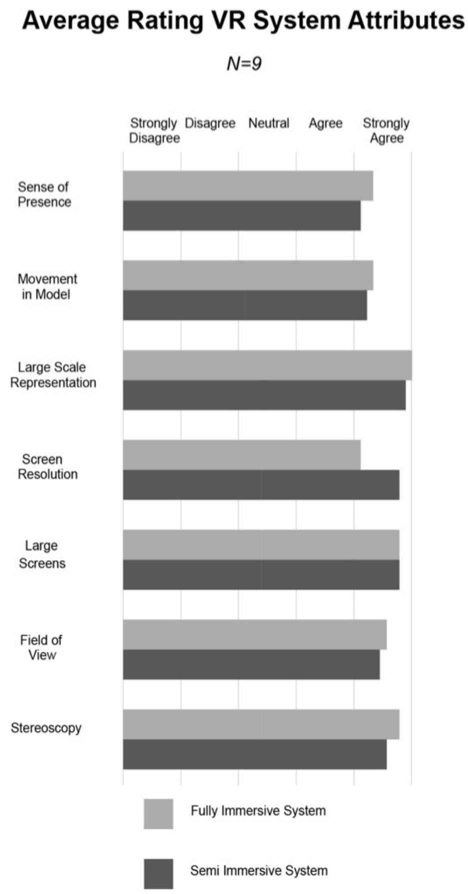

Fig. 6: Rated helpfulness of the two systems' VR attributes

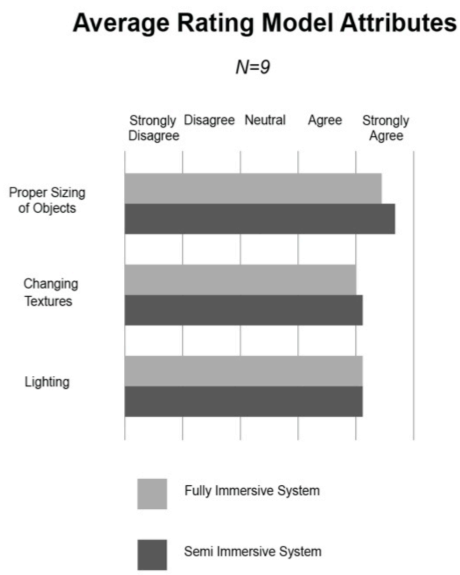

Fig. 7: Rated helpfulness of model attributes

The results from the third survey however, indicate potential differences in the suitability of the two labs for conducting different tasks with different user groups. The project team rated a fully-immersive environment to be slightly more appropriate in conducting future design reviews for smaller groups of users, project teams, and operational staff (Figure 8). However, the participants also confirmed that a semi-immersive system would be considerably more appropriate for larger groups of users, projects teams, and operational staff due to its open footprint. As shown in Figure 9, for conducting future construction reviews, the project team found the semi-immersive system marginally more appropriate for larger groups of contractors and project teams. Similar to future design reviews, the team found the semi-immersive system to be better suited for larger groups conducting clash and coordination reviews (Figure 10)

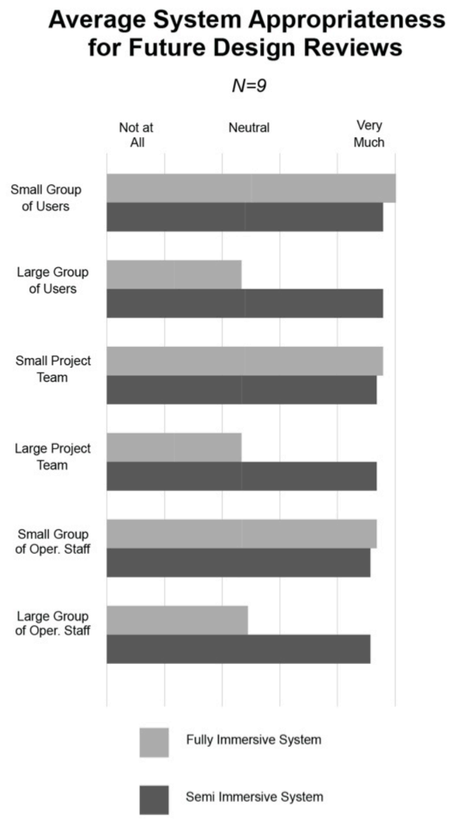

Fig. 8: Design Review Evaluation

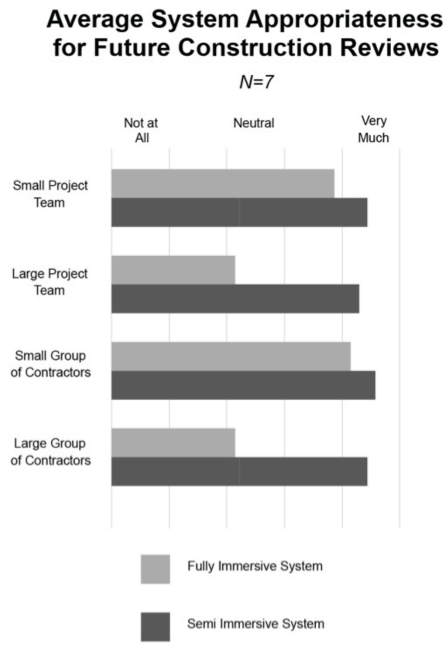

Fig. 9: Construction Review Evaluation

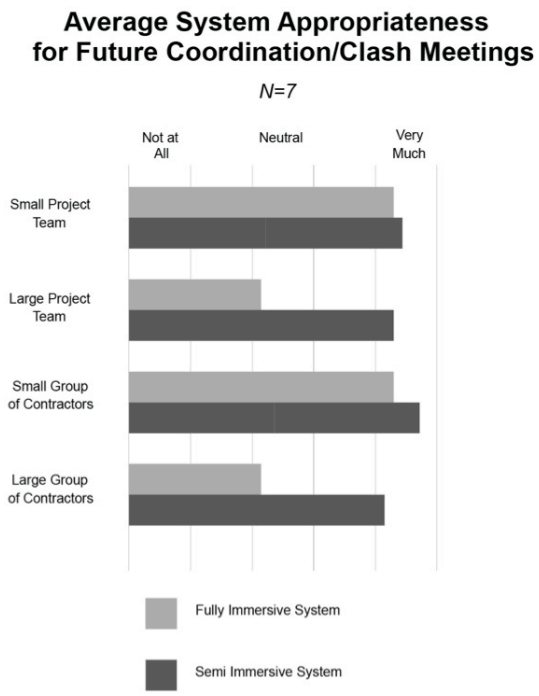

Fig. 10: Coordination/Clash/Trade Meeting Evaluation

The participants' comments provided additional insight into the results. Seven team members favored the surround, 360° field of view of the fully-immersive environment (4.89, N=9) compared to semi-immersive (3.89, N=9) because it allowed an easier movement inside the building and provided a higher sense of "reality". One participant commented that the fully immersive environment felt like being "inside" the model, while the semi-immersive environment felt like only viewing the model. On the other hand, while five participants felt the higher level of immersion was more valuable for the design review, three participants did not see an increased value. One of the participants who rated 360° field of view higher, commented that the wider field of view did not have a greater advantage overall. Lastly, one of the participants suffered from vertigo and expressed difficulty in conducting the review in the 360° field of view environment.

5. LIMITATIONS

Although the results indicate a relatively small difference in the overall effectiveness of the semi- and fully-immersive display systems for the design review task, there are a number of limitations of this case study. Design review is standard and a critical step in the design process. However, very rarely do design review teams have an option to use two different types of display systems. For the duration of this case study, the research team managed to find one project team who agreed to perform design review in both facilities. Therefore the data was collected from a small number of participants limiting the ability to draw broad conclusions about the effectiveness of the systems. In addition, the two design reviews were conducted successively with the review in the semi-immersive lab following immediately after the review in the fully immersive lab. While this ensured the participants were in the consistent "mood" and equivalent experience, the order of facilities may have impacted the participant perceptions of the two systems. For example, due to time constraints in both reviews, the participants may have identified different design issues in either of the systems, which may have affected their perception of the systems' effectiveness. Another limitation was the difference in the navigation methods used in the two systems. User-tracking was used in the fully-immersive but not in the semi-immersive system, where only the Xbox control was used for navigation. This difference in navigation method may have affected the users' sense of immersion.

6. CONCLUSIONS

The review of a proposed design is a critical step in the preconstruction phase. Identifying design errors through a high quality design review using VR in the early stages of design can yield considerable benefits. However, broad spectrum of VR systems ranging in configuration, cost, and features may present users with a challenge of choosing an appropriate system based on the task.

To gain a better understanding of the suitability of different immersive systems for specific uses in the AEC industry, the research team compared a semi-immersive and a fully-immersive system. While the sample size was limited (9 participants), the results indicate few difference in the effectiveness of the two systems. The large screens, field of view, level of immersion and the overall value of both systems for design reviews were rated consistently high. When group size and task are considered key differences were found. For example, based on the comments provided by the project team, the fully-immersive system was found to be more appropriate for smaller groups that desire a higher level of immersion. Furthermore, the semi-immersive system, which has a lower level of immersion, but a larger footprint, was found to be of higher suitability for larger groups for various use cases. These results should allow for future project teams to critically choose an immersive display system that suits their needs, whether it is a higher sense of immersion or larger footprint. The future steps will include conducting experiments with a larger group of different user groups in conducting design reviews of various types of facilities.

7. REFERENCES

Bowman, D.A., McMahan, R.P., 2007. Virtual Reality: How Much Immersion is Enough? Computer 40, pg. 36–42.

Coyne, R.F., Subrahmanian, E., 1993. Computer supported creative design: A pragmatic approach, in: Gero, J.S., Maher, M.L. (Eds.), Modeling Creativity and Knowledge-Based Creative Design. Hillsdale, NJ, Lawrence Erlbaum Associates, pg. 295–327.

Dunston, P.S., Arns, L.L., McGlothin, J.D., 2007. An Immersive Virtual Reality Mock-Up for Design Review of Hospital Patient Rooms, in: CONVR 2007. Presented at the Seventh International Conference on Construction Applications of Virtual Reality, Penn State University, University Park, PA, pg. 9.

East, W.E., 1998. Web-Enabled Design Review and Lessons Learned (No. CERL Report No. A 396443). Champaign, IL: U.S. Army Corps of Engineers Construction Engineering Research Laboratories.

Henry, D., Furness, T., 1993. Spatial Perception in Virtual Environments: Evaluating an Architectural Application, in: VRAIS '93 Proceedings of the 1993 IEEE Virtual Reality Annual International Symposium. IEEE, Washington, D.C., pg. 33–40.

Kalisperis, L.N., Otto, G., Muramoto, K., Gundrum, J.S., Masters, R., Orland, B., 2002. Virtual reality/space visualization in design education: the VR-desktop initiative, in: Proceedings of eCAADe2002, Design E-ducation: Connecting the Real and the Virtual. Warsaw, Poland, pg. 64–71.

Khemlani, L., Timerman, A., Benne, B., Kalay, Y.E., 1997. Semantically Rich Building Representation, in: Proceedings of ACADIA '97, Design and Representation. Cincinatti, Ohio, pg. 207-227.

Kumar, S., Hedrick, M., Wiacek, C., Messner, J.I., 2011. Developing an experienced-based design review application for healthcare facilities using a 3d game engine. ITcon Vol. 16, Special Issue Use of Gaming Technology in Architecture, Engineering and Construction, pg. 85-104.

Leicht, R., Messner, J., Anumba, C., 2009. A framework for using interactive workspaces for effective collaboration. ITcon, Special Issue Next Generation Construction IT: Technology Foresight, Future Studies, Roadmapping, and Scenario Planning 14, pg. 180–203.

Maldovan, K., Messner, J., 2006. Determining the effects of immersive environments on decision making in the AEC Industry, in: Joint International Conference on Computing and Decision Making in Civil and Building Engineering. Montreal, Canada.

Nikolic, D., 2007. Evaluating relative impact of virtual reality components detail and realism on spatial comprehension and presence (M.S. Thesis). The Pennsylvania State University, University Park, PA.

Rice, A., 2003. Exploring the Impact of Emerging Landscape Visualization Tools on Spatial Perception and Design Education, in: Buhmann, E., Ervin, S. (Eds.), Trends in Landscape Modeling. Heidelberg: Wichmann, pg. 173–182.

Shiratuddin, M.F., 2009. A Framework for Design Review in a Virtual Environment: Using Context Aware Information Processing. VDM Verlag.

Shiratuddin, M.F., Thabet, W., 2011. Utilizing a 3D game engine to develop a virtual design review system. ITcon Vol. 16, Special Issue: Use of Gaming Technology in Architecture, Engineering and Construction, pg. 39-68.

Shiratuddin, M.F., Thabet, W., Bowman, D., 2004. Evaluating the effectiveness of virtual environment displays for reviewing construction 3D models, in: CONVR 2004. Lisbon, Portugal, pg. 87–98.

Slater, M., Wilbur, S., 1997. A Framework for Immersive Virtual Environments (FIVE): speculations on the role of presence in virtual environments. PRESENCE: Teleoperators and Virtual Environments 6, pg. 603–616.

Tse, T.K., Wong, K.A., Wong, K.F., 2005. The utilization of building information models in nD modelling: A study of data interfacing and adoption barriers. Journal of Information Technology in Construction 10, pg. 85–110.

Whisker, V.E., Baratta, A.J., Yerrapathruni, S., Messner, J.I., Shaw, T.S., Warren, M.E., Rotthoff, E.S., 2003. Using Immersive Virtual Environments to Develop and Visualize Construction Schedules for Advanced Nuclear Power Plants, in: Proceedings of ICAPP '03. Presented at the International Congress on Advances in Nuclear Power Plants, Cordoba, Spain, May 4-7, 2003.

Whyte, J., 2003. Innovation and Users: Virtual Reality in the Construction Sector. Construction Management and Economics 21, pg. 565–572.

Yessios, C.I., 1987. The Computability of Void Architectural Modeling, in: Kalay, Y.E. (Ed.), Principles of Computer-aided Design: Computability of Design. Wiley-Interscience, pg. 141–172.

Zikic, N., 2007. Evaluating Relative Impact of VR Components Screen size, Stereoscopy and Field of View on Spatial Comprehension and Presence in Architecture (M.S. Thesis). The Pennsylvania State University, University Park, PA.