

# **VR & CONSTRUCTION**

**INVESTIGATING THE POTENTIAL OF IMMERSIVE  
VIRTUAL REALITY TECHNOLOGIES IN THE  
OPERATIONS OF MORTENSON CONSTRUCTION**

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## **INTRODUCTION / PROJECT STATEMENT**

This project is the result of two semesters of work, and is a combination of three related but separate components. The first, the spatial cognition in virtual reality experiment, spanned both semesters. It included an extensive review of literature on spatial cognition in virtual reality, the design, execution, and documentation of an experiment involving 40 subjects, and the analysis of the acquired data. This experiment was the source of inspiration for the second component, a proposal for a portable kit which facilitates an immersive virtual environment. This kit is now approaching development. Finally, it became necessary to understand how emerging immersive virtual reality technology would fit into and improve Mortenson's construction activities. Therefore, the third component is an analysis of Mortenson Construction's use of virtual technology in the design of construction.



# **SPATIAL COGNITION IN VIRTUAL REALITY: DEVELOPING AN EVALUATION TECHNIQUE FOR REPRESENTATIONAL METHODS OF VIRTUAL MODELS**



## **ABSTRACT**

Significant advances in technology driving head mounted displays (HMD's) have greatly increased the quality of immersive virtual environments (IVE's) while drastically lowering the cost to achieve them. Presently, the established experiments employed to quantify the ability of HMD facilitated IVEs to create an accurate perception of scale and spatial relationships are limited, by and large, to measuring egocentric distance perception. This paper proposes a new experiment which was employed to test the ability of three mediums of representation to facilitate the memorization of the spatial characteristics of a 3D virtual environment respective to the human body. Those mediums are (1) a conventional 2D screen, (2) a fully immersive virtual environment viewed through a head mounted display, where navigation is accomplished via hand controls, and (3) a fully immersive virtual environment, viewed through a head mounted display, where navigation is accomplished via one-to-one physical movement. Additionally, a real environment identical to the virtual environment is tested. The experiment was conducted by asking participants to view a simple 3D model (several rectangular solids arranged on a plane) through one of the three mediums of virtual representation, or in a real environment. After viewing the 3D model, participants were asked to recreate the arrangement of the solids in a real environment. Though the proposed experiment tests various immersive environments against each other, the experiment may prove most valuable in measuring iterative changes made to a single HMD or the IVE which it creates.

# DISCUSSION

## Discussion

Immersive virtual environments (IVEs) are recognized as potentially useful in many industries, such as manufacturing<sup>1</sup>, engineering<sup>2</sup>, and architecture<sup>345</sup>. IVEs' usefulness is attributed to their ability to accurately simulate scale and depth from an egocentric viewpoint. IVEs are often created by displaying a virtual model via a head mounted display (HMD). HMDs employ a stereoscopic display which ideally facilitates a wide field of view. When combined with computer generated graphics which simulate depth cues such as shading, perspective, and occlusion, HMDs which create IVEs are considered superior to desktop displays at facilitating a realistic sense of 3 dimensional (3D) space<sup>6</sup>.

Though IVEs have existed for over 20 years, they have not experienced widespread adaptation. This is primarily due to the prohibitive expense and effort of facilitating IVE's, the inability of those IVE's to create sufficient sense of presence (usually due to a combination of a low field of view, low screen resolution, low refresh rate and/or poor positional tracking, and the cumbersome nature of the equipment.) Recently, the technology required to facilitate a satisfactory IVE has become or will become available at a cost which will make IVEs widely available. The architecture, engineering, and construction industries (AEC) especially stand to benefit from this increase of availability and decrease in cost, as it will allow designers, builders, and clients greater access to IVEs which can help them experience an architectural space as they would in real life, before it is built.

However, using IVEs in such a way requires that the IVE facilitate a veridical perception of distance, scale, and spatial relationships. The Literature on spatial perception in IVEs is extensive;

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1 B. Korves and M. Loftus, "Designing an immersive virtual reality interface for layout planning," *Journal of Materials Processing Technology*, V 107, (2000) 425-430

2 John I. Messner, et al., "Using Virtual Reality to Improve Construction Engineering Education (Proceedings of the 2003 American Society for Engineering Education Annual Conference & Exposition, 2003).

3 Gerd Bruder, et al., "Immersive Virtual Studio for Architectural Exploration," (Paper presented at the IEEE Symposium on 3D User Interfaces, Waltham, Massachusetts, USA 2010 20-21 March).

4 May Bassanino, et al., "The Impact of Immersive Virtual Reality on Visualization for a Design Review in Construction," 2010 14<sup>th</sup> International Conference Information Visualization (10.1109/IV.2010.85)

5 Mark P. Mobach "Do virtual worlds create better worlds?," (2008): accessed November 2013, DOI 10.1007/s10055-008-0081-2

6 Michael Mullins, "Interpretation of simulations in interactive VR environments," *Journal of Architectural and Planning Research* (Winter, 2006) 328-49



several quality reviews exist.<sup>7 8 9 10</sup> As these (and many other) papers describe, there is a consistent tendency for viewers of IVEs using HMDs to underestimate egocentric distance within IVEs. Waller and Richardson (2008)<sup>11</sup> reported that across 14 papers they reviewed, subjects estimated distance within IVEs to be 71% of actual, on average. This tendency remains unexplained, though the literature reveals a set of IVE design considerations which may help alleviate the distance underestimation problem. These include equipping users with a high-fidelity virtual avatar<sup>12</sup>, asking subjects to estimate distances when the IVE they view is a high-fidelity replica of the physical room they are actually in<sup>13</sup>, providing subjects with feedback on how well they had estimated distances previously<sup>14 15</sup>, traversing the estimated distance either with a joystick or by walking<sup>16</sup>, and by, providing subjects with a brief, closed-loop period of interaction within the IVE, during which they navigate the IVE physically before estimating distance.<sup>17</sup> Additionally, not specific to distance estimation but significant for spatial cognition, it was found that physical turning of the body was very important in accumulating accurate directional information (as opposed to using virtual means, such as a joystick.)<sup>18</sup>

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7 Adam R. Richardson and David Waller, "The Effect of Feedback Training on Distance Estimation in Virtual Environments", *Appl. Cognit. Psychol.* 19, (2005): 1089–1108

8 Adam R. Richardson and David Waller, "Correcting Distance Estimates by Interacting With Immersive Virtual Environments: Effects of Task and Available Sensory Information," *Journal of Experimental Psychology: Applied*, Vol. 14, No. 1 (2008):, 61–72

9 Richardson and Waller (2008)

10 J. Edward Swan et. al, "The influence of feedback on egocentric distance judgments in real and virtual environments," *IEEE Transactions on visualization and computer graphics*, (May/June 2007): V. 13, N. 3, 429-442

11 Richardson and Waller (2008)

12 Brian Ries et al., "Analyzing the Effect of a Virtual Avatar's Geometric and Motion Fidelity on Ego-Centric Spatial Perception in Immersive Virtual Environments," (Paper presented at VRST 2009, Kyoto, Japan, November 18 – 20, 2009)

13 Lane Phillips, et al., "Distance perception in NPR immersive virtual environments, revisited." In *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization*, pp. 11-14. ACM, 2009.

14 Richardson and Waller (2008)

15 J. Edward Swan et. al (2007)

16 Bob G. Witmer and Paul B. Kline, "Judging Perceived and Traversed distance in virtual environments," *Presence*, (April 1998) V. 7, N. 2, 144–167

17 Richardson and Waller (2008)

18 Fredrik Wartenberg, Mark May, and Patrick Péruch. "Spatial orientation in virtual environments: Background considerations and experiments." In *Spatial cognition*, pp. 469-489. Springer Berlin Heidelberg, 1998.



Loomis and Knapp (2003)<sup>19</sup> note that visually perceived distance, direction, and location are all aspects of consciousness, and as such, cannot be measured directly. Because of this, several experiments have been devised which use a variety of methods to test subject's abilities to correctly estimate distance. Swan et al. review and categorize those experiments.<sup>20</sup> There are three primary categories of experiments employed: Verbal report, perceptual matching, and open loop action based experiments. Verbal report experiments<sup>21, 22, 23</sup> require subjects to view and/or move through a scene and verbally report estimates of distances to objects within the scene. Perceptual matching experiments<sup>24, 25, 26</sup> require participants to view an object virtually and subsequently (or simultaneously) manipulate a physical object to match some specified, visually ascertainable property of the virtual object (e.g., distance from viewer.) These types of experiments are considered closed loop – that is, subjects complete an action while receiving visual feedback on their performance. Open loop action based experiments<sup>27, 28, 29</sup> are defined as an experiment where a subject

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19 Jack M. Loomis and Joshua M. Knapp. "Visual perception of egocentric distance in real and virtual environments." *Virtual and adaptive environments* 11 (2003): 21-46.

20 J. Edward Swan et. al (2007)

21 Ivelina V. Alexandrova, et al. "Egocentric distance judgments in a large screen display immersive virtual environment." In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*, ACM (2010): pp. 57-60.

22 Witmer and Kline (1998)

23 Henry, Daniel, and Tom Furness. "Spatial perception in virtual environments: Evaluating an architectural application." In *Virtual Reality Annual International Symposium*, 1993 IEEE. 33-40.

24 Wu, Bing, Teng Leng Ooi, and Zijiang J. He. "Perceiving distance accurately by a directional process of integrating ground information." *Nature* 428, no. 6978 (2004): 73-77.

25 McCandless, Jeffrey W., Stephen R. Ellis, and Bernard D. Adelstein. "Localization of a time-delayed, monocular virtual object superimposed on a real environment." *Presence: Teleoperators and Virtual Environments* 9, no. 1 (2000): 15-24

26 Marc Schnabel and Thomas Kvan, "Spatial understanding in immersive virtual environments," *International Journal of Architectural Computing*, Vol. 04, No. 1 (2003): 435-448.

27 Lane Phillips, et al. (2009)

28 Brian Ries et al., "Analyzing the effect of a virtual avatar's geometric and motion fidelity on ego-centric spatial perception in immersive virtual environments." In *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology*, pp. 59-66. ACM, 2009.

29 Thompson, et al., "Does the quality of the computer graphics matter when

completes an action without visual feedback. One of the most common types of open loop, action based experiments used when measuring distance perception in IVEs is blind walking. In the blind walking experiment, a subject is shown the location of a mark or target virtually, the HMD is turned off, and the subject is asked to walk to where they remember the mark being. This experiment has been shown to be valid up to around 20m<sup>30</sup>. It should be mentioned, however, that criticisms of the blind walking test exist. In their study, Saham and Creem-Regehr note that "[as of 2005,] blind walking is the only visually directed action task that has been used to evaluate distance perception in VEs beyond reaching distances. The possible influence of the response measure itself on absolute distance perception in virtual environments is currently an open question."<sup>31</sup> Philbeck suggests that this method of testing may be inaccurate. According to his study, "blindfolded walking responses are themselves likely to change the calibration of walking during lengthy experiments."<sup>32</sup>

These experiments are primarily designed to measure subject's ability to accurately perceive egocentric distance. Literature on spatial cognition distinguishes egocentric perception from allocentric (also called exocentric) perception. In an egocentric reference frame, objects are located with respect to a viewer, while in an allocentric reference frame, objects are located within a framework irrespective of the location of that viewer.<sup>33</sup> Simply put, egocentric distance is between a viewer and a point, from the point of view of that viewer, while an allocentric distance is that between two points.

Humans develop a spatial understanding of their environments by integrating information from their egocentric viewpoint with proprioceptive feedback to update their position in allocentric space.<sup>34</sup> This allows us to formulate a mental map of the environment we inhabit. This is an important point, because it highlights the fact that while egocentric distance perception is an important factor in spatial cognition, quantifying the accuracy of a viewer's perception of both allocentric and egocentric relationships is likely to be a more thorough

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judging distances in visually immersive environments?." *Presence: Teleoperators and Virtual Environments* 13, no. 5 (2004): 560-571.

30 Loomis and Knapp (2003)

31 Cynthia S. Sahm, et al., "Throwing versus walking as indicators of distance perception in similar real and virtual environments," *Transactions on Applied Perception (TAP)* 2, no. 1 (2005): 35-45.

32 John W. Philbeck, "Rapid recalibration of locomotion during non-visual walking," *Journal of Vision* 5, no. 8 (2005): 308-308.

33 Klatzky, Roberta L. "Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections." In *Spatial cognition*, pp. 1-17. Springer Berlin Heidelberg, 1998.

34 Gallistel, Charles R. *The organization of learning*. The MIT Press, 1990.

metric for evaluating IVEs' ability to facilitate a vertical perception of architectural space.

As was noted earlier, HMD technology is improving rapidly and is also becoming much less expensive. Therefore, the ability to iteratively modify HMDs and the IVEs they facilitate is becoming much more accessible. A test which is able to quantify the improvements (or regressions) in overall spatial cognition by HMD users would potentially be very useful, as it could allow developers of HMDs to metrically evaluate the impact of HMD and/or IVE interface modifications.

This paper documents an experimental design which is a proposal for such a test. The proposed experiment is loosely based on the perceptual matching experiment completed by Schnabel and Kvan<sup>35</sup> in which they used a cube, based on a 4"x4"x4" grid, which was comprised of 8 different colored "cuboids," each of a unique shape. In this test, subjects studied an enlarged representation of the cube in plan, on a screen, or in an immersive environment, and were subsequently asked to attempt to rebuild the cube with colored wooden blocks at the 4"x4"x4" scale.

This test measured subjects' ability to understand complex spatial relationships but did not test egocentric or allocentric distance perception. To change that characteristic, the 4"x4"x4" cube is replaced with an inhabitable space containing both mass and void. The result is an experiment which tests subjects' ability to accurately perceive egocentric and allocentric distance and spatial relationships simultaneously.

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35 Marc Schnabel and Thomas Kvan, Spatial understanding in immersive virtual environments," *International Journal of Architectural Computing*, Vol. 04, No. 1 (2003): 435-448.

## METHODOLOGY

The experiment was broken into two phases. In the first phase of the experiment, the memorization phase, subjects viewed and attempted to memorize a model for 3 minutes. Immediately after viewing this “memorization model,” the second phase began. In the second phase, or building phase, each subject was asked to attempt to build a full scale replica of the model they had attempted to memorize. The subjects were given as much time as they needed to build the physical test model.

Three different virtual representational mediums were tested during the memorization phase – a 2D screen (fig. 13.1) and two fully immersive environments facilitated by a head-mounted display. The first immersive environment was navigated by using a joystick while sitting on a swivel chair (fig. 13.2), and the second was navigated by walking (fig. 13.3). (The position of the subject was tracked in real time with a camera array.)

Additionally, a physical representation was tested during the memorization phase, where instead of viewing a virtual model, subjects were shown a full scale physical model arranged precisely in the same way as the virtual model (fig. 13.4).

### **Software:**

The virtual environment for the experiment was modeled using Sketchup 8, and then imported to a custom program written in the gaming platform Unity. The program included an interior environment, which was a high fidelity replica of the actual environment subjects were in (the courtyard of the University of Minnesota’s Rapson Hall.) Additionally, the test model was placed within the interior environment, on the floor of the courtyard. The test model was placed differently for each test, to correspond to the position the subjects would actually be in in the real courtyard environment.

### **Hardware:**

#### **2D screen test**

Subjects used a Dell Precision laptop computer with a 2.67 Intel Xeon 2.67 GHz quad core processor and 22.5 GB of Ram. A usb mouse was used to navigate the test model.

#### **Head mounted display – seated joystick navigation**

Subjects used a first generation oculus rift development kit headset and a 3D connexion Spacenavigator mouse, which allowed for forward and backwards movement.

#### **Head mounted display – motion tracked walking navigation**

Subjects were equipped with a sensics headset and were tracked using the UMN 36 camera phasespace tracking array



Fig. 13.1: 2D Screen



Fig. 13.2: Fully immersive environment navigated by joystick



Fig. 13.3: Fully immersive environment navigated by walking



Fig. 13.4: Physical representation

### **Measurements of the Physical model**

Measurements were performed using a Bosch measuring laser.

#### **Physical test model (fig. 15.1)**

The physical test model consisted of a 25' – 0" x 20' – 0" black floor covering, a white reference volume, a red, 1'-0" x 3'-0" reference strip, and (4) brown test volumes. The objects which were used as reference and test volumes are known in the University of Minnesota's School of Architecture as "homosote panels," referring to the material that make up their sides. They are 4'-0" wide x 1'-5" deep x 8'-3" tall rectangular volumes with casters attached to the bottom to allow the panel to be moved around easily. They are typically used to create smaller spaces within the larger common areas, such as the courtyard, for critiques and pin-ups, and are very familiar to all of the subjects who were tested. The reference volume was made of one of these homosote panels, which was then covered in white paper and turned upside down, so that it could not be moved easily.

#### **Memorization model (fig. 15.2, 15.3)**

The memorization model was either virtual, for the three virtual tests, or physical, for the control test. For the virtual model, each of the elements of the physical test model were modeled virtually in a dimensionally accurate manner. For the control test, a duplicate of the physical test model was constructed. The virtual and physical memorization models were arranged identically.

### **Subjects**

40 Participants were tested. 10 subjects were used for each test – the three virtual tests and the control test. Subjects were either first or second year graduate students in the M.Arch program at the University of Minnesota. 5 first year and 5 second year subjects were used for each test. In the 2d screen test, 7 males and 3 females were tested. In the control test, 6 males and 4 females were tested. In the seated immersive test, 4 males and 6 females were tested. In the tracked immersive test, 6 males and 4 females were tested.





Fig. 15.1: The physical test model

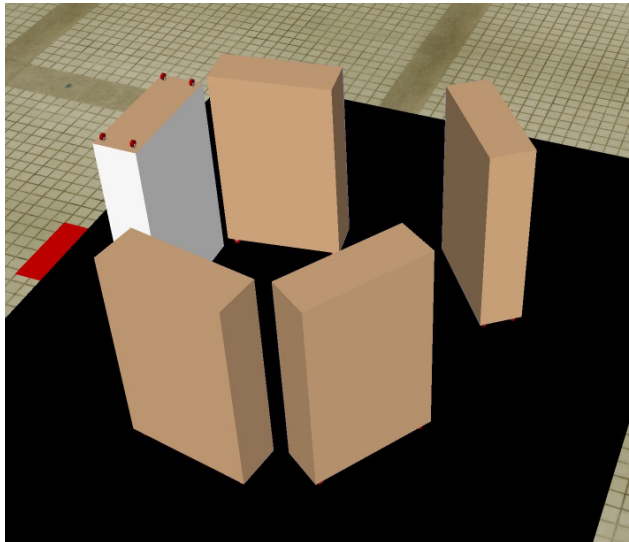


Fig. 15.2: The virtual memorization model



Fig. 15.3: The physical memorization model



## **Test protocol**

An email was sent to every first and second year graduate student in the University of Minnesota's M.Arch program prior to the commencement of the experiment.

To acquire subjects, it was necessary to go from the courtyard of Rapson Hall to the graduate studio, located on the third floor. Subjects were approached in the first and second year sections, at random (except that for each experiment, 5 first year students and 5 second year students were tested.) Subjects were asked if they would be willing to participate in the experiment. If they were not, they were not asked again. Students who were willing to participate were asked to join the tester in the courtyard. On the way down from the studio to the courtyard, the tester explained the purpose and scope of the research, and which experiment they would be tested in.

Once the subject arrived in the courtyard, it was explained that the experiment would involve two phases. In the first phase, they would be viewing and attempting to memorize a virtual or physical model (the memorization model.) In the second phase, they would be asked to attempt to recreate the spatial arrangement of the memorization model by manipulating the physical test model. They were introduced to the physical test model, and they were shown each of the components that made up the model – Floor covering, reference strip, reference volume, and test volumes. It was explained to subjects that they would only be manipulating the test volumes, and that they should attempt to memorize the spatial arrangement of the test volumes respective to the reference volume in the first phase of the experiment. They were then told they would have 3 minutes to memorize the model in the first phase, and as long as they needed to reproduce that model in the second phase. Subjects were asked if they understood, and once they responded with an affirmative, they were asked to sign a consent form. After obtaining consent, the subject was introduced to the first phase of the experiment.

### **Virtual Model: 2D screen (fig. 17.1)**

Each subject was seated at the test table, with the Rapson hall virtual environment loaded, but not the test model. A piece of paper which listed the commands they had available to use was provided. Each subject was asked to familiarize themselves with the navigation of the virtual courtyard. Once they said that they had, they were asked to navigate so that their virtual view of the courtyard model corresponded to their actual, physical position in the real courtyard. Once this task was completed, they were again told that they would have 3 minutes to memorize the test model, and that the tester would notify them when each minute passed. Subjects were asked if they were ready, and when they responded with an affirmative, the keystroke combination (ctrl+e) that would make the test model appear was pressed and the timer was started. Once 3 minutes elapsed, the subject was notified and directed to the second phase of the experiment, the building phase.



Fig. 17.1: Virtual Model: 2D screen experiment setup

### **Virtual Model: Head mounted display, joystick navigation (fig. 19.1)**

Each subject was seated at the test table, with the Rapson hall virtual environment loaded, but not the test model. The seat was a chair mounted on a spindle, so the participant could rotate 360 degrees while seated. They were first introduced to the 3D mouse they would be using as a joystick, and then equipped with the oculus rift. The joystick was handed to them, and they were told they could move forwards and backwards by using the Joystick, and to rotate on the chair and look around to steer. The tester held the cords for the joystick and the Oculus Rift above the heads, so the subjects would be able to rotate freely without becoming tangled. Each subject was asked to familiarize themselves with the navigation of the model. Once they said that they had, they were asked to navigate so that their virtual view of the courtyard model corresponded to their actual, physical position in the courtyard. Once this task was completed, they were again told that they would have 3 minutes to memorize the test model, and that the tester would notify them when each minute passed. Subjects were asked if they were ready, and when they responded with an affirmative, the keystroke combination (ctrl+e) that would make the test model appear was pressed and the timer was started. Once 3 minutes elapsed, the subject was notified and directed to the second phase of the experiment, the building phase.

### **Virtual Model: Head mounted display, walking navigation (fig. 19.2)**

Each subject was equipped with a backpack containing the computer which ran the head mounted display, and then the head mounted display. They were asked to navigate the model of the courtyard by walking until they felt comfortable, and were then asked to return to the position they were equipped with the backpack and head mounted display in. Once this task was completed, they were again told that they would have 3 minutes to memorize the test model, and that the tester would notify them when each minute passed. Subjects were asked if they were ready, and when they responded with an affirmative, the keystroke combination (ctrl+e) that would make the test model appear was pressed and the timer was started. Once 3 minutes elapsed, the subject was notified and directed to the second phase of the experiment, the building phase. (fig 19.3)



Fig. 19.1: Virtual Model: Head mounted display, joystick navigation experiment setup

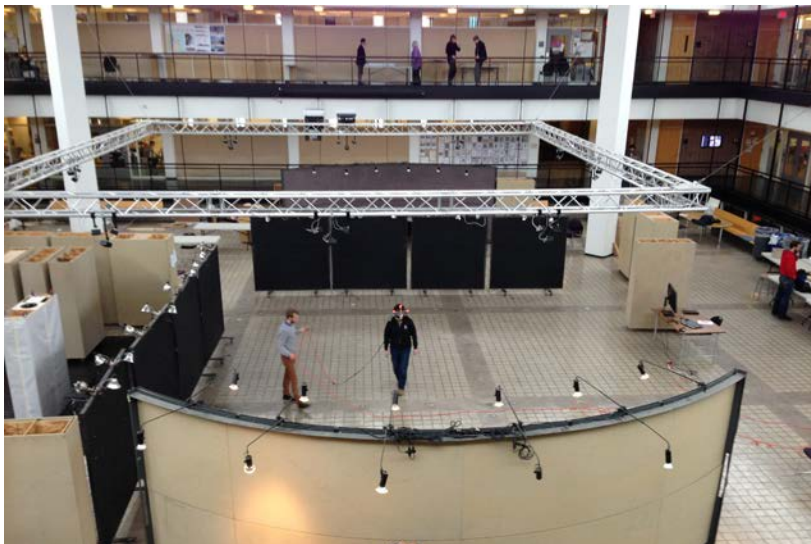


Fig. 19.2: Virtual Model: Head mounted display, walking navigation experiment setup (memorization phase area)



Fig. 19.3 Virtual Model: Head mounted display, walking navigation experiment setup (building phase area, adjacent to memorization phase area)

### **Control test (fig. 21.1)**

A wall composed of movable panels was arranged to obscure the subject's view of the test model. Once each subject had been introduced to the physical signed the consent form, it was explained to them that they would have 3 minutes to memorize the test model, and that the tester would notify them when each minute passed. Each subject was asked if they were ready to begin, and when they responded with an affirmative, they were asked to go around the obscuring wall and the timer was started. Once 3 minutes elapsed, the subject was notified and directed to the second phase of the experiment, the building phase.

### **End of Experiment**

Once the subject had determined that they were finished with the building phase, they were asked to fill out a questionnaire and thanked. This ended each subject's involvement with the experiment.

### **Data capture (fig. 21.2)**

To record the position of the volumes after the building phase, a measuring device was designed and fabricated. The device consisted of an acrylic ring marked with 360 degrees and an acrylic disk which fit inside the ring, which was cut to hold a Bosch laser measuring device in place, and scored to be able to read a degree measurement. This device was affixed to the top of the reference volume. To record the position of the test volumes, the laser was rotated until it was aimed precisely at one of the pegs affixed to the upper corners of each test volume, and a degree measurement and distance measurement was taken. Two pegs were measured for each test volume, and recorded on a record sheet (fig. 21.3)

### **Reset**

Once the position of the test volumes had been acquired and recorded, the physical test model was reset to its original position, and the next subject was acquired.





Fig. 21.1 Control test setup.

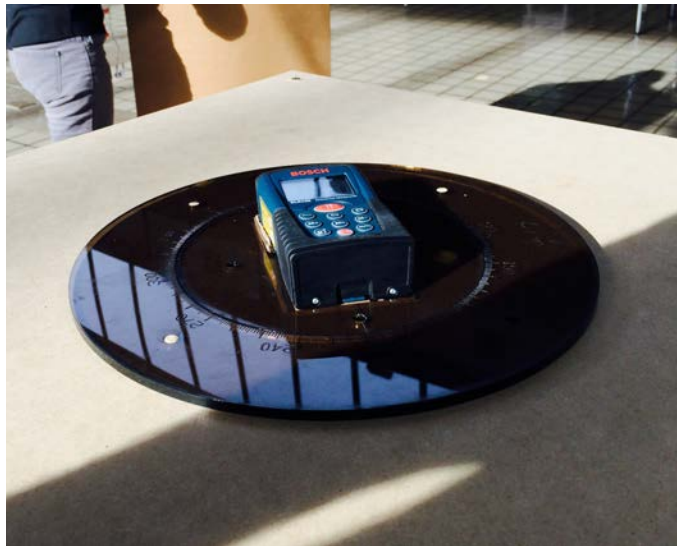


Fig. 21.2 Measuring device



Fig. 21.3 Data capture

## ANALYSIS

The results of the experiment were analyzed by translating the collected data into digital plan diagrams using the visual scripting program grasshopper, a plugin to the 3D modeling program Rhino 5. A script was written which accepted the vector data of the target locations of each test volume as inputs, and output plan diagrams of the test results as well as displacement from the ideal location of the test volume. This was taken as the sum of the distance of the two target locations from their ideal locations. An analysis of variance (ANOVA) was performed on the results. The ANOVA was computed for two different interpretation methods. The first was by considering each test volume as a unique experiment. The results of each test (control, Sensics, Rift, Dell) were compared across the same volume. This was done because the difficulty of placing the volumes accurately with respect to their ideal location was different for each volume, and because due to data collection error, there were different sample sizes for each volume and test. None of the tests could be considered statistically significant when analyzed this way. The mean of the displacement for each volume and test and the corresponding P value is shown in table 23.1, and the volume numbering system is shown in figure 23.2.



CONTROL				
VOLUME 1	VOLUME 2	VOLUME 3	VOLUME 4	
0.66	0.51	2.05	1.50	
1.82	2.02	1.57	2.05	
2.32	3.54	5.23	4.74	
1.70	3.37	4.29	2.38	
1.06	2.34	4.82	3.37	
3.48	1.45	1.41	1.73	
0.56	0.65	1.58	0.44	
0.83	0.79	2.66	2.19	
0.83	2.78	1.99	0.88	
3.57		8.32	2.71	
# of samples	10	9	10	10
mean deviation	1.68	1.94	3.39	2.20

SENSICS				
VOLUME 1	VOLUME 2	VOLUME 3	VOLUME 4	
0.87	2.95	2.53	2.79	
0.69	1.47	2.19	1.20	
1.70	0.96	2.49	1.44	
1.02	2.43	3.00	2.31	
4.04	2.52	2.81	1.37	
1.32	3.31	4.70	1.00	
1.30	7.67	3.51	4.13	
4.82		1.74	1.10	
		4.36	5.02	
# of samples	8	7	9	9
mean deviation	1.97	3.04	3.04	2.26

RIFT				
VOLUME 1	VOLUME 2	VOLUME 3	VOLUME 4	
1.43	2.89	3.26	3.67	
6.29	4.41	3.58	0.95	
3.06	5.09	1.06	3.01	
1.88	2.48	4.44	3.45	
1.94	1.49	3.36	0.73	
0.56	2.12	4.16	0.97	
7.33	4.70		3.54	
1.61	2.62		2.18	
0.76			1.51	
4.07			1.74	
# of samples	10	8	6	10
mean deviation	2.89	3.23	3.31	2.17

DELL				
VOLUME 1	VOLUME 2	VOLUME 3	VOLUME 4	
0.84	2.04	1.77	1.63	
5.15	1.99	4.16	2.52	
1.88	0.35	3.51	4.78	
2.34	4.62	1.44	2.66	
3.09	5.45	2.56	4.32	
1.10	7.97	6.03	2.64	
0.78	1.79	4.15	5.36	
		3.82	2.75	
		4.19		
		3.92		
# of samples	7	7	10	8
mean deviation	2.17	3.46	3.55	3.33

	VOLUME 1	VOLUME 2	VOLUME 3	VOLUME 4
P value	0.46	0.37	0.91	0.2

Table 23.1: per-volume analysis

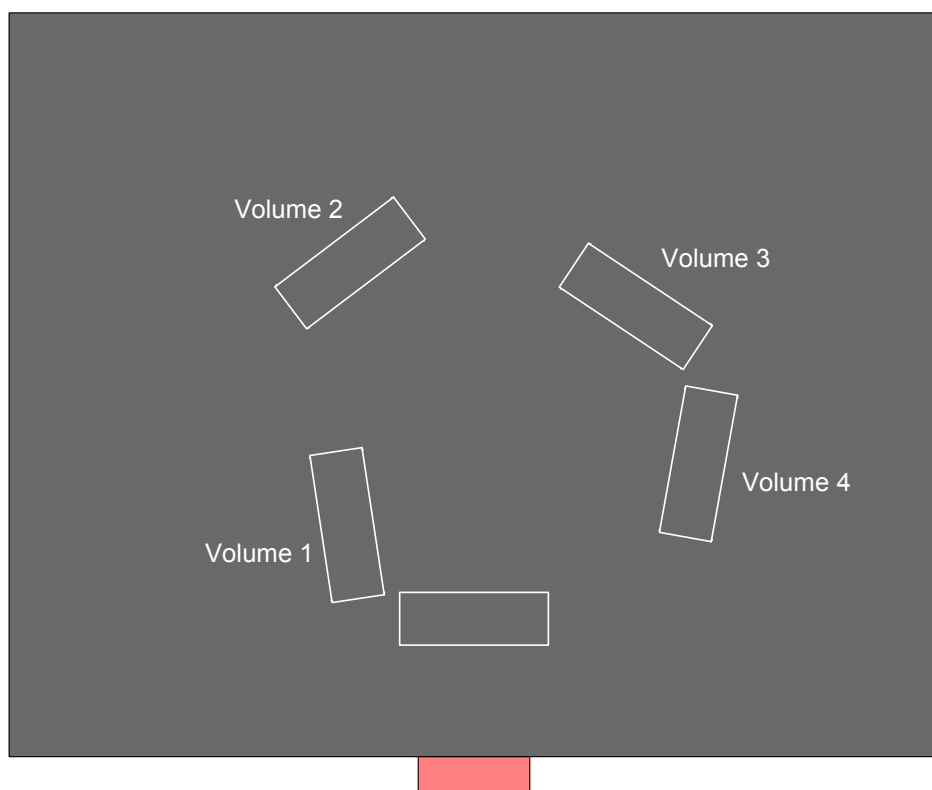


Figure 23.2: volume numbering system

## CONCLUSION

The data was also analyzed by considering each test as a whole. The mean displacement for all volumes respective to their ideal locations per test (control, Sensics, Rift, Dell) were considered. Because the volume difficulty was different, and there were different sample sizes for each volume, the data is likely skewed. (The tests which had more data for the more difficult locations probably had their means raised as compared to the tests which had less data for the more difficult locations. Despite this, the ANOVA ran on the data in this manner reported a P value of .154, which is still not statistically significant but is much closer to being so. Table. 25.1 shows data points which had to be thrown out in red.

Mean displacement for all volumes per test is as follows:

Control Test: 2.31'  
Tracked immersive 2.57'  
Seated immersive 2.83'  
2D screen 3.18'

This data is represented graphically in figure 27.1.

CONTROL			
VOLUME 1	VOLUME 2	VOLUME 3	VOLUME 4
0.66	0.51	1.77	1.50
1.82	2.02	4.16	2.05
2.32	3.54	3.51	4.74
1.70	3.37	1.44	2.38
1.06	2.34	2.56	3.37
3.48	1.45	6.03	1.73
0.56	0.65	4.15	0.44
0.83	0.79	3.82	2.19
0.83	2.78	4.19	0.88
3.57	4.48	3.92	2.71

Table 25.1: Data which had to be discarded (in red)

SENSICS			
VOLUME 1	VOLUME 2	VOLUME 3	VOLUME 4
0.87	2.95	2.53	2.79
0.69	1.47	2.19	1.20
1.70	4.62	3.31	1.44
1.02	0.96	2.49	2.31
4.04	6.85	3.00	1.37
1.32	2.43	2.81	1.00
2.69	6.97	4.70	4.13
1.30	2.52	3.51	2.96
2.49	3.31	1.74	1.10
4.82	7.67	4.36	5.02

RIFT			
VOLUME 1	VOLUME 2	VOLUME 3	VOLUME 4
1.43	2.89	3.26	3.67
6.29	5.09	11.41	0.95
3.06	4.41	3.58	3.01
1.88	5.09	2.25	3.45
1.94	2.48	1.06	0.73
0.56	5.64	9.08	0.97
7.33	1.49	4.44	3.54
1.61	2.12	3.36	2.18
0.76	4.70	1.90	1.51
4.07	2.62	4.16	1.74

DELL			
VOLUME 1	VOLUME 2	VOLUME 3	VOLUME 4
0.84	2.04	1.77	1.63
7.98	5.47	4.16	2.52
5.15	1.99	3.51	4.78
1.88	7.37	1.44	2.84
1.15	0.35	2.56	2.66
2.34	4.62	6.03	7.45
6.13	5.45	4.15	4.32
3.09	7.97	3.82	2.64
1.10	1.79	4.19	5.36
0.78	5.25	3.92	2.75

It is my opinion that if the test were successfully run more cleanly with the same number of participants (I.E., no mistakes were made during data collection and no data had to be thrown out,) the test would have shown to be statistically significant. Though the results of this experiment cannot be considered statistically significant, the spread of the results when each test is analyzed as a whole suggests that the experiment could be modified to become valid. It will be important to attempt a modified version of this experiment in the near future to build upon the findings of the current experiment. In the context of the rapid advancement of affordable, highly capable head mounted displays and tracking systems currently taking place, this experiment may prove more valuable not in testing different virtual display technologies against each other, but in testing the impact of improvements made to a specific IVE system. This could include changes to a specific head mounted display, additions to the immersive experience, such as hand and / or body tracking, auditory feedback, etc.

For this experiment to become such a tool, the design of the experiment will need to be refined. The experiment could likely be modified to be simpler and quicker (I.E., using fewer test volumes which were a similar level of difficulty, or perhaps even just one test volume.) This would potentially reduce the complexity of the test and decrease the number of ways to interpret the data. Also, refining the logic behind the placement of test and reference volumes, the scale of the volumes and experimental area, variation within the size and shape of volumes, developing a more consistent data recording protocol, and building a streamlined data analysis script or program could help this experiment become very useful.

### **The next steps:**

Following the completion of the spatial cognition in virtual reality experiment, I wanted to be able to steer my research towards something which would be more directly beneficial to Mortenson – in Mortenson's professional jargon, this meant something which would add value to their customers. After completion of the experiment, I also realized that Mortenson was in a unique position to be one of, or perhaps the first, construction company to be wielding a purpose – built, inexpensive, and easy-to operate from within-house immersive virtual environment. The proposal for that device is what follows.

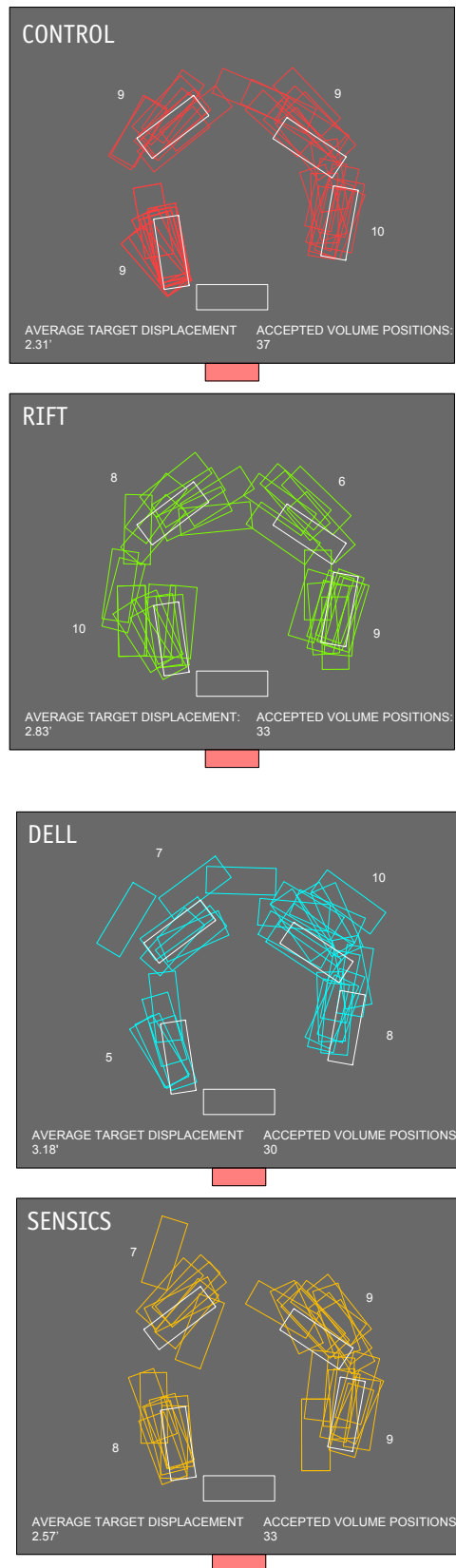
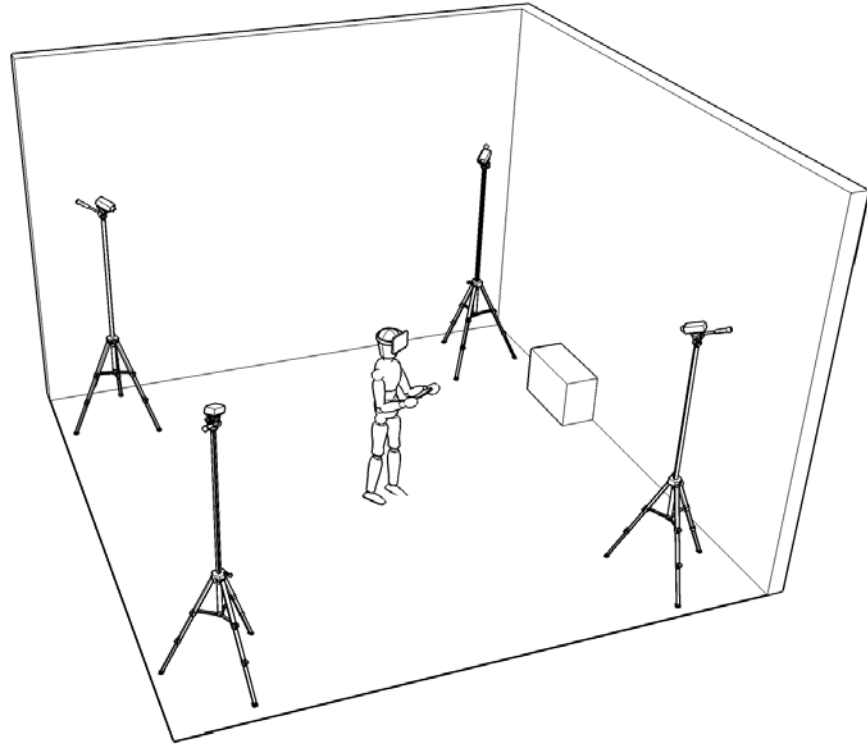


Fig. 27.1 graphic test results



## **PROPOSAL FOR A PORTABLE FULLY IMMERSIVE VIRTUAL REALITY KIT**

During the fall 2013 semester, I began research into the perception of scale and spatial relationships across various methods of viewing virtual, 3D models. Near the end of the semester, I performed an experiment which attempted to quantify those differences. The experiment involved 40 subjects and tested participants' perception of a model in a real environment, on a 2D screen, and in two different fully immersive environments facilitated by head mounted displays.

The results of the experiment showed that subjects who used a fully immersive environment which was navigated by walking to view the virtual model exhibited a significantly better understanding of scale and spatial relationships of the model environment than those using a 2D display.

This suggests that the best way for Mortenson's customers to experience or use a space before it is built is for them to be presented a model within a fully immersive environment which can be navigated by physical movement.

Additionally, while observing subjects interact with the experiment, it became apparent that one of the most important aspects of facilitating an accurate understanding of the virtual model being

presented is an interface which is intuitive, comfortable, and easy for the viewer to use.

Realizing the benefit of fully immersive virtual walkthroughs, Mortenson occasionally invites customers to join them at the University of Minnesota for a walkthrough of a virtual model within the Department of Architecture's Virtual Reality Lab, located in the courtyard of Rapson Hall. Because these walkthroughs involve the mobilization of personnel from at least two separate organizations, and often take up a significant portion of a day, they are very expensive and are typically considered special events. The walkthroughs often include many people who may be experiencing fully immersive VR for the first time, making the walkthrough a novel experience.

Unfortunately, these circumstances conspire to detract from the real benefit of fully immersive virtual walkthroughs, which is to allow customers to experience a space before it is built, when more informed decisions made by the customer allow the project to save time and money.

For fully immersive virtual walkthroughs to be truly useful to Mortenson's customers, they should become a regular component of Mortenson-customer interactions, instead of novel, special events. To facilitate this, Mortenson would be well served by acquiring portable kits which facilitate easy-to-navigate and professional fully immersive VR walkthroughs. This would allow Mortenson personnel to bring VR sessions to the customers regularly, instead of needing to make rare, time-consuming, and expensive trips to the University of Minnesota. If this can be accomplished, immersive walkthroughs could become iterative working sessions, where small groups of customers and Mortenson personnel focus on making informed decisions early in projects. This could improve customer's business outcome as well as their experience of the design and construction process.



## **PROJECT PROPOSAL**

The goal of this project is to allow Mortenson to use iterative, focused, fully immersive VR working sessions to help customers make informed decisions. Therefore, the proposal is to work with the UMN's VRDL lab to develop a prototype of a portable kit which facilitates a fully immersive environment and to deploy the kit to Mortenson Personnel.

### **This project will include:**

Working with VRDL staff to develop a prototype of the portable kit using software and hardware developed by VRDL and third party products.

Deploying and testing the prototype kit with Mortenson personnel with the goal of determining priorities for the improvement of the kit's experience according to how Mortenson personnel use the kit

Refinement of kit components in terms of user interface, portability, performance, durability, user comfort, and aesthetics.

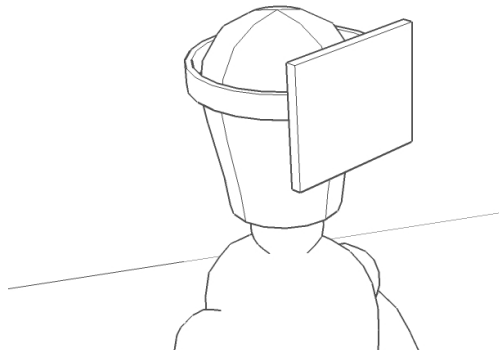
Testing changes made to the kit with experimental methods and field deployment

Research into the short-term and long-term feasibility of the kit.

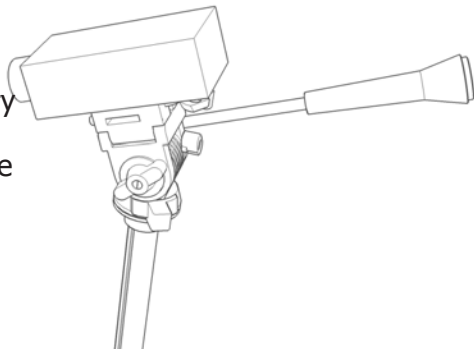
Research into what would increase the kit's value for Mortenson and their customers

### **Kit Components:**

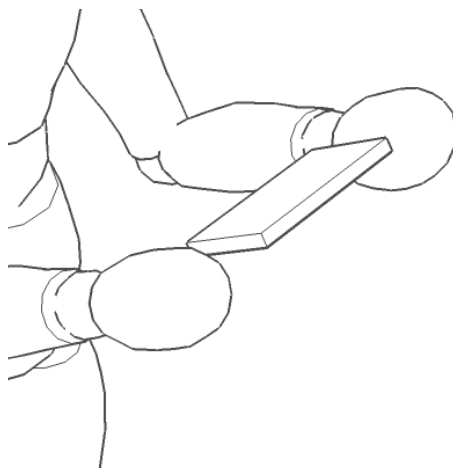
**Head mounted display:**  
This is a device which is worn by the viewer and displays the view of the virtual environment. Recent advances have made a lightweight, easy-to-take-on-and-off head mounted display possible. This head mounted display is not connected to a bulky computing unit, which greatly improves user comfort and freedom of movement. Another recent advancement is the integration of a see-through camera, which is very useful in many ways.



**Tracking Cameras:**  
These are cameras which are specifically designed to track the position of the head mounted display in space. They are necessary to facilitate viewer tracking – that is, to be able to communicate to the computer which is producing the 3D view of the virtual environment where the viewer is located in the environment and where they are looking.



**Controller / joystick:**  
Because the kit is intended to be portable and to be set up in small rooms, it is expected that most 3D models would not be fully navigable within the area a viewer has available to walk around within the tracking area. To facilitate navigation of large models, it will be necessary to give viewers another method of navigation, which they can use to move their “navigable area” of the virtual model.



#### Software:

The VRDL is currently developing software that will allow Mortenson personnel to quickly make changes to the virtual model being shown, using software they are familiar with. Currently, it is necessary to engage with several software platforms, some of which are quite technical, to get 3D virtual models ready for viewing in the head mounted display. This is a barrier to the facilitation of useful working sessions.

#### Outlook:

There are many other hardware and software needs for this project, but they are generally to support the major components of the project detailed above. All the hardware necessary is either in development by the VRDL lab at the University of Minnesota or available commercially.

Overall, I believe this project could prove quite valuable to Mortenson's customers. Some of the potential benefits might include:

Fully immersive VR allows customers to experience a simulation of the building project they have commissioned before any construction takes place. This would allow them to make more informed decisions earlier in the process.

The UMN VRDL has now developed the capacity to support multiple users in the same VR space. Additional head mounted displays could be added to the kit at marginal cost, allowing multiple customers and Mortenson personnel to interact in the virtual environment simultaneously.

Developing a portable VR kit would make it easier for Mortenson to expose many customers to fully immersive virtual walkthroughs; it would be much easier to bring VR to them instead of organizing meetings where everyone travels to the University of Minnesota.

Many kits could be acquired subsequent to development of initial kit. This would allow for multiple deployment across offices, and also a scenario in which virtual building walkthroughs and meetings could occur over a network.

Once the use of immersive VR for customers grows in Mortenson, the same kits might migrate to the job site, where they would be very useful in day-to-day operations, such as the facilitation of communication across trades during construction.

**The next step:**

As the Portable VR kit needed funding to get off the ground, I realized that I needed to help people understand what it is. Subsequently, there are various materials which I produced to help communicate the potential value of the investment in the portable VR kit to the people who could approve funding for it.

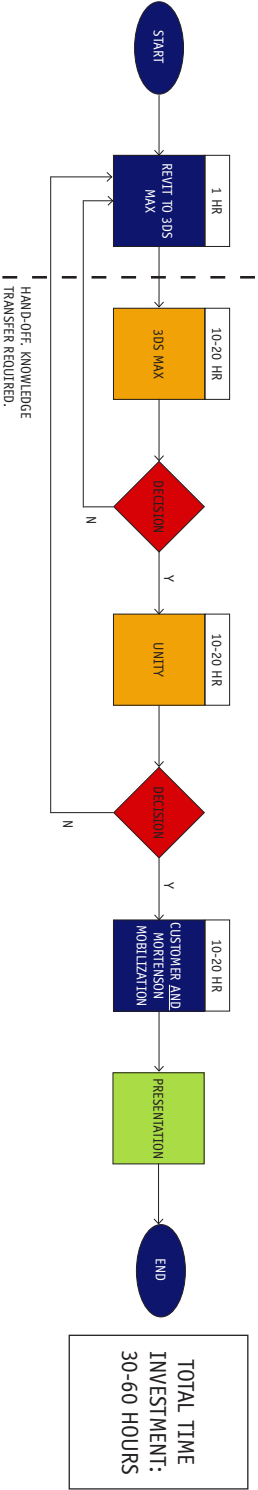
## **PORTABLE VR KIT: COMMUNICATION OF VALUE**

### **Need to improve workflow:**

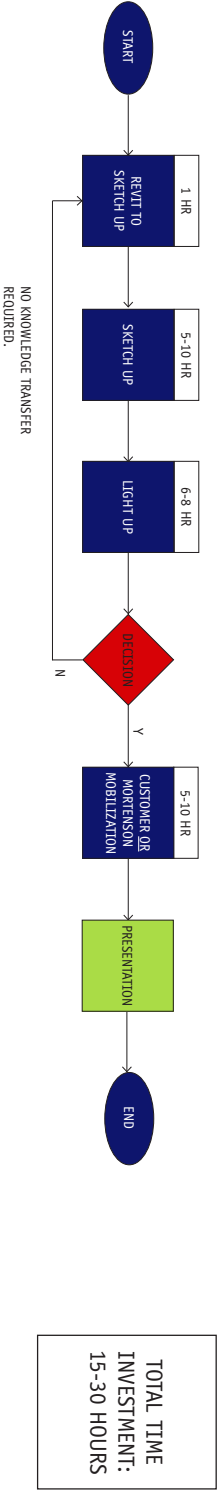
Immersive virtual reality is a 25 year old technology which has rapidly improved to a near-professional level in the past two years. Many resources are currently being dedicated towards the development of Immersive video games, but very few are being dedicated to systems which are specific to the needs of Mortenson. Because of this, Mortenson must contract with institutions which own expensive, inflexible systems which facilitate immersive virtual environments. Mortenson would greatly benefit from a flexible system which Mortenson controls and fits better into existing workflows.

VR lean workflow

CURRENT IMMERSIVE VR WORKFLOW FOR CUSTOMER PRESENTATION



WORKFLOW POSSIBLE WITH PORTABLE VR KIT: CUSTOMER PRESENTATION



KEY:

MORTENSON

THIRD PARTY

CUSTOMER

TOTAL TIME SAVINGS: 50%

Mortenson already produces design review models to anticipate constructability issues. These are further leveraged to enhance communication of what the result of construction will be. This process has been proven in practice to save money, enhance communication, save time, and improve results. Design review models are typically viewed on 2D computer screens, but immersive environments are far better at facilitating spatial cognition than 2D screens. They allow customers to walk through an accurate virtual model of their building before any concrete is poured.

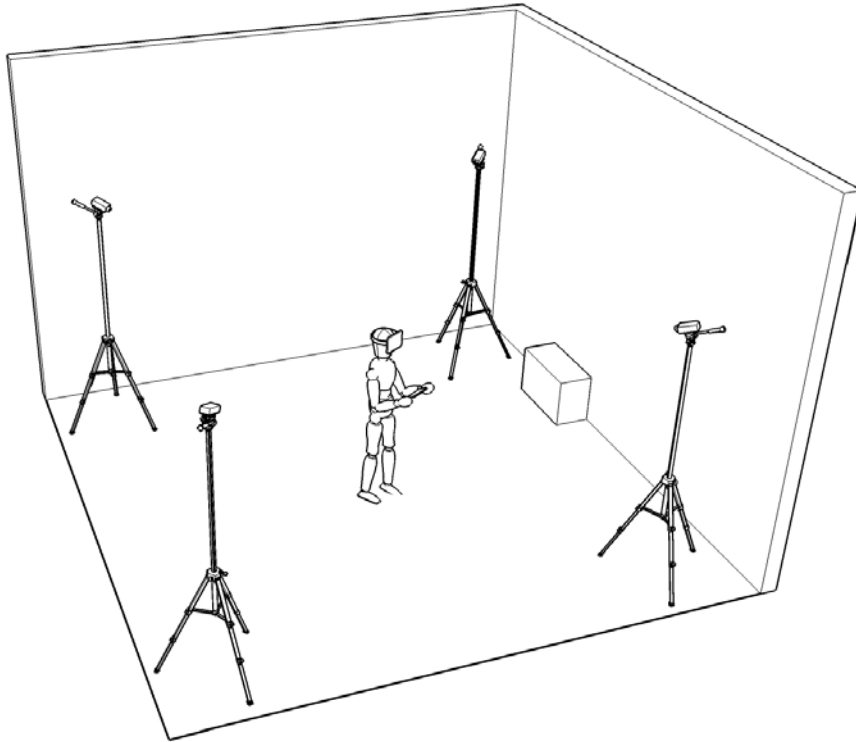
## **UMN VR tracking array**

**-\$300,000**

- Non deployable; users must be at the UMN
- Only one array exists
- Motion tracking over large area
- Recently developed, lightweight, low-cost, wireless head mounted display
- Supports multiple users in virtual model simultaneously





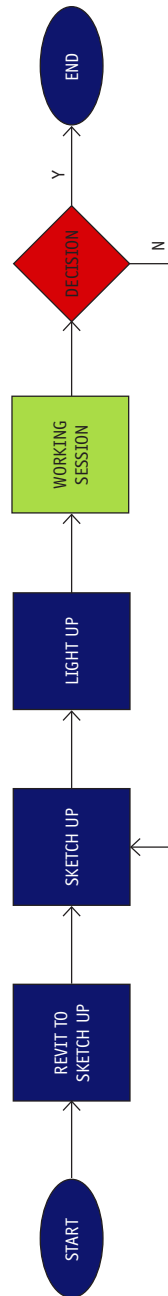


### **Mortenson portable VR kit**

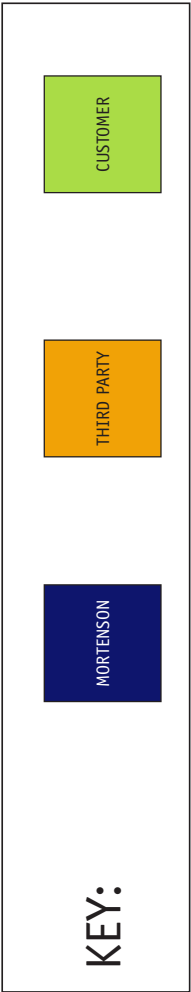
- \$65,000** for development; cost will likely drop dramatically for subsequent kits
- Deployable; set up in 45 minutes at any location
- Many kits possible; virtual building walkthroughs and meetings could happen over a network where attendees are in different locations
- Motion tracking over small area; controller used to move long distances
- Recently developed, lightweight, low-cost, wireless head mounted display
- Supports multiple users in virtual model simultaneously

Customers are not the only parties which benefit from better spatial understanding of unbuilt spaces; immersive environments can be used to facilitate communication between trades. CIFE, the stanford facilities engineering research organization, has evaluated several of Mortenson's projects. CIFE researchers have consistently suggested that Mortenson should implement immersive environments sooner and more often in projects.

ADDITIONAL WORKFLOW POSSIBLE WITH PORTABLE VR KIT: MORTENSON - CUSTOMER WORKING SESSION



INFORMAL, ITERATIVE PROCESS FACILITATED BY RAPID CHANGES MADE TO VIRTUAL MODEL AND SEVERAL IMMERSIVE VR SESSIONS.



VR lean workflow

### **End user design improvements:**

Immersive environments are very useful to **understand potential problems** with building operations **prior to their completion.**

For instance, using an immersive VR environment to verify window placement, lighting placement, sight lines, views, and other aspects which are important to understand from an egocentric point of view saved the Pegula Ice Arena project **\$475,000 of rework.**

### **Customer communication:**

The ability to communicate everything from intricate details to large scale spatial implications in an immersive way gave a much better understanding than could have otherwise been realized. **Fewer surprises and greater certainty of outcome.**

When the client walks into their new space for the first time, they won't be experiencing it for the first time.

Allows Mortenson to better communicate to customers the implications of their decisions. This allows customers to make more informed decisions more rapidly. This saves both schedule and reduces rework.

### **Construction Personnel:**

Clash detection and beyond: For instance, facilities managers can engage in a mechanical room walk-through to provide input on location of access to equipment. Often, the nuances of the spatial issues of access are impossible to understand on a 2D screen but very easy to understand when in an immersive environment.

Immersive environments can also be extremely useful to help different trades to understand the spatial issues they will be dealing with before they start work. This can help subs get work done faster, safer, and cheaper.

Immersive environments can be used to evaluate virtual mockups in a similar manner that a physical mockup would be evaluated. The difference is that **virtual mockups are much less expensive to build and rework** than physical mockups are.

### **Improving customer business outcomes:**

Revenue generating opportunities for the Customer by preselling advertising space.

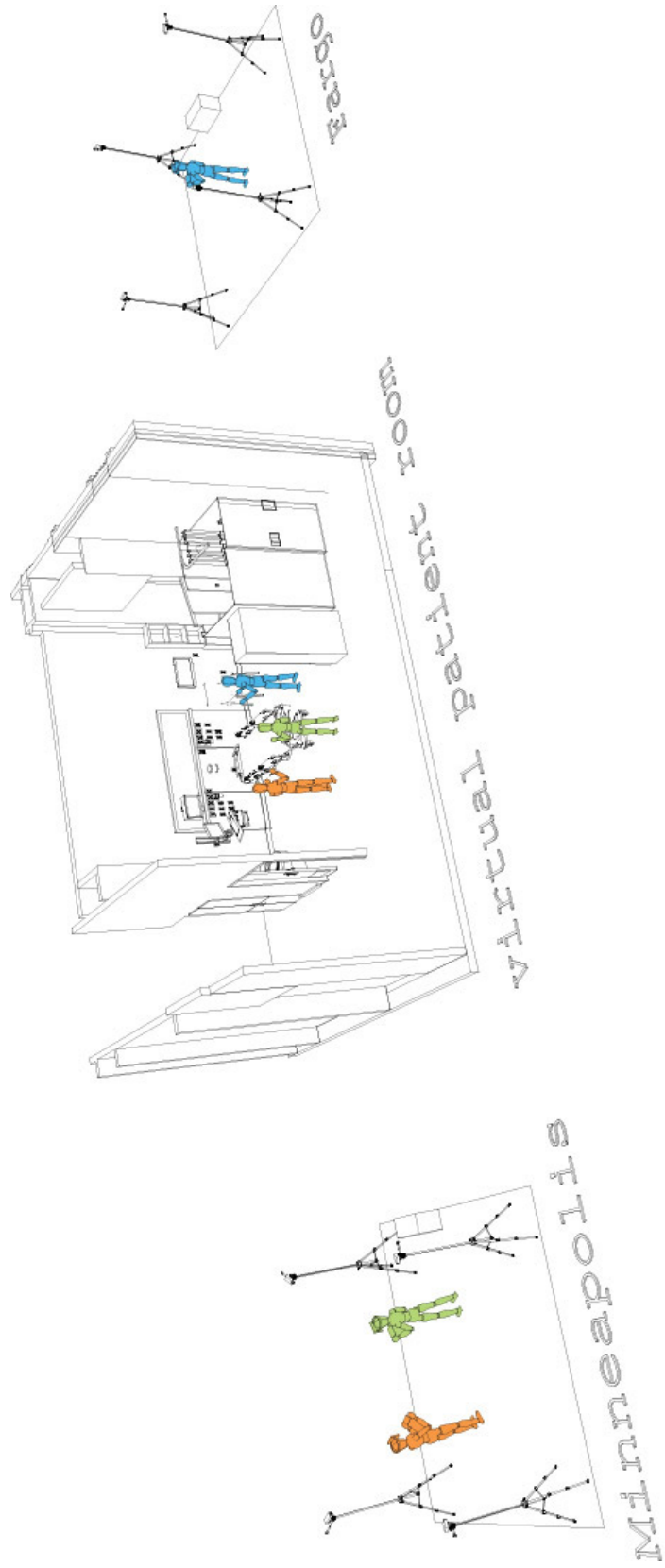
**Revenue generating** opportunities for the Customer by **previewing leased space, or tickets.**

Community outreach: Marketing and PR material for the Customer, such as virtual tours for the public before the project is built. Come down and virtually walk the field!

Improve owner relationship with the Vikings Team: Locker rooms, shared space - have them experience their new home before we build it!

Concessions and sales: What does the bar look like? Where is the vendor located in relation to patron's sight lines?

Wayfinding and Signage: Opportunity to experiment with signage virtually, how it would affect flow, how visible it is from different locations



possible research result: networked,  
multi-party vr walkthrough sessions

90's VR: Clunky, unprofessional, weird.



Now and future: wireless, social, professional experience. Available to Mortenson immediately!



1 year ago: Better experience, but still hard wired, single-person experience.





## CONCLUSION

Though I wanted to focus on the development, implementation, and improvement of the portable VR kit for the semester, it became apparent that some time was needed to iron out the legal status and technicalities of the arrangement between the VRDL lab and Mortenson construction. I therefore needed another project which would help me understand the gap between construction operations and immersive virtual technology in an academic setting. Ricardo, one of my mentors, suggested I use the submissions for AIA TAP awards which his department had submitted over the past 10 years, as he needed some analysis done on that for marketing material anyway. What follows is the marketing material, so it lacks criticality, but it was still quite useful in understanding how Mortenson is using technology now, and what other strategies might fit into their workflow.

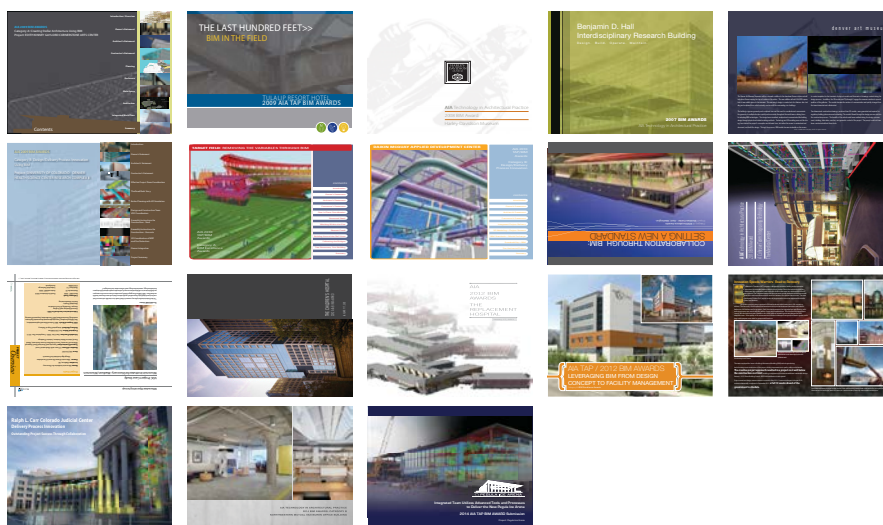


## THE IMPORTANCE OF VIRTUAL DESIGN AND CONSTRUCTION

Over the past decade, Virtual Design and Construction (VDC) has been increasingly leveraged by Mortenson Construction to improve quality, reduce cost and schedule, increase job site safety, and enhance customer satisfaction.

The following report is the result of the analysis of 18 high-performing projects completed by Mortenson construction, the first of which was completed in 2006 and the last in 2013. It details what activities were most often beneficial to the project, what the benefits were, and why VDC activities are important.

The 18 projects analyzed for this report

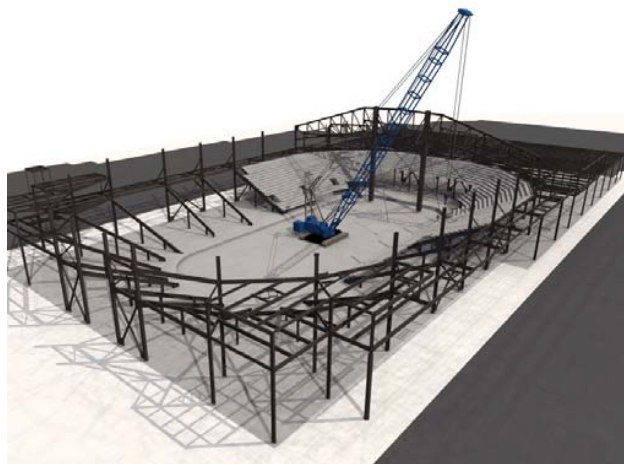


## PROJECTS ANALYZED

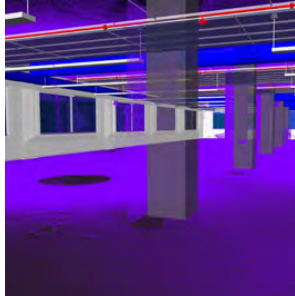
- D ART** Denver Art Museum, completed 2006
- BH IRB** Benjamin D. Hall Interdisciplinary Research Building, completed  
**HRLY** 2007
- C ARTS** Harley-Davidson Museum, completed 2008
- D HLTH** Edith Kinney Gaylord Cornerstone Arts Center, completed 2009  
University of Colorado Denver Health Science Center Research  
Complex II, completed 2009
- TULALIP** Tuliap Resort Hotel, completed 2009
- TARGET** Target Field, completed 2010
- DAIKIN** Daikin-Mcquay Applied Development Center, completed 2010
- SHOW** Showare Arena, completed 2010
- MED C** The Medical Center, completed 2010
- WID** Wisconsin Institutes for Discovery - Madison, completed 2010
- CHLD H** The Children's Hospital, completed 2012
- RPLC H** The Replacement Hospital, completed 2012
- UCWH** Central Washington Hospital, completed 2012
- WIN T** Warriors in Transition Barracks, completed 2012
- CJC** Ralph L. Carr Colorado Justice Center, completed 2013
- NW MF** Northwestern Mutual Fund, completed 2014
- PEGULA** Pegula Ice Arena, completed 2014

## ENHANCING PROJECT TEAM AGILITY

One consistent aspect of construction projects is that they will encounter unforeseen circumstances which have significant potential to delay the project schedule and rapidly increase project cost. Certain VDC activities can enhance flexibility and position project teams for agility, preparing them to quickly address the project's inevitable problems. Flexible, agile project teams are able to shuffle phasing, schedule, and resources to mitigate delays and maintain high productivity levels, ultimately delivering projects on-time or before. Traditionally, construction projects have dealt with uncertainty in a reactive way. VDC allows Mortenson to act in a proactive manner which has shown to consistently reduce project schedule and cost while improving productivity and quality.



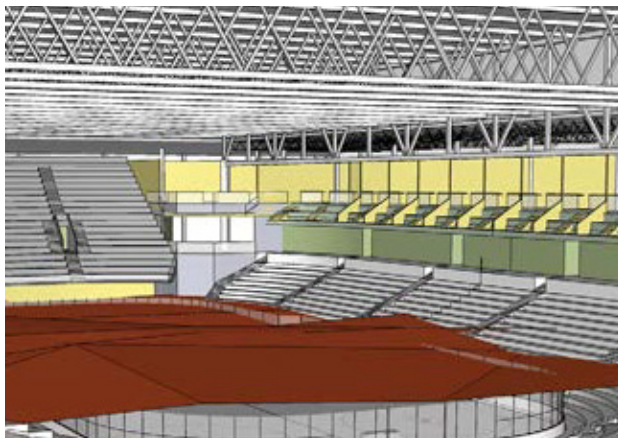
During the construction of the Showare Arena, an accident at the stadia precast plant halted production for nearly a month. Mortenson personnel were able to leverage the 4D model to avoid a 30 day schedule delay and stay on track.



Mortenson developed a point cloud model from laser scanning the existing building Northwest Mutual Fund's offices would be retrofitted into. Analysis of that model showed the existing building's structure was significantly out of square. By doing this, large amounts of rework, additional cost, and schedule delays were averted. In total, the project was over \$1 million under budget and delivered 1 month ahead of schedule.

"BIM was a fantastic tool for our team; it allowed us to visually see our new office space prior to construction starting. The original 1920's concrete construction was renovated many times over the years and few areas were square and plumb . Without laser scans and BIM models , our risk of cost changes would have dramatically increased. The virtual mock-ups proved valuable as we were making final design decisions and ensured the end result would fit our needs , would be easily maintained, and meet our expectations as a 21st Century Workspace. We were also able to post virtual fly-throughs to the internet to share with our employees and it proved to be a great way to engage 6000+ people into the construction process . BIM truly impacted the success of our project ." – Northwestern Mutual

While building the Pegula Ice Arena, modeling the complex geological formation below grade resulted in the realization that a redesign of the foundation as well as the sequence of work was required. The 4D



model was utilized to analyze possible options and to communicate their schedule impacts to the customer. Optimizing the solution for this problem saved the customer \$260,000 and took 30 days off the schedule.

## DIRECT SCHEDULE REDUCTIONS: 600 DAYS

Over 18 projects, VDC activities reduced project schedule was by an average of 32 days. Significant additional schedule savings were realized but were not quantified specifically enough to use in this data set. 4D phase planning, prefabrication, and construction systems design are activities which allow Mortenson greater control over critical-path activities. 3D coordination decreases the likelihood of delays stemming from conflicts between trades.

### Existing conditions modeling

NW MF

### Phase planning (Macro 4D)

D HLTH BH IRB SHOW CJC RPLC H

### Site analysis

PEGULA D HLTH BH IRB

### 3D coordination

C ARTS D ART DAIKIN SHOW

### Construction System Design

TULALIP SHOW CJC RPLC H

### Digital Fabrication / prefabrication

D HLTH DAIKIN NW MF PEGULA UCWH

### 3D Control and Planning

D ART CJC UCWH



**(Quantified days saved. Time savings which went unquantified are not included, though they are significant.)**

**D HLTH** 4D was used to avoid field conflicts between subcontractors scheduled to work in adjacent areas, track critical path components to ensure on-time delivery, and accurately place concrete and structural systems with little danger of needing re-work.

**HB IRB** 4D simulations helped the project be completed 40% faster than the owner's traditional delivery schedule

**SHOW** 30 day schedule delay mitigated by re sequencing construction

**CJC** 2 months saved on project schedule by utilizing highly detailed micro level 4D simulations for critical project components

**RPLC H** Significant schedule loss avoided due to catching steel erection error

**C ARTS** 16 weeks of delays averted for both Contractor and subs, averting a total of \$688,000

**D ART** Steel erected 3 months early

**SHOW** 18 days saved by identifying steel issue; 11 days saved by identifying column wrap issue; 7.5 days saved by identifying catwalk/ductwork clashes

**DAIKIN** 2,600 clashes were resolved, saving 4 weeks / general collaborative sessions saved 6 weeks

**TULALIP** 6 weeks

**SHOW** 13 days saved by identifying issue with ice slab header trench

**CJC** 17% reduction in elevator core schedule, facilitated by lift drawings

**RPLC H** Concrete lift drawings reduced concrete schedule by 79%

**D HLTH** 50% reduction in schedule for mechanical subcontractor

**DAIKIN** Prefab prevented a 5 week delay

**NW MF** 2,500 hours (20%) saved by prefabricating plumbing and piping. 10% overall schedule savings from using prefabrication

**PEGULA** 5 weeks saved by simplifying submittal process and obtaining right-to-rely on BIM.

**UCWH** Prefabricating headwalls saved 18% in man hour reduction, four weeks on interior rough-in, and 3 weeks on casework. Prefabricating exterior framing, sheathing, and moisture barriers saved 6 weeks on the exterior enclosure schedule.

## DIGITAL PROTOTYPING

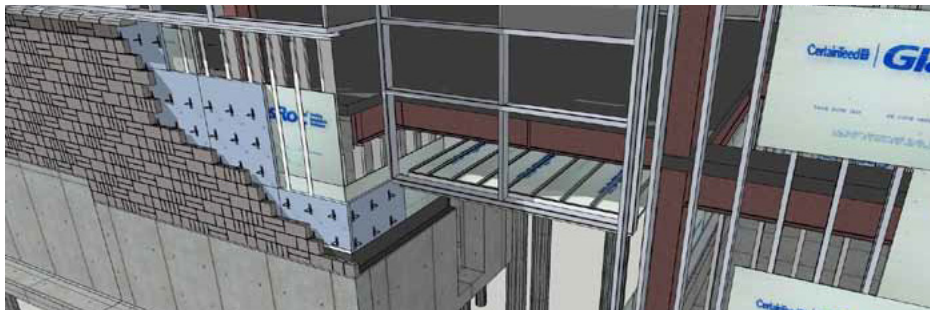
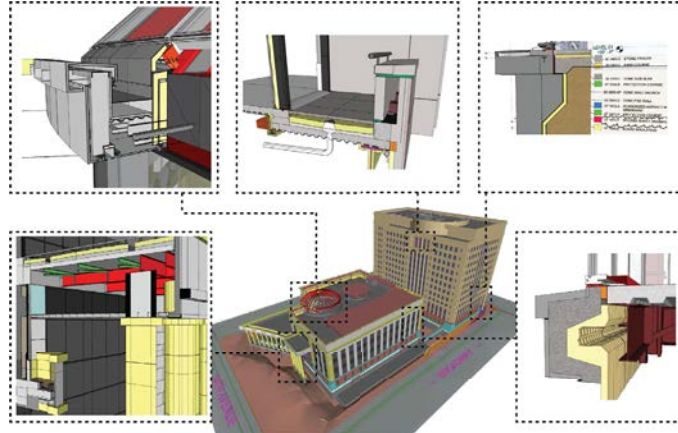
Because each construction project is unique, problems with constructability and detailing are very common. Traditionally, this uncertainty has been addressed in the field with limited information, or by physical mock-ups, where especially complex or critical conditions are worked out before being implemented on the actual project. Both of these approaches are problematic; the first makes it difficult to understand how seemingly small decisions may have a significant impact on the project. The second approach is effective, but time intensive and costly, usually being deployed only a handful of times on each project.

Mortenson has integrated lessons learned by the automotive, aerospace, and manufacturing industries that developing complete, detailed virtual prototypes is an effective way to test assembly strategies. Since implementing this strategy, it has become apparent that virtual prototyping improves the certainty of outcomes and is a very consistent way to reduce the inherent risk of construction activities.



Mortenson saved the Denver Art Museum \$400,000 by resolving over 1200 clashes before the steel arrived and getting the steel erected 3 months early.

By proactively utilizing highly detailed micro level 4D simulations for critical project components, Mortenson was able to save two months on the schedule of the Colorado Justice Center. This played a crucial role in averting an estimated \$2,440,000 in rework costs.



Creating virtual mock-ups of the building enclosure, patient rooms, architectural finishes, nurse stations and lobbies allowed the team to understand design intent, make decisions and procure materials in more timely manner on the Central Washington Hospital, which was completed 10 weeks ahead of schedule and \$7 million under budget.

"We simply could not have constructed this facility and achieved these results without this use of the model. BIM allowed us to anticipate and coordinate extensive electrical and mechanical systems installations with existing integration with virtually no re-work. I used to think this was all good in theory, but real issues are coordinated in the field. This project sure has changed my perspective. I'll never do it the old way again." - Owner, Central Washington Hospital

## DIRECT COST REDUCTIONS: \$5.5 MILLION

Over 18 projects, over \$5 million was returned to customers as a direct result of VDC activities. Additionally, significant cost reductions were realized but unquantified. As is evident below, Design review, 3D coordination, construction system design, and digital fabrication were especially effective at driving project costs down.

### Existing conditions modeling

NW MF

### Phase planning (Macro 4D)

RPLC H

### Site analysis

PEGULA

### Design review

PEGULA SHOW UCWH RPLC H

### 3D coordination

WID TULALIP C ARTS D ART SHOW CJC PEGULA UCWH

### Site utilization planning

PEGULA

### Construction System Design

D ART SHOW CJC MED C

### Digital Fabrication / prefabrication

DAIKIN CHLD H PEGULA W IN T

### 3D Control and Planning

MED C

**(Quantified money saved. Cost savings which went unquantified are not included, though they are significant.)**

- PEGULA** \$475,000 averted by using a CAVE environment to review design elements
- SHOW** Model assisted marketing team in selling 25% of season tickets before construction
- UCWH** \$120,000 in enclosure and structural costs were averted by modeling a "standard worst case scenario" on the upper patient floor.
- RPLC H** Virtual mock-ups reduced need for multiple physical models to one; virtual interior mock ups accelerated approvals for spaces
  
- WID** 30% of construction waste avoided due 3D coordination
- TULALIP** 234 dimensional conflicts and 3 major structural issues were resolved; over 2500 MEP clashes resolved
- C ARTS** \$90,000 saved through preconstruction 3D coordination
- D ART** \$400,000 saved by getting steel erected early
- SHOW** \$153,540 saved by identifying steel issue; \$27,500 saved by identifying column wrap issue; \$31,400 saved by identifying catwalk/duct work clashes
  
- CJC** \$2,440,000 averted by clarifying 60% of envelope design early in design phase; \$755,000 averted by reviewing insulation detailing
- PEGULA** \$161,000 saved by improving coordination
- UCWH** BIM coordination contributed significantly to the project being completed \$7,000,000 under budget
  
- D ART** Concrete Lift drawings resolved extensive coordination issues which would have been costly job site conditions
- SHOW** \$32,000 saved by identifying issue with ice slab header trench
- CJC** \$120,000 saved by using lift drawings to get 100% of all 2242 steel embeds in the CIP elevator cores right the first time
- MED C** Concrete lift drawings reduced cost of concrete work by \$200,000 - \$225,000
  
- DAIKIN** Prefab saved \$370,000
- CHLD H** Med gas used prefabrication to beat estimate by 35%; Hydronic copper prefabbed pipe to beat estimate on floors 3 through 9 by 15% and on floors 15 and 16 by 51%
- PEGULA** \$100,000 averted by simplifying submittal process and obtaining right-to-rely on BIM.
- WIN T** 35% reduction in landfill waste than comparison project

## ENHANCED DECISION MAKING

Customers must make many decisions during their construction projects, and effective communication is necessary for their success. Reliably presenting customers with accurate, digestible information is critical to ensure those decisions are well informed and timely. Mortenson's use of virtual models for visualization dramatically improves upon the traditional process, where customers are asked to make decisions based on arcane, abstract 2D drawings. Through extensive use of virtual models as a communication tool, Mortenson's customers are more confident in their decisions, driving time and cost reductions in the overall design and construction process. Mortenson continues to innovate in this arena, investing in emerging technologies such as immersive virtual reality. This allows customers to intuitively experience and respond to their projects before they are built.



Mortenson's VDC unit used detailed 3D models to help the customer visualize the spaces of the project and their highly designed mechanical systems while working on the Harley Davidson Museum. This proved to be invaluable in ensuring the customer's satisfaction in their finished facility.





Mortenson used immersive virtual walkthroughs were used extensively to evaluate sight lines, office configurations, lighting locations, site signage, and many other design elements prior to construction of the Pegula Ice Arena. Changes made as a result of this directly saved the project \$475,000.

"...drawings are one dimensional. and so it kind of gave us a first step feel of how the arena was going to look. The CAVE experience gets you more excited, and it gets you kind of thinking differently on the usage of the facility." - Kim Pegula, Donor, Pegula Ice Arena



During a fully immersive virtual walkthrough, Mortenson personnel realized that the original position of a recessed light in the ADA shower stall was very close to the wall and prevented light from illuminating the shower stall. Due to this discovery, Mortenson asked the lighting designer review the condition, who relocated the light prior to the construction of the in-place mock-up, averting thousands of dollars in rework.



## THE LAST 100 FEET

All the effort invested into communication, virtual prototyping, and proactive planning can be wasted if the decisions made from those processes are not effectively integrated at the job site. Mortenson is committed to continuously improving the flow of information across all project team members. By implementing technologies such as plan room computers, tablets linked to the Building information Model, and robotic total stations which survey as-built conditions efficiently and to a high degree of accuracy, Mortenson is leading the industry in bridging the gap between the offices where projects are planned and the messy, imperfect job site, where the project is actually realized.

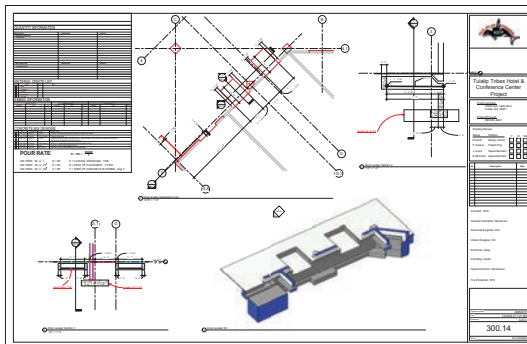


A project manager and trades person review a Navisworks model on site, ensuring that the work done is based on the most up-to-date information. Viewing the model helps them to understand complex spatial conditions which can't be fully grasped through 2D drawings. All job site personnel are trained to use the Navisworks software, allowing anyone access to the most comprehensive source of information at any time.



Tradespeople reviewing an integrated work plan for the Tulalip Resort hotel. The integrated work plan is a document which clearly defines a scope of work and provides all necessary information to complete it. The work plan combines 2D drawings which are useful for layout with an axonometric view of the scope, helping the workers understand what the finished product should look like and what the most efficient sequence of steps will be. This focus on

communication resulted in just 1 RFI per \$127,400 of work in place, compared to an average of 1 RFI per \$37,135 of work in non-BIM Projects.



A project engineer verifying locations of in-wall services on a tablet computer prior to the wall being closed up. This ensures the most up-to-date information is used to verify accuracy and quality, and also streamlines and organizes the reporting procedure for mistakes within the BIM, reducing the chance that errors will go unremediated.



## PRODUCTIVITY ENHANCEMENT:

Mortenson has committed to the goal of reducing the time and cost of projects by 25%. Over 18 projects, VDC activities have made significant strides towards realizing this goal, helping minimize the need for rework while enhancing overall productivity of the project workforce. Prefabrication, Construction systems design, and 3D coordination most often contribute to job site productivity gains.

### Existing conditions modeling

NW MF TARGET

### Model based estimating

PEGULA

### Site analysis

TARGET

### Design review

BH IRB NW MF HRLY

### 3D Coordination

HRLY D ART TARGET UCWH

### Construction systems design

TULALIP D ART CJC RPLC H

### Digital Fabrication / prefabrication

HRLY D ART CJC W IN T BH IRB

### 3D control and planning

D ART TARGET

## 25% OR GREATER

- BH IRB** Over 162,000 hours of work without a single lost-time incident
- NW MF** Virtual mock-up utilized to change lobby design when existing beams which would have been exposed were revealed to be undesirable, while ensuring constructability and MEP coordination
- HRLY** Design visualizations utilized extensively to help decision makers be better informed and make decisions more quickly
- HRLY** Complex, highly visible mechanical systems required no rework; Systems were coordinated early, maximizing construction efficiency of underground utilities; MEP systems installation were assured quality operation and appearance
- D ART** 1200 clashes detected before steel arrived
- TARGET** BIM model was used for coordination and review of 3,000+ tons of steel, reducing traditional 2D shop drawing review to a formality
- UCWH** BIM coordination facilitated a 50% reduction in RFI's relative to a similar project completed 2 years prior
- TULALIP** Increased production rate of shear walls by 26%; iron workers decreased installation time of stud rails by 20%; man-hours reduced by 22% to complete concrete structure
- D ART** BIM used to design means and methods of construction, such as scaffold placement and access systems
- CJC** Colorado Justice: 235% increase in elevator core forming productivity ; 250% increase in elevator core embed productivity. Facilitated by lift drawings.
- RPLC H** Concrete lift drawings reduced time spent waiting during footing and foundation pour 27%
- HRLY** Digital fabrication utilized to solve brick fabrication problem, resulting in high quality and appealing product
- D ART** BIM was used for steel fabrication, reducing knowledge transfer time
- CJC** 25% of mechanical work shifted to prefab facility
- WINT** 50% reduction in punch list work compared to traditional
- BH IRB** Prefabrication enabled a reduction of field labor, construction time, and outstanding quality work

## AN INTEGRATED APPROACH AND CONSISTENT PROCESS

The 18 case studies analyzed for this report utilize a process - virtual design and construction - which is designed to be repeatable, constantly improved upon, and innovative. This approach has shown itself to be very consistent in driving project cost and schedule down, mitigating unforeseen circumstances, and enhancing the customer's satisfaction.

Mortenson has found that certain activities and project characteristics are key performance indicators of a robust VDC investment. The presence of these indicators on a project has proved to be a consistent way to predict a project will enjoy a return on the investment required to facilitate a VDC workflow.

This return is typically realized in the form of value added to the project by reducing schedule and cost, by improving construction quality, and by making sure the customer knows what they are getting and it's what they want.



To realize the benefits of VDC, the VDC Process must be committed to at the beginning of a project and be well leveraged over the project's duration. This is accomplished in different ways over the phases of project completion.

**Pre-planning:**

Project Execution Plan - Formalize process and team

- Define customer success factors; engage owner
- Develop a team wide BIM peer-to-peer network
- Utilize an iIntegrated delivery approach
- Push extensive BIM adoption by project team

**Design phase:**

Improve communication and collaboration through a 3D virtual model

- Utilize model throughout the project to enhance communication
- Build trust through a collaborative approach to project challenges
- Engage the customer to improve decision making process
- Immersive Virtual Walkthroughs
- Constantly integrate software advancements such as Bluebeam, BIM 360 Glue, etc.
- Extensive virtual prototyping

**Construction phase:**

Drive the use of the model into the field by using technology in innovative ways.

- Train workforce on plan room computers
- Deploy cloud-linked mobile technology
- Utilize as built laser scanning to continuously update BIM
- Apply digital fabrication and prefabrication strategies
- Stay agile with strategies such as 4D scheduling

## **CONCLUSION**

These three projects, the spatial cognition in virtual reality experiment, the proposal for a portable, fully immersive virtual reality kit, and the Virtual Design and Construction report, comprise my research project with the University of Minnesota's MSRP consortium and Mortenson construction. All of the projects are incomplete; that is, there is much more depth which could be achieved with each of them. The Spatial Cognition experiment, if continued, could likely become a PHD thesis; The VR portable kit will be continuing during the summer of 2014; I have asked Mortenson for and received an internship to be able to apply the VR kit in the field; the VDC report highlights the need to develop and track metrics in the design and construction industry, a problem which many people are working on.



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