IMMERSIVE VIRTUAL REALITY SYSTEM USING BIM APPLICATION WITH EXTENDED VERTICAL FIELD OF VIEW

A Thesis

by

ADITHYA GANAPATHI SUBRAMANIAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2012

Major Subject: Civil Engineering

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Approved by:

Co-Chairs of Committee,	Stuart Anderson
	Julian Kang
Committee Members,	John Walewski
Head of Department,	John Niedzwecki

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ABSTRACT

Immersive Virtual Reality System

Using BIM Application With Extended Vertical Field of View. (August 2012)

Adithya Ganapathi Subramanian, B.E, Anna University;

Co–Chairs of Advisory Committee: Dr. Stuart Anderson
Dr. Julian Kang

Building Information Modeling (BIM) model contains information about structural, architectural, MEP (Mechanical Electrical and Plumbing) and other numerous components of a building. Among these components, MEP constitutes about 50% of the project cost, and its design is relatively more complex because of the limited headroom available to locate these components. The coordination of these systems involves locating and routing several subcomponents in a manner that satisfies different types of constraints. The earlier version of BIM Computer Aided Virtual Environment (CAVE) did not have provisions to show the overhead components of a BIM model. Conventionally, models had to be tilted to visualize the overhead components. The process of tilting the models to look up is considered counterintuitive. Some of the popular CAVEs developed by leading Universities have a screen on top to show the overhead components but they have a major shortcoming with them. The BIM models had to be converted to a specific format before they can be visualized in the CAVE environments. This study is an attempt to address the shortcomings of the previous version of the BIM CAVE by suggesting a prototype setup with a 55" LCD screen on top of the existing three vertically placed LCD screens. The addition of one more screen on top increases the vertical field of view, that is, the extent to which the user can see vertically in a BIM model. The new BIM CAVE setup is run by a custom built application that makes use of the .Net API (Application Programming Interface) of the commercially available BIM application, Autodesk Navisworks 2012, to control the camera views for achieving an almost seamless semi-immersive virtual environment.

The main objective of this research is to validate the effectiveness of the new setup suggested by using a qualitative research methodology called phenomenological study. Semi-structured informal interviews were conducted with the subject matter experts (SMEs) who are experienced in the field of BIM to know about the differences in the user experience after adding a screen on top of the earlier BIM CAVE setup. The main idea behind this qualitative research technique is to develop an understanding of how the SMEs perceived the idea of looking up to see the overhead components of the BIM model. This thesis explains the steps followed to develop the modified BIM CAVE setup in detail and findings of the qualitative study to know about the effectiveness of the suggested new setup.

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CHAPTER I

INTRODUCTION

Building Information Modeling (BIM) represents the process of development and use of a computer generated model for planning, design, construction and operation of a facility [1]. The 3D models are more effective than the 2D drawings because it makes the visualization process easier as getting 3D information from 2D drawings requires more experience. BIM is also defined as the process of creating electronic 3D models for the purpose of visualization, engineering analysis, conflict analysis, checking code criteria, cost engineering, as-built data, budgeting and many other purposes [2]. A typical BIM model contains information about structural, architectural, MEP (Mechanical Electrical and Plumbing) and other numerous components of a building. Among these components, MEP constitutes about 50% of the project cost [3] and its design is relatively more complex because of the limited headroom available to locate these components. The coordination of these systems involves locating and routing numerous subcomponents in a manner that satisfies different types of constraints. The design for MEP components are provided by multiple firms working independently. The level of difficulty involved with this coordination process is directly related to the complexity and the number of building systems in a facility. Currently, BIM is a tool that is being used by General Contractors and Subcontractors to perform the coordination process more efficiently than the conventional method of overlaying 2D drawings from multiple trades.

The 3D models that are being built today are highly complex because of the complex nature of the buildings. Visualizing 3D models in 2D screens limit the amount of

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The journal model is *IEEE Transactions on Automatic Control.*

information that can be gathered from the model. The way humans interact with computers is totally different from their natural tendency of doing the same actions in the real world. Immersive virtual reality systems can narrow this gap between the real and the virtual world. According to Frank Biocca,“Immersive is a term that refers to the degree to which a virtual environment submerges the perceptual system of the user in the computer-generated stimuli” [4]. It was stated by Hutchins, Hollan and Norman that the interface of the virtual reality system should minimize the distance between the human beings’ thoughts and the physical requirements of the system [5]. Virtual reality offers a natural medium for the users providing a 3D view that can be manipulated in real-time and used collaboratively to explore and analyze design options and simulations of the construction process [6]. Architects will be able to use the immersive nature of the virtual reality to gain a better understanding of both qualitative and quantitative nature of space that they are designing [6]. Moreover, the increased field of view, both horizontal and vertical, will increase the sense of presence [7]. This is the main concept in CAVE (Computer Aided Virtual Environment) virtual reality systems to have the user surrounded by screens to create an immersive environment. Virtual reality systems like CAVE can accommodate more people in it and so it is recommended to be used in the AEC (Architecture Engineering and Construction) industries to achieve effective collaboration among different teams.

A. Research Problem

The MEP (Mechanical Electrical and Plumbing) components are generally located in the building’s ceiling space. Visualizing MEP components in a single screen is very challenging because the user will have to constantly tilt the model to change the orientation for bringing the overhead components to current focus. Even the earlier version of the BIM CAVE, in spite of having wider horizontal field of view compared to a single screen was no better in visualizing the overhead components as its vertical field of view was limited by the single screen's capability. The process of tilting the model makes the viewer lose the sense of presence in the CAVE and disorient his or her (viewer) feel for the spatial location inside the model.

In the phenomenological study conducted by Hussam Neir, Texas A&M University, to test the first version of BIM CAVE with three screens, one of the participants commented-"The only issue I could think with the current setup is that if I have a clash and I am in the room and it is above me, what do I do?" [8].

The existing version of the BIM CAVE has three screens placed at 45 degrees with respect to each other. The total horizontal and vertical fields of views that decide the extent to which the user can see the model elements without rotating the model itself were less in the previous version to achieve a considerable level of immersion. An experiment conducted by J.D. Prothero and H.G. Hoffman (1995), Human Interface Technology Laboratory to test the relationship between field of view and sense of presence indicated a higher degree of presence is felt with a wider field-of-view [9]. Moreover, human centered computing is an emerging academic field, which is mainly focused to enhance the performance of human beings when they interact with computers [10]. The way humans interact with the real world is totally different from their interaction with the virtual world, which is the main reason for the lesser level of sense of presence in the virtual reality systems.

To sum up, the problems that the current research is trying to address is as follows:

- Existing BIM CAVE's limitation to look up in a BIM model, which makes it unsuitable for using it in MEP (Mechanical Electrical and Plumbing) coordination meetings.

- The process of tilting the model to look up is considered counterintuitive in virtual reality systems like BIM CAVE.
- Gap between the real and virtual world.

B. Motivation

With the increasing complexity of construction projects, the BIM models are becoming equally complex. This creates a demand to have an immersive visualization system to view and browse 3D models effectively. Moreover, the coordination of MEP components requires collaboration of multiple trades, which could be made effective by making use of virtual reality systems like BIM CAVE. In order to visualize MEP components, the existing BIM CAVE had to be reconfigured to look up in the BIM model. Human behavioral tendency in virtual reality systems is another major motivating factor considered in the design of the BIM CAVE prototype. The new version of BIM CAVE contains a screen on top in addition to the three vertical screens placed at 90 degrees with respect to each other. The suggested configuration would facilitate visualization of overhead MEP components in a BIM model, which was a major limitation in the previous version of BIM CAVE with three screens. The addition of a screen on top would force the users to look up instead of tilting the BIM model. This process is assumed to narrow the gap between the real and virtual world as the natural tendency of human beings is to look up for visualizing the overhead components.

This research answered the following questions that will address the problems with existing BIM CAVE setup:

1. How can the existing BIM CAVE's (with three screens) limitation to look up in a BIM model be solved?

2. What will be the difference in the visualization of 3D models in a BIM CAVE setup with and without a screen on top?

3. What are the potential benefits of looking up and seeing the overhead components in a BIM model using the top screen?

C. Research Objective

The research objective is to investigate the difference in the visualization capability that could be caused by putting an additional screen on top of existing BIM CAVE which consists of 3 walls.

The following tasks were followed to achieve the objective of the research:

1. BIM CAVE development- Hardware and software components.

2. Validation of the suggested setup using a qualitative research methodology.

D. Limitations

The BIM CAVE developed will only provide visualization of the 3-D models and information retrieval in the commercial BIM application, Navisworks Manage 2012. It will not support other model manipulation functionalities of Navisworks like hiding model elements, moving model elements and 4D simulation. Moreover, this virtual reality system will support only those model files that the Navisworks supports.

E. Thesis Summary

The first chapter of the thesis contains the introduction to the current research topic, which explains about the use of BIM and virtual reality systems in the AEC industry. The problems with the existing BIM CAVE setup, motivation for the current research, objective and the limitations were also stated as a part of this chapter.

The second chapter contains the literature review conducted on the use of virtual reality system in general and also specific to the AEC industry. It also encompasses information about the existing CAVE virtual reality systems developed by other leading Universities.

The third chapter explains the methodology used for this research to achieve the desired objective of investigating the difference in visualization of 3D models in BIM CAVE with and without a top screen.

The forth chapter explains the steps followed in the development of the suggested new BIM CAVE setup in detail.

The fifth chapter contains the data collection part of the research, which was used to validate the BIM CAVE setup developed.

The sixth chapter talks about the results obtained from interviewing subject matter experts (SMEs) to investigate the new BIM CAVE setup.

The seventh chapter discusses the conclusion made from the results obtained from the interviews, which contains the differences in visualization of BIM models due to the presence of top screen in the BIM CAVE. It also includes the benefits of the setup and the direction of the future research.

CHAPTER II

LITERATURE REVIEW

A. Virtual Reality

Immersive virtual reality as defined by Joseph Psotka, U.S Army Research Institute, is a system in which a person placed in the simulated environment will feel like it is the real world, to some extent [11]. A person inside this virtual environment will have a specific sense of self-location in it where one can turn their head and eyes to visually interact with the surrounding virtual environment. Human beings have the general tendency to conceptualize the real world from the 2D drawings and photographs. There is a cognitive phenomenon involved in this process where there is a great amount of imagination going on when the observer tries to grab 3D information from 2D drawings. The most direct benefit from using virtual reality systems is that it reduces the conceptual load because of the simplifying directness of perception of the virtual world [11].

Virtual reality (VR) systems create engagement and excitement to the users, which makes it an ideal tool to be used for education and training purposes [12]. With the help of these systems, effective collaboration of the participants can be achieved facilitating effective communication of ideas and difficult concepts can be explained clearly. Collaborative learning process is proven to be more effective because it helps students clarify their doubts through articulation of ideas and discussion [13].

VR systems can be classified into two groups [14]:

1. Desktop VR (i.e. non-immersive VR)

2. Immersive VR

Some of the common virtual reality systems available are

- Head Mounted Displays
- Goggles and Gloves
- Vehicle Simulators
- CAVE Computer Automatic Visual Environment

A typical immersive virtual reality system consists of virtual reality software, head tracking sensor, a helmet mounted visual display that blocks the users view of the real world [15]. Helmet mounted displays have two goggle sized computer screens near the user's eyes. Electromagnetic position tracking sensors will let the computers know if the person wearing the HMD (Head Mounted Display) changes his/her head position or orientation. The scenes in the virtual world will get updated as the user moves his/her head. This illusion experienced by the users when exposed to VR systems has been proved to contribute to pain reductions in burn patients, and it can also be used to successfully treat phobias and post-traumatic disorders.

B. Virtual Reality For Design Review In Construction

Projects handled by construction industries involve both direct and indirect stakeholders representing different areas of expertise. For a successful completion of a project, different players of the project are needed to share the same understanding about the project. This creates the need for an effective system to accommodate multiple people for making them collaboratively work in projects. It has been estimated that about 75 percent of each working day is spent on some form of communication [16]. In an architectural industry, it is highly essential to communicate the design ideas through visual representation as different types of presentation could alter the perception towards design ideas. The use of VR systems have been tested for real design review case study projects to validate their effectiveness and identify the shortcomings with them. The design review of a disabled bathroom contained a floor area that was reduced due to the addition of a separate shaft for the supply of a ventilation system. This design change was studied in order to respond to new requirements for fire protection and safety. The project members were able to test the feasibility of the design by making use of the virtual reality offered by the VR systems. It has been concluded the use of these systems will reduce the project cost and time considerably as the projects members will be able to foresee design problems and make informed decision well ahead in time [16].

C. CAVE-Computer Assisted Virtual Environment

A Computer Assisted Virtual Environment is an immersive virtual reality environment where projectors are directed to three, four, five or six walls of a room-sized cube. CAVE^{TM} was the first large-scale immersive projection display. It was developed in the year 1991 at the Electronics Visualization Laboratory (EVL), University of Illinois at Chicago, to allow computational scientists to present their research in a one-to-many format on high-end workstations interactively. CAVE^{TM} is a small open theatre made of three screens, each 10'x10', with projectors behind the three screens and a down projection system for the floor. These projectors throw full-color active stereo images. The users wear Liquid Crystal Display (LCD) stereo shutter glasses, which will provide a 3D visual effect by separating the alternate fields. Electromagnetic sensors are used to track the head and hand movements to provide interaction with the 3D world [17].

The Synthetic Environment Applications Laboratory (SEA) at Penn State University has also developed an immersive virtual reality projection system similar to the

CAVE^{TM} developed at the University of Illinois, Chicago. This system was designed with a main motive to experiment the applications of using virtual reality systems for the design and construction of nuclear power plant facilities. This system uses a four-back projection system with stereoscopic and synchronized image rendering capabilities supplemented by a magnetically tracked 3D input device. The system runs a high-end computing system performing as graphic workstations. The four screens will provide a 360 degree horizontal field of view and will enable the users to view the models at a 1:1 scale or at any other modified scales [18].

The Pennsylvania State University has performed an experiment to determine the value of advanced techniques to improve the ability of students to analyze and generate a 4D model. For this purpose, a 3D model of a nuclear power plant was placed in a CAVE like environment and the students were asked to generate a 4D construction sequence of the complex room containing several components with it. The interactive CAVE environment created by the University was used for this purpose and it allowed the students to develop a construction sequence for that particular room in the power plant. The availability of an immersive virtual reality system made a huge difference in their performance as standing in the room before and during the construction simulation encouraged discussion of the actual methods of construction that would be used. The widened field of view enabled the students to obtain a sense of presence and they were able to consider the workspace interferences between trades when planning for parallel activities. They were able to come up with a construction sequence for the room in less than one hour without any prior exposure to the real space and with little experience in nuclear power plant construction. The second half of the study involved construction professionals and they were asked to make a construction sequence of a room in the nuclear plant using the CAVE environment. The solution that came from the construction experts was more advanced than the one obtained from the students and had lots of details in it. Overall, the study showed that the use of CAVE environment causes a 25 percent reduction in scheduling time over the traditional scheduling method [19].

The CAVE virtual reality environments that were built previously operates on custom made application developed using standard set of libraries (e.g. CAVE™ libraries). The application typically support 3D model files formats like 3DS, DWG, DXF and VRML (Virtual Reality Modeling languages) etc. For example, the virtual reality system developed by the University of California, San Diego called StarCave supports 3D model files in VRML format [20]. The VRML format mainly contains only geometrical information of the 3D components. BIM models created using some of the commercially available application have to be converted to the VRML format before viewing them in the CAVE environment. The custom made application used by the CAVE systems also has their own tool to create 3D models rather than importing from the commercial application. Table-I shows some of the popular CAVE environments built by several Universities around the world.

Table I. CAVE Virtual Environments

Name	**Type**	**Description**
3D CAVE at CASALA-Dundalk Institute of Technology, Ireland	4 walls	The CAVE at CASALA has three vertical walls arranged in the shape of a cube and one front projected floor screen with stereoscopic projectors and tracking systems
DIVE (Duke Immersive Virtual Environment), Duke University	6 walls	DIVE has 4 rear projected vertical screens placed in the shape of a cube (3mx3mx3m) with top and bottom screens. It has head and hand tracking system
AZ-LIVE (Arizona Lab for Immersive Virtual Environments), University of Arizona	4 walls	AZ-LIVE has 3 8ft.tallx10ft. wide vertical projection walls and one 8ft.x10ft. projection floor with wireless wand for navigation and head tracking devices.
StarCave- University of California, San Diego	5 Sides with 17 walls	The profile of StarCave is pentagon with 15 wall screens and 2 floor screens. It has totally 17 projectors (2 for each screen) and it supports stereoscopic vision with tracking systems.

CHAPTER III

METHODOLOGY

The research is aimed at investigating the impacts of having a screen on top of the BIM CAVE to visualize the overhead components in a BIM model. In order to achieve the research objective, the earlier version of BIM CAVE had to be rebuilt to the new suggested configuration. BIM CAVE's previous version had three screens placed at 45 degree angle with respect to each other. The effect of the top screen was investigated by building a smaller prototype version of the modified BIM CAVE setup. The prototype version was then used to study the impacts having the top screen in the visualization of BIM models.

The research methodology (Figure-1) contains two main steps. They are:

1. Development of new BIM CAVE setup

2. Validation of the setup

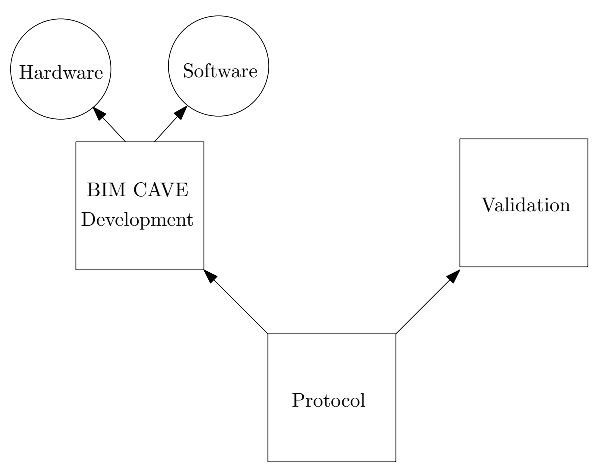

Fig. 1. Research Methodology

A. Development Of New BIM CAVE Setup

The development of the suggested BIM CAVE setup involved fabrication of hardware and development of a software application.

The hardware component of the BIM CAVE involved fabrication of a wooden frame to place the four LCD screens in a specific configuration. The wooden frame was designed to hold the three vertical screens and one screen on top of the three screens facing down. The screens were individually connected to a Central Processing Unit (CPU) and were designed to communicate with one another using a wired router. The CPU running the center screen is the server and the other three CPUs controlling the left, right and top screens are designated as the clients.

The software component of BIM CAVE involved development of a stand-alone application that uses the Application Programming Interface (API) of the commercially available BIM application, Autodesk Navisworks Manage 2012. The BIM CAVE application contains two different versions for the server and client computers. The main purpose of the BIM CAVE application is to update the camera orientation of the clients with respect to the server whenever the user browses the 3D model in Navisworks to provide a synchronized view across the screens. The server BIM CAVE application uses the API to obtain the camera parameters of the Navisworks application. The camera parameters are used in a mathematical rotation algorithm to calculate the axis and angle of rotation for the client computer's camera. The calculated camera attributes are then sent over the network, which will be used by the clients to reorient their camera.

The development of hardware and software components of the BIM CAVE are explained in detail in the next chapter.

B. Validation

The main ideology behind this thesis is to investigate the difference in the visualization capability that could be caused by putting an additional screen on top of previous version of BIM CAVE containing three walls. For the purpose of this study, it is highly essential to study human interactions with the system and obtain feedback about its effectiveness. To evaluate the BIM CAVE setup, qualitative research methodology was used. McMillan and Schumacher defined qualitative research as, “primarily an inductive process of organizing data into categories and identifying patterns (relationships) among categories [21].” The qualitative research technique used for this research is phenomenological study. Phenomenology seeks to understand a person’s or persons’ perspectives as he, she, or they experience and understand an event, relationship, program, emotion, etc. [22]. The phenomenological study helped to understand the participant’s perception towards the idea of having a screen on top of the BIM CAVE. The feedback from the participants was in turn used to identify what kind of differences the top screen in the BIM CAVE make in terms of visualizing BIM models and also to obtain the pros and cons of the setup. Semi structured and informal interviews were conducted with the participants as a part of the research methodology. The main advantage of having an extended informal discussion is that the participants will be able to express their opinion in a clearer and descriptive manner.

1. Investigation Design

The research design allowed accessing the participant’s experience and knowledge about BIM to seek out their perception about the idea of looking up and seeing the overhead components in BIM models and how different it is compared to the earlier version of BIM CAVE, which had only three screens. This research relies on the in-depth interviews with carefully selected sample of participants, which is one of the important criteria in the phenomenological study. A typical sample size for a phenomenological study ranges from 5 to 25 individuals [23]. For this study, five individuals were interviewed. The effectiveness of the research methodology is mainly determined by the four underlying parameters such as:

1. The research participants must be subject matter experts (SMEs) with expertise in BIM and should have working experience in AEC industry (Architecture Engineering & Construction). The SMEs opinions were valued for their in-depth understanding of their field of expertise and rational perspective.

2. The nature of study indicated that there will be some constraints during the study that could hinder the SMEs from fully experiencing the new setup of the BIM CAVE due to the limited amount of time spent in the BIM CAVE. Moreover, the participants might be hesitant to completely describe their experience about the BIM CAVE during the interview sessions when exposed to a new place surrounded by people. It has been made sure that the participants were given enough time to spend with the BIM CAVE and were made to feel comfortable by engaging them in a general conversation before the start of the interviews.

3. The BIM model visualized in the BIM CAVE system during the interviews were relevant to what the participants had experienced before. This process ensured that the participants spent less time understanding the model and more time focussing on the effectiveness of the setup.

4. The researcher during the interaction with the SMEs had to be collaborative

and cooperative.

All the four above-mentioned parameters were addressed to make sure the interviews went without any hindrances.

2. Data Collection

The data collection methodology used for the phenomenological study was semi-structured interviews. The interviews were designed in a way to gain the understanding of the SMEs' perception towards the process of looking up and visualizing the overhead components of the BIM model from the BIM CAVE setup with a screen on top. The interviews were designed to be more flexible and informal by asking open-ended questions to SMEs, thus facilitating them to communicate their thoughts on the new setup effectively. The data collection involved three phases:

1. The Pre-System Introduction Phase

   The purpose of this initial phase was to allow the SMEs to share their general experience about the use of BIM in their company and the kinds of advanced visualizing systems they have used or experienced previously. This phase enabled the researcher to understand the SMEs general notion about BIM and use of advanced visualizing systems to view BIM models.

2. The System Introduction Phase

   The research participants were introduced to the BIM CAVE setup during this phase. A brief overview of how the overall system works and technical details about how the separate computers communicate with each other to achieve an immersive view were explained. The system introduction phase had two main sub phases. First, the screen on top was turned off and the setup was made similar to the previous version of BIM CAVE without any top screen functionality. The participants were then allowed to navigate through the BIM model and were made to visualize the overhead MEP components in Navisworks from the three vertical screens alone. Second, the screen on top was turned on and the participants were asked to visualize the overhead components from the screen on top while browsing the 3D model in Navisworks. This phase acted as a basis for the SMEs discussion with the researcher.

3. The Post System Introduction Phase

   The Post System Introduction phase had a collaborative discussion between the SMEs and the researcher right after the new BIM CAVE setup was introduced. This was the last phase of the interview during which the researcher built up an informal conversation with some preplanned open-ended questions to channelize the thoughts of the SMEs. During this phase the interviewer was also able to obtain the pros and cons of the setup developed apart from how they conceptualized the process of looking up from the screen on top.

3. Validity and Reliability

Data collection through informal interviews can be accurate as the researcher is certain of the source of the data, the interviewees who are subject matter experts. The interviewees selected for the study had at least five years of experience in AEC industry with an expertise in BIM. Typically, findings that emerge from semi-structured interviews can be more accurate and reliable when compared to the findings revealed by the other research methods [24]. The informal interactions with the SMEs reduced the amount of misunderstanding and misinterpretation by the researcher. The semi-structured interviews also facilitated obtaining some divergent perspectives to know about the benefits and limitations of the new setup.

4. Data Analysis

The data analysis was performed after the phenomenological study containing the interview information from the SMEs. In a typical data analysis part, the researcher will look for common themes from the transcripts of the descriptive interviews conducted. The theme of interest for this thesis is the possible differences in the visualization capabilities due to the addition of a screen on top of the BIM CAVE. The researcher will typically take the following steps after transcribing the interviews [22]:

1. Identify the statements related to the topic.

   In this step, any statement or phrase that the SMEs used to describe the effect of having a screen on top and the process of looking up to see the overhead components of the BIM model was identified. It was made sure that the researcher remained unbiased while identifying the statements from the interview transcripts. This step allowed understanding the general perspective of SMEs towards the idea of having a screen on the top in the new BIM CAVE setup.

2. Group statements into meaningful units.

   The identified statements from each of the interview transcripts were carefully scrutinized and the clearly redundant statements were removed [25]. With the set of non-redundant units of meaning in hand from each of the interviews, the researcher examined the statements to group them in to meaningful units to elicit the essence of the interviews.

3. Seek divergent perspectives.

   The interview transcripts were scanned to identify the pros and cons of the suggested setup for the BIM CAVE.

4. Construct a composite.

In this step, the information collected from the previous steps was used to summarize the overall experience of the SMEs with the new BIM CAVE. From the overall description of the five interviews conducted, the researcher summarized the effectiveness of having a screen on top of the BIM CAVE from the five participant's perspective.

CHAPTER IV

BIM CAVE DEVELOPMENT

The BIM CAVE version-2 that was developed as a part of this research is a virtual reality system that uses a commercial BIM application, Autodesk Navisworks. The BIM CAVE uses multiple LCD screens placed at a certain configuration, which is believed to maximize the sense of presence inside the CAVE to better visualize the BIM models. The current version of BIM CAVE is considered as an improvement over the previous version developed in the Construction Science Department, Texas A&M University. The total horizontal field of view (HFOV) of the previous version of the BIM CAVE was 135 degrees, whereas the current version has a HFOV of 270 degrees with an extended (twice as much as the previous version) vertical field of view (VFOV). The BIM CAVE application runs on the .Net API (Application Programming Interface) of Navisworks 2012 as opposed to the previous version, which was running on COM (Component Object Model) API of the Navisworks 2011. This chapter discusses about the software and hardware components that make up the BIM CAVE.

A. Hardware Component Of BIM CAVE

The BIM CAVE version-2 contains four 55” LCD screens. Among the four screens, three screens are vertically placed at 90 degrees with respect to each other and the forth screen is placed on top of the three vertical screens facing down such that all the four screens has a common center. The LCD screens are mounted on a custom made wooden frame. The three vertical screens are attached to a metal bracket, which in turn is fixed to the wooden frame with the help of screws. The metal bracket for the top screen alone is attached to the wooden frame using L-angles to provide additional strength.

Each of the four 55" LCD screens is connected to a Central Processing Unit (CPU) separately with the help of HDMI cables. All the CPUs run an i-7 processor with high-end graphics card. The computers are connected to a wired router, which enables them to communicate with each other across the network. The computers uniquely identify one another with an IP address during the communication process. The computers have conventional mouse and keyboards as input devices. In addition to the conventional mouse and keyboard, the server computer also has a 3D mouse attached to it, which will mainly be used for model navigation purposes. Figure-2 shows the hardware configuration of the suggested BIM CAVE setup.

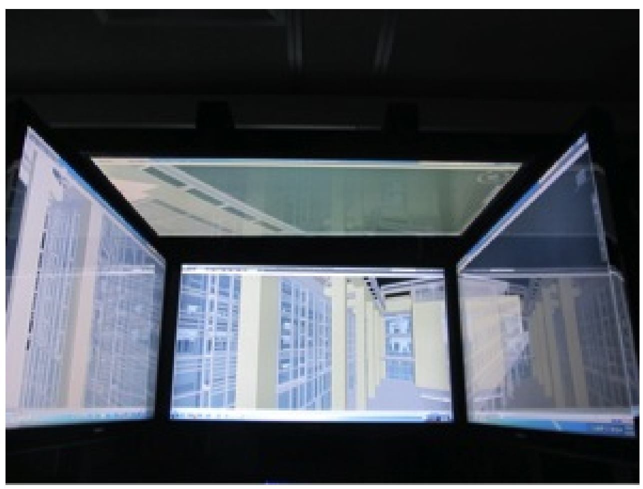

Fig. 2. Screens orientation in new BIM CAVE setup

B. Software Component Of BIM CAVE

The software part of the BIM CAVE has two components. One is the commercial BIM application, Autodesk Navisworks 2012 and the other one is the custom made BIM CAVE application.

1. Navisworks Manage 2012

The Navisworks Manage is one of the commercially available BIM application that can perform model viewing and manipulation functions like clash detection and 4D construction sequence.

The main advantages of choosing Navisworks to build the BIM CAVE are:

- It has a well-documented API (Application Programming Interface) and the recent extended support offered by Autodesk for the .Net framework API, in addition to the earlier COM (Component Object Model) API.
- Autodesk provides a free one-year license for college students to use Navisworks Manage 2012.
- Navisworks is one of the powerful and common applications among general contractors as it can support model files from most of the 3D modeling BIM application like Revit, Tekla and Microstation.
- The use of commercially available application for the BIM CAVE saves the complex model conversion process.

a. Navisworks API (Application Programming Interface)

The BIM CAVE application that has been built as a part of this research uses the .Net framework of the Navisworks API. The .Net Framework is a software framework that was designed for the softwares to run primarily on Microsoft Windows. Originally, Navisworks supported only Component Object Model (COM) API. Later Autodesk extended its support for the .Net API framework from its 2011 version.

The .Net API provided by Navisworks can be used for three different purposes. They are:

1. **Plugins:** Plugins allow the users to extend the functionality in Navisworks. Plugins are generally used inside the scope of the main window of the Navisworks application.

2. **Automation:** Automation is used to drive the application from outside its scope to automate certain tasks and mainly to invoke plugins.

3. **Control:** Control facilitates to embed an Autodesk Navisworks file viewer in to a custom made application to examine Navisworks documents without having the full application loaded.

The Navisworks .Net API is made of several assemblies that has a wide range of classes, structures, methods and events, which provides access to the application itself. The API mainly has four assemblies that are frequently used. They are:

- *Navisworks API Assembly:* This is the core API used when working with plugins or with the controls API. Figure-3 Shows the main classes in API assembly and its relationship with the Navisworks application.

- *Automation Assembly:* Used when working with automation to drive Navisworks from outside its scope.

- *Controls Assembly:* Used to access the Navisworks documents within the third party application.

- *ComApi Assembly:* Used to provide interaction with the older COM API.

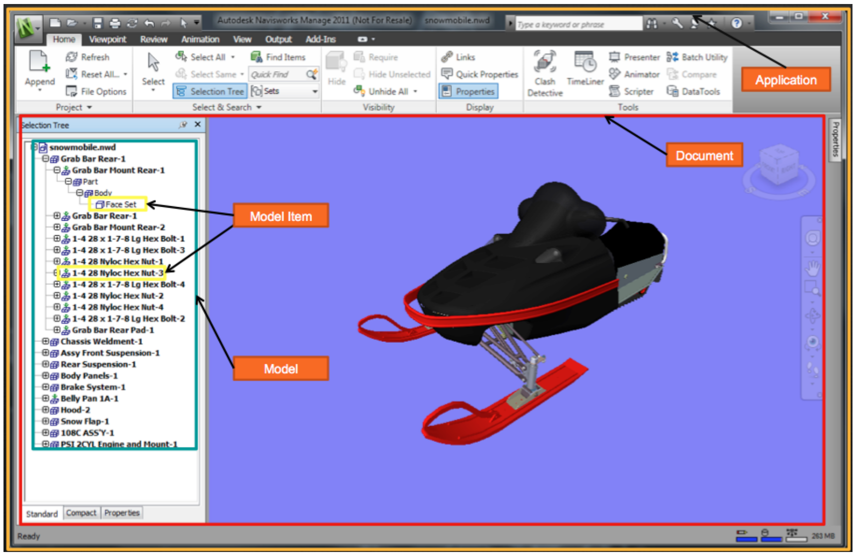

Fig. 3. Navisworks Document Showing Main API Classes

For the purpose of this research, ComApi assembly is the only assembly used among the four for building the BIM CAVE application. Since .Net API is a new framework that is under development, not all the functionalities that were in the COM API are directly implemented in the .Net API. Instead, the application vendor provided a bridge class to access the COM API through .Net API classes.

b. Opening Navisworks And Controlling Camera From .Net API

The *'Document'* class provided under the assembly named *'Autodesk.Navisworks.API.Interop.CompApiAutomation'* is used to open Navisworks from the BIM CAVE application and assign the state object containing reference to the current instance of the Navisworks application. In Navisworks, a complete model is accessed via a state object. In windows terminology, a state object corresponds to a document.

The state contains a component called *'Current View'*. The *'Current View'* component contains *'ViewPoint'*, which defines the camera position and properties that control how the current view is displayed and modified. *'InwNvCamera'* class controls the camera from the internal state classes in the COM API. Table-II below shows the properties and methods of the *'InwNvCamera'* class.

Table II. Members of the camera class

Class Member	**Type**	**Description**
Align up	Input Function	Aligns the camera up orientation
Point At	Input Function	Points the camera at a specified position
GetUpVector	Output Function	Unit Vector representing the up direction of the camera
GetViewDir	Output Function	Unit Vector representing the view direction of the camera
Position	Property	Gets and Sets the 3D position of the camera
Rotation	Property	Gets and Sets the 3D rotation of the camera
Projection	Property	Projection type of the camera
AspectRatio	Property	Aspect ratio of the camera
HeightField	Property	Height field (Radians)

2. BIM CAVE Application

The BIM CAVE application was developed as a part of the research using the .Net framework in C# language. The C# is an object-oriented programming language and its syntax is very similar to the C++ language. The BIM CAVE application that runs on the server and client computers is instrumental in rendering the immersive virtual reality experience in the BIM CAVE. The server computer is the one that controls the central screen and the three client computers are the ones controlling the left, right and top screens of the BIM CAVE. The server and the client computers run two different versions of the BIM CAVE application and the functionalities of these applications are different.

a. Server Application

The BIM CAVE server application is a stand-alone executable file (.EXE). The server application performs two main functionalities to achieve the immersive view as follows:

1. Captures the current camera view of the Navisworks application running in the server computer (using Navisworks API) and applies a mathematical algorithm to the camera coordinates. The camera rotation algorithm that was used in the server application is explained in detail in the sub-sections below.

2. The server application after collecting and manipulating the camera coordinates will send those coordinates over the network to the client computers. The camera coordinates will be sent to the clients whenever the camera position in the Navisworks running on the server changes. The server-client data transfer algorithm is explained in detail in the sub-sections below.

b. Client Application

The client application is similar to the server application and it is also a stand-alone executable file. The client application performs the following tasks:

1. The data packets sent by the server BIM CAVE application containing the camera coordinates will be received by the client application.

2. Once the data packets are received, the client application will process the in-

formation sent and use it to update its current camera orientation in the Navisworks application.

c. BIM CAVE Application Interface

The BIM CAVE's server and client application should be installed in the server and client computers respectively. The server and the client application has a button *'Start Navisworks'*, which will let the user select a Navisworks file and open the same. Essentially all the four computers run a separate instance of the same Navisworks file and only their views are synchronized using the BIM CAVE application. It is highly important to make sure that the files that are opened in the server and client computers are the same to have a meaningful view across the screens. The server application has a dropdown list box that lets the user specify a camera rotation angle for the clients, which is dependent on the orientation of the screens. The *'Connect'* button in the server application opens the port to allow the clients to connect with the server. The server application has a textbox that gets the port number input from the user. The default value for the port number is set as 8000 for both the server and clients. The server also shows a status message indicating whether the clients are connected or not. Figure-4 shows the server BIM CAVE application interface.
The client application has a textbox to get the IP address input from the user. The server computer's IP address displayed in the server BIM CAVE application should be entered in the textbox and the port number should also be same as the server. The *'Connect'* button in the client application will establish a connection between the server and client computers. Figure-5 shows the client BIM CAVE application interface. The operating instructions of the BIM CAVE application are explained in the following steps:

1. Using the *'Start Navisworks'* button in the server and client BIM CAVE application, the same version of Navisworks file is opened in the server and client computers.

2. After opening Navisworks, the server computer's IP address displayed in the server BIM CAVE application is entered in the textbox of the client BIM CAVE application.

3. The server computer should be made to allow the client computers to connect to it by clicking the *'Connect'* button in server BIM CAVE application.

4. The clients are then connected to the server by clicking the *'Connect'* button in the client BIM CAVE application. It should always be made sure that the third client that connects to the server is the top screen client.

5. Once the clients are connected, the angle of rotation for the right and left clients are specified in the drop down list box of the server BIM CAVE application.

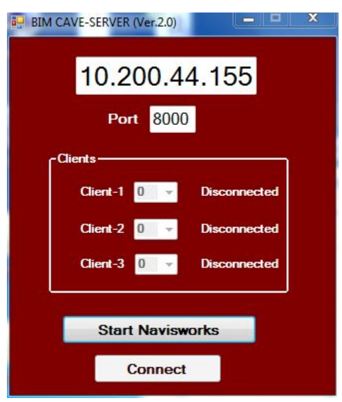

Fig. 4. BIM CAVE- Server Application

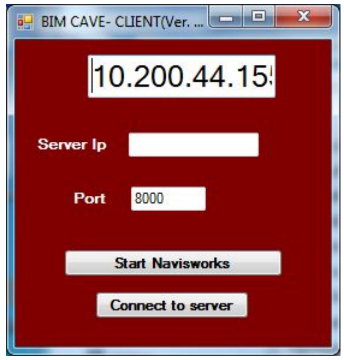

Fig. 5. BIM CAVE- Client Application

d. Server-Client Algorithm

The Server-Client algorithm is written using .Net sockets through which the sever computer communicates with the three clients (Left, Right and Top computer). The server application applies a mathematical algorithm to the camera parameters of the Navisworks based on the configuration of the screens and will send the calculated camera parameters to the clients. The unique data packets for each of the clients containing the camera attributes will be sent through .Net sockets. The data transfer speed is highly crucial in the BIM CAVE, so the server will send the data packets asynchronously, which means it will not wait for the client's response after each and every transfer. This process is also multithreaded in both the server and the client BIM CAVE application. The server listens to the connection requests made by the clients in one thread and sends the data packets to the connected clients in another thread simultaneously. Similarly, the client will listen continuously to receive data packets from the server, which is handled by one thread and processing of the data received is performed by another thread.

e. Navisworks API Algorithm

The Navisworks API algorithm deals with the interaction of the BIM CAVE application and Navisworks. The API algorithm is different for the server and the clients. In server, the API algorithm obtains the camera parameters like camera position in 3D space, camera up vector and camera direction vector. The camera position is represented by *'InwLPos3f'* class, which is a member of *'InwNvCamera'* class. The *'InwLPos3f'* class has properties that are used to retrieve the X, Y and Z values of the current camera position and the *'SetValue'* method is used to set the camera to a known $\{X, Y, Z\}$ position. The up vector and the director vector are the ones representing the up and the viewing directions of the camera. The up and direction vectors are represented by the class *'InwLVec3f'*. The *'InwLVec3f'* also has properties to retrieve the X, Y and Z components of the vector and has a *'SetValue'* method similar to the *'InwLPos3f'* class. Table III shows the members of the *'InwLPos3f'* and *'InwLVec3f'* classes.

C# programming language that was used to develop the BIM CAVE application, supports event driven programming. In other words, a certain set of actions can be performed if a particular event is triggered. This process of event triggering mechanism is used in the BIM CAVE application to obtain the camera parameters from the Navisworks API whenever the position of the camera changes. The *'OnCurrentViewChanged'* event under the *nwOpState* in ComApi is used through the *interop* classes in .Net API to delegate a method to be executed whenever the current view of the camera is changed in the Navisworks application.

The client BIM CAVE application receives the camera position, rotation axis and angle to orient itself with respect to the server's camera for achieving an immersive view. The client application uses 3D rotation under the *'InwNvCamera'* class to rotate the camera. The 3D rotation is represented by the *InwLRotation3f* class, which includes properties and functions as shown in the Table IV.

Table III. Members of the 3D position and vector classes

Class Member	**Member Type**	**Description**
SetValue	Input Function	Sets the camera position
Equals	Input/Output Function	Equality check method
Data1	Property	X- Coordinate
Data2	Property	Y- Coordinate
Data3	Property	Z- Coordinate

Table IV. Members of the Camera 3D Rotation Class

Class Member	**Member Type**	**Description**
SetValue	Input Function	Sets the camera rotation axis and angle
GetAxis	Output Function	Gets the camera rotation axis
Angle	Output Property	Gets the rotation angle in radians

f. Mathematical Rotation Algorithm

The mathematical rotation algorithm is implemented in the server BIM CAVE application to calculate the axis and angle of rotation for the client computer's camera with respect to the server computer in order to achieve an immersive view. The calculated axis and angle of rotation will be sent to the clients using the Server-Client algorithm discussed above, which the clients will use to update their camera position. The rotation algorithm for BIM CAVE version 2 uses quaternion rotation. Quaternions are number systems extending the complex numbers, which primarily finds its use for calculations involving 3D rotations in computer graphics. They represent a four-dimensional vector space over the real numbers. Quaternions have a real and an imaginary part (Equation-4.1).

$$q = a + b.\hat{i} + c.\hat{j} + d.\hat{k} \tag{4.1}$$

Where a, b, c, d are real numbers and i,j,k are the imaginary units.

The Equation-4.1 represents a quaternion, where a is the real part and $(b\hat{i} + c\hat{j} + c\hat{k})$ represents the imaginary part.

The algorithm used for the rotation is as follows.

Step-1:

Take $[0\ 0\ \text{-}1]^T$ and $[0\ 1\ 0]^T$ as the initial orientations of the direction and up vectors and the cross product of those two vectors as the side vector.

Step-2:

(a) For clients with vertical screens, calculate the final orientation of the direction vectors for the camera by rotating the server camera's direction vector $[a_1 b_1 c_1]^T$ about its up vector $[\text{d e f}]^T$ by an angle θ. The angle of rotation is dependent on the orientation of the screens. For instance, if the vertical screens are placed at 90^0 with respect to the server screen, the angle of rotation will be 90^0 and 270^0 for the left and right screens respectively. Let q_1 and q_2 be the quaternions representing the initial and final positions of the direction vectors and q_r represent the rotation quaternion.

$$q_1 = \theta + a_1.\hat{i} + b_1.\hat{j} + c_1.\hat{k} \tag{4.2}$$

$$q_r = \cos(\frac{\theta}{2}) + (\sin(\frac{\theta}{2}).d)\hat{i} + (\sin(\frac{\theta}{2}).e)\hat{j} + (\sin(\frac{\theta}{2}).d)\hat{k} \tag{4.3}$$

$$q_2 = q_r * q_1 \tag{4.4}$$

$$q_2 = \theta + a_2.\hat{i} + b_2.\hat{j} + c_3.\hat{k}(\text{After normalizing q2}) \tag{4.5}$$

From q_2 the rotated direction vectors $[a_2 b_2 c_2]^T$ for the clients can be obtained. The up vector for the rotated position of client's camera will be same as the server because the camera was rotated about the server's up vector.

(b) The direction vector of the client connected to the top screen will be the up vector [d e f]^T of the server's camera and its up vector will be opposite to the direction vector of the server, which is [-a -b -c]^T.

Step-3:

Calculate the side vector for the clients by taking a cross product of its calculated direction and up vectors.

Step-4:

Form the orthonormal basis for the initial and final camera positions with their respective up, direction and side vectors.

Step-5:

Construct two 3x3 matrices M_1 and M_2 with the direction, up and side vectors as rows 1, 2 and 3 respectively for the initial and final position of the camera.

$$M_1 = \begin{pmatrix} 0 & 0 & -1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}, M_2 = \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix}$$

Step 6:

Convert the matrices M_1 and M_2 to quaternions Q_1 and Q_2 where Q_1 and Q_2 are the quaternions representing initial and final camera positions [26].

Step 7:

Find the quaternion Q_T required for transforming the quaternion Q_1 to Q_2.

$$Q_T = Q_2 * Q_1^{-1} \tag{4.6}$$

Step 8:

From the quaternion Q_T, find the axis and angle of rotation.

$$Q_T = qw + qx.\hat{i} + qy.\hat{j} + qz.\hat{k} \tag{4.7}$$

$$X = \frac{qx}{\sqrt{(1 - qw^2)}}, Y = \frac{qy}{\sqrt{(1 - qw^2)}}, Z = \frac{qz}{\sqrt{(1 - qw^2)}} \tag{4.8}$$

$$\theta = 2 * \cos^{-1}(qw); (qw \neq 1) \tag{4.9}$$

Where,

[X Y Z]^T is the Axis of Rotation,

θ is the angle of rotation in radians

Navisworks always rotates the camera with respect to the absolute initial position of its up and direction vectors. The initial position of its direction and up vectors are $[0\ 0\ \text{-}1]^T$ and $[0\ 1\ 0]^T$ respectively. The modified rotation algorithm for the BIM CAVE version 2 is an advancement over the version 1 because of the following reasons:

1. The main advantage of using quaternions for 3D rotation is that they are mathematically more stable than the Euler's rotation and the axis angle rotation.

2. If the angle of rotation for the clients camera position is 180^0 the axis angle rotation will fail to work whereas the quaternion rotation algorithm is stable for that rotation angle.

3. The version 1 of BIM CAVE restricted the camera's orientation and it was fixed to $[0\ 0\ 1]^T$ vector. This limitation was removed in the current algorithm developed by supporting the tilting of camera to any orientation required.

C. BIM CAVE Mechanism

The BIM CAVE application developed for this research integrates the hardware and the software components to achieve a semi-immersive virtual reality environment. The term semi-immersive environment in this current context means that the user is partially surrounded by LCD screens. A fully immersive environment could be developed by adding a screen behind the user to this existing setup. The main factor that helps to achieve the sense of presence in any virtual reality system like BIM CAVE is the field of view. In BIM CAVE, the vertical screens of the clients are placed at 90^0 with respect to the server and so the client's camera views are rotated by the same angle as the LCD screens to achieve a horizontal field of view of 270^0. The placement of one more LCD screen on top of the three vertical screens increases the vertical field of view, which is believed to further enhance the sense of presence. The BIM application executes the three algorithms, Server-Client, Navisworks API and Mathematical Rotation in a particular order to achieve a coherent view in all the four screens. The following steps explain the working process of the BIM CAVE application developed:

1. First, the Navisworks API algorithm is executed in the server BIM application. The API algorithm will collect the camera parameters like position, view

direction vector and up vector whenever the current view of the camera changes.

2. Once the server's camera parameters are generated, the mathematical rotation algorithm will be applied to the gathered camera parameters and the axis and angle of rotation for each of the clients will be calculated.

3. The Server-Client algorithm will be used to transfer the data packets containing the axis and angle of rotation to each of the clients connected with the server.

4. Clients receive the data packets sent by the server using the Server-Client algorithm.

5. The received data packets will be used by the clients to update their camera position with respect to the server in order to achieve an immersive view using the Navisworks API algorithm.

Figure-6 explains the working mechanism of the server and client BIM CAVE application. The source code for the server and client BIM CAVE application are provided in the Appendix-A.

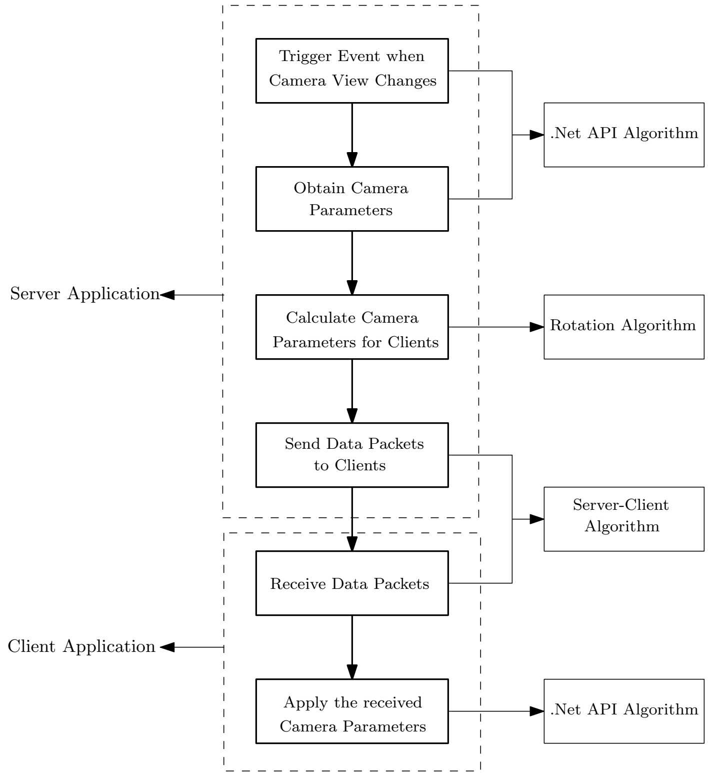

Fig. 6. Working of BIM CAVE

D. Challenges Faced

The alignment of the four 55" LCD screens posed a major challenge to produce a coherent view in the BIM CAVE. Since the screens are rectangular in shape, the screen on top does not cover the top of the CAVE completely. The orientation of the top screen had to be decided based on the vertical and horizontal field of views of the Navisworks camera. Initially, the top screen was placed right above the center screen and the results obtained were not satisfying. Later, it was found out that for producing a meaningful immersive view with the four rectangular screens, the centers of all the four screens had to be the same. In order to bring the centers of the four screens to a common point, the screen on top had to be moved away from the center screen by a small distance. This left a small gap between the center screen and the top screen, compromising the continuity of the views across the screens. The alternative solution for this problem could be to use a square instead of a rectangular LCD screen for the top screen so that it covers the CAVE completely. As it was difficult to procure a perfectly square screen, the researcher stuck to the first solution of moving the top screen away from the center screen. Figure-7 and Figure-8 shows the initial and final configurations of the screens in the BIM CAVE. Moreover, the distance from the observer's eye position to the three vertical screens are different compared to the screen on top. So the field of views for the three vertical screens and the top screen were made different in order to adjust for the varying distances between the observer's position and the screens around. The field of view for the screen on top is more than the field of views for the vertical screens as $D1$(distance to top screen) is less than $D2$(distance to vertical screens). Figure-9 shows the illustration of the adjusted field of view for the screen on top.

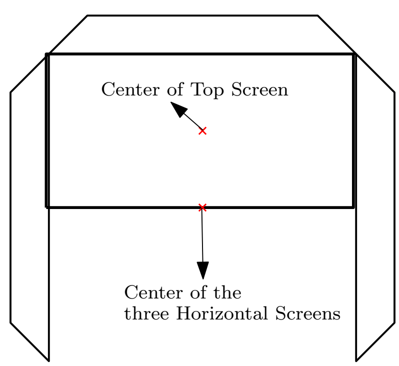

Fig. 7. Initial Configuration of all the 4 screens

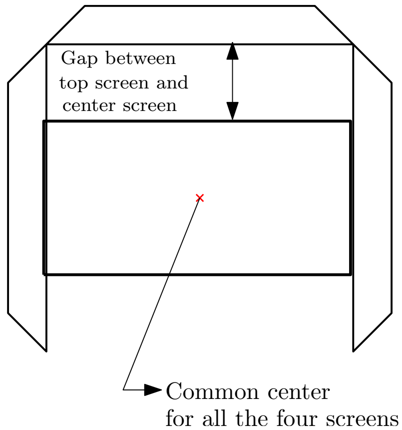

Fig. 8. Modified Configuration of the Top Screen

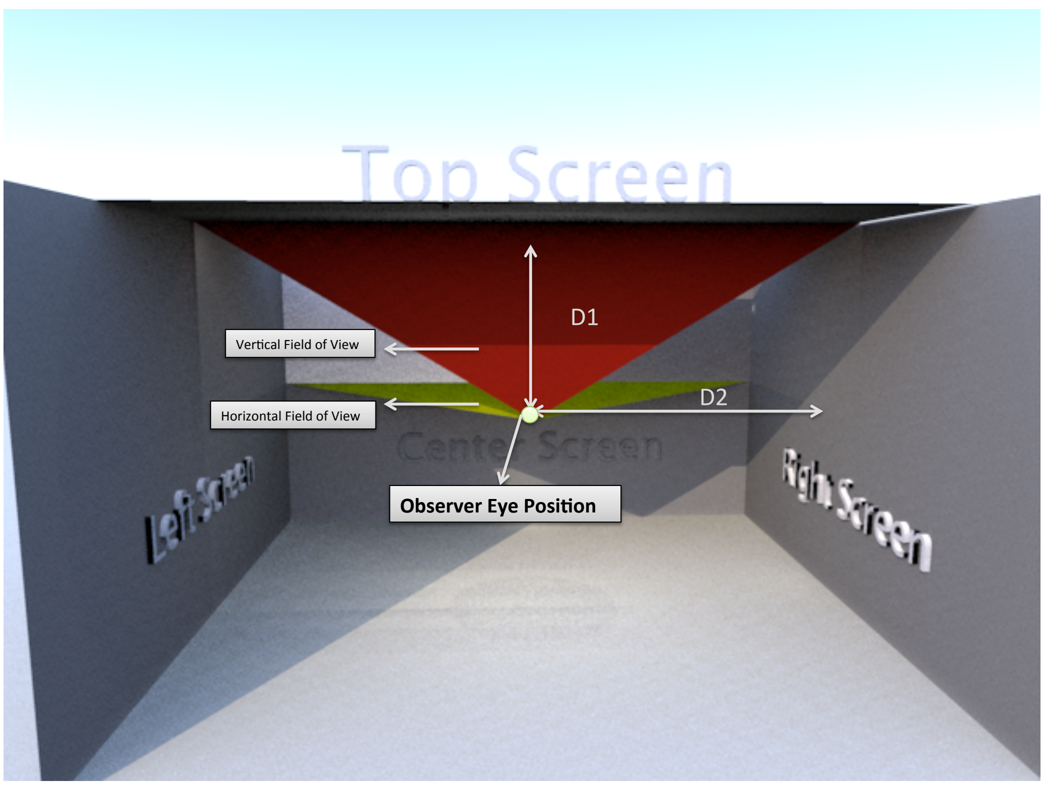

Fig. 9. Corrected field of view for top screen with distance of each screen from the observer's position

CHAPTER V

DATA COLLECTION

Phenomenological study was conducted to validate the modified BIM CAVE setup developed as a part of this research. The interviews were videotaped to make sure there were no interruptions, allowing it to be more informal. The videos were later transcribed and the data was analyzed to understand the SMEs perception about the concept of looking up and seeing in the BIM CAVE setup.

The phenomenological study requires a minimum of five participants to be interviewed. The participants of the study contained five professionals from the AEC industry with expertise in BIM and virtual reality systems. The five participants of this study were an Architect, a BIM Manager, an Engineer and two Business Development Managers representing different companies. In order to protect the privacy of the participants, their identities were not revealed and were mentioned as Interviewee 1, 2, 3, 4 and 5. Since, the results from this study is based on the feedback given by the five participants, their credibility is a major factor for obtaining reliable results. The qualifications of the participants of this study are as follows:

1. Business Development Manager

   Interviewee 1 has about eight years of experience in construction industry with project Management, project Controls, estimation and BIM experiences.

2. Business Development Manager

   Interviewee 2 has about fifteen years of construction experience in project management, estimation, architecture and business development. He has acquired skills to coordinate the pre-construction phase of any project with good appreciation for the concepts of BIM.

3. Architect

   Interviewee 3 has about five years of experience as an architect with experience in Autodesk Revit and other 3D modeling tools.

4. BIM Coordinator

   Interviewee 4 has about five years of experience in construction industry in total. In that five years, he gained about three years of experience working as a BIM Coordinator with skill sets to work with BIM applications like Revit and Navisworks.

5. Engineer

   Interviewee 5 has about five and a half years of experience in construction industry as a Project Engineer and BIM Coordinator. He has acquired skills to conduct coordination meetings involving sub-contractors with the aid of Navisworks.

The following question were asked by the researcher to the SMEs during the interview sessions:

1. Describe your experience of looking up and visualizing the components of the BIM model from the top screen.

2. How is this experience different than tilting the models to look up?

3. What are the advantages and disadvantages of this BIM CAVE setup?

The interview questions helped to know the participants' opinion about the idea of looking up to see the overhead components from the top screen. It also facilitated to understand the impacts of having a screen on top of the BIM CAVE and the differences in the visualization process when compared to the BIM CAVE without a top screen. The benefits and limitations of the suggested setup for the BIM CAVE were also obtained from the participants as a part of the interview process. Appendix-B contains the transcripts of the five interviews conducted to validate the setup developed. The following chapter discusses the results of the phenomenological study.

CHAPTER VI

RESULTS

The interviews conducted as a part of the phenomenological study were transcribed and the data was analyzed to understand the impacts of having a screen on top of the BIM CAVE setup. This section shows the findings of the study, which helped identifying whether there were any significant differences between the BIM CAVE with and without a top screen.

The interview transcripts were analyzed and grouped based on the following three topics of interest:

1. The experience of looking up from the top screen and the differences as experienced by the participants between looking up from the top screen and tilting the model to look up.

2. Benefits of having a screen on top.

3. Limitations of the suggested new setup.

A. Top Screen Experience

The participants were given a demonstration of how the setup works and were allowed to use the BIM CAVE to experience it by themselves. After the system introduction phase, the participants were asked about the experience of looking up and seeing BIM model's overhead components. They were also asked to describe the difference between visualizing the overhead components with and without the top screen in the BIM CAVE.

Interviewee 1, Business Development Manager, described that the presence of top screen is a one more element to look at while browsing the BIM models and it is intuitively different to visualize the overhead components by looking up rather than tilting the models. The participant explained that the main purpose of having a top screen is to look up and see how different systems interact with each other inside the building.

Interviewee 2, Business Development Manager, felt that the presence of the top screen forces the user to look up at something that he/she might not have looked at without the screen on top. In the case of clash detection, the probability of finding a potential clash between the components inside a building is more from the top screen than tilting the model to look up.

Interviewee 3, who is an architect, said that he is used to visualizing BIM models in a single screen. He felt that the idea of having the model stretched out across multiple screens is a new concept. He explained that his natural tendency while browsing the model in the BIM CAVE would be to bring the 3D model from the screens around him to the center screen before visualizing them. He said eventually one would get used to the process of tilting the head to see the BIM model rather than rotating the model itself. He added that as an architect he would be able to look at a plan and identify the locations with potential MEP problems. In those cases, he could navigate to a particular spot in the model and just look up from the top screen to check for any design inconsistencies. He also felt that the process of tilting the model by 90 degrees to see the overhead components is counterintuitive whereas looking up to see the components from the top screen is more natural and intuitive.

Interviewee 4, BIM Coordinator, expressed that the concept of looking up and seeing the BIM model's overhead components is a new experience as he is used to working with a single screen. He felt that the addition of a forth screen to the BIM CAVE adds one more dimension to it. He added that this setup would be helpful for those people who are not used to seeing BIM models at a regular basis as it gives a better

sense of space around them. He also added that the process of looking up is more natural and intuitive than tilting the models.
Interviewee 5, Engineer, said the process of looking up and seeing from the top screen is one less step to visualize the overhead components when compared to tilting the model. He also added that this process is more realistic as it makes the user feel like he/she is in a real space, which will be very helpful to develop a better understanding for the design.

B. Benefits Of Having A Screen On Top

The interview transcripts revealed the potential benefits of having a screen on top of the BIM CAVE in the AEC industry. The advantages of BIM CAVE system as described by the participants can be summed up as follows:

- Effective coordination of the MEP systems and scheduling different trades to avoid spatial conflicts and overcrowding.
- Ease of use for comparing different model elements without having to tilt them to go back and forth.
- Improved visualization of complex industrial buildings with lots of overhead components and connection details.
- Better communication of the design to the owner and among other project participants.
- Training of workers in the virtual space.

Interviewee 1 described that the main benefit of having a screen on top is the ability to stand in one position and see all the components around the user in the same time rather than tilting the model to go back and forth. He also added that the BIM CAVE setup with the top screen could be used to see the connection details in the building model, which is a crucial part for generating shop drawings. The participant said that the interaction of joist girders and the column is one of the many connection details that could be visualized using the top screen of the BIM CAVE.

Interviewee 2 expressed that the use of top screen in virtual reality environments like BIM CAVE would help to better communicate the design to the owners and to other team members especially to explain constructability issues. He quoted that "If you can sit there digitally and say you cannot put a particular component in here as it will not fit and if the owner says, I do not understand why, you can ask him to stand right here and look up and that is huge." The participant also added that the process of looking up and seeing the connection details helps to gain a better understanding of how the building is connected.

Interviewee 3 said that one of the biggest advantages of having a screen on top is its ability to communicate the space effectively to the owners. He commented on the process of looking up and seeing being more intuitive, interference of structural and MEP components could be spotted .

Interviewee 4 explained that the use of this setup with four screens can be very beneficial in coordination meetings where people are trying to resolve conflicts as a team. The presence of four screens will provide a better understanding of the 3D model for the people who are looking at it for the first time. Moreover, a person who does not have better visualization capabilities to understand the 3D model will highly benefit from making use of this setup. He added that this setup would benefit new workers in a project by giving them a better understanding of the whole project:It can also be used to train them in more complex projects even before getting them exposed to the actual site.

Interviewee 5 said that virtual reality systems like BIM CAVE would enable the superintendents to step into a virtual project space and see how things are going to look like even before they are built to manage the construction effectively. Furthermore, he mentioned that the biggest component in construction industry that is still at lag is the decision making process. In order to make critical decisions at the right time, it is highly important to know how a particular building or a facility is going to look like before they are built. Communicating a design to the owners by using conventional visualization setups is very difficult because of lack of experience of owners in dealing with BIM models. Virtual reality systems like BIM CAVE can immerse a user in to a virtual space and can bridge the gap between the real and virtual world. He also added that the use of multiple screens would help during clash detection to look around a particular clash to see if there are any other problems associated with that.

C. Limitations Of The Setup

The SMEs also explained their opinion about the limitations of the suggested new setup. The summary of the limitations obtained from the interview transcripts is as follows.

- The presence of a gap between the center and the top screen prevents the user from experiencing the perspective of the BIM model fully.
- The small size of the setup that limits the number of people inside the CAVE.
- The high cost of installing VR systems like BIM CAVE makes it unaffordable.

Interviewee 1 stated that the main disadvantage of the setup developed is the presence of the small gap between the top screen and the center vertical screen, which prevents the user from seeing how the building raises. He suggested including an intermediate screen between the top and the center screen, which would help to obtain a more seamless and continuous view.

Interviewee 2 expressed that the main limitation of virtual reality systems is its cost as most of the construction companies will not be willing to invest so much money to own a setup like BIM CAVE.

Interviewee 3 said that the size of the BIM CAVE was too small to comfortably move around. He also felt that it would help to have a small 2D view on the bottom right corner of the screen showing the position in the building plan as it will be easy to keep track of ones location inside the building constantly.

Interviewee 4 said that the main limitation of the current BIM CAVE setup is that it restricts the users to visualize the clashes from the bottom whereas the general tendency of the users is to fly around clashes in the 3D model. He also expressed that setups like BIM CAVE will be used occasionally for presentations and meetings: They do not have a great deal of advantage in day to day work as experienced people in construction are comfortable working with a single screen.

Interviewee 5 described that the process of looking up is awkward and the setup is not ergonomic to visualize the BIM model from the top screen. He added that the "old school people" in a company who will have difficulties stepping in to this virtual world might not make use of this setup effectively. He also expressed that there was a lag between the server and the client computers during the navigation process, which affected its performance.

CHAPTER VII

CONCLUSION

The BIM CAVE version 1 had limitations in terms of showing the overhead components of a BIM model. Conventionally, models had to be tilted to look up, which was counterintuitive when using VR systems like BIM CAVE. To overcome the problem of visualizing the overhead components in the existing BIM CAVE, a LCD screen was placed on top of the CAVE. The new setup was built by fabricating new hardware and by developing software programs. The BIM CAVE setup was then validated using qualitative research methodology. Qualitative methodology involved conducting descriptive interviews with SMEs. The interviews revealed that the use of top screen in BIM CAVE makes the process of visualizing the overhead components like MEP systems more effective than the previous setup, and it is more intuitive than tilting the models. People who do not have experience in handling 3D models will be greatly benefitted by this setup because it creates a better sense of presence than the previous setup. The use of top screen also has several other advantages like ease of spotting clashes between the building components, effective communication of the design and visualization of connection details. Thus from the research findings, conclusion can be made that the addition of a top screen will make a substantial difference in the visualization capabilities of the existing BIM CAVE without the top screen.

A. Benefits

In conventional virtual reality systems, the models have to be tilted up to look at the overhead components in the BIM model. During this process the sense of presence is lost. Addition of one more screen on top enhances the visualization of MEP components and the immersive environment experience for the users. Moreover, the addition of top screen would facilitate to see more model elements without tilting the model itself, which would save a lot of time going back and forth in a model.In addition to that, the BIM CAVE has several advantages of the version 1 such as it does not require the models to be converted to a native format, which usually takes a lot of time and results in data loss. BIM models will contain the same amount of information before and after visualization. The BIM CAVE software is written on top of a commercial application, Navisworks and so most of its functionalities could be used with this setup unlike other CAVE environments.

B. Future Research

The interviews with the SMEs revealed that the suggested new setup has some limitations like small size, affordability and the presence of a gap between the center screen the top screen. Considering all the suggestions from the participants, the researcher puts forth the following recommendations for future research

1. The top screen can be replaced with a square shaped LCD screen to fully cover the top without leaving any gaps to produce a seamless and continuous view.

2. Screens with projectors can be used to increase the size of the CAVE and reduce the cost of buying more LCD screens.

3. The Navisworks API can be used to create a 2D map of the building in the bottom right hand corner of the Navisworks window to show the position of the user in the map when navigating through the model.

4. Some of the other features of Navisworks like hiding model elements, timeliner function and other model manipulation functions can be synchronized between the server and client computers in the BIM CAVE.

5. One of the participants in the study stated that the top screen could increase the potential of finding clashes in a BIM model. This statement could be tested and validated in the future study.

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APPENDIX A

BIM CAVE APPLICATION SOURCE CODE

SERVER APPLICATION CODE

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Text;
using System.Windows.Forms;
using inter = Autodesk.Navisworks.Api.ComApi;
using ComApi = Autodesk.Navisworks.Api.Interop.ComApi;
using CA = Autodesk.Navisworks.Api.Interop.ComApiAutomation;
using System.Net;
using System.Net.Sockets;
using System.Runtime.InteropServices;
using System.Collections;
using System.Threading;
using System.Windows;
using Q = System.Windows.Media.Media3D;
namespace WindowsFormsApplication1
{
    public partial class Form1 : Form
    {
        public double tupx, tupy, tupz, temp1 = -1, temp2 = -1, temp3 = -1, tempx =
            0, tempy = 0, tempz = 0, tempx2 = 0, tempy2 = 0, tempz2 = 0, tempx3 = 0,
            tempy3 = 0, tempz3 = 0;
        public delegate void UpdateClientListCallback();
        public AsyncCallback pfnWorkerCallBack;
        private Socket m_mainSocket;
        private System.Collections.ArrayList m_workerSocketList =
                ArrayList.Synchronized(new System.Collections.ArrayList());
        private int m_clientCount = 0;
        public int i = 0;
        public NetworkStream serverstream;
        public CA.Document doc;
        public static ComApi.InwOpState10 state = null;
        public ComApi.InwNvCamera cam = null;
        public Form1()
        {
            InitializeComponent();

        }
        private void button1_Click(object sender, EventArgs e)
        {

            ComApi.nwOpState st = new ComApi.nwOpState();
            doc = null;
            openFileDialog1.ShowDialog();
            if (openFileDialog1.FileName != "" & (System.IO.Path.GetExtension(
                openFileDialog1.FileName) == ".nwd" | System.IO.Path.GetExtension(
                openFileDialog1.FileName) == ".nwc" | System.IO.Path.GetExtension(
                openFileDialog1.FileName) == ".nwf"))
            {
```

```
                doc = new CA.Document();
                st = null;
                doc.Visible = true;
                doc.OpenFile(openFileDialog1.FileName);
                st = doc.State();
                state = doc.State();
                state.CurrentView.ViewPoint.Camera.HeightField = 2 * Math.Atan(Math.
                    Tan(45 * Math.PI / 180) / state.CurrentView.ViewPoint.Camera.
                    AspectRatio);
                st.EventsEnabled = true;
                st.OnCurrentViewChanged += new ComApi.
                    _InwOpStateEvents_OnCurrentViewChangedEventHandler(
                    st_OnCurrentViewChanged);
                st.EventsEnabled = true;
                button2.Enabled = true;
            }
            else
            {
                MessageBox.Show("Please select a valid file");
            }
        }
        private void Form1_Load(object sender, EventArgs e)
        {
            button2.Enabled = false;
            textBox1.Text = GetIP();
            for (double i = 0; i <= 360; i++)
            {
                comboBox1.Items.Add(i);
                comboBox2.Items.Add(i);
                comboBox3.Items.Add(i);
            }
            comboBox1.SelectedIndex = 0;
            comboBox2.SelectedIndex = 0;
            comboBox3.SelectedIndex = 0;
            label8.Text = "Disconnected";
            label9.Text = "Disconnected";
            label11.Text = "Disconnected";
            comboBox1.Enabled = false;
            comboBox2.Enabled = false;
            comboBox3.Enabled = false;
        }
        private void st_OnCurrentViewChanged()
        {
            rot1();
            rot2();
            rot3();
        }
        String GetIP()
        {
            String strHostName = Dns.GetHostName();
            IPHostEntry iphostentry = Dns.GetHostEntry(strHostName);
            String IPStr = "";
            foreach (IPAddress ipaddress in iphostentry.AddressList)
            {
                IPStr = ipaddress.ToString();
                if (ipaddress.IsIPv6LinkLocal == false) return IPStr;
            }
            return IPStr;
        }

        private void button2_Click_1(object sender, EventArgs e)
        {
            try
```

```
            {
                if (textBox2.Text == "")
                {
                    MessageBox.Show("Please enter a Port Number");
                    return;
                }
                string portStr = textBox2.Text;
                int port = System.Convert.ToInt32(portStr);
                m_mainSocket = new Socket(AddressFamily.InterNetwork,
                    SocketType.Stream,
                    ProtocolType.Tcp);
                IPEndPoint ipLocal = new IPEndPoint(IPAddress.Any, port);
                m_mainSocket.Bind(ipLocal);
                m_mainSocket.Listen(4);
                m_mainSocket.BeginAccept(new AsyncCallback(OnClientConnect), null);
            }
            catch (SocketException se)
            {
                MessageBox.Show(se.Message);
            }
        }
        public void OnClientConnect(IAsyncResult asyn)
        {
            try
            {
                Socket workerSocket = m_mainSocket.EndAccept(asyn);
                Interlocked.Increment(ref m_clientCount);

                m_mainSocket.BeginAccept(new AsyncCallback(OnClientConnect), null);

                if (m_clientCount == 1)
                {
                    UpdateClientListControl();
                    comboBox1.Enabled = true;
                }
                if (m_clientCount == 2)
                {
                    UpdateClientListControl2();
                    comboBox2.Enabled = true;
                }
                if (m_clientCount == 3)
                {
                    UpdateClientListControl3();
                }

                m_workerSocketList.Add(workerSocket);
            }
            catch (ObjectDisposedException)
            {
                System.Diagnostics.Debugger.Log(0, "1", "\n OnClientConnection: 
                    Socket has been closed\n");
            }
            catch (SocketException se)
            {
                MessageBox.Show(se.Message);
            }
        }
        public void Onclientdisconnect(IAsyncResult asyn)
        {
            int socnum;
            Socket workersocket = (Socket)asyn.AsyncState;
            workersocket.EndDisconnect(asyn);
            for (i = 0; i < m_workerSocketList.Count; i++)
```

```
            {
                if (workersocket == m_workerSocketList[i])
                {
                    socnum = i + 1;
                    m_workerSocketList[i] = null;
                }
            }
        }
        public void SendMsgToClient(string client1, int clientNumber)
        {
            System.IO.MemoryStream ms = new System.IO.MemoryStream();
            System.IO.BinaryWriter bw = new System.IO.BinaryWriter(ms);
            bw.Write(client1);
            byte[] byData = ms.ToArray();
            Socket workerSocket = (Socket)m_workerSocketList[clientNumber - 1];
            try
            {
                workerSocket.Send(byData);
            }
            catch (SocketException ex)
            {
                MessageBox.Show(ex.Message);
            }
        }
        private void UpdateClientListControl()
        {
            if (InvokeRequired)
            {
                label8.BeginInvoke(new UpdateClientListCallback(updatelist), null);
            }
            else
            {
                updatelist();
            }
        }

        void updatelist()
        {

            label8.Text = "Connected";
        }
        private void UpdateClientListControl2()
        {
            if (InvokeRequired)
            {
                label9.BeginInvoke(new UpdateClientListCallback(updatelist2), null);
            }
            else
            {
                updatelist2();
            }
        }
        void updatelist2()
        {
            label9.Text = "Connected";
        }
        private void UpdateClientListControl3()
        {
            if (InvokeRequired)
            {
                label9.BeginInvoke(new UpdateClientListCallback(updatelist3), null);
            }
            else
```

```
            {
                updatelist3();
            }
        }
        void updatelist3()
        {

            label11.Text = "Connected";
        }
        private void rot1()
        {
            double A, B, C, a, b, c, d, e, f, X, Y, Z, qw1, qw2, qx1, qx2, qy1, qy2,
                qz1, qz2, angle, clientang1, cosang1, sinang1;
            object combo1 = comboBox1.SelectedItem;
            if (state != null)
            {
                ComApi.InwNvCamera cam = state.CurrentView.ViewPoint.Camera;
                cam.HeightField = 2 * Math.Atan(Math.Tan(45 * Math.PI / 180) / state.
                    CurrentView.ViewPoint.Camera.AspectRatio);
                clientang1 = (double.Parse(combo1.ToString()) * Math.PI / 180);
                cosang1 = Math.Cos(clientang1);
                sinang1 = Math.Sin(clientang1);
                a = cam.GetViewDir().data1;
                b = cam.GetViewDir().data2;
                c = cam.GetViewDir().data3;
                d = cam.GetUpVector().data1;
                e = cam.GetUpVector().data2;
                f = cam.GetUpVector().data3;
                Q.Quaternion q1 = new Q.Quaternion(a, b, c, 0);
                q1.Normalize();
                double x1, y1, z1, w1;
                x1 = d * Math.Sin(clientang1 / 2);
                y1 = e * Math.Sin(clientang1 / 2);
                z1 = f * Math.Sin(clientang1 / 2);
                w1 = Math.Cos(clientang1 / 2);
                Q.Quaternion r1 = new Q.Quaternion(x1, y1, z1, w1);
                r1.Normalize();
                Q.Quaternion rotated;
                rotated = Q.Quaternion.Multiply(r1, q1);
                r1.Invert();
                rotated = Q.Quaternion.Multiply(rotated, r1);
                rotated.Normalize();
                A = rotated.X;
                B = rotated.Y;
                C = rotated.Z;
                Q.Vector3D m1 = new Q.Vector3D(0, 0, -1);
                Q.Vector3D m2 = new Q.Vector3D(0, 1, 0);
                Q.Vector3D cp = Q.Vector3D.CrossProduct(m1, m2);
                cp.Normalize();
                Q.Vector3D m3 = new Q.Vector3D(cp.X, cp.Y, cp.Z);
                m1.Normalize();
                m2.Normalize();
                m3.Normalize();
                Q.Vector3D n1 = new Q.Vector3D(A, B, C);
                Q.Vector3D n2 = new Q.Vector3D(d, e, f);
                Q.Vector3D cp2 = Q.Vector3D.CrossProduct(n1, n2);
                cp2.Normalize();
                Q.Vector3D n3 = new Q.Vector3D(cp2.X, cp2.Y, cp2.Z);
                n1.Normalize();
                n2.Normalize();
                n3.Normalize();
                double tr4, tr5, tr6;
                tr4 = 1 + m1.X - m2.Y - m3.Z;
```

```
tr5 = 1 - m1.X + m2.Y - m3.Z;
tr6 = 1 - m1.X - m2.Y + m3.Z;
double tr1 = 1 + n1.X - n2.Y - n3.Z;
double tr2 = 1 - n1.X + n2.Y - n3.Z;
double tr3 = 1 - n1.X - n2.Y + n3.Z;
if ((tr4 > tr5) & (tr4 > tr6))
{
    double S = Math.Sqrt(tr4) * 2; // S=4*qx
    qw1 = (m3.Y - m2.Z) / S;
    qx1 = 0.25 * S;
    qy1 = (m1.Y + m2.X) / S;
    qz1 = (m1.Z + m3.X) / S;
}
else if ((tr5 > tr4) & (tr5 > tr6))
{
    double S = Math.Sqrt(tr5) * 2; // S=4*qy
    qw1 = (m1.Z - m3.X) / S;
    qx1 = (m1.Y + m2.X) / S;
    qy1 = 0.25 * S;
    qz1 = (m2.Z + m3.Y) / S;
}
else
{
    double S = Math.Sqrt(tr6) * 2; // S=4*qz
    qw1 = (m2.X - m1.Y) / S;
    qx1 = (m1.Z + m3.X) / S;
    qy1 = (m2.Z + m3.Y) / S;
    qz1 = 0.25 * S;
}
if ((tr1 > tr2) & (tr1 > tr3))
{
    double S = Math.Sqrt(tr1) * 2; // S=4*qx
    qw2 = (n3.Y - n2.Z) / S;
    qx2 = 0.25 * S;
    qy2 = (n1.Y + n2.X) / S;
    qz2 = (n1.Z + n3.X) / S;
}
else if ((tr2 > tr1) & (tr2 > tr3))
{
    double S = Math.Sqrt(tr2) * 2; // S=4*qy
    qw2 = (n1.Z - n3.X) / S;
    qx2 = (n1.Y + n2.X) / S;
    qy2 = 0.25 * S;
    qz2 = (n2.Z + n3.Y) / S;
}
else
{
    double S = Math.Sqrt(tr3) * 2; // S=4*qz
    qw2 = (n2.X - n1.Y) / S;
    qx2 = (n1.Z + n3.X) / S;
    qy2 = (n2.Z + n3.Y) / S;
    qz2 = 0.25 * S;
}
Q.Quaternion quat1 = new Q.Quaternion(qx1, qy1, qz1, qw1);
Q.Quaternion quat2 = new Q.Quaternion(qx2, qy2, qz2, qw2);
quat1.Normalize();
quat2.Normalize();
quat1.Invert();
Q.Quaternion qt = Q.Quaternion.Multiply(quat1, quat2);
X = qt.X / (Math.Sqrt(1 - qt.W * qt.W));
Y = qt.Y / (Math.Sqrt(1 - qt.W * qt.W));
Z = qt.Z / (Math.Sqrt(1 - qt.W * qt.W));
angle = 360 - ((2 * Math.Acos(qt.W)) * 180 / Math.PI);
```

```
                string posx, posy, posz, X_3, Y_3, Z_3, rotang_3;
                posx = String.Format("{0:0.00000}", cam.Position.data1);
                posy = String.Format("{0:0.00000}", cam.Position.data2);
                posz = String.Format("{0:0.00000}", cam.Position.data3);
                X_3 = String.Format("{0:0.00000}", X.ToString());
                Y_3 = String.Format("{0:0.00000}", Y.ToString());
                Z_3 = String.Format("{0:0.00000}", Z.ToString());
                rotang_3 = String.Format("{0:0.00000}", angle.ToString());
                string client1 = posx + "|" + posy + "|" + posz + "|" + X_3 + "|" +
                    Y_3 + "|" + Z_3 + "|" + rotang_3;
                try
                {
                    SendMsgToClient(client1, 1);
                }
                catch (Exception ex)
                {
                }
            }
        }
        private void rot2()
        {
            double A, B, C, a, b, c, d, e, f, X, Y, Z, qw1, qw2, qx1, qx2, qy1, qy2,
                qz1, qz2, angle, clientang1, cosang1, sinang1;
            object combo2 = comboBox2.SelectedItem;
            if (state != null)
            {
                ComApi.InwNvCamera cam = state.CurrentView.ViewPoint.Camera;
                cam.HeightField = 2 * Math.Atan(Math.Tan(45 * Math.PI / 180) / state.
                    CurrentView.ViewPoint.Camera.AspectRatio);
                clientang1 = (double.Parse(combo2.ToString()) * Math.PI / 180);
                cosang1 = Math.Cos(clientang1);
                sinang1 = Math.Sin(clientang1);
                a = cam.GetViewDir().data1;
                b = cam.GetViewDir().data2;
                c = cam.GetViewDir().data3;
                d = cam.GetUpVector().data1;
                e = cam.GetUpVector().data2;
                f = cam.GetUpVector().data3;
                Q.Quaternion q1 = new Q.Quaternion(a, b, c, 0);
                q1.Normalize();
                double x1, y1, z1, w1;
                x1 = d * Math.Sin(clientang1 / 2);
                y1 = e * Math.Sin(clientang1 / 2);
                z1 = f * Math.Sin(clientang1 / 2);
                w1 = Math.Cos(clientang1 / 2);
                Q.Quaternion r1 = new Q.Quaternion(x1, y1, z1, w1);
                r1.Normalize();
                Q.Quaternion rotated;
                rotated = Q.Quaternion.Multiply(r1, q1);
                r1.Invert();
                rotated = Q.Quaternion.Multiply(rotated, r1);
                rotated.Normalize();
                A = rotated.X;
                B = rotated.Y;
                C = rotated.Z;
                Q.Vector3D m1 = new Q.Vector3D(0, 0, -1);
                Q.Vector3D m2 = new Q.Vector3D(0, 1, 0);
                Q.Vector3D cp = Q.Vector3D.CrossProduct(m1, m2);
                cp.Normalize();
                Q.Vector3D m3 = new Q.Vector3D(cp.X, cp.Y, cp.Z);
                m1.Normalize();
                m2.Normalize();
                m3.Normalize();
```

```
Q.Vector3D n1 = new Q.Vector3D(A, B, C);
Q.Vector3D n2 = new Q.Vector3D(d, e, f);
Q.Vector3D cp2 = Q.Vector3D.CrossProduct(n1, n2);
cp2.Normalize();
Q.Vector3D n3 = new Q.Vector3D(cp2.X, cp2.Y, cp2.Z);
n1.Normalize();
n2.Normalize();
n3.Normalize();
double tr4, tr5, tr6;
tr4 = 1 + m1.X - m2.Y - m3.Z;
tr5 = 1 - m1.X + m2.Y - m3.Z;
tr6 = 1 - m1.X - m2.Y + m3.Z;
double tr1 = 1 + n1.X - n2.Y - n3.Z;
double tr2 = 1 - n1.X + n2.Y - n3.Z;
double tr3 = 1 - n1.X - n2.Y + n3.Z;
if ((tr4 > tr5) & (tr4 > tr6))
{
    double S = Math.Sqrt(tr4) * 2; // S=4*qx
    qw1 = (m3.Y - m2.Z) / S;
    qx1 = 0.25 * S;
    qy1 = (m1.Y + m2.X) / S;
    qz1 = (m1.Z + m3.X) / S;
}
else if ((tr5 > tr4) & (tr5 > tr6))
{
    double S = Math.Sqrt(tr5) * 2; // S=4*qy
    qw1 = (m1.Z - m3.X) / S;
    qx1 = (m1.Y + m2.X) / S;
    qy1 = 0.25 * S;
    qz1 = (m2.Z + m3.Y) / S;
}
else
{
    double S = Math.Sqrt(tr6) * 2; // S=4*qz
    qw1 = (m2.X - m1.Y) / S;
    qx1 = (m1.Z + m3.X) / S;
    qy1 = (m2.Z + m3.Y) / S;
    qz1 = 0.25 * S;
}
if ((tr1 > tr2) & (tr1 > tr3))
{
    double S = Math.Sqrt(tr1) * 2; // S=4*qx
    qw2 = (n3.Y - n2.Z) / S;
    qx2 = 0.25 * S;
    qy2 = (n1.Y + n2.X) / S;
    qz2 = (n1.Z + n3.X) / S;
}
else if ((tr2 > tr1) & (tr2 > tr3))
{
    double S = Math.Sqrt(tr2) * 2; // S=4*qy
    qw2 = (n1.Z - n3.X) / S;
    qx2 = (n1.Y + n2.X) / S;
    qy2 = 0.25 * S;
    qz2 = (n2.Z + n3.Y) / S;
}
else
{
    double S = Math.Sqrt(tr3) * 2; // S=4*qz
    qw2 = (n2.X - n1.Y) / S;
    qx2 = (n1.Z + n3.X) / S;
    qy2 = (n2.Z + n3.Y) / S;
    qz2 = 0.25 * S;
```

```
                }
                Q.Quaternion quat1 = new Q.Quaternion(qx1, qy1, qz1, qw1);
                Q.Quaternion quat2 = new Q.Quaternion(qx2, qy2, qz2, qw2);
                quat1.Normalize();
                quat2.Normalize();
                quat1.Invert();
                Q.Quaternion qt = Q.Quaternion.Multiply(quat1, quat2);
                X = qt.X / (Math.Sqrt(1 - qt.W * qt.W));
                Y = qt.Y / (Math.Sqrt(1 - qt.W * qt.W));
                Z = qt.Z / (Math.Sqrt(1 - qt.W * qt.W));
                angle = 360 - ((2 * Math.Acos(qt.W)) * 180 / Math.PI);
                string posx, posy, posz, X_3, Y_3, Z_3, rotang_3;
                posx = String.Format("{0:0.00000}", cam.Position.data1);
                posy = String.Format("{0:0.00000}", cam.Position.data2);
                posz = String.Format("{0:0.00000}", cam.Position.data3);
                X_3 = String.Format("{0:0.00000}", X.ToString());
                Y_3 = String.Format("{0:0.00000}", Y.ToString());
                Z_3 = String.Format("{0:0.00000}", Z.ToString());
                rotang_3 = String.Format("{0:0.00000}", angle.ToString());
                string client1 = posx + "|" + posy + "|" + posz + "|" + X_3 + "|" +
                    Y_3 + "|" + Z_3 + "|" + rotang_3;
                try
                {
                    SendMsgToClient(client1, 2);
                }
                catch (Exception ex)
                {
                }
            }
        }
        private void rot3()
        {
            double a, b, c, d, e, f, X, Y, Z, qw1, qw2, qx1, qx2, qy1, qy2, qz1, qz2,
                 angle, clientang1, cosang1, sinang1;
            object combo1 = comboBox1.SelectedItem;
            if (state != null)
            {
                ComApi.InwNvCamera cam = state.CurrentView.ViewPoint.Camera;
                cam.HeightField = 2 * Math.Atan(Math.Tan(45 * Math.PI / 180) / state.
                    CurrentView.ViewPoint.Camera.AspectRatio);
                clientang1 = (double.Parse(combo1.ToString()) * Math.PI / 180);
                cosang1 = Math.Cos(clientang1);
                sinang1 = Math.Sin(clientang1);
                a = cam.GetViewDir().data1;
                b = cam.GetViewDir().data2;
                c = cam.GetViewDir().data3;
                d = cam.GetUpVector().data1;
                e = cam.GetUpVector().data2;
                f = cam.GetUpVector().data3;
                Q.Vector3D m1 = new Q.Vector3D(0, 0, -1);
                Q.Vector3D m2 = new Q.Vector3D(0, 1, 0);
                Q.Vector3D cp = Q.Vector3D.CrossProduct(m1, m2);
                cp.Normalize();
                Q.Vector3D m3 = new Q.Vector3D(cp.X, cp.Y, cp.Z);
                m1.Normalize();
                m2.Normalize();
                m3.Normalize();
                Q.Vector3D n1 = new Q.Vector3D(d, e, f);
                Q.Vector3D n2 = new Q.Vector3D(-a, -b, -c);
                Q.Vector3D cp2 = Q.Vector3D.CrossProduct(n1, n2);
                cp2.Normalize();
                Q.Vector3D n3 = new Q.Vector3D(cp2.X, cp2.Y, cp2.Z);
                n1.Normalize();
```

```
n2.Normalize();
n3.Normalize();
double tr4, tr5, tr6;
tr4 = 1 + m1.X - m2.Y - m3.Z;
tr5 = 1 - m1.X + m2.Y - m3.Z;
tr6 = 1 - m1.X - m2.Y + m3.Z;
double tr1 = 1 + n1.X - n2.Y - n3.Z;
double tr2 = 1 - n1.X + n2.Y - n3.Z;
double tr3 = 1 - n1.X - n2.Y + n3.Z;
if ((tr4 > tr5) & (tr4 > tr6))
{
    double S = Math.Sqrt(tr4) * 2; // S=4*qx
    qw1 = (m3.Y - m2.Z) / S;
    qx1 = 0.25 * S;
    qy1 = (m1.Y + m2.X) / S;
    qz1 = (m1.Z + m3.X) / S;
}
else if ((tr5 > tr4) & (tr5 > tr6))
{
    double S = Math.Sqrt(tr5) * 2; // S=4*qy
    qw1 = (m1.Z - m3.X) / S;
    qx1 = (m1.Y + m2.X) / S;
    qy1 = 0.25 * S;
    qz1 = (m2.Z + m3.Y) / S;
}
else
{
    double S = Math.Sqrt(tr6) * 2; // S=4*qz
    qw1 = (m2.X - m1.Y) / S;
    qx1 = (m1.Z + m3.X) / S;
    qy1 = (m2.Z + m3.Y) / S;
    qz1 = 0.25 * S;
}
if ((tr1 > tr2) & (tr1 > tr3))
{
    double S = Math.Sqrt(tr1) * 2; // S=4*qx
    qw2 = (n3.Y - n2.Z) / S;
    qx2 = 0.25 * S;
    qy2 = (n1.Y + n2.X) / S;
    qz2 = (n1.Z + n3.X) / S;
}
else if ((tr2 > tr1) & (tr2 > tr3))
{
    double S = Math.Sqrt(tr2) * 2; // S=4*qy
    qw2 = (n1.Z - n3.X) / S;
    qx2 = (n1.Y + n2.X) / S;
    qy2 = 0.25 * S;
    qz2 = (n2.Z + n3.Y) / S;
}
else
{
    double S = Math.Sqrt(tr3) * 2; // S=4*qz
    qw2 = (n2.X - n1.Y) / S;
    qx2 = (n1.Z + n3.X) / S;
    qy2 = (n2.Z + n3.Y) / S;
    qz2 = 0.25 * S;
}

Q.Quaternion quat1 = new Q.Quaternion(qx1, qy1, qz1, qw1);

Q.Quaternion quat2 = new Q.Quaternion(qx2, qy2, qz2, qw2);
quat1.Normalize();
quat2.Normalize();
```

```
                quat1.Invert();
                Q.Quaternion qt = Q.Quaternion.Multiply(quat1, quat2);
                X = qt.X / (Math.Sqrt(1 - qt.W * qt.W));
                Y = qt.Y / (Math.Sqrt(1 - qt.W * qt.W));
                Z = qt.Z / (Math.Sqrt(1 - qt.W * qt.W));
                angle = 360 - ((2 * Math.Acos(qt.W)) * 180 / Math.PI);
                string posx, posy, posz, X_3, Y_3, Z_3, rotang_3;
                posx = String.Format("{0:0.00000}", cam.Position.data1);
                posy = String.Format("{0:0.00000}", cam.Position.data2);
                posz = String.Format("{0:0.00000}", cam.Position.data3);
                X_3 = String.Format("{0:0.00000}", X.ToString());
                Y_3 = String.Format("{0:0.00000}", Y.ToString());
                Z_3 = String.Format("{0:0.00000}", Z.ToString());
                rotang_3 = String.Format("{0:0.00000}", angle.ToString());
                string client1 = posx + "|" + posy + "|" + posz + "|" + X_3 + "|" +
                    Y_3 + "|" + Z_3 + "|" + rotang_3;
                try
                {
                    SendMsgToClient(client1, 3);
                }
                catch (Exception ex)
                {
                }
            }
        }
    }
}
```

CLIENT APPLICATION CODE

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Text;
using System.Windows.Forms;
using inter = Autodesk.Navisworks.Api.ComApi;
using ComApi = Autodesk.Navisworks.Api.Interop.ComApi;
using CA = Autodesk.Navisworks.Api.Interop.ComApiAutomation;
using System.Net;
using System.Net.Sockets;
using System.Runtime.InteropServices;
namespace WindowsFormsApplication1
{
    public partial class Form1 : Form
    {
        byte[] m_dataBuffer = new byte[20];
        IAsyncResult m_result;
        public AsyncCallback m_pfnCallBack;
        public Socket m_clientSocket;
        public CA.Document doc;
        ComApi.InwOpState10 state = null;
        public Form1()
        {
            InitializeComponent();
        }
        private void button1_Click(object sender, EventArgs e)
        {
            ComApi.nwOpState st = new ComApi.nwOpState();
            doc = null;
            openFileDialog1.ShowDialog();
            doc = new CA.Document();
            st = null;
            doc.Visible = true;
            doc.OpenFile(openFileDialog1.FileName);
            st = doc.State();
            state = doc.State();
            st.EventsEnabled = true;
        }
        private void Form1_Load(object sender, EventArgs e)
        {
            textBox3.Text = GetIP();
        }
        String GetIP()
        {
            String strHostName = Dns.GetHostName();
            IPHostEntry iphostentry = Dns.GetHostEntry(strHostName);
            String IPStr = "";
            foreach (IPAddress ipaddress in iphostentry.AddressList)
            {
                IPStr = ipaddress.ToString();
                if (ipaddress.IsIPv6LinkLocal == false) return IPStr;
            }
            return IPStr;
        }
        private void button2_Click_1(object sender, EventArgs e)
        {
            if (textBox1.Text == "" || textBox2.Text == "")
            {
```

```
                MessageBox.Show("IP Address and Port Number are required to connect to the Server\n");
            }
            try
            {
                m_clientSocket = new Socket(AddressFamily.InterNetwork, SocketType.Stream, ProtocolType.Tcp);
                IPAddress ip = IPAddress.Parse(textBox1.Text);
                int iPortNo = System.Convert.ToInt16(textBox2.Text);
                IPEndPoint ipEnd = new IPEndPoint(ip, iPortNo);
                m_clientSocket.Connect(ipEnd);
                if (m_clientSocket.Connected)
                {
                    WaitForData();
                }
            }
            catch (SocketException se)
            {
                string str;
                str = "\nConnection failed, is the server running?\n" + se.Message;
                MessageBox.Show(str);
            }
        }
        public void WaitForData()
        {
            try
            {
                if (m_pfnCallBack == null)
                {
                    m_pfnCallBack = new AsyncCallback(OnDataReceived);
                }
                SocketPacket theSocPkt = new SocketPacket();
                theSocPkt.thisSocket = m_clientSocket;
                m_result = m_clientSocket.BeginReceive(theSocPkt.dataBuffer, 0,
                    theSocPkt.dataBuffer.Length, SocketFlags.None, m_pfnCallBack,
                    theSocPkt);
            }
            catch (SocketException se)
            {
            }
        }
        public class SocketPacket
        {
            public System.Net.Sockets.Socket thisSocket;
            public byte[] dataBuffer = new byte[1024];
        }
        public void OnDataReceived(IAsyncResult asyn)
        {
            string[] c1 = new string[7];
            bool check = false;
            double[] c1data = new double[7];
            SocketPacket socdata = (SocketPacket)asyn.AsyncState;
            m_dataBuffer = socdata.dataBuffer;
            System.IO.MemoryStream ms = new System.IO.MemoryStream(m_dataBuffer);
            System.IO.BinaryReader br = new System.IO.BinaryReader(ms);
            br.BaseStream.Position = 0;
            try
            {
                string serverdata = br.ReadString();
                c1 = serverdata.Split('|');
                ComApi.InwNvCamera cam2 = state.CurrentView.ViewPoint.Camera;
                ComApi.InwLRotation3f rot = state.CurrentView.ViewPoint.Camera.Rotation;
```

```
                ComApi.InwLUnitVec3f vect = cam2.Rotation.GetAxis();
                ComApi.InwLVec3f vectup = cam2.GetUpVector();
                if (c1.Length == 7)
                {
                    for (int i = 0; i < c1.Length; i++)
                    {
                        double outres;
                        if (double.TryParse(c1[i], out outres))
                        {
                            c1data[i] = double.Parse(c1[i]);
                            check = true;
                        }
                        else
                        {
                            check = false;
                        }
                    }
                }
                if (check == true & c1data[3] != 0 & c1data[4] != 0 & c1data[5] != 0)
                {
                    try
                    {
                        vect.SetValue(c1data[3], c1data[4], c1data[5]);
                        state.CurrentView.ViewPoint.Camera.Rotation.SetValue(vect, (
                            c1data[6] * Math.PI / 180));
                        double x1 = c1data[0];
                        double y1 = c1data[1];
                        double z1 = c1data[2];
                        state.CurrentView.ViewPoint.Camera.Position.SetValue(x1, y1,
                            z1);
                        state.CurrentView.ViewPoint.Camera.HeightField = 2 * Math.
                            Atan(Math.Tan(40 * Math.PI / 180) / state.CurrentView.
                            ViewPoint.Camera.AspectRatio);
                    }
                    catch (Exception ex)
                    {
                    }
                }
                WaitForData();
            }
            catch (Exception ex)
            {
            }
        }
    }
}
```

APPENDIX B

INTERVIEW TRANSCRIPTS

INTERVIEW-1

Interviewee-1

“That is another element for me. If I am using this setup I will be using it for clash detection and we are talking about scheduling so it means one more element to look at. One more dimension to look in to see any issues that might come up. Probably I am not taking full advantage of it right away because I am not used to having a screen on top. But after if I play with it for a while I think it will be more of an asset. But just walking in and using this system for few minutes I dont get the full effect of it. Only if I use it for a while I would really understand how to utilize the top screen.”

Interviewer

“Did you notice any difference between having just 3 screens and 4 screens including the top screen while using the BIM CAVE?”

Interviewee-1

“Yeah, it is intuitively different when you step in. It is at a different perspective than what you would normally see. May be if you have angled it differently you might be able to see how the building raises up rather than right on top of you and that might be something that you want to try. Except when you are inside the building you would want to see right above you and see how the different systems work together. You are probably looking at the mechanical systems and structural systems when you are walking inside the building. Thats where your majority of the conflict is going to be.”

Interviewer

When you are browsing your 3D BIM models imagine you are just using one screen/without top screen. So in that case you would tilt your 3D models to take a look at the things on top you. If you were to compare that process of tilting the model and the suggested new setup with a screen on top how would you explain the difference between these two systems?

Interviewee-1

This system will be much more efficient. Obviously you are running models that are so large. Usually it take a while for it regenerate and I feel it would be much better to stand there in one position and see all of those components in the same time rather than scrolling this way and trying to look over there and come back. Sometimes when I am comparing two things it will be nice to have them all at once rather than having to go on and off the screen to compare those two. So I see benefit to it for sure.

Interviewer

You do loose your position when you are tilting back and forth during that process

Interviewee

Oh yeah

Interviewer

If you were to make some comments about this setup like what could have been done to this setup so that you will feel even more comfortable inside this setup. What will be the suggestions that you would give about this setup?

Interviewee-1

Well there could be an intermediate panel between the top and the center screen where you will see the perspective fully. The gap that you have right there you should try to surpass that problem. I understand that you are in the development level. I do see a lot of benefit to it especially when you are looking the systems above you like

I said the cooling systems. That makes a lot of sense. You could see the column supports. If you are looking at the joist girders they line up with columns. To see those interactions between the structures will be great. So when you are detailing structure the big part of any shop drawing that you have is always the connection details. Like how those line up, the part pieces and sizes. It's easy to say I need 10ft. to hit this column or that column. But how do I connect that piece with this piece is very crucial. Well this setup would allow you to see all those connection details while watching how it connects to the columns too. I could see that a lot on the tilt wall structures where you are trying to lineup embeds and tilt panels with joists and how they come across the tie ins and it would be beneficial to see.

Interviewer

Which model might be benefitted by using this setup? For e.g. you have a process plant model and you have a building model. So which one will be more benefitted to have screen on the top?

Interviewee-1

I think the process plant will be more benefitted because there are so many systems running through the plant like that and they have to be coordinated. You are talking about massive amounts of mechanical popping in the structure that you have to try to avoid. I could see that it will be beneficial to the subcontractor process as well. When you give them plan like that looking at them could be very difficult to visualize how much piping they need. You will have different trades overlapping with one another and it will be great for coordination. I could see instantly that would be a big benefit to those companies.

Interviewer

Can you explain a little bit more about the idea of having the BIM CAVE in the job trailer?

Interviewee-1

Yeah, we would love to have you guys assist us the proper ways to set one up. We are interested in the systems that you have and how we can incorporate that in to our business model so that we could use it to save money by making our projects more efficient. We have got the container company that's the sister concern of our construction company. We get containers from China and we take those containers and use them for mobile storage on jobsite. We also retrofit them in to office space for jobsites. So it was a natural thing for us to think to take one of those containers and put one of these BIM CAVE systems inside of it making a mobile CAVE which we could take it from jobsite to jobsite. We would also want to set one up in our office as well.

Interviewer

During construction there may be several complicated stuff that you may want to explain your worker before they do. Do think these kinds of systems with this setup be beneficial for the demonstration purposes?

Interviewee-1

It would be really beneficial. One of the big issues we always deal with in a jobsite is the coordination between different trades. The ones that take the most coordination is the Mechanical & plumbing as they run overhead and how those systems tie in with one another. There is always an issue with who stops here and who picks this up. The kinds of systems where all things tie together and it would be nice to take a look overhead to see how they relate to the structure to identify who is picking it up here. Scheduling wise also it would help. If you try to do that in 2-dimensional you have to be a very good communicator to do that so that everybody can understand. And to tie that in with the schedule they see the step-by-step process of where you are and how it is going to happen. Not only that I can also see how many trades are going to work around me at the same time. Because you can only put so many people in a space. So if you can show them that the mechanical contractor is out of your way, you are going to follow him behind so that you can use your full crew, as they will be out of your way. Those are some of those things that I could see from being benefitted by this.

Interviewer

Sounds like you guys have been using BIM for coordination meetings on jobsite. How often do you get to use BIM for this purpose?

Interviewee-1

I would behest in to saying that we are using it but rather we are dabbling with it right now. We are very familiar with Autocad and 3d studio. We want to become more engaged in BIM. It is becoming more of a necessity. Like we said before the higher education project it is not just an amenity anymore. It is something they are demanding to be delivered. All the federal projects right now, one of the requirements is that we provide a BIM model. That is something important to our clients and so it is important to us.

Interviewer

Do you like to add one final comment on this setup?

Interviewee-1

I think it is very impressive. It is something I could see to get a lot of benefit out of it. There is just one project that we worked on with Aircraft hanger. The clash detection and the way this setup even the overhead I think would have benefitted us on that project because there were so many systems that run through hanger as well as the structure and mechanical that you have to account for. Probably just the clash detection alone would have saved us around $300,000 and it was a medium sized project with a total budget of $18 million dollars. There were heavy structural in those and a lot of fire protection systems and it is a lot of detailed work.

INTERVIEW-2

Interviewer

When you were looking at the model with three screens and the same model with four screens did you notice any real differences?

Interviewee

I think in the differences I see, first one is going to be in the initial phase of the model. When you are selling, if the owner knows what he wants and you are competing. To be able to walk him to a CAVE, you fly around the model and say this is your 30-story building. He can stand and look what is 20 feet away from him and he can look up and see. I believe that adds a benefit because he can see how the building will be perceived standing 20 feet/30/50 feet away from it. He can walk up to his building and open the door in the model. I think that adds to it. I think the more complex a building is like a industrial building, a power plant where there is going to be a lot of stuff overhead and the screen on top is going to be very beneficial.

Interviewer

So personally you have sensed some differences in having a screen on top?

Interviewee

There are differences. I can think of specific examples where you had the model itself and the overhead, when you are talking to an owner who doesn't understand that you can't put a particular component here, as there is already something in the way. That is huge, especially where the dollars are so limited on everything. If you can sit there digitally and say you can't put it in here, it wont fit. If he says I don't understand why, you can ask him to stand right here and look up and that's huge. There has always been a struggle in the construction industry when dollars get short and when a owner cant have something he cant afford it, you have to make them understand why. I think having a overhead screen to that has an added benefit to that because you can show them why.

Interviewer

What you can do without the top screen is that you can tilt the camera and look up at the things going on overhead. So the difference between three and four screens is that whether you want to tilt the model or not. Will it bother you a lot to tilt the model up to take a look up?

Interviewee

I believe it will really help in the structural department. Whenever you are designing the structural members fitting together, the connection details is something we struggle at that as we need to have someone who understands that. If they dont have a good understanding of how the building is connected, I think there is an added benefit to that where they can actually sitting and look up at a connection and figure out that goes overhead and see that.

Interviewer

What I am saying is that you actually tilt the model and take a look at the same. It will take a little more time but you can still do that.

Interviewee

I think if I have the monitor above me it forces me to look at something that I might not have looked at before. I might see a clash that I wouldn't have caught before because I will have to tilt to see that. If you don't do that you will miss it. Things are often missed in the construction industry. The 2D drawings contain all the information needed and just because it is there it doesn't mean it wont be missed. So the benefit to it is the fact that if it is showing up on a screen, it is more likely that the potential clash will be caught rather than tilting it up. Say if it is 3 am in the morning and you are trying to get something out for the next day. The likelihood that I am going to see it if its above my head with a top screen is more. And that is where I think you are going to get benefitted by this. The top screen helps eliminate human error factor.

Interviewer

What are the advantages and disadvantages with this current setup?

Interviewee

I think the bigger the CAVE gets the better it is but it is going to have a limiting factor of who can afford to have it. I like this 4 four screen setup better because I almost think I can create this but we may never get to own a bigger CAVE with more screens. This setup would be great to have it inside a small container. Where you can walk your owners in and go this week this is what your going see happen and you hit the button it takes you through an hour by hour in a forty or a fifty hour work week. So that they can understand this is why I need this decision. Like you spoke earlier whenever you have a clash you have to wait for 2 weeks and the people who build the nuclear power plant are not the only one that takes two weeks. Ask the Federal Government to do anything other than their schedule and you are wasting your time. Because they are going to do this in their own time. If I can put this system in one of my Federal Government Design-Build jobs and if I can walk him through the model and show him where the problem is, it is going to make the problem go away so much faster.

Interviewer

Do you like to add anything more about this setup?

Interviewee

I think the usefulness of a technology like CAVE is that when everybody can access this. Like the Apple guys where they set out to create a computer that anybody could build with simple parts. To be able to have to everybody should be able to access technologies like this. I think when I turn in a building I would think to have a guy that is responsible for the facility. When his phone wakes him up in the middle of the night because in his building a pipe has sprung a leak. He should able to look in to his smart phone and say shut this value and go back to sleep. You have to start here to get there.

INTERVIEW-3

Interviewer

You have visualized the setup with and without the top screen. How do you find the difference between viewing the same model with and without the use of the screen on top?

Interviewee-3

The top screen is a fascinating thing. It goes back to when we were panning the model, You and I were talking where I said that when I wanted to see something that was on the left screen my natural experience working with one screen made me pull that view to the front not realizing I can simply turn my head. I think it is kind of becoming used to a tool. With the notion I can just look up to see what I needed to see, overtime time once we get accustomed to we would tend to use it more often. Also I talked about something in the right hand corner to let me know where I am to know what I am looking up will be a lot more meaningful. That is from an architect's point of view in terms that we tend to think spatially. I would envision a plan even when moving around in 3D to know where am I. I am thinking about a bit of data that I would want to know being able to see up, the ceilings and fixtures. If I know where I want to be, I can look up and see and even the orientation almost, North South East and West. You expect certain things to be there and when they are not you would know that by looking up.

Interviewer

So it helps to know where you are in the building when you are navigating through the model.

Interviewee-3

Absolutely, that little piece of information will make the top screen even more meaningful. It is almost from an intuitive judgment point of view. You can make use of this screen make a decision if it has been done correctly or not. As an architect or engineer you would expect certain things to be there when you look at it and when it is not it usually signifies a problem. So when we think in plan for smaller buildings, when I look at it, I can find where the potential problems will be happening. So if I were able to go to that area and look up, I know what I should see. If it doesnt look right, then I will know there is a problem, which will make that instantly beneficial. It is essentially what you are doing right here. Its just make a reflected ceiling plans without having to think about. It is the essentially what is happening in revit, the reflected ceiling plans work correctly according to how they program it. But it is not an intuitive understanding of a reflected ceiling plan. Simply being able to lookup and know what I am seeing when I lookup is what is above me with a reference on the plan will be indispensable.

Interviewer

Without the top screen what you would do is tilt your model constantly and see what is above you. How do you rate the difference between looking up and seeing and tilting the model?

Interviewee-3

If the parameters of working in the model say that if I want to see something that I basically have to tilt the model and put the view in front of me as though the building run in its side that's counter intuitive. So the notion of being able to go to a spot and lookup is extremely valuable.

Interviewer

So you feel it is something more intuitive and more of what you would naturally do in the real world?

Interviewee-3

I agree 100%. The idea of having the building and rotate it 90 degrees to see up is counter intuitive.

Interviewer

Moreover this environment is built to experience the building as it is. So in which case if you tilt the model you would not get the real perspective.

Interviewee-3

I am trying to think if I were solving a problem by looking at the rotated view in a screen, I would probably tilt my head sideways to understand it. So tilting the model is definitely counterintuitive. It would be better to just be able to move myself where I wanted to be, with my normal view and may be an indicator here and then look up and then inspect the elements above me. Does it make sense?

Interviewer

That makes a lot of sense. That is what I was hypothesizing about the whole setup where putting a top screen would make it more intuitive than just tilting the model.

Interviewee-3

I think human beings are very amazing to adapt. So if the only option is to tilt the model, It would probably take me a few weeks then I would get used to doing that. Just like when I was trying to navigate in Navisworks, I understand how to do it in revit where I can place the camera and have the plan view open in 2D, move the elements up and down, left and right. Because I can visualize the view I want. If I think about it as a single axis, I can move the two points around and get what I want to see. It was little bit tricky for me to get that but it would take me 20 minutes to understand that and to get used to it.

Interviewer

If you were to have this setup and explain your owner about a particular project you would conventionally show them in a single screen versus this setup. How do you feel this can benefit the owner?

Interviewee-3

As we talked about when we were navigating the model, from a design point of view simply communicating the space it is phenomenal tool. I think being able to sit an owner down in front of these four screens and say here I am going to walk you through your project, here are the spaces that are being created especially if you add things like color. Then also being able to solve technical problems of structural and mechanical interaction and space and structure interaction is phenomenal. It really begins to communicate the notions of structure and space. Structural aesthetic is an amazing thing to be able to communicate to others.

Interviewer

Do you have any specific preference as in a particular model will be more benefitted by this setup more than others?

Interviewee-3

I think this particular building model, if you put in the ceilings and a lot of it will be obscure. It communicates a couple of things depending on your audience. To the people building it, it communicates how much stuff that goes in to a space and where things should be and how it is intended to be. To owners, it communicates how complex the project really is, as the owners don't necessarily understand that. How much work the architects, engineers and contractors do to put a building together and I think this communicates it really well.

Interviewer

One last thing, if you want to talk about some advantages and disadvantages of this setup, what would you name a few.

Interviewee-3

Obviously, visualization and its an amazing communicative tool. I guess I would take one full day to get accustomed to information not just being in front but also in sides and above and utilizing that information. So spend a lot less time moving your model around. Depending on your processor speed you might gain some productivity. I have calculated before the time I have spent waiting on my computer to redo views to show me the information for making the decision I am going after. I have come to the conclusion, which was a justification for a newer computer system. When I hit a total of 10-15 minutes a day, if I do a 40 hr. workweek thats one billable hour per week spent waiting on the computer to process. Then you take that billable hour and multiply that times the 50 weeks you are there and all of a sudden you got a new computer system. In terms of being able to speedup how fast I can make decisions, this environment where I can and get information from the screens around me at the same time could increase the productivity.

Interviewer

Do you have any suggestions for improving this system?

Interviewee-3

Just moving the building around and I guess that could be solved in a day as I get used to it. I am going to give you some more suggestions. For further investigation, you might give someone 30 minutes of time to play around the system and give them a specific task to see how they accomplish it. Given the task of having to go to a certain point, look at the ceiling and see the junction of pipes or a conflict. How did you solve and where could you get the information displayed to make use of it.

Because had you told me to go to a spot in the building and look at the ceiling to get the information about the intersection of a column and duct and tell me how to solve this problem, that might help to know the differences better.

Interviewer

If you imagine this setup in a bigger size compared to the prototype built you would definitely see some difference in the scale of the object's size you will be seeing. What do you think about that?

Interviewee-3

Yes, in that case I would like to touch things and move them around.

Interviewer

So you feel you would feel more immersed in a bigger space?

Interviewee-3

Absolutely, the space was a little bit confining in there. I am not claustrophobic but it felt small. It is just the function of being used to the interaction. In revit, I can select an object and see its properties immediately. So if I am looking at this screen, and were able to look at the other screen, select something and see it data it would be very useful.

Interviewer

There is an option in Navisworks, where you can have a tooltip popup when you place the cursor on a particular element and you don't have to select it every time.

Interviewee-3

I see, that might have come out had we spent longer time interacting with the setup, which goes back to the notion of assigning some prescribed tasks. Then I would try to figure out, how am I going to get there, how am I going to use this to get that information. I think most of those things would have solved if we had more time spent interacting with the system.

Interviewer

Yes you are right, given a 30 minutes time it is not possible to get a lot of information. As iy will take sometime for people to get used to it.

Interviewee-3

I got a lot of information and I am going to lobby for four screens.

INTERVIEW-4

Interviewer:

“Now that you have got a chance to use the setup with and without the screen on top. What was the experience like to take a look up and see.”

Interviewee-4:

“The top screen was beneficial. The entire concept of having three screens around is pretty much intriguing. And the forth screen adds an additional dimension to it. It will be very helpful for people who are not used to seeing such environment like clients, this will definitely give them a better understanding.”

Interviewer:

“You feel it gives a better aspect in terms of ease of visualizing? What do you mean by ease of visualization.”

Interviewee-4:

“By ease of visualization, I mean the sense of the space. You will have a better feel for the sense of space around you. Instead of just looking at one screen and figure out where you are and what direction you are looking at. Especially when you have reference models like architecture models or any model with the grids turned off with mechanical and piping it gives you a better sense of presence.”

Interviewer:

“What you would typically do without a top screen? How do take a look at the components above you?”

Interviewee-4:

"You mean if I just got a clash?"

Interviewer:

"Yes"

Interviewee-4:

"If I want to take a look up I usually navigate through the navigation options and scroll the mouse to look up. If I want to look them closer I would setup a pivot point and then rotate around it."

Interviewer:

"You would bring what ever that is above you to the screen in front of you. In this case you don't have to do that because you have those views around you and all that that you have to do is to take a look at them by tilting your head. In both cases you can see those things. What is the difference that you feel?"

Interviewee-4:

"It is a new experience as I am used to having them in my front screen. As I told you it gives a better feel for the space. But still if I want to take a look at the duct running over my head and there is a clash on top of it. If I want to find out the clearance, I still want to go near and around the clash. In a one-screen setup, I will bring that clash in front of me. In this setup I will probably go up to the clash. Instead of moving the model around you, you are moving in the model."

Interviewer:

"When you are working on projects using BIM models have you ever felt any difficulties while the tilting the model to take a look up?"

Interviewee-4:

"Getting lost usually happens when your mouse snaps. When you are in a certain area and when you get the building out of your focus it happens. Otherwise if you are browsing smoothly, you will have a sense of space. In this setup when I used the 3D mouse, I had some issues with the sensitivity of the mouse but the normal mouse worked perfectly fine."

Interviewer:

"Is there any real difficulty in using a single screen to take a look up? As you would constantly spend some time tilting your model to take a look around you. Do you see any benefit to this setup as opposed to the conventional setup?"

Interviewee-4:

"Yes there are definitely some benefits in terms of having a better idea of space around you."

Interviewer:

"What if you have a meeting with your piers explaining certain conflicts? Is it difficult to visualize the model by constantly titling them?"

Interviewee-4:

"It will definitely help them because many times you have conflict running across a single pipe or single air duct. Some of the time your team players looking at that 3D model for the first time, the 3 and 4 screen setup will definitely help them to better visualize the models."

Interviewer:

"Were you able to feel if this setup is more intuitive?"

Interviewee-4:

"Yes, It is definitely intuitive."

Interviewer:

"What do you feel are some of the limitations of this setup?"

Interviewee-4:

"I don't see any certain issues in the short time I spent with the setup. The idea of having three screens itself was new to me as I am used to having multiple screens only in a single plane. You can rotate your head and get a better sense of it here and its more interesting."

Interviewer:

"If you were to implement this setup in your place of work and ask you to work with this, will you do it?"

Interviewee-4:

"Yes, definitely as it will help anyone in the construction field or any other industry where you need 3D visualization. Yes I would definitely do it."

Interviewer:

"Regarding the gap between the top and center screen, did you experience any odd behavior while using this setup?"

Interviewee-4:

"As a matter of fact I figured that out why the gap was there. If the gap was not there I think it would be difficult to visualize it. It gives a real sense of movement around you. I think that gap dint affect at all. It is just a matter of walking little further to see that missed portion. Having a 3D environment, which is for the scale, is more important than having an undistorted image."

Interviewer:

"How do you like this setup in a bigger scale?"

Interviewee-4:

"It will definitely benefit team players. You can still have your coordination meeting with one screen. But the whole idea of having 3 or 4 different cameras around you giving you a distortion free space will definitely give a better feel."

Interviewer:

"Have you ever had any difficulties explaining your owner about the projects whenever there are any conflicts?"

Interviewee-4:

"The only problem you will have is if they have never seen a 3D model. People who are in construction doing this job daily will know what goes in here and how things look. But the owner they tend to get lost in space where there are different levels in a building when they look from the top and below the model. I think this setup will give them a better feel for the whole model. Especially if you have other elements like wall finishes and furniture. It will be very easy for the owners to visualize it."

Interviewer:

"You mentioned that whenever you are looking at clashes in the MEP systems, you not only look at the clashes from the bottom but also from the top of the MEP systems. In which case whenever you are looking at those clashes with these systems it is not going to be convenient for you to go around and take a look at the clashes from the top. So you are basically confined to some extent. Would it be bothering you to some extent?"

Interviewee-4:

"Sometimes, it is important to look around the clashes to know what space you have to get the right solution. I think its more of getting used to a system of how to navigate through the model because you have an environment around you and you are moving up and down. In a one or two screen setup with just one camera, you are bringing the clash in front of you. Its just about getting used to it."

Interviewer:

"Will it be difficult to look at the clash just from the bottom?"

Interviewee-4:

"Yes, I guess it will be difficult to just look from the bottom for efficient clash coordination because you want to know what your constraints are, ceiling heights etc.

There are other systems that are relying on you."

Interviewer:

"Being able to take a look at the clashes from different locations is critically important for you to be able to understand?"

Interviewee-4:

"And also it gives a better sense of what is the margin because sometimes when you have tight tolerances you need to know them by looking them from different angles. I would also like to add that this setup is good for visualizing the entire project. I would like to make a comment on who would be the best beneficiary of the system. A person who does not have a better visualization of a 3D space will make the best use of this system. Just by looking at the 2D drawings it's difficult to imagine how it would transform in to a 3D environment. For a person who is using the 3D models on a day-to-day basis, I am not sure how beneficial it would be, as he would be more used to seeing the entire project in one screen rather than multiple screens. I don't think he would use it on a day-to-day basis for just getting the work done. You can use it only for presentations with the owner or a client. When I am trying to model the building and when I am trying to find the clashes, I would prefer to use on one screen as I may have a better perception for 3D space. I might feel uncomfortable these objects in the screens around me moving. This would be more beneficial to the actual workers in the field. If a new worker is joining a project, he is looking at the drawings and he is kind of lost. If this is available to him it will give him a better perception."

INTERVIEW-5

Interviewer:

"Now that you got a chance to use the setup. Initially I turned off the top screen for a purpose, for you to make use of just the three screens and browse the model. After sometime I turned back the top screen on. How do you describe your experience of looking up and seeing?"

Interviewee-5:

"First, it is very fun to look at and I liked it. I did feel like it was a little bit awkward having to look straight up. I would think that if you want to produce something that is more like this you may want to find a better chair that is more ergonomic where it is a little more natural to pan your head up. That was the one thing that I dint like very much. I did like how you were able to go to the individual screens and select or highlight one component and you could find out the information about that component and that was very useful."

Interviewer:

"If you don't have the top screen what you would you do is tilt and look up as opposed to this setup where you can just take a look up from the screen on top. How different is this experience?"

Interviewee-5:

"Normally I would use the walk function and use the scroll key and it will pan me up where my view is pitched and that's kind of how I normally get around that."

Interviewer:

"Here in this system where you don't have to do that. What you would do is just go and stand in a place where you want to be and take a look around you without having to tilt the model. What do you think is the big difference between these two processes?"

Interviewee-5:

"I think initially I would take some time to get used to this setup, as I am very accustomed to use the single screen. I definitely see the advantage of without having to tilt the model and it is one less step where you can just look up and its more natural.

I still think there will be portions of components where you want to get in to a tight space. You are still going to have to use your mouse and kind of maneuver to the exact position and that may still have the pan and tilt issues."

Interviewer:

"You do feel that the process of looking up is more natural for you?"

Interviewee-5:

"Yeah, it is something that you are used to. It definitely makes it more realistic because in a computer when you feel like you are there in a space, which is very helpful."

Interviewer:

"In projects that you are working on, you might run in to some conflicts where you have some clashes and there might be cases where your team might need some better explanation of those process. So do you feel this setup will find a place in those kinds of circumstances?"

Interviewee-5:

"I am going to answer this in two ways depending on the group size. If you are in a smaller group, I think this is fantastic and you will be really able to help them feel like they are in the space to figure out exactly where things are. If you are in a larger setting, say you are in a coordination meeting, you are going to have multiple people and a setting like this may be difficult just because of the confined space."

Interviewer:

"Like I told you before, this is just a prototype that we are testing. You can imagine the same setup in a bigger scale. In that case how do you think it will help run your coordination meetings?"

Interviewee-5:

"I do see a lot of benefit. What superintendent doesn't want to walk out in to a virtual project and see how the things are going to look like even before we build the structure? So I think there is a lot of advantage to that. The other caveat you have to think about is you are going to have a lot of old school people and they are going to be a little bit hesitant to step in to this world because of their own personal way of doing things. So if you throw out that group right there, I think it is very helpful and most people would appreciate what it is doing."

Interviewer:

"You do feel that it enhances the way you see the BIM models?"

Interviewee-5:

"Yes I Do."

Interviewer:

"Do you feel any other benefit to this other than visualization purpose?"

Interviewee-5:

"I can't think of anything more right on top of my head. But I feel the visualization itself is one main advantage where people can see how things are going to look like even before they are constructed."

Interviewer:

"Have you ever faced a situation where your owner needs a better explanation of your project?"

Interviewee-5:

"Everyday"

Interviewer:

"In that case you may want to communicate those information better. Do you see any benefit to this setup in those situations?"

Interviewee-5:

"Traditionally people use 3D models to illustrate what something is going to look like.

Recently we are using BIM modeling to show them even better and if we can walk them through something like this and put them in to the virtual environment. I think that is kind of where we want to go by making them feel like they are in the real space and help them make real time decisions. The biggest component to construction still at lag is the decision making process. People have to know what something is going to look like to make a decision. That is hard to explain to an owner or setup just 2D drawings/just a flat screen in front of him. If you have something that can make them feel that they are in the space that helps it."

Interviewer:

"You did make a mention about some of the disadvantages due to the smaller space. Do you have anything more to add to that?"

Interviewee-5:

"The only other thing is the lag where you mentioned is the problem with the Navisworks and I hope they would improve on that."

Interviewer:

"So the concept of having things around you and taking a look them is very different from what you would normally do. How different is this experience?"

Interviewee-5:

"The experience is different. I think we all want to be able to walk in to star trek era and see everything all around us and we are getting closer and closer to that. I can really see a major benefit on just the visualization to superintendents, owners and to other team members to let them see what their building is going to look like. The biggest question is how to explain something is going to look like with just a set of drawings."

Interviewer:

"You spend a lot of time moving back and forth a model to get the view you want with a single screen. Where as you just have them all here around you in this setup. Do you see any benefit to this in you daily work?"

Interviewee-5:

"Yeah, say when I put together a clash report, I am spending time to create views. In each view I spending extra time making sure I am looking all around and not just that one isolated instance. You want to be able to see if there are any other problems that are associated with that. This right here gives me an immediate view of what is on my side and what is above me. What are the things that I should be looking at when this piece move? In these cases it definitely does help."

Interviewer:

"How are using BIM when you have pre construction coordination meeting?"

Interviewee-5:

"First I gather the model from each of my subcontractors, engineers and architects. I put them all together and I run the clash detection. Then the next day, I would have a coordination meeting. I already have all of my clashes on a report and I would see them. We then pull up the same model and go through each of those clashes."

Interviewer:

"How do you navigate to those clashes?"

Interviewee-5:

"I just go to my viewpoint tab and go to that particular view."

Interviewer:

"So you save the viewpoints in advance?"

Interviewee-5:

"Correct, What happens is the day before the meeting, I will send them the clash report and I will send them a .NWD file, which has all the saved viewpoints in it. They will open the file and start looking at it prior to the meeting to see if they can clean things up. Then they come to the meeting and they will provide me any updated files. That way I can put that in to the model and see if that clash is still there. We still look at the view to make sure nothing has been affected. Since I have saved the viewpoint before I dont have to fly in to the model."

Interviewer:

"Once you have brought your audiences to a certain space, you are looking at certain clash. How many chances do you have to move around to give your audiences a better idea?"

Interviewee-5:

"There is a lot of time I have to go in and adjust the viewpoint so that they can see them properly. Lot of times if they haven't changed anything yet, I will zoom out and will walk around little bit just to look around to see."

Interviewer:

"You do have to move around once you have brought them to a particular space?"

Interviewee-5:

"Yes"

Interviewer:

"How often times people are asking you to move around?"

Interviewee-5:

"They do because everyone wants to see how it affects them. Yeah, I am having to shift a lot for them."

Interviewer:

"So it is like you versus many people asking you to move around. How do you handle that?"

Interviewee-5:

"Usually I would try to focus on what the major conflict is. I prioritize and give attention to those people who are directly involved with that clash. The other people who are not directly involved can see if they are ok with the view that they are looking at."

Interviewer:

"When they are looking at the model are they asking you to pull additional information from the models?"

Interviewee-5:

"They really just want to see the graphical relationships and they are not in to the finite data."