

THE VIRTUAL-AUGMENTED-REALITY ENVIRONMENT FOR BUILDING COMMISSION: CASE STUDY

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ABSTRACT

This paper presents a Virtual-Augmented-Reality Environment (VARE) which is an augmented-reality (AR) system integrated with a virtual-reality environment. The system has been developed to support the building commissioning (BC) process. The CAVE, a projection-based virtual reality system, is used as an immersive interactive environment in which the building being commissioned is modeled and displayed in accordance with the user's input. The AR system is a computer vision-based visualization system specially designed for displaying BC data. We also investigated RFID (Radio Frequency Identification Device) technology as an alternative object tracking approach. A series of case studies were conducted to verify the performance of the proposed system with various kinds of information commonly being generated during the BC process. VARE would be well suited to a training program for prospective operators. The system is cost-effective and provides the user with compatibility with other software packages that support the Industry Foundation Classes (IFC).

INTRODUCTION

Building commissioning (BC) includes a series of testing the operation of equipment, building systems, and their sub-systems to ensure that they operate as designed and can satisfy the needs of the building throughout the entire range of operating conditions [1].

During BC, a large quantity of information is created and types of the information are also diverse. The most common types include drawings, inspection documents, specifications of equipment, manuals, and sensor data. Therefore, there has been a need for intuitive systems that manage and display information effectively.

Based on that need, one of the primary objectives of this research was to develop a visualization system that provides easy display of information and support especially for field inspection. Since proper training program for prospective operators is one of the functions needed during BC, development of a cost-

effective training program was also a research goal.

RELATED WORK

Ehret et al [2] presented a visualization system that scales information to meet the characteristic of output devices such as a PDA, a tablet PC, and a desktop PC. The system determines how to display information according to the type of the output device that the user needs. If the user uses a PDA without 3D hardware, the system creates an image of the queried information. The image is then used as an interaction medium between the user and the system. On the other hand, if the user uses a laptop or a desktop PC that provides sufficient computing power for 3D visualization, the system creates a VRML input file with the required information. In this approach, the user needs either a simple image viewer or a regular HTML browser with a VRML plug-in. A merit of this system is that it supports various kinds of information appropriate for field inspection by changing the format of the output medium.

Goose et al [3] introduced a PDA-based AR system integrated with a speech recognition technology, called PARIS (PDA-based Augmented Reality Integrating Speech). The system consists of several sub-systems: an AR-based manager to locate the user and to coordinate other sub-systems, a VoiceXML module to interact with the user, a VRML engine to visualize geometries, and a plant automation software package that manages raw sensor data. PARIS successfully demonstrated that contemporary PDAs have enough computing power to visualize 3D objects and manage multi-modal interactions between users and the system. However, it is still a critical problem to manage the size of VRML files with limited capacity of PDA memory space.

The visualization systems introduced above were developed to mainly support operation and maintenance of building systems. The data exchange issue among sub-systems in different domains does not appear to be a priority. However, compatibility of data among sub-systems is critical for intra-system to communication for the BC domain.

EMPLOYED CORE TECHNOLOGIES

CAVE [4] – An Immersive Virtual Reality Environment

CAVE consists of 2 ~ 6 walls of a 10x10x10' space and projectors that project each part of a scene to directed walls. Observers inside the cube are immersed in the projected visuals, perceiving them realistically.

Figure 1 and Figure 2 show the physical configuration of the CAVE built for this research. The CAVE has three computers: a server and two client computers. The server receives input commands from the user and controls the two client computers. The client computers communicate with the server and render scenes to the screen using projectors to which they are connected. As an input device, we use a wireless joystick so that users can have more freedom of their positions. The device also gives the user extra buttons into which to map custom functions.

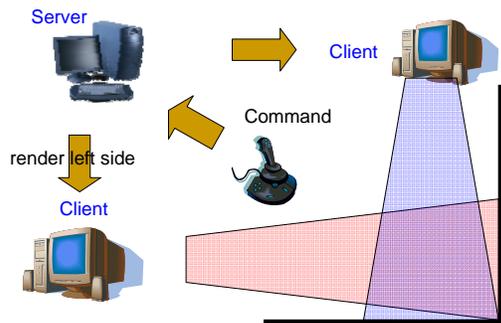


Figure 1. Physical Configuration of CAVE

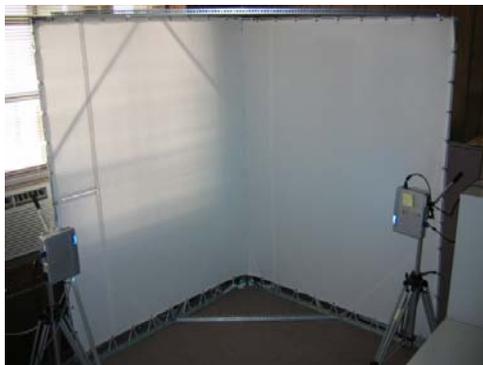


Figure 2. CAVE

A game software package that is furnished with a screen-split function [4] is used as a display engine. The game package also provides a map editor with which users can build their own virtual worlds. Since the map editor can import DXF files and third-party texture images in PCX format, most commercial modeling software packages that can export objects in

DXF format can be used to build virtual environments or their parts to display on the CAVE. To allow the game engine to do CAVE-like display, we use CaveUT, a set of modifications for this purpose, which is developed by Jacobson et al [4].

AUGMENTED REALITY (AR) TECHNOLOGY

AR technology augments the real world with virtual objects. Research in AR has been applied in many different areas including computer-aided surgery, military, telecommunication, and computer-aided design.

ARToolKit [5] is a free software library with which AR applications can be developed. The toolkit is computer vision-based, so applications based on ARToolKit need a camera as an input device and markers that represent each piece of objects. This toolkit has been applied to hundreds of diverse areas. Some of their projects include The BlackMagic kiosk, The MagicBook, and AR groove [6].

RFID TECHNOLOGY

RFID has mainly been used to track packages. Recently, it became popular in construction domain research as a tracking technology of construction materials, equipment, and workers. Researchers use the tracking data to efficiently manage materials and to check their proper installation [7].

THE VIRTUAL-AUGMENTED-REALITY ENVIRONMENT

VARE is an augmented-reality system combined with an immersive virtual reality environment. The CAVE is used as an interactive virtual environment in which the building being commissioned is modeled and displayed in accordance with the user's input. The AR system, on the other hand, is a computer-based visualization system specially designed for displaying BC data. It displays both static data such as the specification of equipment and also live data-streams coming from deployed sensors in relatively real-time. Since many other tracking technologies are currently available such as the RFID, we will also verify their performance and adapt them in appropriate ways. This system uses the BC data model [8] being developed by the BC research group at Carnegie Mellon University (CMU).

Building a Virtual Environment

A virtual environment was built using the technology described in Figure 1. The map editor provides a 3D modeling environment, so users can create their own virtual worlds by creating 3D space configurations and mapping textures onto them.

The editor also allows users to put sound effects and animations in their virtual world. Those effects are very helpful for the training program to simulate various situations that the trainee needs to be aware of, including auditory equipment feedback.

Displaying Information Using Different Types of Output Devices

Figure 3 shows the architecture of the data display system. Most contemporary HVAC control/monitoring systems have their own database to manage sensor data. The data display system also has its own database for BC documents. When the user wants to see BC information only, the visualization server accesses the BC database and displays the retrieved data. On the other hand, if the user needs to see sensor-related data, the visualization server queries necessary information from the HVAC monitoring system and displays the retrieved information, combined with BC data if necessary.

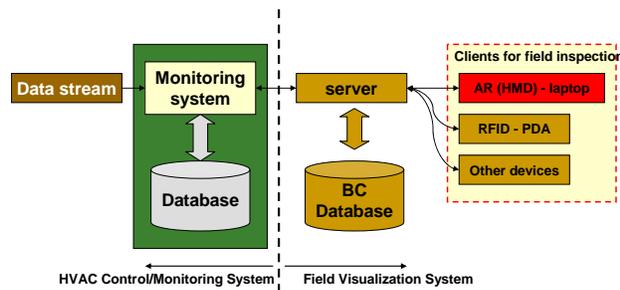


Figure 3. System Architecture of Data Display System

CASE STUDIES

To verify the performance of VARE, a series of case studies was conducted with various types of data created and used during BC process. First, a virtual single-story house was built to ensure that the CAVE could provide all the functionalities we needed. Second, normative scenarios were developed to display various types of information created during BC process: static information such as specification of equipment and inspection reports, and dynamic information such as sensor data. An AR-based display system and an RFID-based system were tested with these scenarios.

The most fundamental scenario we developed is as follows. The operator initiates VARE and stands in front of the CAVE wearing the AR-based display system (or, alternatively holding a PDA in his or her hand). The operator navigates the virtual world projected on the CAVE and approaches the first piece of equipment, AHU1, and sees its ID tag, A1. The camera that the operator wears also detects the ID. The display system displays information that is stored in a central database or the field computer as the operator

inquires. The operator verifies the performance of the equipment and creates a new inspection report, storing it in the database.

Case Study 1 – Build Virtual Environment for CAVE

To verify the procedure for building virtual environments, we built a virtual single-story house with two markers that represent Air Handling Units. Each marker has its own ID, A1 and A2. The house was built using the map editor provided with the game package and the Air Handling Units were created using a commercial 3D modeling software and imported into the map editor in DXF file format. Since DXF file format has only geometry information, we needed to map textures to the objects after they were imported. Figure 4 shows a sample screen shot of the virtual house with the AHU1 unit. In this case, we mapped its ID to one side of the object so that our AR-based display system could recognize the object as the AHU1.



Figure 4. Sample Screenshot

Case Study 2 – Display Static Data Using an AR-Based System

This case study aimed to verify the performance of the AR-based display system with static information. Figure 5 shows the data flow diagram for this case study. The raw input data were chosen from the New House Commissioning report. New House is one of Carnegie Mellon's new dormitories and its HVAC system was commissioned in 2003. We chose the commissioning results of air handling units 1 and 2 for our experiment. The data were stored in STEP-21 file format using the BC data model that has also been developed by BC research group at CMU [8].

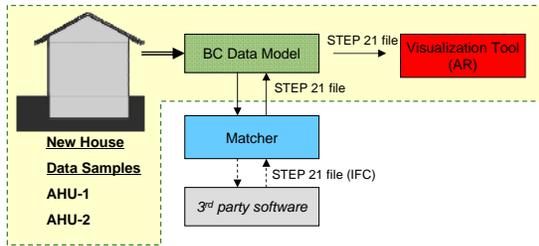


Figure 5. Data Flow Diagram of Static Information

BC research group has also been developing a matcher [9] between different versions of IFC and BC data model. With the BC data model and the matcher, we are expecting that our display system can eventually visualize different kinds of IFC-compatible information created by 3rd party software packages that support IFC.

Figure 6 shows a screen shot of the visualization system. The block with an “A2” marker is a real object and the yellow cube and text information is virtual objects mapped to the “A2” marker. The yellow cube was rendered on the marker in 3D space, so the size and direction of the cube changes in accordance with the user’s position and the view direction. On the other hand, the text information stays still on the output device to ensure that the user can read it with ease.



Figure 6. Static Data Display of AR-based System

Case Study 3 – Display Static Data Using RFID-Based System

Since the AR-based system is computer-vision based, sufficient light source is critical. If the light level is not high enough, the system can easily fail to detect the markers. In this case, RFID is a good alternative to identify equipment.

In this case study, the same system architecture as that of the AR-based system was used, except for the object recognition technology. To assure portability, we

assumed the application would be running on a PDA platform.

Two passive tags were attached to physical markers that represented the two AHUs, respectively, in the same fashion. The inspection data from the New House commissioning report were mapped to each tag. When the RFID reader detected each tag, the application displayed the mapped information as shown in Figure 7.

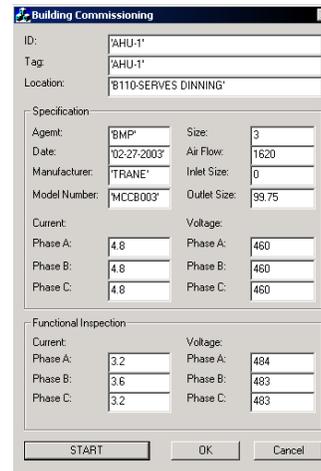


Figure 7. Static Data Display of RFID-based System

The reading range of the RFID reader used in this case study was around 4 ~ 5 inches and therefore equipment had to be right in front of the RFID reader to be detected. Obviously, such a constraint would be quite inconvenient for the field inspector. The reading range of currently available CompactFlash type RFID readers is similar to that of the reader used. However, this limitation can be overcome by using a better antenna or active tags instead of passive ones.

Case Study 4 – Display Dynamic Data Using AR-Based System

One of the primary functions the display system needs to provide is visualization of live data streams coming from sensors. A different test bed was built to verify the performance of the AR-based display system with live data streams.

As shown in Figure 8, the system consists of three independent systems: a testing system, a file server, and a display system. In this case study, one of the testing systems in the Advanced Infrastructure Systems Lab of CMU was used to feed sensor data to the file server every 10 seconds. The file server stored the latest data and the display system retrieved the data every 10 seconds. Figure 9 shows the screen shot of the display result created by the AR-based display system.

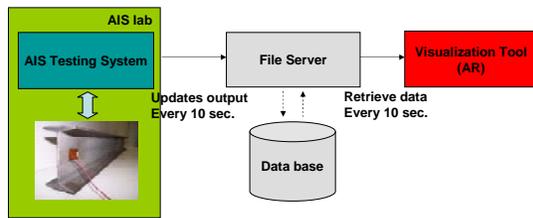


Figure 8. Data Flow Diagram of Dynamic Information



Figure 9. Dynamic Data Display of AR-based System

COMPARISON OF TECHNOLOGIES

Our CAVE was able to provide the user with a flexible and cost-effective immersive environment. With the game display engine with CaveUT and commercial 3D modeling software packages, we could build various ranges of building conditions that the prospective operators could experience.

The AR-based display system was accurate in recognizing markers. A character set was used as the identification of each marker such as A1 and A2. The reading distance of an 8cm x 8cm marker was around 4 ~ 5 feet under the common office environment. The size of a marker can be adjusted if the reading range is not long enough. The character set might not be the best choice for the identification of markers from the system's point of view. Since ARToolKit recognizes markers simply as an image, one doesn't have to stick to character sets, although character sets are more readable to operators. Obviously, the lighting condition was critical for the system to recognize markers, since the ARToolKit thresholded an image and compared the converted one with pre-coded data sets. Therefore, if the contrast of an image is not high enough, the system might not find markers in the image.

The RFID-based system has an advantage in recognizing objects in that environment. Besides, the required computing power is relatively low and the software can be easily migrated onto PDA platforms. The limited screen size of PDAs and reading range of

RFID reader remain as problems to be resolved.

The AR-based display system can provide diverse ways of visualizing information for the user to understand the information intuitively, such as animation of air flows. By its nature, the system requires more appropriate input devices for PDAs than those for desktop PCs such as a keyboard and a mouse for the user to choose ways of displaying information in the field. PARIS [3] uses a speech recognition technology but as cited in another paper of the same author [10], operators tend to avoid using the system if the voice input recognition system is inefficient. From this point of view, development of efficient input devices would be critical for the success of systems of this kind.

CONCLUSION

This paper presented the virtual-augmented-reality environment being developed specially to support the BC process. Through the series of case studies, the performance of VARE was verified and characteristics of each technology employed were compared.

VARE is well suited to a training system. Since the CAVE and other information display systems are independent from each other, the trainee can use exactly the same display systems in the real world as those used for the training system.

VARE can be easily migrated to other types of monitoring/inspection systems in different domains by using IFCs as a data-exchange standard.

FUTURE WORK

The achievements described in this paper are merely foundations on which an intuitive and effective display system for BC process will be built.

To meet the needs described in this paper, the display system should have the following features.

First, a proper geometric model needs to be developed. The size of the data representation for geometric information should be small enough to fit on a PDA that provides only limited storages, as well as for fast file-transfer through not only the Internet but the dial-up connection.

Second, we intend to use the BACnet utility in our cases studies. BACnet [11] is a standard protocol designed for communication between building automation systems manufactured by different vendors. Since BACnet is compatible with Ethernet protocol [12], we consider BACnet to be suitable for sensor data

transfer from building automation systems.

Third, a proper user interface between the user and the AR-based display system needs to be developed. We will explore user interfaces developed for wearable computer systems to find the most appropriate interfaces for AR-based display systems.

Fourth, miscommunication among participants and inspection errors happen commonly due to the fact that all the participants are not in the same phase in terms of information sharing. Some commercial software packages support general purpose version checking function, but information dealt throughout the entire BC process is much more diverse and complicated. Therefore, to fully support BC process, a visualization system needs to support effective management and visualization of temporal information.

In this paper, we explored several object-recognition technologies such as augmented reality, virtual reality and RFID. We noticed that each technology can cover different building environments, and BC related tasks. This is critical for field inspectors to be trained and to do their tasks effectively. In the near future, we will explore more technologies for recognizing, tracking, and locating objects such as a barcode-based system and a Wi-Fi technology.

ACKNOWLEDGEMENT

This project has been supported by the National Institute of Standards and Technology, Grant No. 60NANB3D1114 and No. 70NANB4D1099.

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