Augmented Reality in Architectural Construction, Inspection, and Renovation

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Abstract

We present our preliminary work in developing augmented reality systems to improve methods for the construction, inspection, and renovation of architectural structures. Augmented reality systems add virtual computer-generated material to the surrounding physical world. Our augmented reality systems use see-through head-worn displays to overlay graphics and sounds on a person's naturally occurring vision and hearing. As the person moves about, the position and orientation of his or her head is tracked, allowing the overlaid material to remain tied to the physical world. We describe an experimental augmented reality system that shows the location of columns behind a finished wall, the location of re-bars inside one of the columns, and a structural analysis of the column. We also discuss our preliminary work in developing an augmented reality system for improving the construction of spaceframes. Potential uses of more advanced augmented reality systems are presented.

Introduction

A variety of computer technologies and computer science techniques are now used by researchers aiming to improve aspects of architectural design, construction and maintenance. Virtual reality systems are used to envision modified cityscapes, and to assess the impact of proposed buildings (Novitski 1994). Both virtual reality and conventional computer systems are currently used in demonstration testbeds to

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simulate complex construction operations. These systems promise to improve the optimization of construction operations and to allow checks of constructability and maintainability before building materials are ordered (Virtual 1995, Oloufa 1993); integrated structural, architectural, and mechanical building databases are being combined with engineering expertise to create knowledge-based systems for improving the design process (Myers et. al. 1992). Robotics systems, mostly adapted from the automotive industry, have also been used recently in experimental and commercial attempts to automate various aspects of building construction (Webster 1994, Richards 1994).

Augmented Reality Applications in Architecture and Structural Engineering

Recent advances in computer interface design, and the ever increasing power and miniaturization of computer hardware, have combined to make the use of *augmented reality* possible in demonstration testbeds for building construction, maintenance and renovation. In the spirit of the first see-through head-mounted display developed by Sutherland (Sutherland, 1968), we and other researchers (e.g., Robinett, 1992; Caudell & Mizell, 1992; Bajura & Neumann, 1995) use the term *augmented reality* to refer to enrichment of the real world with a complementary virtual world. The augmented reality systems we are developing employ a see-through head-worn display that overlays graphics and sound on a person's naturally occurring sight and hearing. By tracking users and objects in space, these systems provide users with visual information that is tied to the physical environment. Unlike most virtual realities, whose virtual worlds replace the real world, augmented reality systems enhance the real world by superposing information onto it. The spatial tracking capabilities of our augmented reality systems distinguish them from the heads-up displays featured in some wearable computer systems (Quinn 1993, Patents 1994).

As part of a program aimed at developing a variety of high-performance user interfaces, we have begun work on two augmented reality systems for use in structural engineering and architectural applications. The first, called "Architectural Anatomy," creates an augmented reality that shows users portions of a building that are hidden behind architectural or structural finishes, and allows them to see additional information about the hidden objects. We have built structural and architectural models of parts of Columbia's Schapiro Center for Engineering and Physical Science Research, including the Computer Graphics and User Interface Lab, which provide data for use in this "x-ray vision" demonstration system. The model is based on the as-built construction drawings provided by the building's architects. Our prototype application overlays a graphical representation of portions of the building's structural systems over a user's view of the room in which they are standing. A see-through head-mounted display provides the user with monocular augmented graphics and tracks the position and orientation of their head with an ultrasonic tracking system (Figure 1).

Figure 2 is a view of a corner of the Computer Graphics and User Interface Lab photographed through a version of our head-mounted display that is designed to be worn by a 35mm camera. A corner of the ultrasonic tracker's transmitter can be seen at the lower left. The overlaid virtual world visible in this figure includes the outlines of parts of three support columns and the space between the structural concrete floor and the raised lab floor above it. The middle, larger column is inside the protrusion in the corner. The two other, smaller columns are actually located in nearby rooms. The mouse cursor is visible near the front right corner of the top of the desk. By clicking on a column with the mouse, our prototype allows the user to see more information. In Figure 3, the user has looked up and slightly to the right and has selected the middle column that contained the cursor in Figure 2. This causes the outlines of the other support structures to dim. (This project's display hardware is one-bit deep, so dimming is accomplished through the use of different line styles; in this case, dotted lines.) As shown in Figure 3, the re-bar inside the column is revealed and a structural analysis of the column is presented to the user. The analysis is provided by Dast, a commercially available structural analysis and design program (Das, 1993).

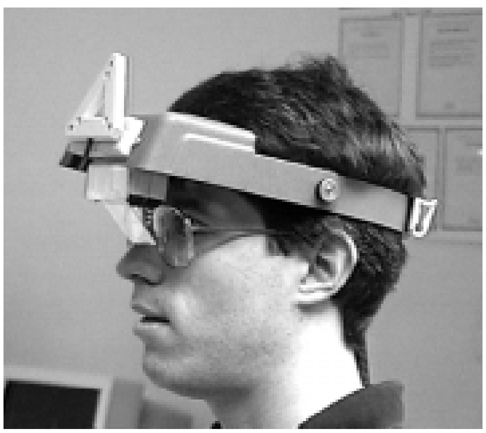

Figure 1.

Figure 2.

Our prototype system is written in a combination of the C, C++ and CLIPS programming languages and runs on the Unix operating system. Each component of the system runs in a separate process, allowing the computational work to be distributed over multiple machines. The graphics component runs on an Intel 486-based PC-compatible machine. The remaining components, such as the tracker controller, run on a wide variety of Unix-based machines. Our head-worn display uses a Reflection Technology Private Eye display whose image is reflected by a mirror beam splitter. A Logitech ultrasonic tracker provides position and orientation tracking (the display and triangular tracker receiver are shown in Figure 1). The display's graphics are rendered in software at 720×280 resolution and, in the application described here, include 3D vectors without hidden-line removal. We provide support for 2D applications such as the structural analysis of the column through a full memory-mapped X11 Window System (Scheifler & Gettys, 1986) server. The X11 bitmap is treated as if it were projected onto a portion of the surface of a virtual sphere surrounding the user and is composited with the bitmap containing the 3D graphics for presentation on the head-mounted display (Feiner et al., 1993). Our augmented reality testbed allows an X11 window to be positioned so that a selected point on the window is fixed at an arbitrary position within the 3D world. We refer to such windows as *world-fixed* windows to distinguish them from windows that are fixed to the display itself or to the body-tracked virtual sphere. Building on our work on knowledge-based augmented reality for maintenance and repair (Feiner, MacIntyre & Seligmann, 1993), we are developing a knowledge-based system that will dynamically control which parts of the structural system are displayed to satisfy the user's goals in exploring the environment.

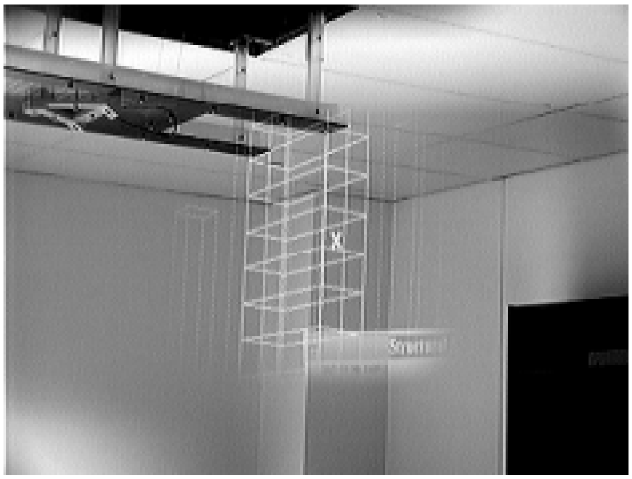

Figure 3.

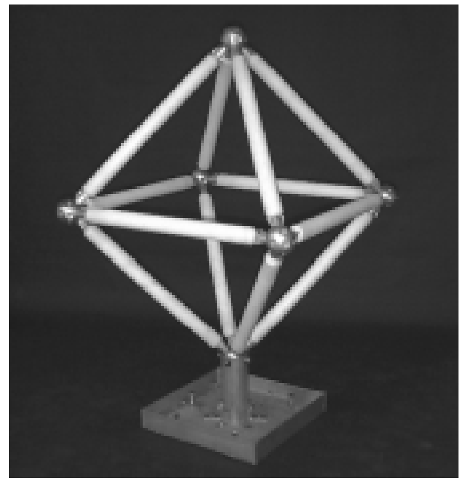

Figure 4.

We are currently developing another augmented reality testbed system that addresses spaceframe construction. Spaceframes are typically made from a large number of components of similar size and shape (typically cylindrical struts and spherical nodes). Although the exterior dimensions of all the members may be identical, the forces they carry, and therefore their inner diameters, vary with their position in the structure. Consequently it is relatively easy to assemble pieces in the wrong position—which if undetected could lead to structural failure. Our augmented reality construction system is designed to guide workers through the assembly of a spaceframe structure, to ensure that each member is properly placed and fastened.

Our prototype spaceframe structure, shown in Figure 4, is a diamond shaped, full-scale aluminum system manufactured by Starnet International (Starnet 1995). We have created a 3D computer model of the spaceframe, an ordered list of assembly steps, and a digitized set of audio files containing instructions for each step. Undergraduate Computer Science, Engineering and Architecture students helped develop the testbed as part of an NSF-sponsored educational grant in conjunction with the Columbia University Teachers College. The head-worn display used in this project is a *Virtual I/O* see-through stereoscopic color display with integral headphones and orientation tracker (Figure 5). Position tracking is provided by an Origin Instruments Dynasight optical radar tracker, which tracks small targets on the head-mounted display and the user's right hand. The user interface also includes a hand-held bar code reader.

The spaceframe is assembled one component (strut or node) at a time. For each step of construction, the augmented reality system:

- Directs the worker to a pile of parts and tells her which part to pick up. This is currently done by playing a sound file containing verbal instructions.

- Confirms that she has the correct piece. This is done by having her read a barcode on the component.
- Directs her to install the component. A virtual image of the next piece, with a textual description fixed near it, indicates where to install the component (Figure 6), and verbal instructions played from a sound file explain how to install it.
- Confirms that the component is installed by asking her to place her hand at a particular location on it (denoted by the barcode), then determining the position of her hand.

Figure 5.

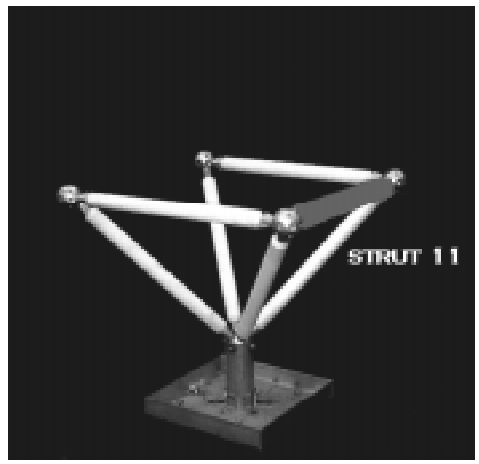

Figure 6.

The testbed we are using for the spaceframe prototype is a multi-platform, distributed system that has been designed to allow a potentially large number of users to interact in a shared environment (MacIntyre 1995). It runs on an assortment of hardware under UNIX, Windows NT, and Windows 95. The majority of the testbed was written in Modula-3, a compiled language that is well-suited for building large distributed systems. The remainder of the testbed, and the majority of the applications, are written in Obliq, an interpreted language that is tightly integrated with Modula-3. Application programmers are free to use either language or both. For this application we use shaded, hidden-surface–removed graphics running on a relatively inexpensive Matrox Millenium 3D graphics accelerator because of the relative simplicity of the models we are rendering. We provide support for 2D applications in a manner similar to that of our previous testbed, except that the windows are displayed using the native window system. This allows us to display X11 application windows on all platforms and native Windows NT/95 windows on those platforms.

We are currently developing a flowchart of the spaceframe construction steps and worker queries, which we will use as the basis for a rule-based system for assembly. The rule-based system will include context-sensitive help, and will accommodate users with varying levels of experience. We also plan to incorporate a tracking system that will track each spaceframe component. This will allow better verification of the installation of each piece, and ensure adherence to the proper assembly sequence.

Conclusions

We believe that the work described in this paper demonstrates the potential of augmented reality's x-ray vision and instructional guidance capabilities for improving architectural construction, inspection, and renovation. Future augmented reality x-ray vision systems may enable maintenance workers to avoid hidden features such as buried infrastructure, electrical wiring, and structural elements as they make changes to buildings and outdoor environments. This promises to both speed up maintenance and renovation operations, and to reduce the amount of accidental damage that they currently cause. Future versions of augmented reality instructional systems may guide construction workers through the assembly of actual buildings and help to improve the quality of their work. Inspectors with augmented reality interfaces may be similarly guided through their jobs—allowing them to work without reference to conventional printed construction drawings and ensuring that every item which needs to be checked is in fact inspected.

The potential impact of augmented reality on architecture and structural engineering will increase as the technology is tied to other emerging technologies. For example, the addition of knowledge-based expert systems (Feiner & McKeown 1991, Myers 1992) to the core augmented reality technology described here could yield systems capable of training workers at actual construction sites while they work to assemble a real building. Such real-time at-site training systems could guide inexperienced users through complex construction operations. The continued evolution and integration of these and other technologies will yield systems that improve both the efficiency and the quality of building construction, maintenance and renovation.

Acknowledgments

Research on these projects is supported in part by the Office of Naval Research under Contract N00014-94-1-0564; NSF Gateway Engineering Coalition under NSF Grant EEC-9444246; the Columbia University CAT in High Performance Computing and Communications in Healthcare, a NY State Center for Advanced Technology supported by the NY State Science and Technology Foundation; the Columbia Center for Telecommunications Research under NSF Grant ECD-88-1111; and NSF Grant CDA-92-23009. Starnet International Inc. provided the spaceframe. The undergraduate involvement in the spacefame prototype were Rod Freeman (Mechanical Engineering), Jenny Wu (Architecture) and Melvin Lew (Computer Science).

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