Use of Real-Time Animation in the Construction Process

A. B. CLEVELAND, JR., AND VERNON FRANCISCO

Recent advances in computer workstation performance and the increasing functionality of computer-aided design (CAD) software make it possible for today's engineers and constructors to interact with and animate complex three-dimensional computer models in real time. This makes the computer model not only a tool to be used in the design process but also a planning device that can be used during the construction of facilities. Major construction tasks can now be simulated routinely with real-time computer animation, allowing construction plans to be developed and verified so that the problems areas can be identified and corrected before the actual task is undertaken. In this paper, a description of Bechtel's real-time animation system, WALKTHRU, will be presented, and methods for application of the model to the construction process will be given.

Productivity in engineering and construction has become an increasingly important and critical issue. Reduced business, the declining U.S. world market share, and intense foreign competition have all contributed to elevating the importance of productivity in the construction industry. A traditional U.S. strength in this ongoing battle to improve productivity is the development, if not application, of new technologies. In engineering and construction, one of the most visible technologies in recent years has been computer-aided design, or CAD.

The engineering and construction industry often appears to lag behind the manufacturing industries (e.g., automotive and aerospace) in the integrated use of CAD technology. There are a number of important reasons for this. With few exceptions, the engineering and construction industry has traditionally lacked two important characteristics that are common in the manufacturing industries and that make it much easier to implement the integrated use of CAD technology cost effectively. These factors are mass production and vertical integration.

The primary use of CAD in manufacturing is the design of mechanical parts, mechanisms, assemblies, and so on. In the construction industry, there is little, if any, design of parts. A typical design consists of assembling and managing an extremely large number of parts, and nearly every project is unique, with little opportunity to reduce unit costs significantly through the use of mass production alone. Every bridge is different, every highway overpass has slightly different dimensions, and every subway station must satisfy a different set of spatial and service requirements. These types of projects are almost always constructed in a location different from that in which they are engineered. The "manufacturing" equipment and personnel are moved to the site and not vice versa. Finally, it is typical of engineering and construction projects that the owner, architect, engineer, and constructor are often different companies. If these different entities ever apply automation to the same degree, with compatible technologies, it is usually only coincidence.

In spite of these disadvantages, it is possible to apply CAD technology to engineering and construction projects in significant and cost-effective ways, over and above the use of CAD as an electronic drafting board. This technology, although often viewed strictly as an engineering tool, presents a tremendous opportunity for streamlining and integrating the entire engineering and construction process. In fact, the argument can be made that in the final analysis, the use of CAD in engineering will provide more benefits to the construction process than it does to the engineering itself. This paper will highlight just a few of the areas in which CAD has helped to enhance the productivity of the overall process and, in particular, construction. Specifically, the application of three-dimensional computer modeling and real-time computer animation in support of engineering and construction will be addressed.

BACKGROUND

The use of computers in the engineering and construction industries has been fairly commonplace for more than 20 yr. In engineering, the early applications of computing were mostly very specific point solutions to well-defined problems. Typically, these applications fell into the category of engineering analysis. Structural analysis, for example, was one of the very first engineering computing uses. Large engineering analyses involved an incredibly large number of calculations that were impractical, if not impossible, to perform by hand. As such, they were very amenable to the batch-processing nature of the computer technology of the day. Other applications were data base operations, such as tracking bulk quantities, materials management, and project management. Again, this use of computing was effective because it involved a well-defined problem in which large amounts of data had to be manipulated.

In nearly all these early uses of computing in engineering

Bechtel Eastern Power Corporation, 15740 Shady Grove Rd., Gaithersburg, Md. 20877.

and construction, real-time interaction with the computer was either limited to the data input process or totally nonexistent. Likewise, graphics were seldom used except to represent the results of the analysis pictorially.

Computer-aided design was one of the first computing applications that was both highly interactive and made extensive use of computer graphics. These early CAD systems were developed for mainframe computers and were thus expensive, a characteristic that limited their application to very specialized and usually repetitive tasks. The advent of the minicomputer and the subsequent development of turnkey CAD systems, based on these less expensive computers, paved the way for more widespread use of CAD.

Although there were some notable applications of CAD that were truly design applications, most of the early usage of CAD in the engineering and construction area was purely as a drafting tool. Two major impediments held back the expansion of CAD use beyond drafting: a lack of software and the limited power of the early minicomputers. Typically, engineering and construction projects must include large amounts of data about the physical geometry of the project. Thus any software that is used to manage these data must be very efficient at generating data and maintaining data integrity. The computer must be able to manage these large amounts of data and still maintain its interactive quality. It was the introduction of the 32-bit minicomputers, with their increased processing power, that opened the door for design applications of CAD in engineering and construction. Ultimately, this led to a number of design systems supporting interactive three-dimensional (3-D) computer modeling.

The use of 3-D computer models has become an integral part of the Bechtel Eastern Power Corporation's activities in the design, construction, and retrofit of process and power plants. These computerized models are extremely economical to develop, enhance, and maintain. The conventional construction drawings and related documents (e.g., bills for material) are extracted automatically and are consistent in style, accuracy, and quality. The electronic model makes it possible for all members of the engineering and construction team to have immediate access to the current design data. It is also possible to link the electronic model to standard computer-aided engineering (CAE) analysis programs and data base management applications. For review purposes, these 3-D models can be downloaded to personal computers, where they can be interactively reviewed, queried, and color shaded. After the design and construction phase of a project is complete, the electronic model remains an important tool for subsequent operation and maintenance of the facility.

WALKTHRU

The effectiveness of 3-D computer modeling has eliminated our use of the plastic model as a design tool. There are a number of very good reasons for this. The computer model is more accurate, it is portable, and the data can be extracted automatically. Also, the computer model is not an "extra." By this, we mean that the 3-D computer model is a natural byproduct of the design process. However, we did pay a price for the demise of the plastic model: reduced visibility of the physical design. In spite of all its advantages, the full-scale use of 3-D computer modeling has limited routine access to the "live" design data to those who are trained to use CAD workstations and who use them on a daily basis, in other words, the physical designers. Those involved with project management, construction, and ownership were restricted to infrequent drawing extractions or looks over a designer's shoulder for their "view" of the physical design. In contrast, when physical models were used, anyone could walk up to the model and get an immediate appreciation for the plant configuration. The viewer did not require a CAD training course to change views, walk around the model, or examine the project design in some other way.

In an attempt to recapture electronically what was lost by giving up the plastic model, we developed WALKTHRU™, a real-time 3-D animation system. It allows users to interact with existing 3-D computer models in much the same way that they would with a real-world model. With this system, the user sits at a color graphics workstation and, with the use of a control panel to control "body" and "head" motion, moves through the 3-D computer model, observing physical objects much as he or she would in the real world.

To take full advantage of the benefits of real-time animation in an engineering and construction environment, a number of criteria were established before the development of WALKTHRU. These will be examined in the next sections.

Use of Existing Three-Dimensional Geometry Data

Unlike manufacturing projects that use CAD with computer-aided manufacturing (CAD/CAM), the projects performed in engineering and construction are typically "one off" projects. That is, after the project is designed, it is constructed only once. For routine visualization, construction simulation, and so on, it is therefore not practical to build a model because it would only be used for a single application. For WALKTHRU to be cost-effective for routine use, the system must be able to accept the 3-D geometry data directly and completely from the design models.

Real-Time Interaction

To be a truly effective simulation tool, WALKTHRU must be able to simulate motion of both the viewer and any object in the 3-D model. Also, the user must have precise control over his own position and the position of the 3-D objects. Thus the system must display at least several "frames" per second, even for complex models. A "freeze" frame every couple of seconds would not be acceptable.

Large Models with Arbitrary Geometry

It is not uncommon for plant design 3-D models to be made up of hundreds of thousands of polygons. The system must therefore have mechanisms for displaying models of this size and still maintain real-time interaction. Also, the system cannot be designed to take advantage of the 3-D model geometry to gain speed. It must be able to handle totally arbitrary geometry, including open surfaces, nonconvex polygons and solids, and other unusual forms.

Sufficient Visual Realism

Because many of the users of WALKTHRU will not be CAD-trained designers, the system must be able to display the model images with sufficient visual realism to be accurately interpreted by casual users. This visual realism includes such features as perspective, color, and smooth shading.

Stand-Alone Workstation

Not all users of WALKTHRU will be located in the design office with direct access to either a mainframe or minicomputer, such as a VAX. WALKTHRU must therefore function on a workstation that can operate in a completely stand-alone environment. Cost considerations are associated with this. We believed that it was appropriate to target the system for stand-alone workstations that cost less than $75,000 each.

Capabilities of the WALKTHRU Workstation

The workstation used for WALKTHRU is a Silicon Graphics IRIS workstation. This workstation uses specialized processors that are specifically designed for the high-speed graphics manipulations required for real-time simulation. The software that actually performs the walk-through functions runs as a stand-alone on the Silicon Graphics workstation, independent of the mainframe, manipulating 3-D data downloaded from the CAD system. The primary input/output device that is used during performance of the walk-through is a "button/dial" box. This device, which interacts with the workstation through an RS-232 interface, has 8 input dials and 32 push buttons. The dials are used to control the viewer motion, and the push buttons are used to invoke a number of functions. Other functions are controlled by the mouse and the keyboard. Some of the basic capabilities incorporated into the WALKTHRU system are summarized in the next sections.

View Control

Direction of Travel

Two of the dials are used to control the direction of travel through the model. One turns the body left and right, and the other controls the up and down inclination of travel. The user can travel both forward and backward.

Travel Speed

Another dial controls the travel speed. Turning the dial clockwise increases the travel speed, and turning it counterclockwise decreases speed.

Head Orientation

The user can also control the orientation of his head independently of the travel direction. One dial pans the head left and right, and the other pans the head up and down. This allows the user to travel in one direction while looking over his shoulder, up at the ceiling, or in any other real world direction.

Zoom

By using another dial, the user can interactively zoom in and out in much the same way that a zoom lens on a camera can go from wide angle to telephoto.

Initial Position

If the user wishes to position herself in a specific position without "walking" to that position, he can specify the position either by keying in *x-y-z* coordinates or by using the mouse and a pop-up map on the screen. To use the mouse and map, the user graphically specifies his position and viewing direction and is subsequently positioned there.

View Clipping

By using two of the dials, the user can interactively change the near- and far-view clipping planes as he is walking.

Perspective

The default display mode is with perspective display on. With one of the push buttons, the display can be toggled between perspective display and a parallel projection display. The parallel projection is the same type of display that is used on traditional CAD systems for wire frame images.

Display Control

Shaded Images

During the real-time walk-through, images are displayed in wire frame. At any time, the user can render a shaded image by using a push button. When the "shade" button is pressed, the motion is frozen and the image is shaded. The shading process uses user-defined color tables. These color tables allow the user to specify specular reflection characteristics for each color.

Location Map

During the walk-through, the user can toggle a location map on and off. The map displays plan and elevation views that give the range cube of the model. The user's position within the model is displayed with two direction vectors, one of which provides the direction of travel and the other the orientation of the head. As the user's position and view direction changes, the direction vectors also move.

Control Panel

In addition to the location map, the user can "pop up" a control panel display that provides a numerical readout of the user's *x-y-z* position, direction of travel, head orientation, and travel speed.

Record/Playback

Record

The user can record "key frames" that save the current view parameters, object positions and orientation, and delta time (from last save frame). These parameters are saved on a disk file with a name specified by the user.

Replay

Any "record" file created with the "record" option or by other software can be recalled. The software interpolates between the key frame parameters and replays the saved sequence in real time. In this mode, the user's travel and the motion of the objects is controlled by the record file.

Object Motion

The user has a number of options for moving and positioning individual objects within the model. Object hierarchy can be defined such that the motion of one or more objects is dependent on the motion of another object. The hierarchy can be defined to an unlimited number of levels.

Constant Motion

The user can assign a constant motion to any object in the model. Both delta translations and rotations can be specified. Once the object is set in motion, the user can continue the walk-through while the object is moving.

Moving Objects

The user can select an object in the model and interactively move (translate, rotate, or both) the object to another position.

Replay Motion

With the "record" option, the user can record the position of the objects at different times and then replay their motion, as in the "replay" function described earlier. However, in this mode, only the motion of the objects is controlled by the software. The user retains full control over travel and viewing parameters while the objects are moving.

Interference Detection

While system is in the interactive object mode, the user can ask that the active object be checked against the other objects in the model to determine if there are any interferences with the active object. The interferences that are detected are highlighted on the screen.

Measure

In the parallel projection mode, the user can invoke the "measure" command from the button box. This function allows use of the mouse to specify an "anchor point" in the view. Then, as the mouse is moved, an instantaneous readout is given, displaying the distance, delta *x*, delta *y*, and angle between the anchor point and the current cursor position. The anchor point may be moved by simply positioning the cursor and pressing a mouse button.

Shaded Image Animation

The number of polygons associated with computer models, particularly nuclear plant models, can easily range in the hundreds of thousands. The sheer volume of model data makes it impractical to perform real-time motion in shaded image. However, WALKTHRU has the capacity to replay the viewer and object motion one frame at a time, shading each frame and outputting the shaded frame to a video recorder. This option is executed as a batch process, in which motion that was recorded as described previously is replayed. The final product is a videotape of the recorded motion, displayed entirely in shaded image.

WALKTHRU Compared with Other Systems

WALKTHRU differs from commercial video-animation systems in a number of significant ways. The most important is that it uses geometry data directly from the 3-D design models and therefore a special model need not be developed strictly for the animation. Second, even though WALKTHRU can produce a shaded animation video, its focus is real-time interaction and not output to videotape, as in the case of commercial animation systems. Finally, the user interface for the real-time interaction is designed to allow the user to interact with the plant geometry as a designer or engineer would, as opposed to as a film director.

The current capabilities of WALKTHRU reflect a balance between our desire to maximize real-time interaction with the 3-D model and the realities of current workstation technology. Many of the features of WALKTHRU were developed in direct response to feedback from project applications. Future enhancements will focus on increasing the functionality of WALKTHRU as a construction planning and simulation tool.

APPLICATIONS

Although WALKTHRU was initially conceived simply as a visualization tool, it has been effective for a wide range of activities, particularly in support of the construction process. Some of the more significant applications are described in the following sections.

Visualization

The importance and value of the ability to quickly and accurately convey the physical configuration of the construction project cannot be overemphasized. The current format and content of many of the traditional construction drawings have evolved as much from the limitations of the manual drafting process as they have from the need to convey design information. As a result, there is a significant amount of symbolic and shorthand notation on these drawings that does not necessarily look like the configuration that is being constructed. This notation has been adopted to streamline the drafting process, but the resulting drawings require some degree of experience to interpret. By using 3-D modeling and a tool such as WALKTHRU, the physical configuration can be conveyed graphically in a form that appears very much like the real thing. Also, views are not limited to a few orthographic projections. The ability to view any portion of the project dynamically in all three dimensions significantly enhances the user's ability to interpret the final configuration.

Construction Planning

In the design office, the use of a 3-D computer model will prove that a design has no interferences and will fit together, but it will not necessarily prove that the design can be built. The construction engineers must deal with a very dynamic situation. They must visualize and plan for a large amount of material, equipment, and personnel working in harmony, all in the same place and at the same time. The problem of scheduling multiple activities in congested areas is difficult at best. Installation and manipulation of large pieces of equipment also require precise planning. Construction simulation is a tool that can streamline this process.

The use of real-time animation for construction simulation in support of construction planning provides an excellent opportunity to significantly reduce construction costs, as evidenced by two examples. The first is that in power plant construction, studies have indicated that construction personnel spend only 35 percent of their time performing actual, direct construction activities. The rest of their time, outside of the normal personal time for coffee breaks and so on, is spent in planning, preparing, getting material, waiting for material, and similar activities. The second is that on a recent large project involving construction of three similar nuclear power plant units, construction costs on the second and third units were reduced by 15 percent and 25 percent, respectively.

In both of these cases, the figures are from power plant construction, but they are likely to be similar for other types of construction projects. Essentially, what the figures indicate is that a lot of time is spent figuring out what to do and getting ready to do it, and that it's easier to do it the second time. Because nearly every construction project is, at the detailed level, a unique effort, the conclusions for the use of 3-D modeling are fairly obvious. The 3-D model aids in visualization of the available work area and planning the sequence of construction activities to allow the most productive work effort in that area. Work crew activities can be scheduled to minimize personnel and equipment congestion in an area, thus improving crew productivity. Also, in simplest terms, real-time animation allows the project to be built once in the computer before it is built in the field.

Training

A natural byproduct of the visualization and planning applications is an effective training tool. The capability to produce videotapes as a result of a planning session makes it possible to inform an entire construction crew of the exact plan to be executed. Videotape provides a very portable and graphic tool for this type of training, bringing the benefits of construction simulation to a very large audience.

CONCLUSION

Almost every aspect of engineering and construction is being affected by automation. Many of the more recent applications have been made practical by the use of 3-D computer models in the initial design phase. In engineering and construction applications, the use of 3-D animation to simulate construction activities is a very powerful planning and training tool. As is well known, mistakes in the field are very costly to correct. This type of avoided cost is difficult to measure but very real.

The use of construction simulation allows the rapid development and rehearsal of plans and the graphical demonstration of those plans to others. We have used the WALKTHRU software for reviewing designs, simulating major construction activities, and training. The capabilities provided by WALKTHRU enable the 3-D computer model to be much more accessible to project and owner personnel. WALKTHRU also increases the value of the 3-D computer model in engineering, construction, and operation by giving it a means to provide an immediate and animated visual impact.

Perhaps the most effective role of WALKTHRU to date has been in support of construction planning. This type of simulation is an excellent planning and training tool. The animation can include not only the individual components being installed but also such construction equipment as cranes, rigging, and so on. Some recent applications have included the following:

- Planning for the replacement of the tube bundles in some large heat exchangers in a nuclear power plant,
- Planning for the complete replacement of the steam generators in a nuclear plant,
- Review of a petrochemical facility for maintenance operations, and
- Several visualization applications for review of both conceptual and detailed plant designs.

This type of simulation has also been used to educate construction personnel about the exact plan for the job. The result is that the supervisor can plan work activities with confidence that the work can be completed according to the plan with a minimum amount of errors and rework.

Publication of this paper sponsored by Committee on Construction Management.