# NIST RESEARCH TOWARD CONSTRUCTION SITE INTEGRATION AND AUTOMATION

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**ABSTRACT:** Current uses of computers in construction include design, planning, scheduling, and cost estimating. Much more could be achieved on a fully computer-integrated construction site. This paper describes initial work at the National Institute of Standards and Technology toward construction site integration and automation, beginning with a simple steel-erection procedure using an instrumented crane. CAD-generated geometry sets are transformed into a library of 3D construction site objects. These objects are then loaded into an augmented simulation system that tracks both equipment and resources based on real-time data from the construction site. With some future enhancements, the end result will be a world model of the site, in which as-built conditions can be assessed, current construction processes can be viewed as they occur, planned sequences of processes can be tested, and object information can be retrieved on demand. A project can be viewed and managed remotely using this tool. Remotely controlled construction in hazardous environments is a natural extension of this environment. The National Construction Automation Testbed (NCAT) is currently being used in various research projects with the intentions of making such possibilities a reality. A major effort in the NCAT is the development and testing of the metrology, communication, and simulation protocols required.

## INTRODUCTION

The use of computers in construction engineering and management can range from spreadsheets to full automation of remotely operated robots. The state of the art is nowhere near full automation. The National Institute of Standards and Technology (NIST) is currently working toward integrating and automating the construction site through the use of real-time metrology and sensor fusion; augmented simulation (AS) of as-built structures, equipment, and associated construction processes; dynamic object-oriented databases; and the standards and protocols necessary to communicate among the different applications used in the construction industry. (Note: In contrast to Virtual Reality, objects in the Augmented Simulation representation are instanced by their initial arrival at the construction site. The object movements are henceforth controlled by live metrology data uplinked from the site. Positions of the objects in the AS represent the current positions in real life.) To this end, NIST has set up the National Construction Automation Testbed (NCAT).

A realistic goal for construction automation is to make it possible for an engineer, in his office, to manage and ultimately control the construction of facility at a remote site anywhere in the world. The components that help us move toward this goal include (1) remote tracking of materials; (2) remote tracking of equipment; (3) remote assessment of the construction site; and (4) augmented simulation (AS) of the construction. Remote tracking of materials and equipment helps construction managers determine where capital assets are located and what resources are available. Remote assessment helps construction managers see what has been done. Augmented simulation adds the abilities to plan and test a construction sequence and to see the sequence as it executes. In addition to this advantage, objects in the AS world can be linked to databases and schedules, as is now often done in design review systems. Usually, such information cannot be easily ascertained by visual inspection on the construction site.

The current project at NIST is the initial stage of a multiyear effort in computer-integrated construction. The current focus of the research is on the assessment of metrology technologies (e.g., GPS, inertial guidance, lasers, etc.) and on the development of a standard wireless communication protocol that can be used to acquire real-time position, orientation, and other sensor data from multiple sources that may be provided by these different technologies. To test these sensors and protocols in a realistic experiment, a crane with six-degrees-of-freedom control called TETRA (Bostelman 1996) was used to place a beam in a structure at a construction site. The placement of this beam was monitored by a wireless video camera whose signals were transferred to the construction shack, then from the construction shack to a remote site using ATM over a fiber-optic cable. ["Asynchronous Transfer Mode", an emerging communications standard. In this experiment, ATM packets were exchanged over an OC3 (155Mbps) fiber-optic link.] An AS representation of the crane operation was run at the remote management site. TETRA is equipped for wireless uplink of its instant geometric configuration. These data are received at the construction shack and piped via Ethernet to the remote site to drive the augmented simulation. The NCAT facility, where the crane is located, represents the construction site. The "construction shack." located next to TETRA, consists of the crane control console and the computer used to convert data for the ATM transfer. The crane is presently controlled through an umbilical-cord link from the construction shack to TETRA. The remote site, physically located 700 m away in the National Automated Manufacturing Testbed (NAMT), represents the remote construction management site. This site was selected as the management site because dedicated fiber-optic cable links it to the "construction site." A schematic representation of the current setup is shown in Fig. 1. Data transfer rates and latencies identified during this project will contribute to the development of a protocol for wireless data transfer in future projects.

## DESCRIPTION OF CONSTRUCTION SITE AND REMOTE MANAGEMENT SITES

The structure to be assembled consists of a beam and two columns, as shown in Fig. 2. The connection between column

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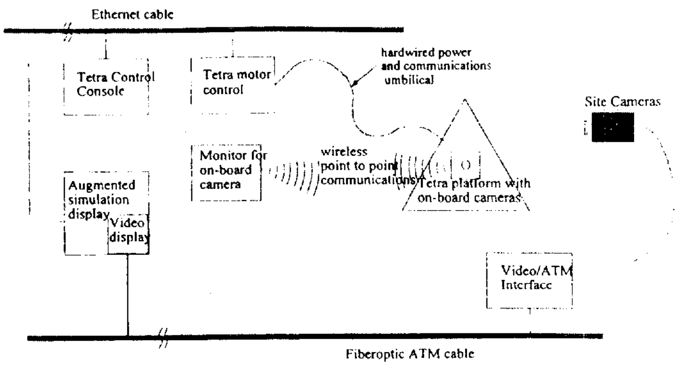

**FIG. 1. Schematic Representation of Current NCAT Control and Communication Scheme**

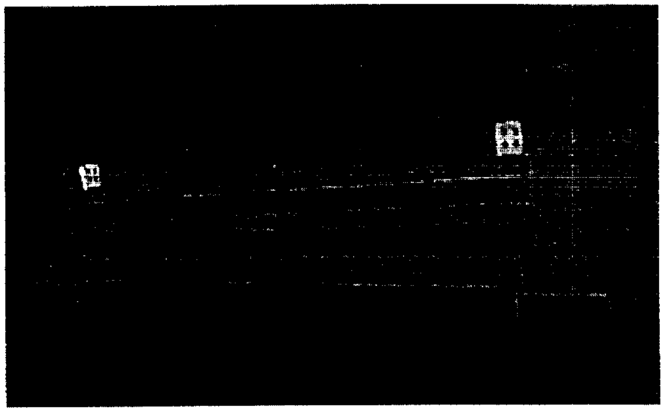

**FIG. 2. Visualization of Frame and Beam Models Including Lehigh ATLSS Quick Connectors**

and beam is made using the ATLSS quick connector (Fleischman 1992), developed at the Lehigh University, that requires no bolting or welding. In this experiment, lifting of the structural element is performed by the inverted-Stewart-Platform crane, TETRA, which is suspended from a 30-ton (267 kN) capacity bridge crane. TETRA's lifting platform has six degrees of freedom of movement. These movements are in addition to the bridge and trolley translation of the main crane, thus providing eight degrees of freedom (DOF) of control. Adjustments to the platform up to 3,000 mm in translation relative to the trolley and bridge locations and ±30° rotation about any axis can be made by the engineer operating the control console. When properly positioned, the male end of the connector on the beam can be attached to the female end of the connector on the column by lowering the beam. The bridge crane-based TETRA system was selected as the initial "construction machine" for several reasons. First, the technology was readily available at NIST and the mechanisms for interfacing the inverted Stewart platform to a full-size bridge crane already present in the NCAT were straightforward. Secondly, TETRA was already instrumented to transmit (via hardwired Ethernet) its internal kinematic state and thus only linear encoder-based translation sensors will need to be added to the bridge and trolley of the parent crane in order to fully sense the machine's position within the construction site. (These same changes could easily be adapted to any existing construction crane.) All of the above sensors were "internal" to the machine itself, in the classical robotic sense. External data (e.g., from GPS) can augment the internal sensor data to periodically update the position of TETRA relative to the construction site coordinates in real-time. Finally, the TETRA/bridge crane combination gave us an immediate tool to begin manipulating and tracking construction components (e.g., the beam with ATLSS connectors). TETRA will eventually be joined by a host of other instrumented and tracked construction machinery at NIST as the program expands over the next several years.

TETRA is equipped with three video cameras viewing downward to aid micro adjustments made by tele-operation. The camera signals are carried to the operator's monitors through wireless transmitters and receivers operating in the 900 MHz band. The operator commands the movement of TETRA through a force sensor-based controller on the command console. The controller input is synthesized into six degrees of freedom of movement. Fig. 2 shows the bank of monitors and the controller at the control console. The movement of TETRA is effected by six winches on board the platform. Their length adjustments are calculated from the commanded movement.

The information sent to the AS world by TETRA consists of the commanded positions. Since the crane has an open-loop control presently, use of commanded positions is accurate only for as long as the commands are faithfully interpreted. The protocol used for the current project contains the following data in floating point numbers: $x$-translation, $y$-translation, $z$-translation, $x$-rotation, $y$-rotation, $z$-rotation. Other data, including bridge and trolley reference positions, are required to totally register the beam manipulator within the world model of the construction site and will be included shortly. For other machines these data will almost certainly be different and may include information about additional degrees of freedom as well as diagnostic information about various parts of the machine (temperature, pressure, fuel levels, forces, strains, velocities, accelerations, etc.).

The command signals will be replaced by feedback signals in the future. A different approach must be used to externally determine the six degrees of freedom of the TETRA platform. Three metrology systems that could be used for this purpose are (1) automatic tracking of three points on the machine by three motorized total stations; (2) fanning laser light sheets and an associated position-capture device; and (3) phase differential GPS. A combination of these three systems, plus possibly other technologies, may have to be used to ensure continuous coverage.

Once the feedback signals are obtained, they will be transmitted to the "construction shack" using the NIST Smart Pod (Stone and Pfeffer 1998). The NIST Smart Pod is a compact stand-alone strap-down embedded data acquisition and wireless-data-transmission package that will broadcast the above protocol. In order to capture the whole picture at the construction site, a standardized Smart Pod will be placed on each movable object. In the present work, the Smart Pods will be placed on the crane's trolley to indicate its position along the tracks, on the crane's bridge to indicate its position along the bridge, and on TETRA to obtain the six degrees of freedom of the crane's platform. Each pod autonomously and wirelessly contributes to the construction site management system's knowledge of the current status of the crane. The system is generic enough that a more centralized piece of construction machinery, e.g., a backhoe, could be monitored using a single unit that might simultaneously monitor GPS position, base orientation, hydraulic cylinder extensions, etc. Ultimately, through hybrid IC design, it is expected that the industrialized version of the Smart Pod will not be much larger than a coffee cup. We have concentrated here on the discussion of tracking captive machinery. Tracking discrete construction equipment will be discussed in subsequent papers.

## CREATION OF VIRTUAL WORLD

The augmented simulation for this project was created using World Tool Kit (WTK). (Note: Sense8, Inc. Any mention of commercial products is for information only; it does not imply recommendation or endorsement by the National Institute of Standards and Technology nor does it imply that the products mentioned are necessarily the best available for the purpose.) WTK is a virtual reality (VR) programming shell that comes with built-in functions to manipulate mathematical representations of any 3D objects within the context of the simulated world. The principal objects in the augmented simulation consist of TETRA, the beam and frame being used, and the building that houses them. TETRA moves as one rigid body. The only parts with independent movement are the beam grippers. There are two grippers; each one has two independent parts. The entire assembly is represented with five parts: the rigid platform with winches and computer, and four parts representing the grippers.

The version of WTK used in this experiment can only import 3D objects in VRML 1.0, DXF, and NFF formats. VRML format was used in this experiment because it is an export option in many off-the-shelf CAD packages and because it can be easily understood and manipulated by hand for experimental purposes. Also, objects in VRML format can be viewed easily by a number of web browsers. This is an important circumstance, since all indications are that the Next Generation Internet (NGI) will permit large-model, real-time simulations, including audio and video, to be transparently and economically transmitted between construction sites and remote management locations without the need for any dedicated infrastructure on the part of the construction company. The use of web browsers available off-the-shelf will simplify the ability for a plurality of management staff to simultaneously and asynchronously access and interpret construction-site data. At the same time, choosing the VRML format introduced the problems described below.

The objects were first modeled using a CAD application. We tried four different commercial CAD systems commonly used in mechanical and AEC design. Two of the systems could export objects directly in VRML 1.0 format. One could export objects only in VRML 2.0 format. One could not export VRML, but could export objects in a format that could be imported into one of the other systems and then reexported to VRML. (This situation is changing rapidly as new versions of these systems are released.) Those systems that did export to VRML converted all their object geometries to lists of polygons, and several also "deconstructed" the objects so that, for example, subassemblies could no longer by identified easily. This behavior is not unexpected, since VRML was created with the representation of surfaced models in mind, but it makes the storage and processing of models very inefficient. In our experiments, the TETRA model, (Fig. 3), which was very compact in a solid-modeling CAD application, comprised some 50,000 polygons when exported to VRML 1.0. The construction site model expanded similarly. It took approximately three seconds to render these models on the screen using WTK on a Silicon Graphics Power Onyx RE2 workstation. The research team felt that a minimum refresh rate of 10 Hz is necessary to dynamically model the construction process in real time. Therefore, improvements were necessary.

To improve the efficiency of the files exported in VRML format, we tried two approaches. The first approach was to edit the VRML file manually (eventually scripts were written to automate this process), and replace the triangular prisms that make up the flat surfaces by quadrilateral prisms. Cylinder, block, or sphere primitives could also be used to replace large lists of polygons created to represent the same. This approach was time consuming, but the result was a smaller file without loss of details. The construction site and the Lehigh frame models were reduced using this approach. The reduction was nearly 50% for the construction site model, which was 560 Kbytes originally, but was reduced o 309. This reduction was obtained without any loss of fidelity, but resulted in only a minor improvement in the refresh rate.

The second approach was to go back to the original CAD model and simplify the objects. To this end, rounded edges

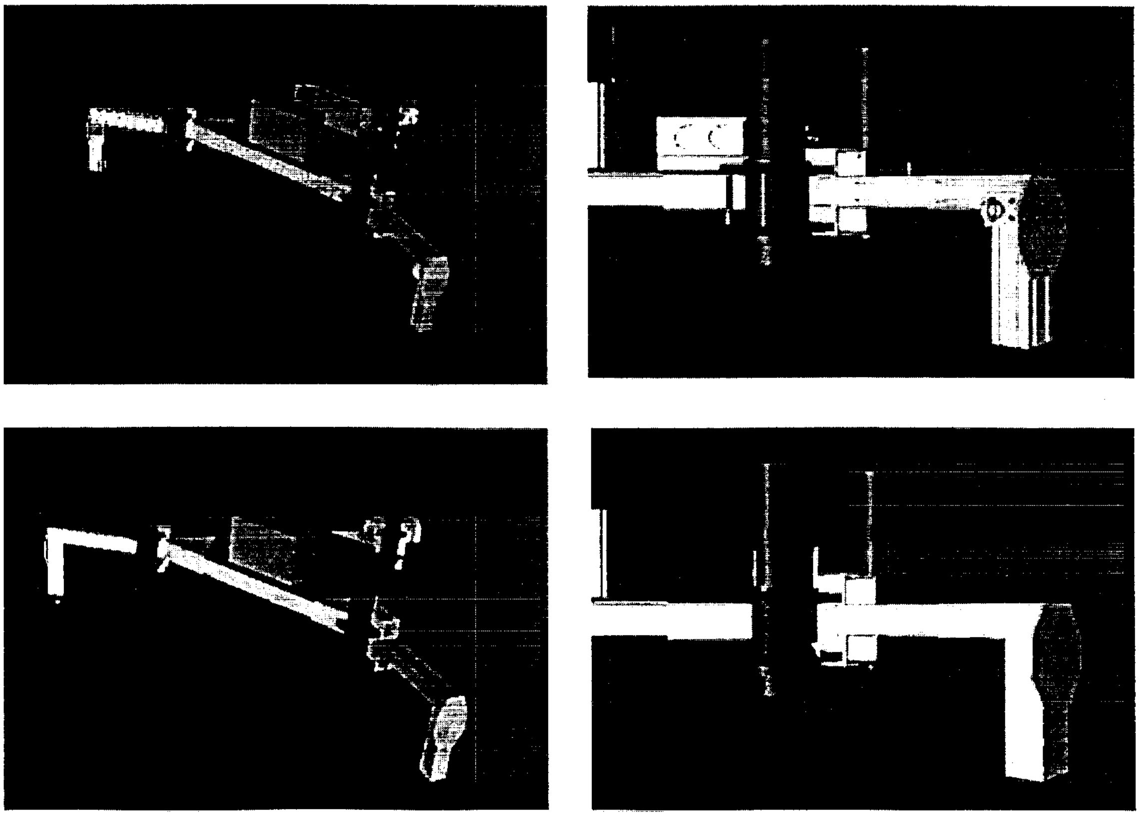

**FIG. 3. Visualizations of Original (Upper) and Simplified (Lower) TETRA Models**

and smaller objects such as buttons and holes that were not highly visible were removed. The resulting models were much smaller than the original one, but some details were lost. The model of TETRA was reduced this way. The simplified model of TETRA required 48 Kbytes of storage compared to the original 1,452. Fig. 3 shows the original and modified TETRA. The close-up view shows that the original model contains details such as hoist ring and screws. Although many details are lost in the simplified model, the global view of the model (the bottom left figure), from the simulation point of view, is nearly undistinguishable. Fig. 4 shows a simplified construction site model. In this case, the original model did not contain unnecessary details, and cleaning up the VRML model did not change the depiction of the construction site. Using these simplified VRML models in WTK, the refresh rate was increased to approximately 10 Hz. Of course, it is well known in the computer gaming industry that models must be simplified to the extreme if realistic refresh rates are to be achieved. A typical rule of thumb is that a given surfaced object should use no more than 100 or so polygons. However, in fast moving games, much of this simplification can be masked by clever use of texture maps, an option not likely to be generally available in construction site simulation.

We have elaborated the above discussion to emphasize practical matters that will determine the performance of a live data-driven simulation of a construction site. Even in view of faster processors and the increased NGI bandwidth, the 3D library representing the components to be tracked on the construction site must be created with level-of-detail judiciously chosen at the outset. Vendors providing a digital representation library of their product line will need to allow for this level-of-detail selection. It should be noted that the criteria for selection will be more complicated than the simple proximity criterion used in current VRML applications. For example, a single model from a vendor may be the source for a simulation of a construction sequence using a bulldozer or of an on-site maintenance procedure for the bulldozer. Details needed for the second are irrelevant for the first.

The WTK world simulation is driven by a companion C program. Software functions to move any rigid-body objects within the context of that world are built into WTK. The C program performs the following functions: (1) Initializes the augmented simulation world; (2) cycles through an event loop indefinitely until a request to terminate is received; and (3) closes files and cleans up temporary files. In the initialization section, the rigid-body components are loaded based on live site data, scaled and positioned in the augmented simulation world. In the event loop, a request for information is sent to the "construction shack" (Fig. 5). In response, the construction shack supplies the six-degrees-of-freedom position of TETRA. The new position of TETRA is calculated and the screen is redrawn with the new TETRA position. This process is shown schematically in Fig. 6.

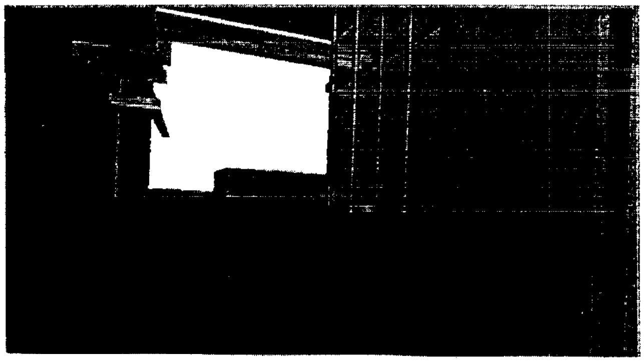

**FIG. 4. Visualization of Construction Site Model**

**FIG. 5. TETRA Control Station in "Construction Shack" (Operator is Manipulating Force Sensor-Based Controller While Watching Images Communicated Wirelessly from On-Board Cameras)**

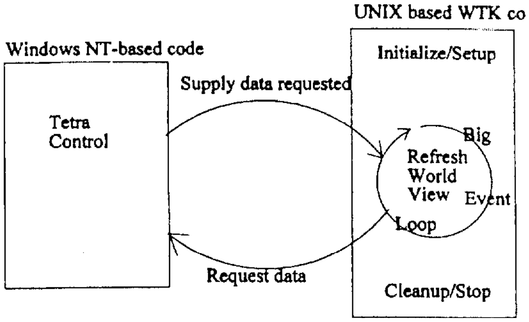

**FIG. 6. Communication between TETRA and WTK (In This Experiment, TETRA Controller Was Passive, Exchanging Data Only When Polled)**

A construction sequence depicting the insertion of the beam is shown in Fig. 7. The AS scene occupies the left half of the computer screen with a live video image shown at the lower right part of the screen. While the video picture is a useful tool for the construction manager, the augmented simulation world potentially can provide far more information. For example, a particular crane maneuver can be tested prior to execution, to verify that there will be no interference with existing objects; the construction equipment could be operated remotely; the construction site could be viewed from different perspectives not always possible in the real job site; information linked to an object could be queried; and as-built information of objects could be obtained.

## INFORMATION EXCHANGE PROTOCOLS

Successful use of augmented simulation systems and dynamic construction site databases will hinge on the ready availability of information from two sources. First, a to-be-constructed model based on actual construction components must be available, along with models of construction equipment. Second, dynamic state information must be available from the construction site. Protocols are needed for exchanging both kinds of information, and are discussed separately in the following.

The AEC industry recognized long ago the need for protocols for the digital exchange of information. Early expressions of this need came from AEC users of computer graphic systems in the early 1980s. By 1984, an IGES/AEC Committee had been formed (Palmer 1986). (IGES = Initial Graphics Exchange Specification. See Appendix.) More recently, the AEC industry has expressed its needs over the facility life cycle, covering many different types of supporting computer

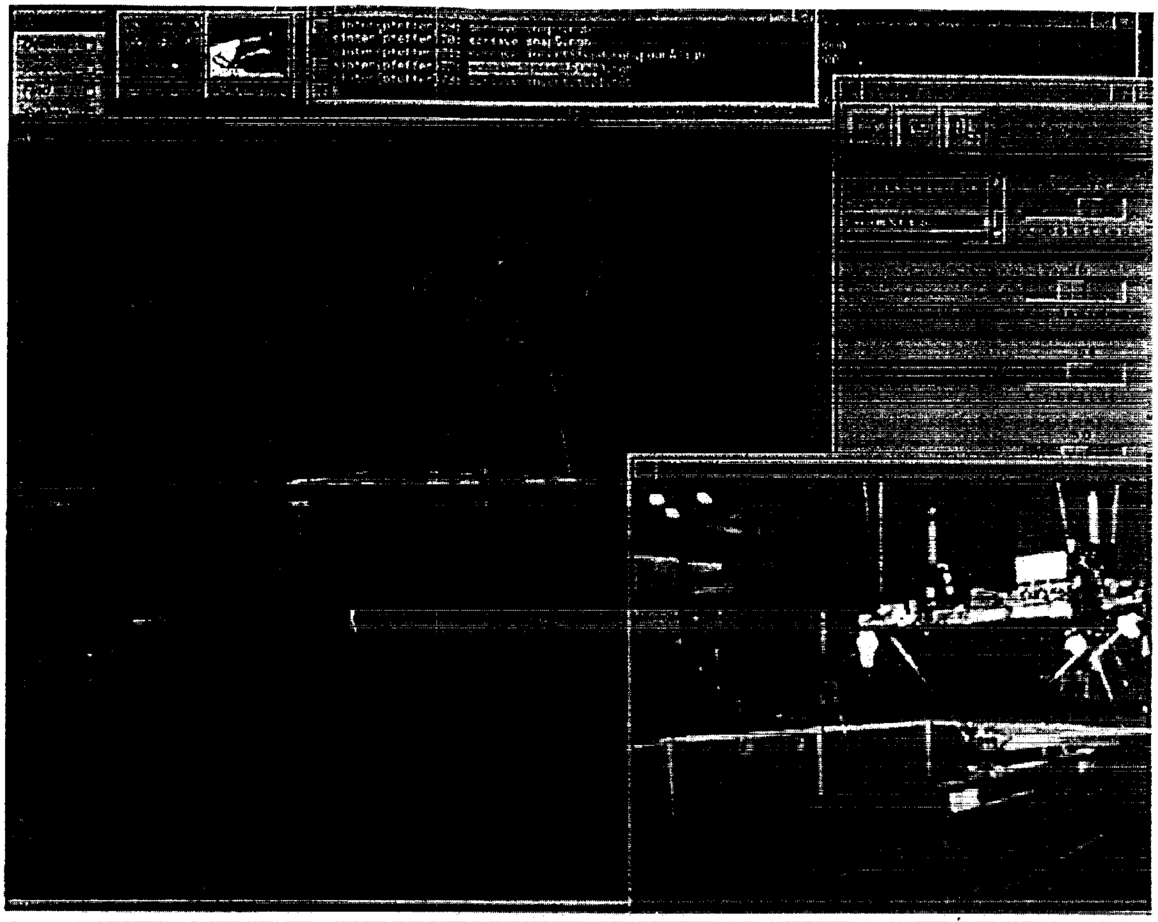

FIG. 7. Augmented Simulation (Left) and Video (Right) Display of NCAT Construction Site As Viewed on Remote Workstation

applications (CII 1997). A common requirement is that the protocols provide for the open, neutral representation of information that can be archived and reused independently of the generating system. Recently, the need has become more acute with the emergence of object-oriented software systems for the AEC industry. Both users and vendors of these systems are seeking protocols for information representation, sharing, and exchange that maximize the interoperability of the systems.

Although VRML was used in this experiment because it was the common denominator for the software systems used, it was used only for the exchange of 3D shape information for visualization purposes. While the VRML specification provides a number of syntactic features that could be used to represent and organize other information about construction objects and machinery, it provides none of the semantics. As a trivial example, in a VRML-formatted file, "BEAM" is just a four-letter symbol with no meaning except by prior agreement between the sending and receiving systems. Two ongoing standardization activities are likely to be the source of the protocols that will be used in the future to represent and exchange design and construction models to and from augmented simulation systems. The older of these two activities is based on ISO 10303, the Standard for the Exchange of Product Model Data (STEP). (See *http://www.nist.gov/sc4* for more information about this ISO activity.) Selected portions of the AEC industry, notably representatives of the heavy industrial construction sector, are developing STEP application protocols for the representation and exchange of facility information. An example that is particularly relevant is the effort to develop ISO 10303-227, Application Protocol for Plant Spatial Configuration, led by PlantSTEP. (PlantSTEP, Inc., is a consortium of owner companies, engineering and construction companies, and software companies. See *http://cic.nist.gov/plantstep* for more information.) The newer of the two activities is the definition of Industry Foundation Classes (IFC) for the AEC industry by the International Alliance for Interoperability. (The IAI is an international organization comprising national chapters comprising users and developers. See *http://www.interoperability.com* for more information.) Both of these activities are defining taxonomies, attributes, and exchange formats for large varieties of construction components and systems. However, the activities are still in progress, and viable

TABLE 1. Data Fields in Proposed Dynamic State Data Exchange Protocol

| Data block (1) | Type of data (2) | Description of data (3) |
|---|---|---|
| 0 | Authorization code | Digital "signature" |
| 1 | Part or machine ID | Alpha numeric string |
| 2 | Time at start of acquisition | Date, hour, minute, second |
| 3 | Position | x, y, z, $\theta x$, $\theta y$, $\theta z$, Fid |
| 4 | Auxiliary position 1 | x, y, z, $\theta x$, $\theta y$, $\theta z$, Fid |
| 5 | Auxiliary position 2 | x, y, z, $\theta x$, $\theta y$, $\theta z$, Fid |
| 6 | Auxiliary position 3 | x, y, z, $\theta x$, $\theta y$, $\theta z$, Fid |
| 7 | Auxiliary position 4 | x, y, z, $\theta x$, $\theta y$, $\theta z$, Fid |
| 8 | Auxiliary position 5 | x, y, z, $\theta x$, $\theta y$, $\theta z$, Fid |
| 9 | Data quality per variable | Measurement system id, statistics, error code |
| 10 | Auxiliary sensor data 1 | Displacement, angles |
| 11 | Auxiliary sensor data 2 | Forces, strains |
| 12 | Auxiliary sensor data 3 | Temperatures, pressures |
| 13 | Auxiliary sensor data 4 | Fluid, pneumatic levels |
| 14 | Messages 1 | Operator entry |
| 15 | Messages 2 | Auto diagnostics |
| 16 | Safety status | — |
| 17 | Checksums/parity/redundancy bits | — |

translators based on ISO/STEP or IAI/IFCs and supporting the applications used were not available, which left us with the use of VRML.

The transfer of dynamic-state information from the construction site to dynamic project databases and augmented simulation systems is a new endeavor in the AEC industry. No protocol exists for this purpose currently. As described previously, an initial protocol was developed for this project around the specific translation and rotation capabilities of TETRA. For the next sequence of experiments, the protocol will be expanded to include the information shown in Table 1.

The data listed in Table 1 is necessary for equipment tracking. In the future automated construction site, a multitude of machines may be tracked. The authorization code is necessary to determine the origin of the information packet. Data block 1 is a description of the part or machine that produced the information packet. This information is redundant to Data block 0, but it is useful for human operators. Time of data acquisition provides a time stamp on the packet. This is particularly important for wireless signals that may be broadcast

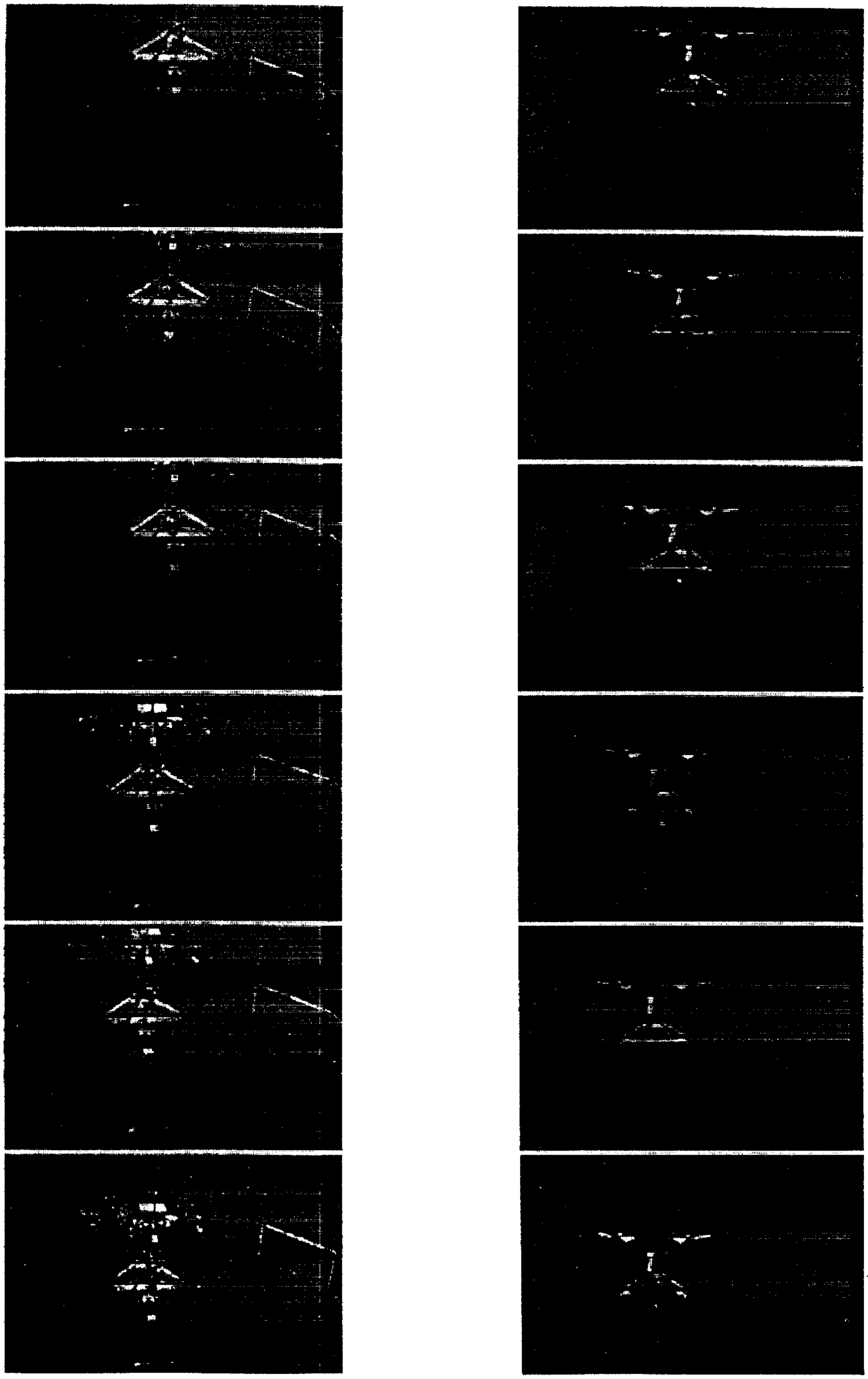

FIG. 8. Video Sequence (Left) and Augmented Simulation Sequence (Right)

from multiple sources. The time stamp allows the simulation to use the most recent information. Knowing the position of the equipment is essential in remote control or simulation. Here we propose six positions. At least one position is necessary to locate the equipment. Additional positions can help locate independent links on the equipment. Block 10 pertains to the quality of the data packet. It allows the user to distinguish reliable data from signals tainted by interference. Auxiliary sensor data may provide necessary additional information for feedback or control. Here, we provide a very limited list. Operator entry allows the operator to issue messages that may be relevant to the interpretation of data. Auto diagnostics allows the equipment-issued messages to be transferred to the remote site. Safety status is particularly important for remotely controlled equipment. A list of predetermined parameters can be used to alert the remote operator that the equipment needs special attention. Finally, Block 17 helps us determine if the information packet has arrived properly. A simple clear-text encoding will probably be used in the initial implementation of this protocol for exchanges via wireless uplink in the NCAT, but substantial work remains to be done.

## RESULTS

In this first experiment, the construction site, crane (TETRA), frame, and beam were all modeled by using a commercial CAD system popular among mechanical designers. The vendor's VRML translator was used to extract object geometries in VRML 1.0. To simplify the resulting models, the VRML files were hand-edited to take advantage of primitive constructions such as cylinders and spheres. In other cases, we took advantage of the different levels of detail generated by the vendor's translator. In some cases, cylinders were represented by prisms at low levels of details. Because these cylinders (e.g., cables) were relatively slender, a lower level of detail was not always perceptible. The final 3D representation of the entire model had a refresh rate of approximately 10 Hz in the workstation used for the augmented simulation. At this refresh rate, the movements in the augmented simulation world appeared to be represented in "real time."

In the current setup, TETRA's control is located in the "construction shack." Control commands and power are supplied to the TETRA platform through an umbilical cord containing a 110 V AC supply and Ethernet data links. The AS representation is driven by relative-motion command signals sent to TETRA, rather than by feedback signals. For comparison with the augmented simulation, the site scene is captured by a digital tracking pan/tilt/zoom video camera; the signals are transformed into ATM format, then transmitted through fiber-optic cables to a remote site located 700 m away. (Note: In a more recent demonstration the remote facility was located in downtown Washington, D.C., 30 km away, without any degradation in performance.) The video is fed to a workstation where it is viewed side-by-side with the AS representation (see Fig. 6).

TETRA, with its 6-DOF rigid platform, can be positioned with the six independent movements or via the overhead crane's bridge and trolley motions, so its absolute location cannot be determined from command signal information alone. At the beginning of each session, TETRA's initial physical position was calibrated to the same initial position in the AS world. Supplied with the relative movements and the initial position, the AS representation of the construction process, as shown in Fig. 8, was very close to the actual images taken through a camera. With this initial success, we are ready to move to the next phase of the project.

## FUTURE ENHANCEMENTS

TETRA is currently attached to a crane. It makes use of off-board power and hardwired communications, which limits mobility of the crane. Controlling the crane and TETRA's movement wirelessly will dramatically increase the versatility of the crane. To accomplish this task, we will install wireless Ethernet systems at the construction shack, on the crane, and on TETRA (using Smart Pods). Power to the crane computers and transmitters will be supplied by an on-board generator. A schematic diagram of this setup is shown in Fig. 9.

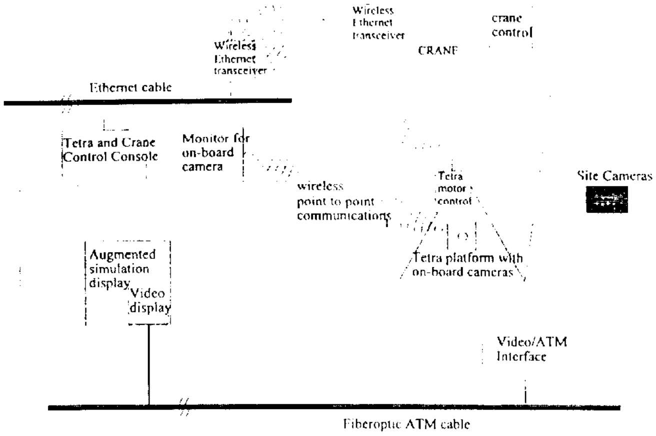

**FIG. 9. Schematic Representation of Future Enhancement of NCAT Control and Communications Scheme**

It is important to note that within the context of NCAT research, TETRA is simply the first piece of full-scale construction machinery. The principal objective of the research is to develop metrology, communications, and simulation protocols that will permit seamless tracking of each machine (as well as delivered components) as it moves about a construction site, and to make that data available to a global project database that is updated in real-time from the up-link data from the construction site. Key issues regarding TETRA that remain to be addressed include external tracking of the position and orientation of the machine, independent translation sensors (which are relative measurement systems), and the development of a real-time position and orientation calibration system to reaffirm the most recent position and orientation up-linked by the machine. These tasks require the development of networked, wirelessly linked metrology systems.

It is imperative that the wireless standard be developed to permit the metrology systems to "speak" a common language to the construction shack site-integration computer, because a mix of technologies will probably be used. To meet this objective, fanning laser technology and Smart Pods will be used to provide feedback signals to future Augmented Simulations at NCAT. A total station will also be set up to provide the measurement control arbiter for the relative position of the crane at the beginning of each experiment.

The latest version of WTK will be installed, and links to information relevant to each object will be established. The last step described allows us to view relevant information corresponding to the selected object, such as schedule of construction, purchase dates, etc., as can currently be done in many design systems. Other world-modeling software will also be integrated into the system so that the protocols developed will be platform independent.

## CONCLUSIONS

A virtual reality representation was developed of the construction site, equipment, and the steel frame being built at the NCAT laboratory at NIST. The construction process was simulated in the AS world in real time. A video capture of the actual construction process was acquired and compared with the AS representation in real-time. This comparison showed that the AS representation was able to model the construction process with a high level of fidelity.

The AS representation can be a valuable tool for remote construction management. Besides viewing the operations and the partially finished structure from a remote site, the construction manager is able to test a planned construction sequence. After further development, the construction manager will also be able to query information from the AS model directly. Information linked to the objects will include cross section type, beam length, purchase and delivery schedule, etc.

The remote management possibility may add a new dimension and improve the efficiency of construction management. In addition, being able to "view" the construction process remotely and with high fidelity opens the possibility of routine remote construction in hazardous environments, such as nuclear waste removal and low earth orbit construction.

## APPENDIX. REFERENCES

Bostelman, R., Jacoff, A., Dagalakis, N., and Albus, J. (1996). "RCS-based RoboCrane integration." *Proc., Int. Conf. on Intelligent Sys.*, Gaithersburg, Md.

Bostelman, R., Albus, J., Dagalakis, N., and Jacoff, A. (1996). "RoboCrane: An advanced concept for large scale manufacturing." *Proc., AUVS Int. Conf.*, Association for Unmanned Vehicle Systems, Orlando, Fla.

Fleischman, R., Viscomi, B.V., and Lu, L.-W. (1992). "Development, analysis and experimentation of ATLSS connections for automated construction," *Proc., 1st World Conf. on Steel Struct.*, Acapulco, Mexico.

Palmer, M. (1996). "The current ability of the architecture, engineering, and construction industry to exchange CAD data sets digitally." *NBSIR 86-3476*, National Bureau of Standards, Gaithersburg, Md.

Stone, W., and Pfeffer, L. (1998). "Automation infrastructure system for a robotic 30-ton bridge crane." *Proc., Robotics 98*, ASCE, Reston, Va., 195–201.