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Automation Infrastructure System for a Robotic 30-ton Bridge Crane

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Abstract

This paper describes the sensing portion of a system used to convert an existing 30-ton bridge crane to computer control for automated placement of construction components. The system is being designed to permit either telepresent or fully autonomous assembly of representative parts of buildings and industrial plants, e.g., girders, tanks, and pipes. In order to achieve six degree-of-freedom manipulation of the components, the traditional crane cable and hook have been replaced by TETRA, an inverted cable-operated Stewart platform equipped with various manipulators. The sensing systems are primarily displacement, force, and other state sensors. What makes this application unique is the scale of the robot: the crane's workspace is 40 m long, 23 m wide, and 24 m high -- a volume of more than 10,000 cubic meters. This scale, and the need to operate without wires has led to a control system based on wireless packet communication by intelligent modules known as "smart pods." The pods interface to one or several force, displacement, or state sensors. The pods broadcast their data via wireless ethernet to base stations which then communicate with the world via higher-speed networks. The present paper discusses issues relating to the architecture of the sensor array needed to operate this large construction robot and the communications infrastructure needed to supply that information to remote sites in real time.

Introduction

Even though the construction industry comprises a large portion of the U.S. GDP, its highly fragmented nature has prevented the full realization of the potential offered by advances in information technology. There exist no standards for communications by which dynamic project data (e.g. girder location, crane loads, fuel levels) can be shared and used by the various machines and processes on the construction site, nor is there, for example, industry-wide concensus relating to the information content of bar codes, smart chips, and RFID tags [1] that are increasingly being used to track material shipments to construction sites. The situation today is that "islands" of automation exist, but cannot communicate with each other. For example, penpad logging of production package progress is now being used on some construction sites. However, the data does not flow seamlessly through the construction site, and must be re-entered into every process that uses it. This procedure is slow, expensive and notoriously error prone.

The successful integration of construction site processes and machinery with real-time construction site metrology and information databases generated by architects, engineers, and suppliers will enable information to be used for automating processes and machines and for concurrent project planning. Without interface standards, communications protocols, and a common dynamic project data interchange format, efforts to integrate and automate new equipment and processes into existing operations and systems will continue to be inordinately time consuming and expensive.

Recent evaluations by top construction industry and design/construct company engineers [2] indicate that the most pressing problem confronting project management is knowing the status of the project -- where things are and what has been done -- in a timely and accurate fashion. More than managers are affected by this, however. Similar information (both in whole and in part) is needed by the jobsite superintendent, crew foremen, and workers.

A fundamental underpinning to success is real-time data flow (predominately metrology data) to and from a (remote) construction site and project management (design & architectural offices, fabrication plants, and material suppliers, etc.) in a standard format that can be made compatible with, or be accepted by, existing commercial software packages. The ultimate objective is to tie together information seamlessly among the various participants in the construction process. In this sense, it should be recognized that construction is a difficult manufacturing scenario: a relatively unstructured environment in which one-of-a-kind parts (plants, buildings, bridges, etc.) must be "manufactured." Because of the cluttered, unstructured, environment, and because of the size of the "manufacturing site" -- which may involve a city block, or a two kilometer stretch of highway -- data flow to and from the actual construction site must involve wireless telemetry, and typically involves a variety of communications media and relays. Therefore, open-architecture interface and data standards are crucial. It is toward the resolution of these problems that a significant research program has been initiated at the National Institute of Standards and Technology (NIST).

Technical Approach

A multi-disciplinary team has been formed within NIST, drawing expertise in the fields of CAD/CAE information systems and data exchange standards, real-time construction site metrology; wireless data telemetry; VR world modeling; and intelligent systems design from both the Building and Fire Research and Manufacturing Engineering laboratories. Strong industry participation is considered essential to the work and collaborators are being actively sought.

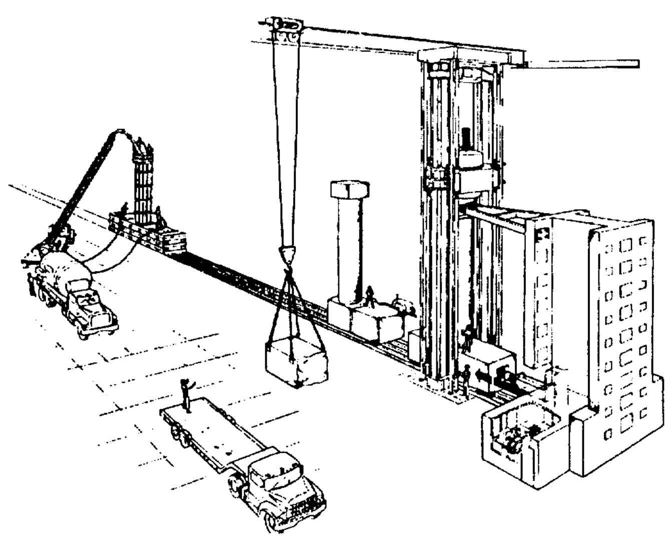

Figure 1: Existing large scale structural test facility at NIST, once used to subject full size highway structures to simulated earthquakes, is now being converted into the National Construction Automation Testbed. The overhead 30-ton bridge crane is one of several construction machines being instrumented and converted to computer control.

The National Construction Automation Testbed (NCAT) is being built at NIST for test and validation of proposed open architecture data exchange and protocol standards; real-time construction-site metrology techniques, including seamless handoff between metrology systems; and the development of standard component identification protocols for barcode, smart chip, and RFID tags. The facility (Figure 1) is networked to the National Automated Manufacturing Testbed (NAMT) [4] facility (also at NIST), and through the NAMT to industry partners, other government agencies, and university labs. The testbed will include:

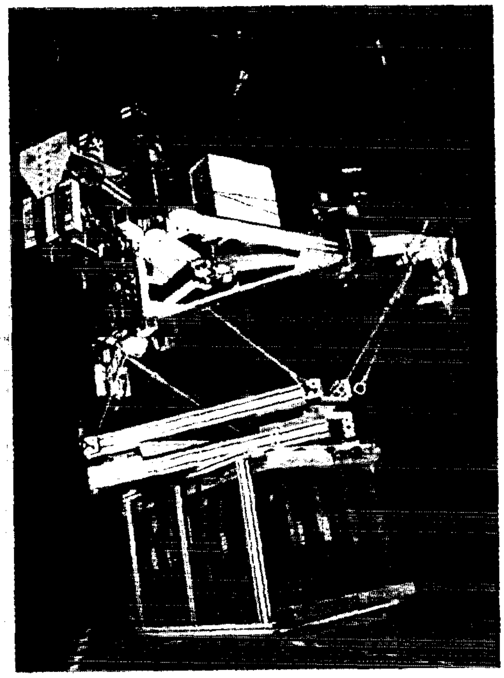

Figure 2: "TETRA" (Tetrahedral Robotic Actuator), an inverted stewart platform manipulator, has been integrated into the 30-ton NCAT bridge crane to provide structural stiffness and six degree-of-freedom control at the payload. It replaces the previous traditional crane hook. Six onboard cable hoists provide both translation and rotation independent of the bridge and trolley location for fine placement control.

1) a collection of advanced sensors, computers, data communications equipment and simulators which will permit testing and evaluation of data exchange standards and site metrology concepts both by NIST and industry.

2) Real-time site metrology systems that will permit experiments in "live" information transfer to the NAMT lab, that represents a remote "construction management" site.

3) A collection of construction machinery, which initially will include a special overhead bridge-crane system that can manipulate and place components in six degrees of freedom, a fork truck, and a semi-tractor trailer component delivery vehicle, all of which are being converted to operate under computer control with real-time metrology feedback to control position, orientation, and forces. This will permit analysis of accuracy, latency, and reliability of both data communications protocols and the real-time metrology system.

4) A local "construction shack" which contains local control computers, high speed fiber (ATM) communications net interfaces, teleoperation consoles, wireless data uplink capabilities, and metrology calibration equipment.

The "glue" which will bind these elements into a useful system will be the interface protocols and geometry representation standards which permit seamless exchange of information and knowledge across the various nodes of the system. The objective is to cleanly integrate the mechanisms, instruments, and software necessary to permit real-time data flow between a remote construction site and the management (design engineering and architectural offices, fabrication plants, and material suppliers) who provide knowledge and products to the construction process. Construction data (e.g. rigid body component location and orientation history, material properties, and other statistics) will be uplinked in real-time using a standard format (that is to be developed during the project) that can be made compatible with existing commercial software formats. More importantly, the project will permit the

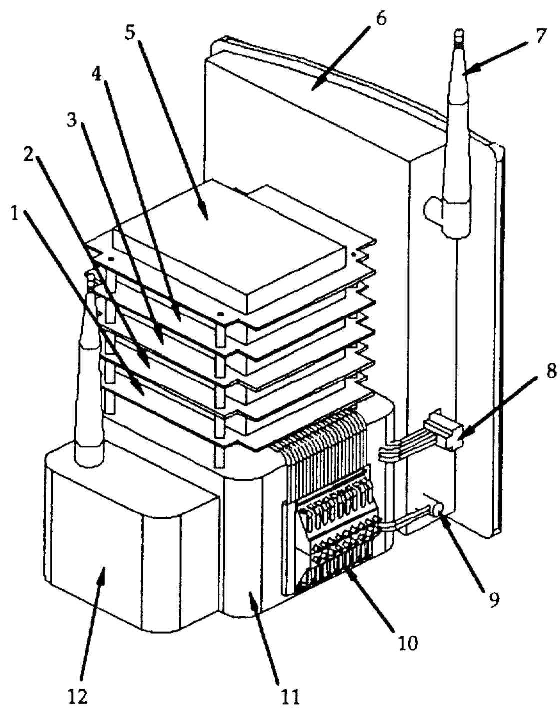

Figure 3: NIST "Smart Pod". 1: PC104 CPU; 2: PC104 Onboard Power Conditioner; 3: PC104 ADC; 4: PC104 flash memory card; 5: PC104 ethernet adapter; 6: Proxim WLAN; 7: WLAN antenna; 8: 10BASE-T ethernet adapter connection; 9: offboard power to WLAN; 10: 8-sensor terminal strip; 11: System Power Supply (battery); 12: RF-actuated switch (remote system power up).

return of "live" data to the "construction site" where advanced means for using it -- on-demand information retrieval fed through on site displays, allowing registered view component placement -- can be proven out and interfacing protocol standards developed. The specific tasks fall into three phases:

1) Develop a means to acquire real-time, position and orientation of discrete construction components (six degree-of-freedom transformations of rigid bodies such as wide flange sections, fixed pieces of equipment etc.) and to transmit (via wireless telemetry) information from the "construction site" concerning that object (position, orientation, time, date, and an estimate of the statistical accuracy of the data) to the construction shack at high data rates (approximately 155 Mbs). At present, there are four real-time metrology technologies that are slated for fusion in the testbed. These are RTK (phase differential, real-time kinematic) GPS; local pseudolites (a GPS derivitive technology involving low power ground reference sites); fanning laser systems; and Non-line-of-Sight (NLS) metrology systems being developed at NIST for tracking through solid walls [3]. The universal use of one or many of these types of systems at construction sites in the future depends on the development of standard interfaces to a global data manager. Ultimately, these information packets must include a measure of "freshness" and quality of the data, such that appropriate choices among various metrology systems can be made automatically.

2) Determine, through experimentation, where the "bottlenecks" are that limit the system throughput, and identify what standard protocols must be developed to track, and model each object at the "site"; to transmit (wirelessly) that data from the site to the nearest high data rate hardwired connection; and to make that information available, and compatible with, a "standard" dynamic project database residing on a remote computer. The "standard" links must be "open" and publicly available, yet allow for interfacing to off-shelf CAD and simulation software. Open communications protocols will be developed that permit data from the dynamic project database to be subscribed to by a wide range of remote computational hardware (e.g., at a remote management building).

3) Close the loop back to the "construction site" by developing a geometrically registered view display feedback system (possibly an HMD [helmet-mounted display]) which can project an image of the desired location of the component relative to the actual position of the real component and the parts around it. Develop protocols for user cues (what information is to be displayed to the user to aid in placing or moving a component) and wireless packet protocols for transmission of the necessary data.

Conversion of Existing Construction Machinery

An important issue in construction automation concerns the conversion of existing machinery for remote monitoring or control. In many cases, these machines may be physically large -- so large that it would be cumbersome or unreliable to retrofit the machine using fixed wiring leading from a central onboard data acquisition computer to remote sensors located on various moving parts of the machine. The 30-ton bridge crane in the NCAT is just such an example. The bridge longitudinal travel is 40 m and the lateral trolley travel is 23 m. with a working height of 24 m.

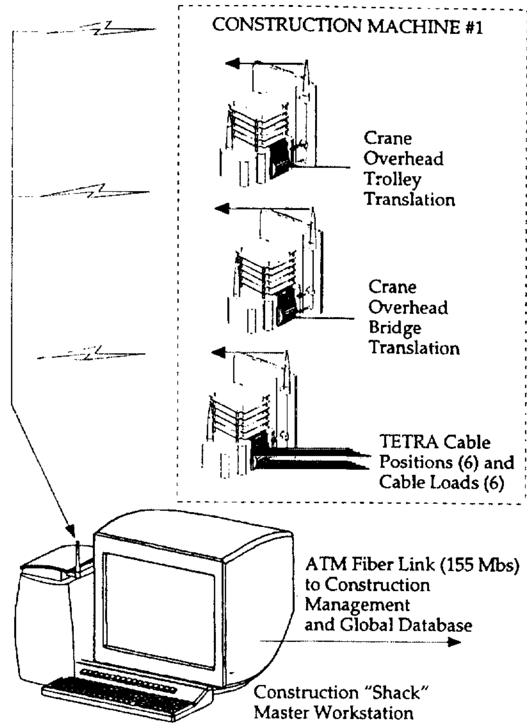

Figure 4: Wireless feedback system for the 30-ton bridge crane at NCAT. Thre NIST "Smart Pods" remotely monitor, respectively, trolley translation; bridge translation; and the six degrees of freedom of the TETRA manipulator (including load and torque feedback). Data is wirelessly linked to the master site intetration workstation and from there ported to the asynchronous transfer mode (ATM) 155 Mbs fiber link to the remote construction management "office" at the NAMT lab (physically 700 m from NCAT).

There is another problem that is particular to cranes: there is no rotational (orientation) control of the payload at the hook, and thus tag lines and construction workers are usually required for all placements. To solve this problem for NCAT a robotic manipulator, known as TETRA (Figure 2) was used to replace the crane cable and hook. TETRA is an inverted, cable suspended Stewart platform. A special triangular load frame was bolted to the trolley frame such that both move as a rigid unit. The TETRA actuator platform is suspended by means of six control cables, two from each corner of the upper and lower triangular load frames. The upper and lower frames are rotated 180-degrees (about a vertical axis) with respect to each other. TETRA [4] is locally powered and contains an onboard cable control system which permits a triangular shaped payload connector frame to be maneuvered in six degrees-of-freedom, independent of the bridge and trolley position. TETRA provides as feedback six cable extension lengths and six cable tensions. From these the system load, position, and attitude can be deduced through forward kinematics.

In all three cases (bridge, trolley, and TETRA actuators) it was unreasonable to consider hardwired sensors for the purposes of sensing the state of the machine. To circumvent this, a standardized "smart pod" was developed as shown in Figure 3. The intent was to design a standalone "blackbox" that could be bolted anywhere on any machine, be hooked up to a variety of local sensors, be powered up via a remote RF signal, to scan, convert, store, and ultimately transmit the sensed data to the "construction shack" master site-integration workstation (Figure 4). To reduce size and power requirements the smart pod was built up from a series of commercially available off-shelf industrial control components and wireless communications equipment. A PC104 bus was selected for its compactness and wide availability.

The main control stack includes a main CPU, power conditioning, analog-to-digital converter (ADC), memory card, and ethernet communications node. The latter is connected via 10BASE-T link to a Proxim* wireless LAN which broadcasts the data at 1.6 Mbs. In the current system 16 broadcast frequencies are available. While this works well for the current planned research at NCAT it presages the coming frequency allocation problem that will need to be addressed in real construction sites where hundreds of such data transmission pods will be in operation simultaneously. Local power for the system is provided by a battery, nominally capable of powering the system for 100 hours. In order to conserve power the system is remotely powered up and turned off using a standard commercial RF switch (similar versions are used for controlling model airplanes). The entire smart pod measures 220 mm high, 200 mm wide x 170 mm deep, about half the size of a shoe box.

In the NCAT the initial instrumentation scheme for converting the 30-ton bridge crane to automated state sensing involves three smart pods: one for bridge translation; one for trolley translation; and one for the six cable load cells and six rotary encoders which provide cable lengths, loads, and torques associated with the TETRA end effector. The bridge and trolley translations are sensed using large-length (40 m) wire-driven potentiometers.

The "smart pod" is a first attempt at developing what will ultimately need to be a plug-and-play industry standard sensing pod that will be an on-site utility in the future, much the same as pen pad computers are now seeing use at some construction sites. The relatively workable size of the Smart Pod will eventually be able to be replaced by a dedicated embedded system with all subsystems, including communications, reduced to the size of a coffee cup. Integration and interoperability, however, remain the primary design drivers.

The present operating system is VxWorks* (a POSIX-conformant O/S) with ControlShell* running on top as the real time sensory acquisition system and data manager. These sensor data are identified with a particular job site machine (in this case the bridge crane) and uplinked in real-time through the job site state integration workstation and then via wire/fiber networks to the NAMT lab. There, the current state of the vehicle can be realistically visualized by driving CAD models, displayed within the context of a virtual world modeler, with the live sensor data. Presently, machine models are being generated in both Pro/Engineer*, AutoCAD*, and SolidWorks*, and VR modeling is being first ported to WorldToolKit* (Sense8) with a secondary target being Envision* (Deneb). These various software systems are mentioned largely to indicate that off-shelf systems are being used to the greatest possible extent for the initial proof-of-concept of the NCAT. This first generation of integration has been extremely tedious and time consuming, with many intermediate code and data format conversions along the way. These point explicitly to the strong need for interface data standards at several critical points in the chain, most notably at the level where the data must be wirelessly transmitted between machines and the construction shack, and in the means by which those status packets are interpreted by various world modeling systems.

Conclusions

The National Construction Automation Testbed is presently under development at NIST. The NCAT represents a major cross-laboratory program in conjunction with industry partners. The overall objectives are to identify and develop data exchange standards and protocols to facilitate the acquisition and use of real-time information to increase the productivity and quality of construction. These data exchange standards and protocols will be developed and tested within the context of an advanced operating construction site.

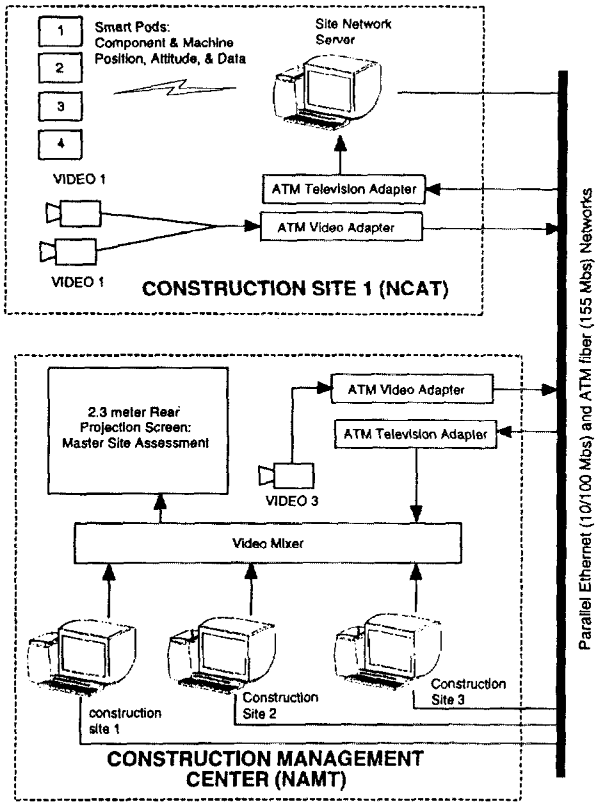

Figure 5: Schematic overview of NCAT construction site and its network connections to the NAMT lab, which is serving as the remote construction management center. Real-time metrology, machine state data, plus live video are piped from NCAT to the networks which connect both to the NAMT lab and to remote industry partners. Two-way live video and audio communications are available between all sites. Importantly, live data from the construction site, along with component identification information, allows for VR re-construction of the real-time "as built" state of the construction site. Construction management software will eventually be able to make use of the live data to permit time-line playbacks, in 3D simulation, of the status of any aspect of the on site work.

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