Towards an Intelligent Job Site: Status of the NIST Automated Steel Construction Test Bed [1]

by

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ABSTRACT: The NIST Construction Metrology and Automation Group, in cooperation with the NIST Intelligent Systems Division, is researching robotic structural steel placement through an ongoing program entitled "Performance of Innovative Technologies for Automated Steel Construction." This program, initiated in response to an American Institute of Steel Construction request for a 25 % reduction in time to erect steel structures, focuses on the development of an Automated Steel Construction Test Bed to research advanced concepts in crane automation, laser-based site metrology, laser radar (LADAR) imaging, construction component tracking, and web-enabled 3D-visualization. This test facility also provides a mechanism to investigate paths towards an Intelligent Job Site as described in the FIATECH Capital Projects Technology Roadmap.

KEYWORDS: construction automation, path planning, robotics, steel, VRML, 3-D coordinate measurement systems.

1. INTRODUCTION

FIATECH is a non-profit consortium of facility owners, operators, contractors, suppliers, government agencies, and government and academic research organizations dedicated to the development and deployment of technologies to improve the delivery process of capital projects. These targeted technological improvements span all phases of capital project delivery including design, engineering, construction, and maintenance [1]. The recently published FIATECH Capital Projects Technology Roadmap (CPTR) describes a vision of the future construction project. One element of the CPTR is the Intelligent Job Site (IJS), which is defined as follows:

> "Future job sites will be fully sensed and 'wired' to provide continuous awareness of the status of all resources and activities against the detailed construction execution plan defined in the master facility model. Personnel and intelligent equipment will have instant access to all information needed to accomplish their tasks, troubleshoot problems, and re-plan on the fly to accommodate changes. Resources will be finely

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[3] Certain commercial equipment, instruments, or materials are identified in this report in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

coordinated to deliver labor, materials, equipment, and tools to the site when needed, greatly reducing inventory and staging requirements. Site monitoring and control systems will continuously track progress and quality of work against the build plan, and assure the safety and security of the site and all of its workers and resources [2]."

NIST Construction Integration and Automation Technology (CONSIAT) researchers are working with FIATECH to define the various elements, functions, needed research, and development projects for the Intelligent Job Site.
In a related CONSIAT effort, the NIST Construction Metrology and Automation Group (CMAG), in cooperation with the NIST Intelligent Systems Division, is researching robotic structural steel placement through an ongoing program entitled "Performance of Innovative Technologies for Automated Steel Construction." This program, initiated in response to an American Institute of Steel Construction request for a 25 % reduction in time to erect steel structures, focuses on the development of an Automated Steel Construction Testbed (ASCT) to research advanced concepts in crane automation, laser-based site metrology, laser radar (LADAR) imaging, construction component tracking, and web-enabled 3D-visualization. This facility will be used for the testing and validation of advanced tools, methodologies, and standards for automated steel construction, and will provide a mechanism to investigate paths towards an Intelligent Job Site as described in the FIATECH Capital Projects Technology Roadmap.

This paper will discuss recent accomplishments, near-term development, and long-term research efforts associated with the ASCT.

2. SYSTEM OVERVIEW

The Automated Steel Construction Testbed has five primary functional elements. These include: (1) The NIST RoboCrane, (2) a Site Measurement System (SMS), (3) a High-level Controller, (4) a Component Tracking System, and (5) a three-dimensional (3D) Visualization system. The RoboCrane, the SMS, and the High-lever Controller are discussed in sections 2.1 through 2.3. The reader is referred to [3] for a discussion of the Component Tracking System and the 3D Visualization System.

2.1 NIST RoboCrane

A specialized six degree-of-freedom (DOF) crane invented by the NIST Intelligent Systems Division (ISD) is used as the base platform in the ASCT. The RoboCrane is an inverted Stewart platform [4] parallel-link manipulator with cables and winches serving as the links and actuators, respectively. The moveable platform, or "lower triangle," is kinematically constrained by maintaining tension in six cables that terminate in pairs at the vertices of an "upper triangle" formed by the cable support points [5]. The RoboCrane concept has been modified and adapted for numerous specialized applications [6, 7, 8]. The configuration used in this project is the Tetrahedral Robotic Apparatus (TETRA). In the TETRA configuration, all winches, amplifiers, and motor controllers are located on the lower triangle in Figure 1. This arrangement provides greater flexibility in adapting the platform to existing overhead lift mechanisms. Figure 1 depicts the RoboCrane upper and lower triangle arrangements. The prism planes formed by the dotted lines show the crane's generalized work volume.

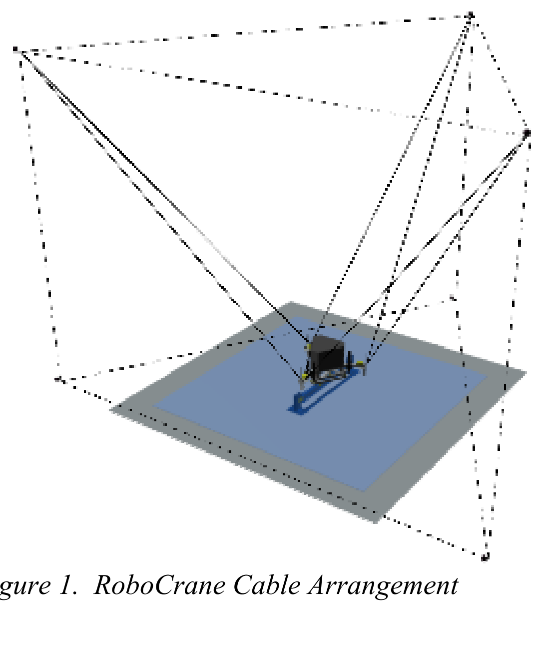

Figure 1. RoboCrane Cable Arrangement

2.2 Site Measurement System (SMS)

A commercially available Site Measurement System (SMS) is used to track the position and orientation (pose) of both RoboCrane and objects within the work volume. The system employs stationary, active-beacon laser transmitters and mobile receivers to provide millimeter-level position data at a nominal 10 Hz update rate.
Line-of-sight (LOS) must be maintained to at least two transmitters to calculate position.

Four laser transmitters are placed around the perimeter of the ASCT to ensure the receivers maintain LOS to at least two and preferably three transmitters.

Three SMS single-detector optical receivers are mounted on RoboCrane at the vertices of the lower triangle. This arrangement is illustrated in Figure 2, which also shows an enlarged view of one of the receivers. Position measurements from each receiver are wirelessly transmitted to a position server, which provides RoboCrane pose information to the high-level controller. Figure 3 depicts RoboCrane docking using SMS-derived pose information.

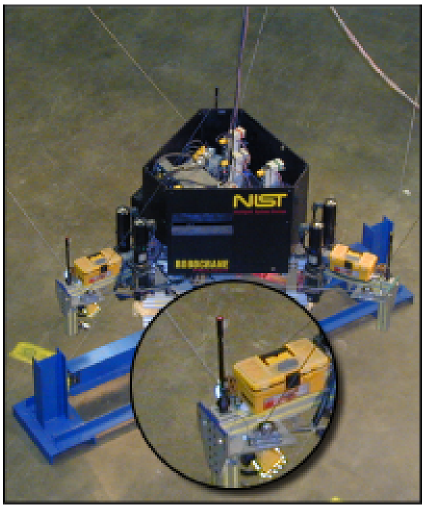

Figure 2. RoboCrane with SMS Receivers

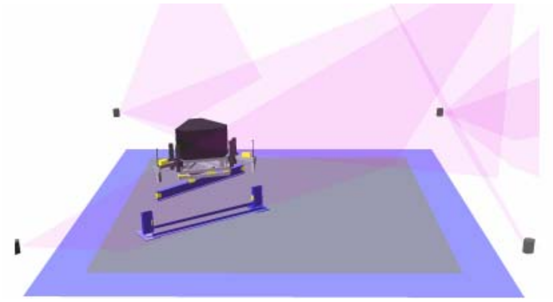

Figure 3. RoboCrane Docking

A digitizing tool consisting of two optical receivers mounted on a rigid pole provides the capability to measure discrete points within the work volume. This tool is shown in Figure 4.

Mapping between the SMS coordinate frame and the site coordinate frame is accomplished by measuring control points with the digitizing tool. Since the vertices, or "anchors", of the RoboCrane upper triangle are known within the site coordinate frame this yields:

$$ {}^{Anchor}_{SMS}\mathrm{T} = {}^{Anchor}_{Site}\mathrm{T} \times {}^{Site}_{SMS}\mathrm{T} \, , $$

where

$$ {}^{Anchor}_{SMS}\mathrm{T} $$

represents the homogeneous transformation matrix between the Anchor and SMS coordinate frames.

Similarly, the location of the RoboCrane work platform within the SMS coordinate frame is given by:

$$ {}^{SMS}_{RoboCrane}\mathrm{T} = {}^{SMS}_{Detector}\mathrm{T} \times {}^{Detector}_{RoboCrane}\mathrm{T} $$

where

$$ {}^{Detector}_{RoboCrane}\mathrm{T} $$

is known based on the initial calibration of the three receiver locations on RoboCrane. This yields the pose of RoboCrane within the Anchor frame by:

$$ {}^{Anchor}_{RoboCrane}\mathrm{T} = {}^{Anchor}_{SMS}\mathrm{T} \times {}^{SMS}_{RoboCrane}\mathrm{T} $$

This calculation enables a direct comparison and correction of the RoboCrane work platform pose calculated from cable-length encoders to the pose measured by the SMS.

Figure 4. Operator with the SMS Digitizing Tool

2.3 High-level Controller

The NIST RoboCrane was initially designed to function in a teleoperated mode, with user commands from a 3D joystick providing input for proportional velocity control. In strictly teleoperated mode, the pose of RoboCrane is calculated based on cable lengths set and then updated through winch encoders. Knowledge of RoboCrane's pose within the work volume is necessary for safety concerns such as keeping the robot within its designed work envelope. The initial cable lengths are hard-coded into the software and an encoder value to cable length mapping takes place during an initial homing procedure.

In order to provide autonomous control of RoboCrane without significant modification of the original controller, a high-level controller was developed to replace the human joystick operator. This additional controller provides numerous functions including goal state management, world model maintenance, and path planning. A functional block diagram showing the relationship between the two controllers is shown in Figure 5.

The high-level controller receives encoder data from the RoboCrane controller and compares them with data from the SMS. The high-level controller then sends back velocity commands that move RoboCrane. The RoboCrane controller, a version of the NIST Real-time Control System (RCS) implemented in the early 1990's, converts these velocity commands to winch controller inputs that effect the desired movement. Closed-loop position feedback from the SMS-calculated pose enables periodic modification of the path until the desired RoboCrane pose is reached. Currently this adjustment is made by simply subtracting the calculated drift from the encoder-based pose. Though this technique is effective, it does not provide a real-time method of pose estimation during movement. A more robust pose estimator which filters both sources of pose information is under development.

3. RECENT RESULTS

Currently, we are able to achieve autonomous placement of a steel beam into a randomly placed target structure using RoboCrane, the SMS described above, and a rudimentary path planner. In recent experiments at NIST, RoboCrane was able to autonomously place a beam in a specially designed holder, albeit at a relatively slow speed not yet suitable for construction purposes. A brief description of the placement process follows.

Once the SMS has been set up and calibrated, the target beam holder is randomly placed within the RoboCrane work-volume. Using the SMS digitizing tool, the holder's pose is measured and entered into the high-level controller. The high-level controller requests RoboCrane's pose from the position server and calculates the required velocity commands that will move the robot to place the beam in the holder (the beam is currently fixed in the robot's grippers). At each waypoint, the robot stops and a new estimate of its pose is requested from the position server by the high-level controller. This process is automatically repeated until the beam is docked.

4. FUTURE WORK

Although this work will demonstrate the ability to perform autonomous steel beam pick and place, it will do so in a fairly structured environment that remains static after initial measurement. The measurement process itself, although simple, still requires a human operator within the site to provide the initial digital model. There are currently no sensors, external or on-board RoboCrane, which would enable any reaction to dynamic changes within the work site without human intervention.

CMAG is currently researching automatic scene meshing and object recognition using high-resolution LADAR (laser detection and ranging) systems. In future work, LADAR and/or standard optical imaging systems will be used to develop and maintain the world model as well as provide obstacle avoidance and docking support. The use of the SMS technology to provide autonomous control of cable suspended robots will also be studied for other applications such as aircraft maintenance and shipbuilding. As additional sensing systems are employed, the SMS technology will also be used to study the performance metrics of other tracking technologies. The ASCT treats sensor input in a modular fashion; thus, future versions could use other positioning technologies such as phase differential GPS in certain applications to replace the present laser-based SMS.

5. CONCLUSIONS

In response to industry demand for improved steel erection, NIST is developing an Automated Steel Construction Testbed to research advanced concepts in crane automation, laser-based site metrology, laser radar (LADAR) imaging, construction component tracking, and web-enabled 3D-visualization. The current system uses RoboCrane, a robotic crane that has been in development at NIST since the late 1980's, as its base platform. The autonomous system also incorporates a commercially available, laser-base site measurement system and a preliminary version of a newly developed, high-level controller that is software-based. Using these technologies we have been able to autonomously place a steel beam inside a specially designed holder. Development of the NIST Automated Steel Construction Testbed is ongoing and future work will incorporate new sensing technologies as well as more sophisticated path planning and sensor fusion techniques. We are also working on significantly increasing the system's pick-and-place rate in an effort to meet or surpass current steel construction practices.

6. REFERENCES

1. Fully Integrated and Automated TECHnology (FIATECH), www.fiatech.org.
2. "Capital Projects Technology Roadmapping Initiative," FIATECH, 2003, www.fiatech.org/projects/cptri.htm.
3. Lytle, A., Saidi, K., and Stone, W., "Development of a Robotic Structural Steel Placement System," 19th International Symposium on Automation and Robotics in Construction (ISARC), September 23-25, 2002, Gaithersburg, Maryland, pp.263-268.
4. Stewart, D., "A Platform with Six Degrees of Freedom," Proc. of the Inst. of Mechanical Engineering, Volume 180(15), Part I:371-386, 1965-1966.
5. Albus, J. S., Bostelman, R. V., Dagalakis, N. G., "The NIST ROBOCRANE, A Robot Crane", Journal of Robotic Systems, July 1992.
6. Bostelman, R., Albus, J., Dagalakis, N., Jacoff, A., "RoboCrane Project: An Advanced Concept for Large Scale Manufacturing," *Proc, Association for Unmanned Vehicles Systems International*, Orlando, FL, July 1996.
7. Bostelman, R. , Albus, J., Stone, W., "Toward Next-Generation Construction Machines." *Proc. Of American Nuclear Society 9th International Topical Meeting on Robotics and Remote Systems*, Seattle, WA, March 4-8, 2001.
8. Bostelman, R., Shackleford W., Proctor, F., Albus, J., and Lytle, A. [2002], The Flying Carpet: A Tool to Improve Ship Repair Efficiency, *Proceedings of the American Society of Naval Engineers Symposium on Manufacturing Technology for Ship Construction and Repair*, September 10-12, 2002, Bremerton, WA.

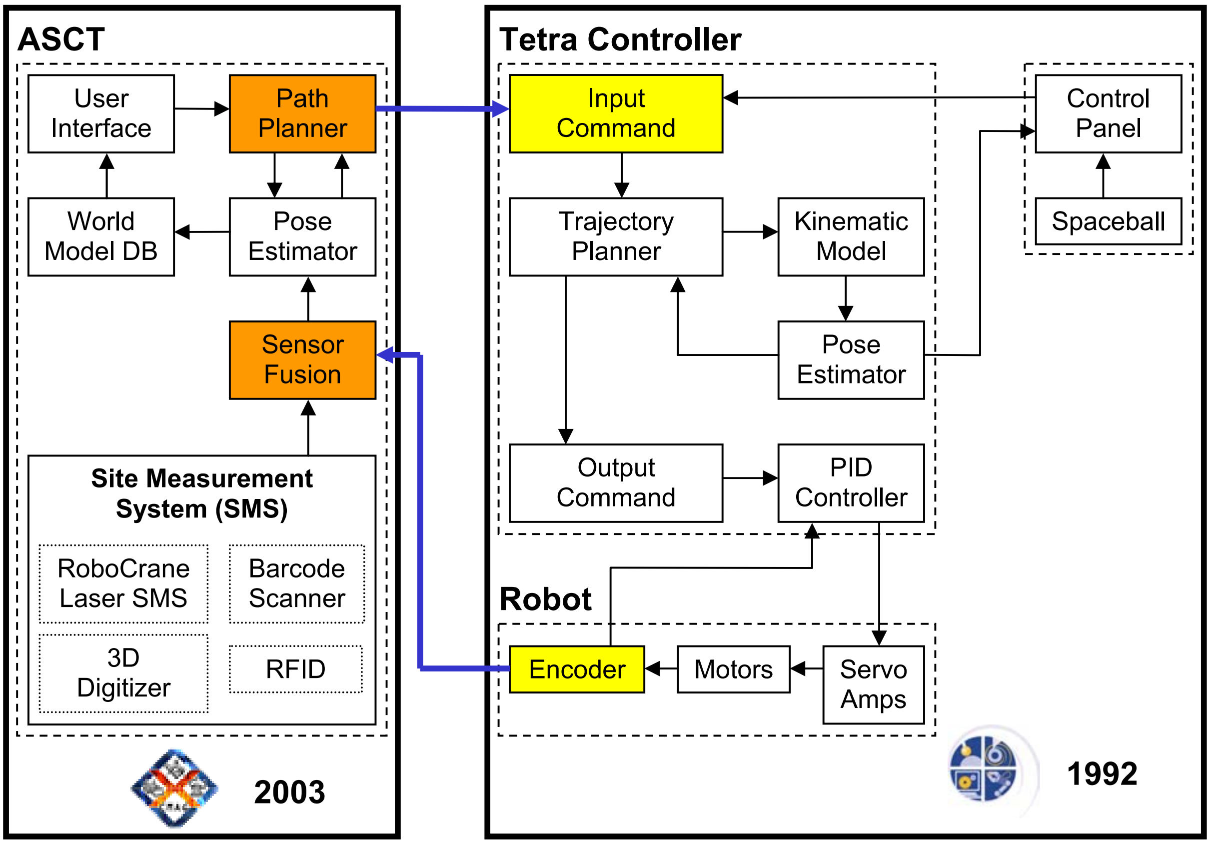

Figure 5. High-Level Controller Functional Block Diagram