Development of a Robotic Structural Steel Placement System [1]

by

Alan M. Lytle[2], Kamel S. Saidi[2], and William C. Stone[2]

ABSTRACT: The NIST Construction Metrology and Automation Group, in cooperation with the NIST Intelligent Systems Division, is researching robotic structural steel placement as part of a project to develop an Automated Steel Construction Testbed. This project was initiated in response to industry requests for advanced tools and methodologies to speed the erection of steel structures while maintaining or enhancing standards for worker safety and facility reliability. This initial effort integrates and extends prior NIST research in robotic crane employment, tele-operated steel beam placement, laser-based site metrology, construction component tracking, and web-enabled 3-D visualization.

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

1.0 INTRODUCTION

The American Institute of Steel Construction has expressed a need for a 25 % reduction in time to erect steel structures. In response to this request, the NIST Construction Metrology and Automation Group (CMAG) is developing a robotic structural steel placement system for the testing and validation of advanced tools, methodologies, and standards for automated steel construction. This effort, the first phase of CMAG's Automated Steel Construction Testbed (ASCT) project, extends prior NIST research in construction component tracking [1] and real-time construction metrology [2]. The work also extends prior efforts in tele-operated steel beam placement [3] to include autonomous control of a six degree-of-freedom (DOF) robotic crane.

The base platform is the NIST RoboCrane, which is an inverted Stewart platform parallel link manipulator [4]. RoboCrane's Real-Time Control System (RCS) is augmented with absolute cartesian position feedback from a laser-based site measurement system (SMS) for trajectory planning and dynamic control. Robot and construction component position data is displayed in a virtual world model of the steel placement operation for supervisory review and control.

The steel structure to be assembled consists of a beam and two columns connected with the ATLSS[3] quick connector. The ATLSS, developed at Lehigh University [5], was chosen because it requires no bolting or welding.

This paper will discuss the concept, current development and future implementation of the robotic structural steel placement system.

2.0 OPERATIONAL CONCEPT

Four laser transmitters are positioned on the site perimeter to illuminate the work volume of RoboCrane with reference beams (Figure 1). A field worker using the SMS digitizing wand then creates a digital model of the construction plane including any obstacles.

---

[2] NIST, BFRL, Construction Metrology and Automation Group, Mail Stop 8611, Gaithersburg, MD 20899-8611; alan.lytle@nist.gov, kamel.saidi@nist.gov, william.stone@nist.gov.

[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.

This world model is then updated with the positions of the as-built structure and the target beam by the field worker through a process of automatic part identification (barcode), part model database access, and part fiducial point measurement (Figure 2). The current pose of RoboCrane is measured from onboard SMS sensors, and the path planner calculates the required transformations for beam pickup and delivery. RoboCrane then executes the movements (Figure 3). The world model, including dynamic tracking of RoboCrane, is displayed to an operator through a visualization system based on the Virtual Reality Modeling Language (VRML).

3.0 SYSTEM OVERVIEW

The current configuration of the Automated Steel Construction Testbed has five primary components. These include:

- RoboCrane
- Site Measurement System
- Component Tracking System
- High-level ASCT Controller
- Visualization System

2.1 RoboCrane

RoboCrane is an innovative, cable-driven, manipulator invented by the NIST Intelligent Systems Division (ISD) and further developed and adapted for specialized applications over a period of several years [6,7,8]. The basic RoboCrane is an inverted Stewart platform 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 all six cables that terminate in pairs at the vertices of an "upper triangle" formed by the cable support points. This arrangement provides improved load stability over traditional lift systems and enables 6 DOF payload control.

The version of RoboCrane used in this project is the Tetrahedral Robotic Apparatus (TETRA). In the TETRA configuration, all winches, amplifiers, and motor controllers are located on the moveable platform. The upper triangle only provides the three tie points for the TETRA cables, allowing the device to be retrofitted to existing overhead lift mechanisms.

2.2 Site Measurement System

The SMS uses commercially available positioning technology (*3D-I*) produced by Arc Second, Inc. in the *Constellation* and *Vulcan* product families[3]. (*3D-I*, *Constellation* and *Vulcan* are registered trademarks of Arc Second, Inc.) These systems use stationary, active-beacon laser transmitters and mobile receivers to provide millimeter-level position data.

2.2.1 SMS Description

Both *Constellation* and *Vulcan* systems use eye-safe laser transmitters to triangulate the position of a tuned optical detector. Each transmitter emits two rotating, fanned laser beams and a timing pulse. Elevation is calculated from the time difference between fan strikes. Azimuth is referenced from the timing pulse. The field of view of each transmitter is approximately 290° in azimuth and +/- 30° in elevation/declination. The recommended minimum and maximum operating ranges from each transmitter are 5 m and 50 m, respectively.

Line-of-sight to at least two transmitters must be maintained to calculate position. The *Constellation* receivers each track up to four transmitters and wirelessly transmit timing information to a base computer for position calculation. The *Vulcan* system is a self-contained digitizing tool with two optical receivers on a rigid pole. A vector projection along the line formed by the two optical detectors allows 3-D measurement of the tool tip. *Vulcan* can track only two transmitters at one time; however, the transmitter selection can be manually switched between any of the four available. Recovery of positional data following momentary signal blockage takes approximately one second.

2.2.2 Prior *3D-I* / Mobile Robot Integration

Early efforts to use *3D-I* laser technology for mobile robot navigation showed that although the system was capable of guiding a mobile robot [9], its use was restricted due to loss of track at relatively low vehicle speeds [10]. Upgrades to the positioning technology continued and a successful combination of indoor 2-D map creation and autonomous navigation was demonstrated in a research project at the Rochester Institute of Technology [11]. Subsequently, a single receiver *Constellation* system was installed on an autonomous lawn mower at the Carnegie Mellon University Field Robotics Center and provided positional reference in a large outdoor setting [12].

2.2.3 The SMS on RoboCrane

Three SMS receivers are mounted on RoboCrane at the vertices of the lower triangle (see Figure 4). The receiver locations are registered to the manipulator during the initial setup process in the local SMS coordinate frame. For convenience, all measurements are calculated in the local SMS coordinate frame, though if required, mapping to an existing world coordinate frame could be accomplished. Receiver timing signals and diagnostic data are wirelessly transmitted to a base station computer running Arc Second's proprietary position calculation software. Position and SMS diagnostic information are polled at approximately 7 Hz using a NIST-developed data communications application. Position data from the three receivers is used to calculate RoboCrane's pose (position and orientation). Diagnostic data such as number of visible transmitters, excess signal noise or multipath reflections is also provided for each position calculation and is used to assess the quality of individual position fixes.

2.3 Component Tracking System

The NIST Construction Metrology and Automation Group has conducted research in construction component tracking for several years. NIST developed the "Comp-TRAK" system, which combines field-wearable computing, automatic identification (barcode and RFID), laser metrology, wireless database access, and VRML-based 3-D model visualization to enable tracking of discreet components on a construction site. The feasibility of such a system was shown during a study tracking delivery and final placement of structural steel members on a NIST construction project [13]. During this study, the Comp-TRAK system was successfully used to identify components, remotely access component library data, guide the field user in measuring current part location, and remotely update a project management database with part data including location within the site coordinate frame.

Elements of Comp-TRAK will be used in the robotic structural steel placement system to locate randomly-placed target components and update the world model through the following sequence:

(a) The field user identifies the component.
(b) The component library is accessed and a model is displayed with specified measurement points (fiducial points).
(c) The field user measures observable fiducial points with the SMS digitizing wand.
(d) The component position and orientation is calculated and transferred to the world model.

2.4 High-level ASCT Controller

A high-level ASCT controller will provide the following task and data management functions for the overall system:

- Goal state management
- World model maintenance
- Navigation
- RoboCrane controller interface

The master goal of "pick and place steel beam" is divided into various sub-goals by the ASCT controller. These sub-goals define various states RoboCrane must achieve to execute the overall task. Examples include (1) maneuver to proper gripper orientation, (2) lower gripper onto beam, (3) grasp beam, (4) maneuver to pre-dock position, and (5) dock beam.

The existence and locations of components of interest are maintained in the ASCT world model. Data to update the world model are provided

either by the component tracking system or by tracking RoboCrane's pose when the crane is carrying an object.

RoboCrane's pose within this world model will be estimated through Kalman filtering of both the SMS position fixes and the RCS position estimates derived from winch encoder feedback. Based on world model component locations, RoboCrane's pose, and volume operating limits, a series of waypoints will be calculated for each goal state. The required platform transformations for the state changes and corresponding cartesian velocity commands (Translation: x, y, z; Rotation: roll, pitch, yaw) are calculated and sent to the RoboCrane controller via a communications interface. The RoboCrane controller, a version of the NIST Real-time Control System implemented by ATR (Advanced Technology & Research Corporation)[3], then converts the cartesian velocity commands to winch controller input to execute the desired movement. Closed-loop position feedback from the SMS position fix enables periodic modification of the path by the ASCT controller until the desired goal state is reached.

2.5 Visualization System

A VRML-based 3-D visualization system will also be used to provide remote visual feedback to an operator or supervisor. Elements of the world model – the construction plane, RoboCrane, and the target components – will be modeled in VRML 97 [14] and displayed within a browser environment giving an observer 3-D "fly-through" review capability. A socket connection between the ASCT controller and the VRML environment will provide pose updates for RoboCrane, components being moved, and other elements of interest. The VRML object models within the visualization system will then be repositioned by a Java applet using the External Authoring Interface browser extension. This provides a non-proprietary, open standard, low-bandwidth method of displaying a 3-D representation of robot operations within the work site.

3.0 CONCLUSIONS

This project will demonstrate autonomous steel structure assembly (pick and place) using a robotic crane and a laser-based SMS. A digital model of the work site is created with the SMS and then the same measurement system is used for closed loop feedback to precisely control the pose of the steel components during assembly.

4.0 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.

5.0 REFERENCES

1. Furlani, K. M. and Pfeffer, L. E., "Automated Tracking of Structural Steel Members at the Construction Site." *Proc., 17th International Symposium of Automation and Robotics in Construction*, Taipei, Taiwan, Sept. 18-20, 2000.
2. Stone, W. C, Pfeffer, L. E. and Furlani, K. M., "Automated Part Tracking on the

Construction Job Site." *Proc., 4th ASCE Specialty Conference and Exposition/ Demonstration on Robotics for Challenging Situations and Environments*, pp. 96-103, Albuquerque, New Mexico, Feb. 27 – Mar. 2, 2000.

3. Stone, W. C., Reed, K. A., Chang P. C., Pfeffer, L. E. and Jacoff, A. S., "NIST Research Toward Construction Site Integration and Automation." Journal of Aerospace Engineering, Apr. 1999, pp. 50-57.
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. Fleischman, R., Viscomi, B.V., and Lu, L.-W., "Development, analysis and experimentation of ATLSS connections for automated construction." *Proc., 1st World Conf. On Steel Struct*., Acapulco, Mexico, 1992.
6. Albus, J. S., Bostelman, R. V., Dagalakis, N. G., "The NIST ROBOCRANE, A Robot Crane", Journal of Robotic Systems, July 1992.
7. 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.
8. 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.
9. Beliveau, Y. J., Fithian, J. E., and Deisenroth, M. P., "Autonomous Vehicle Navigation with Real-Time 3-D Laser Based Positioning for Construction." Automation in Construction, (5) 1996.
10. Lytle, A. M., "Development of a Remotely Piloted Vehicle (RPV) with Real-Time Position Measurement (RtPM) for Hazardous Waste Site Characterization." Master's Thesis, Virginia Tech, Blacksburg, VA, 1994.
11. Rochester Institute of Technology, Society of Manufacturing Engineers (Student Chapter 18), Robot Construction Project, 2001. www.rit.edu/~smewww/project/rc/rc.html
12. Batavia P. H., Roth S. A., Singh S., "Autonomous Coverage Operations In Semi-Structured Outdoor Environments." *Proc., IROS*, Lausanne, Oct. 2002.
13. Furlani, K. M., Latimer, D. T., Gilsinn, D. and Lytle, A. M., "Prototype Implementation of an Automated Structural Steel Tracking System." *Proc., 19th International Symposium on Automation and Robotics in Construction*, Gaithersburg, MD, Sept. 23-25, 2002.
14. ISO/IEC 1477-1, "The Virtual Reality Modeling Language (VRML)." 1997, www.web3d.org

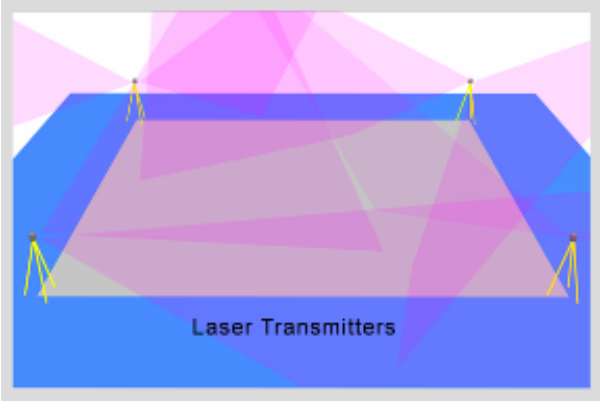

Figure 1: Graphic denoting the illumination of the work site with the SMS.

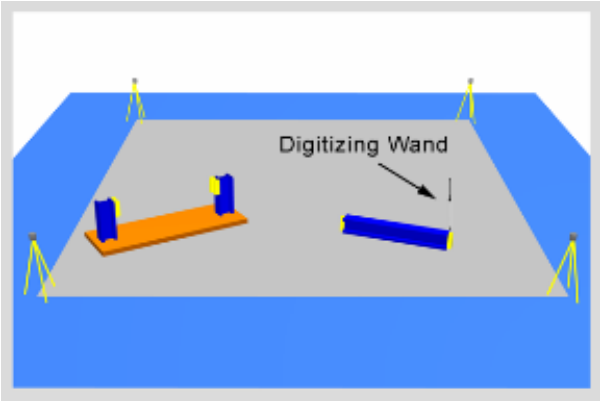

Figure 2: Graphic denoting measurement of component locations with the SMS digitizing wand.

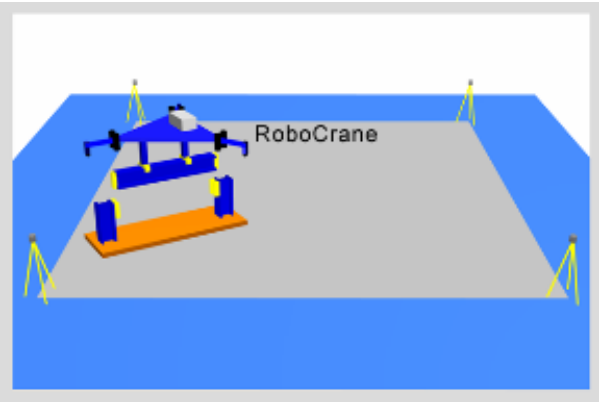

Figure 3: Graphic denoting steel beam placement with RoboCrane.

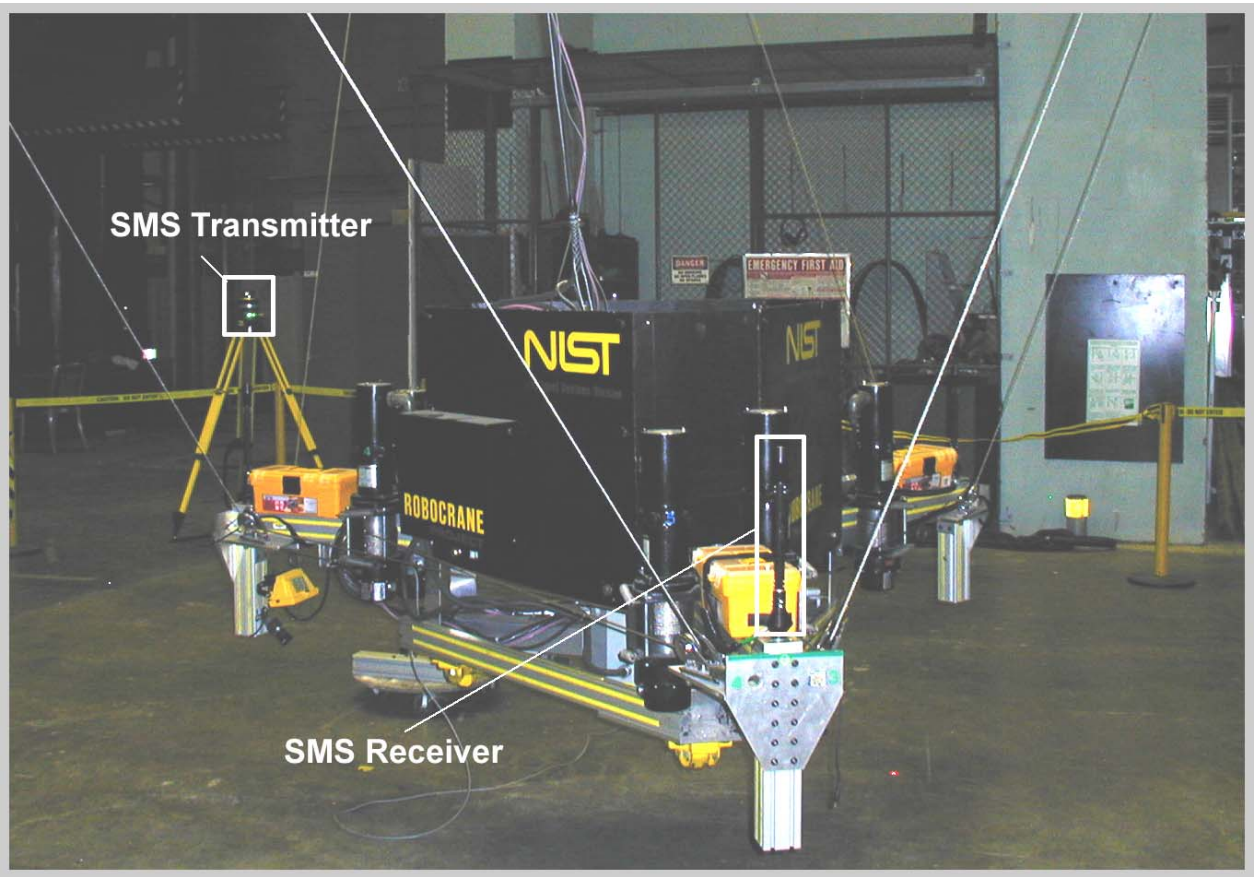

Figure 4: Photograph of RoboCrane with the SMS.