DEVELOPMENTS WITH THE NIST AUTOMATED CONSTRUCTION TESTBED

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Abstract: The NIST Construction Metrology and Automation Group is researching structural steel pick-and-place operations using a robotic crane coupled with sensor data distribution and construction component identification and tracking systems. This paper outlines new developments in this research including the addition of an automated gripper mechanism for RoboCrane and 4D-CAD sequenced multi-component placement. In addition, initial efforts to incorporate high-resolution scanning LADAR (Laser Detection and Ranging) data for world modeling and high frame-rate flash LADAR data for obstacle avoidance are discussed.

Keywords: construction automation, laser tracking, LADAR imaging, robotic crane

1. INTRODUCTION

The NIST Construction Metrology and Automation Group (CMAG) is conducting ongoing research to provide standards, methodologies, and performance metrics that will assist the development of advanced systems to automate construction tasks. Initial efforts in this research project have focused on autonomous large-scale pick-and-place operations using the assembly of structural steel as a test operation. Earlier work involved the integration of a laser-based site measurement system (SMS) with the NIST RoboCrane (TETRA Configuration) for autonomous 6 DOF control and docking of an I-beam payload using ATLSS connectors [1],[2]. Recent developments in this effort include design and construction of a mechanism for grasping I-beams, hardware and software upgrades for providing laser-tracking data, and the scripting of event tasks from a commercial-off-the-shelf (COTS) 4D-CAD package.

This paper describes the above recent developments and provides information regarding future research efforts to incorporate high-resolution LADAR systems for pose determination of target objects, and low-resolution, high frame-rate LADAR systems for obstacle avoidance and docking guidance.

2. RECENT EFFORTS

It is envisioned that a supervisor manning the Automated Construction Testbed (ACT) control station should be able to review a planned build sequence based on model data, and then command the robotic crane to execute the simulated sequence. In order to realize that scenario several items had to be developed. These included an automated gripper mechanism, a new Position Server middleware application to interface between the SMS and the RoboCrane controller, and a 4D-CAD front-end to provide a simulated assembly sequence.

2.1 The Automated Gripper Mechanism

The task of automating the steel beam pick-and-place operation required a mechanism to automatically grasp the target I-beam. The development of an automated gripper mechanism (AGM) is presented in this section.

2.1.1 AGM Design Goals

Two goals were considered during the design phase of the AGM. The primary goal was to provide a means to couple, manipulate, and release structural steel beams reliably and safely. The secondary goal was to enable controlled rotation of the beam ± 90º in yaw with ± 1º of resolution.

2.1.2 AGM Design Requirements

Seventeen functional requirements guided the AGM conceptual design phase. These requirements are outlined in the list below:

- Grip small structural I-beams of standard sizes between 12.7 cm (5”) and 20.3 cm (8”) wide.
- Lift beams with a weight of up to 453.6 kg (1,000 lbs).
- Secure the beam through roll and pitch angles of ±15º.
- Use the electrical power available on RoboCrane (480 VAC, 110 VAC and various VDC sources).
- Easily attach and detach from RoboCrane.
- Provide feedback to the controller that the beam has been gripped and secured.
- Keep beam secure if a power failure occurs while RoboCrane is in operation.
- Fit within the RoboCrane platform's footprint.

- Not to exceed 0.5 m in height.
- Service life of 2 years with light duty use indoors.
- Provide beam position resolution of 1 mm in RoboCrane's x, y, and z axes.
- Provide beam angular resolution of 1º in RoboCrane's roll, pitch, and yaw axes.
- Require a minimal number of mechanical and electrical parts.
- Must not weigh more than 45.4 kg (100 lbs) total.
- Grip and release the beam in 10 seconds or less.
- Be scaleable to handle 4,535.9 kg (10,000 lbs) beams.
- Principally use off-the-shelf parts wherever possible.

2.1.3 AGM Design

The AGM underwent a rigorous design process during which several alternatives were considered and rated based on the above requirements. The design that was selected (see Figure 1) consists of two manufacturing vises spaced 0.41 meters (16 inches) apart (along an I-beam's longitudinal axis) that are chain driven by a single motor. The entire assembly is attached to an aluminum frame, which is suspended from RoboCrane by 6 steel cables in order to provide vertical compliance (see Figure 2). Due to time and resource limitations the secondary goal of enabling controlled rotation of the beam was not pursued, but was assigned as a future-work task. This meant that beam rotation with the current AGM would be limited to RoboCrane's own yaw limits of ±30º.

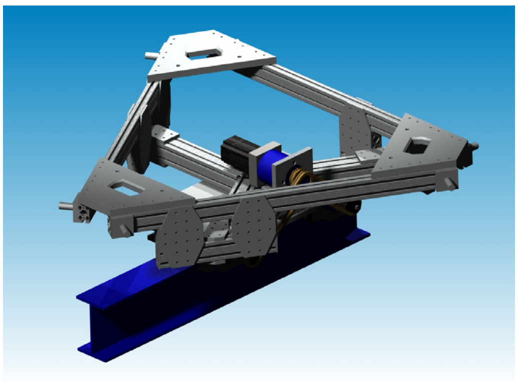

Figure 1: Rendering of Suspended Gripper Mechanism

Although the AGM was designed to be mounted either directly to RoboCrane or via the 6 adjustable-length, steel cables, attaching the AGM directly to RoboCrane does not provide any measure of safety when the robot is docking with a beam or a beam holder. If due to any number of possible positioning errors, the position of the robot ends up slightly lower or laterally offset than the commanded position when gripping a beam, the entire weight of the robot could end up resting on the beam or on parts of the gripper mechanism. This could damage the AGM, the robot, or the beam itself. Thus, the 6 steel cables were added as a means to provide a certain measure of mechanical compliance to the AGM when docking with a beam or when docking the beam with a holder. This way if the actual and commanded position of the robot differ, only the weight of the AGM will have to be carried by the beam or any of the AGM's exposed components.

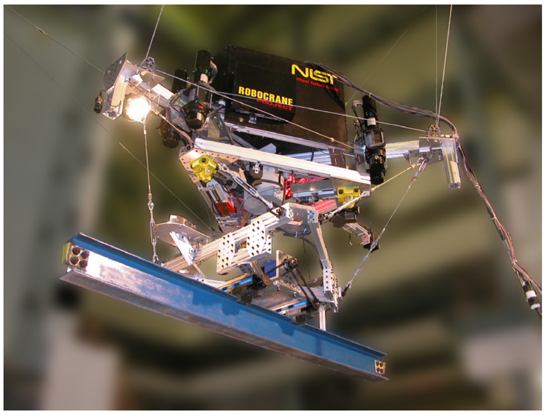

Figure 2: RoboCrane (Tetra Conf.) with Suspended AGM and I-Beam Payload

Figure 3 shows the two modified manufacturing vices mounted inverted to the AGM and coupled to the motor/gear reducer through the dual chain drive system.

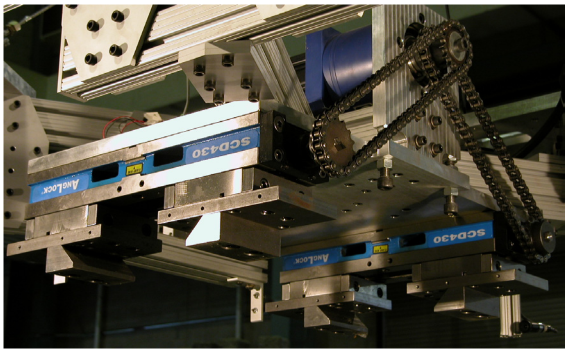

Figure 3: AGM Vice Mount and Dual Chain Drive System

Control of the AGM was achieved through software developed in the motor interface language provided by the manufacturer. This software is loaded on initial power-up of the motor, and requires only high-level commands (e.g. grasp, release) to be provided by the RoboCrane controller via an RS-485 communications link. Limit stops are provided by switches installed on the vices which signal the motor itself. A successful grasp cycle is determined by a combination of absolute vice position and motor torque value.

2.1.4 AGM Final Specifications

Safety: The vises on the AGM feature ACME lead screws, which are not back-drivable. Therefore, if the power fails while the beam is gripped, the weight of the beam cannot cause the vises to open. In addition, the AGM motor includes a built-in brake, which is set to automatically engage when the motor is stopped or when power to the motor is interrupted.

Gripping Size: The AGM is able to grip structural I-beams between 12.7 cm (5") and 20.3 cm (8") wide.

Grip/Release Speed: The AGM motor is capable of rotating at 3,000 RPM while driving the two vises via the chain drive. With the 1:10 gear reducer, the maximum rate of rotation of the gear head will be 300 RPM, or 5 revolutions per second. The vises require 31.5 revolutions in order to travel 66.7 mm (2.6") on either side (since these are self-centering vises). Therefore, the time required to open or close the jaws of the vises from fully closed to fully open (or vice versa) is 6.3 s.

Grip Force: In its final configuration, each of the two grippers on the AGM is able to produce approximately 10 kN (2200 lbf) of grip force. This grip force is sufficient to prevent an I-beam (with a mass of approximately 350 kg) from slipping out when it is gripped in a vertical orientation (i.e., at a 90º roll or pitch angle). Hence the grip force is more than adequate to secure a 453.6 kg (1000 lb) beam through roll and pitch angles of ±15º.

Weight: The AGM weighs approximately 136.4 kg (300 lbs), which is significantly more than the original specification of 45.4 kg (100 lbs). The initial specification may have been too ambitious and we found that meeting that weight limit and still being able to support a 453.6 kg (1,000 lbs) beam was not possible without adding significant cost and complexity to the design. However, considerable effort was made to keep the weight of the AGM to a minimum by using aluminum structural support wherever possible, while also using mostly off-the-shelf components.

Load Carrying Capacity: Due to the high weight of the as-built AGM, it is only able to lift beams with a mass of up to 318.2 kg (700 lbs) rather than the 453.6 kg (1,000 lbs) that was originally specified. This capacity is based on lift limitations of the specific configuration of RoboCrane used in our tests.

Feedback: The AGM provides feedback to the controller when the grippers have closed and when the correct torque has been applied through the motor interface software. In addition, two limit switches were fitted onto the vises to provide a stop signal once the vises have been fully opened. Finally, an onboard camera also provides visual feedback to the operator regarding the status of the AGM.

Dimensions: The AGM fits within the RoboCrane platform footprint and does not exceed 0.5 m in height when attached directly to RoboCrane. However, the AGM does exceed the 0.5 m height specification when attached by means of the 6 adjustable steel cables. Nevertheless, the added vertical compliance of the AGM when attached with the cables is necessary for safety purposes.

2.2 ACT Position Server

The SMS system is provided by the manufacturer with a software interface for managing laser transmitter setup, initial measurement frame calibration, and detector position monitoring. A NIST-developed Position Server accesses detector positions from the SMS interface and provides position and measurement quality data to the RoboCrane controller. The initial Position Server was a console application which managed the socket communications between the SMS interface and RoboCrane. The current Position Server now provides a GUI interface which displays real-time detector position data and status messages regarding system performance. Controls for the data communications stream and data logging are also provided. A screen capture of the Position Server is shown in Figure 4.

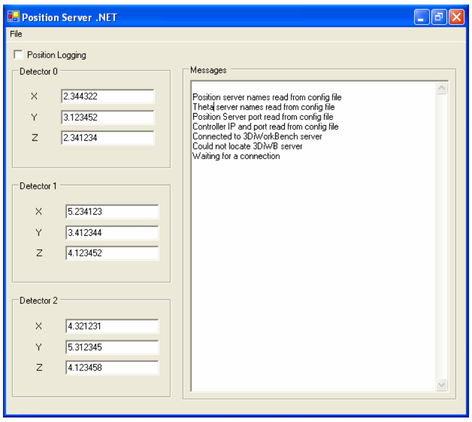

Figure 4: Position Server Screen Capture

In addition to software upgrades the detector hardware on RoboCrane has been modified. Initially, a PDA equipped with an 802.11b wireless network card was used with each detector to provide communications to the computer hosting the SMS interface and the Position Server. The PDA links were replaced with wireless serial LAN radios which improved data throughput and eliminated data loss resulting from the PDA's periodically dropping the connection. Overall data throughput increased, and position updates to the RoboCrane controller are now available at approximately a 10 Hz data rate. Projected tracking software improvements should improve the data rate to approximately 20 Hz, enabling significant improvement in the motion control algorithms.

2.3 4D-CAD Interface

In order to provide an operator with a review of the planned build sequence, a COTS 4D-CAD package was integrated as a front-end to the ACT controller. Models of the holder and three I-beams used in the test structure were created and imported into the 4D-CAD package using VRML as a transfer format. The assembly sequence was then designated from within the 4D-CAD environment.

A parser program examines the 4D-CAD file, extracts the assembly sequence, and delivers a command script sequence to the RoboCrane controller for assembly of the test structure. Modifications to the assembled test structure (i.e. eliminating a beam from the assembly) can be accomplished from within the 4D-CAD system. However, the locations of the test structure's parts and their associated assembled positions cannot be modified from within the 4D-CAD system. Figure 4 shows a screen capture from the 4D-CAD system.

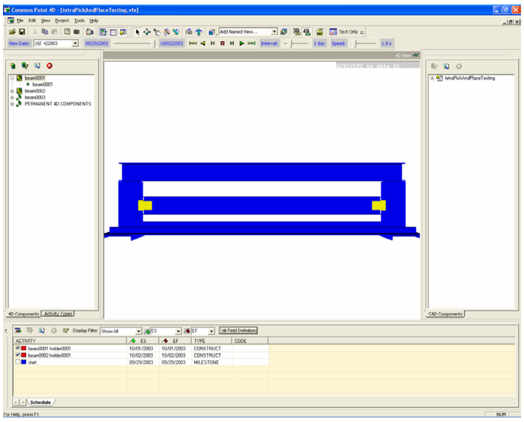

Figure 4: 4D-CAD Screenshot Showing Target Holder and Two Placed I-Beams

3. FUTURE WORK

In order to complete the autonomous pick-and-place operations, the location of all target objects must be known to the RoboCrane controller. In the current ACT configuration, locations of all components are known a priori based upon digitizing fiducial points on each of the objects using the SMS. Although some compliance is mechanically available through the suspended gripper mechanism and the ATLSS connectors, the assembly process is intolerant of positioning errors in either object location or the RoboCrane trajectory. As a result, objects in the assembly process must be carefully measured using the SMS digitizing system (human required) and no object movement is allowed following registration. To alleviate these restrictions, CMAG researchers are investigating the use of high resolution LADAR for pose determination of target objects and low resolution, high frame-rate LADAR mounted on RoboCrane for obstacle avoidance and docking control.

3.1 Locating Target I-Beams with High Resolution LADAR

Preliminary experiments demonstrated the feasibility of providing pose information from high resolution LADAR scans. Using a binning algorithm to segment the data set and then comparing the remaining data to a set of vertex points from a 3D model of the target beam, center mass position of a target I-beam was resolved to cm-level uncertainty and the z-axis rotation was found to within 0.1 of a degree. Details of the algorithm, experimental setup, and initial results can be found in [3]. Figures 5 and 6 show high resolution scans of the RoboCrane work environment.

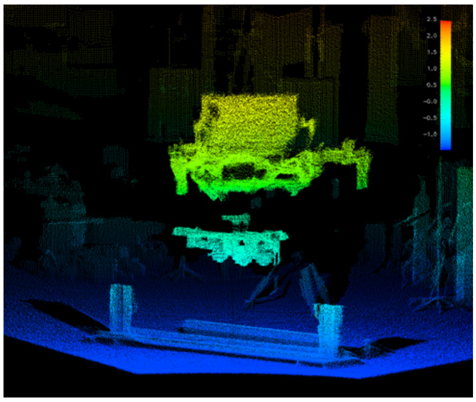

Figure 5: High-resolution LADAR Scan of RoboCrane and Target Structure.

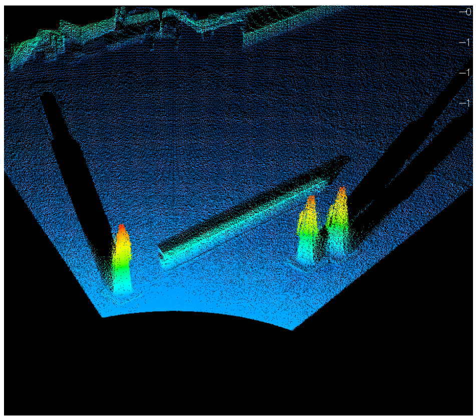

Figure 6: High-resolution LADAR Scan of I-Beam for Pick-Up (Safety Cones in Foreground)

3.2 High Frame-Rate LADAR for Obstacle Avoidance and Docking Control

Although initial tests indicated that pose data of target beams can be provided through high resolution LADAR scanning, the resulting pose information contains too high of an uncertainty for position-only crane guidance. In addition, the time required to capture and process a high-resolution scan is not suitable for real-time control, and therefore cannot accommodate changes in target beam location or appearance of new obstacles in the work volume. To overcome these limitations, the robot manipulator must be equipped with a means of perceiving its environment in real time.

CMAG researchers are investigating the use of a high-frame rate (approximately 30 Hz) low-resolution (160 pixels x 124 pixels) 3D optical range camera for obstacle avoidance and docking guidance. Details of the 3D range camera technology are provided in [4]. Figure 7 depicts a rendering of the range camera on RoboCrane during a docking sequence. Figure 8 shows range data obtained during a simulated docking approach. Figure 9 is a still video image from a separate camera recording of the simulated docking approach provided for a visual reference.

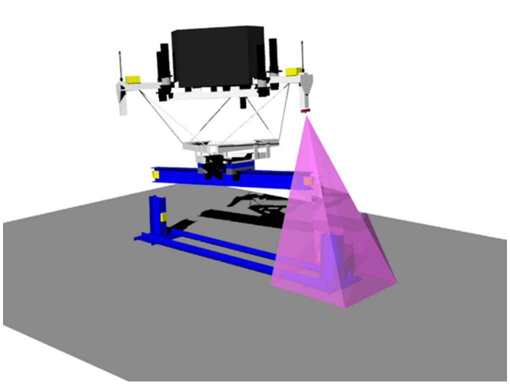

Figure 7: Rendering of RoboCrane Using LADAR for Docking Guidance

4. CONCLUSIONS

The NIST Construction Metrology and Automation Group is conducting ongoing research to provide standards, methodologies, and performance metrics that will assist the development of advanced systems to automate construction tasks. Recent development efforts in this research project demonstrated autonomous assembly of a multi-component test steel structure using a robotic crane with pose tracking provided by a laser-based site measurement system and assembly scripts generated from a COTS 4D-CAD package. Future efforts will incorporate LADAR scanning to eliminate the need for manual measurement of object locations and to provide greater sensing capability and autonomy for the robotic crane.

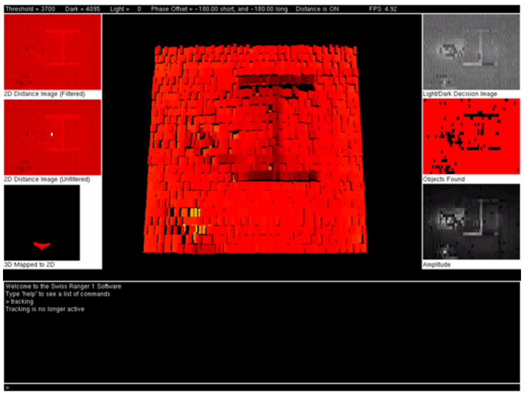

Figure 8: Range Data from a Simulated Docking Approach

Figure 9: Video Still from a Simulated Docking Approach

REFERENCES

[1] Lytle A. M., Saidi K. S., Bostelman R. V., Stone W. C. and Scott N. A., "Adapting a Teleoperated Device for Autonomous Control Using Three-Dimensional Positioning Sensors: Experiences with the NIST RoboCrane," *Automation in Construction*, 13 (1): 101-118 January, 2004.

[2] Lytle, A. M., Saidi, K. S., Stone, W. C. and Scott, N. A., "Towards an Intelligent Job Site: Status of the NIST Automated Steel Construction Test Bed," *Proceedings of the 20th International Symposium on Automation and Robotics in Construction*, Eindhoven, Netherlands, September 21-26, 2003.

[3] Gilsinn, D. E., Cheok, G. S. and Lytle, A. M., "Pose of I-beams for Construction Site Automation," Paper to be presented at the 21st *International Symposium on Automation and Robotics in Construction*, Jeju, Korea, September 21-25, 2004.

[4] Oggier, T., Lehmann, M. Kaufmann, R., Schweizer, M. Ricther, M., Metzler, P., Lang, G., Lustenberger, F., Blanc, N., "An all-solid-state optical range camera for 3D real-time imaging with sub-centimeter depth resolution (SwissRanger™)," SPIE, Conference on optical design, St. Etienne, September, 2003.