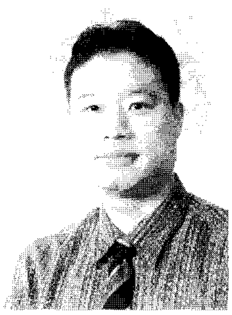
RAPID GEOMETRIC 3D MODELING FOR AUTOMATED CONSTRUCTION EQUIPMENT

조용권, The University of Texas at Wisconsin



Carl T. Hass The University of Texas at Austin

Abstract

Unstructured workspaces which are typical in construction contain unpredictable activities as well as changing environments. Most automated and semi-automated construction tasks require real-time information about the local workspace in the form of 3D geometric models. This paper describes and demonstrates a new rapid, local area, geometric data extraction and 3D visualization method for unstructured construction workspaces that combines human perception, simple sensors, and descriptive CAD models. The rapid approach will be useful in construction in order to optimize automated equipment tasks and to significantly improve safety and a remote operator's spatial perception of the workspace.

Keywords: 3D CAD; laser rangefinder; manipulator; graphical simulation; construction

Introduction

Improving the operating efficiency and safety of hydraulically-actuated construction equipment has become one of the leading motivators behind construction automation efforts. Automated and semi-automated control of earth moving equipment in particular has been made feasible by real-time position measurement and satellite-based positioning systems such as GPS. Tremendous cost savings result from eliminating the manual surveying cycle (Beliveau et al. 1995). A safety related motivation for automating construction equipment using robotic controls has been to distance the human operator from the working environment. Reducing or eliminating a worker's exposure to the risks associated with construction equipment operation sets the stage for robotic manipulators to deliver many potential benefits (Bernold and Huang 1996).

Controlling equipment in an unstructured workspace can be difficult and dangerous due to the operator's inability to gather continuous visual feedback from the changing work environment. Since construction sites are characterized by extreme variations in lighting, temperature, humidity, sound, and air quality, they are somewhat unpredictable. Loud noise emanating from equipment may contribute in a large part to miscommunication between the operator and a guide on whom the operator relies for geometric information about obstructed areas. An operator's limited vision or depth perception may also cause fatal collisions between the end-effector (e.g., a man-lift basket or a concrete pump boom) and nearby structures or people working in the vicinity.

Modeling geometric information about the workspace surrounding a piece of equipment can significantly improve equipment control in several construction automation applications such as heavy lifting, earth moving, material handling, and infrastructure repair and maintenance (Haas et al. 1995). With such geometric model, real time obstacle avoidance is possible. Equipment can be directed by the operator to servo off of a critical surface, such as a trench bottom. Equipment can even be directed to accurately place an object in a location that the operator is obscured by other structures from seeing.

This paper presents a method for rapid geometric modeling and visualization of a local areas based on spatial information about objects obtained using simple sensors (such as a single-axis laser rangefinder and a video camera) for better planning and control of automated construction equipment operations in unstructured workspaces.

2. RAPID WORKSPACE MODELING

Current approaches to workspace modeling include: (1) manual interpretation of stereoscopic images, (2) analysis and fusion of dense laser range scanning point clouds (Stentz et al. 1998), (3) human assisted selected-points based local area sensing (described in this paper), and (4) analysis of sparse range point clouds, using such methods of least-square-fits to planar and curved surfaces (currently being investigated). The third approach is developed in this paper, and the results of its application are presented.

2.1. Human Assisted Selected-Points Based Local Area Sensing

Successful automation requires a balance between exploitation of a machine's ability to efficiently process a vast amount of information while also executing tasks with high accuracy and force, and a human's ability to react intelligently to unforeseen circumstances or to extract patterns out of apparent chaos (Kim and Haas 2000).

For construction applications, the speed of modeling and the precise measurement of the distances between equipment and target positions in a changing environment are critical issues. In contrast to the work environments of other industries such as manufacturing and architectural design, construction has a more dynamic environment, which allows little time to gain precise geometric information. By strategically incorporating human assistance, geometrical data acquisition of real-world objects can be simplified and accelerated considerably since distance and orientation may be acquired without the need for dense area range maps.

Since most target objects are known and man-made, they can be described as a generic set of parametrically defined graphical objects in a computer database. Such a library of pre-stored models (related to facility design elements), with manual guidance, can provide graphic representations of forms that can be matched and fitted to sensed data from 3D position sensors deployed in the work environment. The matching and fitting process is equivalent to setting the values of the object parameters that define it.

2.2. Boundary Representation of Objects

Boundary representation is based on the idea that all solid objects are composed of geometrically closed surfaces. Faces, edges and vertices are the basic geometric elements required for a boundary representation of a solid object. As long as the Cartesian coordinates of a certain number of vertices, or points on the edges or on the faces of the object, are identified, position and orientation of most solid objects can be determined. The number of vertices or points on the edge or a surface depends on the geometric and topological features of the solid object. Two different types of solid modeling methods - parametric modeling and complex modeling- were introduced in the following sections.

2.2.1. Parametric Modeling

Parametric modeling can be defined as a modeling method that uses parameters to define the size and geometry of features and to create relationships between features. Changing a parameter value updates all related features of the model altogether (Lockhart and Johnson 2000). Geometric primitives can be considered parametric models. A single-axis laser range finder was used to obtain the minimum required points with regard to an objects' position and orientation. Given the lack of precise control of the measuring device and hand-eye coordination of a typical operator, acquiring these points is sometimes difficult to implement in practice. Practical means to deal with this issue are partially addressed by this research but are more fully addressed in subsequent follow-up research.

2.2.2. Complex Object Models

Unlike primitives, most complex models have surfaces which represent their unique geometric shapes. So, they need to be pre-designed and imported to the scene for the fitting and matching process based on the measured surface data.

Hence, in theory, even with only a partial view of an object, or even if the object has occluded areas, as long as a few points on the surface can be measured, and as long as the partially-visible object can be recognized by a human operator, the proposed method can accurately represent the object.

The aforementioned modeling method can produce a very precise graphical model of the immediate environment of the construction equipment and can significantly reduce sensor data-acquisition time and computer processing, when compared to current other laser range scanning-based 3D modeling methods that require a combination of substantial time for merging and interpreting dense clouds of laser scanned range data.

3. SYSTEM DESCRIPTION

3.1. The Large Scale Manipulator (UT)

The University of Texas' Large Scale Manipulator (LSM) is a 6 Degree of Freedom (DOF) hydraulically-actuated manipulator that was originally designed for handling pipes during construction operations. In its conventional configuration, it is attached to the boom of a rough terrain mobile crane (Figure 1). To allow research to continue in a more controlled environment, the LSM was moved to an indoor facility.

In addition to manual control, autonomous control is also currently used to operate the LSM. The computer controls the LSM in a feedback control configuration using sensors that determine joint positions and actuates each joint until the desired position, entered via a joystick or command script, is reached within a specified tolerance.

Figure 1. LSM mounted on a Crane

3.2. The Laser/Camera-Based Data Acquisition System

For this study, a single-axis laser rangefinder was installed. The measurements can be remotely executed and transferred directly into the computer through an RS232 interface. The range of measurement for the laser rangefinder is 100 m with a $\pm$ 3 mm accuracy.

A Charged Coupled Device (CCD) camera was used to allow a remote operator to manually guide the laser rangefinder and operate the LSM. The camera is mounted with the laser/the PTU (See Figure 2) and connected to a frame grabber installed in the control computer.

The step size of the PTU is critical in order for a laser rangefinder to measure the desired point on a target. The rotational measurement errors of a motorized PTU (2 DOF) depend entirely on the resolution of the stepper motors. For this reason, this study used a trackball-controlled PTU with very high resolution (0.0128571 °Δ/step). The trackball control allowed the operator to acquire specific geometric point data fast and accurately. Its maximum speed is a little over 60°Δ/second. Its error contribution is thus about 2 mm for example for measurements at 10 m distance, which is an acceptable amount for the LSM operation.

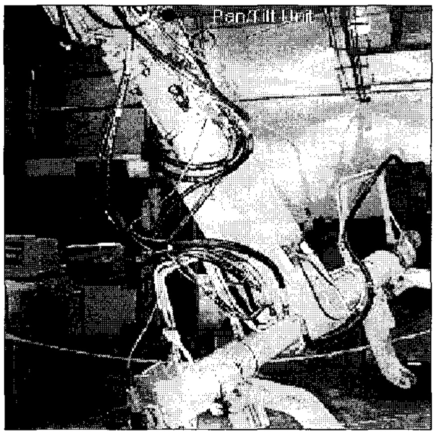


Figure 2. Position Data Acquisition System mounted on the LSM

3.3. Kinematics

In order to obtain accurate desired position control, understanding the manipulator's link structure, sensory system (including the laser system), and control programs is very important. Inverse and forward kinematics equations, computer algorithms, feedback encoders, and control interfaces were implemented for the various control strategies for the LSM (LeBlond et al. 1998). Figure 3 shows the current 6 DOF configuration of the LSM.

The 6 DOF forward kinematics for the laser/camera system, and the pan and tilt unit mounted on the LSM were solved to obtain the final position of the laser beam (Cho 2000). From the selected mounting position, the position of the laser and the pan and tilt unit can only be affected by the swing, lift, and telescopic joints.

The laser/camera coordinate system provides the final target point of the laser beam with respect to the LSM's base coordinate system by using the forward kinematics. In other words, all points (xi, yi, zi) measured by the laser/camera system are registered to the LSM's base coordinate system (see Figure 4 and 5). To move the end-effector to a desired location and orientation in the local area workspace modeled via the laser/camera system, the required joint angles of the LSM are obtained through inverse kinematics calculations. By giving a measured target position value in a motion script format to the current LSM's computer control system, the LSM can be commanded to automatically approach this position. This automated, resolved inverse kinematics control was solved in previous research efforts for the LSM in its 6 DOF mounted state in the lab as well as in its 8 DOF mounted state in the field (on a 22 ton rough terrain crane) (Owen 1998).

The LSM control system calculates a series of joint angles through which to move the joints in order for the end-effector frame to move from its initial location (frame {E}) to its final location (near frame {G}). Then, the link transformations are multiplied to find the single transformation that relates frame {G} to frame {B}. As with vectors and rotation matrices, symbol T is called the spatial transformation operator. Here, describes frame {G} relative to frame {B} and forms the following transform equation (assuming the camera is fixed axially along the 3rd link):

$$ {}^{B}_{G}T = {}^{B}_{C}T \; {}^{C}_{E}T \; {}^{E}_{G}T $$

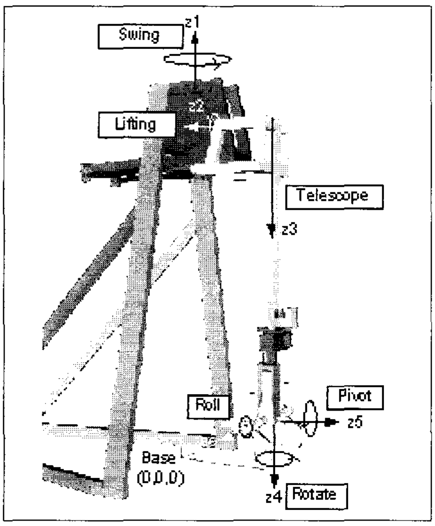


Figure 3. 6 DOF Kinematic Configuration for the LSM [16]

Similarly, the location and orientation of the laser beam illustrated in Figures 3 and 4 can be calculated with respect to the base coordinate system by multiplying six transformation matrices as follows:

Each joint angle can be computed from the transform equation.

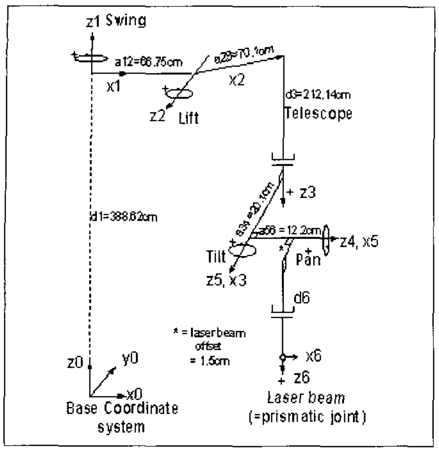


Figure 4. 6 DOF Kinematic Configuration for the Laser mounted LSM [4]

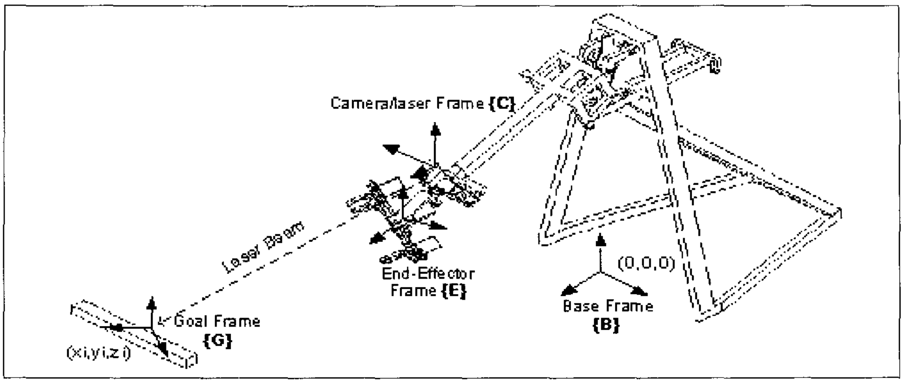


Figure 5. Simplified Illustration of Kinematics Frame Assignments for the *UT LSM*

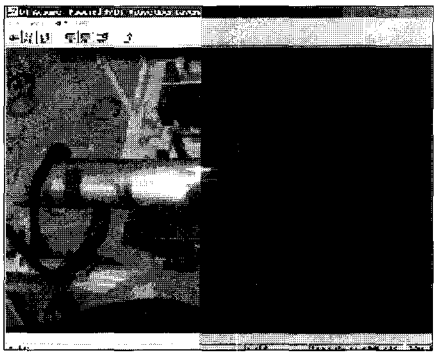
$${}^{Base}_{Laser}T = {}^{Base}_{Swing}T\ {}^{Swing}_{Lift}T\ {}^{Lift}_{Tele}T\ {}^{Tele}_{Pan}T\ {}^{Pan}_{Tilt}T\ {}^{Tilt}_{Laser}T$$

In the same way that the previous 6 DOF forward kinematics was solved, the 3 DOF forward kinematics problem for the camera/laser system mounted on a tripod was solved based on D-H parameters and transformation matrix. By using a standard camera mount, the whole unit can be easily detached from the LSM and mounted on a tripod. Since the LSM-based operation was limited to indoor experiments only, a tripod configuration for the laser/camera system was useful for outdoor experiments.

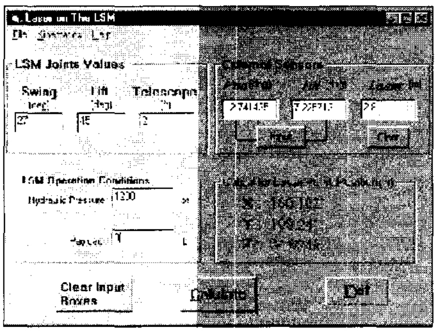
3.4. Interface Design for Data Integration

The control programs manipulate output data from the PTU and laser rangefinder and calculate forward kinematics, inverse kinematics, and the laser end-point's kinematic position.

User input is mainly used to adjust for the final position of the laser end-point according to the error attributes which are calculated from the error modeling, which was previously presented. The operator remotely selects interesting areas and controls the laser and the manipulator through a real-time video image. Figure 6 shows a live video image of a pipe placement on a pipe rack captured using a frame grabber (a) and the user interface for the laser point position (b). Hydraulic pressure and payload inputs are related to the LSM's position error adjustment.



(a)



(B)

Figure 6. Live Video Image and User Interface for Position Data Capture

4. DEMONSTRATION AND VALIDATION

Two outdoor experiments were designed and conducted to graphically model construction work sites in 3D workspaces for better planning and control of construction equipment operations.

4.1. Electric Power Cables and Poles on a Street

The purpose of this part of the experiment was to rapidly provide a virtual workspace for equipment with long booms or arms, such as cranes, truck mounted concrete pumps, or man-lifts, working under or around high voltage electric power cables on a street.

Figure 7. The Selected Street Scene and Target Objects

A crossroad including electric cables and poles was selected for the modeling test (Figure 7). For this test, the laser system was mounted on a tripod and a portable computer was used.

To locate and model four tapered poles and four cable connections, eight points were measured to locate the cables and four points to indicate the bottom of each pole's position. Pre-designed poles were fitted and matched to the end points of the cables and to the bottom points (Figure 8).

4.2. Trench Modeling (with pipes and a crane)

A small trench was created at the laboratory's outdoor facilities, and the laser/camera system was used to obtain geometric data for the trench, two aluminum pipes, and a pipe connector placed in

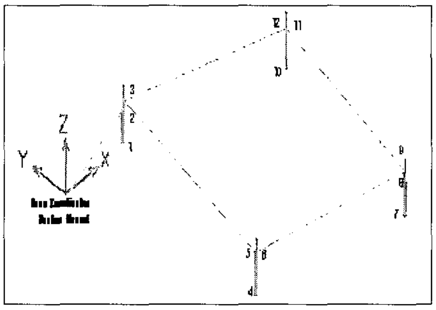


Figure 8. Scanning process and CAD results

front of a crane (Figure 9). The laser/camera system was mounted on a tripod rather than on the crane (a crane requires a more complex kinematic solution than a tripod

The purpose of this graphical modeling experiment for a trench site was to demonstrate the potential of this method to keep people out of a trench, to provide a safety boundary representation of a trench with a form of non-parametric model, and to provide the operator with precise spatial information that can potentially improve equipment control for high precision pipe placing and connecting tasks in a trench.

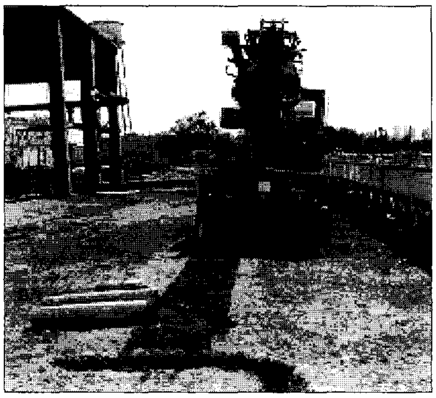


Figure 9. Simulated Trench Work Site

The pipe connector was formed by three cylinders and a quadrant of a torus. As long as two circles are defined with six points on the boundary edge, a pre-designed pipe connector can be easily located (Figure 10). Three points were measured to locate the crane's model. The crane was also pre-designed and imported to the scene. Figure 11 shows the completed 3D virtual workspace.

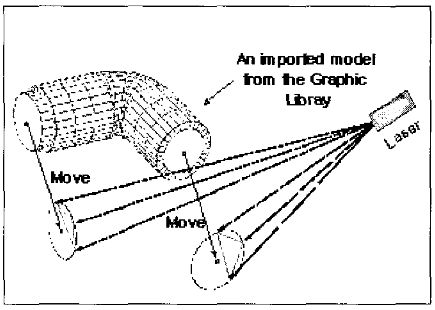


Figure 10. Fitting and Matching Process for a Pipe Connector

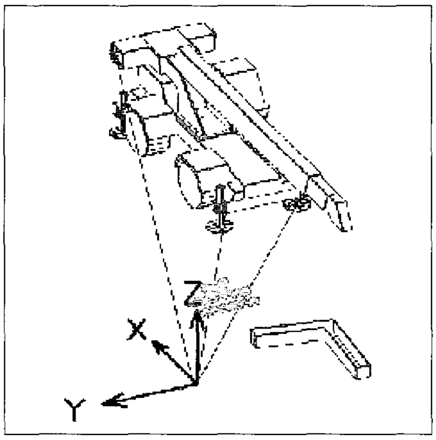


Figure 11 Completed Virtual 3D Workspace

Regardless of the complexity and size of the objects, the average processing time for graphically modeling an object was approximately 30 seconds using the current prototype system. In order to increase the modeling speed, as an on-going project, this research is currently focusing on improving the data acquisition and modeling process by optimizing the manual guidance of sensor data acquisition process and by minimizing the demand on the operator in the modeling process.

4.3. Validation

The main purpose of the graphical simulation and real execution (i.e. off-line programming) tests was to verify the overall proposed method including the usefulness of the hardware and software platforms developed as part of this study. The tests proved that the overall system that has been developed in this study effectively improved the operation of the LSM. The most crucial issue in the off-line programming test was the correspondence between the two systems, the graphic workspace and the real world workspace. Both the graphic LSM and the real LSM are registered to each corresponding base coordinate system in their workspaces (see Table 1). The LSM was also carefully calibrated by using additional external sensors such as a laser and string encoders. The test results indicated that, within the limited tasks performed in the experiments, the overall correspondence accuracy was acceptable for the LSM's operation.

5. CONCLUSION

A new feasible framework for rapid local area workspace modeling has been developed by combining human perception, pre-stored CAD objects, and use of simple low-cost ensors such as single-axis laser rangefinders and remote video cameras. This method can significantly reduce modeling time while potentially increasing modeling accuracy in terms of volume, position, and orientation. Potential impact of this research includes safer and more efficient operations with computer-assisted construction and maintenance equipment. The developed method can be extended to a broad class of construction automation design, simulation, and graphical control problems such as generating as-builts, assessing infrastructure conditions, and controlling construction operations.

ACKNOWLEDGEMENTS

This paper is based on the research funded by National Science Foundation (Grant #: CMS-0000137). The authors gratefully acknowledge their financial support and encouragement throughout this study.

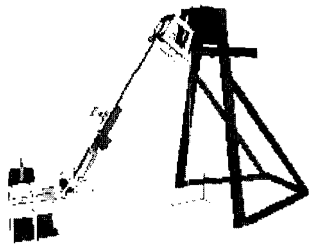
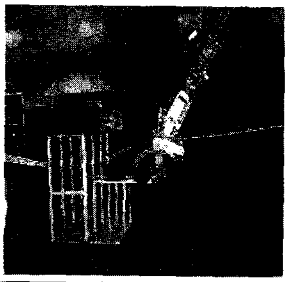
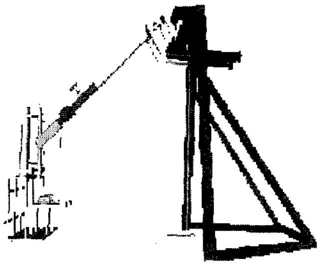
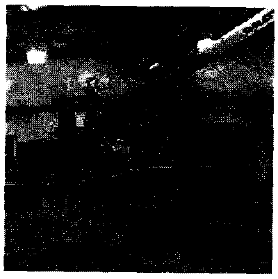
Simulated Position (x, y, z) of the End-effector (cm)	Graphical Simulation	Real Task Execution
(325.18, -14.22, 98.72) when, -Swing: -2.7°Δ -Lift: 34.8°Δ -Telescope: 57.4 cm -Rotate: -8°Δ -Pivot: 0°Δ -Roll: -7°Δ		
(409.63, 8.37, 174.85) when, -Swing: 1.2°Δ -Lift: 51.4°Δ -Telescope: 73.2 cm -Rotate: 90°Δ -Pivot: -38°Δ -Roll: -8°Δ		

Table 1. Graphical Simulation and Real Task Execution for the Pipe Placing by the LSM

REFERENCES

Beliveau, Y.J., Williams, M., King, M.G., and Niles A.R. (1995). "Real-Time Position Measurement Integrated With CAD: Technologies and Their Protocols." Journal of Construction Engineering and Management, 121 (4).

Bernold, L. and Huang X. (1996). CAD-Integrated Real-Time Control for Robotic Excavation and Pipe-Laying: Development and Field Testing, Final Report, Federal Highway Administration.

Cho, Y. (2000). Human-Assisted Rapid Workspace Modeling for Construction Equipment Operations. Ph.D. Dissertation, Department of Civil Engineering, The University of Texas at Austin.

Craig, J. (1986). Introduction to Robotics: Mechanics & Control. Addison-Wesley, Reading, MA.

Haas, C., Skibniewski, M., and Budny, E. (1995). "Robotics in Civil Engineering." Microcomputers in Civil Engineering, October, pp371-381.

Kim, Y.S. and Haas, C. (2000). "A Model for Automation of Infrastructure Maintenance using Representational Forms." Journal of Automation in Construction, Vol.10, No.1.

LeBlond, D., Owen, F., Gibson, G., Haas, C., and Traver, A. (1998). Performance Testing and Characterization of Advanced Construction Equipment." ASCE Journal of Construction Engineering and Management, Vol 124, No.4, pp. 289-296.

Lockhart S. and Johnson C. (2000). Engineering Design Communication, Prentice Hall, Upper Saddle River, NJ.

Owen, F. (1998). Development of Smooth Resolved Motion and Computer- Assisted Teleoperation for a Large Scale Manipulator. Ph.D. Dissertation, Department of Mechanical Engineering, The University of Texas at Austin.

Stentz, A., Bares, J., Singh, S., and Rowe, P. (1998). "A Robotic Excavator for Autonomous Truck Loading." Proceedings IEEE/RSJ International Conference on Intelligent Robotic Systems, October, Victoria, B.C., Canada.