CONTROL IMPROVEMENT FOR ADVANCED CONSTRUCTION EQUIPMENT

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ABSTRACT: Advancements in the control of construction equipment can have significant benefits in the industry. Better control can lead to improvements in safety, cost, labor turnover, and productivity. It is helpful to characterize improvements in a control system using performance tests. Results of such tests provide a means of comparing control systems. Research at The University of Texas at Austin has resulted in the development of tests to characterize improvements in the control of a large-scale manipulator (LSM). Tests have shown that autonomous control of the LSM has better performance capability than manual control for well-defined movements or simple tasks. However, computer-enhanced manual control is still required for operation in a typical construction environment. Object-oriented programming was used to implement computer-assisted operation modes that enhance the LSM's performance. This paper discusses the development of performance tests for characterizing control systems for LSMs. The new computer-assisted operation modes also are explained. A description is included identifying lessons learned during this research that should be considered during future development of LSMs.

INTRODUCTION

A primary goal in the automation of construction operations in recent years has been the improvement of traditional control systems. Some common operator interfaces are being improved with computers while keeping a human in the loop. Other systems are being completely automated. Both types of advanced control have the potential to improve construction operations.

With such capabilities as obstacle avoidance and improved accuracy, advanced control of construction equipment can reduce the quantity and severity of accidents. State-of-the-art control systems also improve safety by reducing labor requirements and removing workers from unsafe environments (Haas et al. 1995). Lightweight controls supported by hydraulics and electronics allow a new operator to master control of the equipment much sooner than traditional interfaces (Phair 1997).

Significant economic savings can be realized using advanced control because the need for such things as surveying and rework is reduced. For example, the Blade-Pro motorgrader control system from Spectra-Physics Laserplane, Inc., decreases production costs by reducing conventional grading time by 30–50% (Spectra-Physics Laserplane, Inc. 1993). Another important benefit of enhancing control of construction equipment is that productivity can be improved greatly. The Spectra-Physics Laserplane, Inc., automatic grade control systems enable site preparation to occur with less staking and rework and better accuracy, while reducing machine and operator downtime (Spectra-Physics Laserplane, Inc. 1995).

The potential benefits of developing advanced control systems for construction equipment are significant. Improvements in equipment control are often gradual and occur in steps. To characterize advancements in a control system, performance tests can be developed that will allow researchers to compare current and previous interfaces and modes. Such tests provide a standard method to evaluate the relative quality of control advancements. They can be interspersed effectively with more expensive field productively trials (Hsieh et al. 1993).

Research at the University of Texas at Austin (UT) has resulted in the development of performance tests to characterize control system improvements for a large-scale manipulator (LSM). An important feature of these tests is that they provide both a graphic and a numeric representation of the benefits of advancements in the LSM's control system. The tests can be used in their current state or can be modified to test control improvements for other construction manipulators. This research also has led to the development of computer-assisted operation modes that significantly improve the ability of the LSM to operate in a construction environment.

BACKGROUND

The UT LSM originally was designed and fabricated by Grove Manufacturing for DuPont in 1980. It was designed for handling piping during construction operations. In its conventional configuration, it is attached to the boom of a Grove 22-ton rough-terrain mobile crane. Fig. 1 shows the LSM on the crane. The LSM has a 725-kg lifting capacity and it is electrohydraulically controlled. After several years of field testing, it was sold to UT in 1992 for further research and development.

The LSM has five degrees of freedom (DOF) and a pair of two-fingered grippers for handling pipe of various diameters. When the LSM is attached to the three-DOF Grove crane, the system has eight DOFs. Field trials have been conducted to assess the productivity of the equipment in its original config-

FIG. 1. LSM Mounted on Grove Crane

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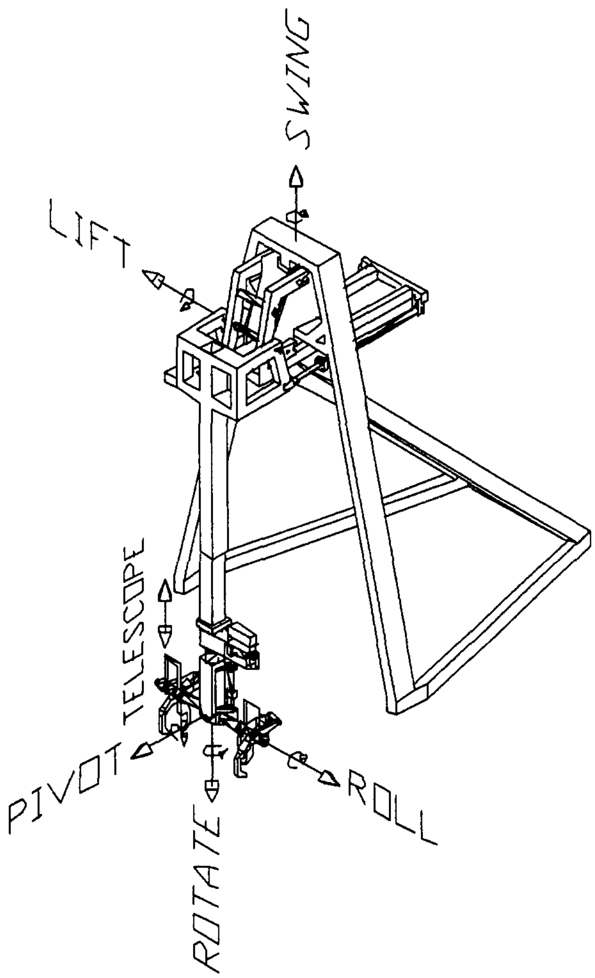

FIG. 2. LSM Mounted on Its Laboratory Test Stand

uration. However, to allow research to continue in a more controlled environment, the LSM was moved from the crane to an indoor facility in 1995. It now sits on a cantilever space frame in the UT construction automation laboratory. An extra DOF was added to the laboratory frame to represent the boom rotation on the mobile crane. The LSM's laboratory configuration has six DOF. Fig. 2 shows the LSM on its laboratory frame.

LSM Operator Interfaces

In its original form, the LSM is operated from a control station with eight levers. Each lever corresponded to one joint on the LSM. Translational joints could be extended or retracted by moving the corresponding lever up or down. Rotational joints could be rotated by moving the appropriate lever up or down. Operation of the LSM with this control station was difficult because an operator could only use two levers at once and it is not easy to remember which joint each lever exercises. Performance tests proved that this was not an efficient control station (Glass 1984).

In an attempt to improve the eight-lever system, an Ergostick control system was developed. This system consisted of two multiple DOF action levers mounted on either side of a cart. One Ergostick had five DOF to correspond to the five DOF of the LSM. The other Ergostick had three DOF to correspond to the three DOF of the crane. Performance tests were conducted to compare the Ergostick control system with the original eight-lever system. Results from earlier tests were used as a benchmark. Comparison of the test results combined with researchers' intuitive analysis based on experience with

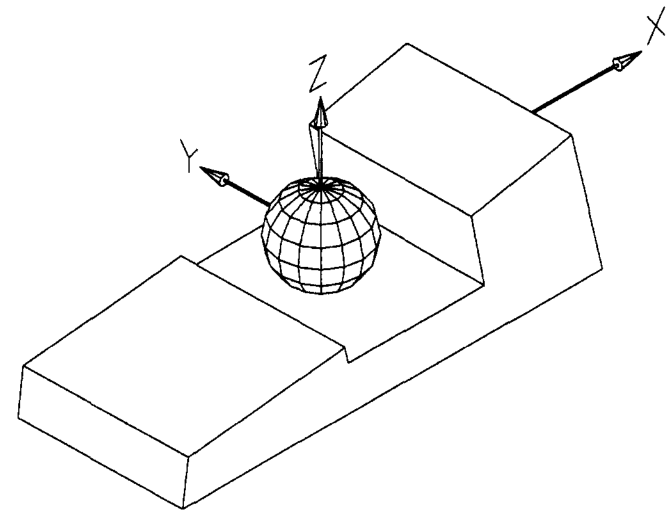

FIG. 3. Six DOF Spaceball

both control systems led to the conclusion that the Ergostick control system was not an improvement over the eight-lever system (Hughes 1990).

To improve manual control of the LSM, a more advanced controller was purchased. Researchers selected the Dimension 6 Geometry Ball manufactured by CIS Graphics, Inc., also called a spaceball. The spaceball has three translational DOF and three rotational DOF. The inverse kinematics required to translate the spaceball's commands for the LSM's end effector to the manipulator joints had been solved previously for both the laboratory and the crane configurations. The spaceball was connected to the LSM via the control computer. Its six DOF was connected directly to the six DOF on the LSM in its laboratory configuration. Fig. 3 shows the spaceball and its coordinate system.

The spaceball only has been used to control the LSM in its laboratory configuration. However, in the future it will be used to control the LSM and the crane. That means the eight-DOF LSM/crane combination will need to be controlled with the six-DOF spaceball. This will be achieved by having separate control modes programmed into the spaceball. One mode will allow control of the LSM with all six of the spaceball's DOF active. Another mode will allow control of the crane with only three DOF active.

The third interface currently used to operate the LSM is autonomous control. Motion commands are preprogrammed into a computer and sent to the LSM to achieve the desired motion. The computer controls the LSM using sensors to determine joint positions and actuates each joint until the desired position is reached. Because it is difficult to attain an exact commanded position, the attained position is within a specified tolerance.

Related Work

Advanced construction equipment research is a relatively new field. A survey conducted by Hsieh and Haas (1994) to gather information on worldwide developments in LSM research revealed that most existing systems are in either the development or the field testing stage. That research also concluded that a critical factor in determining the usefulness of a LSM for a particular project is an estimation of the manipulator's performance capabilities.

A key area of research and development of robotics in construction is the use of sensors for feedback control. Sensor data combined with powerful computers enable the implementation of resolved motion control. Haas et al. (1995) suggest that this type of control allows such innovations as an operator speci-

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fying an excavator bucket to scrape horizontally or a series of LSM operations being repeated with preprogrammed modifications. Huang and Bernold (1997) explain that a human-machine interface, which integrates the human operator's decision-making ability with the computer's control skills, may be a more valid approach to improving control of construction equipment instead of attempting to fully automate construction processes. During the research and development of their computer aided earth moving systems, Caterpillar (1996) used an effective process that required repeated testing and redesign. The frequent testing after each redesign resulted in significant improvements in performance, functionality, and durability for the next redesign.

An advanced control feature that is becoming more common is the use of optimum modes. Optimum mode settings on an excavator allow engine and hydraulic-pump power to be set for a particular type of job (Phair 1997). The concept of having optimum control modes can be incorporated into other types of construction equipment. Recent research has resulted in the development of optimum modes for control of the UT LSM. Future research will include the testing and characterization of these modes.

DEVELOPMENT OF TESTS

Tests were developed to assess and compare the performance of the LSM with various operator interfaces. The tests were derived from the American National Standards Institute (ANSI) tests specifications for industrial robots and robotic systems. This standard, ANSI/RIA R15.05, describes static and dynamic test paths for a manipulator to follow. These test paths are displayed in Fig. 4. Static tests measure a robot's ability to reach specific points along the test path. The end effector's motion between these points is irrelevant. Dynamic tests measure the ability to follow the entire test path. The end effector's ability to follow the pattern is measured at intermediate points along the entire path. The combination of results from static and dynamic tests characterize the capability of a robotic system.

The LSM's work space required the researchers to modify the ANSI specified test paths. The orientation of the test plane defined by ANSI/RIA only allowed for a small intersection between the LSM's work space and the test path. To keep this orientation would have required very small test paths to be used. The writers feel that it is unacceptable to use small test paths to characterize such a large manipulator. To solve this problem, the laboratory floor was used as the test plane because it shares a large enough intersection with the LSM's work space. The ANSI/RIA standard designates a large number of tests to be performed. To reduce wear and tear on the manipulator, researchers greatly reduced the number of tests to be performed by the LSM.

These modifications of the ANSI/RIA specifications are justifiable because the primary goal of these tests is to assess control improvements over past performance. The purpose of the ANSI/RIA standard is to bench mark the capabilities of normal industrial robots meant for commercial use. Current research on the LSM does not aim toward immediate commercialization. Also, the research environment does not require highly repetitive operations like those of industrial robots on an assembly line. The tests developed for this research serve the primary goal of providing a means to characterize the performance of current and future control systems for the LSM.

Although these test paths were designed to test autonomous robots, the decision was made to use the same paths to test manual and computer-assisted manual operation of the LSM. This allows a reasonable comparison to be made between manual operation of the LSM and autonomous operation. To test the manual control systems, an operator attempted to follow the dynamic test path first with the eight-lever control station and then with the spaceball.

Testing Conditions

These performance tests were conducted with the LSM on its indoor frame at the UT construction automation laboratory. Static and dynamic tests were conducted five times each for autonomous control. An additional set of dynamic tests were conducted for autonomous operation with a 363-kg test load in the LSM's jaws. The purpose of this was to compare the LSM's path following capability in its unloaded and loaded state. The manual tests were all conducted with the test load in the LSM's jaws. A stylus was attached to the test load pointing straight down toward the test path. The operator's task was to follow the test path with the stylus while maintaining its vertical orientation. Fig. 5 shows an operator attempting to follow the dynamic test path with the stylus.

EXPERIMENTAL TEST RESULTS

Static Tests

Three parameters are used to characterize the static capability of each control system: positional accuracy, positional

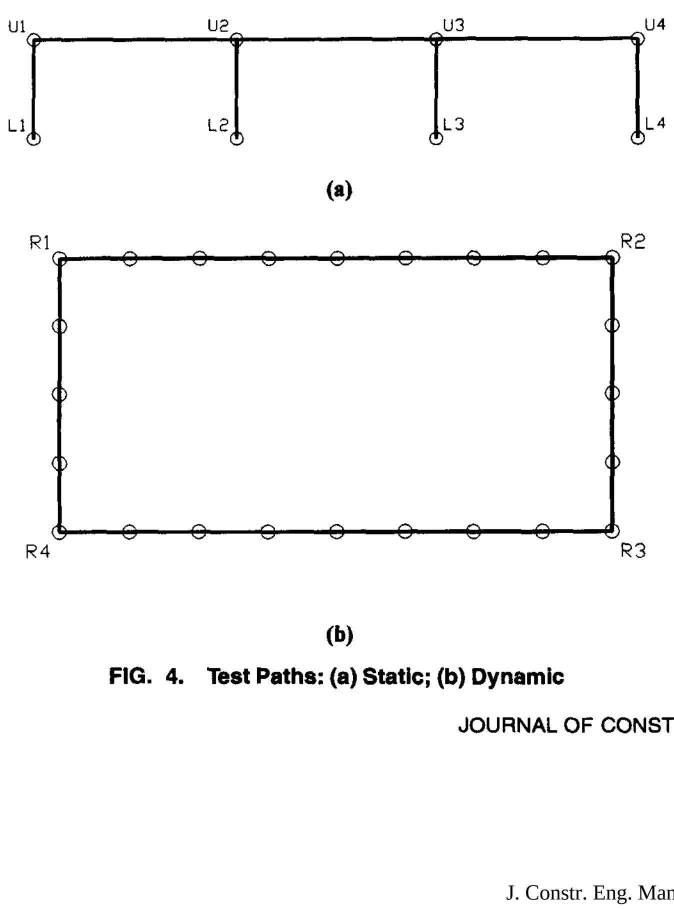

FIG. 4. Test Paths: (a) Static; (b) Dynamic

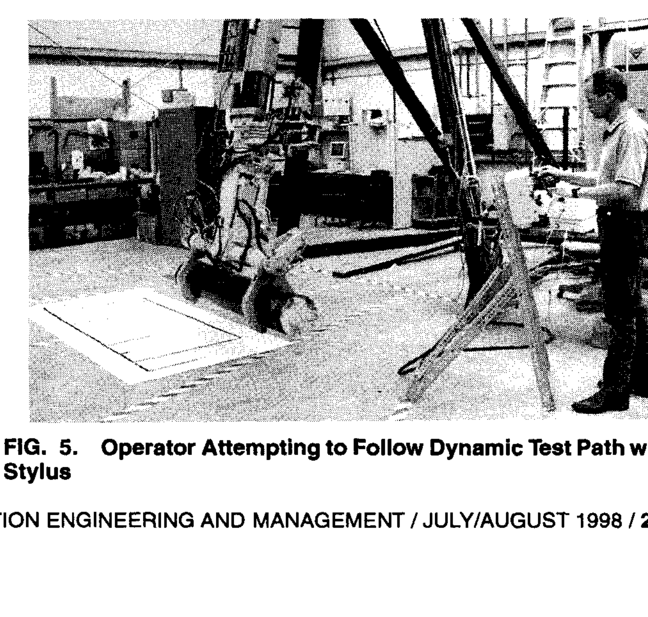

FIG. 5. Operator Attempting to Follow Dynamic Test Path with Stylus

TABLE 1. Static Test Results

Static test (1)	Characteristic (2)	Result (3)
Unloaded, five trials	Positional accuracy	3.34 cm
	Positional repeatability	0.596 cm
	Mean speed	3.37 cm/s

TABLE 2. Dynamic Test Results

Characteristic (1)	Result (2)
(*a*) Unloaded, five trials	
Path accuracy	3.13 cm
Path repeatability	0.608 cm
Mean speed	3.37 cm/s
(*b*) Loaded, five trials	
Path accuracy	2.86 cm
Path repeatability	0.122 cm
Mean speed	0.924 cm/s

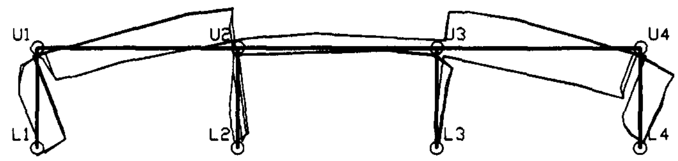

FIG. 6. Static Test Results for Five Trials

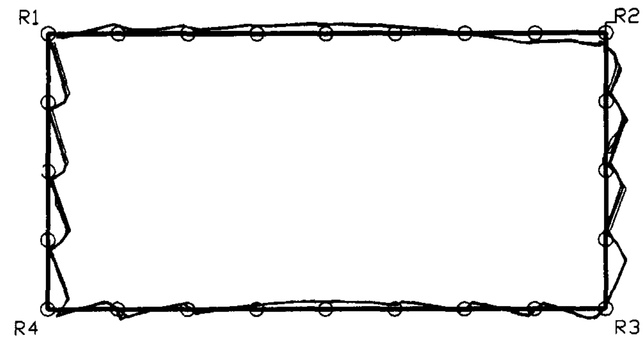

FIG. 7. Dynamic Test Results for Five Trials

repeatability, and mean speed. Positional accuracy is the deviation between the end effector's commanded and achieved position. Positional repeatability is the deviation between the end effector's achieved position and the mean position achieved after attempting to attain that position *N* times. Mean speed is the average speed attained by the end effector for *N* trials. The results of the static tests are presented in Table 1.

Dynamic Tests

Three similar parameters are used to characterize the dynamic capability of each control system: relative path accuracy, path repeatability, and mean speed. Relative path accuracy is the average distance between the path attained by the end effector and the commanded path. Path repeatability is a measure of the closeness between multiple attained paths. Mean speed is the average speed attained by the end effector for *N* trials. The results of the dynamic tests are presented in Table 2.

Manual Tests

Quantitative measures were not used to assess the performance of the LSM under manual operation with the spaceball. During testing, it became obvious that autonomous control exhibits significantly higher accuracy and repeatability than manual operation of the LSM.

ANALYSIS OF TEST RESULTS

The results of these tests are useful for identifying and quantifying improvements in control systems for the LSM. However, they are not effective tests for large-scale hydraulic manipulators in general. Because they were designed for small, industrial robots, the tests do not provide significant information about how the LSM will perform in a construction environment. Although the results have merit in the research stage, it is important to understand that specific tests for commercial large-scale hydraulic manipulators should be developed for analyzing performance, productivity, and control improvements.

Static Test Performance

The static test results show that the LSM has good positional accuracy and excellent positional repeatability for a robot of its size. Its average attained position for five trials was within 3.34 cm of the commanded position. The average positional repeatability of 0.596 cm means that on average, an attained position during one trial was within 0.596 cm of the average attained position for all five trials. The high degree of repeatability is depicted in Fig. 6, which shows five trials. This accuracy and repeatability is acceptable for such LSM potential applications as pick-and-place operations and materials handling. These applications require primarily static (point to point) motion. The LSM's movement between certain points is irrelevant as long as it behaves safely.

The mean speed of the end effector during the static tests was quite slow. The LSM only traversed the static test path at 3.37 cm/s. This speed is unacceptable for most of the LSM's potential applications. The primary reason for the slow speed is that as it approaches each commanded point, the LSM spends a lot of time making fine adjustments to maximize its proximity to the point within a certain tolerance. The speed could be improved by relaxing this tolerance but that would sacrifice accuracy and repeatability.

Dynamic Test Performance

The dynamic test results show good path accuracy and excellent path repeatability. The average attained path of the unloaded LSM was within 3.13 cm of the commanded path. The average attained path of the loaded LSM was within 2.86 cm of the commanded path. The average path repeatability for the unloaded and loaded LSM, respectively, was 0.608 and 0.122 cm. This means, for instance, that a path attained by the unloaded LSM during one trial was within 0.608 cm of the average path attained for all five trials. Fig. 7, which shows five trials, demonstrates the excellent repeatability attained by the LSM with no test load. This accuracy and repeatability is acceptable for some potential LSM applications, such as surface painting, sandblasting, and material handling. These applications require primarily dynamic (path following) motion.

The mean speed of the end effector during the dynamic tests was 3.37 cm/s for the unloaded LSM and 0.924 cm/s for the loaded LSM. These speeds are quite slow and will need to be improved with a more advanced control system if the LSM is to be used commercially.

Manual Test Performance

Manual operation of the LSM was characterized by poor accuracy, low repeatability, and slow speed. The poor accuracy is shown clearly in Fig. 8, an attempt to follow the dynamic test path using the spaceball. This illustration does not show

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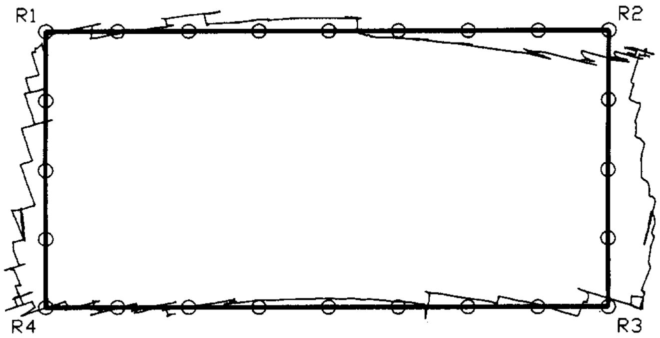

FIG. 8. Manual Following of Dynamic Test Path

the changing orientation of the end effector, which is supposed to remain constant as it traverses the path. It is extremely difficult to maintain the orientation of the end effector during manual control.

The reason for the slow speed is the inability for a human operator to move all of the LSM's joints at one time. On the eight-lever control station, each joint is controlled by one lever. An operator with two hands can operate a maximum of two joints at a given time. Theoretically, in its current configuration, an operator can move all six LSM joints at once using the spaceball. However, in reality the thought process is too complex. During testing, the operator never moved more than three joints at once. This inability to exercise all six joints at once requires the operator to adjust joints constantly to maintain orientation and follow the path. These frequent adjustments, combined with the operator's difficulty in judging the end effector's position, make such manual operation of the LSM a slow process.

MANUAL OPERATION IMPROVEMENT

Although autonomous (computer-controlled) operation of the LSM proved to be more accurate than manual control, it is necessary to improve manual operation because the unpredictable nature of construction activity makes it a poor candidate for preprogrammed, autonomous motion. Testing revealed that the spaceball is a better operator interface than the eight-lever console; however, it did not significantly improve LSM operational ergonomics. It is simply the replacement of an awkward user interface with one that is more compact yet still cumbersome for a human operator.

Recently, completed research has enhanced significantly manual operation of the LSM. To give an operator better control when performing basic motions required for standard LSM tasks, computer-assisted modes were developed for the spaceball. Including its original (DIRECT) mode, currently, there are six modes of spaceball operation. These six modes can be used as a basis to develop other modes to enhance control for unanticipated tasks.

The different spaceball modes were created by mapping the spaceball coordinate system into specialized coordinate frames attached to the LSM work space. When an operator exercises the spaceball DOF, a tug vector is created that represents the magnitude and direction in which the spaceball was exercised. The control software then maps that movement into the work space as a starting point and a target point. The starting point is established when the mode is selected. The target point is projected from the starting point by the tug vector. The starting point and target define a straight path for the LSM to follow. With this computer-generated path, the LSM control computer solves the inverse kinematics problem to produce control commands in joint space that will cause the LSM to follow that path.

The software infrastructure needed for these improvements is substantial. To support a structured but flexible research effort, object-oriented programming was used. A population of diverse software objects was coded in C++ to support advanced control of a flexible operator interface.

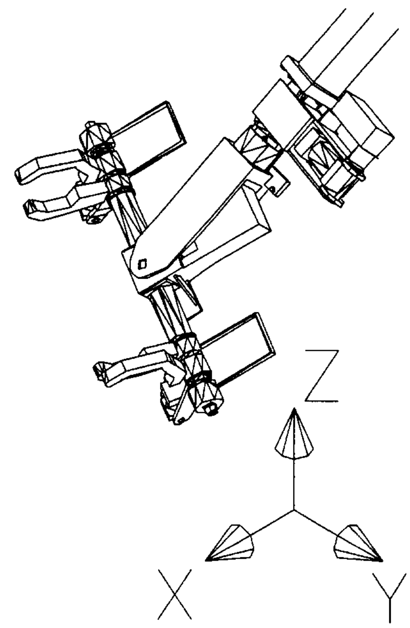

FIG. 9. GLOBAL Coordinate Frame

DIRECT Mode

The DIRECT mode is the spaceball's original configuration, in which there is a one-to-one mapping of the spaceball's six DOF to the LSM's six DOF. Each spaceball DOF is connected to a joint on the LSM. Translational DOF are exercised by pushing the spaceball along the *X*-, *Y*-, and *Z*-axes. Rotational DOF are exercised by twisting the spaceball about the *X*-, *Y*-, and *Z*-axes. In DIRECT mode, no path from a starting point to a target point is generated using the spaceball. Actual movement of a spaceball DOF results in a comparable motion by the corresponding LSM joint.

GLOBAL Mode

This mode is operated using the three translational DOF of the spaceball. The three rotational DOF are inactive. The three active DOF are attached to the *X*-, *Y*-, and *Z*-axes of the GLOBAL coordinate frame shown in Fig. 9. For example, pushing forward on the spaceball will move the end effector directly outward into the LSM's work space along the GLOBAL *X*-axis. During this motion, the end effector orientation will not change.

BOOM Mode

This mode also is operated using only the three translational DOF of the spaceball. The BOOM mode is similar to GLOBAL mode except that the special work space coordinate system for this mode is aligned with the boom plane of the manipulator. The GLOBAL coordinate frame is merely rotated through the swing angle to attain the BOOM coordinate frame. Fig. 10 shows both the GLOBAL and the BOOM coordinate frames in the LSM work space. A forward force on the spaceball causes the end effector to move directly out into the work space along the *X*-axis of the BOOM coordinate frame.

SWIVEL Mode

This mode uses the three translational DOF of the spaceball. They are used to operate the positioning DOF (swing, lift, and

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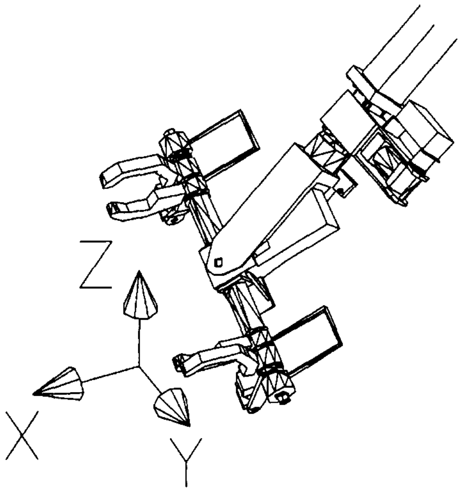

FIG. 10. BOOM Coordinate Frame

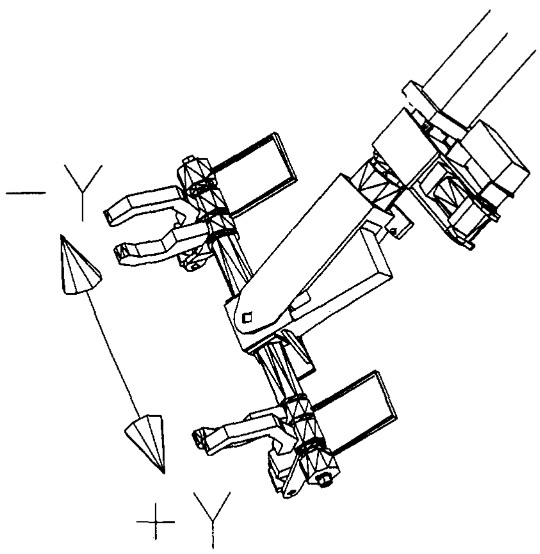

FIG. 11. THREAD Coordinate Frame

telescope) of the LSM. As these joints are exercised, the orientation of the end effector is maintained as it was when SWIVEL mode was selected. This allows the operator to move the end effector all over the work space but the end effector orientation remains constant. Like DIRECT mode, SWIVEL mode does not use a path generated from a starting point to a target point.

THREAD Mode

The THREAD mode is used to thread a pipe held by the LSM into a confined space. The operator must line the pipe up with the opening in which it will be inserted. Once THREAD mode is selected, the only active spaceball DOF is the Y-axis. A target point is projected from the current point along a line parallel to the pipe axis. This THREAD coordinate frame is shown in Fig. 11. If the operator pushes the spaceball to the right along the Y-axis, the LSM will move the pipe in a straight line along the path from the starting point to the target point.

PLACE Mode

This mode uses the X and Z translational DOF of the spaceball. It allows simple control of the LSM with a pipe in its jaws. Exercising the spaceball DOF along the X-axis results in horizontal movement of the pipe along a line perpendicular

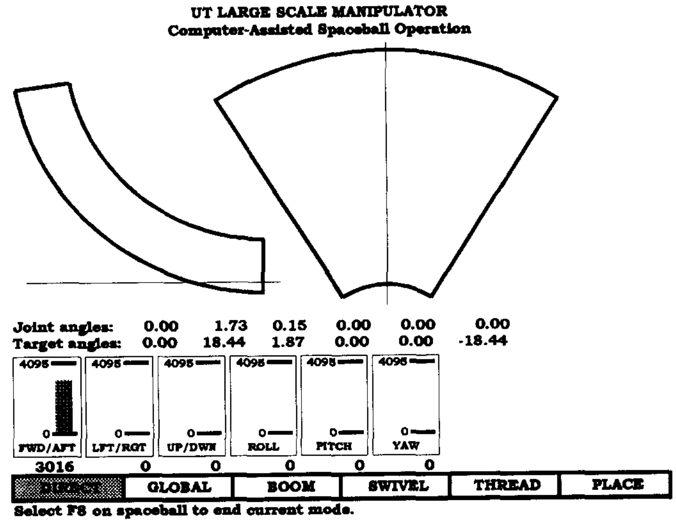

FIG. 12. Modes Display Screen

to the pipe axis. Exercising the spaceball DOF along the Z-axis results in vertical motion of the pipe along a line perpendicular to the pipe.

Graphical Interface for Modes

A computer graphical interface was developed to simplify computer-assisted operation of the LSM. When this software is started, the spaceball is in DIRECT mode. The display screen shown in Fig. 12 appears on the computer monitor. The row of cells at the bottom of the screen shows the modes available to the operator. When the program is started, the DIRECT cell at the bottom of the screen is highlighted to indicate the active spaceball mode. A new mode then can be selected by choosing the selection key for the desired mode.

The upper portion of the screen displays graphical representations of the LSM work space. The left plot is a profile view and the right plot is a plan view. The profile view is not a traditional profile view because it is not a side projection of the work space onto a plane parallel to the global X-Z plane. Instead, it is a radial cross section of the work space on which every cross section of the work space is projected circumferentially. The horizontal line on the profile view represents the laboratory floor. These plots show the power of a graphical interface in providing views of the work space that are not accessible to the operator's eye. The current location of the LSM wrist joint and a stylus tip are plotted on these graphs as the LSM moves. This provides a real-time graphical representation of the path traversed by the LSM.

Current and desired angle positions are displayed just below the graphical plots. Directly below that are a series of cells containing bar gauges that graphically show the force and torque being applied to each of the six spaceball DOF. A digital readout of each bar gauge appears below each cell. Active DOF are highlighted, so all six bar gauges are highlighted in DIRECT mode. When a mode that does not use all six DOF is selected, only the active DOF are highlighted. For example, if THREAD mode is selected, only the cell for the left/right DOF is highlighted.

Analysis of Modes

Performance tests have not been developed to characterize the various computer-assisted manual operation modes. However, qualitative analysis reveals that these modes significantly enhance the capability of the spaceball as an operator interface. The ability to select different modes at any time means the operator can maneuver the LSM about the work space per-

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forming various tasks, selecting the most useful mode for the task at hand. This ability to change modes at any time is especially beneficial in construction because of the unpredictable nature of the work space.

LESSONS LEARNED FOR FUTURE LSM DEVELOPMENT

While researching the development and testing of new operator interfaces for the LSM, many lessons were learned that need to be considered by designers and manufacturers of future large-scale hydraulic manipulators. Issues to be considered fall into three categories: computer-assisted operation issues, field-related issues, and electrical and hydraulic system issues. Some of these considerations were intuitive prior to testing; however, data collection has reinforced their importance. Consideration of these issues during the design and manufacturing stages can lead to more productive and useful large-scale hydraulic manipulators in the future.

Computer-Assisted Operation

Need for Standardized Tests for LSM Operation

As previously stated, the tests used for this research are not effective tests for large-scale hydraulic manipulators. These tests were designed to characterize the performance of small robots in an industrial environment and do not provide significant information of how an LSM will perform on a construction site. Also, the tests are not useful for testing computer-assisted operation. Although results from these tests have value for research purposes, it is important to understand that standardized tests are needed for characterizing performance, productivity, and control improvements of commercial LSMs.

Development of Resolved Motion Capability

A primary goal of this research has been to achieve resolved motion capability for the LSM. Resolved motion capability allows the end effector to maintain its orientation while traveling from the starting point to a target point. This motion requires coordination of all six joints of the LSM in its laboratory configuration. The original operator interface, the eight-lever console, does not allow for resolved motion because an operator can only control a maximum of two joints (one control lever per hand) at a given time.

The new computer-assisted modes allow the operator to select simply a mode for a specific task and move the spaceball in the desired direction. The LSM control software then determines the appropriate inverse kinematics necessary to produce joint control commands that will achieve the desired end effector motion while maintaining its orientation. This capability can be effective in a construction environment because it gives an LSM operator a higher degree of control. This is an excellent example of the flexibility that is offered by including a computer in the control loop for a manipulator.

Field-Related Matters

Safety Using Computer Control Must Be Addressed

It became evident while using the LSM in the testing laboratory that certain issues would need to be considered during use in the field. One important issue, particularly from a manager's point of view, is safety. Because of the inherent danger associated with operating large construction equipment, it is essential that a safety system be incorporated into the control loop of any LSM. This is even more important when a computer is included in the control loop. Software will inevitably have bugs in it. This uncertainty in the performance of a computer in the control loop requires a hierarchical safety net for immediate shutdown of the entire system.

A safety system like the one used for the UT LSM could be used for large-scale hydraulic manipulators on the construction site. In its current laboratory configuration, the UT LSM has a four-phase safety hierarchy during computer-assisted operation. The first phase is for the operator simply to stop exercising the spaceball. This is a safety measure to protect against errant commands from the operator. The second phase is to press a key on the computer that will stop sending control signals to the LSM. The third phase is to press a button that will shut off the hydraulic pump and discontinue the LSM's motion. The second and third phases are important because they do not require the computer to be shut down. This means that the data stored in the computer can be analyzed to try to diagnose what went wrong. The fourth safety phase is to press a button that shuts down the entire system—both the electric supply to the computer and the hydraulic supply to the LSM. This final phase is to be used if none of the previous shutdown methods work. It is important to try to keep the computer running so that data can be analyzed and a solution may be found to prevent future problems.

Spatial Orientation Must Be Considered for Development

Another matter to consider during operation of an LSM in the field is its spatial orientation to the work space. To allow for the spaceball coordinate frame to be mapped into the LSM work space, the location of the LSM within the work space must be known. In the testing laboratory, the UT LSM's coordinate frame is attached to a designated origin point on the floor, directly below the swing joint. This enables the encoders to tell the computer where the LSM joints are relative to that origin point. All software is written using that origin point. When the LSM is attached to the crane, it must be oriented to the crane with a new reference frame. This is a relatively simple task. The LSM coordinate frame could be attached to the coordinate frame of the crane's chassis.

The difficulty arises when the crane and LSM are used in the field. The crane must be attached to a reference frame within the work space. This orientation process will have to be performed at each new location. One way that this may be done is by using a global positioning system (GPS). The GPS surveying equipment could be used to obtain coordinates for the LSM's work space. The control software would then be updated using these GPS coordinates to link the crane to its work space.

Mechanical and Hydraulic System Considerations

Size and Mass Considerably Complicate Control of Large Equipment

The control of large-scale equipment used in construction is complicated by the size and mass of the machine as well as mechanical control phenomena. Rapid starting and stopping of large masses can cause excessive wear between mating parts. The large size makes it uneconomical to machine to the tolerances common on smaller, industrial robots. Large manipulators may have geared, rather than direct drive joints. These geared joints combined with the equipment's size cause large manipulators to exhibit backlash that is uncommon in smaller machines. The large size also means that the mating surfaces in large manipulator joints are larger. Thus, the forces needed to overcome static friction, called stiction, are substantial. Both backlash and stiction complicate position control. These two phenomena cause a control situation that must be accommodated and an inaccuracy that must be tolerated.

The effect of these physical phenomena is reflected in the

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single-loop control algorithm used for the manipulator. It is derived from a proportional control scheme. In a proportional algorithm for joint positioning, the control signal sent to an actuator is proportional to the difference between the current joint position and the desired joint position. Thus, if a joint is in a position far from the desired position, a large actuation signal is sent to move it to the desired position. If a joint is close to the desired position, a small signal is sent to nudge it to that position.

In the case of backlash, a driving link contacts a driven link with a finite velocity. This causes the driven link to jolt into motion and lurch back and forth about an average velocity until the oscillation damps out. This problem was alleviated by applying a soft start to a joint with a lot of backlash. The soft start is achieved by gradually applying the initial control signal to a joint at rest, rather than applying the full signal at once.

Stiction nullifies the proportional control law in the vicinity of the current position. A minimum force or torque is needed to initiate joint motion from rest. Thus if a joint is at rest in a position close to its desired position, the force or torque dictated by a pure proportional control law may be smaller than the minimum force/torque necessary to overcome stiction. However, if the minimum force/torque necessary to overcome stiction is applied, it may cause the joint to jump from its desired position to a position past the desired position. Then the control will apply an opposite force/torque to drive the joint back the other way. An improper control algorithm will cause the joint to slam back and forth from one side of a desired position to the other side until, by chance, the joint happens to land very close to its desired position. Such action, if persistent, will cause excessive wear and pounding of the joint.

Power Supply Limitations Must Be Addressed to Overcome Saturation

Another control problem arises because the LSM crane is a mobile machine with a limited power supply for delivering hydraulic energy to the joint actuators. In both the laboratory configuration and the crane configuration, all of the LSM joints receive hydraulic power from a single source. This limited power supply causes the actuators to saturate. Saturation occurs when the hydraulic actuators are delivering the maximum amount of power they can to a joint, but it is still less power than the amount desired by the joint controller. An additional problem stems from this hydraulic system configuration of a single power source supplying a parallel network of actuators. It is impossible to control each joint separately because changes in the actuation of one joint affect the actuation of other joints. This can be overcome by using multiple power supplies or by using the control software to regulate joint usage.

Selection of Feedback Sensors Must Be Carefully Considered

Another factor that introduces inaccuracy to attained joint positions is the type of sensors used. Four of the LSM's six joints are equipped with rotary encoders. Each encoder outputs a digital signal to the computer that quantifies how far the respective joint has traveled. The two remaining joints; the lift and telescope, are equipped with linear transducers called Temposonics. Each Temposonic outputs an analog voltage that represents the distance the joint has translated. The computer detects this voltage with an analog/digital interface card. Because the Temposonics are analog devices, their output signals contain noise that can affect the accuracy of the position information supplied to the computer.

Joint Configurations Should Be Carefully Considered and May Improve Performance

In addition to the valuable lessons learned about mechanical and hydraulic impediments to computer-assisted control of the LSM, some consideration also should be given to the configuration of the LSM. This research has proven that the pivot joint has a very limited range of motion. Increasing this range of motion would give the end effector greater mobility. Also, in its crane configuration, the LSM can use only the crane's swing joint to move from side to side. This means that even to move the LSM a slight distance sideways, the large crane swing joint must be used. By including a redundant, smaller swing joint in the LSM, it would have the ability to execute small side-to-side motions in the work space. This also could be achieved by adding a translational joint that moves sideways instead of an extra swing joint.

CONCLUSIONS

Control of construction equipment is being improved with the development of computer-enhanced manual systems and fully autonomous systems. Many potential benefits can be achieved by enhancing construction equipment control systems. Foremost among these benefits are improvements in safety, costs, labor turnover, faster learning curves, and productivity. An effective method to characterize improvements in control systems for construction equipment is to develop performance tests. The results of these tests provide researchers with numeric and graphical means of comparing the efficacy of control systems. Testing of the LSM showed that autonomous control exhibits better performance characteristics than manual operation in a controlled environment. However, construction usually takes place in an uncontrolled environment. For this reason, the writers developed computer-assisted operation modes to improve the performance of manual operation while keeping a human operator in the loop to counter the unpredictability of construction operations. An important derivative of this research is a series of eight lessons learned that should be considered during future development of large-scale hydraulic manipulators. By addressing these issues, LSMs will become more effective in future field construction operations. Such tasks include cleaning, sandblasting, and painting complicated geometries, pipe spool erection, and remote, semiautonomous manipulations in a hazardous environment.

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