Performance Testing of a Large Scale Manipulator to Determine Relative Utility of Several Operator Interfaces

Frank C. Owen[1], Graduate Research Assistant, The University of Texas at Austin
Gwan Park, Graduate Research Assistant, The University of Texas at Austin
Carl T. Haas, Associate Professor, The University of Texas at Austin
G. Edward Gibson, Assistant Professor, The University of Texas at Austin
Alfred E. Traver, Senior Lecturer, The University of Texas at Austin

Abstract

Performance tests were conducted on the University of Texas's Large Scale Manipulator (LSM) while it was being operated via three input command interfaces. Two of the interfaces were manual interfaces–a conventional eight-lever operator console and a six-degree of freedom (DoF) spaceball. The third input interface was preprogrammed motion, in which the LSM performed motions preprogrammed into an input file without operator intervention. The tests were based on ANSI tests for industrial robots. The tests measured accuracy, repeatability, and speed. The purpose of the tests was to rate the performance of the LSM under each command interface. Tests showed preprogrammed path following be the superior to manual operation. Current research aims to develop special computer-assisted modes of operation for the spaceball that should make path following under manual control viable.

1: LSM introduction

The UT LSM was originally developed in the 1980s as a pipe manipulator mounted on the end of an all-terrain crane. Past and present research has enhanced its pipe handling capability and has endowed it with a level of performance that makes it useful as a general purpose, heavy duty robot for a variety of construction tasks [1,2,3].

The manipulator has been moved indoors to a laboratory test frame to allow for development in a more controlled environment [5]. As configured in the laboratory, the LSM has 5 revolute (rotating) joints and 1 prismatic (telescoping) joint (Figure 1). With all but one joint revolute, the LSM is basically a spherical manipulator. That is, it most naturally can perform motions along circular arcs. Most of the paths specified for tasks in a construction environment are rectilinear. Thus the fundamental problem in research with this construction robot is to make a spherical manipulator follow rectilinear paths.

The LSM is hydraulically actuated from a single hydraulic pressure source, which supplies individual hydraulic actuators on each joint. To move the manipulator end effector along a line while maintaining end effector orientation, all six LSM joints must be exercised simultaneously, at different rates determined by the path and orientation. This is very difficult to achieve because the action of the hydraulic actuator at one joint influences the action of the hydraulic actuators at every other joint. That is, the system is highly coupled, and thus difficult to control. We have implemented *pseudo-resolved motion*. It is

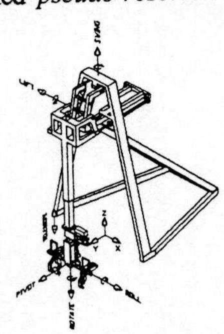


Figure 1. LSM mounted on laboratory test stand with DoFs shown.

[1] Correspond to fowen@mail.utexas.edu or (512) 471 7950.

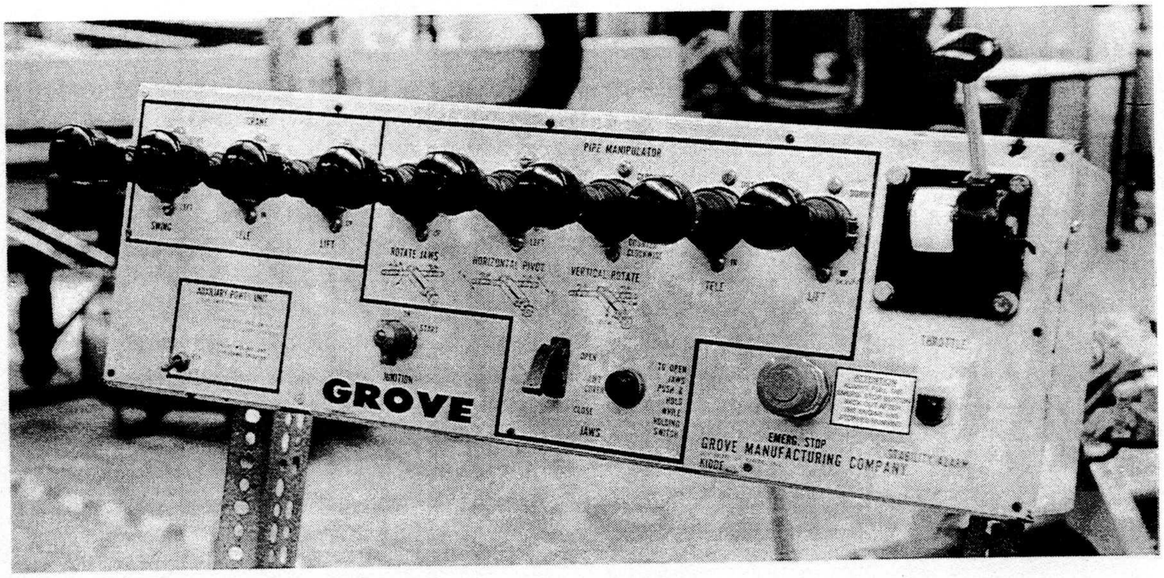


Figure 2. Eight-lever operator console.

not true path following, as described above, but rather point-to-point path following. The proper position and orientation of the LSM occurs only at designated points along a desired path not continuously along it. Future research is aimed at developing true resolved motion and special computer-assisted operation modes for the spaceball interface.

2: Description of interfaces

The eight-lever operator console consists of eight dual-action joysticks, each connected to a joint on the crane or the LSM (Figure 2). A joint can be moved forward or backward by moving its control lever up or down. Also the speed of the joint can be varied by the extent of motion imparted to its control lever. The console is a cumbersome device in that it is neither intuitively apparent which lever controls which joint nor how the lever direction complies with the joint direction. Also, an operator cannot operate more than two joints at a time with his/her two hands.

The spaceball puts control of six of the LSM's joints into a single device (Figure 3). The spaceball has six DoFs. An operator can push it or pull it along any of its three coordinate axes, or he/she can twist it about any of its coordinate axes. Thus it is possible to move all six joints simultaneously by pushing and twisting the spaceball along and about its coordinate axes.

With preprogrammed control, the operator is removed from the loop. Closed-loop control was implemented in which movement commands are read from a command file. A computer controls the LSM by sensing current joint positions, comparing them with desired joint positions, and actuating each joint until the current position is within a prespecified tolerance of the desired position.

3: Testing

3.1: ANSI test format

Tests were based on ANSI/RIA R15.05, American National Standards Institute test specifications for industrial robots and robotic

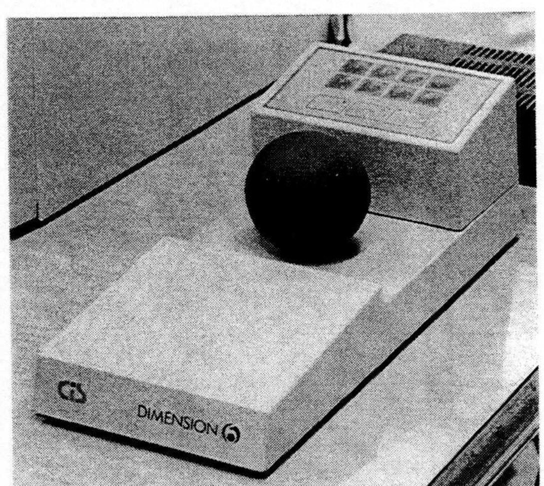


Figure 3. Six-DoF spaceball.

systems. The ANSI/RIA standard specifies paths that the manipulator must follow in its workspace [6]. There are two test patterns, one for static tests and the other for dynamic tests. (These patterns are shown with test results in Figures 5 and 6.) The standard specifies that these patterns must lie in a designated oblique plane in the robot's workspace. The tests paths used for these tests were modified because of difficulties encountered with the ANSI/RIA designated plane orientation. Because of the shape of the LSM's workspace, the test plane specified by ANSI/RIA has only a small intersection with this workspace. This would have resulted in quite small test paths that would be unreasonable to use with such a large manipulator. A different test plane was used, namely the laboratory floor, because it has a bigger intersection with the robot's workspace. This modification was not considered significant in the research because a rectilinear test path in any plane would serve the purpose of assessing the ability of the manipulator to follow straight lines.

The ANSI/RIA standard also specifies a great deal of repetitive testing. The standard was written to benchmark the capabilities of normal industrial robots meant for commercial use. The LSM is not a robot that functions in a highly repetitive industrial environment like an assembly line. This research also is not directed at immediate commercialization of the LSM. Therefore it was felt that the number of specified repetitions could be significantly reduced, since the results serve rather as a milestone against which to measure future performance improvements, than as a performance test preliminary to commercialization or for acceptance of a purchase.

In manual tests the LSM was loaded with a 363 kg test load equipped with a stylus. Figure 4 shows the LSM loaded with its test load. Note the test pattern on the lab floor and the stylus fitted to the test payload. The operator's task was to make the stylus follow the test path while maintaining the original orientation of the test load and stylus. The preprogrammed tests were run both in a loaded condition and an unloaded condition.

3.2: Test results

The ANSI/RIA standard specifies the data to be collected for each test and how they should be analyzed. The static tests measure only a robot's ability to arrive at specified points on the static test pattern. It does not make any requirement on the end effector's path between the test points. The dynamic tests do measure path following at intermediate points along the test pattern. A grid is laid over the dynamic test pattern. It intersects the test pattern at waypoints. The end effector's proximity to these waypoints as it moves along the path is measured.

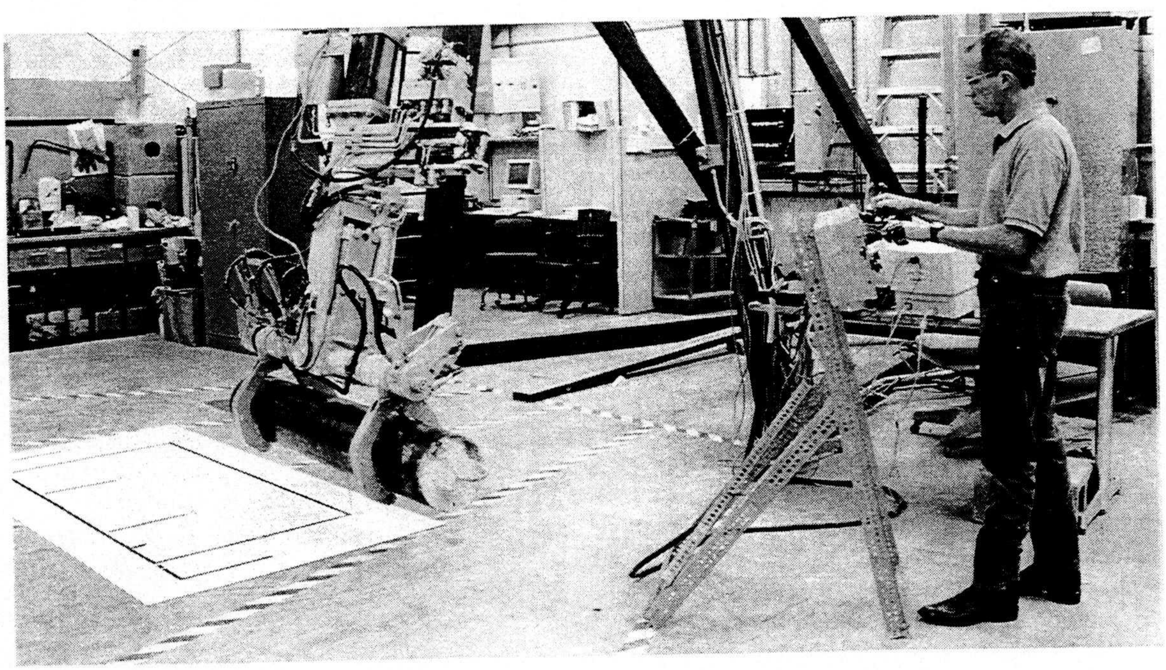


Figure 4. LSM loaded with test load under manual operation.

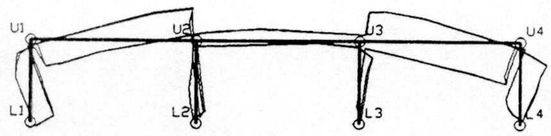


Figure 5. Static test results.

Tests measured three performance parameters–accuracy, repeatability, and speed. Accuracy is the deviation of the attained points from the test points on the test patterns. Two such deviations are reported–average path deviation and maximum path deviation. In the repeatability tests, the average attained test point was determined. Then the deviation from these average points was determined. This measurement is very much like a standard deviation. In the speed test, the average traversal speed of the path was determined as well as the maximum deviation in speed over two different path segments.

The results for the static tests are shown in Table 1. The data show that accuracy and repeatability are very good, especially for a robot of this scale. Figure 5 is a qualitative illustration of these test results. Note the high degree of repeatability in these tests.

The most disappointing test result was the speed. There are two reasons for the slow speed. First, the control algorithm for closed-loop control was somewhat simplistic. It took quite some time for the LSM to attain each of the desired points. The speed could be improved by improving the control algorithm or relaxing the tolerance on displacement error.

Results from the dynamic tests are shown in Table 2. The quantities reported are the same as those reported for the static tests. Two sets of tests were run–one in an unloaded condition and a second with a 363 kg test load. Again, accuracy and repeatability were satisfactory, but the speed was unacceptably slow. These results are displayed qualitatively in Figure 6.

The sawtooth nature of the path indicates that the LSM does not have true resolved motion but rather only pseudo-resolved motion. The LSM wrist joint follows a desired path by intersecting it only at certain specified intermediate points. This is because only displacement, not velocity, is controlled. Finer path following could be achieved by placing intermediate points closer to

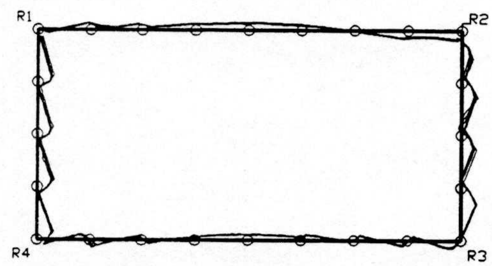


Figure 6. Traversal paths of end effector over dynamic test pattern.

Test	Quantity	Value
Accuracy	Average path deviation	3.34 cm
Accuracy	Maximum path deviation	4.53 cm
Repeatability	Average path repeatability	0.596 cm
Repeatability	Maximum path deviation	1.52 cm
Speed	Average speed	3.37 cm/sec
Speed	Maximum cycle speed fluctuation	2.10 cm/sec

Table 1. Static test results.

Test	Quantity	Unloaded	Loaded
Accuracy	Average path deviation	3.13 cm	2.86 cm
Accuracy	Maximum path deviation	5.92 cm	4.82 cm
Repeatability	Average path repeatability	0.608 cm	0.122 cm
Repeatability	Maximum path deviation	3.07 cm	0.748 cm
Speed	Average speed	3.37 cm/sec	0.924 cm/sec
Speed	Maximum cycle speed fluctuation	1.48 cm/sec	5.21 cm/sec

Table 2. Dynamic test results.

each other. The drawback to this approach is that seeking each point is time consuming. So the overall time needed to traverse the path is unacceptably long. True resolved motion involves velocity control. Current research is directed at developing true resolved motion for the LSM. It is further described in section 5 below.

Besides the closed-loop tests described above, path following under manual operation was also tested. Two different manual interfaces were used–the original eight-lever console and the spaceball. It quickly became evident that path following under manual operation was much less accurate than closed-loop path following. Operation with the eight-lever console was more cumbersome than with the spaceball. Figure 7 shows an attempt to follow the dynamic test pattern on the laboratory floor with spaceball input. Besides wandering off the path, the operator sometimes had to backtrack to recover a position on the path.

The problem with manual control is that it is impossible for the operator to perform inverse kinematics in an intuitive way so that he/she knows what joint movements are necessary to achieve a desired rectilinear movement. In the general case, all six joints must be exercised to follow a straight-line path. With the eight-lever console, it is physically impossible for an operator to manipulate more than two joints at a time. But even with the spaceball interface, where the operator can move six joints at once, the informational burden needed to move these joints correctly and simultaneously was simply too great for an operator to process. Rather than using all six joint movements simultaneously, the operator limited movements to two or three joints, to reduce the amount of feedback information that needed to be processed. So even though the operator could move six joints at once, he/she did not do this because of the inability to synchronize so many motions. For this reason, though path following with the spaceball was superior to eight-lever operation, it was not strikingly better. But because of the ability to reprogram the spaceball, new modes of operation are being developed that will improve spaceball input so that it has a utility similar to that of closed-loop control.

To summarize, test results demonstrated the superiority of preprogrammed, closed-loop operation over manual operation. Operation with the eight-lever console was particularly cumbersome. Operation with the spaceball, though clumsy, can and is being improved through the development of special computer-assisted modes of operation.

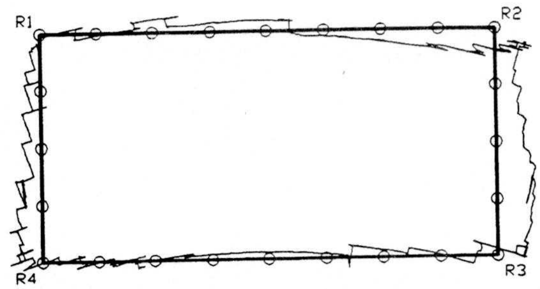


Figure 7. Attempt to follow dynamic test pattern using spaceball as input device.

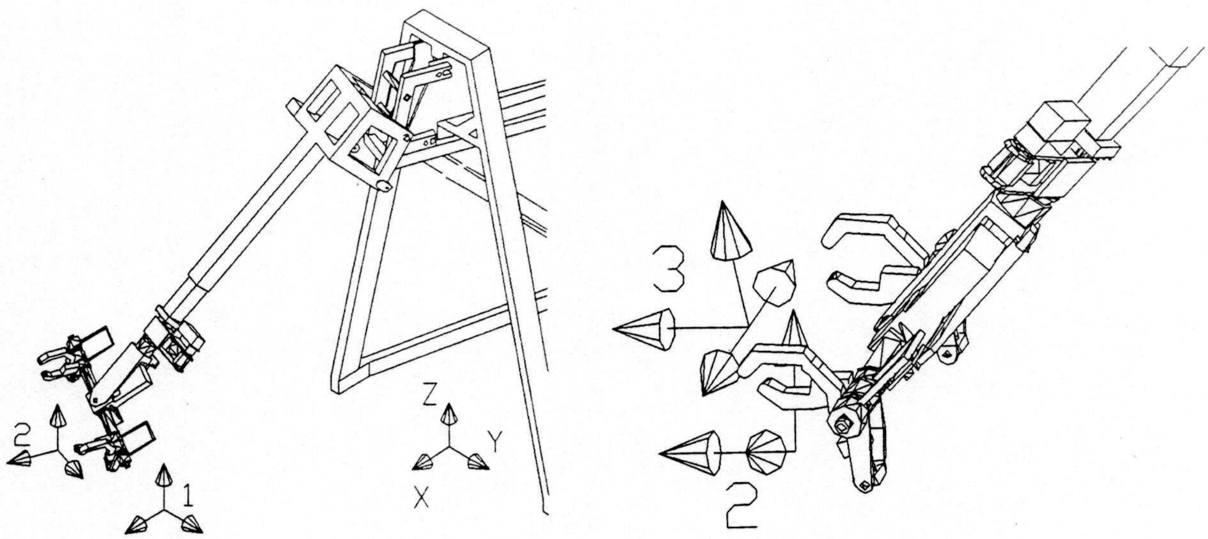
4: Computer-assisted manual modes

Testing showed closed-loop control to be superior to control via either manual interface. Unfortunately in a construction environment only a small number of motions can be preplanned. There is a great need to be able to perform ad hoc motions as the need arises in the construction environment. Thus some type of computer-assisted manual operation of the LSM would be useful.

Though control of the LSM through the spaceball was not as accurate as preprogrammed control, this deficiency is not inherent in the spaceball's configuration or geometry. In fact an important feature of a programmable input device is its flexibility. The relative inaccuracy of path following via the spaceball was attributed to the simplified method of connecting it to the LSM. This is *direct* mode, in which there is a one-to-one connection between the spaceball's DoFs and the LSM's DoFs.

To improve the performance of the LSM with this device, several computer-assisted modes of spaceball operation are under development. These are described below. Figure 8 illustrates these modes. All modes will have true, resolved motion. Ongoing work to develop control for resolved motion is described in the following section.

Global rectilinear mode: In this mode the three translational DoFs of the spaceball are active. For example, motion straight out into the workspace on a horizontal line is initiated by exerting a forward force on the spaceball. This motion is parallel to the global X axis.



(1) Global rectilinear vs. (2) boom plane mode (2) Boom plane vs. (3) pipe placement mode (note threading (double) axis in (3))

Figure 8. Computer-assisted modes of manual operation.

Boom plane mode: This mode is similar to the previous mode except that the spaceball coordinate system is rotated about the global Z axis so that forward/aft motion of the spaceball results in in/out motion of the LSM end effector on a horizontal line in the plane formed by the first two links of the manipulator.

End effector swivel mode: The three translational DoFs of the spaceball are active. They are directly connected to the three gross-motion DoFs of the LSM (swing, lift, telescope). Those joints can be exercised as desired. As the end effector wrist location is moved about the work space, end effector orientation remains constant in global coordinates.

Pipe threading mode: This mode is motivated by the original end use of the LSM, to assemble pipe spools in a supporting structure. In this mode, three DoFs of the spaceball are activated, but only one motion results from exercising any of them. LSM motion is forward or backward along a line described by the axis of a pipe held in the manipulator jaws.

Pipe placement mode: The three translational DoFs of the spaceball are active. Forward/aft motion of the spaceball makes the end effector wrist point move in a horizontal line perpendicular to the axis of a pipe grasped by the jaws. Up/down motion of the spaceball causes motion perpendicular to the axis of a grasped pipe and the horizontal line of the forward/aft motion. Left/right motion of the spaceball causes pipe threading motion, as described above.

All computer-assisted modes work by generating simple rectilinear one-segment paths. The manipulator's inverse kinematics are performed in real time to convert the desired path into joint space, where closed-loop control can be done.

5: Control for resolved motion

The pseudo-resolved motion exhibited by the LSM under its present control scheme has two flaws: 1) the coarse path following exhibited in test results and 2) the slowness of motion along the intended path. The following is a description of the current research plan to address these two performance defects.

The sawtooth nature of the test paths under closed-loop control resulted from the control system ignoring the coupling in the LSM hydraulic actuation system. Conventional industrial robots are equipped with separate electric motors for each joint. Actuation of one motor does not effect actuation of any other motor. In contrast, with a hydraulic system, typically one hydraulic pump supplies fluid to more than one hydraulic actuator. Joint velocity depends on the flow rate of fluid to the joint's actuator.

To move the LSM's end effector along a rectilinear path, multiple joints need to be moved in unison at set relative speeds. So the flow rate of hydraulic fluid needs to be properly balanced between actuators. The control system cannot deal with each joint separately because of this coupling. In the terminology of control theory, the system is a multiple-input/multiple-output (MIMO) system.

The pseudo-resolved motion used in the tests reported here treats the system as a collection of single-input/single-output subsystems. The control system consists of a set of single-loop controllers that supposedly operate independent of each other. See [4] for a complete account of the research to implement single-loop control.

There are a number of proven ways to deal with MIMO systems. In general they consist of developing a mathematical model of the system to be controlled and then using this simulation to develop a control law that will give the proper signals to the actuators to make them move as desired. The performance of the control is highly dependent upon how accurately the mathematical model of the system mimics the behavior of the real system.

Unfortunately the LSM has certain physical characteristics that are difficult to capture in a mathematical model, including backlash, stiction, hydraulic fluid properties that vary with time and temperature, the pronounced nonlinear dependence of joint torques on payload and workspace location, etc. Because of this, it was decided to use a two-tiered controller. The base controller is a very simplified model-based controller. The secondary controller will compensate for the gross simplifications that are made by the base controller.

The LSM model has been simplified by ignoring all dynamic effects in both the actuation system and the LSM structure itself. This cannot be done with conventional industrial robots. The speed at which these devices are operated makes dynamic effects dominant. These devices generally have payload limits that are less than 10% of their structural weight [7]. Large manipulators, on the other hand, may carry payloads in excess of 50% of their weight. High speeds are dangerous in that a heavy payload can be dropped or flung inadvertently from the gripping assembly. Also sudden rapid accelerations and decelerations subject a robot with a high payload/weight ratio to unacceptable jolting and pounding.

The low, steady velocities thus permit treating LSM motion as pseudo-static. The base controller under development computes joint torques for the actuation system based upon static calculations. The dynamics of the hydraulic system are ignored also. Control signals to the hydraulic system are calculated assuming acceleration time up to a steady speed is negligible. In moving from one point to another, the joints spend most of the time at a constant velocity.

Control of the LSM has been implemented on a standard PC compatible microcomputer. The computer is equipped with interface cards that allow the computer to sense joint positions and to send actuation signals out to hydraulic valves that control the flow rate of fluid to each joint's actuator [4].

Control software for driving the LSM has evolved during the past year of concentrated effort into a modular, reusable, and flexible system. Libraries of C and C++ functions have been written to implement the interface between the LSM and the control computer, to perform the kinematics and inverse kinematics for the manipulator, for the spaceball interface, for data acquisition, and for control. The reusability of C++ objects has shortened development time of new applications and programs written to test performance characteristics of the LSM.

6: Conclusions

The UT LSM was equipped with a six-DoF spaceball input device to take the place of a conventional eight-lever operator console. This allowed the operator to control more than two joint movements at a time. Each joint on the LSM was also fitted with position indicating devices that could be read by a computer. This allowed for closed-loop control of LSM motions.

Tests were conducted to compare control of the manipulator via the eight-lever console, the spaceball, and by the computer in an autonomous mode. The tests were based on the ANSI/RIA R15.05 standard for industrial robots, modified to suit specific characteristics of the UT LSM as well as use as a researching benchmark.

The tests showed that pre-programmed, closed-loop operation gave better performance than manual operation through either manual interface. In general, accuracy was acceptable, repeatability was surprisingly good, but speed was slow. The slow speed resulted from pseudo-resolved motion, where only position is controlled and it is controlled only at specified intermediate points along a desired rectilinear path.

The short term research strategy was outlined, including a description of the improvements that will be added to the spaceball interface. These improvements consist of a number of new modes of operation that will allow the operator essentially to run the manipulator with real-time, closed-loop control.

References

[1] D. Alciatore, Automation of a Piping Construction Manipulator and Development of a Heuristic Application-Specific Path Planner, *Dissertation*, The University of Texas at Austin, December 1989.

[2] T. Hsieh and C. Haas, Determining Functional Requirements for Large Scale Manipulators, *Automation in Construction*, 3 (1994) 55-64.

[3] P. Hughes, Construction Manipulator Teleoperation with Ergosticks, *Dissertation*, The University of Texas at Austin, May 1990.

[4] G. Park, Digital Control of a Hydraulically-Actuated Large Scale Manipulator, *Thesis*, The University of Texas at Austin, December 1996.

[5] G. Thomas, The Development of an Advanced Control System for the University of Texas Large Scale Hydraulic Manipulator, *Thesis*, The University of Texas at Austin, May 1995.

[6] M. Wiersma, Standards and Benchmark Tests for Evaluating Large Scale Manipulators with Construction Applications, *Report*, The University of Texas at Austin, December 1995.

[7] W. Wolovich, *Robotics: Basic Analysis and Design*, Holt Rienhart and Winston, New York, 1987, Chapter 1.