Design of the Langley Laboratory Telerobotic Manipulator

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NASA Langley has developed a new, precision, dual arm telerobotic manipulator system which has seven degrees of freedom in each arm. As delivered, a master/slave control mode is implemented from a pair of kinetically identical master arms with force reflection; however, robotic or manual control from a variety of different input devices can be implemented. The Langley Laboratory Telerobotic Manipulator (LTM), its installation at Langley, and plans for a comparative evaluation study of various control input devices to the system, are described in this article.

Introduction

The Shuttle Remote Manipulator System (RMS), though crude, has demonstrated that teleoperated manipulator arms can perform useful tasks in space. It has launched satellites, repaired broken satellites, acted as a mobile platform for astronauts building trusses in space, and dealt with many other unexpected problems.

But jobs of much greater complexity, beyond the capability of the RMS, and often requiring the coordinated motion of more than one arm, will be required in the near future. Very large orbiting stations will have to be built to gather solar power for retransmission to Earth; to accommodate specialized, reduced gravity manufacturing; to support deep space exploration; to house large telephone relay operations; to provide facilities for general experimentation in the space environment; and to accommodate a variety of other similar operations. It will not be practical, or perhaps even possible, to assemble these expansive orbiting platforms with simple telerobotic arms like the RMS or with EVA astronauts alone. NASA will need advanced automation, robotics, and telerobotics with a high degree of sensory feedback to make assembly of these space platforms a practical reality.

Basic research is ongoing at several NASA installations to create the enhanced teleoperator capabilities needed. Progress has been made, but most of the technology has been developed and evaluated at the part-task level. Development has centered around modified industrial manipulator arms such as the Unimate PUMA which are not designed for space operations or for the robotic generality needed in space applications. What has been needed is a systems level testbed based on new manipulators designed specifically to accommodate the operational constraints of space.

Design Responds to Space Constraints

Langley Research Center is assembling a new research laboratory which will begin to address this need. The focus of the new facility is a new manipulator system called the Laboratory Teleoperator Manipulator (LTM). It is a new one-of-a-kind manipulator built by the Oak Ridge National Laboratory under the direction of the Langley Research Center to accommodate the tasks and conditions of space operations. The LTM is a full, dual-armed, force reflecting, master/slave manipulator in its basic form. In master/slave operations the master arms are moved directly by a human operator using grip handles at their ends. The slave arms, in turn, replicate the movement of the master arms exactly or according to some scale factor. The LTM also has full robotic capability in which both the slave arms function under total computer control. The master arms can be controlled similarly. The arms are designed to have a high degree of modularity. Most links can directly replace each other on the master and slave. Friction drives in the joints are used, rather than gears to minimize backlash and provide the more repeatable end effector positioning needed for robotic control. The LTM employs seven degrees of freedom (DOF) in each arm to give each of them one redundant degree of freedom for configuration control and singularity avoidance.

At Langley the LTM slave is being placed on a specially built tracked carriage with a turntable which provides a translational and a rotational DOF.

The first studies to be carried out in the Teleoperator Systems Research Laboratory (TSRL) will explore the relative effectiveness of various control input devices and methods of controlling the LTM slave arms. A quick study will compare master/slave control using various combinations of the master arms' available seven DOF, taken six at a time. That is, each of the master degrees of freedom will be locked one at a time and the same task performed with the remaining six. This study will be followed by a much larger study which will compare control of the LTM slave by a number of individual controllers.

In addition to the LTM master, the following control input devices will be used:

- Kraft Controllers, which are reduced scale masters having controller motion kinematically similar to the slave motion, and six DOF with force reflection in all but the wrist. The kinematic similarity provides an intuitive relationship with the slave, but because of the differences in degrees of freedom between them, redundancy algorithms are required to implement control.

- JPL force reflecting hand controllers which have six DOF with force reflection in all axes. These controllers accommodate a large range of motion comparable to that of a full scale master, and have one prismatic joint as opposed to the usual all-revolute joints.

- CAE controllers which are a ball-type, having limited Cartesian motion and a full six DOF, including three rotational and three translational DOF.

- Dimension Six controllers which are also ball-type, but produce Cartesian output from forces and torques applied to the ball. As with the CAE controller there are three translational and three rotational DOF.
Objectives and Philosophy of Design

The LTM was designed to be used in a ground-based laboratory setting to study both robotic and telerobotic applications in space. Hence, its design includes characteristics considered necessary and desirable for use in space as well as design compromises to bridge the gap between human and purely robotic control. Previously, this type of research has centered around modified industrial manipulator arms such as the Unimate PUMA which are not designed for space operations or for general research in robotics. Man-in-theloop control is currently required because the present level of robotic generality is insufficient for most near-term space applications. It is also likely that a hybrid human/computer control will continue to be desirable as an option, even if human control is ultimately relegated to a backup or contingency for unanticipated situations. Control of the LTM requires blending fundamentally different design objectives to simultaneously achieve both good robotic and good teleoperator control. High joint back drivability for force reflection with minimum reflection of friction and inertia are the most important considerations for master/slave manual operation, but end effector accuracy and speed, along with mechanical and control stiffness are the important considerations for robotic control [1].

The LTM master and slave manipulator systems each have two arms, each of which has seven DOF giving them kinematic redundancy. In master/slave operation, the most basic mode, the slave arms replicate the motion of the master arms according to any of several motion ratios as well as force reflection ratios. Force reflection is bilateral with the corresponding arm on the opposite arm pair. The links which make up the arms (i.e., upper arm, forearm, etc.) are modular and replace each other exactly except that the slave shoulder and upper arm are a scaled larger version to give the slave greater capability. Thus, the larger arm elements replace each other and the smaller elements replace each other. Movement of the links in the LTM arm is implemented by a differential joint (Fig. 1) located between the links and producing a pitch/yaw relative motion between them. The output shaft of the joint rotates about its own axis as well as about an orthogonal axis located in the joint. The direction, axis, and speed of the output shaft motion depend on the combined speed and direction of the input pinion rollers which are individually driven by permanent magnet motors through zero backlash gears to increase their mechanical advantage. An additional roll motion was put between the forearm and end effector to form a third axis for the wrist. To make the LTM a more exact and repeatable positioner, traction drives are used in the differential [2]. They permit smooth, steady transfer of force without the backlash associated with gears. Gold plating on the surfaces acts as a space-suitable, dry lubricant. Normal forces between the surfaces are produced by variable preload mechanisms which make the joint more back drivable and efficient. These mechanisms were designed especially for the LTM to produce normal loads which change so that they remain proportional to the torque being transmitted. Friction drives have not been used previously to mechanize manipulator systems and thus represent a high-risk technology application in the LTM, but one that holds significant potential in the space environment. Because input to the differential is from two rollers, each roller is required to produce only half the needed torque. This reduces the required motor size and resulting weight. Two intermediate rollers interface with both the single output roller and the two input rollers. An "L" bracket which is connected to the output shaft and to the following arm element causes that element to move in an apparent pitch/yaw motion.

As a part of its installation at Langley, one translation and one rotation DOF were added to the LTM slave base by placing it on a turntable which is in turn mounted on a 25-ft long track. The turntable presently is limited to 290° of motion. These motions can be controlled either manually or by the computer.

Control Electronics

The electrical and electronic hardware that implements the LTM control schemes and other related information processing consists of both commercially available systems and custom electronics [1]. Most of the custom electronics packages were designed to be housed in the arm links where sensory information could be locally assimilated, processed, and multiplexed for transmission to the more powerful external computing hardware. This permits the use of serial communication links thus reducing the cabling requirements sufficiently that all the arm cables (power and communication) could be passed internally through the friction-drive differentials. Each arm link contains two custom boards, a joint processor logic board, and a joint processor power board, which are multilayered with high density surface-mounted components on both sides. The logic board monitors and processes sensor outputs, while the power board supplies power and reference voltages to components in the arm link. A transceiver on the power board communicates bidirectionally over a single optical fiber with a paired transceiver located at the external computer. The transceivers transmit and receive on different wavelengths communicating such parameters as motor positions and velocities; shaft pitch and yaw positions, velocities, and torques; and temperatures within the joint.
The bulk of the information processing electronics which controls the LTM consists of Motorola 68020 single-board computers operating in parallel over a VMEbus system. These are housed in two separate cabinets, one for the master and the other for the slave, and having intercabinet communication over a high-speed serial link. A Macintosh II computer connected to the master rack interfaces the human operator to the system through a variety of menu selections of optional control commands and input parameters. The sketch of Fig. 2 shows the top-level organization of the electronics hardware. The master and slave racks also contain the pulsewidth modulator amplifiers which power the individual motors in the manipulators.

**Initial Studies**

Initial studies in the TSRL facility will evaluate teleoperator control of the LTM in terms of the relative advantages of various forms of operator input. These forms will primarily consist of several specific input devices. However, one substudy will investigate optional ways of using subsets of the seven available DOF within the replica master. Subsets will each have six DOF. The concern is that when all seven DOF are active, the replica master will respond like a wet noodle to operator attempts at control inputs creating unintended coupling into axes that produce counterproductive motion of the slave. The full seven-DOF master will be compared with several instances of the master with one DOF locked. It is possible that the axis needing to be locked is a function of the subtask scenario, thus suggesting that the operator should be provided the capability to make this selection on a real-time basis.

Several experimental tasks will be used as a basis for the comparisons stated above. These studies, in addition to providing data for the comparative evaluations, will supply the first indications of the LTM general capabilities. The tasks to be performed will be both generic ones and ones which are subtasks selected from real space application scenarios. Each subject will perform each task with each of the various input devices to be compared. A balanced rotation of subjects and tasks will be devised to eliminate effects of learning and biased groupings of runs from the data. An analysis of variance will be applied to the data. Although the LTM master will be included as one of the input devices in this study, the "locked joint" comparisons using it will be made in a separate, but similarly conducted study.

Two task boards will be used. The first one has been used previously by Langley, Grumman Aerospace, and SRI in earlier Teleoperator studies, thus providing us a link to and continuity with previous work. This board measures generic alignment capabilities through peg-in-the-hole tasks and button-pushing which are performed with various sized pegs yielding hole-to-receptacle tolerances as small as 0.001 in. A second task board looks at the mating of a number of different standard electrical connectors.

Two representative application space tasks will be performed.

1) The first task will use a hydrazine refueling probe, similar to one proposed for a Shuttle experiment. The LTM slave will be controlled to release the refueling probe from one receptacle and place it in another, followed by turning a hex head bolt with a ratchet to secure the probe and then similarly turning five additional bolt heads to open individual valves in the probe.

2) The second task will be to connect both ends of a long "Space Station type" column simultaneously to receptacles like those proposed for Space Station truss nodes. This operation requires precise coordination of both slave arms. It is important to look at and develop robotic capability for such applications to lay the groundwork for robotic assembly of the large repetitive trusses comprising the extremely large space platforms beyond Freedom. The actual Space Station columns are 5 m long, but the ones used in TSRL are only 3.94 m long because of the...
working volume available in the lab. Fig. 3 shows the same task being performed automatically in the Intelligent Systems Research Laboratory using two PUMA manipulators. The objective will be to release the column from the nodes, lift it well away from them, replace it within the nodes, and finally lock the columns in place.

Four subjects selected from a number of undergraduate engineering students on the basis of aptitude for manual control will perform the tasks. Each task/condition will be replicated five times and scored according to the time required to complete the task and the number of performance errors. Additional performance measures are being formulated to include total energy input to master, total energy output by slave, histograms of end effector rates, histograms of individual joint angle rates, histograms of end effector forces and torques, and histograms of individual joint torques. Assessments will be attempted to determine the "best" mix of attributes of control methodologies and input devices for particular jobs which have generic transfer. For instance, with one input device a given subject may perform the task in minimum time while with another he may do it with minimum energy, and with still another he may minimize performance errors. There may also be anomalies such as a condition in which minimum energy for the operator is maximum energy for the slave.

The primary study variables will be subject, task, control input device, and motion ratio from controller to remote manipulator. Additional data for force reflection ratio will be acquired for those controllers which permit it as a variable.

Concluding Remarks

The Laboratory Teleoperator Manipulator represents Langley Research Center's newest, most advanced facility for evaluating the effects of subsystem changes on the overall performance of telerobotic systems. In this context, an extensive evaluation of hand controllers and other input devices has begun. Results of the current effort should provide substantial aid to NASA programs, such as the Flight Telerobotic Servicer, which will apply telerobotics in actual space missions.

The true utility of results from individual telerobotic research projects and studies is realized only when they are incorporated into real or simulated systems and evaluated as the system performs various tasks. Evaluations of this nature are needed by designers who synthesize full scale operational space telerobotic systems. Basic research in the LTM facility will contribute by integrating and testing at the system level enhancements resulting from very focused, individual, subsystem-level telerobotic research. Output of this effort will also help to relate telerobotic system performance in simple, well-controlled, generic tasks to performance in representative complex tasks. Likewise, it will relate results in representative, ground-based tasks to flight results. Finally, this work should promote the development of improved quantitative measures and indices of telerobotic performance as well as increase the data base of design requirements for future systems.

References


