Teleoperation Experiments with a Utah/MIT Hand and a VPL DataGlove

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Abstract

We describe a teleoperation system capable of controlling a Utah/MIT Dextrous Hand using a VPL DataGlove as a master. Additionally the system is capable of running the dextrous hand in robotic (autonomous) mode as new programs are developed. We present the software and hardware architecture used and describe the experiments performed. We further analyze the communication and calibration issues involved and investigate applications to the analysis and development of automated dextrous manipulations.

1 Introduction

The research in Dextrous robotic hands has been fueled by two main factors: the interest in more versatile manipulators and the availability of truly dextrous end effectors like the Utah/MIT hand [5] and the Salisbury hand [7]. Research has ranged from low level control [13] to high level task planning or grasping issues [8,12]. However, because of the large number of degrees of freedom to be controlled implementations of complex manipulations tasks have been few. The great similarity between the human hand and the Utah/MIT hand suggested that a master-slave pairing should be possible if we could measure the human joint angles accurately and in real time. The VPL DataGlove provides just that capability.

At the Robotics Research Laboratory of New York University we have set up a hardware and software architecture suitable for teleoperating the Utah/MIT Hand with a VPL DataGlove. The Utah/MIT Hand is attached to a PUMA 560, whose position is also teleoperated. Thus, as the human wearer of the DataGlove moves his hand and fingers, the Utah/MIT Hand and PUMA mimic him closely. This work includes a sophisticated calibration procedure for the DataGlove and a supervisory real time operating system which made communication between the different system components possible. The current implementation allowed us to perform the following tasks:

- stacking blocks

- picking up a milk carton and pouring milk into a cup

- picking up the cup using the handle and pouring the milk into another cup

- picking up a nut and screwing it into a bolt.

Moreover the system also allows the operation of the robotic hand in an autonomous mode providing for a smooth transition between the different modes. This lets the operator transfer control to preprogrammed motions when appropriate. The system will be described in the following sections.

2 Other related work

Our system is purely positioned controlled and uses only the operator's visual feedback. We have not analyzed other feedback needed by the operator to facilitate the manipulation task nor have we developed a force reflecting master [1,6,11,14]. Our work is, however, unique in providing the operator with a nearly anthropomorphic end effector and a very natural interface.

The main emphasis of our work is in dextrous manipulation. Most research in that field is still in the exploratory stages, including building computer systems suitable for real time control [4]. Much of our effort has gone into this as well, as a result of which our system is quite flexible and fast; it will be compared to other systems in detail elsewhere [2,10]. As for accomplishing actual manipulation tasks using the Utah/MIT Hand, to our knowledge[4] our work is among the most successful.

3 Hardware

The hardware components of the system consist of: a VPL DataGlove, a Utah/MIT Hand, a PUMA 560, a SUN workstation and several single board 68020 based computers. The communications between the different parts of the system were either through serial lines or through Ethernet (see Figure 1).

The VPL DataGlove (or simply Glove) consists of a cloth glove with fiber-optic cables attached to the back and palm and passing over the finger joints (see Figure 2). The fiber-optic cables in the Glove are treated at the sites where fingers flex so that light escapes when a finger is bent. More light is lost when the movement is greater. Phototransistors convert the light into an electrical signal which is then digitized. Coupled with a Polhemus sensor (which can be mounted on the back of the Glove), the position and orientation of the hand in space (6 degrees of freedom from the Polhemus sensor) as well as 14 finger joint angles (from the DataGlove) can be measured in real time (about 60 times a second).

The Utah/MIT hand (henceforth simply Hand) is a 16 degree of freedom manipulator consisting of 4 anthropomorphic fingers and a palm (see Figure 2). The fingers are arranged so that one of them opposes the other three much as in the human hand. The "thumb" however, has exactly the same design as the other fingers and it must always oppose them, not allowing for a flat palm configuration. Each finger has four joints and each joint is operated by a pair of opposing tendons connected to pneumatic pistons. It has position sensors at each joint and tension sensors for each tendon, mounted on the wrist. This sensory information is used by the controller to servo the joint position and/or joint torque. The actuator package is separated from the hand by an articulated extension linkage (the remotizer) which allows the hand to be conveniently attached to a robot arm. Control signals for the pneumatic pistons come from an analog controller box which is connected to a VME bus via D/A and A/D boards. Several 68020 based Ironics boards on the bus allow implementation of a variety of digital control schemes. A SUN workstation, connected to the VME bus via an HVE bus to bus connector, is used for program development and compilation. Programs are then run on the SUN or (more commonly) downloaded for running on the Ironics boards. In our current setup both the program that maps the Glove angles to Hand angles and a monitoring
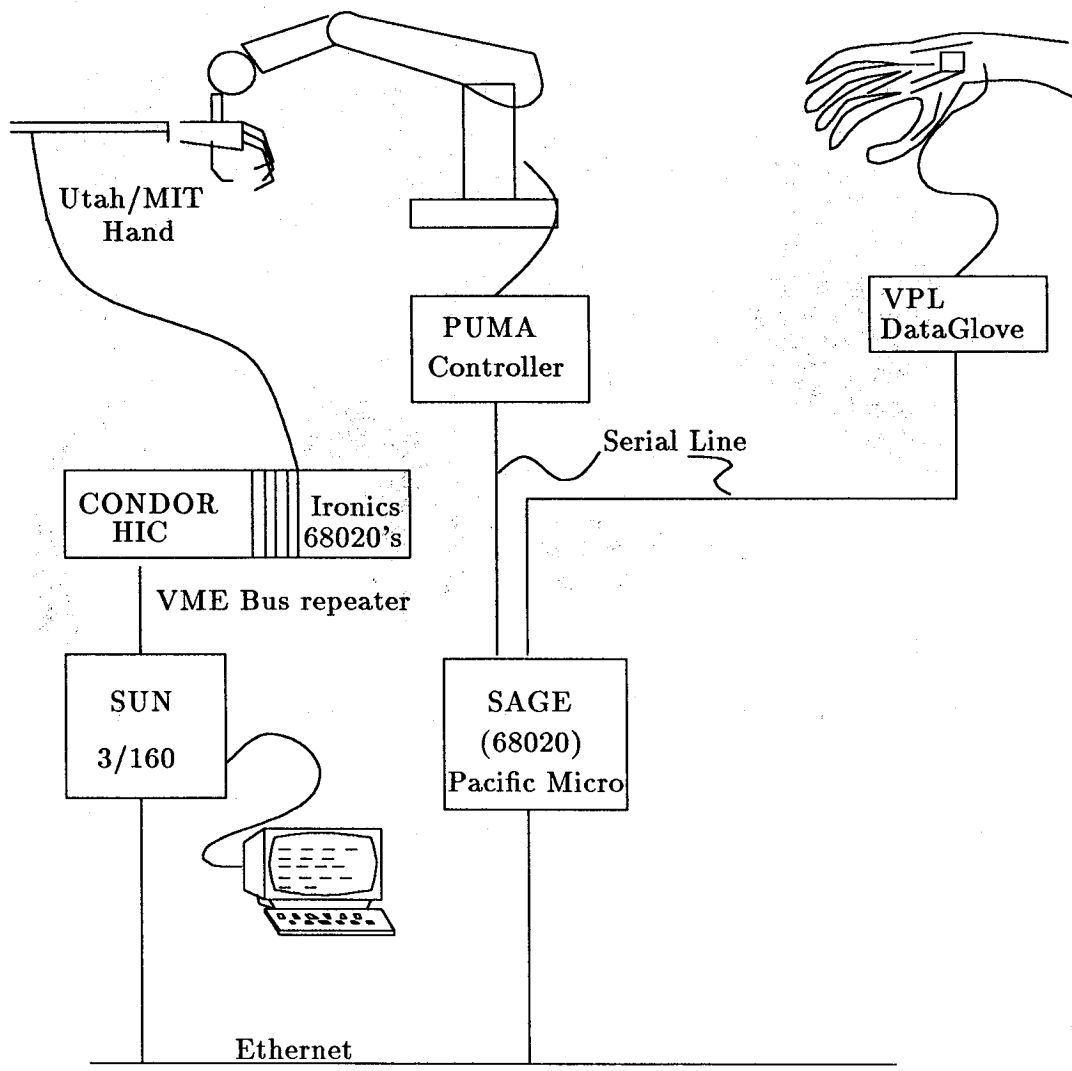
Figure 1: Architecture of Hand Teleoperation System

program run on the SUN while a joint level servo loop and a mode-switching program run on the Ironics.
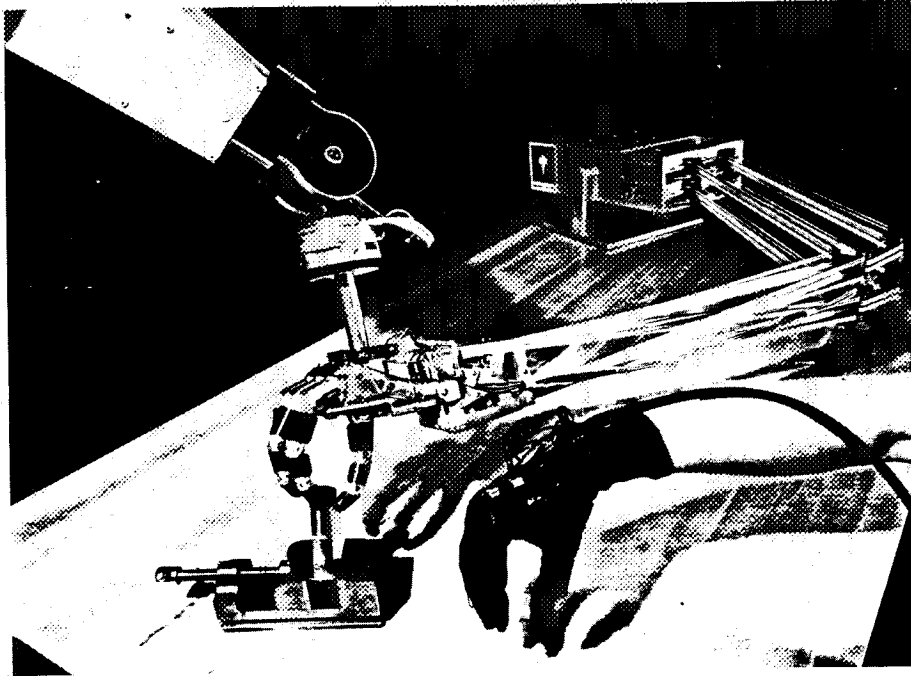

Figure 2: The VPL DataGlove and the Utah/MIT Dextrous Hand attached to a PUMA 560

The Hand is mounted on the end of a PUMA 560 robot arm. To control the position and orientation of the Hand in real-time, a 68020 generates new robot setpoints every 28 msecs based on the current Polhemus sensor readings. These setpoints are then sent over a serial line to the PUMA VAL-II controller using the ALTER interface, which performs independent joint PID control at a 1 msec servo loop rate.

4   Software

The software components of the system include SAGE, a real time operating system; Condor, a runtime environment for controlling the Hand; and HIC, a servo loop scheduler for hierarchical controllers.

A major component of the remote teleoperation system is the SAGE operating system, which interfaces the Glove, arm, and Hand. SAGE is designed specifically for real-time robotics supervisory control, and has multi-tasking, memory management, low-overhead synchronization, and network communications capabilities.

Both HIC and Condor run on four 68020 boards mounted on a VME bus. Condor [9] provides the development system, the inter-processor communication, the user interface, the timer interface, and the debugging support for control of the Utah/MIT hand. HIC provides the process or event

scheduler and the Periodic Data Queues used for inter-process communication. HIC's scheduler performs the same functions as the Minimal Operating System (MOS) in Condor (and in a similar manner) but has more flexibility.

An essential part of this teleoperation capability was a very complex calibration procedure developed for the DataGlove which mapped the sensor data to Utah/MIT hand joint angles in a way that looked natural to the wearer of the Glove.

4.1 Raw joint servo.

To control the Hand from the Glove only the lowest level of control is required of the Hand's controller. This is called the *raw joint servo* since it works entirely in the Hand's native joint position and tendon strain units. Figures 3,4 show the raw joint servo schematically and the communication between the servo and the controlling Sun. The box at the bottom of the figure
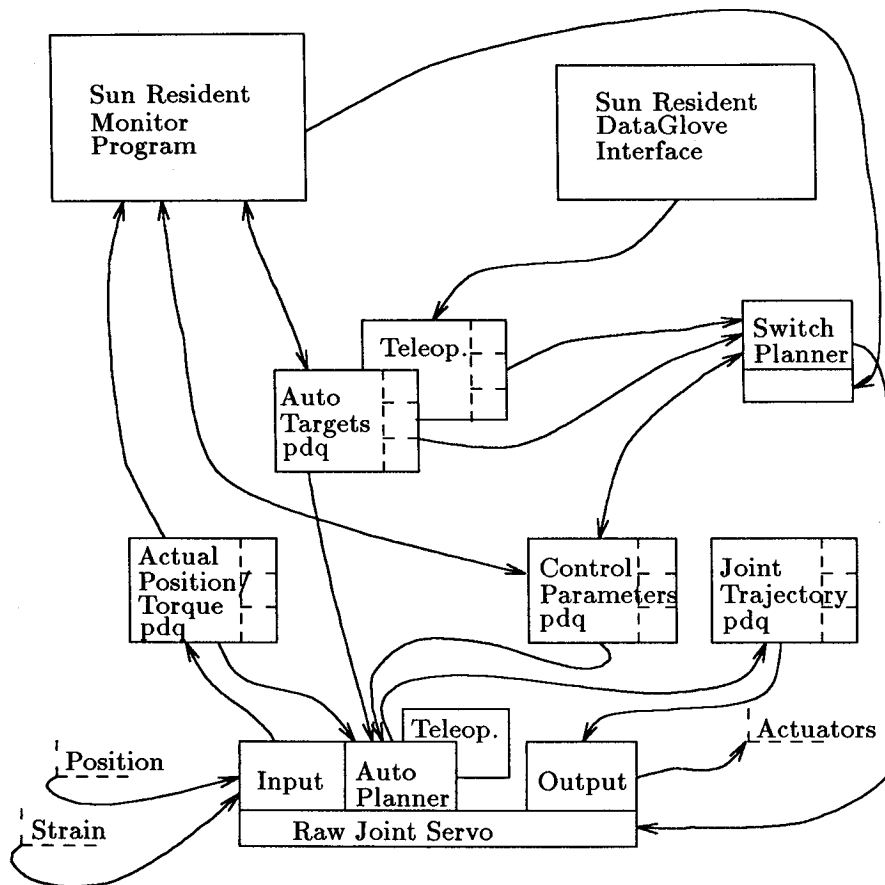

Figure 3: Communication with the Joint Servo (teleoperated mode).

represents the joint servo. This is a HIC process running on one of the Ironics processors. The three phases of the servo, input — planning — output, are represented by the top four sub-boxes. Notice that there are in fact two separate planners for the two different modes of operation (autonomous and teleoperated). The mode switching done by the switch event (box on center right) is achieved by changing the pointer for the current planner. The switch event is now triggered by a SUN

resident monitoring program (but could in fact be triggered from anywhere in the system). Some position offsets are also computed by the switch event in order to make the transition smooth (and are placed in the control parameters buffer).
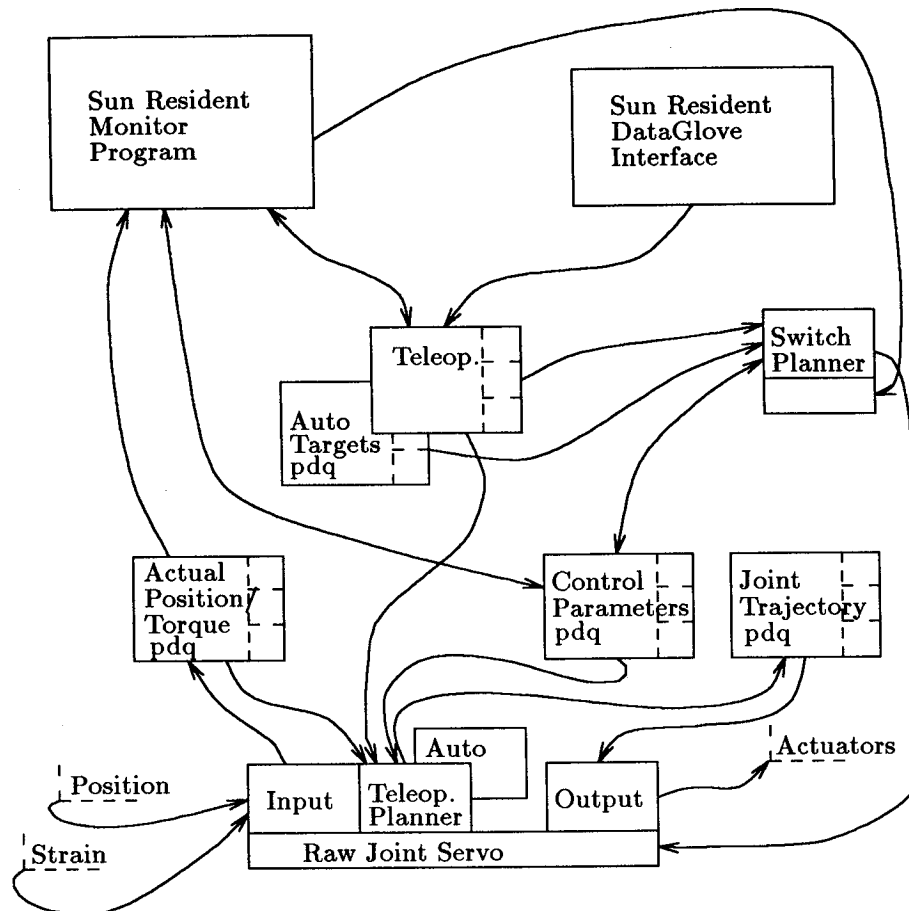

Figure 4: Communication with the Joint Servo (autonomous mode).

Above the servo are the five periodic data queues (pdq's) used by the servo (however only four of them are in use at a given time since the two planners use different target pdq's). The *input* procedure obtains values from the joint position and tendon strain sensors and produces position and torque values which are placed in the *actual position/torque* pdq. The second phase, the *planner*, takes these actual values and the target values and control parameters from the *target position/torque* pdq and the *control parameter* pdq respectively. The planner uses a combination of force and position control to produce trajectories for the joint actuators. The planner places the trajectories in the *trajectory* pdq. The *output* routine picks up the trajectories and applies them to the Hand's actuators. This loop is repeated 250 times per second.

The top two boxes in the figure represent programs running on the Sun3/160 host computer. The monitor program watches the actual, target, and control parameter pdq's and displays their values. To control the Hand with the Glove a second program on the Sun is run which supplies target joint positions based on the sensed position of the operator's joints in the glove.

As higher level servo loops are implemented, controlling, say, the fingertip positions, they will

generate the joint level targets in autonomous mode. While no such servo is running, the joint level servo uses the last targets specified.

The pdq's are the unifying data structures in HIC. Their use provides a disciplined way for numerous multirate hierarchical servo loops to communicate in a timely way.

5   Calibration and workspace constraints

The calibration problems involved in interfacing the Glove with the Hand are several. First, the kinematic structures of the Hand and the human hand are different. Second, the Glove can only measure some of the joint angles of the human hand. Third, the Glove sensors do not measure individual joints separately but rather there are strong nonlinear correlations among the sensors. The most complex part of the calibration procedure turned out to be the elimination of these correlations.

The calibration procedure is described in detail in [3]; we outline it here. The calibration procedure is decomposed into three levels. In the first level the raw sensor values are converted into joint angles by a parameter identification procedure. After considerable experimentation it was found that the relationship between raw output from the Glove sensors and the joint angles could be modeled satisfactorily by using a function of the form

$$\alpha = ar + b + c\log(r)$$

where α is the joint angle, r is the sensor reading and a, b, and c are parameters to be identified.

In the second level the correlations between the different calibrated angles were eliminated. This was done by first identifying those joints which were correlated and then eliminating the influence of one of the angles on another one by one. It is important to note that these correlations are not linear.

Finally, in the third level, we used forward kinematics on the human hand and inverse kinematics on the Hand to map the Glove angles to suitable Hand angles which would put the Hand fingertips in the same relative positions as the Glove fingertips.

Because of limitations in the workspace of the remotizer constraints had to be put on the motion of the joints of the PUMA. Finding the appropriate set of constraints required solving the inverse kinematics for the remotizer. Those were approximated using a simple open kinematic chain model. The precise kinematics are much harder to describe because of flexibility of the rods and the complex arrangement of joint and links.

6   Experiments

With the setup described above we were able to successfully teleoperate the Hand using the Glove to supply finger angles, and the Polhemus sensor to supply position and orientation for the PUMA 560 carrying the Hand. The following experiments were performed.

1. Stacking blocks. Three two-inch cubic blocks were picked up using two or three fingers and then stacked up. The whole task took a trained operator 1 minute and 45 seconds to perform.

2. Picking up a milk carton and pouring milk into a cup. A regular half gallon milk carton was opened by pushing back the flaps of the (already unglued) spout. Then it was picked up by grasping it from the side. After tilting it enough the milk poured into the cup without spilling out. The task took 2 minutes and 20 seconds to perform, including time to move to carton to a position where it could be grasped more firmly.

3. Picking up the cup using the handle and pouring milk into another cup. Three fingers were moved through the handle while the thumb pushed against the side of the cup. (1 minute and 50 seconds)

4. Picking up a nut and screwing it onto a bolt (see Figure 2). A nut is picked up by the thumb and two fingers. It is then started on the 3/4in bolt and screwed in using two fingers. When successful it took a trained operator under $1\frac{1}{2}$ minutes to perform. However starting the nut on the thread was difficult and 3 out of four times either the nut was dropped or the grip became unstable and the experiment had to be restarted.

These experiments were performed fully in teleoperated mode and only visual feedback was used. Preliminary results using both the autonomous mode and a transition to a purely force controlled mode for releasing a grip indicate that we may greatly improve the performance in experiments such as 1 and 3 above. A force controlled mode can be achieved by setting the position feedback gain (specified in the control parameters data structure) to zero using the monitoring program.

7 Applications

The most immediate application we foresee for our current teleoperation setup is as an aid in developing automatic control schemes for dextrous manipulation tasks. Teleoperation can be used to perform the parts of a complex task which have not yet been automated. For example, in stacking up blocks we may teleoperate the hand until a grasp is achieved and then let a preprogrammed routine maintain it while we perform other motions with the whole hand. Then, when more fine positioning needs to be done to properly align the blocks control can again be transferred to the operator. Later when a grasping routine is written the initial teleoperation may be reduced to a simple pregrasping position at which point the autonomous program takes over and the rest proceeds as before. In this way smaller parts of a more complicated task can be tested before the whole task is automated. Our current setup also easily allows a mixed teleoperation/automated mode. An example could be found in writing with the Hand. The compliance of the pen on the paper could be preprogrammed while the shaping of the characters would be teleoperated.

8 Conclusions

We described a teleoperation system for the Utah/MIT Dextrous hand using a VPL DataGlove. While the system could be greatly improved in many areas it provides a new facility with which to perform fine manipulation experiments. The ability to switch back and forth between a teleoperated mode and an automated mode both allows the operator to rest while some already preprogrammed motions are performed and helps in the development of complex dextrous manipulations. The teleoperated mode is facilitated by the use of the natural interface provided by the DataGlove.

Acknowledgments

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