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A Force-Reflecting Teleoperated Hand System for the Study of Tactile Sensing in Precision Manipulation

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Abstract

This paper describes a teleoperated hand system specifically developed to study the role of tactile and fine force sensing in telemanipulation. Both master and slave manipulators are two fingered hands designed for precision tasks that humans typically execute with a pinch grasp between the thumb and index finger. A direct drive, parallel linkage configuration and brushless DC servomotors permit smooth, accurate control of contact forces and small motions, which is essential for effective tactile sensing and display. Initial experiments have demonstrated that an operator can perform precision tasks using this system, and that the ability to convey small force levels to the operator requires careful attention to the coupling between the operator's finger tips and the master manipulator. The system has also been used to demonstrate that a tactile display can convey frictional information sensed at the slave manipulator. Future work will include development of tactile displays for contact phenomena and object shape, and investigation of force feedback bandwidth requirements for dextrous manipulation tasks.

1 Introduction

If teleoperated manipulation is to approach human dexterity, we must determine what sensory information is required to perform various tasks, learn how to sense this information at the remote manipulator, and find means to convey this information to the operator. For the precision manipulation tasks that humans usually accomplish with fingertip grasps, tactile and fine force information is particularly important. Neurophysiological research has shown that tactile information permits adaptation to variations in friction, weight, and load forces while handling a wide range of objects (Johansson and Westling 1984; Westling and Johansson 1987).

Most work in force-reflecting teleoperation has considered interactions at the arm level. Recent interest in dexterous telemanipulation has focused on constructing master hands with many degrees of freedom that can be used at the end of force-reflecting master arms. (See Burdea and Zhuang 1991 for a current overview.) This presents an extremely difficult design problem since it requires placing many sensors and actuators around the human operator's hand at the end of the arm. Proposed solutions often entail the use of cables or gears, which makes it difficult to accurately control the small forces and displacements that are essential for effective tactile sensing and display.

In contrast, this paper describes a teleoperated hand system specifically developed for the study of tactile and fine force sensing and display in precision telemanipulation. These hands are designed as laboratory instruments rather than practical telemanipulators: they provide only a few degrees of freedom and are not intended to be mounted at the end of an arm. However, the simplicity of the design permits smooth, accurate control of contact forces and small motions. The tasks which the system is designed to execute (planar grasp-lift-replace, contour following, peg-in-hole assembly, catching, etc.) are those for which sensing and manipulation strategies have been studied in both humans (e.g. Johansson and Westling 1984, Westling and Johansson 1987) and autonomous robots (e.g. Howe et al. 1990, Berger and Khosla 1991). Thus it is possible to draw upon the knowledge gained in these related fields in developing tactile feedback for telemanipulation.

2 System design

Because good control of small forces and motions is essential for the study of tactile sensing, we have avoided the complexity inherent in providing a large number of degrees of freedom in favor of a clean design that can perform simple manipulation tasks well. Master and

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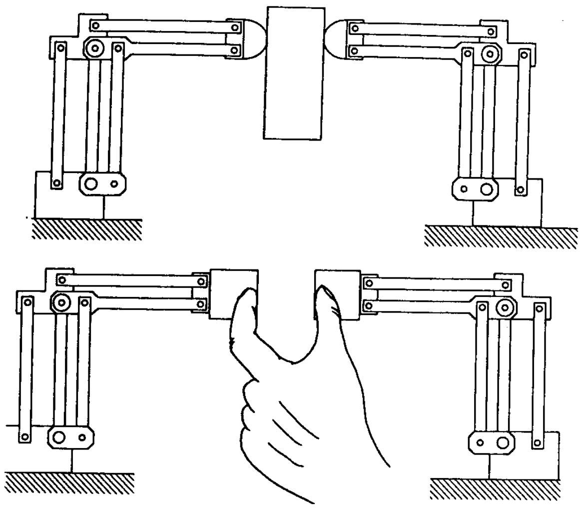

Figure 1: Diagram showing an operator's hand in the master manipulator and the slave manipulator grasping an object.

slave hands each consist of two fingers that move in a plane. The design is not anthropomorphic, and the operator makes contact with the master only at the tips of the thumb and index finger, as when manipulating an object in a precision pinch grasp. For most tasks the operator's wrist rests on the table top and the manipulation is performed with the fingers only (Figure 1).

The fingers of both master and slave hands are two degree-of-freedom mechanisms (Figure 2). Each finger has two serial links where the links consist of four-bar pantographs, so that the orientation of the finger tip does not change as the fingers move. The pantographs are 75 mm long, resulting in a roughly circular useful workspace about 100 mm in diameter.

Brushless limited-angle DC torque motors are used in a direct drive configuration to avoid friction, backlash, and torque ripple effects from transmission mechanisms such as gears and cables. Both motors are fixed at the base of the finger to minimize moving mass; the lower link is connected directly to the motor shaft at the base, while the upper link is driven by an offset parallel linkage. All joints move on precision ball bearings, and the resulting system has very low friction. Maximum continuous tip forces are at least 6.0 N in any direction in the plane (peak forces are over 20.0 N), while friction is less than 0.02 N.

Joint angles are measured by magnetoresistive sensors coupled to the motor shafts, and joint velocities are "calculated" from these signals by analog differentiators to ensure good velocity signals at low speeds. Finger tip forces on both master and slave fingers are measured by strain gauge force sensors with a range of 0.01 N to 10.0 N. Figure 3 shows the block diagram for the system. The controller is a 33 Mflop DSP board with 250 kHz, 32 channel A/D and D/A boards. Servo rates in excess of 5 kHz for 4 fingers (8 axes) in force-reflecting teleoperation have been achieved. The DSP board is connected to an 80486 PC which provides the programming environment (C language compiler, downloader, monitor, and debugger) as well as facilities for acquiring and analyzing data in manipulation experiments.

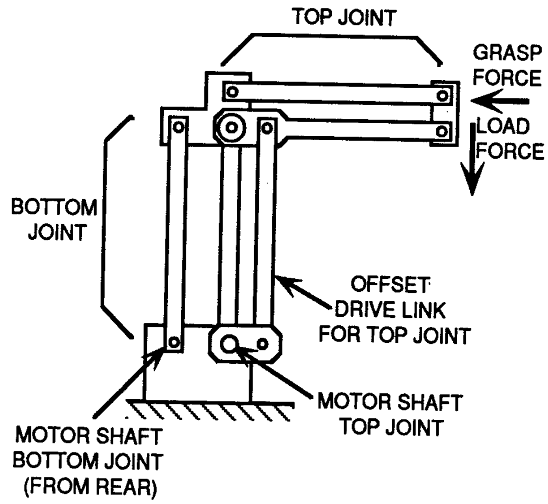

Figure 2: Side view of one finger mechanism. The fingers have two joints and are 30 mm wide. Master and slave hands each consist of two fingers.

3 Preliminary experiments

Initial experiments confirm that the system can perform precision telemanipulation operations and demonstrate some of the ways that tactile information can be relayed to the operator. A position feedforward-force feedback control mode is used for the experiments reported here. The joint angles of the master manipulator are the command inputs for position control of the joints of the slave manipulator. Conversely, the forces measured at the slave fingertips are the command inputs for force control of the master. Thus the slave follows the motions of the master (which are coupled to the operator's fingers, as detailed below) and the master applies the forces measured at the slave finger tips to

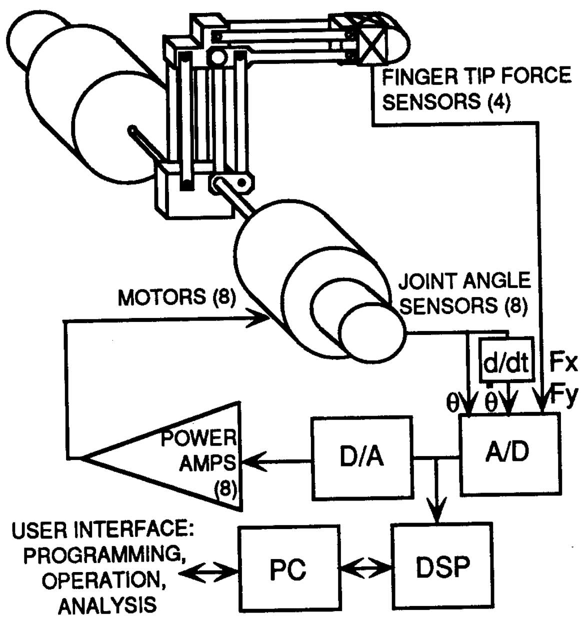

Figure 3: Block diagram of major system components.

the operator's fingers. This control scheme is adequate for many simple tasks; more sophisticated control algorithms that we are working to implement are described below in Section 4.

3.1 Coupling to the operator's fingers

Preliminary tests of the system revealed that the means of coupling the operator's fingers to the master manipulator makes a great difference in the operator's abilty to perceive small forces. Initially, the operator's fingers were inserted into close-fitting metal tubes resembling thimbles attached to the force sensors on the master finger tips. When the slave fingers move in space before contact with an object, there is no force on the slave fingers and the master controller servos the net force on the operator's fingers to zero. Because the thimbles completely enclose the operator's fingers, they ensure that the master follows the operator's movements, even when the controller keeps the net force between the operator and master very small. However, once the slave fingers make contact with an object and the master begins to apply forces to the operator's fingers, the thimbles prevent the operator from accurately perceiving small forces. Apparently human perception of small finger tip forces relies on deformation of the finger tip pulp and skin, which the thimbles preclude.

The solution for the experiments reported here is to use a square frame somewhat larger than the operator's fingers, so the operator's finger tip contacts only one flat surface (see Figure 1). This allows the finger tip to deform in both the normal and shear directions as the contact forces vary. However, when the slave is moving in space and the net force on the operator is servoed to zero, the master can lose contact with the operator's fingers. To prevent this the master controller is set to provide a small constant bias force normal to the operator's finger when the commanded force from the slave is zero. This permits the master to stably track the operator's fingers during free motion, and greatly improves the operator's ability to sense small forces. However, even this improved coupling mechanism interfered with the operator's perception of the light touch at the first stages of contact between the slave and objects in the environment, since there was already a small contact force at the master. In Section 4 below we discuss methods for improving the operator's ability to detect first contact.

3.2 Relaying frictional information

For precision manipulation perception of friction is very important. If an object's friction is overestimated then the object may unexpectedly slip from the grasp. Conversely, an underestimate can lead to the use of excessive grasp force which may damage fragile objects and waste effort. Furthermore, humans often use controlled sliding to reorient an object within the hand, which requires knowledge of the friction of the object. Thus the ability to sense frictional properties at the slave manipulator and to relay this information to the master promises to increase the dexterity of teleoperated manipulation. The preliminary experiments described below demonstrate one means of doing this.

Humans show a remarkable ability to adapt to a wide range of surface friction (e.g. Johansson and Westling 1984; Westling and Johansson 1987). When lifting an object between the fingertips people use a grasp force that is as little as ten percent greater than the minimum required to hold the object without slipping. This adaptation to the friction at the contact is based on tactile signals and is maintained throughout changes in the task load. When small slips are detected the ratio of grasp force to load force is increased to maintain a small safety margin against future slips. The adjustment of the forces occurs unconsciously and about twice as fast as conscious changes in force or position can be achieved.

A similar ability to respond to frictional conditions by detecting slips has been demonstrated for autonomous robots. One device for slip sensing, the skin

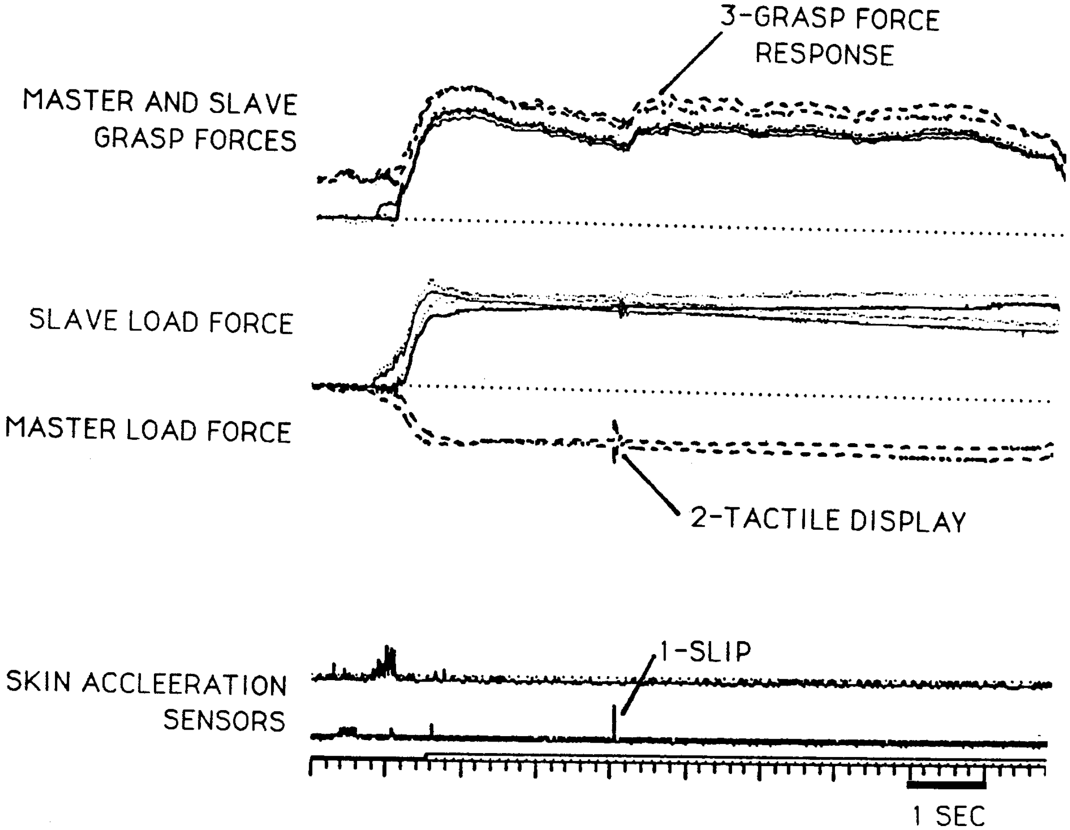

Figure 5: Signals from teleoperated grasp-lift-replace task showing tactile display function.

4 Future work

These preliminary experiments indicate the types of studies for which the teleoperated hand system is designed. This section describes some of the further work that is underway on tactile displays, manipulator control, and the effect of tactile information on task performance.

4.1 Tactile displays

While the effectiveness of the slip display in initial tests is encouraging, much additional work remains. Grasp force response latencies are longer than the 60-80 ms for slip response in direct manipulation, and the operator does not invariably respond to the display with an effective grasp force increase. Further effort will be devoted to studying the effects of varying the display parameters, including force and vibration duration, amplitude, direction, etc.

Another important phenomenon to convey to the operator is contact. As the finger tips move towards an object, the ability to detect the first instant of contact allows rapid adaptation to the changing mechanical impedance of the environment. Initial contact is readily detected by the skin acceleration sensor, which can trigger a display consisting of a small, short-duration force increase in the *normal* force direction. Another display can be used to convey information about remote contact between the grasped object and another surface in the environment, such as when the object first touches the table top as it is set down.

Once appropriate tactile displays have been developed with this manipulator system, it will be possible to design devices that can produce the tactile display phenomena (forces and vibrations) without involving the master manipulator's controller. This would permit the use of these tactile displays on master manipulators that do not have high bandwidth force-reflection capa-

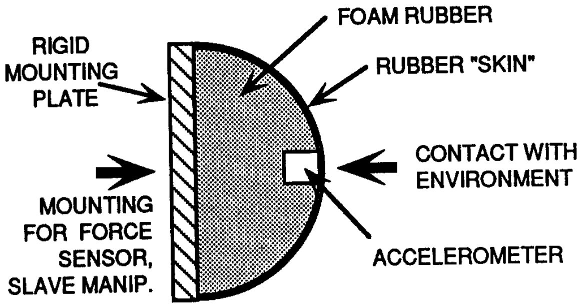

Figure 4: Cross section of slave finger tip which consists of a thin rubber "skin" stretched over a half-cylinder of foam rubber approximately 50 mm long and 25 mm in diameter. A miniature accelerometer is bonded to the inner surface of the rubber skin in the center of the contact area, forming a skin acceleration sensor. This sensor can detect the small vibrations that indicate the earliest stages of slip.

acceleration sensor, is easily adapted to dextrous telemanipulation (Howe and Cutkosky 1989). It consists of a miniature accelerometer bonded to the inner surface of the rubber "skin" covering the robot finger. Because it is located in the compliant gripping surface of the robot finger it can detect the small, fast vibrations produced by the first stages of incipient slip. Experiments have demonstrated that the signals from this sensor can be used to trigger an increase in grasp force fast enough to prevent the object from sliding from the grasp. For these experiments the finger tips fitted to the slave manipulator include a skin acceleration sensor (Figure 4).

Once the skin acceleration sensor detects a slip the local controller for the slave can increase the grasp force. However, this will result in a disparity between the grasp force applied by the operator to the master and the grasp force applied by the slave to the grasped object. Since it has been observed that in direct manipulation people may spontaneously decrease their grasp force until a slip prompts an increase (Johansson and Westling 1984), this disparity could grow quite large. A large disparity obviates the advantages of providing force feedback and could cause problems as the task proceeds.

It would be preferable to alert the operator that slips are occurring so that the operator can increase the grasp force directly. Edin, Howe, Westling, and Cutkosky (in press) have demonstrated that a carefully structured tactile display can reliably trigger an unconscious reflexive increase in the grasp force in humans similar to the reaction to small slips during direct manipulation. This display consists of short-duration, high-frequency vibrations and a slight redistribution of the load forces on the thumb and finger grasping the object. This redistribution presents a small increase in the load at one digit and a decrease at the other, and mimics a phenomena observed during direct manipulation of instrumented objects when the grasped object actually slips at one digit and reorients slightly in the hand (Johansson and Westling 1987). This type of display is preferable to an audible or visible display because these sensory substitution techniques do not trigger the grasp force reflex. Instead, they require conscious attention from the operator, which decreases performance and increases fatigue.

Using the dexterous telemanipulator system we have demonstrated that slip information from the slave can be used to trigger a fast, quasi-reflexive grasp force increase by the operator during telemanipulation. Signals from the skin acceleration sensors in the slave finger tips were digitized by the controller. If the RMS signal level exceeded a fixed threshold the tactile display was triggered. In these experiments the tactile display consisted of a "load redistribution" by the master manipulator, so that the vertical load force on one digit was briefly increased while the load force on the other was decreased. A range of display amplitudes and durations were examined; the smallest effective values used were 30 msec duration and 0.4 N amplitude.

Figure 5 shows the tactile display and the operator's response in a grasp-lift-replace task. Here the operator uses the master manipulator to control the slave to grasp an object, lift it about 5 cm, hold it in space for a few seconds, and return it to the table top. The operator directly views the slave manipulator from a distance of approximately 1.5 m. The operator has been instructed to use minimum grasp force but to prevent the object from slipping, and is aware of the function of the tactile display. As seen in the force record for this trial, after holding the object for about 3 sec the operator decreases the grasp force too much and the skin acceleration sensor in the left finger detects vibrations indicating incipient slip at that digit. This triggers the tactile display, which can be seen as "blips" in the master load force trace. This in turn causes the operator to increase the grasp force. In preliminary tests the latency for the beginning of this increase in grasp force was 80-100 msec, which is significantly faster than the minimum of 130 ms that humans require to generate a voluntary response to a tactile stimulus. This indicates that the response is reflexive and that the frictional information has been effectively conveyed to the operator.

bilities. The result would be improved performance for lighter weight and lower cost telemanipulators.

Another area of investigation involves the display of shape information to the operator. Tactile array sensors in the slave fingertips can measure the shape of objects at the contact. We are investigating several designs for tactile display devices for geometric information including array of moving pins, resembling a large-scale dot-matrix printer head covered by a layer of elastomer, and deformable metal plates with variable curvature actuated by tendons.

4.2 Control and task performance

The controller for the preliminary experiments described here employs a position feedforward-force feedback design with fixed gains. This controller is adequate for many tasks, but tests with several operators show that the mechanical impedance of human fingers varies widely between individuals, so optimum settings for one operator are sub-optimal or even unstable for another. Furthermore, previous work has shown that humans vary the impedance of their limbs during task execution and that it is advantageous to adjust the telemanipulator's impedance to suit task characteristics as well. We are thus working to implement a variable-impedance control scheme that can adjust the gains of the controllers during task execution, depending on the observed impedence of the operator's fingers (Hannaford and Anderson 1988), or on the operator's command for a given task.

Another area this manipulator system is well-suited to investigate is bandwidth requirements for dextrous telemanipulation. Prior studies have suggested that force information up to 5-10 kHz is important for dexterous tasks (Sharpe 1988), although it is not clear that human mechanoreceptors can provide information about forces above 100 Hz or even about nonlocalized vibrations above 1 kHz. The manipulator is designed to provide high bandwidth force information to the operator, but bandwidth can be easily decreased through filtering. This will permit evaluation of task performance as a function of the frequency content of the information available to the operator.

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