An Instrumented Glove for Grasp Specification In Virtual Reality Based Point-and-Direct Telerobotics

Myung Hwan Yun*, David Cannon**, Andris Freivalds**

* : Department of Industrial Engineering, Pohang University of Science and Technology
**: Department of Industrial and Management Systems Engineering, Penna State University

Abstract

Hand posture and force, which define aspects of the way an object is grasped, are features of robotic manipulation. A means for specifying these grasping '"flavors" has been developed that uses an instrumented glove equipped with joint and force sensors. The new grasp specification system is being used at the Pennsylvania State University (Penn State) in a Virtual Reality based Point-and-Direct (VR-PAD) robotics implementation. In the Computer Integrated Manufacturing (CIM) Laboratory at Penn State, hand posture and force data were collected for manipulating bricks and other items that require varying amounts of force at multiple pressure points. The feasibility of measuring desired grasp characteristics was demonstrated for a modified Cyberglove impregnated with FSR (Force Sensitive Resistor) pressure sensors in the fingertips. A joint/force model relating the parameters of finger articulation and pressure to various lifting tasks was validated for the instrumented "wired" glove. Operators using such a modified glove may ultimately be able to configure robot grasping tasks in environments involving hazardous waste remediation, flexible manufacturing, space operations and other flexible robotics applications. In each case, the VR-PAD approach improved the computational and delay problems of real-time multiple-degree-of-freedom force feedback telemanipulation.

INTRODUCTION

Point-and-Direct robotics was initially explored by the second author at Stanford University[1]. This initial research demonstrated that an operator could direct a robot to perform tasks in a natural and interactive way by pointing to objects and destinations while giving directives such as "put that there" (Figure 1).

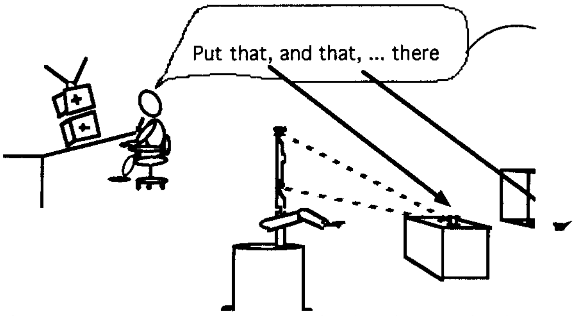

Figure 1. To operate the Stanford Point-And-Direct (PAD) telerobot, a remote operator views two video monitors and aligns objects in each view by rotating the cameras on the robot much like remotely controlling a model airplane.

In demonstrations, this point-and-direct (PAD) Telerobot put trash in a wastebasket, and blocks on a pallet, and tools in a toolbox. These actions loosely represented tasks of hazardous waste disposal, manufacturing material handling and space telerobotics. The Veterans Administration provided funding for development of the telerobot which was ultimately purchased in its entirety, including camera tower, mobile base, and articulated arm, by the NASA AMES Research Center in Sunnyvale, California for their mobile robotics activities. One limitation of the original Stanford PAD telerobot was that while it could be directed to pick up objects and release them at desired locations in unstructured environments, the orientation of the robotic gripper could not be easily specified. Because of this, the PAD telerobot was generally configured to approach objects along a line of sight proceeding to the target from where the robot was at the time of pointing.

Subsequent work in the Penn State VR-PAD Program has maintained the naturalness of pointing while providing orientation vectors as well as position coordinates using virtual tools that are interwoven into the live video scene. Such virtual tools, which are graphical representations of actual tools including robotic end-effectors, are simply flown to an object of interest in the scene by moving one's instrumented hand in free space (Figure 2). This avoids laborious movement of a full multiple degree-of-freedom robot that has multiple links and often complex inertial dynamics. An invisible cut-plane, graphically draped at the object's depth, provides a correspondence between the virtual cyberspace in which graphics reside and the physical workspace in which real objects reside -- so that virtual tools appear to engulf real objects in the interwoven reality scene. Solid rendering is changed to wireframe rendering behind the cut-plane. Once object and destination points are specified by engulfing an object, the robot calculates its own trajectories for moving from objects to destinations so the human need provide only task conception at the object level.

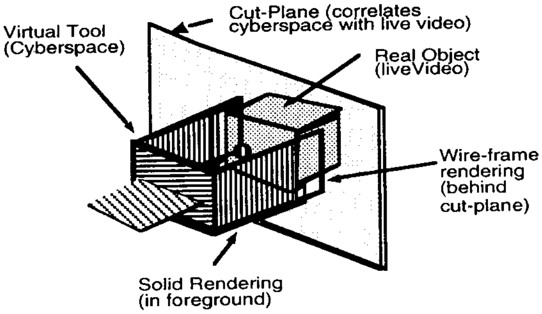

Figure 2. A cut-plane, at a depth determined by camera triangulation, allows graphically represented robot end-effectors to fly in cyberspace and yet be correlated with objects in a live video scene. Thus, a virtual tool, such as the robot gripper shown, can be made to disappear behind a real object while a robotic task is specified at the object level.

Thus, virtual tools have been interjected into a live videographic cyberspace creating an "interwoven reality" in which graphically represented end-effectors, such as a robot gripper, fly as if present in a real scene. Robots and machines can now be directed to do tasks in the same natural way that humans instruct one another using intuitive commands such as "put that there". Using this concept, the Penn State VR-PAD Program is developing an interactive system for hazardous material handling for Sandia National Laboratories and for agile manufacturing for the National Science Foundation. While previous to this work, the VR-PAD Program had successfully built a point-and-direct system with the basic features described above, the robot gripper of this implementation had always applied the same amount of force to every object and had no force feedback in the gripper fingers. There are cases in telerobotics, however, where robot hands have multiple fingers and where the magnitude of force must be specified. A heavy brick, for example, cannot be gripped in the same way and with the same amount of force as an egg because the thin wall of the egg will buckle under high loads. Yet, in developing a means of specifying variation in joint articulation and force, continuous full force feedback to the operator as in telemanipulation is not generally necessary. Specifying hand posture and force once for most objects is quite sufficient. (Even when reorientation is required *en route*, a simple algorithmic representation of dynamics in the presence of gravity may automatically adjust grasp force distributions without requiring human input). The human operator need not resort to manual control which may be time consuming, manually exhausting, and prone to unanticipated overshoot and error. Such telemanipulation is, after all, but one extreme on a telerobotics continuum that includes a potential line of possibilities stretching to full autonomy on the other extreme. The point-and-direct approach represents a class of telerobots sharing good characteristics of both extremes. VR-PAD interaction remains natural, and at the object level, while capabilities such as autonomous trajectory planning are fully utilized.

Toward the purpose of developing a simple means of specifying joint articulation and force at a point for a robot with sophisticated grasping capability, this study explores posture measurement and force sensing with FSR's implemented into an instrumented glove. Several observations about human grasping provide perspective. It is well known, for example, that humans heavily depend on force or pressure sensing when exercising a gripping action. As a person uses a tool such as a screwdriver, position and strain-sensing neurons in the muscle and tendon fibers of the hand, finger and wrist keep the brain informed about the overall spatial arrangement of the hand and the forces applied. Many clues about the objects material properties — stiffness and strength—emerge from these senses. Specifically, a class of sensory neurons known as SA-I (slowly adapting system), which is arranged under the skin in a two dimensional grid like photoreceptors in a retina, gets credit as the primary means of perceiving, for example, the screwdriver's shape. This class of neurons also detects low-frequency vibrations that signal when the screwdriver has made contact with other surfaces, such as the groove on the head of a screw. A separate, denser grid of neurons—the RA (rapidly adapting systems)—relays spatial information, with about one third of the clarity of the SA system, but this grid can pinpoint much subtler movements between skin and surface, such as the vibrations that occur when a screwdriver slips slightly in the hand during turning. Such neural information presumably is the key to perceiving fine textures and adjusting the forces applied to tools during their use [2]. Approximating such tactile capability with artificial sensors is a challenge.

A practical approach to gripper control is suggested in this study while referencing the work of others including [3], [4], [5], and [6] who are similarly engaged. The approach presented here involves empirically based grasp specification and the use of a statistical model to preshape the gripper. Gripping control using an instrumented glove to provide joint/force coordination in virtual reality based point-and-direct robotics is explored. To specify hand posture and force distributions in a robotic gripper with two or more fingers, an understanding of the relationship between joint articulation and finger pressure must be acquired. An underlying model of this relationship is paramount. Instrumented gloves provide both an avenue to help understand the joint/force relationship and, later, an ideal input device to specify characteristics of grasping that will allow improved handling of an object without requiring manual control and robotic force feedback to the operator.

SYSTEM DESCRIPTION

For 3-D interaction, VPL research in California was early in creating an instrumented glove that could be used to manipulate on-screen virtual images in an effectively 3D graphical cyberspace. Their DataGlove system uses optical fibers that measure the degree of bending of the user hand joints. A Polhemous magnetic sensor keeps track of the absolute position of the hand with respect to a given source. The DataGlove has been used in various research environments and was investigated by [7]. In an initial study, a resolution of better than 0.5 degrees for an angle less than 36 degrees, and better than 1.0 degree between 36 to 54 degrees was obtained.

The Cyberglove, a similar instrumented glove, was chosen for this research. The tipless glove that allows fingertips to protrude was developed by Virtual Technologies Inc. of Stanford, California. The Cyberglove uses up to 22 strain gauge sensors: three bend sensors and one abduction sensor per finger, thumb and little finger [8]. In conjunction with the Cyberglove, a Polmeus magnetic sensor device (the same active locating element used with DataGlove) gives the position of the hand with respect to a reference. Both instrumented gloves would be suitable for recognition of hand posture, and the use of an instrumented glove was found to be more effective than menu selections in a position and orientation speed test [9]. Furthermore, an instrumented glove can be modified with pressure sensors to differentiate the various gripping actions such as grasp, pinch, and firm grasp.

Many research projects have been conducted to simulate the force control mechanism of the human hand. The control theory model is the most heavily mentioned approach (see [4]). As yet, however, there is no consensus regarding a universal idealization of a remote manipulator system. One ideal is to achieve a remote manipulator response that is a completely transparent interface between human and machine. In other words, the operator should feel as if the task object were being handled directly. [10] suggested that the ideal telemanipulator can be represented by an infinitely stiff and weightless mechanical connection between the end-effector of the master arm and the slave arm. [4] proposed a master-slave controller in which the human operator at the master port interacts with a task object at the slave port in a remote location. The gain of the force feedback was modeled to be selected based on the stability requirements and specification of the desired port impedance given models of the task and the human operator. [11] proposed a model of bi-lateral control of force feedback and prediction. Mathematical modeling of a grasp function was conducted by [12]. They developed a mathematical model and an algorithm to plan the grasp action of a multi-fingered manipulator operating in uncertain environment. They divided the grip action into four steps; reach, pre-shape, enclose, and grip and developed separate algorithms to perform each step of the grasp phase for a multi-fingered robot hand.

Among experimental studies on remote manipulators, [5] performed an experiment for the remote manipulation tasks with various conditions of force feedback, direct viewing, visual angle, and task difficulty. Their result showed that the performance of the manipulation tasks with force feedback is the highest of all task combinations. [3] developed a taxonomy of grasp function based on [13]'s definition of power grip and precision grip. Using the taxonomy, he developed a scheme for selecting a particular grip posture for gripper manipulation. [12] studied teleoperator comfort and stability by measuring finger forces and fatigue effects for the pinch forces of the human operators. Further, dynamics of the hand has been studied in the microsurgery environment. [14] attached a force sensor and a location sensor on the operator hand and microsurgical tool and studied workspace and manipulation forces of a surgeon. In those applications, techniques of sensing force on the hand have also been considered important as well as in biomechanical studies and ergonomics. However, most techniques of sensing force exerted by human body segment involved complex and expensive instrumentation with limited portability (see [15]-[18]). Recent technological advances have provided small, thin sensors for use in directly sensing individual finger forces during normal grasping activities. A conductive polymer sensor that can be attached to the palm surface of the hand is one such device [19]. A form of the same conductive polymer sensors, Force Sensitive Resistors (FSRs) have recently begun to emerge as a major alternative. By using these latter devices, it was possible to measure the force distribution pattern of a hand tool, for example, during various activities [20].

FSRs are made from two sheets of polymer film (higher temperature polymide). On one sheet, a conducting pattern is deposited in the form of a set of interdigitating electrodes. Another sheet, with a proprietary semiconductive polymer film, is adhered across the finger network. Applying force to the resulting sandwich causes the resistance between the two contacts to decrease following an approximate power law [21]. Although the response to force changes is not linear, the FSRs can be calibrated for force measurement using a logarithmic regression [22]. A FSR shows a response that varies as the reciprocal of the square root of the area of the applied force. This holds true where the force footprint is smaller than the FSR active area, and larger than the spacing between the conducting fingers. With a proper mechanical arrangement of the constant contact force and distribution of each sensor, it is the ideal sensor to measure finger forces of the human hand.

TEST EXPERIMENT

For the purpose of measuring the joint angles of the fingers and wrist joint, an angle transducer glove system (Cyberglove™ CG1801, [8]) and a set of data acquisition programs specific to finger joint measurement were developed. The Cyberglove system provided measurement of 18 joint angles. There were two flexion sensors on each of the five fingers. On the thumb, these two sensors measured the metacarpophalangeal (CMC) and interphalangeal (IP) joint flexions. On the remaining four fingers, the two flexion sensors measured the metacarpal phalangeal joint (MP) and proximal interphalangeal (PIP) joint flexions. Two wrist motions, flexion/extension and radial/ulna deviation angle, was also measured. The hand calibration procedure included the joint location specification and the flexion calibration. First, the coordinate system of the hand based on the three dimensional hand model by [23] was defined. Flexion-extension, Radial-ulnar deviation, and axial rotation angles of the finger digits were also defined. The data from the sensor system, which represents the amount of finger movement expressed in the local coordinate system, was converted to the global coordinate system taking the wrist joint as the origin. The digitized values were converted to an appropriate joint angle in radians. The detailed description of the hand model used in this study can be found in [23].

The resulting joint flexion angles were digitized in radian format and transferred to a PC (TOSHIBA 3200) using file transfer software. All of the hand calibration procedures were performed internally using the software program developed. The hand size of each subject and joint location of the subjects were measured prior to the experiment using a anthropometric measurement system. Each flexion sensor was calibrated individually using the software provided with the Cyberglove system.

For the measurement of finger forces, a sensor matrix with ten Force Sensitive Resistors [21] was developed. This set up has been used to measure pressure distributions on foam grip handles [24], to study finger pinch forces [25], and hand-tool coupling effects [26]. Each of the FSR sensors were covered with 2 mm thick plastic glue over a 12 mm^2 sensing area for effective force measurements. The sensors had an effective force sensing range of 1 to 50 N with 1 N precision. Voltage outputs from the ten sensors were recorded using a DASH 16/F analog-to-digital converter installed in a PC (TOSHIBA 3200). The glove was calibrated to force levels in Newtons(N) as a function of digitized Voltage(V) value using a second order polynomial regression : Force(N) = 0.23 - 0.61*voltage (V) + 0.56*voltage^2 (V). The coefficient of determination for the pressure calibration regression was 0.98. The overall set up for the experiment is presented in Figure 3.

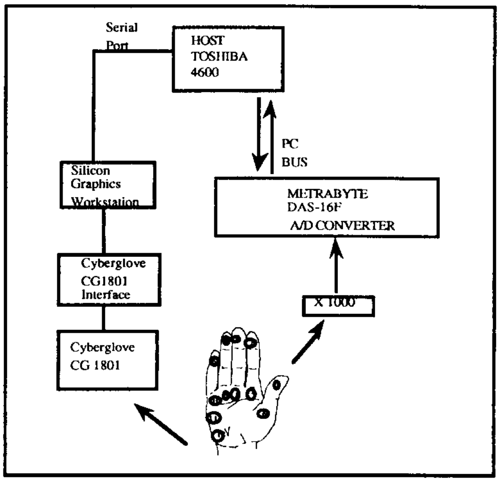

Figure 3. Equipment was set up for the measurement; joint articulation data was sent to separate interfaces and then transferred to a PC through a serial port. The force data simultaneously was recorded using an A/D converter. The number

on the hand represents the location of the force sensors attached to the hand.

Figure 4 shows the diagram of flexion angles and abduction angles measured by the Cyberglove system for the index finger. Positive sign was used for flexion angles and negative sign in the flexion angle specifies the corresponding extension of the joints. In abduction angles, positive signs were used to define ulnar deviation (twisting away from the thumb side) and negative signs were used for radial deviation (twisting to the side of the thumb).

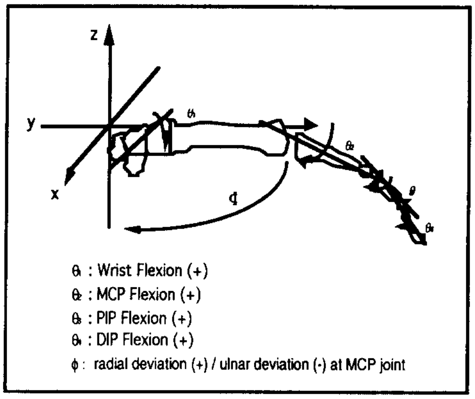

Figure 4. The definition of the joint angles and the coordinate system of the hand uses three dimensional Cartesian coordinate system at all of the hand joints including the wrist joint.

In order to express a hand posture in a mathematical form, introduction of the three dimensional coordinate system is necessary. In this study, an individual 3-D Cartesian coordinate system was defined at each joint of the finger as well as at the wrist joint. As shown in Figure 4, the coordinate system of the wrist joint was defined as the origin point. The coordinate of each subsequent joint was defined with respect to the MCP joint (next to the wrist), PIP joint (second next to the wrist), and DIP joint (closest to the finger tip) respectively.At each joint, the proximal system (palm side) is related to the distal system (finger tip side) through a transformation. Eulerian angles are introduced to handle the transformation of the coordinates to the wrist origin. The reference position of each hand segment in this system is defined as zero degrees of articulation for all joints with respect to the proximal segments. Using an Eulerian angle transformation, proximal coordinates of a point defined at the distal coordinate system can be calculated [27].

The Z-Y-X Euler angle defined at any finger joint is :

$$\begin{vmatrix} P_x' \\ P_y' \\ P_z' \end{vmatrix} = \begin{vmatrix} c\theta c\psi - s\psi s\phi s\theta & s\theta c\psi + s\psi s\theta c\phi & -s\psi c\phi \\ -c\phi s\theta & c\phi c\theta & s\phi \\ s\psi c\theta + c\psi s\theta s\phi & s\psi s\theta - c\psi s\phi c\theta & c\psi c\phi \end{vmatrix} \times \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix}$$

where, P':parameters at the angulated posture
P :parameters at the neutral posture
c : cosine, s : sine, q: flexion-extension angle
f: radial-ulnar deviation angle,
y: axial rotation angle

If we consider the hand grip posture with no rotation, the Eulerian matrix becomes :

$$M = \begin{vmatrix} c\theta & s\theta & 0 \\ -c\phi s\theta & c\phi c\theta & s\phi \\ s\psi c\theta & -s\phi c\theta & c\phi \end{vmatrix} \quad (2)$$

Therefore, the location of the joint i expressed in the (i-1) th coordinate is :

$$\begin{vmatrix} X_{i-1}' \\ Y_{i-1}' \\ Z_{i-1}' \end{vmatrix} = [M_i]_{\phi i \theta i} \times \begin{vmatrix} X_{i-1} \\ Y_{i-1} \\ Z_{i-1} \end{vmatrix} + \begin{vmatrix} X_i \\ Y_i \\ Z_i \end{vmatrix} \quad (3)$$

where : X_i, Y_i, Z_i :coordinates of the i-th joint
X_{i-1},Y_{i-1},Z_{i-1} : coordinates of the i th joint defined at the coordinates of i-1th joint
Mi : Euler matrix defined at i-th joint
q: flexion-extension angle
f:radial-ulnar deviation angle

Using these equations, the algorithm to calculate the joint locations and force parameters on the hand during grasp action was defined. Based on the angle and force data from the measurement system, the program calculates the joint torques and moments at all joints of the hand.

Overall, it was found that the grip force is a complex function of the size of the object, shape of the contact surface, and the types of the tools used. However, it was found that finger forces, index finger in particular, can be measured for the purpose of specifying the amount of force needed to maintain the grasp posture of the hand. Together with the joint angle data of the hand at that specific posture, a fairly good designation of position and force requirements could be possible for a robot. The force specification, is presumed to be initiated from the human operator based on his or her knowledge of the objects being grasped. The human operator holds an object similar to the one in the remote environment such as a brick. With the measurement system developed in this study, hand and finger posture as well as force to be applied are then relayed to the robot based on grasping performance using the instrumented glove. The force and position sensors attached to the Cyberglove™ system recognize the posture and the amount of force exerted to the finger tips and transfer the data as a specification to the manipulator for it to maintain during an otherwise autonomous grasping endeavor. With a basic robot algorithm to adjust for movement with gravity and to increase forces with the onset of slip, the instrumented glove specification system should allow the human to provide important data yet operate at a much higher level of strategic control than is possible with continuous telemanipulation.

This simultaneous specification of force and joint articulation serves as a first step toward improving human supervision of grasping for remote telerobotics particularly in the case where humans point and give directions rather than provide continuous telemanipulative input. Robotics community may progress further toward such strategic control of grasping as more sophisticated robot mechanisms are developed. With such robotic capability adapted to the point-and-direct paradigm, the role of the human may be raised to the level of giving target grasping angles and forces while letting the robot adjust and maintain a reliable grasp during its own complex trojections. Future research may consider the proper means to specify articulation angles and forces for robot grippers even when these grippers do not exactly resemble the human hand or the instrumented glove used to develop the grasp specifications.

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