DESIGN OF A MULTI-FINGER HAPTIC INTERFACE

FOR TELEOPERATIONAL GRASPING

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Abstract

In this paper the design of a multi-finger force-reflecting haptic interface device for teleoperational grasping is introduced. The haptic interface or "master" controller device is worn on the human operator's hand and measured human finger positions are used to control the finger positions of a remote grasping manipulator or "slave" device. The slave may be a physical robotic grasping manipulator, or a computer generated representation of a human hand such as used in virtual reality applications. The forces measured by the robotic slave, or calculated for the virtual slave, are presented to the operator's fingertips through the master providing a means for deeper human sensation of presence and better control of grasping tasks in the slave environments. Design parameters and performance measures for haptic interfaces for teleoperation are discussed. One key performance issue involving the high-speed display of forces during initial contact, especially when interacting with rigid surfaces, is addressed by the present design, reducing slave controller computation requirements and overcoming actuator response time constraints.

The design presented utilizes a planar four-bar linkage for each finger, to represent each finger bend motion as a single degree of freedom, and to provide a finger bend resistance force that is substantially perpendicular to the distal finger pad throughout the full 180 degrees of finger bend motion represented. The finger linkage design, in combination with a remote position measurement and force display assembly, provides a very light weight and low inertia system with a large workspace. The concept of a replicated finger is introduced which, in combination with a decoupled actuator and feed forward control, provides improved performance in transparent free motion, and rapid, stable touch sensation of initial contact with rigid surfaces. A distributed computation architecture with a PC based haptic interface controller and associated control algorithms are also discussed.

1. Introduction

A haptic interface often called a "master" is used to measure the positions of an operator's body, and utilize these positions to control the motion of a remote manipulator or "slave". If the haptic interface is also a haptic display, or provides haptic feedback, the interface presents to the operator, through the master, a touch sensation representing touch sensations experienced by the slave (Burdea, 1996). In this paper, a new design of a haptic interface with display is discussed. The design is for an interface capable of measurement of several fingers' motion, and force display to several fingers. In teleoperation, the slave hand or manipulator may be either a robotic hand capable of grasping motion, or a "virtual" hand, often utilized in virtual reality simulations. A virtual hand merely consists of a computer generated image of a hand that is used to interact with a computer simulation environment. Applications of teleoperation may therefore be divided into those of a virtual reality type or those of a physical type. Popular virtual reality applications include computer-aided design, training, and entertainment, while physical teleoperation applications include space missions, underwater exploration and manipulation in toxic environments. The value of haptic display as an interface for teleoperational grasping is that the operators can use their highly developed natural motor skills to very precisely control the slave manipulator (Shimoga, et.al., 1996) In virtual reality applications, the value is that the operator experiences a deeper sense of immersion in the virtual environment, and the "virtual" environment more closely resembles "reality".

2. Background

While many haptic interfaces have been proposed, a common feature lacking in prior designs is the ability to accurately represent rigid bodies. Traditional design of force reflecting haptic interfaces employs one or more actuators such as motors or fluid piston-cylinders directly coupled to the human operator during use. Thus when the operator executes a motion, in the absence of contact between the slave and any object in the slave environment, the operator back drives the actuator, and when the slave contacts an object in the slave environment, the actuator is powered to provide a force sensation to the operator. In virtual environments, the force is calculated typically as a function of the slave penetration distance (x) into the object, the slave's velocity (x'), and the virtual object's properties. The force is often calculated by:

$$F = Kx + B x' \qquad (1)$$

Where K is the stiffness of the object and B is the damping coefficient of the object. In physical teleoperation, the force to be displayed by the master is typically measured at the slave by a force

sensor. One problem area that has been repeatedly cited in the virtual applications literature is that the master of a traditional design is not capable of display of very rigid or hard objects. When the values of K and B in EQ. 1 are set to very high values, undesirable oscillations often occur, and the touch sensation experienced by the operator is quite unnatural (Burdea, 1996), (Colgate, et.al. 1993), (Kazerooni, 1993). In physical teleoperation, the time lag between force sensing at the slave and force display by the master requires that all master motions be limited in velocity. For example in a physical teleoperational experiment by Shimoga, et.al. (1996), a three finger grasp required 20 seconds, whereas a real human hand grasp is completed in as little as 100 milliseconds (Klatzky, et. al., 1996). If artificial master velocity limits are not included as part of the system, very high forces of contact between the slave and grasp object are likely to occur, resulting in damage to the robot or the grasped object. For human grasping, initial contact forces can be highly transient in nature [Sculteis et.al.(1996) shows force transients with a slope of 1.5 N / 0.1 s in a tele-operation task, while Lawrence et.al. (1996) show force transients of up to 2 N / 0.005 s during a tap on a virtual wall], and thus delay in display can cause extreme forces to be applied by the manipulator fingers. The haptic interface design and control algorithm discussed in this paper addresses both representation problems of virtual rigid bodies in a stable (non-oscillatory) manner and rapid response force display for more natural grasping in physical teleoperation. Springer and Ferrier (1999) give a detailed analysis of the dynamics involved during initial contact for both traditional interface design and the new design discussed in this paper.

Previous attempts at hand mounted single controlled degree of freedom finger tip force displays have provided forces that vary widely with finger bend angle, and/or are able to represent motion through only a fraction of the 180 degrees of real finger bend motion. For example, the palm mounted air cylinder method of Burdea's (1996) RMI and RMII provide a force at an angle that widely varies with finger bend angle, and can only represent finger bend from approximately 40 to 90 degrees. The angle of applied force also varies with finger bend angle for the tendon approach of Kramer (1993). The tendon with additional moment arm modification of Virtual Technologies (1997), more closely provides normal direction fingertip forces throughout full finger bend range, but at the expense of applying ghost forces to the back of the second finger phalange.

3. System Mechanical Design

The concept utilized for this design is based on the prioritization of the modalities and degrees of freedom within the haptic senses. The modalities and controlled degrees of freedom were prioritized with the most important being those capable of representing the widest range of dexterous manipulation tasks. From the prioritization study it was concluded that forces to multiple fingertips in the normal direction provided the most valuable haptic display for grasping operations (Springer and Gadh, 1996, 1997). This type of display is consistent with "precision grasp of highest dexterity" as found by Cutkosky and Howe (1990). To implement this mode of display, it was first recognized that in order to display forces to multiple fingertips development of a portable haptic display wherein the mechanism reaction forces were grounded to the operator's body in a location near the fingertips, offered significant advantages. These

advantages include low mass of the mechanical structure carried by the operator in changing hand positions, lack of hand workspace limitations, and the ability to develop a simple, lightweight structure for contact force display. The disadvantage of this approach is that global force to the hand as described above can not be truly represented unless the haptic interface is attached to a master robot. In this application, it may be desirable to not have the haptic interface contain an earth grounding linkage, so that the hand position and orientation measurement can be attached to a master robot arm of the same design as the slave robot arm. For VR applications, position and orientation measurement of the hand as a single point is readily available in the form of a magnetic tracker, such as Flock of Birds (Ascension, 1998).

The present interface utilizes a four link serial planar mechanism for transmitting force resistance to finger bend toward the palm. The same linkage is utilized for transmitting output motion of the finger bend (or position of the fingertip with respect to the back of the hand) to a linear motion of a flexible sheathed cable. The hand mechanism for a single finger is shown in FIG. 1, and is provided with three rotational degrees of freedom, matching those of the finger in its longitudinal plane. The mechanism is also configured such that position measurement and/or force input to one of the three degrees of freedom is sufficient to represent the natural finger bend motion or restriction thereof.

When mounted to the hand, the interface hand mechanism in combination with the hand form a six bar closed loop kinematic chain as shown in FIG 1.
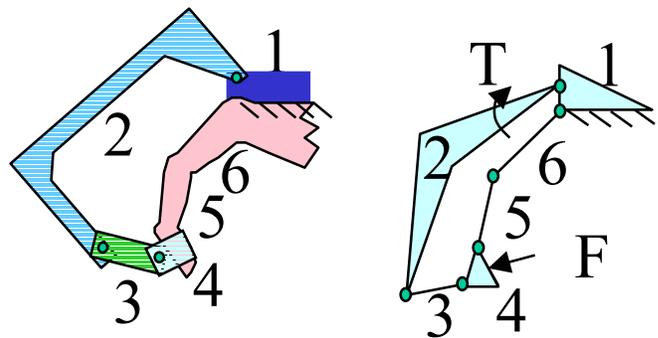

Figure 1 - Six Bar Linkage Formed When Operator Wears Haptic Mechanism

The six bar chain consists of the hand outer surface and the hand attachment of the hand mechanism, which together make up link1, which is the ground link. Connected to the ground link is link 2, the inverted "U" shaped link of the interface hand mechanism, which is in turn pivotally connected to link 3. Link 3 is pivotally connected to link 4, which comprises the fingertip thimble and the finger distal phalange. Link 5 forms a pivotal connection with link 4 and link 6, comprising the second finger phalange, while link 6 comprises the proximal finger phalange.

In this linkage design, the driver for clockwise rotation is link 2, driven to simulate interference with an object. However, links 4, 5, 6 can also drive the linkage for both clockwise and counter-

clockwise rotation. As can be seen from FIG 2, the six bar chain permits an approximate perpendicular angle formation between link 4 and link 3 throughout the range of motion.
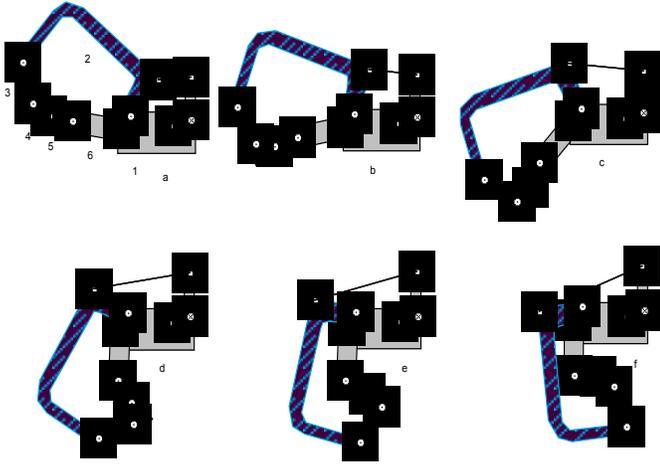
Figure 2 Positions of Six Bar Chain During Grasp

Because link 3 is a two force member, the force between links 3 and 4 is directed along a line formed by the two revolute joints of link 3. Considering this line of action for the force presented to the operator, one can evaluate the directional error of the force applied, with respect to normal to the distal phalange (link 4). For the positions shown, the errors are as follows: (a) –20°, (b) 0°, (c) +17°, (d) +19°, (e) +30°, (f) -18°. It may appear initially that an error as large as 30° would be problematic, but a closer inspection such as given in FIG. 3, demonstrates the quality of human adaptation to the application of the highest directional error of FIG. 2e. FIG. 3 shows an observed positional adjustment by the operator during a force application, to compensate for an initial force application angle of 30° off perpendicular.
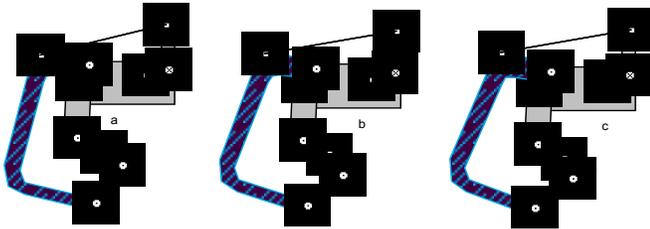
**Figure 3 - Rotation of Distal Phalange During Force Application**

In this type of compensation, it appears from preliminary experimentation, that the operator can choose not to compensate for directional error, or in the absence of a concentrated effort, will automatically compensate for the error. This results in a change of finger joint angles from FIG. 3a to that of FIG. 3c, wherein the applied force assumes a normal direction. For situations when the applied force assumes a normal direction. For situations when the operator does not compensate for off-normal directions, the haptic sensation (for angular errors in the less than 30° range) does not appear erroneous. This is presumably due to the ability to sense relatively large magnitude forces primarily in the normal direction. Thus, a benefit of the linkage design is that throughout 180 degrees

of motion for the finger, resistance forces are applied approximately normal (within 30°) to the distal finger pad, accurately representing the direction of normal forces that occur during real grasping and manipulation of objects.

The hand mounted mechanism is capable of representing the fingertip position, throughout a wide range of grasping motions (FIG. 2). The motion of the finger during grasp can be represented as a single variable, indicated by the rotational position of link 2. This single variable representation is not unique, since several relative link angles are possible. The range of relative link angles is quite small and thus introduces a small amount of uncertainty in fingertip position. A benefit is that because there are two uncontrolled degrees of freedom, the linkage is effective for a variety of operator's hand sizes, without the need for adjusting link lengths.

Given the single variable representation of finger motion, we can map the finger bend angle to a position of the "replicated finger". The contact drum can be controlled to track the replicated finger position, offset by a few degrees. The contact drum can be controlled to maintain a constant position preventing replicated finger clockwise rotation and thus preventing finger retraction. Alternatively, the contact drum can be controlled to provide a variable magnitude force to the replicated finger that is transferred to the operator's finger.

The rotational motion of link 2 is transmitted via a sheathed cable to a remotely mounted pivotal link, and called a replicated finger. This approach permits position measurement and force application apparatus to be remotely located, and the operator need not carry the bulk and weight of these systems. The replicated finger (as shown in FIG. 4) pivots on the input shaft of the position measurement potentiometer that converts the motion of the replicated finger into an analog voltage signal. The voltage signal is thus proportional to the degree of finger bend. This signal is read into the haptic control PC by a data acquisition (DAQ) board. The analog voltage signal is converted to a digital value for use in controlling the slave finger positions and in various control calculations as described in the following sections.
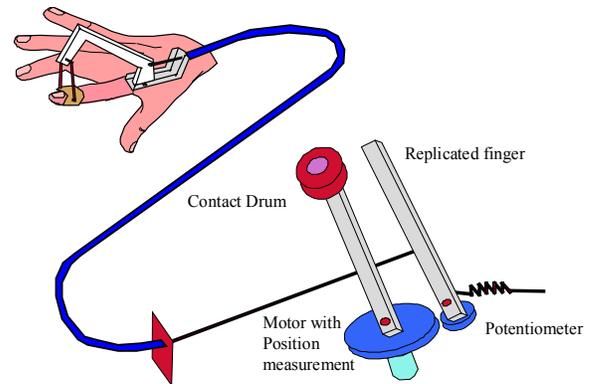
Figure 4 - Hand Mounted Mechanism, Measurement & Force Display

The replicated finger described above is also used to present forces to the fingertip that resist finger inward bend. This is possible because the replicated finger accurately reflects the motion of the operator's finger as a single degree of freedom pivoting link, and resistance to motion of the replicated finger provides a proportional resistance to the operator's finger. The contact drum provides the resistance to replicated finger motion. The drum occupies a position that under control of the computer selectively interferes with replicated finger rotation. After initial contact the force available at the contact drum is controlled by pulse width modulation (PWM) through the haptic control PC.

Thus, the mechanical system described above is capable of transmitting finger position, selectively defining interfering and non-interfering positions, and displaying a variable and controllable force magnitude. This is done while requiring only minimal control I/O of replicated finger position measurement, motor position measurement, and digital motor output. The number of control parameters is very important, because the cost and computer execution time both increase with the number of control parameters.

4. System Control Algorithm

The control system includes a distributed computing platform as has been utilized extensively in the haptics field. The present platform consists of a low end PC for execution of all haptic device data acquisition and control algorithms, connected by a serial line to either a slave manipulator control computer, or a virtual reality simulation computer. The haptic control PC software is implemented in C++ language. The C++ code is capable of an execution cycle less that 1 ms (1000 Hz) for all five fingers. The haptic control code has three main algorithms: (1) configure multi-function I/O board and calibrate for the individual user finger motion, (2) contact position control for initial contact with virtual objects, (3) variable magnitude force display control. The configuration and calibration algorithm performs DAQ board initialization functions and a user calibration routine. The calibration routine requests the operator to fully extend and retract their fingers, during which the program records the minimum and maximum voltage signal delivered by the finger bend potentiometers. Subsequently, the finger bend angle (β) is then calculated by:

$$\beta[i] = 180*(read\_volt[i]–pos\_low[i])/(pos\_high[i]–pos\_low[i]) \quad (2)$$

This delivers a value of 0 to 180 degrees for the current position of finger (i), wherein 0 degrees corresponds to a fully extended finger and 180 degrees reflects a finger position completely retracted to the palm. In order to calibrate the motor position control, a screen prompt asks the user to fully retract their fingers and allow the contact drum to extend the fingers under a loose grasp. The control algorithm then advances the contact drum, periodically recording the voltage of the motor position potentiometer when the finger bend is at predetermined intervals. This mapping yields a contact drum position accuracy of +/- 2 degrees with respect to the replicated finger position for recorded replicated finger position intervals of 20 degrees.

For the present implementation test bed, the global position of the hand is not recorded, as the grasp task only is under investigation.

However, it would be possible in other applications to attach the haptic display to a master robotic arm which, in turn, would control a duplicate slave robotic arm equipped with a grasping end effector similar to that of the of the implementation test bed. Alternatively, especially for VR applications, the global position and orientation of the hand in the virtual space can be provided by a commercial tracking device, shown as cube on back of hand in FIG. 5.

Position control variables for each finger denoted by subscript i are shown in FIG. 5. The interface between the master controller and the slave controller is shown in FIG. 6. Finger bend angle (β) is provided by periodic calls to the finger bend routine described above. Bend angle (β) is measured at the master and sent to the slave to control the position of the slave finger. Pre-contact distance (α) and force magnitude (F) are measured (or calculated) at the slave and sent to the master to control the contact drum position or force. The goal of providing fast response and highly stable contact sensation display is accomplished by selectively controlling the position or force of the contact drum as follows. Prior to contact between the slave and any slave environment object, the force (F) sent by the slave to the master is zero and the pre-contact distance (α) is greater than zero. In this case, position control is used. If there are no objects within the range of pre-contact distance (α) sensing, the value of α sent by the slave is a maximum range value (α_{max}). If an object is within the range of distance sensing, the measured or calculated value of α and a force (F) of zero is sent by the slave to the master for each finger. The master controller uses the received distance value (α_i) to calculate the contact drum position (γ_i) for each finger (i) as follows.
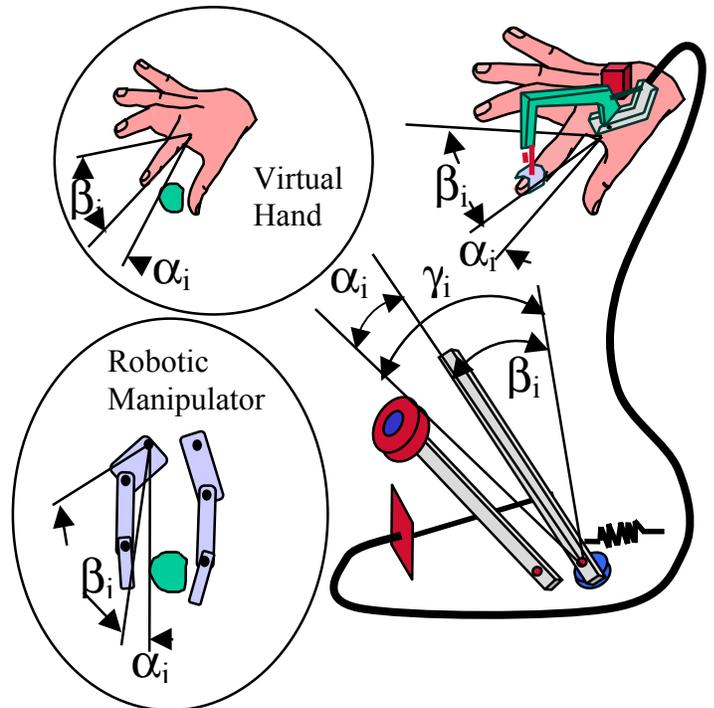

Figure 5 – Position Control Variables

If pre-contact distance (α_i) is greater than a predetermined offset distance (α^*), the contact drum for finger (i) is controlled to assume a position (γ_i) as:

$$\gamma_i = \alpha_i + \beta_i \qquad \text{for } (\alpha_i > \alpha^*) \qquad (3)$$

If the operator moves a finger (i) closer toward the palm, so as to cause the slave finger (i) to become closer to an object in the slave environment than the offset distance (α^*), the proximity contact drum position (γ_i^*) is defined as:

$$\gamma_i^* = \alpha_i + \beta_i \qquad \text{for } (\alpha_i(t) <= \alpha^*) \qquad (4)$$
$$\text{and } (\alpha_i(t-1) > \alpha^*)$$

Where $\alpha_i(t)$ is the pre-contact distance of the current calculation cycle and $\alpha_i(t-1)$ is the pre-contact distance of the previous calculation cycle. While the slave finger is closer to an object than the offset distance (α^*), the contact drum is controlled to maintain the proximity position (γ_i^*).

$$\gamma_i = \gamma_i^* \qquad \text{for } (\alpha_i <= \alpha^*) \qquad (5)$$

For slave objects that are rigid or have a high stiffness (K) and/or high damping (B), the force (F_i) sent to the master by the slave makes a (nearly) instantaneous step from a value of 0 to 100%. In this case, position control is continued.

$$\gamma_i = \gamma_i^* \qquad \text{for } (F_i >= 100\%) \qquad (6)$$

For slave objects of lower stiffness and damping, the force will more gradually increase with the penetration distance (x) and velocity (x'). With these objects the slave sends a contact force:

$$0 < F_i < 100 \qquad (7)$$

In this case, the master controller executes the variable magnitude force control algorithm.
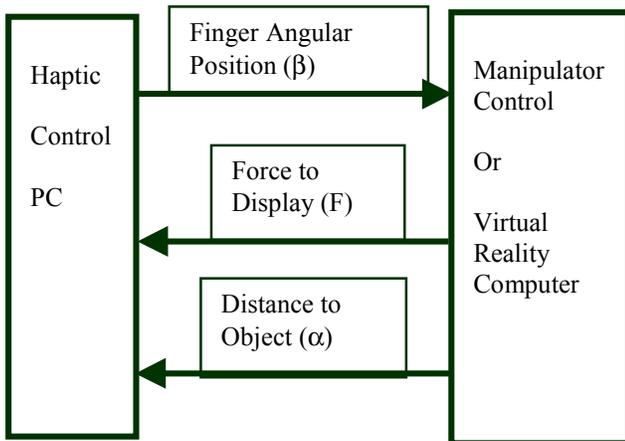
Figure 6 - Interface definition

To display a variable magnitude force, the control algorithm uses pulse width modulation (PWM) torque control to the motor driving the contact drum as shown in FIG.7. The force applied to the operator's fingertip is proportional to the motor torque. Neglecting cable friction, the fingertip force is given by the following geometry based (constant) function of motor torque:

$$F_{finger} = (a/b) * (d/c) * (1/e) * T_{motor} \qquad (8)$$

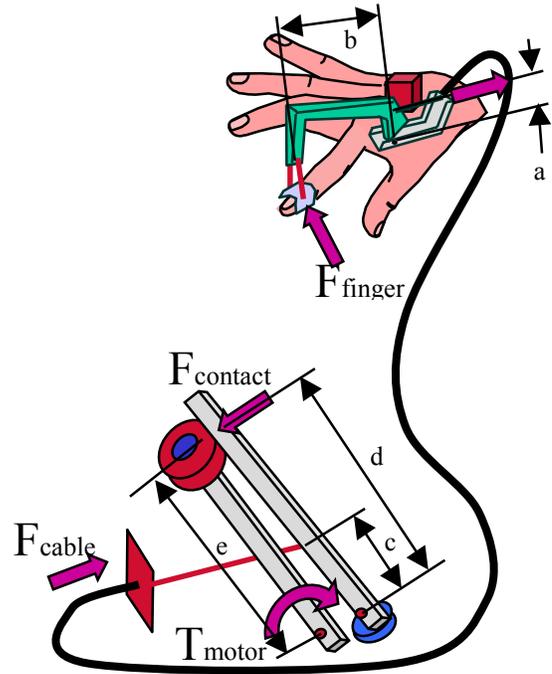Where lengths a, b, c, d, and e are depicted in FIG. 7.

Figure 7 – Variable Force Display

Knowing the desired force to be displayed, either by a scale of manipulator force or determined as a function of penetration distance and object stiffness (EQ. 1), and by *apriori* measurement of the maximum fingertip force that can be delivered by the system, we can present a PWM (Φ = % of stall torque) controlled force as follows.

$$\Phi = F_{finger}(\text{desired}) / F_{finger}(\text{max}) \qquad (9)$$

The force delivered is dependent on the penetration distance, and as with prior haptic displays during this mode the penetration distance will be that given by the previous finger bend input and virtual reality environment calculation. To implement PWM force control within the haptic PC, several motor control calculation cycles are required. The basic implementation is such that for a given percentage of maximum force (Φ), the motor digital output is given an "on" signal for a corresponding percentage of calculation cycles

followed by an "off" signal for $(1 - \Phi)$ cycles. For example an 80% of stall force ($\Phi = 0.80$) is delivered by giving 4 "on" signals to the motor followed by 1 "off" signal, repeating the sequence.

5. Conclusions

In this paper a new design of a multi-fingered haptic interface has been discussed. Several advantages of this new design have been outlined. The new design provides an interface mechanism that is lightweight, comfortable, with a large workspace, and delivers force display substantially normal to the operator's fingertips throughout a full 180 degree range of finger bend motion. Further, the design demonstrates high transparency and introduces a new control algorithm that permits several previously cited deficiencies in haptic interfaces to be addressed. Through the use of a decoupled actuator, the design presented here allows for better haptic rendering of rigid surfaces and more rapid delivery of haptic sensations. This control method offers a significant contact display speed advantage over previously reported haptic interfaces for grasping tasks, which at best only provide a signal to the user in the calculation cycle *following* the one in which the slave finger contacts or penetrates the grasped object. In the present method, contact between the robotic (or virtual) finger and an object can be displayed instantaneously, since the contact drum is in the proper position *prior to* robotic (or virtual) finger and object contact. The present system with a de-coupled actuator and the above described position control overcomes the instability problem of interacting with high stiffness virtual objects during grasp tasks.

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