Freedom 6S Force Feedback Hand Controller

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Abstract: A six-axis force feedback hand controller is described, suitable for interaction with virtual worlds or as part of a teleoperator system. It is composed of a 3 DOF positioner base, a 3 DOF balanced translation stage, and a 3 DOF rotational distal stage which carries the handle. High spatial resolution, low friction and accurate force reproduction are available over an elliptical volume of $22 \times 24 \times 22$ cm, appropriate for wrist size motion. The development and characteristics of the device are discussed, along with an example application to space telerobotics with appreciable time delay.

Keywords: force, feedback, virtual reality, stability analysis, computer control, teleoperation, computer simulation.

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1. INTRODUCTION

Haptic (or force feedback) devices, whether providing tactile or proprioceptive sensations, constitute powerful means of enhancing the interaction between humans and machines (Burdea, 1996). Beyond mice, trackballs, and conventional joysticks, they offer bi-directional communication, accepting position commands and reflecting forces to the users. In this way, haptic devices talk to the complex and personal sense of touch, by giving an immediate result to a given motion.

Force feedback hand controllers are among the first and most important haptic devices. The original motivation was to use them as masters in teleoperation systems (Sheridan, 1987), especially for hazardous and/or remote sites, such as underwater operations and in the nuclear industry. The birth of Virtual Reality (VR) in the late 1970's and the steady increase in computer power over the years (following Moore's law of doubling every 18 months for personal computers) opened up a whole new field for various types of haptic devices. From military training to entertainment, from scientific analysis to education, force-feedback is now one of the most intensive areas of research in VR. With the availability of such an intuitive and high bandwidth display in an interactive fashion, the human experience can be extended to previously unexplored subjects, such as moving in microscopic worlds around atoms and molecules, or sensing the active areas of a human brain.

Various devices have been developed for proprioceptive feedback. Two degree of freedom (2-DOF) force feedback devices are available commercially. Microsoft released its SideWinder Force Feedback Pro joystick in Fall 1997 (Microsoft, 1997) and the Pantograph is available from Haptic Technologies Inc. (Ramstein and Hayward, 1994). While both are 2-DOF devices, their respective workspaces make them quite distinct. The low-priced Microsoft model offers torque-feedback over a portion of a spherical surface, while the Pantograph works on a 10 cm square planar area, with position in one to one match to the 2-DOF computer screen.

A popular 3-DOF device is the PHANToM, produced by SensAble Devices Co. (Massie and Salisbury, 1994). This device provides force-feedback along the three cartesian axes over a volume suitable for wrist-size motion. The force is delivered either to the finger with the help of a thimble, or at the tip of a pen-like handle. If the object used to probe the virtual world is small (i.e. a small sphere or a larger object with little friction forces) and the force is sensed sufficiently

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close to its point of application to avoid induced torques, the realism of the feedback may be sufficient.

For more general simulations, such as turning a key in a lock, or in general for probing the virtual world with an extended instrument (e.g. a scalpel) and/or in the presence of friction, the addition of torque feedback may well be compared with adding color capability to a television set. In that case, new sets of sensitive muscle combinations are involved in the resulting proprioceptive feedback. Although some attempts have been made at making a useful 6-DOF force feedback device, the technical challenge has proven to be non-trivial and involves a number of tradeoffs with a result that will depend on the targeted applications. We summarize here our effort to build Freedom 6S (a name derived from the number of degrees of freedom offered by the device and the serial nature of the distal stage) based primarily on the following requirements:

- Small fictive forces (i.e. minimal inherent inertia and friction).
- A workspace suitable for wrist-size displacements with a complete rotation around the handle axis.
- Position and force resolution sufficient for smooth feedback (without graininess).
- Capable of rendering virtual stiffnesses large enough to make contact with hard surfaces credible in both force and torque.
- A maximum torque commensurate with the maximum force.

We discuss below some of the choices made to achieve those requirements. In particular, special attention is paid to the issue of the position sensor location, in the presence of a force transmission mechanism with finite stiffness. We then provide a number of measured characteristics of Freedom 6S and further comment on the high level software setup and a sample application in telerobotics.

2. TRANSLATION STAGE

In order to maintain the maximum in force fidelity, it was decided to work with direct drive motors. Without belts or gears, the friction and backlash are then minimized, giving a smooth operation with reduced noise level. Moreover, with minimum friction it can be assumed that nearly all the energy supplied to the motor is turned into joint torque in a predictable fashion, allowing an accurate presentation of forces to the user.

However, in order to reduce motor load, it is sensible to work with a balanced mechanism. Any torque that the motor has to exert to keep the hand controller in position would not be available for imparting forces to the user's hand. With a balanced mechanism, inertia is slightly increased, but the whole motor torque is available for haptic interactions.

The conceptual drawing of the Freedom 6S translation and distal stages is shown in Figure 1. The three motors for translation are shown explicitly. The axis of Motor 0 is constant, pointing in the direction *Z*. It can be seen that when Motor 0 is rotated, the axes of both Motor 1 and Motor 2 also rotate. Motor 1 induces a rotation with an axis in the XY plane, which coincides with the *X* axis when the device is at home position (as shown). Motor 2 acts through a 4-bar mechanism to provide force feedback around Joint 2.

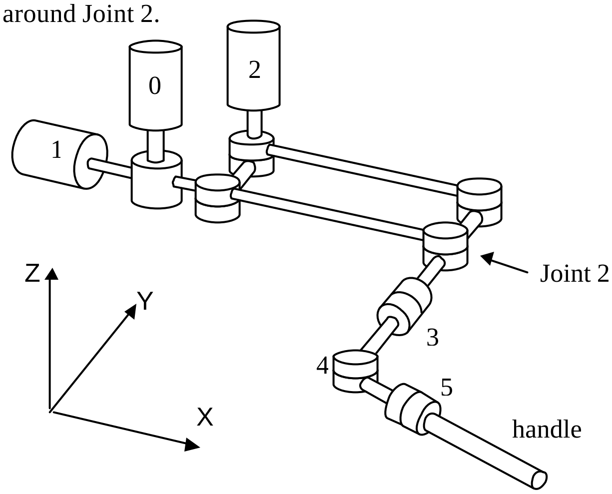

Figure 1: Concept drawing of Freedom 6S, showing the three translation motors, along with joints 3, 4 and 5 forming the distal stage.

As mentioned above, one of the design objectives is to reduce the forces of inertia presented by the mechanism to the user when displacing the handle. In that regard, the position of the motor is clearly crucial. Suppose a given motor of mass *M* is located a distance *R* from the rotation axis. Then let the arm be represented by a mass *m* located a distance *r* from that rotation axis, but on the other side. Then the two are balanced if

$$MR = mr.$$

On the other hand, the rotational inertia around the rotation axis is given by

$$I = MR^2 + mr^2$$

(up to numerical factors or order one depending on the actual geometry of the objects). Given the quadratic dependence on *R*, the inertia *I* is in fact minimized if *M* is as large as possible, and consequently *R* is as small as possible. The translation stage was therefore engineered with all translation motors, together with any other counterweights, as close as possible to the rotation axis. For example, Motor 2 is located close to both the rotation axes of Motor 0 and Motor 1. This was accomplished with a close eye on clearances allowed for movement of the parts and for the passage of drive tendons for the distal stage.

Each limb introduced is designed to be both stiff and light. This was obtained by making use of a closed form aluminum central member, reinforced by sheet metal cladding. The arm members are connected by joints with preloaded bearings, so as to eliminate any backlash when shifting the direction of the force.

3. DISTAL STAGE

The distal stage is the assembly starting with Joint 3, which is cantilevered at the end of the translation arm (see Figure 1). It is powered by a cluster of motors located on a fixed portion of the base (see Figure 3 below). Each rotary motor drives a tendon loop through a capstan attached to the motor shaft. A tensioner behind each motor maintains the tendon in a moderately taut position. A small tension suffices to keep the tendon in place; too much tension would give rise to unnecessarily high bearing friction. Polymer tendons were chosen for transmitting forces. They have a number of advantages over the alternative means of power transmission:

- lightweight, adding little to the arm mass
- reduced weight and inertia, since motors are not carried in the distal stage
- reduced backlash and friction compared to a linkage or gear system (Brooks, 1990).
- a tough, wear-resistant surface
- low bending resistance
- long life and low short-term stretch.

Compared to steel tendons, they are more flexible in bending, but they do have a long term creep, a slow lengthening under load. Pre-stretching the tendons before installation on the hand controller can reduce the effect of this creep.

The distal stage is a serial mechanism, with one tendon driving each degree of freedom. The forward kinematics and jacobian computation is thus simplified and numerically more stable, compared with a parallel mechanism. The angle sensors used in the distal mechanism operate on the magneto-resistive effect, providing high accuracy, low-noise and non-contact sensing. One sensor is attached to each degree of freedom, except for rotation around the handle's axis, where two sensors are used. This permits the handle roll to be sensed over a full rotation by combining data from the two sensors. Moreover, by integrating the sensors to the arm, their bearings can be made part of the joint structure, reducing the parts count and keeping the weight to a minimum. As an upgrade, this mechanism may also accommodate an additional degree of freedom for scissors (e.g. in medical simulations) or grip-like operation. Interestingly, this can be done while preserving the workspace of the rotational degrees of freedom. Within the Freedom 6S model, deciding on the precise location of the sensors is an important question, to which we now turn our attention.

4. SENSOR LOCATION

Given the tendon transmission mechanism for the distal stage, there are a few good reasons why one would want to have the sensor close to the handle. An obvious one is the preservation of sensor calibration. Given the occasional stretch and/or small repositioning of tendons along the path, added to the mechanical elasticity of the structure carrying the tendons, the handle positioning accuracy is generally better off if the measurements are made directly on the handle. Moreover, more rotational range (and thus less resolution) is generally required for a sensor mounted away from the handle, due to the (redundant) rotation induced from moving the translation part of the arm. On the other hand, other criteria such as low inertia and simplicity of design (e.g. electric wire routing) would tend to favor having the sensors closer to the motor. More importantly, the question arises as to what location will make the control loop more stable, so that for example, higher virtual stiffness can be rendered.

In order to gain insight into this important problem, we consider a simplified 1-dimensional problem with direct relevance for our serial mechanism. The setup is shown in Figure 2. A rotating motor is connected to an otherwise freely rotating handle through a transmission mechanism of stiffness K. At time t, let the angle of the handle be $j_h(t)$, and the angle of the motor, $j_m(t)$, as measured from a vertical reference. Consider the problem of a user holding the handle, making contact with an angular virtual wall modeled with Hooke's law, of angular stiffness k, effective for angle $j > 0$. With the sensor located at the motor, the virtual wall imparts a restoring torque $-k\, q(j_m)\, j_m$, proportional to the depth of penetration, where the step function, θ(φ) is defined as usual:

$$\theta(\varphi) = \begin{cases} 1 \text{ if } \varphi > 0 \\ 0 \text{ if } \varphi < 0 \end{cases} \qquad (1)$$

Having the sensor at the handle, the virtual wall provides instead a torque $-k\, q(j_h)\, j_h$. If the operator brings the handle in touch with the virtual wall at time t, the motor will generally react only at time t +

Dt. The (small) time Dt accounts for any delay in the processing and transmission of data.

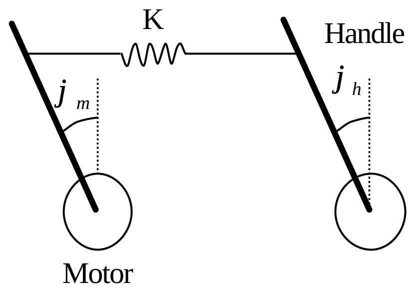

Figure 2: Motor, handle and transmission of stiffness K.

If the sensor is located at the motor's axis, then the equation of motion for the motor is,

$$I_m \ddot{j}_m = -q(j_m(t-\Delta t))\, k\, j_m(t-\Delta t) - K(j_m - j_h) - b\dot{j}_m \qquad (2)$$

where I_m is the motor inertia, b is the friction coefficient and a dot is used to indicate a time derivative. The last term in Eq. (2) accounts for friction in the mechanism and the various angles are at time t when not explicitly written. Taylor expanding $j_m(t\text{-}Dt)$ to first order in Dt (going to second order merely modifies the effective inertia of the motor), the equation can be rearranged as follows:

$$I_m \ddot{j}_m + \left[b - k\, \Delta t\, q(j_m(t-\Delta t))\right]\dot{j}_m + \left[K + k\, q(j_m(t-\Delta t))\right] j_m = K\, j_h \qquad (3)$$

If the velocity coefficient $[b - k\ Dt\ q(j_m(t\text{-}Dt))]$ becomes negative, the system is no longer damped, but is instead anti-damped, or unstable. If the physical friction b is low (a design objective), this instability will occur even for relatively low values of the virtual wall stiffness k.

Consider the situation with the sensor at the handle. This time, the equation of motion for the motor reads

$$I_m \ddot{j}_m = -q(j_h(t-\Delta t))\, k\, j_h(t-\Delta t) - K(j_m - j_h) - b\dot{j}_m \qquad (4)$$

Taylor expanding $j_h(t\text{-}Dt)$ to first order in Dt, Eq. (4) becomes

$$I_m \ddot{j}_m + b\dot{j}_m + K j_m = \left[K - k\, q(j_h(t-\Delta t))\right] j_h + k\, \Delta t\, q(j_h(t-\Delta t))\, \dot{j}_h \qquad (5)$$

where the RHS appears as a time-dependent perturbation on the damped motion of the motor. The potentially destabilizing second term in the perturbation will in fact be small when the handle is slowly rotating (small $\dot{j}_h$), as is usually the case owing to the operator's holding it. As for the first term on the RHS, it reduces the effective transmission stiffness K whenever the handle is inside the wall (as in general, one should keep $k < K$). Thus, as long as the noise level in the measurement of the handle position j_h remains small near the resonant frequency of the system, one expects stable motion of the motor at the virtual wall surface.

Although in reality the feedback loop is implemented in discrete steps rather than continously as presented here, our experimentally obtained results on Freedom 6S have confirmed the improved stability obtained by locating the sensors closer to the handle. This is not altogether too surprising. Working at 1 kHz for the force update rate, the quantizing effect produced by discretization acts in effect as a high frequency perturbating noise in the loop. Given the high frequency, this noise is filtered out mechanically through inertia I_m and friction b (thus being above the resonant frequency) and/or by making use of an explicit low pass electronic filter.

5. DEVICE CHARACTERIZATION

The complete hand controller is shown in Figure 3. It features a base that can put the controller into a wide variety of working positions, both by rotation in three degrees of freedom and by raising and lowering the device. Control electronics are in a box attached to the base. The translation stage is located behind the distal motor pack, carrying the distal stage with its handle.

The translation workspace, the movement space of the handle, is an elliptical volume 22 × 24 × 22 cm; within this volume, the distal stage rotates in 100° of pitch, 100° of yaw and 320° of roll (about the length of the handle). The importance of low damping and inertia at the handle has been stressed (Hayward and Astley 1995). Static friction in translation and rotation is near 0.06 N and 0.02 Nm respectively, while the static inertia is near 200 g around Motor 0 and 100 g along the other two motor axes.

With 16 bit digitization, the position resolution is some 20 microns in translation. In rotation, the resolution is a small 0.005 radians. (A figure of some

25 microns has been mentioned for a high performance haptic device, so that quantization effects are safely placed below measurable threshold (Rosenberg 1995)). The maximum translational force of 2.5 N can be delivered for some 50 secs at a time. Demands for the maximum force for longer periods are typically infrequent however, as force modulations in time and space are more useful in exploring the virtual space. In any case, a dual temperature model (Demers, 1998) will restrict the current to an overheating motor, providing a maximum continuous output force of 0.6 N. In rotation, a maximum torque of 125 mN·m can be sustained for some 30 seconds at a time, with a maximum continuous value of 80 mN·m. When writing forces, the resolutions are 1.5mN in translation and 0.1 mN·m in rotation.

Figure 3: The Freedom 6S with active gimbal

A basic test to assess the overall capability of the device and control software is to simulate a virtual wall in cartesian space using a spring model of variable stiffness. By gradually increasing the spring stiffness, gentle contact with the wall will eventually generate a degree of instability. Working with a feedback loop closing at 1 kHz, stiffness of some 700 N/m was achieved in a stable manner in both force and torque. This was done with an elongated virtual probe of some 12 cm in radius, reproducing the feel of a hard rubber surface. The addition of a damping term (a dissipative force opposing the speed of contact with the wall) was found to significantly add to the wall-like impression of the contact.

6. SYSTEM ISSUES AND APPLICATION

As part of a virtual reality computer system, Freedom 6S is attached to a control computer , which links via Ethernet (TCP and UDP protocols) to a host computer running the simulation. The host computer interface to the haptic side is currently provided by the Armlib API from the University of North Carolina (Mark et al., 1996), with which connection can be made from Windows 95/NT and Unix platforms. At its lowest level, the simulation program may read cartesian position from the hand controller, and send back cartesian force and torque vectors. Except for the simplest simulations, it is usually preferable to work with *intermediate representations*. After the host sets a virtual plane of variable orientation, stiffness, friction and adhesion, contact with that plane is done in a fast (e.g. 1 kHz) force/torque feedback loop between the control computer and the haptic device. Suitable changes of virtual planes, (or other intermediate representations) along with smoothing between them are required to present a complex shape while preserving the high bandwidth required for good quality of contact.

Figure 4: Operator working with a virtual model of a remote robot.

One of the interests of teleoperation is to undertake ground to space control with appreciable time delays. Under the recent STEAR 8 program, a system was set up to allow an operator to control a virtual robot, and have the remote space robot slaved to the virtual system (Figure 4). Known as CAST or Configurable Architecture for Space Telerobotics, the system is comprised of two parts: a virtual teleoperation on the ground and the actual space teleoperation, with a slow link between the two subsystem closedloops. The ground component has a World Model with a graphic display of the space scene and is updated at regular intervals by sensor data from the space component. Tests with delays up to six seconds were conducted in a laboratory environment. Force feedback was found to add greatly to the realism of the situation, keeping the operator aware of actual and virtual constraints that may exist in space. In one of the demonstrations, virtual bubbles were put around two miniature astronauts, and the system prevented the space arm from entering the protected space.

7. CONCLUSION

A sensitive six degree of freedom hand controller has been described, along with some of the design issues that were encountered. The device can successfully operate in a variety of virtual reality systems, and is expected to take its place in a number of important applications, including surgical training and space teleoperation.

8. ACKNOWLEDGMENTS

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