Elements of Haptic Interfaces

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Adapted from Section 3.1 of Professor Kuchenbecker's Ph.D. thesis [3].

A haptic interface plays the important role of connecting the user to the controller during interactions with remote and virtual objects. Such systems incorporate mechanical, electrical, and computational elements, which all interact to create the touch-based sensations experienced by the user. This document is concerned specifically with actuated impedance-type interfaces, which currently dominate the field due to their excellent free-space characteristics and their widespread use in a variety of applications. During an interaction, the controller of an impedance-type device must measure the user's hand motion and apply an appropriate force in response. Impedance-type haptic interfaces vary in design, but they usually include a series of electrical and mechanical elements between the handle and the computer, as described below.

Overview

Haptic interfaces typically provide two or three degrees of freedom in position, sensing the user's motion and applying feedback forces within this workspace. Many devices also permit changes in the orientation of the end effector; these rotational degrees of freedom can be unsensed, sensed but not actuated, or sensed and actuated. The remainder of this discussion will focus on translation rather than orientation, though the described design features can be applied to either.

Figure 1 illustrates the chain of elements typically present in each axis of a haptic interface. For clarity, the illustration depicts a device with a single degree of freedom, but typical systems combine several degrees of freedom in parallel or series to allow unrestricted translation and/or orientation. Although differences exist, individual position axes of most mechanisms can be represented by such an arrangement. The terms "haptic interface" and "master" are often used interchangeably to represent all electrical and mechanical elements depicted in Figure 1, extending from the amplifier and encoder to the handle.

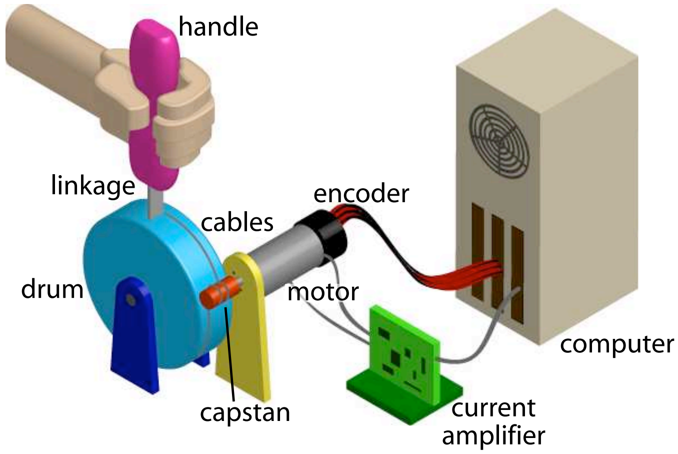

Figure 1: One axis of an impedance-type haptic interface.

Computer

The haptic interface's controller typically runs on a real-time enabled computer at a fixed servo rate, which is often one kilohertz. Each time the servo loop code executes (once per millisecond for a one kilohertz update rate), it samples all of the system's sensors, computes the new location of the user's hand, determines the forces that should be exerted in response, and sends appropriate current commands to all of the system's actuators.

Whether they are computed from a remote interaction or a virtual environment, the haptic feedback forces are converted to a desired current for each DC motor using the transpose of the mechanism's configuration-dependent Jacobian matrix, the gear ratio of each joint, and each motor's torque constant. These current commands are communicated as analog voltages to a set of self-contained amplifiers through a digital-to-analog converter (DAC) that often resides on a control card on the computer's ISA or PCI bus. Some amplifiers also accept digital commands, communicated over a parallel or serial connection.

Current Amplifier

Each amplifier is connected to one motor, and it attempts to drive the commanded current through that motor via pulse-width modulation (PWM) or linear control techniques. PWM amplifiers are presently somewhat more common in haptics due to their widespread use in industrial robotics where their lower power consumption is important. Unfortunately, PWM amplifiers generate significant high-frequency electrical noise at their switching rate and its harmonics, which can contaminate analog sensor lines. Additionally, PWM amplifiers are often tuned by the manufacturer to a low bandwidth, often on the order of 100 hertz, which is adequate for industrial applications but must be increased for high-frequency haptic interaction. If their additional power consumption can be tolerated, linear amplifiers are generally preferable, as they can provide very clean, high-bandwidth current output without interfering with the system's sensing requirements.

Motor

Haptic interfaces typically use small, brushed DC motors such as those available from Maxon Precision Motors, Inc. [4], as they provide very smooth torque generation and have high power-to-weight ratios. Current flowing through the motor creates a torque on the motor shaft, to which a small capstan is attached. The relationship between the motor current, i_m, and the applied motor torque, τ_m, is governed by the motor's torque constant, k_t, as follows:

$$\tau_m = k_t \, i_m. \tag{1}$$

The torque constant for a motor can be obtained from the manufacturer's data sheet and can also be calibrated using an ammeter and a torque sensor. When used in a haptic interface, the net torque output of the motor will be diminished by the friction present at the motor shaft, so low-friction motors and bearings are desirable. It is also desirable to keep the inertia of the motor as low as possible, since the user will need to accelerate it during all motions.

Another important set of characteristics for a DC motor are its heat dissipation capabilities and its internal temperature limit. The flow of current through the motor coils produces heat that raises the temperature of the rotor. A motor that is driven with high levels of current that cause it to exceed its internal thermal limit will burn out and need to be replaced. This phenomenon is often viewed as setting a maximum steady-state current that a motor can sustain indefinitely. Most interface designers conservatively choose to operate under this limit at all times, though more sophisticated thermal monitoring schemes can also be employed [1]. As another consideration, a rise in motor temperature increases the motor's electrical resistance and therefore reduces its electrical efficiency.

Encoder

Motion of the haptic interface is usually sensed with an optical encoder attached to the back end of the motor shaft. This type of sensor provides two digital output lines, often denoted A and B, that stem from two optical sensors in the encoder. These two sensors are pointed at a reflective disk that has many thin radial lines cut out of it or painted onto it; this disk rotates with the motor shaft. Each sensor reads high and low as lines pass before it, and their locations are chosen to place the signals 90° out of phase from one another. A quadrature decoder chip, which is usually located on a control card on the computer's ISA or PCI bus, observes the output of these two sensors to determine the present angular position of the motor shaft. The output of the quadrature decoding is an signed integer that designates the number of ticks the shaft has rotated away from an arbitrary zero location. Each tick represents one quarter of one line on the disk; haptic interface programmers can determine the number of lines in an encoder either from the manufacturer's data sheet or from calibration. This information enables computation of the encoder resolution, Δ, which is measured in radians per tick and is calculated as

$$\Delta = \frac{2\,\pi}{4\,n}, \tag{2}$$

where n is the number of encoder lines per revolution, commonly between 500 and 2,500 (and occasionally reaching as high as 25,000 for very high-resolution encoders).

Once the resolution of the encoder is known, the digital output from the quadrature decoder chip can be transformed into a quantized motor angle reading, θ_m, as follows:

$$\theta_m = \Delta(Q - Q_{zero}), \tag{3}$$

with Q standing for the present quadrature output and Q_{zero} being a calibration value. This zero offset must be determined every time the system is initialized, often by recording the quadrature readings at a certain known position in the device's workspace.

Cables

Thin stranded cables couple motion of the motor's capstan to that of a larger drum. Cable drives are used instead of belts or gears to enable smooth, efficient motion of the device [6]; the human hand is very sensitive to high-frequency vibrations, so non-vibratory transmission elements must be used to maintain the realism of free-space motion. When pre-tensioned, the low-stretch, highly-stranded cables available from manufacturers like Sava Industries, Inc. [7], provide a zero-backlash connection between capstan and drum, which is important for ensuring a close coupling between the user's hand and the motor.

Drum

The drum diameter, d_d, is typically five to twenty times as large as the capstan diameter, d_c, providing the unitless gear ratio, ρ, as follows:

$$\rho = \frac{d_d}{d_c}. \tag{4}$$

Assuming that they are perfectly inextensible, the cables couple the motion of the capstan and drum together by this gear ratio with the following two equations:

$$\tau_d = \rho\,\tau_m \tag{5}$$

$$\omega_m = \rho\,\omega_d, \tag{6}$$

where τ is a torque, ω is an angular velocity, and the subscripts d and m denote drum and motor respectively. The cable drive thus serves the dual objectives of amplifying the motor's torque to enable stronger haptic feedback and amplifying the drum's motion to enable higher resolution position measurement. The primary disadvantage of a high gear ratio is that it also increases the effect of the motor's rotational inertia and rotational friction at the user's hand, relationships that go with ρ^2 and ρ respectively. Device designers typically balance the four objectives of torque amplification, motion amplification, inertia minimization, and friction minimization to select an appropriate gear ratio.

Linkage and Handle

The drum is attached to the endpoint of the device through a mechanical linkage, and the user holds a handle, stylus, or thimble at the endpoint. Here, the distance between the rotational axis of the drum and the point of user-handle contact is defined to be h, and it relates the translation of the user's hand to the rotation of the drum. Note that the distance h usually depends on configuration for devices with series (rather than parallel) actuation. If the linkage were perfectly stiff, the coupling relationships would be

$$F_f = \frac{\tau_d}{h} = \frac{\rho\,\tau_m}{h} \tag{7}$$

$$\omega_m = \frac{\rho\,v_h}{h}, \tag{8}$$

where F_f is the haptic feedback force applied to the human, and v_h is the translational velocity of his or her hand. Such devices are designed to have low friction and low inertia so that the user can easily move them by hand and so that the applied haptic feedback is more salient than the forces resulting from the natural dynamics of the device.

User

The final element that affects the behavior of a haptic interface is the user. When an individual grasps the handle at the end of the system's long dynamic chain, he or she gains the ability to physically affect its motion and to be affected by it in turn. The skin and muscles of the human hand are somewhat compliant and dissipative, and the flesh and bones of the hand have significant mass [2, 5]. While all of the other elements in the master's dynamic chain are generally time invariant, with the possible exception of configuration dependence, different users consistently possess unique dynamic characteristics. Additionally, the dynamic response of each user can vary over time with changes in grasp configuration and the co-contraction of various muscle groups. This combination of computer, device, and human forms a complex electro-mechanical-biomechanical dynamic system; configuring its many elements correctly enables touch-based communication between the user and a remote or virtual environment to enable performance of a wide range of tasks.

References

[1] J. Fiene, K. J. Kuchenbecker, and G. Niemeyer. Event-based haptic tapping with grip force compensation. In *Proc. IEEE Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 117–123, Mar. 2006.

[2] A. Z. Hajian and R. D. Howe. Identification of the mechanical impedance at the human finger tip. *Journal of Biomechanical Engineering*, 119(1):109–114, Feb. 1997.

[3] K. J. Kuchenbecker. *Characterizing and Controlling the High-Frequecy Dynamics of Haptic Devices*. PhD thesis, Stanford University, Department of Mechanical Engineering, 2006.

[4] Maxon Precision Motors, Inc., http://www.maxonmotorusa.com.

[5] D. T. V. Pawluk and R. D. Howe. Dynamic lumped element response of the human fingerpad. *Journal of Biomechanical Engineering*, 121(2):178–183, Apr. 1999.

[6] J. K. Salisbury, Jr., W. Townsend, B. Eberman, and D. DiPietro. Preliminary design of a whole-arm manipulator system (WAMS). In *Proc. IEEE International Conference on Robotics and Automation*, volume 1, pages 254–260, Apr. 1988.

[7] Sava Industries, Inc., http://www.savacable.com.