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GETTING A FEEL FOR DYNAMICS: USING HAPTIC INTERFACE KITS FOR TEACHING DYNAMICS AND CONTROLS

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ABSTRACT

Low cost, single-axis force reflecting joysticks were used to teach students about electromechanical systems, dynamics and controls. The students assembled the devices from kits, tested and analyzed them, and used them to interact with computer models of dynamic systems. The devices helped students to appreciate such phenomena as equivalent inertia, friction and the effects of changing control system parameters. They also generated high enthusiasm among the students, particularly when used in cooperative "haptic video games" at the end of the course.

1. INTRODUCTION

Instructors of courses on dynamics and controls continually face the challenge of making the material more interesting and accessible. Laboratory exercises are helpful, as are software programs for simulating and analyzing dynamic systems. But even with these aids, concepts such as eigenvalues, hysteresis, and time constants can seem mysterious to students encountering them for the first time. Haptic interfaces provide an engaging way for students to obtain an understanding of these dynamic phenomena.

We knew from in-class demonstrations that commercial human/computer interaction products were an exciting "high-tech" subject. We also knew from previous efforts to develop "haptic video games" (Costa et al., 1996) that the combination of force feedback and computer graphics could create a compelling sense of physical interaction with objects in a computer simulation.

Motivated by these considerations, we designed simple single-axis haptic interface kits that students could assemble, model, connect to a computer, and use for interacting in a physical way with computer simulations of dynamic systems. The students were enrolled in a ten-week course on Linear Dynamic Systems, a part of the undergraduate sequence in Mechanical Engineering at Stanford University. The enrollment in this course is approximately 60 students, and the students worked in groups of 2 or 3, requiring a total of 24 kits.

2. DEVICE DESCRIPTION

It is well known that haptic interfaces need to have low inertia, good dynamic response, and very smooth motion to avoid imparting artificial sensations to the user. The solution in commercial force-reflecting devices such as SensAble Device's PHANToM[1] and Immersion's Impulse Engine[2] is to use low-friction, low-inertia DC servomotors connected to a linkage through a cable transmission. These devices provide excellent performance, at a cost of several thousand dollars.

The main challenge in designing our interfaces was to provide good performance at a very low cost. The kits we developed are single-axis force-reflecting joysticks (Fig. 1). Most of the components are made of laser-cut acrylic, to minimize costs

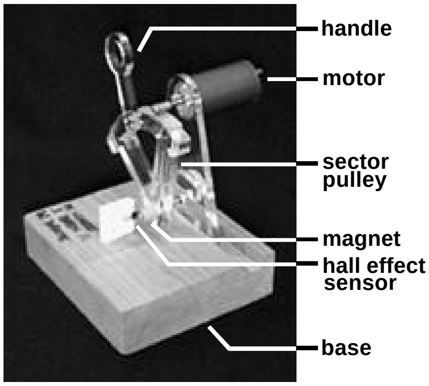

Fig. 1. Single axis haptic interface

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[1] SensAble Devices Inc., Cambridge, MA. http://www.sensable.com

[2] Immersion Inc., San Jose, CA. http://www.immerse.com

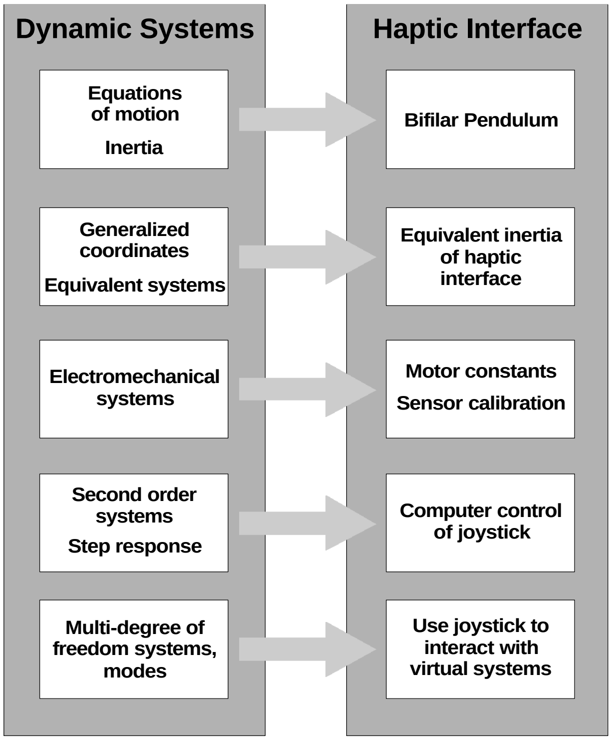

Fig. 2. Correspondence between course material and haptic device experiments

while obtaining smooth surface finishes and good dimensional control. The actuator is a smaller and less expensive version of the servomotors found in commercial haptic devices. Other substitutions (e.g., using heavy duty Dacron thread for the cables, Teflon bushings for the bearings, and Hall effect sensors for position feedback) kept the kit costs below $30. Design details and a parts list are provided in the Appendix.

3. HAPTIC INTERFACES AS EXAMPLES OF SYSTEMS TO MODEL AND CONTROL

As shown in Fig. 2, the assembly, testing and control of the kits provided a vehicle for illustrating concepts introduced at each stage of the course. In this section we describe the exercises conducted at each stage.

3.1 Modeling mechanical systems

The first two weeks of the course focused on obtaining the equations of motion for mechanical systems. The students were introduced to the concepts of equivalent kinetic and potential energy and power dissipation to obtain lumped-parameter values of the equivalent inertia, stiffness, and damping of single-degree of freedom systems. Upon receiving their kits, the students glued the major acrylic pieces together and inserted bushings and fasteners. Then they formed teams to measure the weight and moment of inertia of the sector pulley/handle assembly, using the bifilar pendulum method (Steidel, 1993), as illustrated in Fig. 3. The students were also asked to estimate their measurement errors using the standard formula for the variation in a function, y, of several toleranced variables, x_i:

$$\delta y \cong \left[\left(\frac{\partial y}{\partial x_1}\delta x_1\right)^2 + \left(\frac{\partial y}{\partial x_2}\delta x_2\right)^2 + \ldots + \left(\frac{\partial y}{\partial x_n}\delta x_n\right)^2\right]^{1/2} \qquad (1)$$

The students were pleased to see that their measured values had an estimated accuracy of 3%.

The next exercise was to determine the equivalent inertia, M_{eq}, felt by a user moving the joystick back and forth, as a function of the inertias of the motor and sector pulley assembly. Assuming small angles of motion about the upright position, the equivalent (linear) inertia of the handle is

$$M_{eq} = \frac{(J_s + J_m N^2)}{l_x^2} \qquad (2)$$

where:

J_m = rotary inertia of motor (from manufacturer's data sheets) and motor pulley

J_s = rotary inertia of sector pulley and handle, about the pivot point (from bifilar pendulum experiments and parallel axis theorem).

N = speed ratio between motor pulley and sector pulley (approximately 25/1)

l_x = length from joystick pivot point to the grasp point on joystick handle (approximately 11.5 cm).

By playing with the assembled kits the students could readily confirm that the motor inertia, while only about 1/70 the inertia of the sector pulley and handle, dominates the equivalent inertia sensed by the user because of the N^2 effect. Similarly, the friction (Coulomb + viscous) in the motor, and in the cable transmission between the motor pulley and the sector pulley, dominates the overall friction in the device. The students also found that the devices were unstable in the absence of feedback because the center of mass of the sector pulley/handle assembly is above the pivot point (for some of the devices, the friction was low enough that the handle would fall to one side given a slight tap).

After the equivalent inertia, stiffness, damping and friction were determined, the students could describe the haptic device as

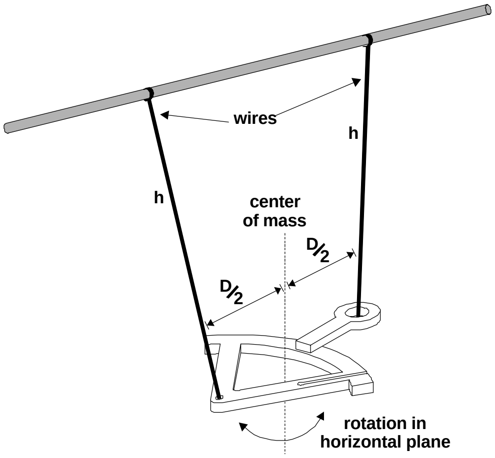

Fig. 3. Using the bifilar pendulum method to measure the moment of inertia

a simple second order system using the generalized coordinate *x*, to represent the horizontal movement of the joystick handle.

3.2 Electromechanical system parameters

During the third and fourth weeks of the course the students were introduced to electrical and electromechanical systems. At this time the students measured the torque and speed constants of their motors and estimated the maximum force (approximately 7.5 N) that the devices would be able to generate at the handle. The torque and speed constants were measured using a variable voltage power supply, ammeter, encoder, a set of weights ranging from 10 to 200 kg, and some 3.0 cm diameter pulleys. To obtain the torque constant the students attached a pulley to a motor and suspended various weights from a thread wrapped around the pulley. They were told to measure the current while adjusting the voltage so that weights appeared to be “neutrally buoyant” against gravity, when moved slowly up or down by hand. This procedure allowed the small motor friction to be accounted for. To obtain the motor voltage/speed constant, they spun the motor shaft at known velocity (using another motor equipped with an encoder) and measured the voltage generated. The results were consistent for each of the several models of motors used in the class.

The students also calibrated the Hall effect sensors for later use. The use of analog position sensing was motivated mainly by the availability of lab stations equipped with standard A/D and D/A data acquisition cards. However, the choice of an analog sensor also gave the students some insight into the procedure of device calibration, using a simple setup involving an oscilloscope to measure the sensor voltage and a protractor to measure the handle angle.The sensors are mounted on the base (Figs. 1 and 6) and respond the changes in magnetic field of a small cylindrical magnet mounted at the pivot point. The output is nearly linear for small motions, but noticeably sigmoidal over the full ±35 deg. range of motion. The sensors were therefore calibrated using a best-fit cubic. The coefficients of the cubic were entered into the control system in the following experiments.

3.3 Computer control and dynamic response

In order to demonstrate how changing parameters affect system behavior, a DOS program was written to allow the students to 1) modify the gains of a proportional + derivative control law, 2) apply step inputs of various magnitudes and 3) record the position data. The controller ran with a sampling rate of 1000 Hz, with position data saved every 10 msec for plotting.

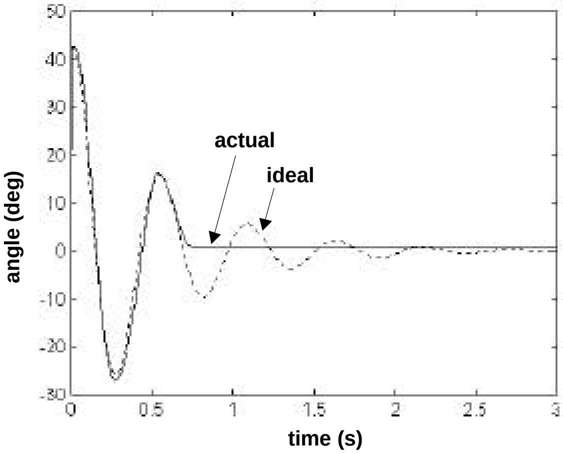

Fig. 4. Step response of a somewhat sticky haptic interface versus an ideal second order system

Students were first asked to try different positive values of proportional feedback and observe how the stiffness of the system and the frequency of oscillations changed when the joystick was disturbed from equilibrium. At low gains, the systems were stable without velocity feedback, due to the presence of friction and damping in the motor and cable transmission. The students observed that the kits with higher friction could accept higher gains before instability appeared.

Next, the students used negative values of stiffness to observe the effect of destabilizing torques and compared this with the effect of gravity on the device. The derivative feedback (obtained by estimating the velocity from the Hall effect position data) was also modified. The students soon learned that for large values of proportional feedback they needed to increase the effective damping to avoid instability.

Finally, students were asked to tune their system to make it respond to step inputs like a classic lightly damped second order system. From the position data taken during the response, students were asked to determine the corresponding dimensionless damping parameter, ζ, and resonant frequency, ω. The students also observed that their plots did not precisely match those of an ideal second-order system due to the presence of Coulomb fric-

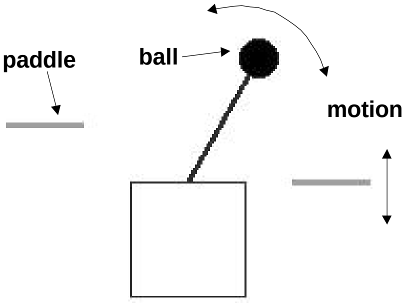

Fig. 5a. Haptic tetherball side view in XZ plane (YZ plane is equivalent)

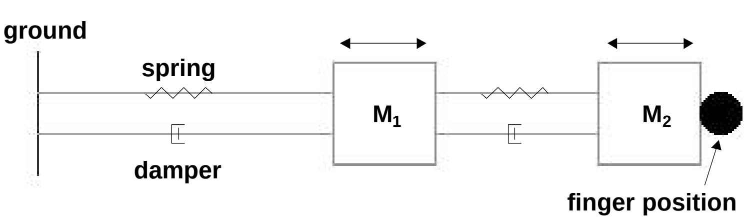

Fig. 5b. Excite the modal frequencies (one of four systems running concurrently)

tion. There was significant variation in the friction, depending on the amount of cable tension. In some cases the friction was hardly noticeable, in others it was like the example shown in Fig. 4.

3.4 Interacting with virtual environments

As a final demonstration of the haptic devices, two virtual environments were designed in which four haptic devices could be used simultaneously. In the first virtual environment, called "haptic tetherball," four students using haptic devices cooperated to make a virtual inverted pendulum with a small amount of Coulomb friction stand upright (Fig. 5a). Force feedback, and a simple visual representation, allowed students to sense when the ball hit their paddles and to feel the force it took to bat the ball back towards the apex. If a student hit the ball too gently, it fell back against her paddle, if she hit it too hard it continued past the apex to land on the paddle of the player on the opposite side.

The second environment, "excite the modal frequencies" (Fig. 5b), used a virtual model of a two degree of freedom system. To impart forces from the system to the finger, each haptic device was virtually attached to a mass M_2 through a stiff spring. (The spring was chosen to be sufficiently stiffer than the springs in the virtual system that it did not noticeably affect the perceived dynamics.) This attachment allowed the students to directly manipulate the virtual system and feel the inertia of both masses. The goal was to move the haptic device such that only one of the two modal frequencies of the system was excited.

4. CONCLUSIONS

While it is difficult to quantify the pedagogical effectiveness of the haptic interfaces, the qualitative impact was unmistakable. The students responded enthusiastically to having their own examples of high-performance electromechanical systems. Several students personalized their kits and made design modifications to improve the performance (see *Suggested design improvements* in the Appendix).

Once the kits were assembled and connected to the computer, many students who had already heard about resonant frequencies, feedback, stability, etc., in the lectures were clearly surprised at how small changes in the feedback gains could have a profound effect on the system behavior. It was also evident while watching the students compare their actual versus ideal step responses and estimating the dimensionless damping and frequency response, that many of the students were fully understanding these concepts for the first time.

The feedback on the end-quarter course surveys was overwhelmingly positive. The only complaint was that the students would have liked more computer stations available to expedite testing. A possibility for the future is to replace the PC-based controller with a number of DSP-based microcontrollers with onboard A/D and D/A channels.

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APPENDIX

A.1 Design and construction notes

The major components of the kits were constructed of 1/4 inch thick acrylic plastic (see Fig. 6). We sent our acrylic sheets along with DXF files of the part geometries to a local laser cutting firm, resulting in a per-kit cost of approximately $8.00. Although acrylic has lower strength and stiffness than aluminum or steel, it is adequate for the loads encountered in the single-axis joysticks, provided that stress concentrations are avoided. Acrylic has the advantage of being easy to glue and easy to laser cut. Laser cutting provides an inexpensive way to obtain complex planar geometries with dimensional tolerances to 0.005 inch. The

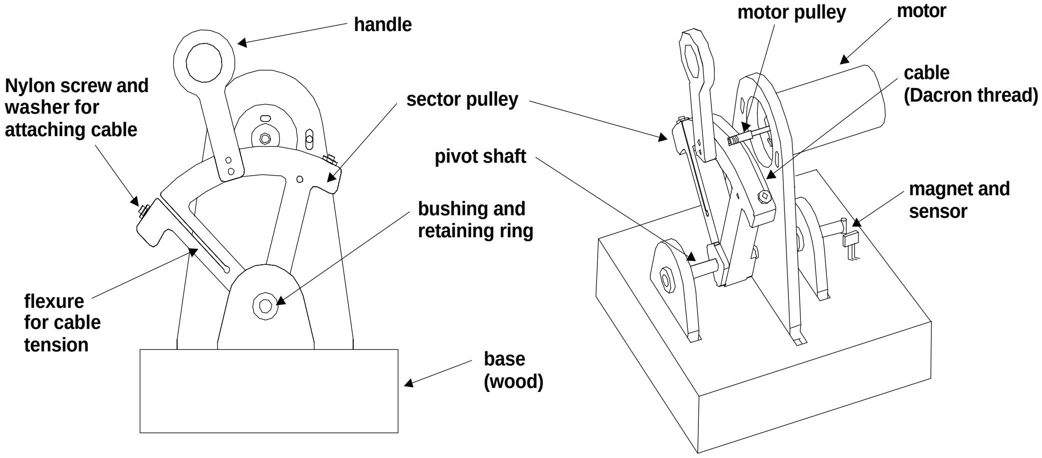

Fig. 6. Haptic interface kit (improved design)

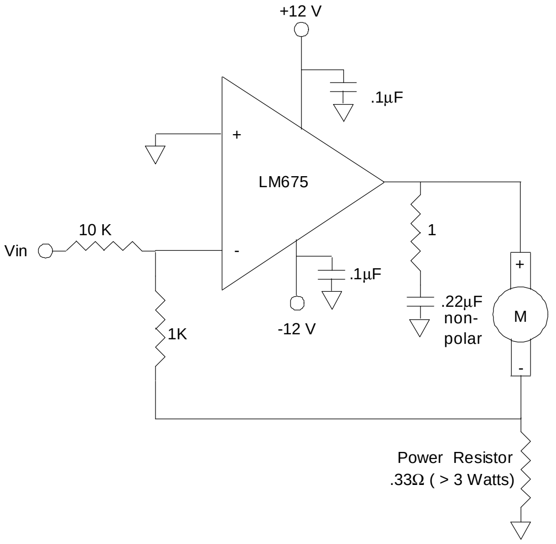

Fig. 7. Circuit diagram for current amplifiers

laser-cut features also have a smooth finish, which helps to reduce stress fractures.

A side effect of the laser-cutting process is that all holes have a slight taper. After some experimentation we found the right nominal hole diameter such that Teflon bushings could easily be pressed in from one direction to obtain a snug fit with the 1/8 inch diameter steel shafts.

The actuators for our system are low-inertia, low-friction DC servomotors, similar to those used in commercial haptic devices but smaller and less powerful. They were obtained from various San Francisco-area surplus electronics stores at an average cost of $9.00. Similar motors are often available from mail-order surplus electronics houses such as C&H Sales, Pasadena, CA and Servo Systems Co., Montville, NJ.

The motors are powered by small current amplifiers constructed from LM675 power operational amplifiers, which were donated by the manufacturer. The circuit diagram is shown in Fig. 7. With a power supply of 12 volts and D/A output of ±5 V, the amplifiers generated a maximum current of 1.5 amps,[1] resulting in a maximum motor torque of 0.035 Nm and a maximum force of 7.5 N at the joystick handle.

A cable, pinned at both ends of the sector pulley and wrapped several times around the motor pulley, provides a smooth “cogless” transmission. The cable represents a compromise between cost, strength and resistance to creep. We ultimately chose heavy-duty Dacron thread and designed an elastic flexure into the sector pulleys (see Fig. 6) to minimize problems associated with cable stretch. Because the flexure is always under preload, it does not affect the system dynamics. The ends of the cables are fastened with nylon screws and washers to avoid damaging the thread and acrylic. The position of the sector pulley was sensed using a Hall effect sensor and a small cylindrical magnet glued at the pivot. This strategy avoided the cost of an encoder for each kit and allowed us to use existing analog input hardware in the laboratory. As mentioned earlier, the output of the sensor varied linearly with small angles, but fell off near the ends of the ±35 degree range of motion. It was therefore necessary for the students to calibrate the sensors using a cubic polynomial.

Table 1: Parts list for haptic kits

Part Description	*Cost per kit*
Laser-cut 1/4” acrylic parts: sector pulley, handle, support parts. (DXF files are available from the authors.) *Laser Custom Designs, Fremont, CA*	$8.00
Motor (Maxon No. 2332.966-12.216-200, or similar). *Various electronics surplus outlets.*	$9.00
Motor pulley 4.5 mm dia. x 1.5 cm lg. Aluminum bar stock	$0.50
(2) 1/8” Flanged teflon bushings (B9-3) 1/8” Stainless steel shaft (S2-20) (2) 1/8” Retaining rings (Q7-12) *W.M. Berg, Inc., East Rockaway, NY*	$3.00
Nylon screws, nuts, and washers, #8-24	$0.50
Wood base	$0.50
Cable (heavy Dacron thread) *Mettler Metrosene Nm 30/3*	$0.01
Linear Hall Effect sensors (Allegro #3517) *Sterling Electronics, San Jose, CA.*	$2.35
1/8” dia. x 1/4” lg. rare earth magnet *Dexter Magnetics, Fremont, CA.*	$2.71
Total	$26.57

A.2 Suggested design improvements

In general, we were satisfied with the performance of the kits. Fig. 6 shows a slightly modified design with relocated bushings for better stiffness in the direction perpendicular to the motion of the handle. For the modified design we have also redesigned the Hall effect sensor and magnet to make it easier to ensure proper alignment and reduce the sensitivity of the calibration. It may also be worthwhile to reconsider the alternative of using an inexpensive shaft encoder or a low friction potentiometer.

Finally, we are considering replacing the PC-based controller with dedicated single-board micro-controllers. This would make the system more mobile and allow multiple joysticks to be run simultaneously.

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[1] The amplifers are capable of 3.0 amps with higher signal voltages.