PERCEPTION OF MECHANICAL PROPERTIES AT THE MAN-MACHINE INTERFACE

J.K. Gotow, M.B. Friedman[1], M.L. Nagurka, and J.M. Dolan

Department of Mechanical Engineering
and [1]The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213

Abstract

In order to improve the performance and information transfer of manual controls, it is important to characterize the way in which man and machine interact. To this end, a method is discussed for studying the human perception of basic mechanical components (spring, dashpot, and mass) and the effects of their use in delayed feedback. Knowledge of how these components contribute to the qualitative "feel" of a system is useful in developing control strategies for effectively interfacing man and machine.

A one degree of freedom rotational system, consisting of a motor and high speed controller, is presented as the basis for a test apparatus. Combinations of position, rate, and acceleration control are used to digitally simulate springs, viscous dampers, and inertias, and human interpretations of these elements are obtained through subjects' quantitative and qualitative evaluations. Findings based on initial experimentation are then discussed, and revisions and extensions proposed.

Introduction

A significant amount of work has been done regarding the effect of the physical characteristics of control sticks (ie. the "feel" of the control) on operators' ability to perform manual tracking tasks [1,2]. These studies have focused primarily on end applications, correlating tracking ability in specific tasks to stiffness, damping, inertia, and friction of the control element. However, little has been done to generalize these studies to the man-machine interface as a whole. The question of precisely how humans scale kinesthetic inputs and how well they can be separated and resolved is of practical importance in conveying information to an operator, as well as in the design of manual controls. In undersea and space teleoperation, these factors are further complicated by the presence of time delays in data transmission, a topic which has again been studied on the task level, but seldom in a general sense [3,4,5].

The action of most mechanical systems can be described by various combinations of three basic elements: springs, dampers, and masses. They provide forces to resist displacement, velocity, and acceleration, respectively. By combining these three primitives in varying proportions and transmitting them to a human operator through a manual control, we can poll the operator to quantitatively and subjectively describe the "feel" of the control. Similarly, time delay effects can be explored.

By employing a microprocessor to control a motor actuated handle with which the human operator interacts, it is possible to produce almost any combination of characteristics and time delay. This paper relates the configuration of an experimental test bed and initial findings using such a computer controlled system. To simplify the interaction between elements, only spring stiffness and damping are incorporated for this initial report.

Experimental Apparatus

The experimental setup takes the form of a large panel from which four 3.8 cm. diameter knobs project. Three of these knobs are attached to physical systems: springs, dashpots, inertial masses, or some combination thereof; and the fourth knob turns the shaft of a servo controlled DC motor. All four knobs rotate on the shafts of identical motors, though the motors are unpowered in the three physical systems. This is done to ensure that the slight but unavoidable basic friction and inertia are equivalent in each configuration.

The elements from which the passive physical systems are constructed are as follows:

- The inertial system is simply a large disk with weights mounted along the perimeter.

- The dashpot consists of gears and a small nylon chain which transfer the knob's rotational motion to a linear, oil filled damper. This arrangement was necessary because no adequate, low speed, rotational dashpot could be obtained. Another method for supplying damping force is simply to short the terminals of a DC motor together; the inductance of the coil when the electrical loop is closed provides a torque proportional to the armature's velocity. The latter method was used for the preliminary testing discussed in this paper.

- A rotary spring is used as the third reference.

The motor on the fourth knob is actively controlled through an IBM AT computer to simulate any combination of stiffness, damping, and inertia, thus providing a variable system which subjects can be asked to describe. The motor itself is capable of 1.9 N.m of torque, enabling the simulation of a large range of physical constants. It is driven by a voltage following amplifier and a 12 bit digital to analog converter, which acts on control signals from the computer. These command voltages are derived from the motor shaft position, which is found using an optical encoder directly mounted on the shaft.

Here, it is obviously assumed that supplying a voltage across the motor terminals results in a desired motor torque. This is true as long as the motor's back emf remains low, so that the effective voltage across the terminals is equal to the voltage we supply. Providing this is the case, the constant resistance of the motor coil linearly relates this input voltage to a current which, in turn, generates a proportional torque. Since human interaction is quasi-static and back emf is proportional to motor speed, the assumption is a good approximation after an initial warm up period allows the motor coil resistance to stabilize. Additionally, a compensation discussed below effectively negates the small back emf that does arise.

The control algorithm that generates the required voltages is based on discrete differentiation of position signals and a table lookup of the desired outputs. Position readings from an incremental optical encoder are queued at a rate of 20 kHz and then velocity and acceleration are found by finite difference approximations. Due to the relatively slow movement of human operators, it is not possible to resolve significant velocity or acceleration over one sampling interval, and thus the current position and the position 1500 samples (0.075 seconds) ago are used. Since this is done at 50 microsecond intervals, the motor's motions are smooth despite the large time sample needed for the higher order approximations.

Based on the values of position, velocity, and acceleration, corresponding voltage output levels are found in tables stored in memory and placed in an output queue. This queue allows signals to be output immediately or delayed as much as 100 milliseconds in order to study the effects of transmission delays on human perception.

Several factors have also been added to the control algorithm to compensate for imperfections in the system:

1) A positive feedback term in the velocity control offsets the small back emf that is developed when the motor is in motion.

2) Two velocity approximations are actually made. The first

uses a 0.075 sec. sample, while the second uses only a rough, 100 microsecond sample. The algebraic sign of the first is checked against that of the second to verify that the motor has not changed direction in the last 0.075 seconds. If it has, the velocity is set to zero to avoid providing positive feedback to the system instead of the intended damping. This aids stability when the subject releases the knob and allows it to freely oscillate.

Experimental Design

The first goal of our initial experimentation is to validate the simulator. This consists of presenting the panel of knobs to subjects and requesting that they evaluate the difference between two reference systems and two experimental ones. Subjects' ability to distinguish between the controlled motor and an actual physical system are evaluated, and any problems with the controller are noted so further refinements can be made. The second objective is to estimate the subjects' ability to separate the effects of stiffness and damping when they are combined in a single system, and if the components are reliably separable, to evaluate the subjects' scaling of each.

Subjects are presented a pure spring (spring constant = 0.11 N.m/rad), a pure damper (damping constant = 0.0045 N.m.s/rad), a spring and damper coupled in parallel, and the servo motor controlled to emulate a parallel spring and damper system. The pure spring is explained to be a reference with a spring constant of 10 and damping of 0; the pure damper has a spring constant of 0 and a damping factor of 5 [1]. Subjects are then asked to evaluate the two remaining systems (one actual and one simulated by the motor), giving them appropriate numerical values of spring tension and damping. This is then repeated for another pair of systems. Afterward, subjects are asked to elaborate on their perceptions, noting any of the more subtle differences in "feel." They are then told that one system is passive and one is simulated with a motor, and are asked to distinguish between the two.

Results

An initial sampling of 10 subjects was used to evaluate the test setup and procedures. Although the population was not large enough to rigorously apply statistical methods, their responses evinced the general trends necessary to evaluate the setup and procedures. These observations indicate that some refinements are necessary in the experimental apparatus before large scale sampling is undertaken.

1) Because of some slight fluctuation in the power supply to the motor, the active simulator was identified by all but one subject. They described the effect as a "jumpiness" or "vibration" in the knob, although only one individual indicated that it hampered his attempts to quantify the stiffness and damping. This effect was evident primarily when the subjects held the motor stationary, requiring it to exert a constant torque. In motion, few were able to identify any differences between the active and passive systems.

2) The large majority of the test subjects found it difficult to separate damping from stiffness, and two indicated that higher damping of the reference knob might help by contrasting more with the undamped case. Subjects tended to numerically rate the spring stiffnesses more consistently than damping, with standard deviations being half as large for the stiffness ratings as those for damping.

Discussion

Based on the results obtained, improvements will be made to the motor power supply. The damping constant of the damped reference knob will also be increased.

The inability of the subjects to reliably decouple the effects of springs and dampers suggests that in studies of scaling, inertia, damping, and spring stiffness must be observed separately. This confusion in decoupling is also interesting from the standpoint of

---

[1] To maintain the same force magnitude scale between the spring and damper, the damper reference number is set lower.

manual controls and information transmission to the operator. It implies that some parameter settings in manual controls may be indistinguishable from others, and therefore have little effect on the operator's control actions. Previous work in tracking studies supports this [1].

Also, if information is being transferred by way of the manual control, some signals may go unseen by the human operator. This might occur in the case of bilateral telemanipulators, where forces on a slave arm are reflected back to the operator through the master arm. The perception of an increase in damping, for example, can be masked by a high spring constant acting in parallel. If necessary, compensation can be developed for such problems by filtering or signal enhancing. The recent advent of real-time digital telemanipulation provides new flexibility along these avenues, employing microprocessors which can be quickly programmed to alter and enhance force feedback characteristics based on current operating parameters.

Continuing research will address the above issues in more detail, as well as investigate human perceptual scaling of feedback parameters and the effects of time delays on this perception.

References

[1] W. Krüger, "Optimizing Spring Force, Viscous Damping, and Inertia of a Joystick," in Proceedings of the 15th Annual Conference on Manual Control, vol. 2, pp. 471-482, 1979.

[2] E. C. Poulton, Tracking Skill and Manual Control. New York: Academic Press, 1974, pp. 306-322.

[3] T. B. Sheridan and W. R. Ferrell, "Remote Manipulative Control with Transmission Delay," in IEEE Transactions on Human Factors in Electronics, vol. HFE-4, pp. 25-29, Sept. 1963.

[4] W. R. Ferrell, "Remote Manipulation with Transmission Delay," in IEEE Transactions on Human Factors in Electronics, vol. HFE-6, pp. 24-32, Sept. 1965.

[5] J. W. Hill, "Comparison of Seven Performance Measures in a Time-Delayed Manipulation Task," in IEEE Transactions on Systems, Man, and Cybernetics, vol. SMC-6, no. 4, pp. 286-295, Apr. 1976.