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CONTROLLED IMPEDANCE TEST APPARATUS FOR STUDYING HUMAN INTERPRETATION OF KINESTHETIC FEEDBACK

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ABSTRACT

Many feedback control systems, especially those for complex applications, involve humans in the control loop. Visual information traditionally has been presented to human controllers who make manual responses (i.e., via keyboard, joystick, or other interfaces). To expand system bandwidth, other information channels can be presented to human operators. Kinesthesis, the perception of body positions and forces, represents an attractive supplementary form of human-machine communication, since the limbs (e.g., an operator's hand) can be used both for input and output of information in the control loop. Although psychophysical studies have measured perception of isolated mechanical properties, limited work has been conducted to study human kinesthetic abilities in the context of control. The research described here assesses judgement of coupled properties, including the superposition of linear stiffness, damping, and inertia. Quantitative perception of these properties may depend upon correct models of the mechanical system with which a user interacts. Similarly, perception of fundamental mechanical properties may be influenced by system delays (on the order of magnitude of human reaction time). This paper describes both an apparatus for understanding kinesthetic interaction with mechanical systems and an approach for studying human perception of mechanical properties.

1. INTRODUCTION

Historically, remotely actuated devices, such as teleoperators or telemanipulators, were controlled by a human operator via cables, linkages, and gears. The mechanical coupling enabled the operator to move the remote device, as well as feel any forces acting on it, and thus served as a route for kinesthetic feedback to the operator from the remote environment. The development of electrical servomechanism systems effectively replaced the mechanical coupling by electrical wires, position sensors, and servo-motors, permitting remote manipulators to be guided from greater, and thus safer, distances. The feedback of forces, however, was lost, since electrical signals were used to transmit position information from the operator to the manipulator. In such implementations, it was found that tasks were more difficult because operators worked solely from visual cues, without the aid of kinesthetic (force and position) feedback [1]. This deficit was addressed by installing servo systems acting in the "return" direction, from the remote device to the human operator. Forces sensed in the remote environment were simulated by actuators in the operator's control handle, emulating some of the cues that would be experienced by physically interacting with objects in the remote location.

Long distance communication, data encryption, and computer pre-processing add time delays to kinesthetic feedback. Control theorists have considered the effects of delays on force feedback in teleoperation, emphasizing the stability of the telemanipulator, and seldom considering the human operator as part of the control system. Manual control studies include the human in the control loop, but consider the overall effect which delays have on the efficiency of task completion, and on human planning and manipulation strategies. Neither discipline attempts to characterize the effect of delays at the interface, as related to the transfer of information to the operator. Work in the field of human factors determines how humans perceive kinesthetic inputs, but the effects of time delays are not addressed. This paper describes an approach, and the development of a testbed, to better understand kinesthetic feedback. The kinesthetic testbed is being used to provide preliminary insights into human abilities for bidirectional manual communication with machines.

Kinesthetic feedback, for the purposes of this research, consists of a linear combination of three ideal physical components: linear stiffness, damping, and inertia. Many mechanical systems can be described by these components, which generate resisting forces directly proportional to displacement, velocity, and acceleration, respectively. Previous studies [2,3] have indicated that nonlinear effects such as static friction are also significant in manual controls, and may have a detrimental effect on operators' ability to modulate their actions. It is assumed, however, that with proper design, such undesirable components can be minimized in kinesthetic feedback and are not considered in this study.

Numerous human interface experiments have addressed the use of gauges and displays. An important area of research has focused on the performance of aircraft pilots in tracking visual inputs, using various display and control modes. Comparatively little has been done, however, in studying other sensory modalities or providing any general knowledge base for interface design. For communicating information, sight and sound predominate, yet we use all five senses. Although not explicitly used as an information channel in human-machine interaction, kinesthesis, which involves the knowledge of the positions of the limbs and the ability to judge the forces acting upon them, could be used for communication purposes. For example, while working with a manually controlled machine, an operator may recognize a problem upon feeling the handwheel suddenly "stick." This "sticking" sensation represents kinesthetic feedback and provides an indication that some part of the process has changed or encountered an obstacle; as a result, the operator may adjust his control action appropriately.

With modern servo systems there is often no direct mechanical coupling between the control and the process it affects. Kinesthetic feedback must be actively generated to feed back the state of the process to the operator; a servomechanism must produce the "sticking" sensation in the control when the process itself begins to stick. In implementing this feedback, the flexibility of servo-controlled systems also gives us the liberty to dictate what information is supplied to the operator. It may not be mechanical information which is fed back, but perhaps a feature of a chemical process – we may choose to allow the operator to "feel" the concentration in a mixer approaching dangerous levels, even though there is no mechanical resistance in the real system.

Servo controls allow great freedom in selecting and modifying the "feel" of an operator's manual control, provided we have some knowledge of how the operator will interpret the artificially generated kinesthetic feedback. A prime example of such an implementation of kinesthetic feedback, and the one which prompts us to examine kinesthesis and time delays, is bilateral telemanipulation.

Telemanipulators can be concisely described as general purpose, dexterous, remote-manipulation devices. In bilateral telemanipulation the forces generated at the control handle (the master manipulator) directly correspond to those sensed in the remote process (the slave manipulator). There is generally very little modification of the signals as they pass between the slave and master. However, the development of affordable and powerful microprocessors in the last decade has provided many new opportunities for altering the signals as they are fed back to the human operator. With the increased computing ability, compensation could be added for small time delays (as incurred due to data encryption or communication delays), coordinate transformations can be made, and signals from additional sensors may be incorporated. The latter option is particularly interesting, in that it may provide a means of translating information into a signal that can be more effectively used by the operator.

The flexibility of servo controlled systems allows us to translate information from one sensory modality to another, providing cues to the operator in a more usable form. With digital processing, the transformation between modes can be defined and selected properties can be enhanced, *e.g.*, for giving light objects more mass, imposing artificial stiffnesses to help direct the operator, or possibly imposing nonlinear or conditional effects in the "feel" of the system.

Together, stiffness, damping, and inertia comprise a set of force-displacement relations which can be collectively referred to as the impedance of a given system. Thus kinesthetic feedback consists of presenting a desired impedance to the human operator. This study examines the process in which the human operator gathers impedance information (by manipulating a control interface and subsequently resolving the force felt into stiffness, damping, and inertia components.) Specific issues to be addressed include:

1) Strategies in manipulating the human interface control. In particular, how does the manner in which the control is manipulated affect how well the physical characteristics can be distinguished and quantified?
2) Acuity and limits of kinesthetic sensing, including stiffness, damping, and inertia components individually and interacting.

3) Effects of time delays on kinesthetic sensing. How do time delays alter perception of kinesthetic inputs, and below what threshold do they become negligible?

Both an apparatus for understanding kinesthetic interaction with mechanical systems and an approach for studying human perception of mechanical properties are described.

2. BACKGROUND

Research in kinesthetic perception can be sharply divided into two classes: general psychophysics research and performance evaluation for a specific task. Psychophysics research has addressed basic human perception. Stevens [4] provides a survey of studies of the perceptual scaling of a number different phenomena, including loudness, brightness, angular acceleration, and heaviness. Perceptual scaling is the process in which the human scales the magnitude of different inputs, usually based on a power function. Doubling the brightness of a light, for instance, is perceived as an increase of 2^n; quartering the brightness results in a perceived value of 0.25^n, where n is the exponent of the power function.

An example of such work is Clark, Handel, and Kreifeldt's [5] inquiry into the scaling of mass moment of inertia. To determine the exponent for mass moment of inertia scaling, a pivoting bar was constructed with holes spaced along its length from which weights could be hung. Weights were placed at different locations, and subjects were asked to numerically relate the different configurations. Other work concerning the perception of properties considers the limits of sensing. Jenkins [6], for example, performed an experiment in which he found the minimum difference in force which could be resolved in three different controls, *i.e.*, a stick, wheel, and pedal.

In contrast to such basic psychophysics research, many studies have been undertaken to examine human performance in specific types of tracking and manipulation tasks. The effects of control stick characteristics on an aircraft pilot's ability to track a moving target have been the focus of numerous studies. Telemanipulation has been examined in the same light, although to a much lesser extent.

Krüger [2] addressed the effects of spring force, viscous damping, inertia, and static friction in a control stick on performance in two-axis compensatory tracking tasks. The experiment employed a video screen on which subjects were to minimize the deviation between a cross pointer and a reference aircraft symbol during simple simulations of wind gusts. A control stick was used for operator input. Krüger found that the resistance parameters had little effect on performance, with the exception of spring stiffness, which increased performance significantly. Howland and Noble [7], however, found that small amounts of viscous damping also increased performance when a small knob was used as the control input.

Krüger also obtained what the subjects perceived to be the most effective parameters for the control stick by allowing them to adjust the values with a knob. Further, for Krüger's work and many other tracking experiments, a small number of subjects were used due to the large amount of training required before proficiency in tracking was attained. Significance in the results was achieved by using several subjects with a large number of runs per subject, as well as employing several different measurement methods for cross-reference.

Book and Hannema [8] have employed similar methods in analyzing the effects of friction, natural frequency, and backlash in a two-degree-of-freedom, unilateral telemanipulator. Performance was not measured in dynamic tracking, however, but for a rapid, point-to-point positioning task. Subjects were required to move the end point of the manipulator from one position to within a tolerance band surrounding a desired position. The performance measures were execution time and position error.

The influences of time delays on both tracking and telemanipulation have been the subject of several studies. Delays are generally recognized as detrimental to performance in both tracking and manipulation, and experiments in single-axis tracking tasks, such as those performed by Stark [9], concentrate on the improvements gained by different tracking modes (pursuit vs. compensatory, for example), and on the benefits of a predictive preview in the display.

In Stark's study, the subject was to perform pursuit tracking by attempting to follow a moving target on a computer display with a cursor, using a pair of keys on the keyboard as controls. The closed loop gain of the operator in the tracking system was found to drop as the delay was increased from zero to 0.5 s. The phase of the closed loop system directly reflected the time delay. Adding a predictive display which informed the operator of the target's upcoming movements reduced the phase lag, but had little effect on the suppression of operator gain in the system.

The effects of delays on a specific manipulation task have been evaluated by Sheridan and Ferrell [10,11]. Two separate experiments were performed on a two-degree-of-freedom manipulator, in which subjects were required to move the manipulator to an object and grasp it in a parallel-jaw gripper. This was essentially the same task used by Book and Hannema, described above, in that it required positioning from one point to within a tolerance band around another. The modification here was that the tolerance band was given by the size of the opening of the manipulator jaws, not by a set of markings on the table. The experiment was performed with time delays ranging from zero to 3.2 s by a small number of trained subjects. The significant result of Sheridan and Ferrell's work was the subjects' conscious development of a "move and wait" strategy. This experiment and one with a more complex task indicated that task completion times increased linearly as the delay increased.

In summary, previous research has addressed the perception and use of kinesthetic feedback in controls and the effects of delays on tracking and manipulation separately, but the two concepts have yet to be combined. At least part of the reason for this is the instability which arises when force feedback is used under the effects of delays. For long delays (0.5 to 5.0 s) which have been of concern in the past, kinesthetic feedback has resulted in unstable systems, and thus its effects were superfluous. With the growing use of digital systems to implement manual controls, however, processing and transmission delays on the order of tens of milliseconds are now being generated. These delays do not always result in instability, and their effects on kinesthetic feedback are of significant interest .

3. APPARATUS

An apparatus was designed to test human perception of controlled impedance, and to record subjects' manipulations of the control interface. Based on the concept of a computer controlled knob with a programmable impedance, the system employs DC torque motors and a high speed controller to digitally simulate mechanical inertias, dampers, and springs. Rotating knobs are used instead of translational devices because of their compactness, and because other studies have found that human control is generally more exact with rotational systems [12].

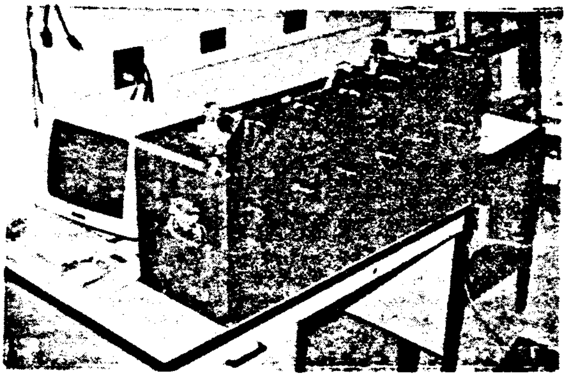

Figure 1: Testing Apparatus

The testbed consists of a 0.96 × 0.36 m cabinet face through which twelve 2.6 cm diameter knobs protrude (Figure 1). Six knobs are attached to mechanical systems and arranged along the top of the box, so that subjects can see the mechanisms over the top of the face plate (Figure 2). The other six knobs protrude through a faceplate from inside the cabinet, so subjects cannot see what is attached to the other end of their shafts. The visible knobs are linked to physical masses, dashpots, and springs, while five of the six "hidden" ones are coupled to computer controlled motors which are used to simulate combinations of those elements.

The motor-driven knobs are controlled by means of an IBM AT computer. The overall layout of the system is shown in Figures 3 and 4. The position of the motor shaft is fed to the computer from an optical encoder through a custom interface board. The board also derives velocity information from the quadrature frequency, and acceleration is then found by discretely differentiating the velocity values in software. Proportional position, rate, and acceleration control are used to generate a desired torque value, which is then output through a digital-to-analog converter (DAC) as a command to a voltage-to-current converting amplifier, and fed back to the motor.

The physical components used for the exposed knobs are simple rotary springs, rotary and linear dashpots, and inertial disks, combined in various configurations. The unsuitability of available rotational dashpots made it necessary to use linear (translational) elements. Levers were attached to convert their action to rotary torques on the knobs, and their range of motion was limited to keep their action as linear as possible.

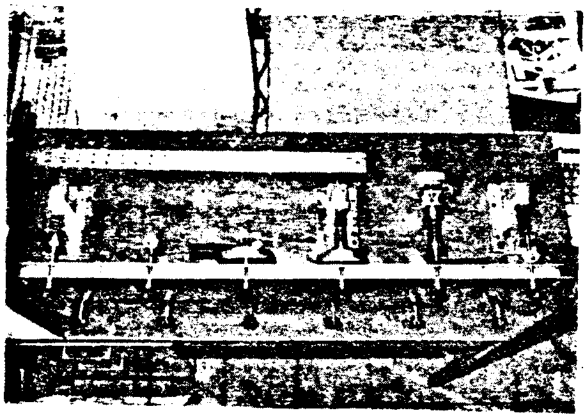

Figure 2: Testing Apparatus, top view of mechanical systems

Constraints limiting the design of the experimental hardware included:

1) Human sensory abilities: Although we were concerned with kinesthetic feedback, we had to contend with human tactile senses as well, which have a much higher bandwidth than kinesthesis. Generally, humans can sense vibration up to several thousand hertz (depending on signal amplitude), while kinesthesis is limited to a few hundred cycles per second. To produce a convincing simulation of physical systems we had to prevent vibration or other spurious signals over a mechanical bandwidth of several kilohertz.
2) Data collection: A means had to be provided for collecting data to quantify the interaction of human and machine. The simplest measurement was the subjects' conscious evaluation of the physical system, which was accomplished by having subjects fill in values on a form. However, we also wanted to record the process by which humans decided on these values. This was accomplished by recording the controller states at desired intervals.

The motors provide the interface with the test subjects, and need to be powerful and responsive enough to simulate a reasonable mass-spring-damper system. Based on preliminary experiments, a steady-state torque capability of at least 0.2 N-m, and a rotor inertia less than 5.0×10^{-5} N-m-s^2 were found to be desirable. "Pancake" motors (Ricoh Type 7K00011), with low Coulomb friction, were selected.

The motors were fitted with optical encoders which supply TTL level quadrature signals at a resolution of 400 counts per revolution. By triggering a counter at the edges of each quadrature pulse, this resolution is effectively increased by a factor of four, to 1600 counts per revolution. The power amplifier must use a signal from the computer controller and generate a proportional torque in the motor. An analog DC amplifier design was chosen over pulse width modulation (PWM) for its simplicity in providing closed loop current control to the motor.

In brushed DC motors, the armature resistance tends to vary as the temperature of the coil changes, and the brushes' arcing and overlapping of two commutation zones intermittently reduces motor efficiency. Under a voltage regulated supply, these effects cause the current through the motor to fluctuate, and consequently the torque output deviates from the desired value. This deviation is commonly known as torque ripple. By using a voltage-to-current amplifier, we implemented closed loop control of the current supply. Outputting a voltage level from the computer to the amplifier produces a proportional current through the feedback circuit. This greatly reduces the cogging problem produced by torque ripple, as compared to a first generation implementation, which used a voltage regulating DC amplifier.

The interface between the computer, amplifier, and optical encoder is implemented on a single PC expansion board. The board provides for memory mapped addressing from the IBM AT bus for three different functions: 1) Quadrature decoding of optical encoder signals for determining motor shaft position; 2) Velocity computation based on quadrature pulse width; and 3) Latching and digital to analog conversion of the output command for the amplifier.

The output interface to the amplifier is an AD7545 12-bit multiplying DAC, which latches data and converts it when a specified memory location is accessed by the control program. The chip has buffered registers, which latch the input and thus serve as a zero order hold to maintain the signal between output cycles. The twelve bit resolution provides for output precision of approximately 0.001 amps, which corresponds to steps in torque of 4.6×10^{-5} N-m.

The input circuits function autonomously from the programs running on the PC, continually monitoring the quadrature signal and updating the registers which hold position and velocity values. An HCTL-1000 motor controller chip is used for position input, counting quadrature edges and maintaining the current position count in an internal register. This chip was originally selected because it can accomplish velocity decoding as well as position, but that capability was been found to be too slow and imprecise for this application. Therefore, a custom circuit was designed in which a 62.5 kHz oscillator is used as a pulse generator, and a set of counters simply count the number of pulses which elapse between quadrature edges. The counter value represents the instantaneous frequency of the quadrature signal, which is inversely proportional to the actual velocity. The value is latched after every new measurement, along with the motor's direction of rotation, so that data are always available whenever the registers are addressed.

The software for control and data collection is divided into two modules: an interface shell, written in BASIC, and the real time control software, written in 8088 assembly language. Together they allow the user to: 1) Model any desired stiffness, damping, and inertia with the motor; 2) Insert transmission delays in the controller output signal; 3) Save any group of characteristics and settings to a file for later use.; and 3) Collect data on the position, velocity, acceleration, and torque of the motor and plot it or save it to a file for analysis.

The shell serves as the user interface for the system, taking all the necessary variables and placing them into specific memory locations. The control code then simply accesses these memory locations for the parameters it needs to command the motor and gather data. When the user executes the control code from the shell, it immediately begins governing the motor operation. Data collection starts when the keyboard is hit, and on the second keyboard strike, the program stops taking data and exits back to the shell. The interface shell is written in compiled BASIC because of the language's screen handling capabilities, simple absolute memory addressing, and the ability to "sub-launch" assembly language code. The program is operated through three menus which control program functions, parameter setting, and plotting.

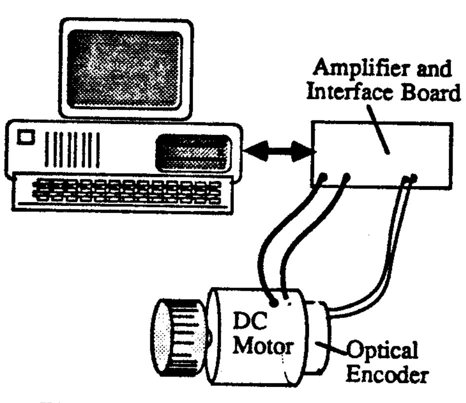

Figure 3: Physical Layout

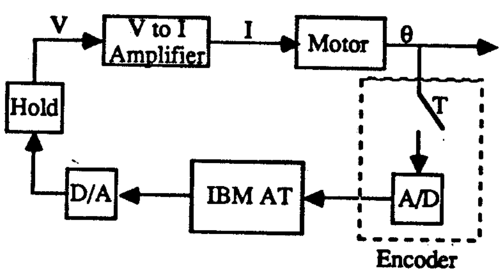

Figure 4: Organizational Layout

The major data structures that the shell provides for the control software are precomputed lookup tables. These allow the controller to map any given input to its appropriate output, thus obviating the need for most real-time calculation. The tables speed up operation considerably, allowing an update rate of about 5 kHz. This frequency was found to be above the range in which human taction can sense small amplitude vibrations, so subjects feel no evidence of the active controller.

The variables placed in memory by the interface shell are used to implement a standard state feedback regulator. The interface board is polled for position and velocity values, and acceleration is estimated using a backward finite difference approximation. Gains are applied to the position, velocity, and acceleration by using the states as offsets into lookup tables, and the resulting command signal is sent to the interface board for output to the amplifier.

The software implements a first-in-first-out (FIFO) queue so that a time delay may be inserted into the output channel. The length of the queue determines the delay. A pair of queues is also used in calculating finite difference approximations so that both a high update rate and adequate resolution are maintained. Simple filtering is done by averaging two consecutive acceleration calculations together, and limit checking is also done to assure smooth operation.

In order to impose a desired impedance with the DC motor, a model of the motor is first fed forward to cancel its properties of damping and inertia, J and B. Then the gains K_s, C_s, and M_s are applied in position, velocity, and acceleration feedback as shown in Figure 5. The motor is modeled as a linear system.

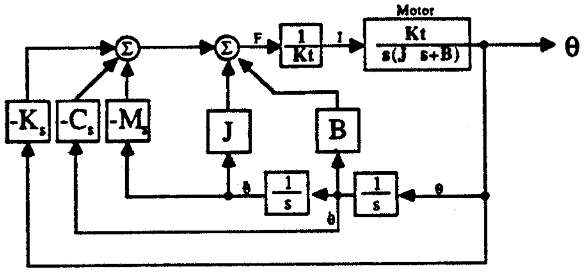

Figure 5: Control Loop Implementation

By prescribing the desired impedance of the motor, we have effectively limited the overall design of the controller to two options. Setting a stiffness, damping, and inertia requires that the controller regulate the force at the interface based on position, velocity, and acceleration. The design given above relies on an exact model for the system, since it assumes that the model parameters can be used to generate a force at the interface without sensors located there. The final force output is essentially open-loop, which results in errors if the model is only approximate or its parameters are improperly measured.

Another method of impedance control requires force sensing at the interface, and then closing a force loop around the sensor, as shown in Figure 6. This method is more robust than the previous one with respect to errors in the system model, since it explicitly measures the forces at the interface. It has been employed successfully in a project to implement impedance control of a robot manipulator [13]. Many variations on these architectures are, of course, possible, but they are generally encompassed by one of these two formulations.

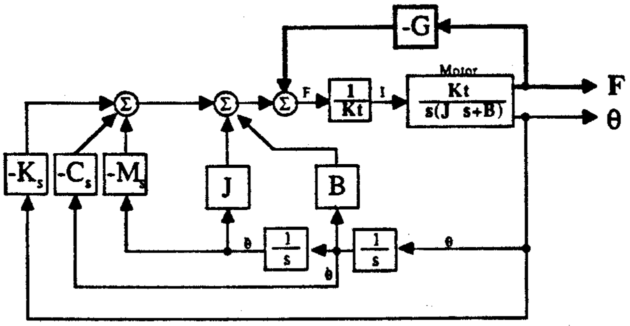

Figure 6: Impedance Control Using Force Feedback

The method shown in Figure 5 proved to be adequate. The motor performance is very nearly linear, and model parameters can be determined relatively easily.

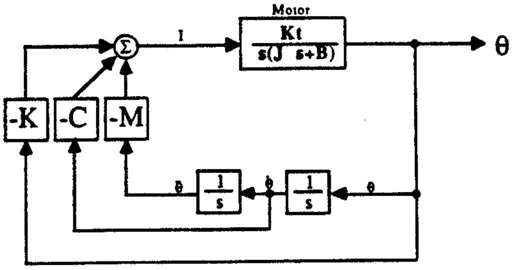

Figure 7: Simplified Controller

In the controls analysis, the controller is simplified from that shown in Figure 5, to the one in Figure 7. This is done by subtracting the feed forward gains from the feedback gains and dividing through by K_t, so only three gains, K, C, and M, are necessary to specify the impedance. The translation from Figure 5 to Figure 7 is done by using the following relations:

$$K = \frac{K_s}{K_t} \qquad C = \frac{C_s - B}{K_t} \qquad M = \frac{M_s - J}{K_t}$$

Stability is a primary concern when working with systems which involve time delays, and an approximate analysis was undertaken to determine the limiting factors and values for the apparatus discussed here. Three primary sources of instability that exist in the motor controller are: 1) The quantization and hold caused by sampling data into the digital system; 2) The lag caused by use of finite difference calculations; and 3) The intentional lag introduced to study human reactions to time delay.

The model for the electromechanical system used in the test apparatus is simple, but complications arise in evaluating stability when attempting to include the human operator in the model. The impedance of the human arm can vary with position, excitation frequency, task length, and many other factors, and thus it is very difficult to model [14, 15].

The approach here is to rely on the fact that the human generally acts as a dominant second order system with light damping [16]. The exact location of the dominant poles is dependent on the activation levels of the muscles in the arm, but the system is always damped. In fact, during precision movements, McRuer *et al.* [14] indicate that an average tension acting on opposing muscles ordinarily causes the system to be overdamped. We further presume that the operator will modify the stiffness of his arm to prevent its resonant frequency from coinciding with any oscillation frequency generated by the knob. That is, a user will modify the poles of his arm to avoid instability. This assumption is based on observed reactions to oscillation in knobs, which subjects tend to stabilize by increasing tension in the hand and wrist. Under these assumptions, we can view the operator as an adaptive system which aids in stabilizing the knob with which he interacts. The critical condition, where the stability margin is least, occurs when the operator releases the knob, removing his stabilizing input. Evaluating this worst case provides limits on gains and delays, giving conservative estimates on the values which may result in instability during interaction with an operator.

The impact of digital sampling is addressed separately from that of long signal delays in order to simplify the analysis. Traditional discrete systems analysis methods do not easily lend themselves to the inclusion of large delays since the resulting z-transforms or discrete state matrices are of very high order. It seems prudent to first examine the stability of a sampled data model of the control system, assuming that all states are available for feedback. Without the influence of the differentiation lags and intentional delays, critical values of the programmed stiffness, damping, and inertia values K_s, C_s, and M_s are on the order of 0.34 $\frac{N \cdot m}{rad}$, 1.2 $\frac{N \cdot m \cdot s}{rad}$, and 1.3×10^{-4} $\frac{N \cdot m \cdot s^2}{rad}$, respectively. (The desired maximum values of 0.08 $\frac{N \cdot m}{rad}$ and 0.01 $\frac{N \cdot m \cdot s^2}{rad}$ for the spring and the damper, respectively, are much less than these limits, indicating that the contribution of sample-and-hold effects to instability is very small for the range of values we wish to implement. But for programmed mass, theory indicates that the full desired range of 2×10^{-4} $\frac{N \cdot m \cdot s^2}{rad}$ cannot be used. In practice, however, experimentation has found that this parameter can be extended up to the desired limit, presumably due to the unmodeled effect of Coulomb friction, which helps to dissipate some of the system's energy and thus keep it stable. The full analysis is carried out in [17].)

The simple sampled-data system is stable with respect to K and C, and the discussion below indicates that the effects of M on stability are invariant with delay. In light of this, and the fact that the delays incurred in sampling are small with respect to those generated during discrete differentiation, we approximate the discrete system as a continuous one. Using a continuous transfer function, delays can be incorporated with an exponential term and the stability analyzed by using Pontryagin's Theorem, as discussed by Thompson [18,19].

The analysis of the system with the large delay which results from the finite difference calculation of acceleration is contained in [17]. The graphical method suggested by Thompson is very useful in determining the limits of stability and, for the delay of approximately 15 ms which is incurred in the controller code, the analysis indicates that the system is stable up to a programmed mass of $1.3 \times 10^{-3} \frac{N\text{-}m\text{-}s^2}{rad}$. This threshold is nearly invariant with the delay.

Referring to Figure 7, an open loop transfer function, G(s), is obtained by cutting the feedback loop at the motor input. We add a delay term in the acceleration feedback, and the resulting open loop transfer function is then:

$$G(s) = \frac{\frac{K_t}{J}(K + Cs + Ms^2 e^{-\tau s})}{s\,(s + \frac{1}{Q})}$$

As the frequency, $\omega = \frac{s}{j}$, becomes large, the open loop transfer function tends towards

$$G(\omega) = \frac{\frac{K_t M}{J}\omega^2 e^{-\tau\omega}}{\omega^2} = \frac{K_t M}{J} e^{-\tau\omega}$$

On a Nyquist diagram, this would be represented by a circle centered about the origin, with a radius equal to $\frac{K_t M}{J}$. Stability can be assured in this situation only if the radius of the circle is less than unity. Thus, for any value of τ, the inequality

$$\frac{K_t M}{J} < 1$$

must hold. In this system, $K_t = 0.048$ and $J = 6.25 \times 10^{-5}$, thus requiring that M be less than

$$\frac{J}{K_t} = \frac{6.25 \times 10^{-5}}{0.048} = 1.3 \times 10^{-3}.$$

This inequality must be true for any delay value, and this condition is the limiting factor in simulating masses with the controller.

Incorporating a transmission delay into the feedback loop results in all three programmed characteristics – mass, damping, and stiffness – affecting the system stability. The programmed mass is limited by the same factors as discussed above, but the three different components are interdependent, and stiffness and damping effects vary with time delay as well. Because of the complex nature of these interactions, which can be examined by hand using Thompson's method [18, 19], a graphical representation of the stability region is not feasible. For the system discussed here, stability was tested on a case-by-case basis.

Stable upper limits for the programmed mass and damping with a 50 ms transmission delay are about $1.3 \times 10^{-3} \frac{N\text{-}m\text{-}s^2}{rad}$ and $0.001 \frac{N\text{-}m\text{-}s}{rad}$, respectively, when either component is acting alone. Analysis of a number of cases indicate that these limits generally decrease as the components are combined. On the other hand, an examination of delayed position feedback using Pontryagin's criterion indicates that the system is only stable when stiffness is combined with either velocity or acceleration feedback, a situation which prohibited the testing for the effects of delays on perception of a pure stiffness. In addition, the nature of the effects of K in the graphs used in Thompson's method reveal that it is very much dependent on the delay involved.

When analyzing long delays, the approximations made in the discussion above involve the assumption that the system is continuous in time. The high stability shown in the discrete analysis with respect to K and C implies that this is generally valid for these parameters, and the subsequent analyses reinforce this by indicating that the instabilities caused by the longer delays limit the choice of the parameters C, and K much more than the effects of the sampling. The fact that the influence of the acceleration gain, M, on stability is invariant with delay allows either a sampled or delayed continuous model to be used, since the maximum critical value of M never varies.

4. PROCEDURE

The method used to evaluate operator interpretation of kinesthetic feedback consists of gathering responses from subjects as they quantify what they "feel" when interacting with the test apparatus. By using a microprocessor to control a motor actuated handle, a large range of characteristics for the human operator can be presented for evaluation.

The experimental apparatus simulates the components of inertia, damping, and stiffness with values in a "comfortable" range, as prescribed by ergonomic studies. Drury [20] recommends that torques no greater than 0.5 N-m be required to turn 30 mm diameter knobs. The controls used in this study are approximately 25 mm in diameter, and the maximum values of position, velocity, and acceleration are about 2 rad, $30 \frac{rad}{s}$, and $1000 \frac{rad}{s^2}$, respectively. Calculating maximum stiffness, damping, and inertia from this data gives maximum values of $0.25 \frac{N\text{-}m}{rad}$, $0.017 \frac{N\text{-}m\text{-}s}{rad}$, and $5 \times 10^{-4} \frac{N\text{-}m\text{-}s^2}{rad}$. To allow for combinations of the components, values of approximately half these were used. In actual tests, the stiffness was subjectively judged too high, and was thus reduced further. The ranges of simulated properties which were implemented are as follows:

	Min.	Max.
Stiffness $\left(\frac{N\text{-}m}{rad}\right)$	0.0	0.08
Damping $\left(\frac{N\text{-}m\text{-}s}{rad}\right)$	0.0	0.01
Inertia $\left(\frac{N\text{-}m\text{-}s^2}{rad}\right)$	0.0	2.0×10^{-4}

Details describing the hardware and software, such as electronic circuit schematics and program listings, analyses of the control system, as well as the test protocol for the experiments, and the data which were collected are not presented here, but can be found in [17].

Subjects were first read an explanation of the experiment, which included a definition and discussion of stiffness, damping, and inertia, and several methods that might be used to determine them. This teaching was added to combat a learning curve which was found in developing strategies for determining the components. During testing, subjects were also asked to first qualitatively describe what they felt by drawing a picture using a predefined set of components. This helped them establish a more complete mental model to which they could assign values, and also differentiated the modelling process from the perception of components in the resulting data.

Baseline data on subjects' abilities to resolve complex mechanical stimuli into the three basic components, *i.e.*, stiffness, damping, and inertia, were obtained during a first exposure to the test apparatus. Subjects (from the engineering and science fields) were asked to draw a schematic of a lumped-parameter model from a symbol set that was provided prior to numerically assigning values to the parameters. Simultaneously, the motions the subjects made during these assessments were recorded.

Later, this procedure was repeated with selected feedback time delays in order to evaluate the interaction between delay and subjective parameter estimation. The same group of subjects was used so that comparisons in the undelayed and delayed cases could be made for single individuals. Thus, despite variations in perceptual scaling between subjects, general trends were revealed in case-by-case analyses.

5. RESULTS AND CONCLUSIONS

In the previous sections, we described an apparatus for studying human interaction with mechanical systems It consisted of a computer controlled state feedback system for the simulation of mechanical properties at single degree of freedom rotary interfaces.

The results of studies with a similar, previous prototype apparatus revealed that human perception of the complex "feel" of an interface during controlled kinesthetic feedback could not easily be described by the sum of ideal mechanical components. The wide variability of subjective reports of quantitative estimations of stiffness, damping, and inertia suggested that impedance perception during "human in the control loop" tasks, especially with delayed feedback, is more than simple sensory discrimination.

This difference between *perception* and *sensation* has analogs in other sensory modalities. In listening to spoken English, if one word terminates in an "s" sound and a subsequent word begins with an "s" sound, we may *perceive* the two sounds even though the spectral components show a broadband frequency distribution that corresponds to only a single spoken "s" sound. Similarly, in vision we *perceive* a fully colored environment even though our sensory organ, the eye, *senses* full color in only a narrow region surrounding the point of regard. We *perceive* the world through internal representations that are periodically updated by our roving eyes, rather than directly through our sensory organs used simply as cameras.

We hypothesize that users' internal representations of mechanical systems being controlled may affect their perceptions of the properties of the systems. Accordingly, in the present study, we asked our subjects to record their model of the mechanical system prior to reporting their quantitative estimates of its component values.

The test apparatus, which consisted of six visible rotary mechanical systems and six rotary interfaces whose mechanisms were hidden, was used in two phases. Subjects were used as their own controls. First they reported their models and perceptions for the component values for all twelve systems, none of which had delayed feedback. In the second phase, although the six visible systems were unchanged, the hidden systems incorporated delayed feedback in their simulations.

In the first test runs, subject errors in rating the stiffness, damping, and inertia in the knobs were compared to the maximum velocity and frequency at which they rotated the knobs. A direct correlation was found between their error in estimating parameters, especially damping, and the frequencies over which they turned the knob. A plot of subject error against the maximum frequency used to turn the knob was generated from the data, and is shown in Figure 8. The straight line represents a least squares fit to the data, with a correlation factor of -0.697. The plot indicates that the subjects who rotated the knob back and forth at higher frequencies were better able to numerically evaluate damping.

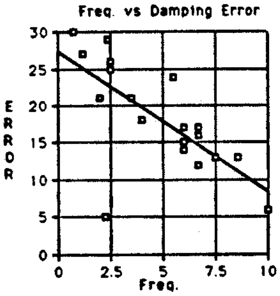

Figure 8 : Frequency vs. Damping Error

Similar but somewhat weaker correlations were found for the error in estimating inertia, as well. In the revised testing procedure, these correlations were pointed out as part of the teaching process, to inform the subjects about the best methods for evaluating the knobs.

It should be noted that because the knobs had a limited excursion, the subjects generally turned them back and forth in an oscillatory manner, often nearly sinusoidally. They usually used a fairly consistent range of angular displacement throughout the test, and thus higher frequencies translated into higher velocities and accelerations, and vice versa.

The results of experiments with time delays showed that the subjects could be separated into two major groups: those who perceived the delay and attempted to attribute it to some addition to the mechanical system, and those who did not report perceiving the delay. The threshold at which delays were perceived seemed to vary from subject to subject, as well as with the kinesthetic feedback being provided.

The aforementioned correlation between higher manipulation frequency and lower error ratings did not extend to the perception of time delays. The subjects who turned the knobs at a higher frequency or velocity in the revised protocol did not always perceive the delays more consistently than subjects who turned the knobs more slowly. The difference was one of perception, not of evaluation strategy.

With respect to the effects of kinesthetic feedback on subjects' ability to detect delays, the data suggests that delays in position feedback are not as readily identifiable as those in velocity or acceleration feedback. Nine of thirteen subjects perceived the delay in a knob, which was subjected to moderate acceleration feedback with a 50 ms time delay. However, only 4 noticed the same 50 ms delay in a knob, where moderate stiffness and light damping were simulated. Similarly, a 20 ms delay was modelled differently by nine of the subjects, while conditions with higher damping were modelled identically to the undelayed systems by the vast majority of people.

The limits on perception of delay may be largely a result of the different stability margins for position, velocity, and acceleration feedback. As the limits of stability are approached, the instability often begins to "creep" into the feedback in the form of oscillation or cogging, although no objective measure of this phenomenon was made.

Nearly all of the subjects who added components to their models to account for the altered perception induced by delay modelled the effect by including a spring between the knob and whatever system the controller was simulating. The natural frequencies of these systems, as determined by the subjects' rated mass and stiffness on each knob, exhibited significant variation.

It should also be noted that because of the lag in the finite difference approximation of acceleration, there was a 15 ms delay in even the "undelayed" feedback of acceleration. Two subjects may have noticed this delay, where they modeled the system with a spring preceding the mass.

When the subjects did not perceive the transmission delay as an additional mechanical component in the system, they accounted for the physical differences by adjusting their estimates of the magnitude of stiffness, damping, and inertia. Although data collected thus far are too sparse to adequately specify the relationship between feedback delay and perceived mechanical impedance, a few patterns are emerging. With delays between 10 - 50 ms, damping and inertia values are underestimated, while stiffness values show no trend, *i.e.*, the variance in stiffness estimation increases without a clear directional bias.

The need to understand how humans perform within the control loop becomes more important as the trend toward the use of telerobotic (*i.e.*, computer mediated telemanipulator) systems in critical situations increases. Kinesthetic feedback offers an attractive means of increasing communication bandwidth between machines and humans. However, in order for kinesthetic feedback to be practical, it is necessary to understand how humans will interpret simulated mechanical environments. This research shows that the same mechanical stimuli may be perceived differently (qualitatively as well as quantitatively) by different individuals. Efforts are currently underway to quantify the relationship between the perception of impedance (stiffness, damping, and inertia, and their interaction) and feedback time delays.

6. REFERENCES

[1] Hill, J.W., "Study to Design and Develop Remote Manipulator Systems," Quarterly Reports 5 and 6, Jan 1977, Stanford Research Institute..

[2] Krüger, Walther, "Optimizing Spring Force, Viscous Damping, and Inertia of a Joystick," *Proceedings of the 15th Conference on Manual Control*, 1979, Vol. 2, pp 471-482.

[3] Sanders, Mark S., and McCormick, Ernest J., *Human Factors in Engineering and Design*, McGraw-Hill Book Co., NY, 1987.

[4] Stevens, S.S., *Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects*, John Wiley, New York, 1975.

[5] Clarke, Margaret M., Handel, Stephen, and Kreifeldt, John G., "Cross Modality Scaling: Mass and Mass Moment of Inertia," *Proceedings of the Eighteenth Annual Conference on Manual Control*, Dayton, OH, June 8-10, 1982, pp 413-18.

[6] Jenkins, W., "The Discrimination and Reproduction of Motor Adjustments with Various Types of Aircraft Controls," *American Journal of Psychology*, Vol. 60, pp 397-406, 1947.

[7] Howland, D., and Noble, M., "The Effect of Physical Constraints on a Control on Tracking Performance," *Journal of Experimental Psychology*, Vol. 46, pp 353-60, 1955.

[8] Book, W.J., and Hannema, D.P., "Master-Slave Manipulator Performance for Various Dynamic Characteristics and Positioning Task Parameters," *IEEE Transaction on Systems, Man, and Cybernetics*, SMC-10, No. 11, Nov, 1980, pp 764-771.

[9] Stark, L., et al., "Telerobotics: Display, Control, and Communication Problems," *IEEE Journal of Robotics and Automation*, RA-3(1), February, 1987, pp 67-75.

[10] Sheridan, T.B. and Ferrell, W.R., "Remote Manipulative Control with Transmission Delay," *Proceedings of the IEEE Transactions on Human Factors & Electronics*, Vol. HFE-4, Sept. 1963, p. 25.

[11] Ferrell, W.R., "Remote Manipulation with Transmission Delay," *IEEE Transaction on Human Factors in Electronics*, Vol. HFE-6, pp. 24-32, Sept. 1965.

[12] Shields, Nicholas Jr., et. al., *Human Operator Performance of Remotely Controlled Tasks*, National Technical Information Service, Springfield, VA, 1982.

[13] Hogan, N., "Stable Execution of Contact Tasks Using Impedance Control," *Proceedings of the 1987 IEEE International Conference on Robotics and Automation*, pp. 1047-54.

[14] McRuer, D.T., Magdaleno, R.E., and Moore, G.P., "A Neuromuscular Actuation System Model," *IEEE Transactions on Man Machine Systems*, MMS-9, No. 3, Sept., 1968, pp 61-71.

[15] Sheridan, T.B., and Ferrell, W.R., *Man-Machine Systems: Information, Control, and Decision Models of Human Performance*, The MIT Press, Cambridge, MA 1974.

[16] Stark, L., "Neurological Feedback Control Systems," in *Advances in Bioengineering and Instrumentation*, F. Alt, Ed., New York, Plenum, pp. 289-385. 1966.

[17] Gotow, J.K., *Human Interpretation of Kinesthetic Feedback: Testbed Development and Preliminary Investigation*, M.E. Thesis, Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA, August 1988.

[18] Thompson, W.M., "Force-Reflecting Servomechanisms with Signal-Transmission Time Delay," Ph.D. Thesis, Illinois Institute of Technology, 1967.

[19] Thompson, W.M., "Pontryagin's Time Lag Stability Criterion in Force Reflecting Servos," *Proceedings of the 9th Joint Automatic Control Conference*, Ann Arbor, 1968.

[20] Drury, C.G., "The Hand-Machine Interface," in *Ergonomic Data for Equipment Design*, Heinz Schmidtke, *ed.*, Plenum Press, NY, 1984.

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