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ENVIRONMENT IDENTIFICATION AND CONSTRAINT MONITORING FOR ROBOTIC INTERACTIVE TASKS

J. M. Jourdain and M. L. Nagurka
Department of Mechanical Engineering and
The Robotics Institute

Carnegie Mellon University
Pittsburgh, Pennsylvania

Abstract

This paper describes testbed hardware and the results of initial experiments using that hardware aimed at controlling a robot interacting with an unknown, unbounded environment. An identification scheme consisting of an environment probing operation utilizing a least-squares-based strategy was implemented. Tests involving a simple unknown environment, i.e., a helical mechanical spring, demonstrate the utility of the approach for determining stiffness and damping equivalent properties. Also described and demonstrated are related techniques, called "constraint" or "cycling" control (modified hybrid control strategies), designed to directly satisfy (and resolve conflicts between) task-based constraints during the execution of interactive tasks.

1. Introduction

In the investigation of robotic grasping and manipulation, there is significant interest in the execution of compliant or force control tasks (Mason, 1981, Whitney, 1985, Hogan, 1987, Paul, 1987). These tasks can be identified as "interactive tasks", defined as tasks where the manipulator comes in contact with the environment and affects some change, such as an object grasp or reorientation, an assembly, or a material-removal operation. These tasks are fundamentally different from non-interactive tasks such as pick-and-place operations or spray painting, where the interaction forces are negligible and the robot can be controlled solely via position control. Using a position control scheme in an interactive task usually results in the generation of large forces in response to any "unexpected" robot/environment contact. These large forces are caused by the combination of high position feedback gains used to decrease position errors and high system (robot plus environment) stiffness. Such forces are undesirable and lead to poor task execution, with possible damage to the robot and/or part (Kazerooni, 1987, Paul, 1987). In contrast, the use of force control alone in an interactive task results in instability when all system components have high stiffness. The instability has been attributed, among other reasons, to high effective feedback gain associated with the high system stiffness (Eppinger, 1986, An, 1987, Hogan, 1987). The significant differences in system response between pure force control and pure position control are well documented (Eppinger, 1986, An, 1987). The successful completion of an interactive task, such as grasping and manipulating an object, grinding, or turning a crank, requires use of an interactive or compliant control strategy, with regulation of both position and force (Mason, 1981, Raibert, 1981).

A significant difficulty with most current approaches to the interactive task problem is noted in (Jourdain and Nagurka, 1988). Either implicitly or explicitly, existing methods require a starting estimate of the environment against which the robot system will be operating. Without this initial estimate, task performance and stability cannot be predicted nor guaranteed.

In the previous work (Jourdain and Nagurka, 1988), several ideas for addressing the environment parameter problem defined above were developed and demonstrated in simulation:

- A system identification technique (Hsia, 1977) was used to determine (either "on-line" or "off-line") parameters of the environment with which a robot arm or hand is interacting. Nearly all existing control methods utilize information about the external task environment (stiffness, damping), either implicitly or explicitly. The adopted approach is an attempt to directly obtain the necessary information, without resorting to *a-priori* information.
- A simple, yet flexible and powerful, constraint specification technique was proposed to shape the response of a robot/environment system in terms of intuitive or natural quantities (e.g., maximum allowable displacement or velocity).
- From the combination of the first two points, a learning strategy was developed. In this strategy, a robot may stably interact with a largely unknown environment (through constraint specification), and simultaneously determine (with increasing confidence as time elapses) environment parameter values.
- A strategy of "cycling control" was also proposed that allows for repeated switching between different control modes (such as force and position). Through this switching or cycling, a new form of "hybrid" control in which different control modes along the same axis may be used. This type of method may allow the determination of a "best" control mode for a given robot/environment situation.

This paper describes the construction and function of an experimental hardware system designed to test these ideas in a simple, yet "real-world" application; also discussed here are the results of preliminary experiments using the hardware system. This work was largely motivated by the importance of practical control schemes for robotic fingers, and ultimately hands, as they operate in less structured (and hence less well-known) environments, such as in manufacturing domains.

As noted above, earlier work (Jourdain and Nagurka, 1988) was directed toward the development of a control strategy for interactive robot tasks that would not require *a-priori* estimates of environment parameters, and would ensure that the finger or hand remained well-behaved while "learning" about its environment and carrying out a task. The work described here represents an additional step toward the goal of demonstrating the utility of these strategies via implementation.

2. Background

Many useful robotic tasks including grinding and assembly can be categorized as "interactive", requiring special control considerations (Whitney, 1985, Hogan, 1987, Paul, 1987). Much of the control challenge centers around the fact that the dynamic behavior of the robot is quite different, depending on whether or not it is in contact with the environment. As a result, it is non-trivial problem to maintain stable robot behavior both in and out of environment contact (Hogan, 1985, Kazerooni, 1987).

Difficulties arise with existing control methods when the characteristics of the environment are not well known. If the environment properties are known, these existing methods are usually able to assure stable, predictable behavior both prior to and during contact with the environment. If the actual environment properties are unknown or difficult to assess, the behavior of existing control methods cannot be predicted accurately. Recently, there has been some interest in techniques for adapting to an "unknown" environment (Slotine, 1987). Unfortunately, most control strategies which adapt to an "unknown" environment require a relatively accurate initial estimate of the environment parameters in order to function satisfactorily (Fukuda, 1986, Fukuda, 1987). Furthermore, the values of environment parameters for which adaptive methods will function reliably are typically bounded, also requiring some advance knowledge of the environment parameters (Kazerooni, Kim, and Waibel, 1988, Fasse and Hogan, 1988).

As noted above, earlier work (Jourdain and Nagurka, 1988) was directed toward the development of a control strategy for robotic interactive tasks in which the system could "learn" and adapt to its environment, with a minimum of limiting requirements. The aforementioned concepts were initially explored via simulation studies of a simple one degree of freedom system (Jourdain and Nagurka, 1988). It was shown that the physical (mechanical) attributes of an environment, such as stiffness, damping, and inertia (mass), may be determined in "real-time" from measurements (such as joint position, velocity, acceleration). The stiffness, damping, and inertial attributes were assumed to completely describe the mechanical properties of the environment. In addition, it was shown that the specification of constraints allows the detection and termination of unstable or otherwise undesirable system responses. As an alternative approach to the interactive task problem, a force-position cycling scheme was simulated and shown to be implementable.

The remainder of this paper presents (i) a description of the hardware development effort undertaken to test the ideas of environment reconstruction and constraint monitoring, and (ii) a discussion of force-position cycling control implementation issues.

3. Hardware Design

Toward the validation of the theories presented and simulated in (Jourdain and Nagurka, 1988), an experimental system, schematically shown in Figure 1, was assembled as a testbed to study the control of a single robot finger in interactive tasks. It consists of six basic elements:

1. Motor and motor drive amplifier.
2. Optical encoder and decoding circuitry for motor position sensing.
3. Strain gauge and amplifier system for force sensing.
4. Gear reduction, single axis finger, and "backstop" (ground) for testing various "environments".
5. Custom-built Multibus^{TM} based real-time control system, with MC68000 microprocessor, VERSABUG bootstrap monitor, parallel interface, A/D-D/A interface module, and ethernet download module.
6. VAX 11/750 host with editing, plotting, and MC68000 cross-compilation utilities.

In addition, a significant body of support software was written to facilitate the use of the experimental hardware. The software developed includes terminal input/output software, A/D-D/A module interface software for analog input/output, timer interrupt software, optical encoder interface software, and data storage and upload software.

The key hardware elements of the system are discussed briefly below. These include the finger hardware, strain gauge force sensor, and optical encoder position sensor.

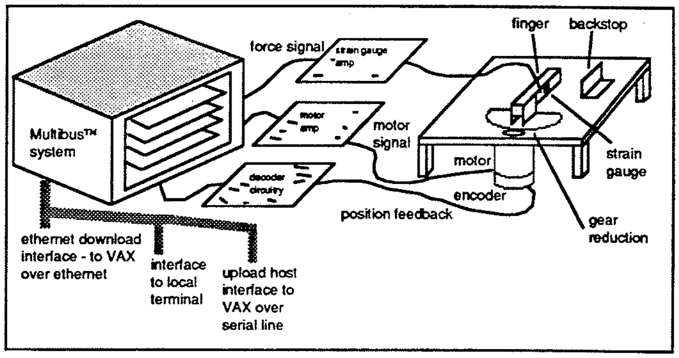

Figure 1: General Experimental Setup

3.1. Finger Hardware

The finger hardware consists of a single link with revolute joint. The finger is driven by a small DC servomotor with a torque constant $\tau = 8.0\frac{oz\text{-}in}{amp}$ $(0.057\frac{N\text{-}m}{amp})$. The motor drives the finger via a 6:1 direct gear reduction. The power supply and amplifiers supply a maximum of 3 amperes of current to the motor. This arrangement results in an effective maximum torque about the finger rotational axis of 144 oz-in (1 N-m). The finger contacts the "environment" at a single distal point, nominally 4 in (10.2 cm) from the finger center of rotation; thus, a maximum force of 2.25 pounds (10.0 N) can be exerted on the "environment". If the rotational position of the finger is θ, the linear displacement of the contact point may be approximated as 4θ from $4\sin\theta$, with $0° < \theta < 7°$, so that the approximation error is less than 0.002 in (0.0508 mm). In the tests, the "environment" was represented by a coil spring compressed by the finger against the "backstop" (Figures 1, 2, 3).

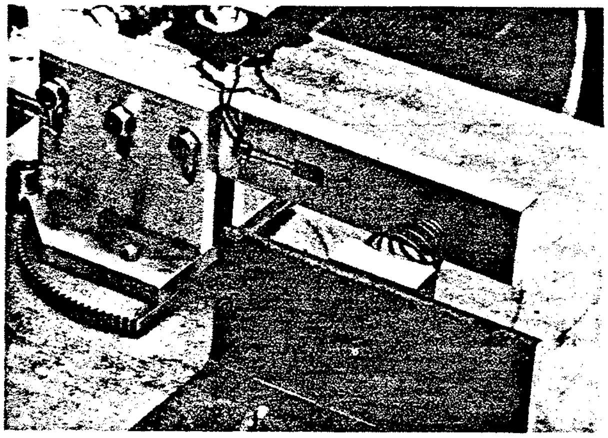

Figure 2: Detail of Experimental Mechanism

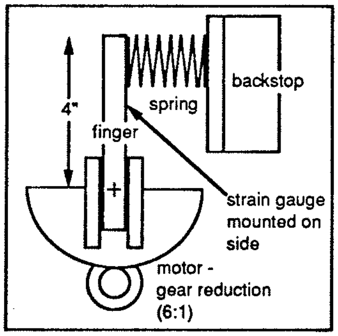

Figure 3: Finger Operating Against Environment (Spring)

3.2. Strain Gauge Force Sensor

To construct a simple force sensor, a strain gauge was bonded to both lateral surfaces of the finger (Figure 1,2). A half-bridge configuration was utilized for increased sensitivity with improved noise and temperature compensation. A two-stage strain gauge amplifier was constructed to amplify low level strain gauge signals (Figure 4). The amplifier was designed so that 120Ω compensation resistors may be switched into the bridge circuit. This allows the amplifier to easily adapt for use with full, half, or quarter bridge configurations.

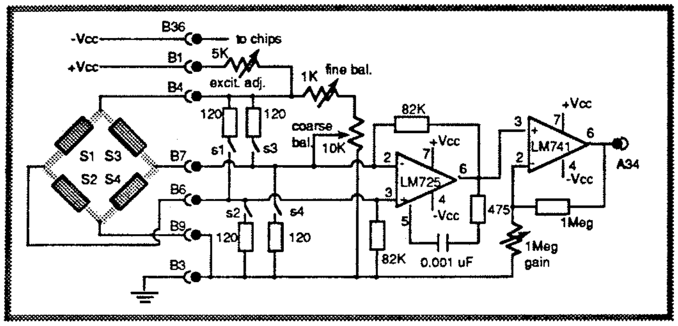

Figure 4: Strain Gauge Amplifier Schematic

The strain gauge force sensor was assumed to be essentially a perfectly linear device for the experiments performed. A proportional calibration coefficient was determined and used to convert each sampled A/D reading into force units.

Since this strain gauge amplifier is a high gain device, some provision became necessary to accommodate the increased noise levels at the output. A simple low pass RC (R=10KΩ,C=.73µF) filter on the amplifier output was used; it preserves a flat unity gain response to approximately 22 Hz. The filter has zero phase angle at the corner frequency of 2.2 Hz, and a slope of $-45 \frac{degrees}{decade}$ above this frequency (Figure 5).

Since the environment is represented by a mechanical coil spring, the "real" environment damping is quite low. The RC filter, in addition to filtering out high frequency noise, adds some "artificial damping" to the system. The "damping", which is electrical rather than mechanical, will still be detected by the identification method as a velocity dependent term. A schematic of the mechanical system and RC filter combination is shown in Figure 5.

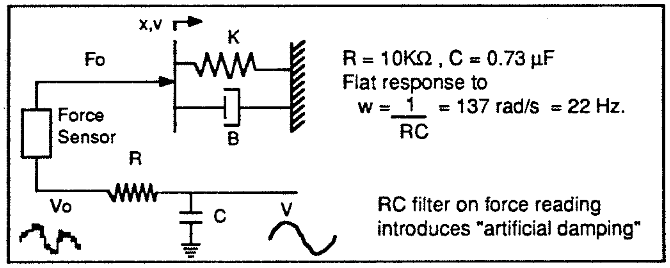

Figure 5: Model of "Artificial Damping" Resulting from RC filter

The relationship between the resistance R and capacitance C filter values and the "artificial damping" can be determined as follows:

First, the mechanical and electrical segments of the system may be characterized by the following transfer functions:

$$\frac{X}{F_0} = \frac{1}{K + Bs} \qquad \frac{V}{V_0} = \frac{1}{1 + RCs} \tag{1}$$

Assuming that the force/velocity transducer is a unity gain device, the overall transfer function for the mechanical/electrical system is as follows:

$$\frac{X}{V} = \frac{1+RCs}{K+Bs} \tag{2}$$

Considering the frequency response of the overall system, there is a zero at $\frac{1}{RC}$, and a pole at $\frac{K}{B}$. It can be seen that if $\frac{K}{B}$ is much larger than $\frac{1}{RC}$, $\frac{1}{RC}$ will appear to be the only factor present, as long as the input frequency is well below $\frac{K}{B}$.

Furthermore, if equation (2) is re-expressed by multiplying by $\frac{1 - RCs}{1 - RCs}$, the resulting transfer function is

$$\frac{X}{V} = \frac{1 - (RCs)^2}{K + (B - KRC)s - BRCs^2} \tag{3}$$

From the characteristic equation of this transfer function, it can be seen that if B is much less than the quantity KRC, the system will appear as a spring and damper only, with spring constant K and damping -KRC. Note that the conditions placed on the magnitude of B here, and the conclusions drawn are equivalent to those in the previous paragraph, where the system dynamics are dominated by the zero at $\frac{1}{RC}$.

In essence, this concept of "artificial damping" functions because the environment reconstruction algorithm is formulating stiffness and damping estimates from measurements of position, velocity, and force. The algorithm is "expecting" stiffness and damping effects only, so that the additional dynamics added by the electrical RC component will be interpreted as "artificial damping", as derived above. The inertial effects introduced by the RC electrical component will not affect the damping and stiffness estimates, because they are derived from only position and velocity samples. If a mass were included in the environment model (and acceleration samples taken to determine its value), it **would** be affected by the inertial component added by the RC filter.

3.3. Optical Encoder Position Sensor

The principles behind optical position encoders are well-known, and will not be re-explained here (HP, 1984), other than to state that the optical encoder used in this system is a Hewlett-Packard model (HEDS-5010), with N=500 slots per revolution, or an effective maximum resolution of $2000 \frac{counts}{motor\ rev}$. This sensor functions quite well as a position feedback element, and is used as a velocity sensor through a simple backward differencing technique.

Since the optical encoder is a digital feedback device, and is sampled at finite intervals, quantization errors are introduced in attempting to measure small velocities (i.e., from one to ten counts per sampling interval). To minimize these effects, it was found that the velocity should not be less than 10 counts/interval for a sampling interval of 0.005 seconds. This implies that a 5-10 Hz sinusoidal position profile for the system might give reasonable results for position, velocity, and force signals that could be used to determine the environment stiffness and damping properties. In fact, such a strategy was used in the actual experiments, as shown later. (It is theoretically possible to obtain an acceleration estimate in the same manner as the velocity estimate. However, in practice, high frequency artifacts limit the utility of such multiple approximations/differentiations.)

The encoder pulse train is clocked in and decoded by a custom IC (HEDS-2000) from Hewlett-Packard. This IC makes the current incremental position available as an 8 or 12 bit word, which is read by the processor board via the onboard parallel interface, which also drives the chip control lines. If a 12 bit word is needed, a multiplexing operation is necessary, since the chip data bus is only 8 bits wide. Some additional circuitry was designed and constructed to coordinate the multiplexed read operations and insure valid data readings for 12 bit positions (HP, 1986).

4. Experimental Methods

In the experiments, the motion of the single link finger was controlled in the manner shown in Figure 6, with the control loop being executed at a rate of 200 Hz. The position, force, and calculated velocity information was saved and uploaded for viewing, but not used in controlling the finger motion; the constraint specification scheme mentioned earlier handled the control of the system in the "learning" phase. The specified constraints were checked upon being read on each loop (e.g., if there were only a constraint on maximum position, it would be checked immediately after the position was read on each loop). Finally, the stiffness and damping estimates were produced in one of two ways:

1. In real-time, at the same point in the servo loop where the command signal is calculated. However, this update is done at a lower rate than the servoing, since the calculations involve non-trivial numbers of operations. This method is more appropriate for situations where the information will be used to dynamically change control parameters, or where the environment is dynamically changing.

2. Off-line, or in "batch mode", so that the parameter estimates are obtained after a short probing operation of approximately two seconds. This method is more appropriate for situations

where only a single estimate of the environment parameters is needed; generally this would mean that the parameters were assumed to be constant.

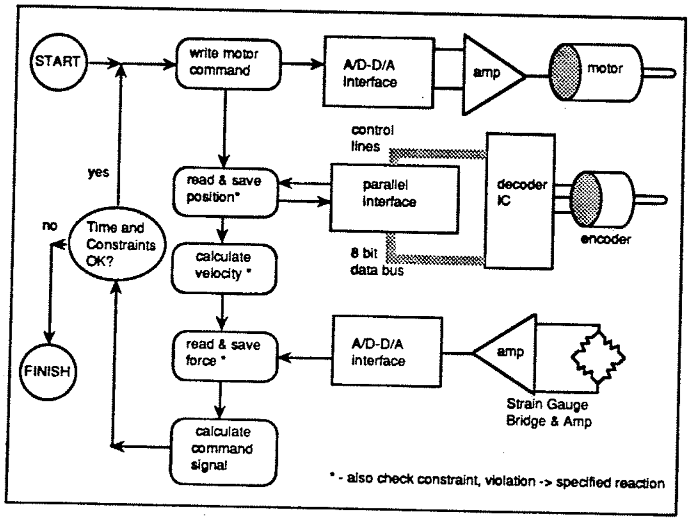

Figure 6: Schematic Showing General Control Strategy in Experiments

4.1. Experiment 1: Probing and Parameter Determination

In this section, a "probing" operation is described for initial determination of environment parameters. During this probing process, a 5 Hz sinusoidal force command signal of a nominally specified magnitude is applied to the motor. The force applied to the environment, finger position and velocity are sampled, stored, and used to update environment stiffness and damping estimates. This process allows the determination of properties for *arbitrary* environments; the only assumption is that the mechanical properties of the environment may be modeled by a simple spring-damper.[1] Stability and system response needs are accounted for by a constraint specification scheme.

The single finger was used to "squeeze", i.e., probe, the environment several times, and to gain an initial estimate of the environment stiffness and damping. Figure 7 shows the time history of the input force command and measured force output at the fingertip (in units of pounds x100). Figure 8 shows the corresponding time history of the position and velocity in encoder counts and counts per sampling interval, respectively. These plots essentially represent the data available to determine the model parameter estimates of the environment.

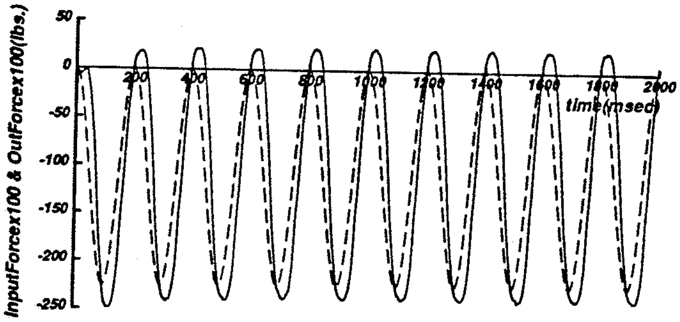

Figure 7: Input-Output Force Results of Probing Process
(Solid=Fingertip Force, Dashed=Command Force Input)

While the probing operation is being carried out, stiffness and damping estimates may be updated at a rate below the servo rate. The sampled force and position, along with the calculated velocity value, are input to an iterative estimation method, with the stiffness and damping estimates being the output. Details of this method are presented in

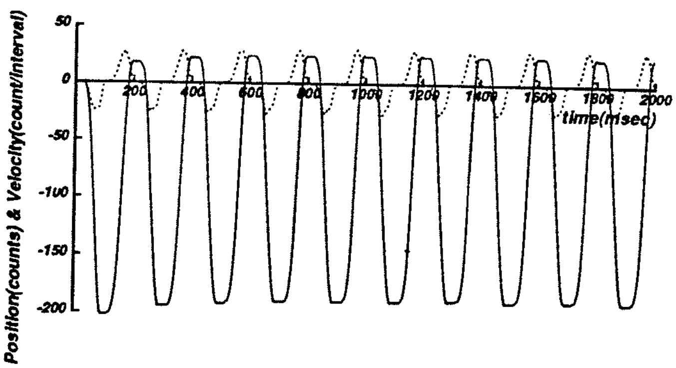

Figure 8: Position & Velocity Results of Probing Process
(Solid=Position, Dotted=Velocity)

(Jourdain and Nagurka, 1988). The stiffness and damping estimates for the probing operation of Figures 7 and 8 are shown in Figure 9. These particular estimates were obtained off-line (by the "batch method"), applying the reconstruction technique to the data after the probing operation had taken place. The estimates are produced very quickly, in a second or two of real-time after the data is gathered. Notice that the stiffness and damping estimates both converge on a "steady-state" value quickly (within 0.2 sec), each starting from zero.

Note that both the force exerted on the environment and the finger position in Figures 7 and 8 exhibit some "zero-crossing" properties. For example, the fingertip force starts at zero and is primarily negative (compression), but its value is positive momentarily for part of each "probing cycle". This behavior is due to errors in the setup of the probing experiment, and stiction in the mechanism used. The finger and environment were set up manually, and all readings zeroed, but once the probing operation starts, a new zero (null position/force) is established, which does not coincide with the manually established zero value. This new zero is quite repeatable, as seen in the plots (Figures 7 and 8) showing multiple "squeezing" operations, where the same force and position values are recorded on each pass.

In Figure 9, the estimates for stiffness are in units of $\frac{force\ counts}{motor\ encoder\ count}$, and those for damping are in units of $\frac{force\ counts \cdot sample\ interval}{motor\ count}$. "Force counts" are the integer values read back from the force sensor system; "motor counts" are the count values read back from the optical encoder, and "sample interval" is the digital equivalent of time (e.g., the motor velocity is in $\frac{counts}{interval}$ instead of $\frac{radians}{second}$). The values are most easily used in the digital control algorithm in this form. These stiffness and damping values are converted to $\frac{lb}{inch}$ $(\frac{N}{m})$ and $\frac{lb\text{-}sec}{foot}$ $(\frac{N\text{-}sec}{m})$, since $150 force\ counts = 2.25 pounds (10N)$ (determined through calibration of the strain gauge force sensor on the single-link finger). The final necessary relationship can be stated as:

$$fingertip\ disp. = motor\ counts \cdot \frac{2\Pi\, rad.}{2000\, cts.} \frac{1}{6} 4\, inches \tag{4}$$

Converting the "steady-state" stiffness value from Figure 9 results in an estimate of $5.6 \frac{lb}{inch}$ $(982 \frac{N}{m})$, which reasonably approximates the measured spring stiffness value of $5 \frac{lb}{inch}$. The extracted damping value of $-1.18 \frac{fcount \cdot int}{mcount}$, when compared to -KRC (derived earlier) of -1.12, matches within 5%.

The parameter estimation method results shown here are a representative sample. They show that the theoretical environment parameter determination technique (Jourdain and Nagurka, 1988) functions satisfactorily in a "real-world" application. As a check, the extracted mechanical parameters were compared to the actual values, and were found to agree. Note that initially, *nothing* was known about the environment against which the finger was pressing. After "probing", a stable and reasonably rapid operation, the environment parameters were identified. At this point, a large number of subsequent actions are possible, using the new knowledge about the environment.

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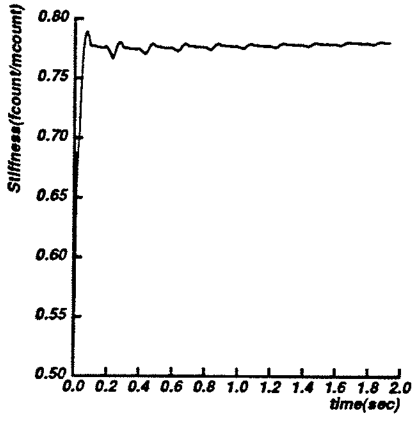
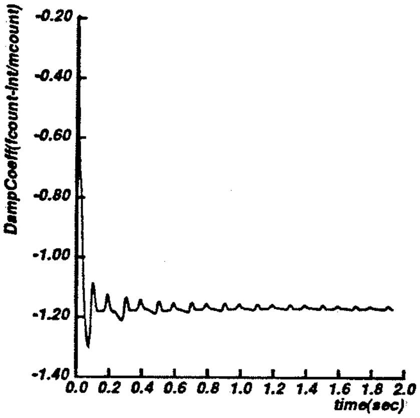
[1] An acceleration measurement, necessary to extract an inertial parameter estimate, is very difficult to make with the hardware available. In addition, the environment inertia is low and has a limited effect on the response in the types of motion under consideration. For these reasons, the inertial parameter is ignored, and only the stiffness and damping parameters are considered.



K estimate vs. time



B estimate vs. time

Figure 9: Reconstruction Results from Figures 7 and 8

4.2. Experiment 2: Constraint Feasibility

This section discusses a test of the probing process in which constraint limits are met. In this test, sinusoidal probing starts with a preset nominal force magnitude, which is too large for the weak spring "environment". Because the probing force is too large, a maximum position limit constraint is violated. In response to this violation, probing stops, and a new probing input of lower force magnitude is applied.

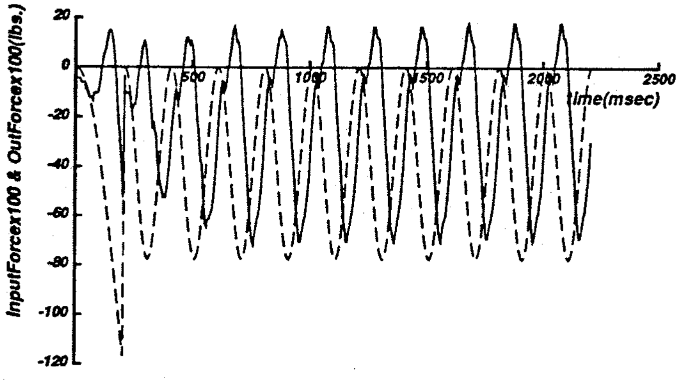


Figure 10: Probing Process with Force Modification in Response to Constraint Violation (Solid=Fingertip Force, Dashed=Command Force)

Figures 10 and 11 show the experimental results. At about 200 msec, a maximum position constraint of 250 counts is violated 11. The corresponding command force is approximately 1.20 lb (5.34 N)10. The algorithmically specified response to this particular type of constraint violation first causes the applied force (and position, in this case) to drop quickly back down to zero. Then, the probing input force magnitude is recalculated on the basis of the force level at the point of constraint violation, and the environment is probed again (the recalculation takes approximately 1 sec). The constraint response allows a "recalibrated" probing operation to be completed successfully, as seen in the figures. After the violation at 200 msec, a sinusoidal probing operation takes place as before, with no constraint violation occurring. The resulting stiffness estimate from this process is shown in Figure 12. This estimate is in close agreement with the actual measured spring rate of $1\ \frac{lb}{inch}$.

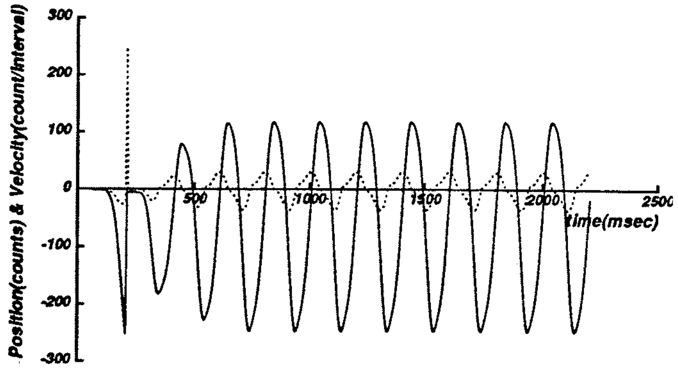
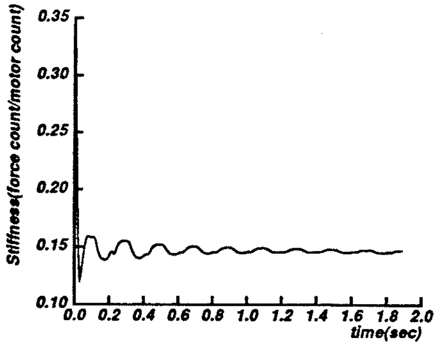


Figure 11: Probing Process Position Modifying in Response to Constraint Violation (Solid=Position, Dotted=Velocity)



K estimate vs. time

Figure 12: Stiffness Parameter Estimate for Constraint Situation

In this experiment, an implementation of an environment reconstruction scheme with constraint detection has been demonstrated. The violation of a constraint was determined, and an appropriate modified action taken, leading to a stiffness parameter estimate for an unknown environment.

It is possible to program almost any desired response to a particular type of constraint violation, and many operational combinations are possible. One scenario has an impedance control scheme operating as the primary control, with a constraint check "in background". Upon violation of a constraint, the environment is probed, and new gains for the impedance control are produced from the environment parameter information. The system then continues to operate under impedance control. This "adaptive" approach promises to solve a difficulty that many adaptive control strategies have with widely varying environments/systems. The constraint mechanism allows the environment parameters to be determined with a minimum of limitations such as parameter bounds.

5. Cycling Between Force and Position Control

Some interactive tasks such as grinding have both force and position needs that must be satisfied *at the same time* and *in the same direction*. In an attempt to satisfy both force and position demands (along the same axis) in a task, the concept of cycling between simple force and position control strategies was proposed (Jourdain and Nagurka, 1988). Switching between different control modes was seen to offer a way of monitoring and modifying *both* position and force along a task axis, while not violating causality. It was envisioned that force and position could be (nearly) "simultaneously" influenced as the switching interval was made smaller. The concept was not limited to only force and position control; any control algorithm (e.g., impedance, stiffness and/or accommodation control) could theoretically be implemented.

Cycling between multiple control modes at a rate well below the system natural frequency may be simply stated as a case of "trying" one control mode, evaluating the response, then trying another if the response is not "satisfactory". A constant value steady-state response would not be achievable, since each control mode will have its own steady state response, and the control would tend to oscillate between steady state responses for each control mode as the cycling scheme switched between the modes. Additionally, there is the problem of what happens when control is passed from one algorithm to another; it is quite easy for discontinuities to arise in the command signal, resulting in undesirable behavior.

Cycling at a rate near the system natural frequency would presumably result in some form of resonance, which is undesirable.

A strategy of *cycling at a rate well above the natural frequency*, might lead to (nearly) "simultaneous control" by different controllers. However, as shown in Figure 13, at a high switching rate, the cycling can be compared to a blending or summing strategy. The "switch" in the cycling strategy (Figure 13) essentially becomes an averaging element at higher switching frequencies.

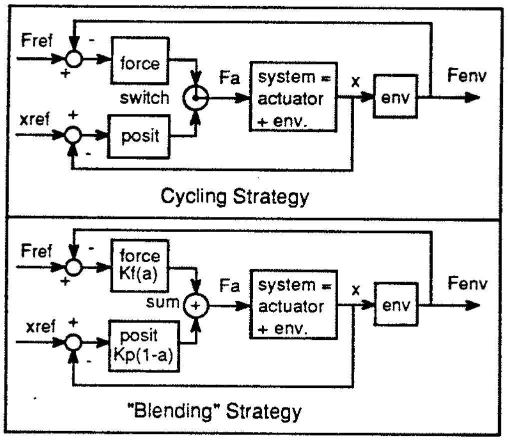


Figure 13: Cycling and Force-Position Blending control strategies

6. Conclusions and Future Work

This paper outlined the construction of an experimental system used to determine the stiffness and damping parameters of an unknown system. In addition, the use of a constraint specification scheme to shape system excitation and response was demonstrated.

It is hoped that these environment parameters can be used to choose an "optimum" control method (this "optimum" is obviously task dependent). Although the complexity of the problem suggests a heuristic approach, an algorithmic method may also be possible. One strategy might start with the probing of the unknown system. After the environment parameters are obtained, a decision about the "best" controller can be made. This decision might consist only of the choice of some gains for an impedance controller (a fairly algorithmic approach). After the principal controller is set up, the environment parameters may be reevaluated periodically, with the variance in the parameters being monitored.

Another concept for future consideration is the inclusion of force-position task needs. One possible approach is to weight the force and position needs of the task, and then have an optimal control strategy minimize the weighted sum of force and position errors.

A further interesting idea for future work is the use of multiple fingers in determining environment parameters. One implementation might involve a two-fingered hand with each finger alternately probing a grasped object (while the other finger is held steady). The result would be a representation of the environment each finger is operating against (the object, as well as the other finger); the representations could be compared and averaged.

In another scenario, the fingers could "self-calibrate" by squeezing against each other, with one finger actively probing and the other passively resisting (acting with a specified stiffness/compliance, or mass-spring-damper characteristic).

Finally, in contrast to the event-based behavior of the constraint specification shown so far, a "real-time constraint control" may be hypothesized, as implied in the current work. Instead of the strategy reacting to constraint violations, the entire system response could be shaped by specifying continuous constraints on position and force, for example. A "constraint map" would update command signals each servo period in response to sensed position, velocity, etc. This idea is similar in form to the potential field approach, but includes domains other than the position space, with the various domains (force, position, etc.) being superimposed to yield one composite potential map.

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