EXPERIMENTS RELATING TASK AND MANIPULATOR CHARACTERISTICS TO PERFORMANCE

Wayne Book
School Of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

and

Lawrence Field
Graduate Student
School Of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

Introduction

A review of literature shows that little progress has been made towards quantifying the manipulator characteristics necessary to provide a given performance at a given task. Controlled single factor experiments can be performed by simulating the characteristics of interest and inserting them into the dynamics via the joint control system. Backlash, Coulomb friction, and many other important effects can be studied in this manner. The authors' research utilizes an experimental electric arm controlled by microprocessor, which is described below.

In the twenty-five or so years that remote manipulation devices have been in use, various authors have described qualitatively the characteristics of a good manipulator. The manually controlled manipulator has evolved into the computer controlled manipulator, but the desirable characteristics are still only described qualitatively. The research underway in the School of Mechanical Engineering at Georgia Tech is attempting to quantify the relationship between manipulator characteristics and manipulator performance for a specific task, and to gain insight into the basic nature of maipulation.

Background

The complex system formed when man interacts with machine has been quantitatively described with varying success. Accurate and useful models have been developed for a human operator tracking a target which moves in a random appearing fashion for various displays, controls and plant dynamics. The concepts have found application in design of vehicle controls for example. While the manipulation task has similarities to the tracking task the important differences include:

1) The operator is not paced by a target in manipulation
2) In manipulation the operator has knowledge of the future position of the "target" (similar to preview or precognitive tracking)
3) In manipulation the operator's objective changes as he completes portions of the task. (The tracking task is never completed, although some results exist for change in plant dynamics which may be applicable.)

An understanding of how the characteristics of the manipulator and the characteristics of the task determine the system performance is needed to more efficiently design the manipulator. This trio, manipulator characteristics, task characteristics, and performance have been referred to variously as tool, task and performance (Sheridan[1]) secondary figure of merit, task, and figure of merit (Corliss and Johnsen[2]) and response, task, and system performance (Pesch and Bertsche[3]). It is significant that these three references above span almost 10 years, discuss essentially the same topic, represent a refinement in thinking, but no advance in the quantitative relationship between the variables presented. (Pesch describes work which has this as a goal.) It is the authors' contention that this is due in large part to the lack of controlled experiments varying a single characteristic.

Characteristics of interest in arm design are widely agreed on. Table 1 gives some of these characteristics by author. But while agreement exists that "backlash is bad" for example, no conclusive results indicate how bad, and for what task.

Pesch and Bertsche are reported to have tested full scale manipulators to determine their response and relate this information to performance. The difficulties in this approach are obvious. Manipulator characteristics are essentially fixed. To add to the data base requires evaluating other manipulators, probably by other experimenters. Pesch states "The question remaining is how to utilize the methodology in the future to add to the existing data base. One solution is to replicate the tests....This is a viable solution where identical facilities exist." But since this approach would vary many characteristics, and the effects of each will be difficult to determine solely on the basis of this data. Such data would be very useful for verification of results obtained from more controlled experiments however.

This view is supported by previous experience. The most conclusive and quantitative results along these lines relate time delay in visual feedback to performance. Ferrell[4] performed the former experiments with one primary variable, delay time. Ferrell also performed experiments on task tolerance applying Fitts' index of difficulty for motor tasks to remote manipulation with a two degree of freedom manipulator. McGovern[5] recently extended this verification with experiments on two, seven degree of freedom manipulators.

Controlled, Single Factor Experiments

Many of the characteristics of interest can be varied via the arm control system. These are indicated in Table 1. The present research by the authors adapts the following strategy: 1) build the best possible manipulator with a limited number of degrees of freedom; 2) introduce the undesirable characteristics such as Coulomb friction or backlash via real time simulation on the digital computer which controls the joints; 3) experiment with well defined tasks; 4) vary a single manipulator characteristic to determine its effect on performance. An argument for this approach can be found in Jelatis[6].

With fewer degrees of freedom better manipulator response can be obtained at a reasonable cost. Two degrees of freedom have presently been implemented. The

The third will provide general motion in a plane. Since not completely general these results should be verified with 6 degree of freedom experiments.

Description of the Manipulator

As presently configured the arm is a two link, two degree of freedom device with revolute joints designed for operation in a horizontal plane. It is driven by two electric D.C. torque motors, both mounted at the "shoulder". The "elbow" motor drives the second link through a pair of aircraft cables. Each link is designed to have the approximate length (12 inches) and speed of the human arm.

The computer controlling the arm is a Texas Instruments 990/4 microcomputer. It accepts reference angles from the shoulder (θ_{so}) and elbow (θ_{eo}), the measured actual angles θ_s and θ_e and the velocities $\dot{\theta}_s$ and $\dot{\theta}_e$. The outputs are the signals to the torque motors T_s and T_e. Analog to digital and digital to analog conversion employs 12 bits. The control law is

$$\begin{bmatrix} T_s \\ T_e \end{bmatrix} = \underline{A} \begin{bmatrix} \beta_s \\ \beta_e \end{bmatrix} + \underline{B} \begin{bmatrix} \dot{\beta}_s \\ \dot{\beta}_e \end{bmatrix} \qquad (1)$$

where $\beta_s = \theta_s - \theta_{so}$, $\beta_e = \theta_e - \theta_{eo}$, $\dot{\beta}_s = \dot{\theta}_s$ and $\dot{\beta}_e = \dot{\theta}_e$.

The coefficients in equation 1 were derived from the equations of motion of the arm linearized for small changes in angular displacement and velocity.

Since the motor electrical time constant is 2.2 m sec a goal of 1 m sec maximum sampling interval was set for the program to insure that no sampling effects were evident.

The A/D and D/A scaling factors result in digital values (primed vectors) which are related to analog values as shown in equation 2.

$$\bar{\beta}' = D\bar{\beta} \ , \ \dot{\bar{\beta}}' = V\dot{\bar{\beta}} \text{ and } \bar{T}' = \begin{bmatrix} W_s T_s \\ W_e T_e \end{bmatrix} \qquad (2)$$

D, V, W_s and W_e are scale factors expressed in digital parts per analog unit. By expressing equation 1 in terms of these factors, the dominant arm undamped natural frequencies (ω_1 and ω_2) and damping ratio (ζ) one obtains an equation of the form

$$\bar{T}' = A(W_s, W_e, \omega_1, \omega_2, \alpha_{ij})\bar{\beta}' + B(W_s, W_e, \omega_1, \omega_2, \gamma_{ij})\dot{\bar{\beta}}' \qquad (3)$$

The α_{ij} and γ_{ij} are eight coefficients which depend on the elbow angle only and are input via cassette. The eight values of the A and B matrices are per computed at 64 positions per quadrant by the microcomputer to avoid unnecessary time consuming multiplications (17 μ sec for an unsigned multiply) while controlling the arm. The minimum of eight multiplications must be performed real time. The user may change scale factors; eigenvalues or damping ratios by simply entering a keyboard mode. Integer arithmetic is used with all coefficients being expressed as a ratio of an integer over a power of two. The final A and B matrices are automatically scaled to have of uniform denominator of 2^{16}, thus requiring only 512 words of storage. Additionally, no division or shifting is necessary while the arm is being controlled. The result is a fast, flexible system. Without additional subroutines to simulate arm characteristics the sampling rate is a minimum of 1280 hz. This allows considerable time for execution of additional subroutines. Keyboard commands to stop the arm are supplemented with emergency commands given by limit switches at the extremes of joint travel.

Conclusion

Using the arm described in the text experiments are being performed with a unilateral master slave command. It is expected that these results will indicate meaningful relationships between manipulator characteristics, task characteristics and overall performance.

References

1. Sheridan, Thomas B., "Evaluation of Tools and Tasks: Reflections on the Problem of Specifying Robot/Manipulator Performance. Performance Evaluation of Programmable Robots and Manipulators. National Bureau of Standards (NSB) Special Publication 459, pp. 27-38, October 1976.

2. Corliss, William R. and Edwin G. Johnsen, Teleoperator Controls, NASA SP 5070.

3. Pesch, Alan J. and William R. Bertoche, "Performance for Undersea Systems" NBS Special Publication 459, pp. 175-196, October 1976.

4. Ferrell, W. R., "Remote Manipulation with Transmission Delay" NASA TN D-2665, February 1965.

5. McGovern, D. E., "Comparison of Two Manipulators Using a Standard Task of Varying Difficulty", ASME Paper 74 WA/Bio-4.

6. Jelatis, Demetrius G., "Characteristics and Evaluation of Master Slave Manipulators," NBS Special Publication 459 pp. 141-146, October 1976.

TABLE 1

Manipulator Characteristics Cited as Influencing Performance

Characteristic	Ref. 2	Ref. 3	Can be Simulated at the Joint
Torque or force	X		X
Speed	X		X
Rise time		X	X
Slew rate		X	X
Bandwidth		X	X
Settling time		X	X
Ease of indexing	X		
Accuracy	X		X
Articulateness	X		
Stiffness	X	X	X
Friction	X	X	X
Inertia	X	X	X
Backlash	X	X	X
Stability	X		X
Sensitivity (Deadband)	X	X	X
Cross coupling	X		X
Drift	X	X	X
Time delay		X	X
Minimum motion		X	X