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Master–Slave Manipulator Performance for Various Dynamic Characteristics and Positioning Task Parameters

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***Abstract*—The performance of manually operated remote manipulators is limited by friction, tolerance of mating parts, limited speed of response, and other unavoidable factors which affect dynamic behavior. A review of the literature shows that little progress has been made towards describing or predicting these effects quantitatively. Such knowledge would be valuable both in understanding human motor behavior and in improving manipulator design. Single factor experiments were performed for a simple manipulator positioning task. The manipulator used was an experimental, two-degree-of-freedom, unilateral, master–slave manipulator. Microprocessor control of the dc electric torque motors which drive the joints enforced an approximately linear dynamic behavior of the arm throughout its range of motion. The characteristics of behavior which were studied were arm natural frequency, simulated Coulomb friction, and simulated backlash (deadband). The parameters of the positioning task which were varied were positioning accuracy and distance traveled. Performance was measured in task completion time. The data were analyzed statistically and regression coefficients obtained to explain the results in terms of information transmission concepts. In general, the information transmission rates were found to differ for the gross motion (travel) and fine motion (positioning) components of the task. For a well-trained subject and the best manipulator behavior, the two rates were the same, yielding the performance variations predicted by "Fitts' law." The variation in performance with manipulator characteristics and task parameters is explained in terms of operator strategies to minimize time within the error constraints by changing the point of transmission from fast gross motion to the slower and more conservative fine motion.**

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I. Introduction

Mechanical devices for performing general purpose manipulation without direct human contact have been produced and used in a variety of tasks. These devices originated with the hot lab manipulator for handling radioactive material and have been adapted to undersea, outerspace, and industrial applications. Although manipulators were originally devised more than 35 years ago, it is surprising to find how little is known about manipulation or about the dynamic characteristics required of a manipulator to perform a given task well. This was noted in an NBS workshop [1]. It was noted that the relationship between the three elements that Sheridan calls tool (manipulator), task, and performance is quantitatively unknown.

Manipulation may consist of positioning, following constrained paths, the application of forces and moments, and other complex maneuvers. Only the positioning task will be considered here. This task consists of moving the end point of the manipulator from one position to within a tolerance band surrounding a desired position and stopping it there. It is a major requirement for most manipulator systems.

The present work investigates the effect of three dynamic characteristics of the manipulator, described here as backlash, Coulomb friction, and bandwidth. These characteristics are generally described by a number of authors (as summarized in [2]) as being of great importance in the performance of practical manipulators. The effect of these characteristics for positioning tasks with varying distances of motion and positioning tolerances is explored.

McGovern [3] and Hill *et al.* [4] found a significant difference in the mean task completion time for two manipulators used in a simple positioning task. This difference could be qualitatively explained, but since the two manipulator systems had vastly different designs, it would have been an impossible task to determine which dynamic characteristic, say Coulomb friction or backlash, had how much influence in affecting the performance. It was not possible to quantify the effect of manipulator characteristics on performance. To do this one could compare the performance of many slightly different manipulators, but the cost would make such experiments prohibitive.

Bertsche *et al.* [5] under sponsorship of the U.S. Office of Naval Research identified important characteristics affecting undersea manipulator performance including the characteristics studied here. Bertsche *et al.* [6] in 1977 studied these characteristics to a limited extent but proposed no systematic way to predict their effects.

One of the most methodical investigations of manipulator performance was performed by Ferrell [7]. Transmission delay to command signals of a two-degree-of-freedom manipulator was varied and the resulting performance and operator strategies were studied. Black [8] studied a similar problem with a full six-degree-of-freedom manipulator. These results agreed with and extended Ferrell's results. Other, more commonplace manipulator characteristics have not been so methodically studied.

Other investigators have compared manipulator configurations and control strategies. Mullen [9] compared resolved motion rate control to master–slave control and joint rate control. Berson *et al.* [10] compared the performance of computer-aided manipulation in various forms with unaided manipulation. Extensive work on performance evaluation of remote manipulators has been performed at the Jet Propulsion Laboratory and is

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summarized by Bejczy [11]. This work has focused on the man–machine interface, sensors, and control modes. Thompson [12] studied performance variation with the number of directions in which it was necessary to constrain the end point to accomplish the task.

II. The Experimental Mechanical Arm

The mechanical arm used in the experiments (Figs. 1 and 2) is a two-degree-of-freedom system, having two joints ("shoulder" and "elbow") and two links that move in a horizontal plane. The arm dynamics are nonlinear due to variations in the arm moment of inertia with joint angle, and Coriolis and centrifugal forces which depend on products of joint velocities. The latter terms will be negligible during the critical positioning or fine motion phase but not during the travel phase when velocities are high. As nonlinear dynamics are the rule in manipulator arms, their existence does not detract from the validity of the experimental results but does make the results more difficult to generalize. To alleviate this problem a controller was designed to provide the arm with a standard response at all joint angles, at least at low velocities. The standard response chosen for implementation was linear with each joint behaving as a decoupled second-order system. Feedback gains were varied with joint angle so as to maintain decoupling with constant natural frequency and damping ratio. Natural frequency and damping ratio were chosen to be the same for each joint for simplicity. The controller design is an important part of the experimental apparatus and is described below.

The fourth-order equations of motion were linearized about zero velocity and arbitrary joint angle to the standard form

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}. \tag{1}$$

The states of the system $\boldsymbol{x}$ are the angular positions and velocities of the two joints. The input vector $\boldsymbol{u}$ consists of the torques that are applied to the joints.

To obtain the closed-loop master–slave manipulator system we apply state variable feedback to the mechanical arm comparing the positions of the slave arm to the corresponding reference states of the master manipulator. The reference velocity used is zero since this variable is not measured. The input torques to the slave mechanical arm are obtained as

$$\boldsymbol{u} = \boldsymbol{M}(\boldsymbol{x}_r - \boldsymbol{x}). \tag{2}$$

The closed-loop system that results in

$$\dot{\boldsymbol{x}} = \boldsymbol{A}_d\boldsymbol{x} + \boldsymbol{B}\boldsymbol{M}\boldsymbol{x}_r$$
$$\boldsymbol{A}_d = \boldsymbol{A} - \boldsymbol{B}\boldsymbol{M} \tag{3}$$

where $\boldsymbol{A}_d$ is the desired closed-loop system matrix that is selected so that the closed-looped response corresponds to that of two uncoupled second-order systems, i.e., the movement of one link does not disturb the other. The system block diagram can be seen in Fig. 3.

If $\boldsymbol{A}_d$ is selected to have the form

$$\boldsymbol{A}_d = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\omega_1^2 & 0 & -2\zeta\omega_1 & 0 \\ 0 & -\omega_2^2 & 0 & -2\zeta\omega_2 \end{bmatrix} \tag{4}$$

then the closed-loop control system equations will be analogous to those of two uncoupled, damped, second-order oscillators.

The control law, rewritten from (2), to be implemented is

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{bmatrix} x_{r1} - x_1 \\ x_{r2} - x_2 \end{bmatrix} + \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} -\dot{x}_1 \\ -\dot{x}_2 \end{bmatrix}. \tag{5}$$

A Texas Instruments TI990/4 microcomputer was used to implement this control algorithm, computing the necessary torque signals and providing them to the power amplifiers that drive the dc torque motors which in turn drive the links. By computing the torques in the discrete-time domain, the idealized time response was found to be a Taylor series' approximation of the time response for the continuous-time state-variable feedback of (5). The computer program actually implements a nonlinear control having 64 control matrices stored in memory corresponding to linearization about 64 operating points of the mechanical arm. The flexibility of the program allows one to change the parameters of the closed-loop system such as the natural frequencies and damping ratios. It also allows one to simulate Coulomb friction in the joints of the mechanical arm and backlash in the joints of the master manipulator.

Fig. 1. Experimental manipulator system.

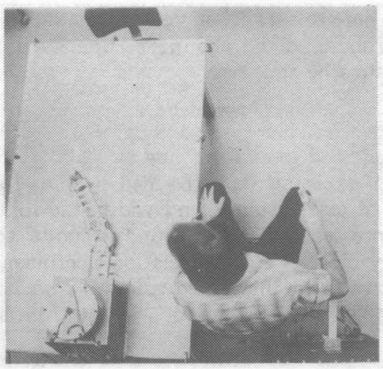

Fig. 2. Overhead view of master and slave of manipulator.

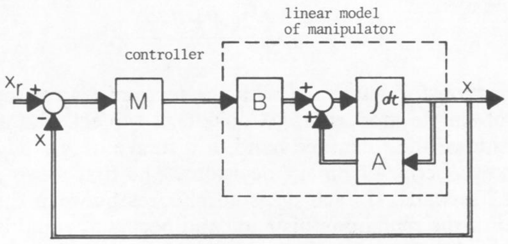

Fig. 3. Closed-loop block diagram.

III. Fitts' Law

A. Experiments

Consider the following classical experiment. A subject is asked to move his hand through a given distance to within a predefined space and tap in the minimum amount of time. This experiment was conceived by Fitts [13] in 1954 and consisted of alternate taps with a stylus inside two tolerance bands of width B placed at a center-to-center distance A (see Fig. 4). Fitts

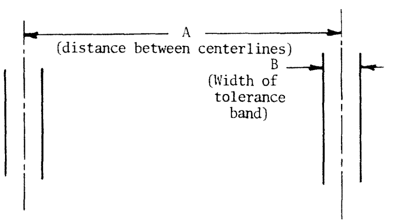

Fig. 4. Schematic of positioning task.

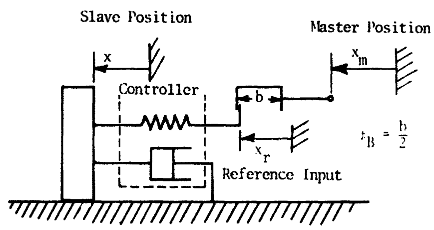

Fig. 5. Backlash in master manipulator.

proposed an index of difficulty

$$I_d = \log_2\left(\frac{2A}{B}\right) \tag{6}$$

which is a measure of the information content of the task. One can model the subject as an information channel of limited capacity. The time t to transmit the information required by the task is proportional to the channel's capacity if the subject is working as fast as he can:

$$t = a + bI_d. \tag{7}$$

This is often referred to as Fitts' law.

In a range of experiments performed by Fitts for 16 different combinations of task distance and width, the time to complete the task as expressed by (7) was found to model the experimental results very closely. The correlation coefficient was greater than 97 percent for the linear regression of t on I_d.

Welford [14] in 1960 proposed a slightly different index of difficulty

$$I_{d(w)} = \log_2 \frac{2(A+0.5B)}{B}$$

which results in a task time of

$$t = a + b\log_2\left[\frac{2(A+B/2)}{B}\right]. \tag{8}$$

Justification for a formula with the form of (8) can be found in several simple models [15]. Consider a subject who aims for the far side of the tolerance band, a distance of $A+B/2$ away, and makes a series of binary decisions. The first move is made after "a" seconds. If each decision chooses between the far or near end of the remaining distance and occurs at equal intervals of b seconds, then the user will reach the midpoint of the tolerance at the time t given by (8). Each decision conveys one bit of information, thus $1/b$ is the information transmission rate in bits per second.

Another justification can be based on modeling the subject's hand position as a pure time delay t_0 plus a first-order response with time constant $1/k$ to a step input of amplitude $A+B/2=A'$. The position x at time τ is

$$x(\tau) = A'\{1 - \exp[-k(\tau - t_0)]\}.$$

The time to complete the task t is found when $x(\tau=t)=A$. Solving the above equation for the value of τ at which this occurs results in (8). The simple models may indicate the reason for success of Fitts' formula (with Welford's modifications) which is of a very versatile form.

Welford [16] in 1969 proposed that there were in fact two processes involved: a travel part and a positioning part of the task. If the task information is transmitted at two different rates (reflecting different channel capacities), the movement time can be modeled as

$$t = b_1\log_2\left(\frac{2A'}{W_0}\right) + b_2\log_2\left(\frac{W_0}{B}\right) + a \tag{9}$$

or

$$t = b_1\log_2 A' - b_2\log_2 B + t_0 \tag{10}$$

where $t_0 = a + b_1 + (b_2 - b_1)\log_2 W_0$ and W_0 is the point that separates the two parts of the task. Welford suggested that two separate control processes were involved. An essentially motor control process governs distance traveling (gross motion or the first term of the right-hand side of (9)). He also noted that the motor control is closely related to a "ballistic" movement aimed at covering a given amplitude but not a definite target. Following the work done by Fitts and Welford [3], Hill and McGovern [4] extended the positioning task analysis to manipulators.

B. Design of Experiments

As implemented with the experimental manipulator system, the positioning movement or "tapping task" consists of moving the master with one's hand and arm (as can be seen in Fig. 4) so that the slave, which follows the master, taps inside the tolerance band. The movement starts from the band farthest from the subject. The tapping is done by pressing a microswitch button on the master that will produce a tap of the end-effector onto the surface. If the tap is outside the tolerance band, the sound of a buzzer indicates to the subject that an error has been made. All taps and errors are recorded by the computer.

The variation of task parameters was patterned after Fitts' experiments (1954). A factorial design combines four values of distance A and four values of width B. Fitts' values had to be increased approximately 50 percent to allow a meaningful task for the minimum width treatment due to the size and characteristics of the end effector and the distance of the subject from the task. The values of the distances were 8, 16, 32, and 64 cm and the widths were 1, 2, 4, 8 cm. The combination of 8-cm width and 8-cm distance was deleted because it was not meaningful, leaving 15 combinations of task parameters.

Natural frequency values of $\omega = \omega_1 = \omega_2 = 30$ rad/s and critical damping ($\zeta = 1$) resulted in the best performance of the experimental system. Torque motor saturation and analog filter bandwidth prevented higher values of ω from being used. From this reference point the performance was degraded by the dynamic characteristic of interest. Three such characteristics were selected for study: reduced arm natural frequency ω, Coulomb friction, and backlash. These characteristics have been cited [1], [5], [6] as prevalent in manipulators and influential in their performance. Four values of each characteristic were investigated. Zero backlash and Coulomb friction less than 0.4 lb·ft (shoulder) and 0.12 lb·ft (elbow) were inherent in the physical arm.

Natural frequency was varied by changing $\omega = \omega_1 = \omega_2$ in the control algorithm as described in (4) and (3). Values of $\omega = 6$, 14, 22, and 30 rad/s were used.

Backlash within both joints of the master arm was simulated. The resulting passive analog for the arm is shown in Fig. 5 for one of the two decoupled joints. Values of the backlash angle ϕ_B of 0, 5.25°, 10.49°, and 15.74° were used. (ϕ_B is half the total possible angle error.)

Coulomb friction was simulated as if it occurred within each of the joints of the slave arm. Fig. 6(a) shows the passive analog for this characteristic. The friction torque F_c was subtracted from the controller torque signal before it was output from the computer. The idealized nature of F_c is shown in Fig. 6(b). Maximum friction torques of 0, 1.71, 3.42, and 5.13 lb·ft for the shoulder joint and 0, 0.49, 0.98, and 1.46 lb·ft for the elbow joint were

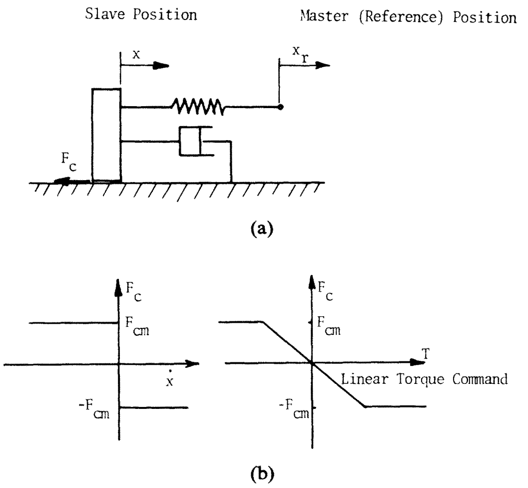

Fig. 6. (a) Coulomb friction in joints of slave manipulator. (b) Coulomb friction idealization.

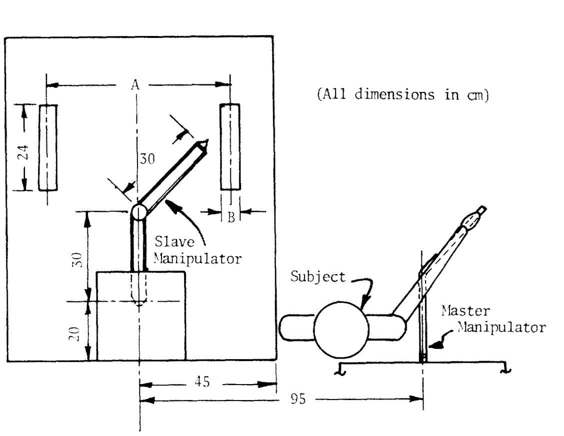

Fig. 7. Experimental layout.

used. These values correspond to percentages of the torque motors' maximum torques of approximately 0, 25, 50, and 75 percent.

To reduce the number of combinations of experimental treatments only one manipulator's characteristics were varied from the base value for any case. Thus main effects only (not a full-rank factorial design) were considered. With all the values of task parameters and manipulator characteristics, there are 150 different combinations to experiment with. Three subjects were willing to go through this time-consuming procedure. The subjects were all male, right-handed, between 25 and 35 years of age with no apparent handicap for the positioning task. One of the subjects repeated the whole sequence of experiments. This was done to determine the influence of learning and to have additional data available. The order of the 150 conditions was partly randomized and partly balanced. For each of the 15 tasks (combination of a distance and a width) selected at random, all ten values of manipulator characteristics were treated in random sequence. For each condition, the subject was allowed to practice several minutes until he felt at ease with the task. It was assumed that at this point most of the "transfer" or influence from a previous task condition was overcome. Two sets of 30 taps were then performed in sequence. The time for each set and the number of errors (the number of times a movement ended with a tap outside the tolerance band) were recorded. After these initial sets, two more sets of 30 taps were performed and times and errors were recorded. The second set of times and errors were then taken as data if the subject had made no more than four errors. If more than four errors were made, the set was repeated. It was found that this method worked fairly well, since

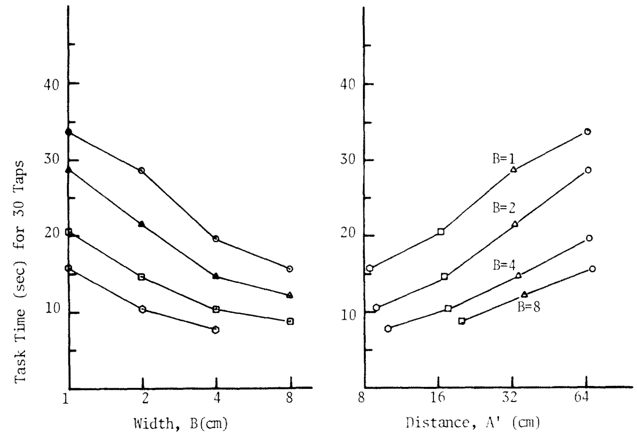

Fig. 8. Subject DH2: natural frequency 30 rad/s. Center-to-center distances A are ○ = 64 cm, △ = 32 cm, □ = 16 cm, ⬡ = 8 cm.

although more practice may bring movement time down slightly, it will also increase the total time that the subject is moving back and forth, which decreases his motivation and performance.

There was no fixed time length for each experimental session. The subject decided when to stop, for example, if he felt tired. The sessions generally lasted between one and two hours. Although this may seem long, after each condition several minutes of rest were taken. The experiments were conducted over a period of about a month. The experimental layout can be seen in Fig. 7.

IV. Regression

A. Regression Models

Different approaches can be used to analyze the experimental results obtained. There are five independent variables: distance (A), width (B), natural frequency (ω), Coulomb friction (F_{cm}), and backlash (ϕ_B). To find the influence that each one of these variables has on the dependent variable, movement time (t), a multiple regression model can be proposed:

$$t=\beta_0+\beta_1 A+\beta_2 B+\beta_3\omega+\beta_4 F_{cm}+\beta_5\phi_B$$

where the β_i are the various regression coefficients. Since we suspect that the movement time is influenced by the log of the distance and of the width, we could also propose

$$t=\beta_0+\beta_1\log A+\beta_2\log B+\beta_3\omega+\beta_4 F_{cm}+\beta_5\phi_B. \quad (11)$$

These models assume that the effect of each variable on movement time is independent of the others, and that the variables are linearly related; i.e., we construct a hyperplane in a six-dimensional space. The independence and linearity assumptions, while convenient, are not necessarily correct. A specific nonlinear functional dependence of t on ω, F_{cm}, and ϕ_B could be postulated, but either a theoretical basis or additional experimental values are needed for justification.

In a more conservative approach, we may not wish to follow these assumptions. Referring back to Section III, we notice that (10) has the same form as (11) with the last three terms deleted. To use this model, we make the following basic assumption: whatever the characteristics of the manipulator (with simulated backlash, friction, etc.), the task movement time can always be divided into gross motion and fine motion. This means that the task distance and width have separate effects on the movement time as stated by (9).

Data for the most experienced subject, DH2, are plotted in Figs. 8, 9, and 10 in two different ways; movement time versus log task distance (lines of constant task width) and movement time versus log task width (lines of constant task distance). For a

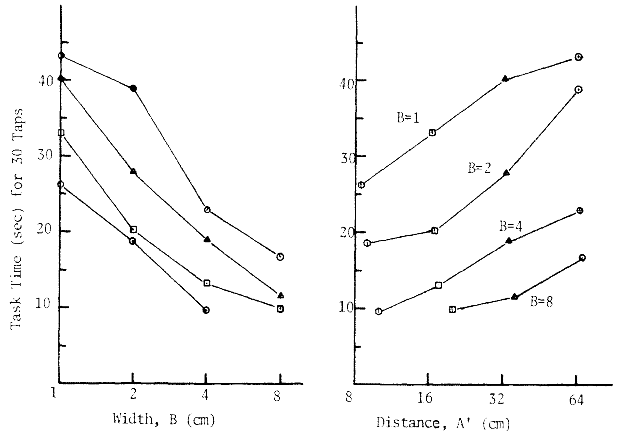

Fig. 9. Subject DH2: Coulomb friction 50 percent. Center-to-center distances A are ○ = 64 cm, △ = 32 cm, □ = 16 cm, ◯ = 8 cm.

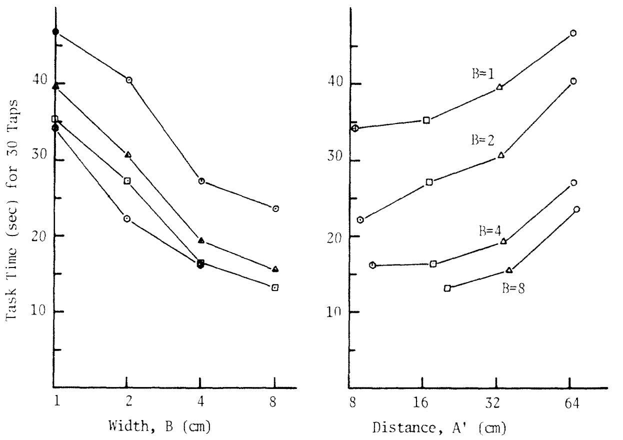

Fig. 10. Subject DH2: backlash 10.49°. Center-to-center distances A are ○ = 64 cm, △ = 32 cm, □ = 16 cm, ◯ = 8 cm.

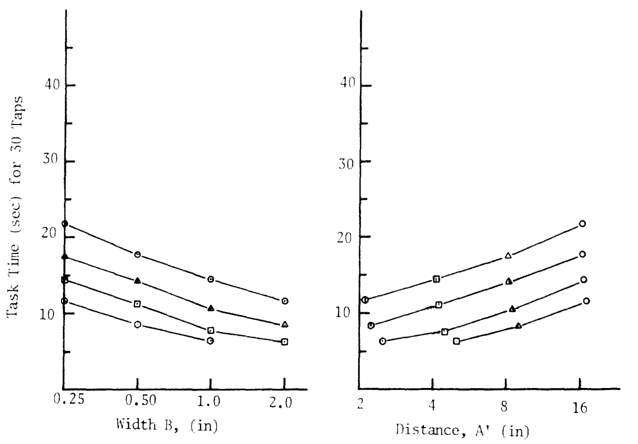

Fig. 11. Hand experiment (Fitts' data). Center-to-center distances A are ○ = 16 in, △ = 8 in, □ = 4 in, ◯ = 2 in.

qualitative judgement on the correctness of the model (10), the slopes of the lines must be constant in each plot as a check for linearity. For the distance and the width to have an independent effect on the movement time, the lines of constant distance must be parallel to each other. This is also true for the lines of constant width. Observing the figures, we notice that both assumptions seem to hold fairly well for all the manipulator characteristics treated. Similar arguments applied to the model (11) show the assumptions are not always justified for the variables ω, ϕ_B, and F_{cm}. The nonlinear effect of ω on t is especially pronounced as discussed in Section IV-D. Notice also that, if the slopes of the two plots are equal, the separate effects formula (10) is not necessary, and it collapses back into Fitts' law (in Welford's form).

Fitts' data is plotted in Fig. 11, which shows a remarkable linearity and only a very small variance. This is partly due to the fact that each data point represents the mean of between 600 and 2700 movements.

B. Regression Results

A multiple regression analysis was performed for each of the three characteristics of the manipulator. The data were divided into two groups: the second set of subject DH (DH2, trained subject) and the mean of the results of the other two subjects and the first set of subject DH (WB-KM-DH1, moderately trained subjects). The regression results for the two groups are presented in Tables I and II.

The regression results should be cautiously analyzed. One does not know where the separation of gross and fine motion occurs. Still, the coefficients b_1 and b_2 in (10) indicate how much extra time it takes to double the distance, or to halve the tolerance. In other words, b_1 and b_2 are a measure of the speeds of gross and fine motion, respectively.

The regression of Fitts' data is of interest since the values of b_1 and b_2 are very nearly the same. No distinction can be made between gross and fine motion and (10) collapses back into Fitts' law (see Table I). Two standard test statistics were used to test the significance of the regression coefficients: the F statistic and the t test.

For the F statistic the test statistic is

$$F_0 = \frac{MS_R}{MS_E}$$

where

MS_R regression mean of sum of squares,
MS_E mean squared error.

The test hypotheses are

H_0: $b_1 = b_2 = 0$
H_1: $b_1 \neq 0$ or $b_2 \neq 0$.

In the results of the analysis of variance found in Tables I and II, F_0 can be compared to the statistic value for a confidence level of 0.01 which is 6.93. The null hypothesis is easily rejected in all cases, the smallest value of F_0 being 73.17.

The t test evaluates the significance of the individual regression coefficients. The test hypotheses for coefficient b_1 are

H_0: $b_1 = 0$
H_1: $b_1 \neq 0$

where the test statistic is

$$t_0(1) = \frac{b_1}{\sqrt{MS_E \times C_{11}}}.$$

The test hypotheses for coefficient b_2 are

H_0: $b_2 = 0$
H_1: $b_2 \neq 0$

where the test statistic is

$$t_0(2) = \frac{b_2}{\sqrt{MS_E \times C_{22}}}$$

and the $MS_E C_{ii}$ are the estimators of the elements of the covariance matrix of the regression coefficients b_1 and b_2.

We reject the null hypothesis when $|t_0| > 3.055$ for a confidence level of 0.01. Comparing this value to the values of $t_0(1)$ and $t_0(2)$ in Tables I and II, we reject H_0 and conclude that both

TABLE I
REGRESSION COEFFICIENTS AND THEIR SIGNIFICANCE (DH2 AND FITTS)

movement time = $t = b_1 \log_2 A' - b_2 \log_2 B + t_o$
(30 movements)

$A' = A + 0.5 B$, A = center to center distance, B = width

Natural Frequency	Coulomb Friction	Backlash	Regression Coefficients			Correlation Coefficients	Test Statistics 2 Degrees of Freedom					Transfer Point
ω rad/sec	$F_{c,max}$	ϕ_B	b_1	b_2	t_o	ρ	Sum of Squares	Mean Square	F_o	$t_o(1)$	$t_o(2)$	W_{oe}
6	0	0	10.296	8.997	.981	.990	2487	1243	293	19.5	17.9	.592 *
14	0	0	5.928	6.315	3.595	.984	1009	504	186	14.0	15.8	625. *
22	0	0	5.577	5.667	-0.099	.985	847	424	192	14.7	15.7	.467 *
30	0	0	5.744	5.422	-1.838	.985	833	416	191	15.2	15.1	52.28 *
30	25%	0	5.324	7.209	5.044	.983	1108	554	171	11.6	16.5	6.39
30	50%	0	5.956	9.158	8.204	.983	1674	837	169	10.4	16.9	5.91
30	75%	0	5.950	10.427	12.956	.985	2060	1030	192	10.0	18.5	7.43
30	0	5.25°	4.597	7.820	13.000	.982	1171	586	159	9.3	16.7	16.37
30	0	10.49°	4.998	8.523	15.530	.975	1390	695	117	8.0	14.4	21.20
30	0	15.74°	5.621	10.604	20.289	.982	2082	1041	166	8.8	17.4	16.82
Fitts data human hand alone			3.270	3.300	1.350	.995						

*W_{oe} is an inaccurate estimate of W_o due to $b_1 = b_2$ and/or t_o not small relative to t_r.

TABLE II
REGRESSION COEFFICIENTS AND THEIR SIGNIFICANCE (DH1, KM, WB)

movement time = $t = b_1 \log_2 A' - b_2 \log_2 B + t_o$
(30 movements)

$A' = A + 0.5 B$, A = center to center distance, B = width

Natural Frequency	Coulomb Friction	Backlash	Regression Coefficients			Correlation Coefficient	Test Statistics 2 Degrees of Freedom					Transfer Point
ω rad/sec	$F_{c,max}$	ϕ_B	b_1	b_2	t_o	ρ	Sum of Squares	Mean Square	F_o	$t_o(1)$	$t_o(2)$	W_{oe}
6	0	0	9.473	12.893	13.143	.987	3532	1766	217	13.	18.6	14.35
14	0	0	5.393	8.480	11.808	.980	1421	711	145	9.5	15.7	14.17
22	0	0	4.824	7.034	8.466	.987	1013	507	221	12.4	19.1	14.23
30	0	0	5.447	7.092	4.957	.979	1098	549	141	10.8	14.8	8.07
30	25%	0	4.832	8.640	12.252	.976	1405	703	120	7.8	14.7	9.30
30	50%	0	5.029	10.825	18.158	.979	2100	1050	135	7.1	16.	8.77
30	75%	0	5.426	12.083	20.745	.983	2598	1299	168	7.6	17.9	8.67
30	0	5.25°	3.725	9.896	23.667	.961	1697	849	73	4.3	11.9	14.27
30	0	10.49°	3.422	11.291	32.095	.968	2171	1086	90	3.9	13.4	16.90
30	0	15.74°	3.664	12.089	36.516	.971	2489	1244	99	4.0	14.1	20.17

distance and tolerance have a significant influence on the movement time.

C. Interpretation of Results

The values of the multiple correlation coefficient and the conclusions based on the test statistics justify a further careful analysis of the regression results. In the introduction we stated that one of the purposes of this research was to quantify the relation between manipulator characteristics and performance for a specific task. Basically, we have three characteristics of interest: natural frequency, Coulomb friction, and backlash. We must therefore divide the regression results into three groups.

A convenient plot of the regression results can be obtained by rewriting (10) in the form

$$t = \underbrace{[t_0 + (b_1 - b_2)\log_2 W] + b_1 \log_2 \frac{A'}{W}}_{t_1} + \underbrace{b_2 \log_2 \frac{W}{B}}_{t_2} \tag{12}$$

or

$$t = t_1 + t_2. \tag{13}$$

Choosing $W = 8$ cm as a reference distance is convenient since all values of B will then contribute a positive time to (13). Figs. 12–14 plot t_1 and t_2 separately versus the two task parameters $\log_2 A'$ and $\log_2 B$. The total time is represented as the "vertical" distance between two curves of the same value of manipulator characteristic. For example, for variation of ω from the reference to $\omega = 14$ rad/s refer to Fig. 12(a). Find on the two ordinate scales the values of A' and B of interest, for example $A' = 16$ cm, $B = 4$ cm. The value of t_1 is read from the t_1 axis where the upper $\omega = 14$ line crosses $A' = 16$ cm. The value of t_2 is read from the t_2 axis where the lower $\omega = 14$ line crosses $B' = 4$ cm. The total predicted times for 30 taps is t_1 plus t_2.

The manipulator design problem poses a question which is better answered by Figs. 12(b), 13(b), and 14(b). In these figures times t_1 and t_2 are plotted versus the manipulator characteristics,

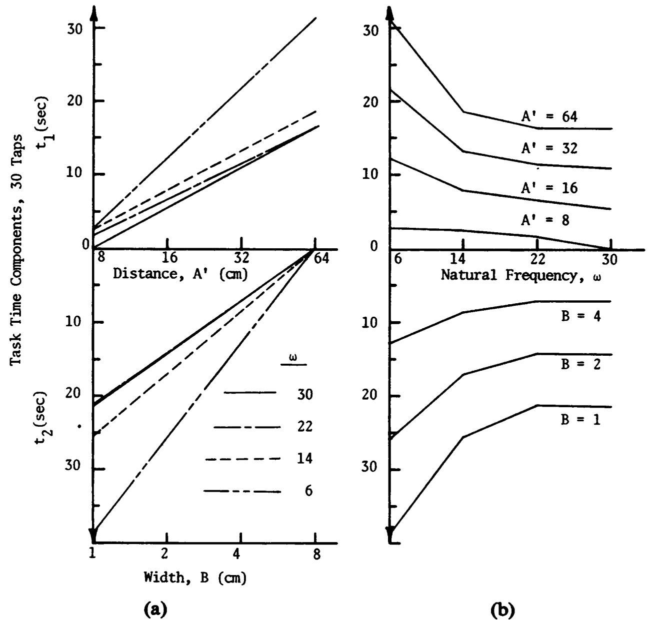

Fig. 12. Subjects WB-KM-DH1 regression results: natural frequency. (a) Gross (t_1) and fine (t_2) motions. (b) Design format.

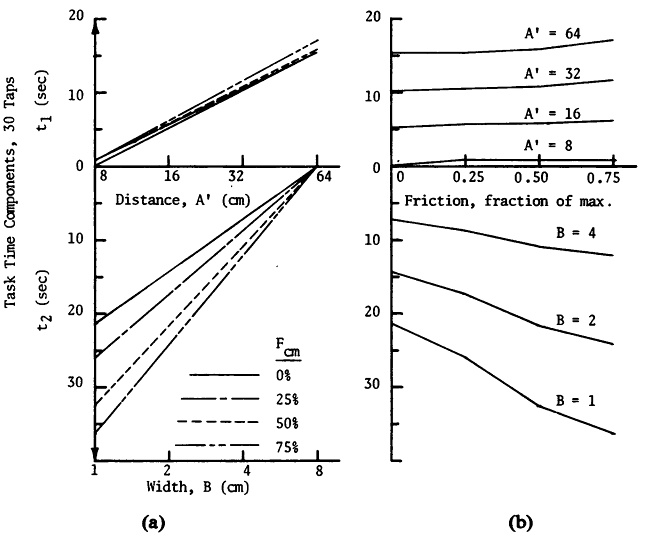

Fig. 13. Subjects WB-KM-DH1 regression results: Coulomb friction. (a) Gross (t_1) and fine (t_2) motions. (b) Design format.

natural frequency, Coulomb friction, or backlash. The task parameters are constant along the lines shown. This information can be coupled with a design strategy such as provided in [17] for structural design for stiffness and strength.

The arbitrary value chosen for W of 8 cm influences the constant (intercept) but does not change the slope of the curves. In Figs. 12–14 the constant $t_0 = (b_1 - b_2)\log_2 W$ is included in the gross motion time t_1 for simplicity. If W could be chosen equal to W_0 of (9), the movement time could be separated into times attributable to 1) gross (travel) motion information requirements processed at rate $1/b_1$; 2) fine (positioning) motion information requirements processed at rate $1/b_2$; and 3) perhaps a reaction time. If the reaction time t_r were known, one could calculate an estimate W_{0e} of W_0 from (14):

$$W_{0e} = 2\left(\frac{t_r - t_0}{(b_1 - b_2)}\right). \quad (14)$$

A further approximation is made to facilitate a solution namely,

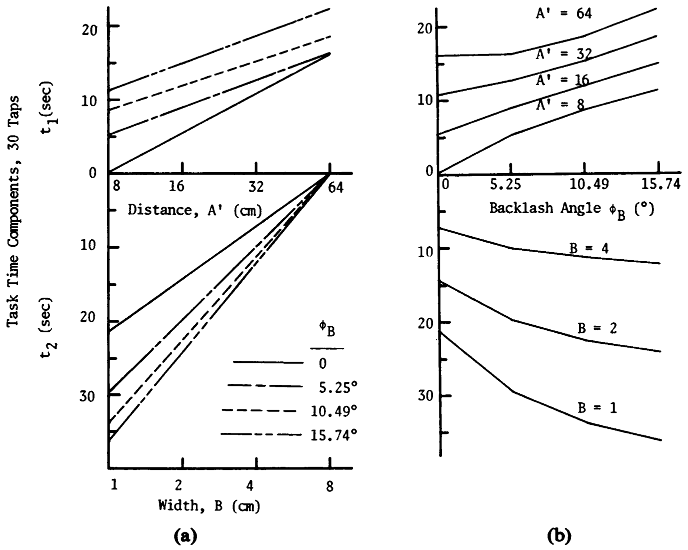

Fig. 14. Subjects WB-KM-DH1 regression results: backlash. (a) Gross (t_1) and fine (t_2) motions. (b) Design format.

that $t_r \ll t_0$. Given the uncertainty of the experiments this solution is reliable only if b_1 and b_2 are substantially different. W_{0e} is listed in the right columns of Tables I and II. The values of W_{0e} which should be discounted due to small values of t_0 or $b_1 - b_2$ are enclosed in a box. These occur for the experienced subject DH2 for whom $b_1 = b_2$ (no separate effects).

D. Discussion

A discussion of these results is now in order. First, the effects of additional training are significant. The performance of DH1 was not substantially different from the other moderately trained subjects, KM and WB. With additional training he was able to improve his times by an average of 17 percent for variations of ω, 15 percent for friction, and 18 percent for backlash. In the study of natural frequency, b_1 and b_2 were made almost equal. Thus he behaves as predicted by Fitts' law for the hand alone. This would be expected since his familiarity with the manipulator increases to the point that he "feels a part of it" (subject's comment). $b_1 = b_2$ may provide a good indication of an operator's adaptation to a manipulator since it is the strategy that has evolved for manipulation using the hand alone. For Coulomb friction the experienced subject seems to reduce W_0 from that of the less experienced subject as if his experience enables him to depend more on the ballistic gross motion which has a higher information transmission rate. The backlash characteristic was the most difficult one for the subject to contend with, and error rates and variance tended to be high. With experience the subject DH2 reduced both the gross and fine motion components of his times. A greater dependence on visual feedback is indicated by higher values of W_{0e} in the cases $\phi_B = 5.25°$ and $\phi_B = 10.49°$. For the maximum backlash, $\phi_B = 15.74°$ W_{0e} for DH2 is lower and not consistent with the trend. A possible explanation is the ordering of treatments for DH2 which began with $B = 8$ cm and progressed to $B = 1$ cm. The following discussion addresses the relation between the manipulator characteristics and task parameters.

For natural frequency variations (Fig. 12) the coefficients b_1 and b_2 decrease in roughly the same proportion indicating that variations in gross and fine motions are equally affected. Increasing ω from 22 to 30 brings little improvement in performance. This conclusion may be tempered slightly by the tendency for the torque output to saturate at $\omega = 30$ for large amplitude motions, introducing a parasitic characteristic which can be observed in the comparison of b_1 for $\omega = 30$ to b_1 for $\omega = 22$.

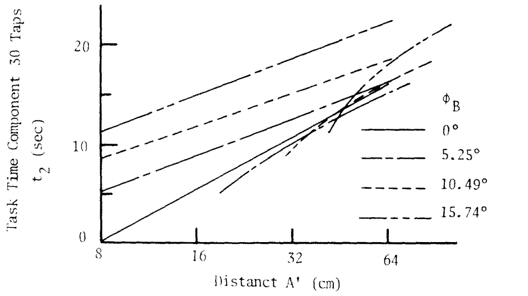

Fig. 15. Correlation of Fig. 14(a) adjusted to show increased distance due to backlash (curved lines) as well as unadjusted correlation (straight lines).

For Coulomb friction variations the gross motion times and W_{0e} are almost constant, but the fine motion (positioning) times were noticeably influenced. If the friction had decreased the maximum torque output one might expect gross motion to suffer as well. (This was not the characteristic simulated.)

The addition of backlash greatly increases fine motion time requirements. W_{0e} increases, indicating more visual feedback (available during fine motion) is necessary. The distance the master arm was required to move in order to move the slave the required amount increased with backlash. For example, $\phi_B =$ 5.25° at the "shoulder" joint corresponds to 11 cm of additional motion at the end of the arm. Shifting the curves in Fig. 14 for t_1 to the right by the distance which corresponds to the total backlash angle $2\phi_B$ places the curves for $\phi_B = 5.25°$, 10.49°, and 15.74° almost upon one another as shown in Fig. 15. (Subjects were observed to use primarily the shoulder joint with backlash.) The change in slope b_1 from the case $\phi_B = 0°$ to the case $\phi_B = 5.25°$ seems to result from the addition of small amounts of backlash.

V. Conclusion

A first attempt has been made to quantify the relationship between the performance of an experimental master–slave manipulator and each of three dynamic characteristics: natural frequency, Coulomb friction, and backlash. Performance is measured in terms of time to accomplish a simple positioning task.

The relative simplicity of the manipulator and the ability to specify the change in its closed-loop characteristics or transfer function makes it possible to relate the dynamic characteristics to measured performance for a simple task. The characteristics are those of two uncoupled second-order damped oscillators with variable Coulomb friction and backlash.

Experiments were performed to quantify the relation between manipulator performance and manipulator characteristics. A statistical analysis showed that a simple linear model could be constructed relating the task parameters of distance and width to performance measured in time to accomplish the task. This influence is also shown graphically which enables an easier interpretation to the regression results.

These results can be applied in the cost–performance trade-off of the manipulator design. This trade-off is desirable due to the increase in cost of a manipulator with improved dynamic characteristics (less backlash, less friction, etc.) and the decrease in cost of performing the task due to a better performance (less time to accomplish a task). The solution of this optimization problem will determine the minimum total cost, i.e., to what degree it will be justified to implement a better design in order to achieve a higher performance of the manipulator.

The results have been interpreted in terms of an information transmission model of the man–machine system with separate transmission rates for gross (ballistic or travel) motions and fine (positioning with visual feedback) motions and a point of transfer between the two motions. The rates and point of transfer appear to explain variations in performance in a logical and consistent manner.

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Thresholding using the ISODATA Clustering Algorithm

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***Abstract*—An investigation is made of the use of the ISODATA clustering algorithm as applied to a one-dimensional feature space. For two classes, the ISODATA turns out to be an iterative thresholding scheme,**

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