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PERFORMANCE EVALUATION OF A 6 AXIS HIGH FIDELITY GENERALIZED FORCE REFLECTING TELEOPERATOR

Blake Hannaford & Laurie Wood
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

Introduction

Teleoperation is widely expected to perform a wide variety of tasks in future space operations. In order to pursue the goal of a realistic sense of presence at the worksite, many manipulator designs, starting with Goertz (1954), have incorporated force feedback capabilities. As a result, many of the studies attempting to quantify the performance of various teleoperator designs have concentrated on the question "can force/torque feedback improve teleoperation performance?".

Kugath (1972) studied the effects of a compliant manipulation arm and force feedback on manipulation of an inertial load. Results showed force feedback had a large effect on task completion time and error (hitting wall) rate for the maze task. Hill & Salisbury (1977) evaluated three master-slave teleoperators (the Ames Exoskeletal Master Slave, MA11 & MA23) with an instrumented task board which emphasized the peg-in-hole task. Their results documented task completion time for the different arms as a function of peg tolerance and showed improved performance when force feedback was present and reported bare-handed operator performance.

Recent evaluation studies (Draper et.al. 1987) have put emphasis on broadening the base of measurements against which task performance can be judged. Besides task completion time, useful measures included number of task errors, peak force and variance in force (see also Hannaford 1987). Although ANOVA did not show a significant completion time improvement due to force feedback, the other measures did indicating that force feedback allowed the task to be performed with higher quality if not at a faster rate.

The JPL teleoperation Laboratory has recently developed a unique telemanipulation system featuring advanced modes of force feedback and shared control based. This system is described in detail elsewhere in this volume (Szakalay ,Kim, Bejczy 1989). The Enhanced 6-Axis Breadboard (ESAB) teleoperation system consists of the JPL-Stanford Force Reflecting Hand Controller (recently refurbished and upgraded from the original [Bejczy & Salisbury, 1981] design), Puma 560 manipulator, and JPL Puma Smart Hand (Fiorini, 1988). The master side of the system is installed in a separate control station without a direct view of the robot work area. Three television cameras provide top, upper left rear, and right rear views of the task board area. The two rear view cameras could be remotely controlled for focus and zoom but fixed views were used for all of the experimental tasks.

The ESAB system can be configured by the user in a wide variety of ways. All control modes and gains can be independently selected for each task space axis. Motion control modes include position control, rate control, and "disabled". The system thus provides a rich set of control possibilities. In this study, five control modes plus direct human task performance were experimentally tested. However, only preliminary experiments were performed with the two modes of shared control. Because of space limitations, this paper only presents three control modes: position control only, position control with force feedback (FFB), and barehanded operator manipulation.

This study is part of a longer term effort to quantitatively evaluate a snapshot of present telemanipulation technology to expose improvements needed for real-world applications. The overall approach was to design a preliminary experiment which looked at a relatively large number of independent variables.

Experiment Design

The experimental design varied control mode, task, and subject. The dependent measures were task completion time, sum of squared forces, and number of errors. Three repetitions of each sub-task were performed by each subject in each of the control modes. All sub-tasks were performed in random sequence to form one repetition (randomization without replacement). All subjects performed all repetitions of a given control mode before the next mode was tested.

The tasks used in experimental teleoperator evaluation fall naturally into two classes: generic tasks and application tasks. Generic tasks are idealized simplified tasks which are designed to test specific telemanipulation capabilities. Application tasks are designed as much as possible to mimic real world uses for teleoperation. Evaluation based on generic tasks illustrates the telerobotics technology push, while application tasks guide the technology in the direction of greatest payoff.

The task board consists of a 21" by 21" frame which accepts modules of either 7" x 7" or 14" x 7". An advantage of the modular task design is that the tasks can be mounted individually on a six-axis force-torque sensor to enable force torque recordings during direct manual operation of the tasks. The four tasks used were: velcro, peg in hole matrix, electrical connectors, and bayonet connector. Each task is in turn broken down into component subtasks:

Task 1 Velcro attachment. Exchange the position of two differently shaped blocks attached to the task board module with velcro. Attempt to attach the blocks securely while minimizing unnecessary force.

Task 2 Peg in hole matrix. this task consists of nine holes arranged in a square matrix. The rows each have a progressively larger clearance, and each column has a different chamfer. The subtasks are to take the standard peg and insert it into a given hole. Peg/hole clearances ranged from 0.005" to 0.0026". Peg diameter was 0.998".

Task 3 Electrical Connectors. The subtasks consists of the mating and unmating of three standard electrical connectors: a 3 prong chassis power cord connector, DB25 25pin signal connector, and 1/4" telephone style plug.

Task 4 Bayonet Connector. This task consists of unlocking, unmating, mating, and locking a Bendix bayonet style electrical connector (type PT06A-20-16S/16).

Each task was performed according to a pre-specified procedure to which the subjects trained. The task sequences were interspersed with "taps" in which the operator made momentary contact with a designed point on the task board either with the bare gripper, or with a held object. The "taps" injected distinct spikes in the force record (especially the X axis: normal to the task board surface, see Figure 1a). The tasks all began and ended with a tap on a designated square on the task board surface. The resulting force spikes provided well defined benchmarks for measurement and interpretation of the progress of the task by inspection of the force records alone.

Five test operators for this experiment were chosen who would have technical background, but not have in-depth knowledge of robotic technology. Detailed robotic knowledge or knowledge of the specific system itself was felt to be distracting and to not reflect forseeable operator populations. Subjects recruited were graduate and undergraduate students who were not specialists in robotics. Each subject received 2 to 4 hours of practice on the apparatus. The practice sessions consisted of four, 30 minute sessions in which the task set was performed with and without force feedback.

Analysis and Performance Measures

The raw force torque data is a rich load of information which can be understood in terms of the task description and which can in turn be used to quantify task performance (Figure 1). This section will describe computations which were performed on the force/torque data to produce performance measures. Completion time, can be determined from the length of the data file containing the force torque data.

Sum of Squared Force (SOSF) is computed by taking a nondecreasing sum of the square of the force or torque values.

$$\text{SOSF} = \sum_{i}^{N} f_i^2 d_t$$

where N = number of data samples (task time over dt), f_i is the ith sample of force or torque, and dt is the sampling interval (0.01 sec in this experiment). SOSF is accumulated separately for each force and torque axis. A third way in which performance can be measured is through an observer's notations of the "quality" with which a task is performed. In our experiments, a set of "errors" was defined and explained to the test operators and experimenters. A test operator watched each repetition of the experiment and counted occurrences of each error.

In some cases it is desirable to compare performance measures among different segments of the same task. For example, to compare the completion time and SOSF for peg insertion vs. peg extraction. This was accomplished through a computer program which could recognize benchmarks in the force signal and divide it in time between a set of segments. Returning to the peg-in-hole example (see "x axis force", Figure 1), the data can be clearly divided into "translation" (the manipulator is in free motion: no contact forces), "taps" (sharp spikes in force), "insertion" (predominantly positive forces) and "extraction" (predominantly negative forces). Both "completion time" and SOSF can thus be computed for each segment of the task.

Results

When experimental records for the peg-in-hole task performed in the several control modes are compared together (Figure 2), the X axis force traces tell most of the story because of the alignment between the task axis and the force/torque sensor's X axis. Comparison of performance in the several control modes shows the reduced completion times and force levels achieved when capability is added to the system.

Although fascinating in themselves, these raw data records are isolated anecdotes of individual task performances. To draw conclusions, the data were reduced to the three basic performance measures. Records of this type for each repetition of each task were processed to produce the performance data points upon which the results below are based. The visually scored error rates were manually correlated with the reduced performance data.

The completion time, SOSF, and number of errors data can be simplified by averaging across one or more dimensions of the design. As a first look at the data, we have computed averages over all subjects and over the first three tasks, "velcro", "peg-in-hole", and "electrical connectors". The fourth task was not included in this average because it took significantly longer than the others (approximately 150 seconds vs. 75 seconds), and was often not completed due to its difficulty. There are 9 subtasks for the peg-in-hole task (corresponding to the 9 test holes) vs. 2 for the velcro and 3 for the electrical connectors. These averages (Figures 3a, 3b, and 3c) show clear trends in performance as the level of capability progresses from position control, through force reflection, up to the bare handed operator.

Completion time (Figure 3a) for the three primary tasks drops from an average of 92 seconds with position control to an average of 63 seconds when force feedback is added. Completion time drops to only 14 seconds for the bare-handed human. SOSF (Figure 3b) drops even more dramatically (from about 3500 to 500 lbs^2 sec) when pure position control is augmented with force feedback and further (to 200 lbs^2 sec) for the bare-handed case.

The number of errors observed (Figure 3c) per repetition drops from 3.0 to 1.1 as force feedback is added. No errors were observed in the bare-handed data.

The probability of the null hypothesis that there was no effect of force feedback (calculated by the two-tailed Z test) was much less than 0.01 in all of the differences reported above giving them a high degree of statistical significance.

These results summarize one of the main results of this study, that the provision of force feedback reduces completion time for a task mix emphasizing energetic interaction and precision manipulation by approximately 30%, reduces SOSF by a factor of 7, and reduces errors in performing the task by 63%.

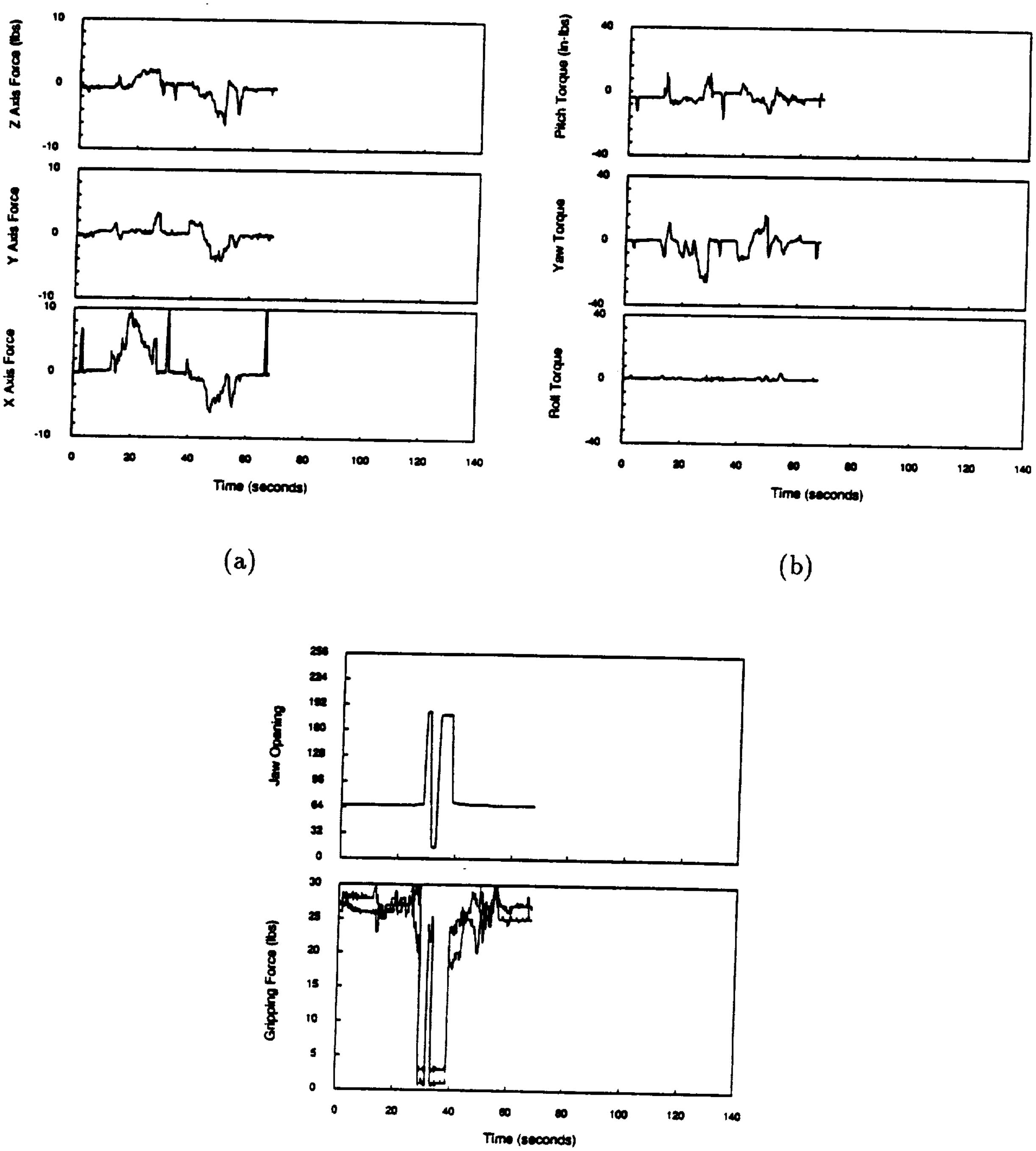
The first level of detail to add to the summary results is to break them down by individual task (Figures 3d, 3e) instead of averaging all the tasks together. Doing this shows that the effect of force feedback is not the same for all of the tasks. For the peg-in-hole task, completion time (Figure 3d) follows the expected course dropping by almost a factor of two from 105 to 59 seconds as force reflection is added. For the velcro blocks task, completion time increases from 72 to 83 seconds. Both of these changes are statistically significant by the method described above. For the electrical connectors, only a slight change is observed which was NOT statistically significant. Of course all of the tasks were completed much faster by the bare-handed operator. The average time in this case is about 15 seconds.

The SOSF data (Figure 3e) tell a different story. As with completion time, for the peg-in-hole task there is a dramatic drop in SOSF (from 5400 to 500 lbs^2 sec) as force reflection is added. The increase in completion time seen for the velcro task is accompanied by a significant decrease in SOSF (from 800 to 400 lbs^2 sec). For the electrical connectors, the SOSF measure declines significantly in spite of their unchanged completion time.

The performance measures were calculated for the segments of 150 repetitions of the peg-in-hole task (Figure 4). Total time (Figure 4a) spent in the movement phase is unchanged at 32 sec by the addition of force feedback. The tap phase is also unchanged at a negligible 2 sec. But the insertion and extraction phases are accomplished markedly faster (31 vs. 11 for insertion, 35 vs. 10 for extraction) when force feedback is present. The two pie charts (Figure 4b,c) illustrate the changing nature of the task mix. As force reflection is added the dominant component of completion time changes from insertion/extraction, the environmental interaction phases, to the free motion phase of the task.

Conclusions

This paper has presented a few of the results of a major study of over 100 hours of experimental teleoperation. Force and torque data recorded from the robot wrist is a rich source of information on the performance of tasks. Performance measures can be computed for whole tasks, or for specific task segments. As a general principle, the performance increases as manipulation capability is increased although the effects may depend on task and performance measure. This study has laid the groundwork for much future work. Further reports will detail additional results which could not be presented here due to lack of space as well as follow-on experiments investigating manipulation under time delay and shared control conditions.



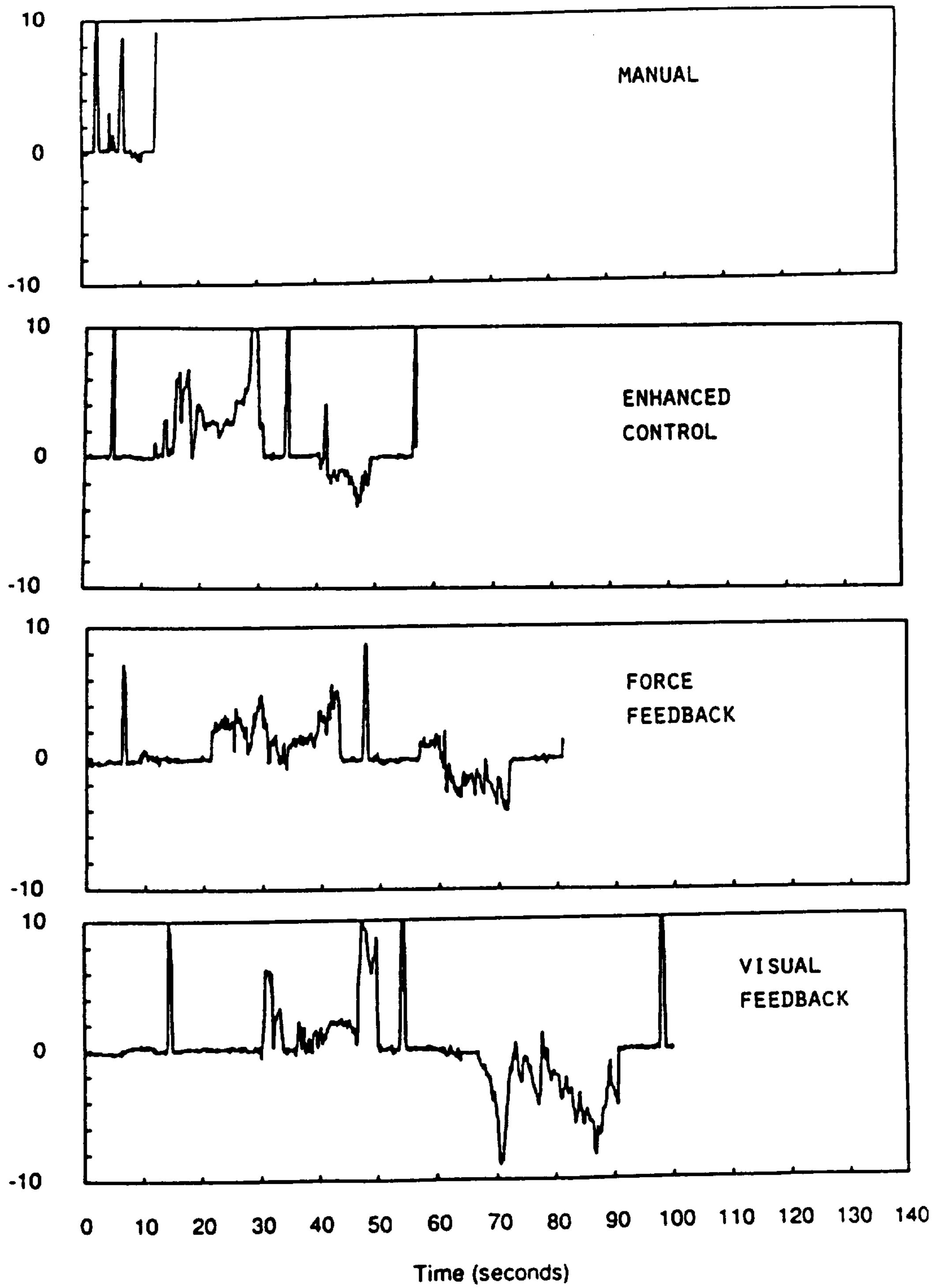
(a)

(b)

(c)

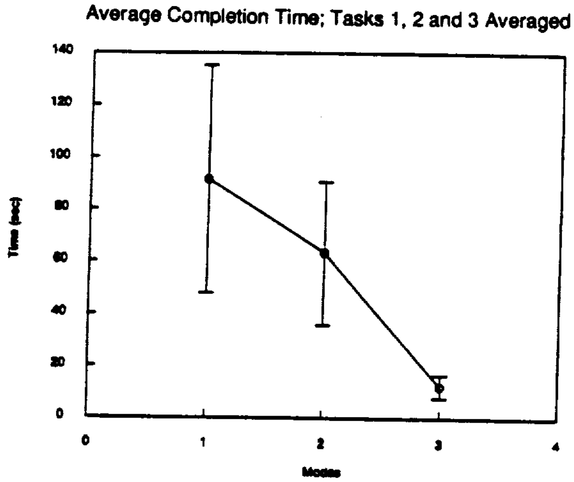
Figure 1

Raw Force Torque Data

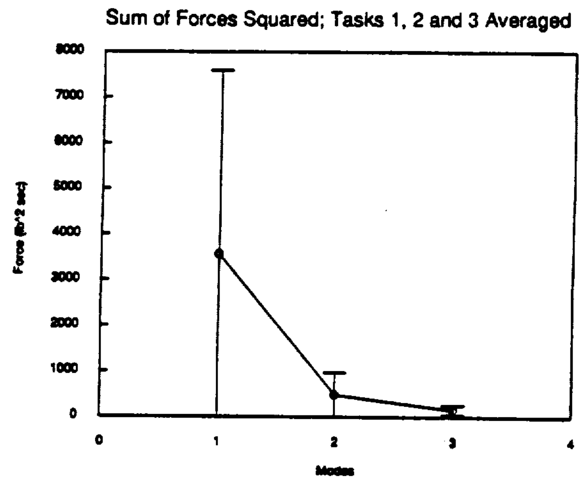


PEG-IN-HOLE #9: X AXIS FORCE

Figure 2



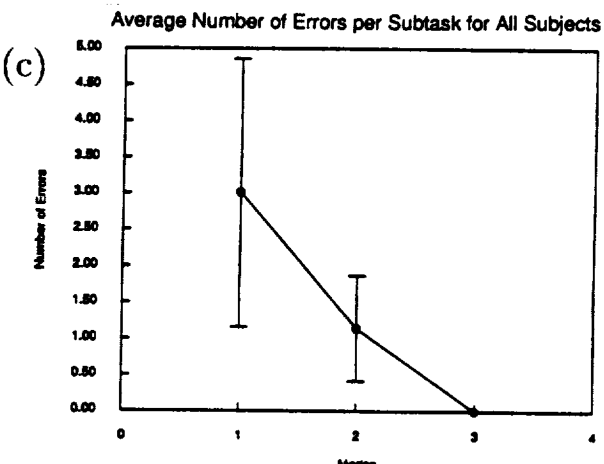
(a)



(b)

Modes:
Mode 1: No FFB   Mode 2: FFB   Mode 3: Manual

Tasks:
Task 1: Velcro Blocks   Task 3: Electrical Connectors
Task 2: Peg in Hole

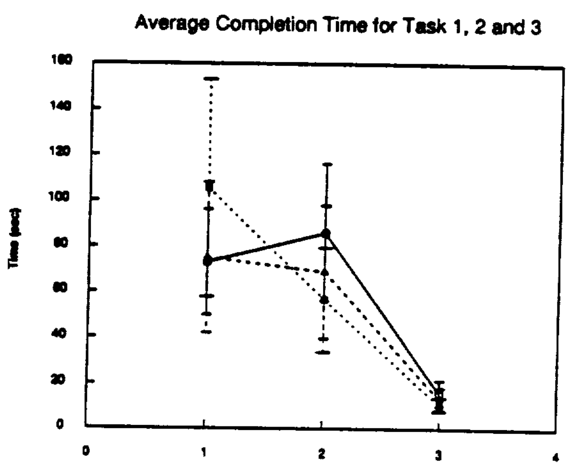


(c)

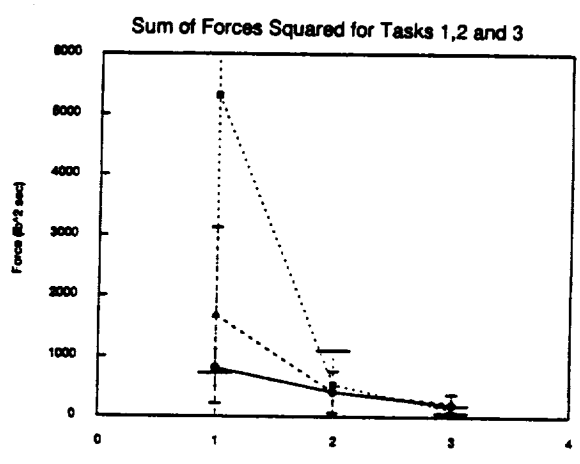
Modes:
Mode 1: No FFB   Mode 2: FFB   Mode 3: Manual

Figure 3

Task Averages



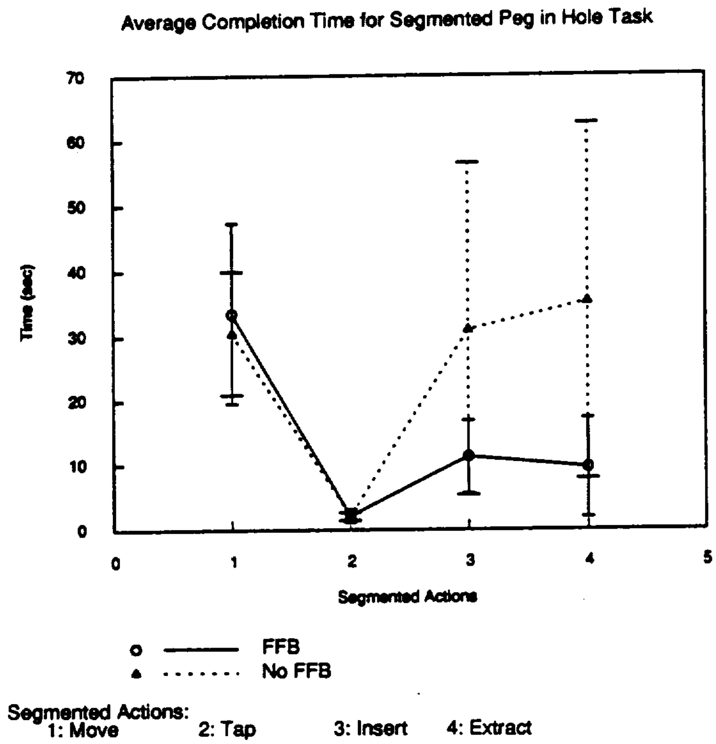
(d)



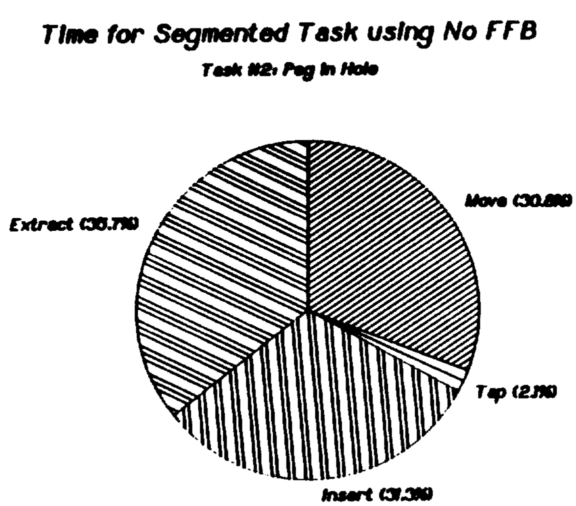
(e)

o Task 1 – Velcro Blocks
▪ Task 2 – Peg in Hole
▴ Task 3 – Electrical Connectors

Modes:
Mode 1: No FFB   Mode 2: FFB   Mode 3: Manual



(a)



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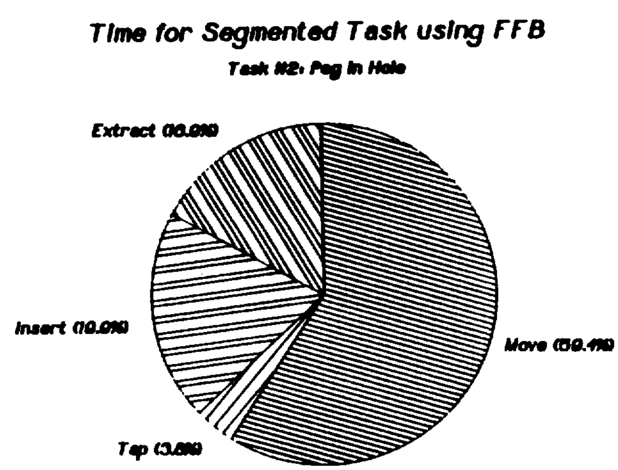

(c)

Figure 4

Segmented Data

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