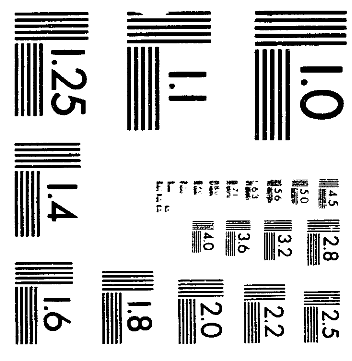

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PERIODIC COMPONENTS OF HAND ACCELERATION/DECELERATION IMPULSES DURING TELEMANIPULATION*

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Periodic components of hand acceleration/deceleration impulses during telemanipulation

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ABSTRACT

Responsiveness is the ability of a telemanipulator to recreate user trajectories and impedance in time and space. For trajectory production, a key determinant of responsiveness is the ability of the system to accept user inputs, which are forces on the master handle generated by user hand acceleration/deceleration (a/d) impulses, and translate them into slave arm acceleration/deceleration. This paper presents observations of master controller a/d impulses during completion of a simple target acquisition task. Power spectral density functions (PSDF's) calculated from hand controller a/d impulses were used to assess impulse waveform. The relative contributions of frequency intervals ranging up to 25 Hz for three spatially different versions of the task were used to determine which frequencies were most important. The highest relative power was observed in frequencies between 1 Hz and 6 Hz. The key frequencies related to task difficulty were in the range from 2 Hz to 8 Hz. Differences were also observed from 9 Hz to 12 Hz. The results provide clues to the source of the performance inhibition.

2. INTRODUCTION

When a task requires dexterity in an environment too hazardous for people and not sufficiently structured and predictable for autonomous robots, it requires a *telemanipulator* (the term *teleoperator* is also common). Telemanipulators are robotic devices which are manually controlled by human operators; they combine powerful human sensory and decision making abilities with robot hardiness (or expendability) relative to environmental hazards. Telemanipulator human-machine interfaces have considerable breadth and depth because all sensory inputs to the user must come across the boundary between human and remote environment artificially and commands from the user must be at the level of control necessary to tighten a bolt, grasp a wrench, or lightly touch a surface. This may be contrasted with a more common human factors application, high-performance flight. High-performance flight control requires that the aircraft respond to pilot decisions in a timely fashion; high-performance telemanipulation requires that the manipulator recreate operator movements in real time. Human-machine interfaces for fighter aircraft must be designed to help the pilot adapt to the performance of the aircraft; human-machine interfaces for high-performance telemanipulation must be designed to allow the machine to reproduce the performance of the human user. The adaptation in high-performance flight is difficult for the user and in telemanipulation it has proven difficult for the machine, as shown by the well-documented performance differences between humans and teleoperators for tasks requiring dexterity.

Responsiveness, the ability of a telemanipulator to recreate human input trajectories and impedance in time and space, is the ultimate criterion of telemanipulator performance. If a telemanipulator can follow a user's inputs with no variation in spatial positioning and impedance of the end-effector and with no time lag, it is very responsive. If the end-effector path deviates from the input path, has different impedance than the human arm, or if there is lag between command input and execution, the telemanipulator is not very responsive. Because responsiveness depends on the match between human and machine, human movement capabilities, specifically (1) the rate at which human operators can respond to force and trajectory perturbations, and (2) the bandwidth of the acceleration/deceleration (a/d) impulses that comprise responses, are important parameters for telemanipulator designers. The present experiment is concerned with the second of these capabilities, specifically with providing a frequency domain description of a/d impulses produced during telemanipulation.

Data applicable to the first type of human movement capability, response rate, have been generated by studies of Fitts' tapping task[1], a target acquisition task which requires rapid movements to make contact with a target and is generically similar to tasks performed during telemanipulation. Movement time (MT) for a Fitts' task is predicted by a measure of relative movement accuracy called the Index of Difficulty (ID), which expresses relative accuracy as bits of information per movement. Participants making movements which do not require accurate target acquisition can complete them within 200 ms[2], and for more constrained movements typically require 100 msec per bit for arm movements. However, response rate is not equivalent to the number of reciprocal taps a user can make in a second. The level of reduction is inappropriate, because any number of course corrections may occur between starting and stopping a movement: goal-directed movements comprise a series of submovements which are optimized (in terms of speed and accuracy) to minimize the sum of the submovement times[3]. Therefore, the true response rate is the rate at which these submovements can be made (although it is likely that very fast movements are made in open-loop fashion without trajectory corrections[4]). The lower bound for detecting a position error and initiating a corrective action seems to be 135 msec[5], although humans anticipate the need for corrections, which allows response execution and error detection to overlap. The period for complete a/d impulses during unencumbered movements varies with the submovement for tasks with ID of 3 and above; it averages 265 msec (3.77 Hz) during the first a/d impulse and 218 msec (4.59 Hz) during succeeding ones[6].

Unfortunately, data describing the a/d impulse waveform are more rare than data describing response rate. One study[7] hypothesized that hand acceleration during handwriting is affected by task-related variability (typically with a dominant frequency of 5 Hz for handwriting), corrective actions based on feedback (less frequent than 9 Hz), physiological tremor and myotatic reflex action (9 Hz to 12 Hz), mechanical noise (above 21 Hz), mechanical residuals of fluctuations in motor unit firings (also above 21 Hz), and measurement noise (occurs at all frequencies). Power spectral density analysis performed on measurements of stylus acceleration during a drawing task seemed to confirm the importance of these sources of movement variability. One could infer from this that 9 Hz is an upper limit on a/d impulse bandwidth during telemanipulation. Another experiment[8] found that when bandwidth limits were imposed during telemanipulation, participants performing precision-positioning tasks required longer times to complete the tasks, committed errors at a faster rate, and rated ease of use lower when the positioning bandwidth was limited to 0.32 Hz but found no significant differences between a 0.64 Hz limit and a 1.28 Hz limit. One may infer from these results that raising acceleration bandwidth above 1.28 Hz does not have an impact on performance. These two experiments seem to present conflicting evidence; however, it may be that the friction and inertia imposed by a master controller reduces the bandwidth of acceleration impulses, or, in other words, the master controller may function as a low-pass filter on a/d impulses. A more recent study, conducted in the context of positioning a cursor on a computer screen, found a/d impulse bandwidths averaged in excess of 5 Hz for the first submovement in a target acquisition and in excess of 9 Hz for succeeding submovements[6].

To date, because few attempts to investigate input period or waveform in the context of telemanipulation have been made, development has proceeded primarily on an intuitive basis. A survey of telemanipulator researchers and developers[9] found a wide range of opinions when participants were asked "What...is the minimum acceptable master-slave frequency response for a telemanipulated system?" Responses varied from 0.25 Hz to 10 Hz, but most were higher than 2 Hz and 6 of the 12 respondents indicated that bandwidth should be 5 Hz or higher. However, respondents may have made different interpretations of the term "acceptable". The first author of the present paper and at least one other respondent interpreted the question as referring to the minimum bandwidth which allowed useful work to be done, while responses from other participants seem to indicate that they equated "acceptable" and "full human performance capabilities". Hopefully, as more data describing human inputs become available these can be translated into a better understanding of telemanipulator response requirements and greater consensus among developers about what constitutes "acceptable frequency response".

The present study attempted to characterize the a/d impulse waveform by using the Fast Fourier Transform to determine the frequency components of master controller a/d impulses during performance of Fitts' reciprocal tapping task. The Fast Fourier Transform is an algorithm which decomposes a repetitive signal into a unique set of sine waves which vary in frequency, amplitude, and phase. This allows evaluation of the contribution of the signal at each frequency to the total signal. The study also attempted to discover whether master controller friction and inertia have an impact on MT and the a/d impulse waveform, by observing completion of identical tasks in orientations requiring simultaneous movement of varying numbers of telemanipulator joints.

3. METHOD

3.1. Participants

Six adult males participated in this experiment. All were between the ages of 20 and 40, were right-handed, and had normal vision or vision corrected to normal. Four of the participants were experienced telemanipulator users with in excess of 500 hours of operating experience with the telemanipulator used in the present study. Two of the participants were relatively inexperienced at the start of the experiment, but each had participated in a training course for manipulator operators.

3.2. Experimental Tasks

Participants completed Fitts' reciprocal tapping task with circular wooden targets 5.08 cm in diameter, painted matte black and mounted 50.8 cm apart (measuring from the center of each target) on a gray surface. The ID for this task was 4.32. Participants touched the targets with a stylus made from a 12.7 mm diameter, white PVC tube and grasped by the telemanipulator gripper. Participants were instructed to touch the target with the region within 6.35 mm of the tip of the stylus, which was covered with a single layer of gray duct tape.

3.3. Apparatus

The telemanipulator was the Oak Ridge National Laboratory's Advanced Servomanipulator (ASM). The ASM has six positioning degrees-of-freedom and a two-finger end-effector. It has links similar to the human upper arm and forearm and it's normal stance is anthropomorphic or elbows-down. Users control the ASM with a replica master controller; this requires grasping a handle and moving it, which produces identical movements of the slave arm in the remote area. Master controllers make control of slave motions intuitive and provide the most efficient way to control telemanipulators[10,11]. The ASM master controller has a 6 kg capacity and its breakaway friction threshold (the force necessary to initiate a movement) is 0.25 kg or less at each joint[12]. The ASM slave velocity capability is greater than 1 meter per sec at the end-effector (master controller velocities as high as 2.8 meters per sec have been observed[13]). The ASM updates slave position every 10 msec, that is, slave arm position is updated 100 times per sec. Normally, the ASM provides force reflection by back-driving the master. Force reflection provides information that is often useful for controlling forces applied to remote objects[14]. However, for tasks that require rapid movements over long distances (like Fitts' task) it can lengthen movement time because it increases system inertia. In the interest of maximizing responsiveness, force reflection was disengaged during the present experiment.

Participants viewed the task and telemanipulator slave with monochromatic, closed-circuit television with 48.26-cm diagonal monitors located approximately 1 m away from participants' seat (the distance is approximate because participants were free to roll their chair or lean forward during trials). Participants could choose from views from a camera behind and 60 degrees to the left of the slave arm, a camera located beside the slave arm, and a camera located 90 degrees to the right of the slave arm. All of the camera views showed the whole task with the same magnification.

3.4. Procedure

Participants completed 3 repetitions of each of 3 versions of Fitts' task with the ASM. The 3 versions of the task differed in the master controller motions made to move the slave from target to target. In the *horizontal* orientation the path from one target to the other was horizontal and perpendicular to the participant's sagittal plane. This version required side-to-side master controller motion. In the *oblique* orientation the path was horizontal and at a 45-degree angle to the sagittal plane. This version required a master controller motion away from the participant's body and towards the right-hand side, and then a reciprocal motion towards the body and to the left-hand side. In the *vertical* orientation the path was vertical and required up-and-down master controller motions. Because of the telemanipulator configuration, the different orientations required simultaneous movement of differing numbers of telemanipulator joints: the horizontal task mainly required movement of shoulder roll; the oblique task mainly required combined movement of shoulder roll, shoulder pitch, and elbow pitch; and the vertical task mainly required combined movement of shoulder pitch, elbow pitch, and wrist pitch. Figure 1 illustrates the ASM master controller joint arrangement.

Participants completed 1 repetition with each orientation, in random order, then a second repetition of the set in a different random order, and then a third repetition of the set in yet another random order. Data collection sessions were preceded by 12 practice repetitions to insure asymptotic performance. Data collection sessions for a single participant were scheduled at least 2 hours apart to prevent fatigue. Participants were instructed to touch the top of the target with the stylus, they were told not to proceed to a reciprocal tap until they had successfully touched the preceding target, and during trials an observer in the ASM control room insured that participant's adhered to this rule.

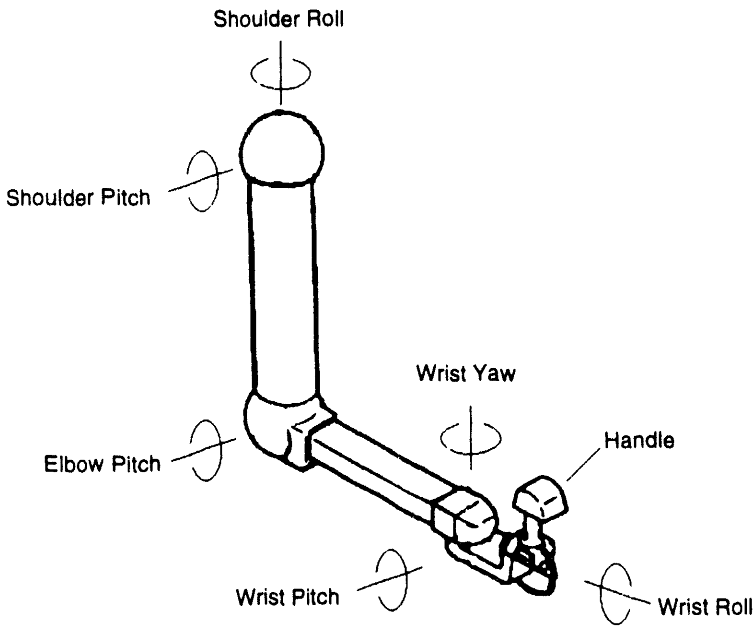

Figure 1. Master controller configuration.

3.5. Design and Analysis

A data recording system integrated into the ASM control software provided readings from the position encoders attached to 5 of the 6 master joints 100 times per sec (wrist roll data could not be collected because of memory limitations but this joint would not contribute much to handle trajectory in these tasks). These data were converted to 3-dimensional coordinates describing the position of the master handle relative to its mounting bracket in the control room. These intermediary data were in turn converted to the distance in meters between the handle and the position of the handle when the system was first activated. The resulting data describe the trajectory of the handle through 3-dimensional space with a single number, in 10 msec intervals. The second derivative of position was calculated to find master handle acceleration.

Participant	Task Orientation	MT(secs.)
A	Horizontal	1.57
	Oblique	2.08
	Vertical	2.46
B	Horizontal	1.33
	Oblique	1.81
	Vertical	2.05
C	Horizontal	0.83
	Oblique	1.04
	Vertical	1.63
D	Horizontal	1.76
	Oblique	2.52
	Vertical	2.67
E	Horizontal	1.89
	Oblique	2.33
	Vertical	3.13
F	Horizontal	1.29
	Oblique	1.96
	Vertical	2.38
Average	Horizontal	1.45
	Oblique	1.96
	Vertical	2.38

Table 1. Average MT for each participant and task orientation

Accelerations recorded during the first 512 time samples (5.12 sec) of each trial were subjected to a Fast Fourier Transform (FFT) using a custom C-language program using pre-packaged FFT algorithms[15]. The FFT calculated percentages of total signal magnitude attributable to frequency intervals up to 50 Hz, in 0.39 Hz intervals. Frequencies above 25 Hz did not contribute significant signal amplitudes and were not included in further analyses. The resulting power spectral density functions (PSDF's) were summed into frequency intervals 1.17 Hz wide.

Movement time was submitted to a fully crossed Analysis of Variance (ANOVA) using task orientation (3 levels), repetition (3 levels) and operator (6 levels) as predictors. The PSDF's were submitted to a fully-crossed ANOVA using signal magnitude as the criterion, and frequency interval (21 levels), task orientation (3 levels), repetition (3 levels) and operator (6 levels) as predictors. Student-Newman-Keuls mean difference tests were conducted when the ANOVA found a significant effect.

4. RESULTS

Table 1 shows the average MT for each operator within each task orientation. The ANOVA found a significant effect of task on MT ($F_{[2,10]}=62.23$, $p \leq 0.0001$); MT was shortest in the horizontal orientation (1.45 sec., on average), significantly longer in the oblique orientation (1.96 sec.), and significantly longest in the vertical orientation (2.38 sec.).

Figure 2 shows the PSDF's for each task orientation, averaged across operators and repetitions. The task spectra are similar platykurtic distributions, with peaks within the 3.6-4.7 Hz interval for the horizontal and oblique orientations and within the 1.3-2.3 Hz interval for the vertical orientation. The figure clearly illustrates the shift of the spectra for the oblique and vertical orientations towards lower frequencies. From Figure 1, it appears that the differences among the orientations fall mostly within the 0-1.2 Hz interval, the 1.3-2.3 Hz interval, and the 2.4-3.5 Hz interval. There also appear to be differences between the vertical orientation and the other two in the 6.0-7.0 Hz interval, the 7.1-8.2 Hz interval, and the 8.3-9.4 Hz interval. The ANOVA found a significant impact of frequency interval ($F_{[20,100]}=38.81$, $p\leq 0.0001$) and a significant frequency interval by orientation interaction ($F_{[20,40]}=5.50$, $p\leq 0.001$). The interaction was evaluated by conducting separate ANOVA's within each frequency interval. The ANOVA's found significant differences within the 0-1.2 Hz interval ($F_{[2,10]}=9.81$), the 1.3-2.3 Hz interval ($F_{[2,10]}=15.33$), the 8.2-9.4 Hz interval ($F_{[2,10]}=7.28$), and the 11.8-12.9 Hz interval ($F_{[2,10]}=6.66$). The mean difference test found that within the 0-1.2 Hz interval the horizontal orientation had a significantly lower percentage of magnitude than either of the others, which were not significantly different than each other. Within the 1.3-2.3 Hz interval the vertical orientation had a significantly higher percentage than either of the other orientations, which were not significantly different than each other; within the 8.2-9.4 Hz interval the vertical task had a significantly lower percentage than either of the others. Within the 11.8-12.9 Hz interval the vertical orientation had a significantly lower percentage of magnitude than the oblique orientation, but neither the vertical orientation nor the oblique orientation was significantly different than the horizontal orientation.

5. DISCUSSION

The MT results are similar to those produced by other Fitts' task experiments with telemanipulators in that there was longer MT than would be expected for hands-on performance of the tasks. In one study[16], the best manipulator MT was 1.4 sec at an ID of 4, and in another[14] MT averaged 0.75 sec at an ID of 2.81. These translate to 350 and 267 msec per bit, respectively, both much longer than the hypothesized 100 msec per bit for unencumbered arm movements. In the present experiment, MT averaged 1.93 sec at ID = 4.32, or 447 msec per bit. (The MT for the horizontal orientation alone was 1.45 sec, or 335 msec per bit, which is more like the two prior studies.) While some of the telemanipulator effect is attributable to viewing the task by television, at least one experiment has found that the impact of a telemanipulator is far greater than the impact of television viewing[17]. The argument that master controller friction and inertia are one source of the teleoperator performance decrement is supported by the MT findings across task orientations. The oblique and vertical orientations required simultaneous movement of more master controller joints than the horizontal orientation, and they had longer MT. The vertical orientation also required movement against gravitational acceleration, and it had longer MT than the oblique orientation. The per-joint friction is the likely source of the MT and PSDF differences between the horizontal and oblique orientations, and the addition of gravitational force is the likely source of the differences between the oblique and vertical orientations.

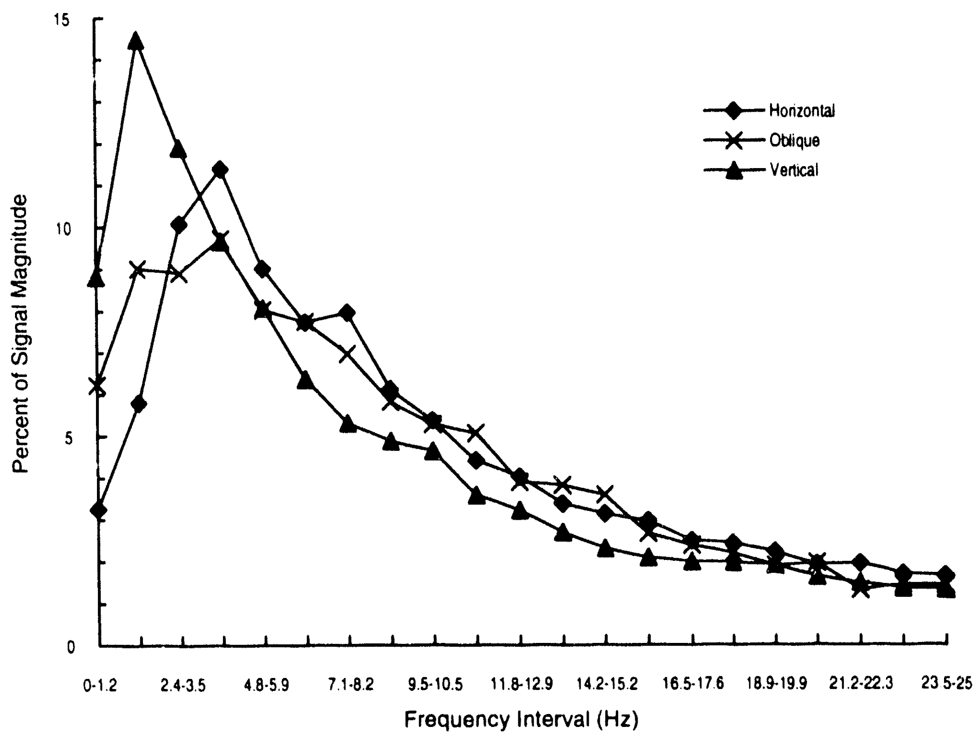

Figure 2. Power spectral density functions for each task version.

There was a considerable shift of signal magnitude towards lower frequencies, compared to observations of unencumbered human hand acceleration during target acquisition or handwriting. Often the bandwidth of a system is calculated by providing an input signal of known amplitude (the forcing function) and measuring the output signal; using this method, bandwidth is arbitrarily defined as the frequency at which the output amplitude is half the input amplitude. In the past this has been done for human tracking performance by presenting moving targets (the forcing function) and observing how well participants can match cursor movement (the output signal) to target movement. Tracking bandwidth is in the range from 0.5 Hz to 3 Hz depending on the predictability of the forcing function[18]. Unfortunately, data produced by this method seem to have little validity for teleoperation because the bandwidth of the a/d impulses generated during a particular positioning attempt is the critical variable for teleoperation, but tracking bandwidth is the positioning bandwidth of the entire human-machine system. This difference is very important: several acceleration impulses may be observed within a single movement and a teleoperator must be able to respond to every impulse produced by users to achieve ultimate responsiveness. Furthermore, tracking experiments impose the pace of movements, while during teleoperation movements are almost always self-paced. In the setting of the present experiment, the usual bandwidth definition was not applicable because a/d impulses were measured in situ and could not be manipulated. There is no method for providing a hand a/d impulse forcing function that could be used to generate data generalizable to real-world operations. Therefore, a different bandwidth definition was used: bandwidth is the frequency at which the cumulative percentage of magnitude reaches 50% of total signal magnitude. Using this definition, bandwidth for unencumbered hand a/d impulses during target acquisition[7] or handwriting[8] is above 9 Hz. In the present data, using the center of the frequency interval within which cumulative magnitude reached 50% of total magnitude, the bandwidth was 7.6 Hz for the horizontal orientation, 6.5 Hz for the oblique orientation, and 5.3 Hz for the vertical orientation. This is further evidence of the filtering effect of master controller friction and inertia on performance.

One important question is whether or not representing a/d impulses as the summation of a set of sine waves of varying frequencies, as the FFT analysis does, accurately models human activity during telemanipulation; and, if this is the case, what is the mechanism which governs the duration, bandwidth, and amplitude of the sine waves? In fact, such a phenomenon, arising from human neuromuscular organization, has been observed: force pulse amplitude depends upon the number of motor units (a motor unit is a motoneuron and the set of muscle fibers which it activates) participating in the force pulse and the duration of participation[19]. Increasing the duration of motor unit participation increases force pulse period and probably tends to reduce pulse bandwidth. Observations of increased EMG activity duration occurring with increased movement distance during wrist movements[20] support this model. The force pulse effects are probably mirrored by the a/d impulse waveform, so the implications of using the FFT to decompose the a/d waveform into its components seems to have a physical corollary. The frequency components of the a/d impulse may represent groups of similar motor units.

The data produced in the present study address the performance of a telemanipulator with a unilateral (i.e., not force-reflecting) master controller. These data demonstrate how much such a system inhibits human performance of manual tasks and suggest a source of the performance inhibition. Hopefully, advances in teleoperator technology will lead to lighter, less cumbersome master controllers that can operate at bandwidths closer to unencumbered human hands. Given the present state of display technology, it may be that improving the feed-forward capabilities of telemanipulators will be the most fruitful method for improving overall telemanipulator performance in the future.

6. ACKNOWLEDGMENTS

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