Effects of Friction Parameters on Completion Times for Sustained Planar Positioning Tasks with a Haptic Interface

Peter Berkelman and Ji Ma
Department of Mechanical Engineering
University of Hawaii-Manoa
2540 Dole Street, Holmes Hall 302
Honolulu, HI 96822
Email: peterb@hawaii.edu

Abstract—Haptic interface devices and teleoperation masters are multiple degree of freedom devices manipulated by an operator to generate realtime motion commands to simulated environments or robot manipulators. In this work we examine the relationship between the simulated friction parameters of a particular spatial positioning master device and the completion times of planar positioning tasks by human operators. It is expected that increasing the Coulomb or viscous friction of the device would tend to increase the completion times of less difficult, quicker positioning tasks and decrease completion times for more difficult fine positioning tasks requiring higher precision from the operator.

A common haptic interface device was used to perform continuous sequences of planar positioning tasks. Each trial required 10-12 minutes to complete and consisted of 15 positioning sequences which varied in the size of the target regions and the magnitude and type of simulated friction in the device. With a sample size of 10 test subjects, small effects were generally observed as expected, with the exception of the first 3 to 4 sequences of the trials which are concluded to be an adaptation or learning period for the users during each trial.

I. INTRODUCTION

When an input device is manipulated by a user to generate position commands to either a simulated or actual positioning device or manipulator, the user must overcome the inertial and frictional resistance forces of the input device as it is moved in order to perform any given task. In this study we consider the effects of variations in the magnitude and type of friction in a particular position input device on the task completion times for a set of planar positioning tasks.

It would be particularly advantageous to determine which tasks could be performed more easily by adding friction to the interface device, and the optimal magnitude and type of friction in the device for each task. Less costly position input devices with greater inertia and friction may in fact be preferable to more sophisticated low friction and inertia devices for these tasks. Similarly, it is common to add simulated friction to solid surfaces in haptic simulations for stability and ease of manipulation, otherwise the virtual objects slide over each other as if on an ice sheet and are difficult to position accurately.

Coulomb and viscous friction are the most common models of friction. The simplest model of Coulomb forces between moving parts is given by \( F_f \leq \mu F_n \), where \( \mu \) is a coefficient determined by the materials and smoothness of the surfaces in contact, \( F_n \) is the normal force between them, and the resulting friction force \( F_f \) is in a direction opposite to the applied force. A more detailed model accounts for “stiction”, a higher coefficient of friction when the moving parts are at rest relative to each other. Viscous friction is given by \( F_f = -bv \), where \( b \) is the viscous friction coefficient and \( v \) is the relative velocity of the objects in contact. Friction forces can be added to a mechanism by increasing the contact forces between its moving parts or the viscosity of its lubricating fluid, or they may be actively simulated using a force feedback device. In our study the viscous and Coulomb friction forces are simulated.

A similar study to ours was undertaken by Richards and Cutkosky [1] for a generalized single degree-of-freedom [DOF] positioning task with variable actual and simulated friction characteristics. They used an experimental device with a mass of 1.4 kg and a computer mouse shell as a user handle. Brouwer, MacLean, and Hodgson have proposed a more comprehensive study of the effects of interaction device dynamics on task performance using a specialized hardware platform to simulate less costly devices [2].

Our study uses a Phantom Omni\(^1\) [3] interface for position input, a common commercial haptic interface device with low inertia and friction. The Phantom uses a pen-shaped handle attached to a 3 DOF linkage by a 3 DOF gimbal, with force feedback applied through the 3 linkage joints only, so that 6 DOF of position and orientation input are provided with 3 DOF of force feedback. We apply this spatial 6 DOF input device to planar 2D positioning tasks. The orientation of the pen and the gimbal mount angles are disregarded, and the 3D position of the pen is projected onto the vertical plane of the screen.

Our subject experiments consisted of a continuous 10 to 12

\(^1\)Sensible Technologies Inc.
minute trial period where position targets were presented to
the operator in succession without pauses, rather than short in-
dependent trial tasks typical of classic early human interaction
studies. The results obtained from our study of 10 test subjects
are to be applied to the teleoperation of a prototype minimally
invasive surgical robotics system described in [4]. An example
of a difficult fine position task in surgery is suturing, due to the
small size of the needle. Tasks such as electrocautery require
less accuracy on the part of the operator as the instrument tip
and the zone of tissue affected by it is much larger.

A survey of selected haptic interface devices and teleoper-
ation masters is given in the following section, followed by
a brief background on human interface studies. Our experi-
mental trials are then described, the results are presented and
discussed, and plans for further study and conclusions of the
work are given.

II. SAMPLE HAPTIC INTERFACES AND TELEOPERATION
Masters

Any given user-interactive positioning device with force
feedback capabilities may be used either as a haptic interface
or teleoperation master; force feedback to the user is necessary
for haptic interaction but not for teleoperation. Thus, any
haptic interface device may be used as a teleoperation master
but only teleoperation masters with force feedback capabilities
can be used in haptic interaction. To achieve the best possible
fidelity of haptic feedback to the user and “transparent”
interaction, the dynamic range and closed-loop position con-
trol bandwidths of a haptic device must be maximized. The
actuators must have as little hysteresis, motor cogging and
other nonlinearities as possible.

Haptic interface devices and teleoperation masters are gen-
erally based on lightweight jointed linkages and designed to
have minimal inertia and friction and high accuracy. Counter
weights may be used in the device mechanism to cancel any loads at the device handle due to gravity, however this
approach increases the inertia of the device. Direct-drive or
cable transmission motors must be backdrivable and are used
for their low friction characteristics.

A. Teleoperation

The earliest applications of electronic teleoperation were
for manipulation of nuclear materials as described by Goertz
in [5], [6]. Current ongoing research addresses issues of
supervisory or shared control and transmission delays which
occur in space teleoperation [7].

B. Parallel Platforms

Examples of haptic devices based on platforms or handles
supported by multiple links in parallel include the Delta
haptic device [8] developed at the Swiss Federal Institute of
Technology in Lausanne, the Haptic Master [9] from Iwata
at the University of Tsukuba, and the Colorado University
haptic device [10] by Lawrence and Pao. Their kinematic
configurations may be classic 6-link Stewart platforms or
other variations such as multiple parallelogram or 4 and 5 bar
linkages to support and position the moving platform. Parallel
devices generally provide better accuracy and less manipulated
inertia than an equivalent open serial linkage, as actuator errors
tend to be averaged rather than added in the endpoint position
and the mass of the actuators may be concentrated on the
base of the device. Their range of motion workspace is limited,
however, and complex kinematic optimization procedures may
be necessary to maximize the reachable workspace of the
device and realize isotropic dynamic behavior. Furthermore,
the Coulomb and viscous frictional forces to be overcome
by the user may be larger for a parallel device than a serial
one due to the multiple links which must be backdriven simultaneoulsy in the parallel device.

C. Magnetic Levitation

The IBM magic wrist [11] is a magnetic levitation device
which was developed as a compliant robot wrist for fine
motion and assembly. It is based on Lorentz force magnetic
actuation using sets of permanent magnet assemblies and thin
coils of ribbon wire and uses optical sensing for position feed-
back. The Carnegie Mellon magnetic levitation haptic interface
[12] and the University of British Columbia Powermouse [13]
and teleoperation wrist [14] are devices based on the same
Lorentz force magnetic levitation technology which have been
used both as force-reflecting teleoperation masters and as
haptic interfaces.

The single moving part and noncontact actuation and posi-
tion sensing of these devices eliminates Coulomb friction in
their motion dynamics. Viscous friction may exist in Lorentz
force magnetic levitation devices due to the generation of eddy
currents if metallic sheets on the levitated body move through
the magnetic fields of the permanent magnets on the base. The
degree of viscous damping can be adjusted in the design of the
device by varying the thickness of the metal sheets to provide
sufficient damping for stable motion control yet not so much
as to be excessively perceptible to the user.

D. Other Devices

The 3-DOF Phantom is based on a single parallelogram
linkage on a pivoting base. A pantograph haptic interface has
been developed by Hayward [15] and is the basis of higher
DOF linkages such as a 5-DOF pen-based device by Stocco
and Salcudean [16]. The inertia and friction of devices such
as these depends primarily on their materials and the quality
of their components.

The da Vinci surgical robotic system [17] uses serial link-
ages with pen-type handles in its master console and the
ZEUS [18] system used larger counterweighted linkages with
manipulation handles held in the palms of the user, both
as teleoperation masters without haptic feedback. A tele-
chegraphy robot [19] developed to perform ultrasound exam-
inations remotely uses a Phantom device as a force-reflecting
master controller. Many glove and joystick devices are also
available which provide haptic feedback. Cable-based devices
[20] have also been developed for large-scale interaction.
All the referenced devices have some degree of inherent viscous and/or Coulomb friction from lubricated or dry contacts in their linkages depending on the design, type, and components of each device. The friction in the joints largely determines the overall costs, and the added costs of more sophisticated devices produce diminishing returns as the friction can never be eliminated entirely. Therefore it would be beneficial to be able to estimate the amount of friction which can be tolerated in the devices while performing various interactive application tasks. Force feedback devices can easily simulate additional Coulomb or viscous friction, but to reduce the apparent inertia of a backdriveable device requires highly accurate position and/or force sensing.

III. TASK AND INTERFACE PERFORMANCE STUDIES

Task and interface studies are well-established in human interaction research fields. Earlier studies were performed for mechanical targeting and positioning tasks and current studies most commonly examine human-computer interaction tasks such as point-and-click or drag-and-drop actions using a computer mouse.

A. Fitts’ Law

A primary result in human-computer interaction is Fitts’ law [21], which is a model for the completion time of target positioning tasks based on distance and target size:

\[ T = a + b \log_2(A/W + 1) \]  

where \( T \) is the task completion time, \( A \) is the amplitude or distance to the target, \( W \) is the target width and \( a \) and \( b \) are empirical constants.

The original form of Fitts’ law is only for single DOF point-to-point positioning tasks. Multiple dimensions can introduce additional factors in the interaction, so an extension of Fitts’ law to planar positioning cases is described in [22]. Applications of Fitts’ law to various different devices are described in [23].

B. Other Studies

Two other relevant recent studies in addition to those described in [1] and proposed in [2] are a study of a 1-D positioning task shared between two people described in [24] from Northwestern, and a study of human perception of friction in haptic interfaces in [25] by Lawrence and Pao.

Haptic fixtures to improve performance of haptic positioning task are proposed by Rosenberg in [26]. Bettini and Okamura have studied haptic fixtures further in [27].

IV. EXPERIMENTAL STUDY

Our experimental trials consisted of a 10-12 minute sequence of using the haptic device to place a pointer circle representing the device handle position within a randomly positioned target circle on the screen and clicking the selection button on the pen handle of the Phantom device. After each successful positioning task the center of the target circle moved to a different random location, and the size of the target circle and degree and type of simulated friction in the device was varied periodically. Task completion times of 10 test subjects were recorded for each sequence with a different combination of target sizes and friction characteristics.

The HLAPI library in the OpenHaptics software provided with the Phantom was used to implement variable additional simulated viscous or Coulomb friction in the dynamics of the haptic device. The simulated Coulomb friction implementation is presumed to be a simple stick-slip Karnopp model.

The test subject volunteers for our experimental trial were engineering students with no previous experience with haptic devices or teleoperation masters. The subjects each had 3-5 minutes to familiarize themselves with the haptic device and practice manipulation and targeting tasks before starting the experimental trial.

No added force or tactile feedback was given as the pointer circle was aligned with the target circle. The position of the pointer circle was given by the projection of the haptic device coordinates to the vertical \( xy \) plane parallel to the screen.

A. Phantom device inertia and frequency responses

The Phantom Omni device inertia at its gimbal was measured from the period of harmonic oscillations in the \( x \), \( y \), and \( z \) Cartesian directions with a simulated spring to provide return forces. The inertia was measured to be 0.246 kg in the \( x \) or radial direction, 0.183 kg in the \( y \) or vertical direction, and 0.104 kg in the \( z \) or radial direction. Frequency response testing shows the presence of the following higher-order dynamics in the Phantom for input frequencies up to 100 Hz: The \( x \) axis shows resonant peaks at 19 and 37 Hz, the \( y \) axis has smaller peaks at 19 and 54 Hz, and the \( z \) axis has a resonance at 55 Hz.

B. Test Setup

The setup of the Phantom device and computer display during the experimental trials is shown in Fig. 1. Each test subject was allowed to reposition the haptic device, the screen, and the chair to the most comfortable configuration before starting. The following variations of simulated device friction and target sizes were tested in all combinations:

<table>
<thead>
<tr>
<th>Friction:</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive only</td>
<td>Gain 0.0</td>
</tr>
<tr>
<td>Medium viscous friction (1)</td>
<td>Gain 1.0 N/(m/s)</td>
</tr>
<tr>
<td>Higher viscous friction (2)</td>
<td>Gain 4.0 N/(m/s)</td>
</tr>
<tr>
<td>Medium Coulomb friction (1)</td>
<td>Magnitude 0.1 N</td>
</tr>
<tr>
<td>Higher Coulomb friction (2)</td>
<td>Magnitude 0.2 N</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Target Size:</th>
<th>Screen pixels</th>
<th>Physical distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Small target</td>
<td>3</td>
<td>1.125 mm</td>
</tr>
<tr>
<td>(2) Medium target</td>
<td>9</td>
<td>3.375 mm</td>
</tr>
<tr>
<td>(3) Large target</td>
<td>27</td>
<td>10.125 mm</td>
</tr>
</tbody>
</table>

The different friction parameters were selected to be noticeable but not bothersome to the user. The target sizes were selected to demonstrate the hypothesis that added friction
would cause task completion times to decrease for sufficiently difficult fine positioning tasks, but increase for easier, faster positioning tasks.

Each of the 15 possible combinations was active during a continuous sequence of 30 positioning tasks, for a total of 450 position targeting tasks during each trial. The same random sequence of target positions was repeated for each combination of target size and friction parameters during each trial. The order of the combinations was also randomized, but repeated in the same order for each subject trial. The completion times for each of the 15 sequences of 30 positioning targeting tasks was recorded.

The center of each target was randomly placed in a 300x300 pixel region each time. The average distance between successive target spots during each sequence was 161 pixels, corresponding to an average motion distance of 60.4 mm.

C. Results

The positioning task sequence completion times of each test subject and their averages for each combination of target sizes and friction parameters are shown in Figs. 2, 3, and 4. In Figs. 5, 6, and 7, the completion times are normalized by dividing the added friction times by the times with passive friction only for each test subject so that each subject’s times with added friction are measured relative to that subject’s times without added friction, reducing the variations in the resulting data.

Several of the test subjects remarked that the additional resistance during the sequences with additional simulated friction seemed to reduce the difficulty of the positioning
V. Discussion

The effects of the added simulated friction on the positioning task sequence completion times are as expected, with the exception of the first 3-4 sequences in each trial. The sequence with the largest variation in average completion time for each target size is the \textit{Viscous1} sequence for the large targets as shown in Figs. 4 and 7; this particular sequence was the first sequence completed in each trial. The next sequences in each trial are the \textit{Coulomb2} sequences with large targets, the \textit{Viscous1} sequence with small targets and the \textit{Coulomb2} sequence for medium targets. In each of these cases the completion times are greater than the average for each target size, but the difference decreases for each successive sequence.

After these first 4 sequences, the hypothesis holds true that the sequence completion times decrease with increasing viscous or Coulomb friction for the small targets, but increase for the large targets. For the medium targets, the completion times increase only very slightly with increasing friction, so this target size may be close to a critical "tipping point" of task difficulty which determines whether moderate increases in friction increase or decrease the positioning task completion times. Although the effects of the added friction on the task completion times are qualitatively as predicted, the size of the variation is fairly small. After the 4 initial sequences of each trial, the task completion times vary by less than 10% with the different friction parameters for each set of target sizes.

Test subject fatigue does not appear to be a factor during the trials; task completion times were not observed to significantly increase during the last sequences. The adaptation of the test subjects during the first 3-4 sequences of the trials was found to be the most significant effect; this effect was present even though each subject practiced the positioning tasks for a few minutes before the measured trials. It is possible that such an adaptation period of up to 2-3 minutes could be observed even for experienced users during sufficiently long procedures.

Observation of the test subjects during the experimental trials and discussions afterwards suggest that the difficult fine positioning tasks with the smallest target sizes can be considered to consist of separate approach and fine positioning phases of the targeting tasks. In this case, it would be optimal to have low friction during the quick approach phase and higher friction during the slower fine positioning phase. This could be achieved by implementing nonlinear or variable simulated friction which would vary depending on the velocity of the pointer or the intent of the user. This approach would be difficult to apply consistently successfully, however, due to the small amount of variation in task completion times with added simulated friction and the difficulty of predicting the intent of the user in unknown, complex, unstructured environments such as during teleoperated robotic surgical procedures.

VI. Proposed Further Work

Given the observed effects of user adaptation during the first 2 minutes of the trials, further experimental trial data
should be recorded only after the first few sequences of each trial period. Variable friction parameters as described in the previous section may be attempted; this approach would be similar to the implementation of haptic fixtures.

The effect of variable inertia can be tested as well as friction, however to simulate inertia effectively an accurate acceleration or force measure is required. Increased inertia may have a positive effect for certain tasks; handheld tools are often said to have “right” weight for each task and high-performance computer mouses for video games are available with mass which can be varied by changing small gram weights inside the body of the mouse. Further task trials could involve more sophisticated 3D trajectory following and spatial orientation tasks instead of only planar position targeting; a representative assembly task is the peg-in-hole task.

VII. CONCLUSION

The results of increased simulated friction depending on task difficulty were as predicted, but the overall effects were relatively minor for the friction parameters tested.

Although all test subjects handled the Phantom and practiced the positioning task for several minutes before undergoing each trial, the user adaptation during the first 2 minutes of each trial was a more significant factor. Therefore adaptation over the first few minutes during each individual trial may be a more significant factor than overall previous experience. Further testing of different tasks, conditions, and friction parameters is necessary to form a comprehensive picture of the variations of task completion times with different dynamic parameters of the master device, with or without haptic feedback.

ACKNOWLEDGMENT

The authors thank the University of Hawaii College of Engineering for its provided support.

REFERENCES