High Bandwidth, Large Workspace Haptic Interaction: Flying Phantoms

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ABSTRACT

It is well understood that for haptic interaction: free motion performance and closed-loop constrained motion performance have conflicting requirements. The difficulties for both conditions are compounded when increased workspace is required as most solutions result in a reduction of achievable impedance and bandwidth. A method of chaining devices together to increase workspace without adverse effect on performance is described and analysed. The method is then applied to a prototype, colloquially known as ‘The Flying Phantom’, and shown to provide high-bandwidth, low impedance interaction over the full range of horizontal movement across the front of a human user.

KEYWORDS: HAPTIC DEVICE, LARGE WORKSPACE, FAST MOVEMENT, MACRO MICRO

INDEX TERMS: K.5.2 [INFORMATION INTERFACES AND PRESENTATION]: HAPTIC I/O; H.1.2 [USER/MACHINE SYSTEMS]: HUMAN FACTORS;

1 INTRODUCTION

The ideal force reflecting hand controller (haptic device) has been described as one which presents no perceivable resistance when there is no contact in the remote system and allows no perceivable movement during completely stiff contact [1]. The design requirements for producing these two conditions are in conflict and devices are typically designed to perform well in one area at the expense of the other. When increased workspace is required the performance of one or both conditions will likely suffer.

Larger devices are typically heavier, increasing the inertia presented to the user and longer linkages normally mean greater compliance and reduced sensor accuracy which reduces the closed-loop performance.

Active control systems which assist the motion of the user based on force/acceleration sensors can effectively reduce the perceived inertia and friction but at the expense of a sharp increase in impedance as the input movement exceeds the bandwidth of the system [2].

Safety is also a key issue in large volume haptic displays [3]. As devices become larger and more powerful the risk of injury to the human user increases also.

A number of large workspace devices exist or have been proposed. Many produce ungrounded forces and are worn or carried by the user. Ungrounded devices cannot reproduce object weight or inertia [3] and are not considered here.

Some are simply larger versions of a small device such as Sensable’s Phantom 3.0 [4] or the string based SPIDAR system [5] with the resultant performance trade-off making the choice of device task dependant.

Large devices based on active assistance control strategies (admittance control) such as the Haptic Master [6] perform well for smooth movements but cannot respond quickly enough for connection to the fingertip. This is because interactions between sensor dynamics and structural dynamics cause such control strategies to become unstable at high bandwidths [2].

The practice of mounting a small, high performance robot on a larger coarse positioning stage, often referred to as a macro-micro configuration, has been well researched in the manipulator robotics literature [7, 8]. However, the concept does not seem to have been widely applied or studied in the haptic interfaces domain, especially in terms of large, fast movements.

Salcudean et al. proposed the use of a macro-micro architecture to overcome the severe workspace limitations of magnetic levitation devices [9, 10]. While the total achievable workspace increased dramatically it was concluded that the limited workspace of the maglev device meant the coarse transport stage was required to achieve the full motion bandwidth of the human hand.

Luecke et al. employed a similar principle by mounting a multi-finger electromagnetic haptic device on to a PUMA 560 industrial manipulator [11]. This setup effectively reduced the weight and increased the workspace of the haptic device. However, the user was required to move the manipulator robot by gripping a force/torque sensor which limited the available bandwidth and caused instabilities if gripped too hard.

Although not concerned with matching human performance, another adaptation of the macro-mini concept is the mobile haptic interface (MHI) [12, 13]. The intent of an MHI is to permit haptic interaction in very large virtual environments, much larger than the reach of a human. Here a small haptic device is mounted on a mobile robot which tracks the movement of the user as they walk, theoretically allowing an infinite workspace though only at low velocities.

This paper revises the mathematical analysis (for haptics) and implementation of a macro-micro style haptic interface. The solution couples a small back-drivable haptic device to a larger servo-mechanism which attempts to keep the small device within its workspace. The intent is to achieve near human movement performance and workspace without affecting the achievable range of impedances produced by the back-drivable device.

Section 2 discusses the advantages and limitations of the principle in terms of simple mass-spring-damper systems. The implementation of a prototype system is presented in section 3 and a number of control strategies are then evaluated.

2 CONCEPT

The well known Z-Width performance measure [14] is not used here as it does not fully encapsulate how achievable impedance varies with bandwidth. Instead the following analysis is based on the work presented by Lawrence and Chapel [1].
Consider a simple back-drivable haptic device as a general impedance consisting of a mass with damping and a stiffness which is implemented as a position feedback term in the control loop, figure 1.

Lawrence and Chapel defined the performance of a force reflecting hand controller as an impedance transfer function in terms of the motion of the device \( X(j\omega) \) and the force applied \( F(j\omega) \). Using this definition the impedance transfer function of figure 1 would be:

\[
Z(s) = \frac{F(s)}{X(s)} = m_1 s^2 + b_1 s + k_1
\]

(1)

\( k_1 \) is set close to zero for free space \( (Z_f) \) and to some positive value (usually close to the limit for stability) for constrained space \( (Z_c) \). An example response of such a system is plotted as the solid line in figure 2.

If the workspace of the device is made larger then the inertial mass of the system will also increase. The response of an identical system but with a higher value for \( M_1 \) is represented by the dashed line in figure 2. It is clear that a higher mass reduces the low impedance, free space bandwidth. The closed-loop performance is also affected but it can be assumed that a larger workspace device would have higher values of damping and larger motors which would reduce the affect on the closed loop response.

Now consider that rather than increasing the size of the back-drivable device to increase its workspace it is instead mounted on a much larger servo mechanism. The servo mechanism attempts to move the base of the smaller device to keep the human interaction point centered. Extending the mass-spring-damper analogy to this new system gives figure 3.

To simplify the analysis we have assumed mass and damping of the servo is always much greater than that of the haptic device \( (m_2 >> m_1, b_2 >> b_1) \) and as such the closed-loop force generated at \( m_1 \) by \( k_1 \) is negligible compared to \( f_2 \) and can be ignored. Thus, as observed by Sharon et al. [2], high mass and damping in the coarse stage is actually beneficial in preserving the performance of the micro device. The coupled system can now be described as:

\[
\begin{bmatrix}
F_h \\
0
\end{bmatrix} + F = M\ddot{x} + B\dot{x}, \text{ where:}
\]

(2)

\[
M = \begin{bmatrix}
m_1 & 0 \\
0 & m_2
\end{bmatrix}
\]

(3)

\[
B = \begin{bmatrix}
b_1 & -b_1 \\
-b_1 & b_1 + b_2
\end{bmatrix}
\]

(4)

With the controller:

\[
F = -Cx
\]

(5)

Where:

\[
C = \begin{bmatrix}
k_1 & 0 \\
-k_2 & k_2
\end{bmatrix}
\]

(6)

Figure 4 shows this system in diagrammatical form.
The stiffness matrix $S$ of the coupled system in the Laplace domain can be found from (2) as:

$$
[S_h \ 0]^T = SX =
\begin{bmatrix}
    s^2m_1 + sb_1 + k_1 & -sb_1 \\
    -sb_1 - k_2 & s^2m_2 + s(b_1 + b_2) + k_2
\end{bmatrix}
$$

Finally to produce the impedance relationship equivalent to (1) we need to solve for $x_2$:

$$
Z(s) = \left| \frac{F(s)}{X(s)} \right| \left/ S_{2,2} \right|
$$

(8)

Figure 5 shows the response of the simple low mass system (solid line) compared against the coupled system of (7) (dashed line) where $m_1$ and $b_1$ are equivalent and $m_2$ and $b_2$ are much larger.

The impedance term in (8) is not a proper function when referred to the human, but can still be reformulated for simple frequency analysis as:

$$
Z(s) = \frac{s^2m_1 + sb_1 + k_1}{(s^2m_2 + s(b_1 + b_2) + k_2)}
$$

(9)

Thus the combined low and high mass system can be considered as the back-drivable low mass based on $m_1$ and the high mass servo-motor mechanism based on $m_2$ with the feedback term $k_2$ determining the ability of the large mass to keep up with the small mass. The steady state behavior of the system is:

$$
s \rightarrow j\omega = \frac{F(s)}{X(s)} = k_1
$$

(10)

As Bode diagrams are commonly used to help gain understanding of a system we can reformulate (9) and take the natural log of the absolute value to get a gain/frequency relationship:

$$
\log_e Z(s) = \log_e \left| S_{1,1} \right| + \log_e \left| \left(1 - S_{1,2}/S_{1,1} \right) \right|
$$

(11)

We can convert (11) into the more familiar decibel value simply by multiplying the result by $20\log_{10}(e)$, i.e. about 8.686. The second term can be approximated with the Mercator series expansion (Taylor series for logarithms) providing:

$$
-1 < \left( S_{1,2}/S_{1,1} \right) \leq 1
$$

(12)

Which can be shown to hold true for positive values of mass and friction. The result of this is that the Bode plot of the combined system consists of the Bode plot of the low mass back-drivable system plus a frequency shaping function i.e.

$$
\log_e Z(s) \approx \log_e \left| s^2m_1 + sb_1 + k_1 \right| + \log_e \left| S_{1,2}/S_{1,1} \right|
$$

(13)

Which gives an approximation of the revised Bode diagram. Writing the shaping function as:

$$
G_e(j\omega) = \frac{j\omega b_1(j\omega b_1 + i)}{k_1 k_2 (\omega^2 m_1 / k_1 + j\omega b_1 / k_1 + 1) \ldots}
$$

(14)

It can be seen that the shaping function will have a minimal effect at low frequencies, when $\omega \rightarrow 0$. Likewise at high frequencies the shaping function again tends towards zero. At the key frequencies determined by $\omega_{c1} = \sqrt{(k_1/m_1)}$ and $\omega_{c2} = \sqrt{(k_2/m_2)}$ the shaping influence is determined by $b_1/k_2$. Since $b_1$ is, by design, small and $k_2$ is chosen to be large this tends mitigate the effect of the shaping function at these crossover frequencies.

The response shown in figure 5 is only relevant up until either the servo or smaller device saturates and reaches the limit of its workspace. If we assume that the servo can be made as large as necessary then only the saturation of the back-drivable device is of interest.

For a particular amplitude of input movement that is greater than the workspace of the back-drivable device alone there will be a bandwidth over which the servo is able to keep the smaller device within its workspace. At some frequency $\omega_s$, the distance between the position of the servo and the input position will exceed the workspace of the haptic device and it will have reached saturation.

The critical values $\omega_{c1}$, $\omega_{c2}$, and $\omega_s$ define the bandwidth over which the system can sustain a level of performance at least as high as the uncoupled back-drivable device. Unlike the simple back-drivable device the performance of the servo mechanism can be increased without adversely effecting either the closed or open loop response felt by the user. Thus the only limit on the achievable workspace and input bandwidth are the dimensions of the servomechanism and the acceleration it can produce.
3 IMPLEMENTATION

A prototype system has been developed based on the principles discussed in section 2.

3.1 Hardware

The prototype system comprises a 1.6m TKO linear track on which one or two Phantom 1.5 haptic devices can be mounted. The horizontal workspace of the Phantom 1.5 is approximately 381mm [4] thus the theoretical total horizontal workspace is approximately 2.0m. The linear truck is servoed by two printed armature DC motors connected via a toothed drive belt. The motors are driven at 40V/10A by two Maxon ADS 50/10 motor amplifiers. The position of the truck is measured directly via a linear encoder strip eliminating position errors due to backlash. Figure 6 shows the prototype system.

![Figure 6. Prototype Coupled System](image)

The track is controlled by a dual Xeon 2.8GHz PC with 1Gb of Ram running Windows XP. The same PC is also responsible for haptic, graphical and sound rendering. Communication with the track is via a Sensoray 626 interface board. An ADXL210 +/-10g accelerometer is mounted at the base of the Phantoms to measure the acceleration of the servomechanism. The servo loop on the PC runs at approximately 500Hz.

3.2 Control

A number of control strategies have been implemented and evaluated. The strategies were evaluated by comparing the position and velocity traces of a number of test subjects performing a reciprocal tapping task similar to a Fitts’ Law experiment [15, 16]. Each subject was asked to alternately tap two targets spaced 600mm apart in a quick, smooth and continuous manner. The criteria for a good response were: minimum movement of the haptic device (relative to itself) and the similarity of the combined (servo + haptic device) velocity to the natural ‘bell’ shape expected in a target acquisition task.

3.2.1 PD Control

The first control method considered here is that which was used in the analysis of section 2, a simple position feedback controller. The control loop uses the distance of the haptic device’s end-effector from the center of its workspace as the error signal with an extra damping term using the velocity of the servo itself to reduce oscillations. Figure 7 is the block diagram schematic of this system where: \( P_H \) is the position of the haptic device relative to its own coordinate frame, \( P_s \) is the position of the servo, \( k_1 \) is the position feedback gain and \( D \) is the value of additional damping.

![Figure 7. Simple PD Controller for the Servomechanism](image)

Figures 8 and 9 are the averaged position and velocity traces, respectively, for a single subject performing the tapping task with the PD controller of figure 7 in use.

The workspace of the Phantom 1.5 is approximately +/-180mm and in figure 8 it can be seen that only a small fraction of this workspace is used with the servomechanism performing most of the movement. However, as the user decelerates, the servo begins to oscillate about its target position. These oscillations and the resultant distortion to the bell shape of the combined velocity profile can be clearly seen in figure 9.

![Figure 8. Averaged position profile for a target acquisition task using the PD controller](image)
3.2.2 Dead-Band

To reduce oscillation of the servomechanism a dead zone of +/- 100mm about the center of the haptic device is introduced. Now the servo mechanism will only move if the haptic device lies outside the dead zone. Figures 10 and 11 show averaged position and velocity profiles for the dead-band controller. The effect of the dead band on the motion of the haptic device can be clearly seen in figure 10. The haptic device now accounts for a much greater portion of the total movement. The ultimate result of this would be to reduce the saturation bandwidth for movements greater than the workspace of the haptic device. Oscillations, however, have been reduced but at the expense of the bell shape of the combined velocity profile, figure 11. The much greater acceleration of the servo has flattened out the acceleration/deceleration portions of the combined movement and increased the average peak velocity. It is assumed from this that the subject is not moving in the manner which they intended, reducing the transparency of the system as a whole.

3.2.3 Velocity Feedback

The third control scheme adds the velocity of the haptic device into the error signal. The intent is to smooth out the sharp accelerations of the servo due to the dead-band and also to restore some of the saturation bandwidth by allowing the servomechanism more time to respond to high velocity movement by the user. Figure 12 shows an outline of the controller with the dead-zone and haptic velocity feedback, where $V$ is the haptic device velocity feedback gain. Figures 13 and 14 are the position and velocity profiles for this controller. From these plots it can be seen that the motion of the haptic device and the servomechanism are both smooth and continuous with the resultant combined velocity resembling the bell curve more than previous controllers.
3.2.4 Acceleration Compensation

Adding the velocity of the haptic device into the servo controller smoothed out the combined velocity profile as the magnitude of servomechanism’s acceleration was reduced substantially. However, sudden discontinuous input movements by the user will still result in high acceleration of the servomechanism. These high accelerations will be felt by the user as disturbance forces, distorting the intended motion and impairing the transparency of the device as a whole.

The disturbances felt by the user are caused by the base of the haptic device accelerating. If the haptic device itself can apply the correct force to cause an equal but opposite acceleration then the disturbance felt by the user should be greatly reduced.

If the dynamics of the haptic device and the desired acceleration are known then the required torque at each degree of freedom can be calculated using, for example, the Lagrangian (15).

$$\frac{d}{dt} J(t) \frac{d \theta(t)}{dt} = \frac{d}{dt} V(t)$$  \hspace{1cm} (16)

Then, rearranging for joint space acceleration:

$$\frac{d^2 \theta(t)}{dt^2} = J^{-1}(t) \left( \frac{dV(t)}{dt} - \frac{dJ(t)}{dt} \frac{d \theta(t)}{dt} \right)$$  \hspace{1cm} (17)

In order to test the effectiveness of the acceleration compensator the dead-zone only controller was used because the higher accelerations produce clear trajectory disturbances which the compensator should be able to reduce.

Figure 15 shows the velocity profile for the dead-band controller with acceleration compensation running on the haptic device. Comparing with figure 11, the dead-zone only plot, it is clear that even though the servomechanism is moving in a similar manner the resultant combined profile closely resembles the desired bell shape suggesting that the disturbance force has been greatly reduced.

3.2.5 Safety

The larger and more powerful a human interface robot becomes, the greater the potential for harm if an uncontrolled collision occurs. Zinn et al. [17] introduced the principle of parallel, distributed actuation for robotic manipulators to reduce the risk of human injury if a collision occurs. The principle of
their solution was to divide the manipulator into a low bandwidth, high torque section located at the base of the manipulator and a smaller, high bandwidth, low impedance section at the distal end of the manipulator. Using this configuration they were able to produce a high performance manipulator with very low contact impedance.

The same principle is apparent in the prototype system described here, though Zinn et al. do not consider the idea in the context of a haptic device where there is changing impedance. By having the user only interact with the system through the low impedance, back-drivable haptic device there is a very low risk of injury should the system become uncontrolled as long as the high mass, high torque part is always kept away from the user though the use of physical stops.

An additional element is added to the servo controller to reduce large, discontinuous decelerations at the physical limits of the servo’s workspace. The controller employs a max velocity limiter based on a predefined maximum deceleration and the distance to an end stop. At any position the maximum allowable velocity of the servomechanism is calculated using the maximum acceptable deceleration $a_{\text{max}}$ and the distance to the end-stop in the current direction of motion $d_e$.

$$v_{\text{max}} = \sqrt{2a_{\text{max}}d_e}$$

This additional control scheme reduces sudden, sharp decelerations as the servo reaches its physical limits, thus preserving transparency and enhancing safety.

4 Discussion
In section 2 the proposed method of chaining a small low impedance device and a larger servo mechanism was presented as a coupled mass-spring-damper model. It is clear that, up to a certain bandwidth, the new combined free space impedance is actually lower than the haptic device on its own and the closed loop impedance is identical at low frequencies, dropping off after a critical frequency. Therefore, for a certain range of frequencies (the equivalence bandwidth) the performance of the system is at least as good as the back-drivable haptic device on its own but over a workspace only limited by the dimensions of the servo mechanism. The equivalence bandwidth of the coupled system can be increased by using larger, more powerful servo motors and, unlike a single back-drivable device, there is no necessary trade-off between closed loop and open loop conditions, increasing the performance of the servomechanism increases the equivalence bandwidth of both.

The result of this from a design point of view is that the performance of the back-drivable part of the system can be increased by reducing its workspace, i.e. the free-space impedance is reduced and the closed loop impedance is increased. The useable workspace can then be restored by a sufficiently powerful servomechanism that can actuate the smaller device quickly enough to achieve the required equivalence bandwidth.

Logically then, the ideal coupled system has a very small back-drivable part and a very large, powerful servomechanism. However, the smaller the back-drivable device the greater the required acceleration of the servomechanism and thus the greater the disturbance forces felt by the user.

In section 3 it was shown that for the prototype system large accelerations of the servomechanism produced disturbance forces large enough to distort the intended motion of the user. An acceleration compensator was shown to be able to greatly reduce the disturbances felt by the user when large base accelerations were present. Therefore, the limiting design factor is now the accuracy to which the disturbance forces can be compensated for by the smaller device.

5 Conclusion
The paper has demonstrated the performance advantages of chaining a back-drivable haptic device to a servo mechanism. The additional benefit of this approach is that with careful design it is also possible to increase the safety of high performance large reach haptic interfaces. The prototype system increases performance only in a horizontal movement. The vertical movement of the back-drivable device (two phantom 1.5s) allows pick and place operations over a table like workspace. A second servomechanism could easily be added to allow vertical movements. This would enable greater vertical performance in operations such as reaching to a high shelf. In any future system it is likely these servomechanisms will be optimised for the task workspace.

In addition to the results presented here the prototype system was capable of keeping the micro device within its workspace at very high input accelerations, with significant effort required from users to exceed it. The authors intend to implement a Fitts’ Law based test to evaluate to what degree users are impeded by the device in large, fast movements.

References