SIGNAL DETECTION PERFORMANCE WITH A HAPTIC DEVICE

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Haptic interfaces are becoming more widely used in virtual reality simulations because of their enhancement to performance in training and simulation. Unintended vibration degrades the effectiveness of a haptic device and can reduce the user's ability to detect small details in the surface of simulated hard objects. Two important design factors for controlling haptic device vibrations are servo update rate and resistive force magnitude. This work employs a signal detection and receiver operator characteristic methodology to evaluate the interaction of these two factors on a user's ability to perceive small details in a hard surface. In a two-factor, full factorial experiment, six male research participants rated their confidence in detecting a 5mm upward step along a simulated hard surface. The independent variables were resistive force magnitude (1.63N or 4.88N) and update rate (468Hz or 1630Hz). The results indicate a significant interaction of the two variables. Participants demonstrated a 69% success rate with the strong force, slow update rate compared with a 86% success rate in the other 3 conditions. The participants may have employed a strategy of detecting the lack of oscillations when entering the surface and then noted their kinesthetic motion while moving back to the oscillating state experience when sliding along the surface of the simulated edge. Either increasing the update rate or reducing the resistive force magnitude can mitigate the effects of vibration when using a haptic device.

INTRODUCTION

Many researchers are interested in using haptic feedback devices to enhance their virtual environment research because simulating touch in virtual worlds has led to increased performance in training simulators (Salisbury, 1997; Massie, 1998). Haptic devices allow an operator and a computer to exchange mechanical energy. The majority of haptic devices are force feedback joysticks, although thimble and pen devices have been used in many interesting applications. By applying time-varying or position-dependent forces, the devices provide operators virtual object shape and surface texture information. A common application of these devices is to simulate touch for learning physical skills, such as those required in medicine (Chang, 1998; Chen, 1998; O'Neill, 1993). We are developing the Iowa Dental Surgical Simulator, for example, to train dental students to detect carious lesions. Our experience indicates that haptic device vibration is an important factor in the success of a haptic technology, but the amount of acceptable vibration and techniques to avoid vibration is not well described in the literature. This work describes two critical design factors, force magnitude and update rate, that can cause vibration and measures the effect of these factors on an operator's ability to detect small features on a simulated hard surface.

BACKGROUND

The haptic interaction between a point object and a virtual wall has been investigated by a number of researchers (Colgate, 1994; Rosenberg, 1993; Salcudean, 1994). Achieving stability is recognized as a primary concern because haptic devices tend to vibrate when interacting with a virtual hard surface. Several researchers have attempted to overcome this problem by applying control theory. Kazerooni and Her (1994) developed a sophisticated analysis that accounts for the dynamics of the human arm and its relationship with the haptic devices. Their model requires that the haptic device measure the force exerted by the operator on the device, but many force-feedback joysticks are manufactured without a force transducer to provide this information. Colgate et al. (1995) present a control theory model that requires the device to sense only position information and apply a linear function response force as the cursor intrudes into the wall. They conclude that this approach can provide walls that feel "stiff" if the following conditions are met: (1) the position is sampled quickly and (2) the haptic device has a large amount of inherent damping. Since programmers are often not in a position to change the damping coefficient of the haptic device, they must concentrate on sampling positions quickly. Chen and Marcus (1998) report that "The common rule of thumb for stable, smooth, and crisp force-feedback control loops dictates that the servo rate should be at 1000 Hz or above". Chang and Colgate (1997) report that their unpublished experiments indicate that haptic devices require an update rate of 500 Hz - 1kHz. Several other approaches to dealing with haptic interactions with solid objects, including Zilles and Salisbury's object model (1995) and Adams, Moreyra and Hannaford's (1998) virtual coupling network, also require high update rates on the order of 1kHz.

Practical implementation requires designers to balance update rate and the stiffness of the virtual surface. Fast update rates require simple servo algorithms, particularly when other processes run on the same computer that runs the servo functions. For example, a virtual reality application might present graphics showing the cursor movement while the haptic device is interacting with the hard surfaces. The graphics and the servo routines must compete for the system resources. The designer must balance the realism and complexity of the simulation with the need for a fast update rate. Unfortunately, little information is available in the literature for this common problem.

To reduce vibration associated with slower update rates, designers typically choose to have the device respond with a force proportional to the distance inside the surface (linear gain), up to the device's maximum attainable force. Zilles (1995) reports that "most users tend to use less than 5N of force" when exploring virtual environments. Many devices provide much greater forces, such as 18N for the Phantom (Massie, 1998) and 6.5N for the device used in the experiments reported here (Immersion, 1999). A high gain prevents the user from penetrating very far into the surface of the object, but tends to create more noticeable vibrations. A low gain does not create much vibration, but allows the user to penetrate deeply into the surface of the object, making the object feel spongy rather than stiff. Designers of virtual environments with haptic interfaces must select an appropriate gain.

This work develops the hypothesis that vibration caused by designer's choice of update rate and gain is perceived as noise and causes the operator to miss subtle features on the surface of object. Consequently, the designer must balance the machine's ability to run parallel processes in order to render a virtual environment, for example, with the operator's ability to detect small features with the haptic interface.

METHODS

The experiment reported here explored the effects of gain and update rate on an operator's ability to perceive small step-like features along a smooth, hard edge. Six participants (male, mean age of 25.8) slid the haptic device along the virtual edge at a prescribed pace and indicated whether they detected a small, upward step on the surface. The update rate and magnitude of the resistive force were varied according to a full-factorial design.

The haptic device used in the experiment was an Impulse Engine 2000 (Immersion, 1999), a 2-degree of freedom joystick. The device consists of a 13 cm long hard plastic handle atop a metal box housing the direct-drive feedback motors. The device can produce a maximum force at its tip of 6.5N in its 15.2 x 15.2 cm workspace. Since the joystick rotates, the workspace describes a portion of the surface of a sphere with a radius 13 cm. The optical encoders mounted on the motor shaft provide a position resolution 0.02 mm. Joystick position was represented in a 700x700 pixel window on the monitor screen.

Participants held the joystick near the tip with their elbows resting comfortably on the table. They viewed the display, which was divided horizontally into a black region on top and white region on the bottom. If the user moved the cursor down into the white region, the joystick responded with a resistive force, which provided the effect of a hard edge in the white region. Participants were asked to slide the cursor along the edge, keeping within the pace circle, and attempt to detect the presence or absence of a 5 mm upward step on the edge surface, which was not represented in the graphical display. They were asked to stay on the surface and follow a pace circle (about twice the size of the cursor), which traveled at 3 pixels per frame (about 75 pixels/sec). The user slid across the surface for about 10 seconds and tried to perceive a step up in the line. At the end of the trial, the participant was asked to provide their confidence of the presence of a step on a 6-point scale with 1 indicating definitely yes and 6 indicating definitely no. After they entered their response, the computer provided feedback indicating the correctness of their response.

The experiment consisted of 160 randomly presented trials for each of the six research participants. Half of the trials included a step edge. The experiment included 20 repetitions of a fully crossed, 2^3 full factorial design of the two force levels (4.88N or 1.63N), the two

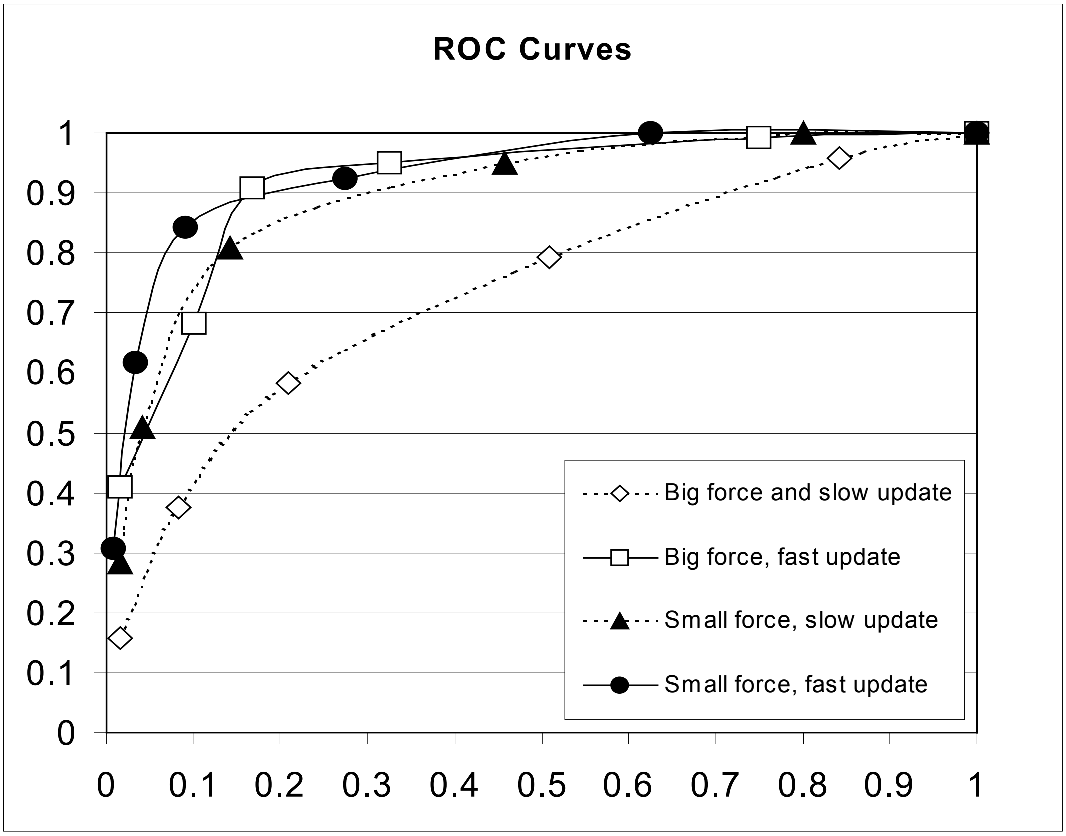

Figure 1: Response Operator Characteristic curves averaged across subjects for the four experimental conditions.

update rates (1630Hz and 468Hz) and the presence or absence of the step edge. The level of force and update rate were programmed by ambiguous whole number units which were later converted into Newtons and Hertz. The location of the step along the edge, when present, was randomly varied along the center 75% of the line.

RESULTS

The responses were analyzed using the method described in Green and Swets (1966). Response Operator Characteristic (ROC) curves shown in Figure 1 were constructed by averaging across subjects for each condition and confidence level. The figure illustrates a separation in the performance levels for the condition with a strong force (4.88 N) and slow servo rate (468 Hz) versus all other conditions. For this condition subjects responded accurately with a combined average of only 69% (n=6) versus 86% (n=18) for the combined average of the other conditions, a statistically significant difference, $t(2.73)$ $p < .05$.

The forces and cursor position was also recorded throughout the experiment. Samples of these results are presented in Figure 2 for one trial with one research participant in the large force, slow update (left) and small force, fast update (right) conditions. The top portion of the figure displays the position data for the two trials. The bottom portion shows the force data for the two trials. These results are characteristic of most of the trials in that the position oscillated over a greater pixel range with the large force than the small force. In the three conditions with better discrimination exhibited by participant the pattern on the right-hand side was often evident. The position graph indicates that the participant plunged the cursor directly into the step edge. While the cursor was inside the surface, a continuous, upward force replaced the oscillation.

DISCUSSION

The resulting data gives us some insight into the human's perception of small details. The trial type that presented the largest force and the slow update rate resulted in the poorest performance, while the trial with a large force and a fast update did quite well. If the difference in update rate was the only discriminating factor, than one would expect the same performance gap between the two small force trials, which differed only

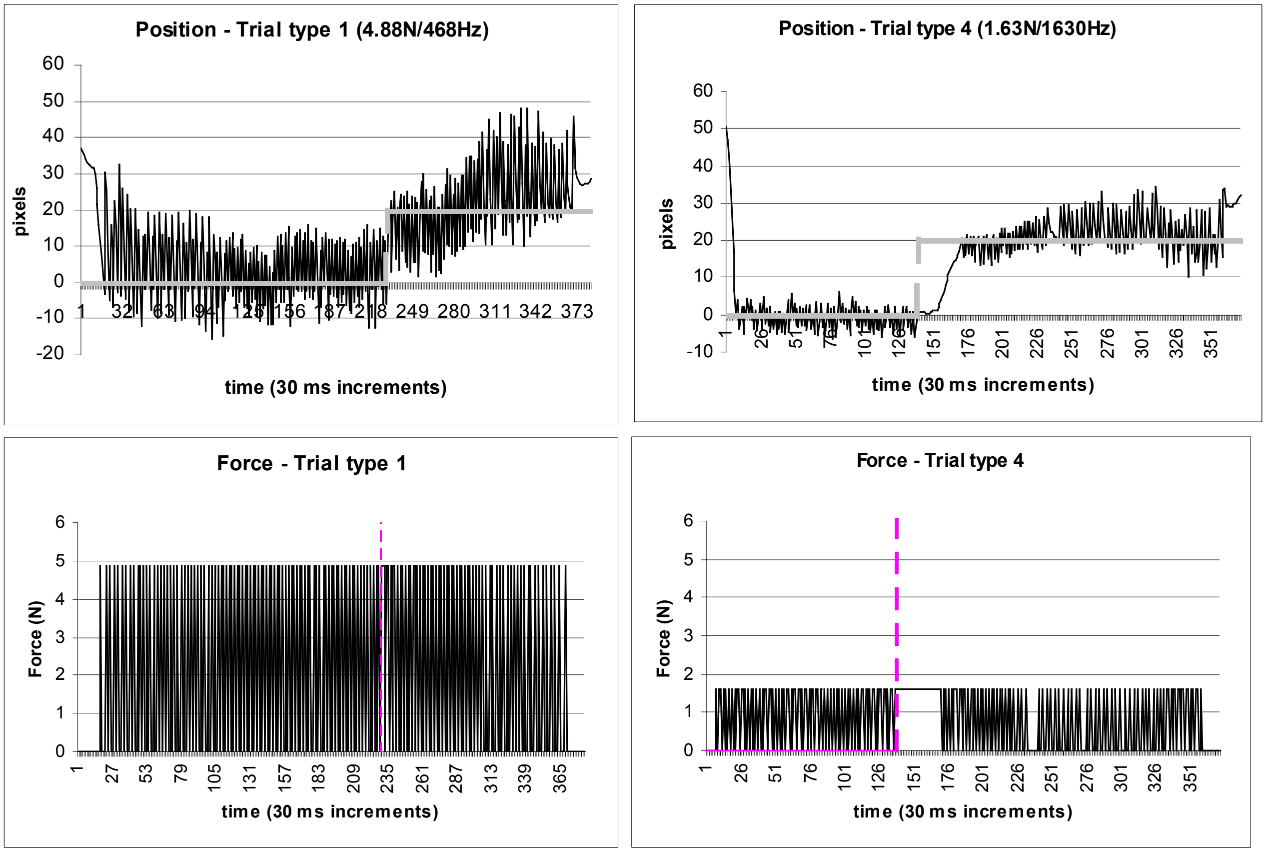

Figure 2: Sample data for one subject showing position (top) and forces (bottom) during sessions with slow (left) and fast (right) update.

in update rate. Data from individual trials tells more of the story. As expected, the position graphs of the big force/slow update and big force/fast update trials indicate that the slow update causes larger vibrations. These large vibrations leave the user uncertain about the position of the virtual wall, hiding the presence of small details, so the performance is poor. Turning to the trials with smaller output force, we discover that the participants received two clues about the presence of a small step: kinesthetic movement of the hand, and a momentary lapse of vibration. For the small forces, the user entered the step from the side and did not feel vibration until they moved back up to the surface. We hypothesize that the participants used both cues, the momentary gap in the vibration and the change in kinesthetic positioning of the hand, to detect the edge. For the trials with big forces and slow update rate, there was no gap in vibration, so the clues about the presence of a step came solely from discerning the change in position of the virtual wall.

To better understand these effects, we are planning further experiments designed to eliminate the momentary lapses of vibration in the other three conditions so that the only clues the participant receives are from the change in position. From there, we could look at the effect of update rate and force magnitudes independently to see if one has a greater influence than does the other.

Haptic interface designers should consider the level of touch detail needed before setting the force and update rate. Also if the sense of touch is more important than the graphics, performance of the system can be improved by displaying simple graphics. Another recommendation is to implement control theory by considering the user's force input as the adjustment variable.

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