Virtual Force Display: Direction Guidance using Asymmetric Acceleration via Periodic Translational Motion

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Abstract

This paper describes the development of a handheld haptic display based on a new force perception method. The method uses periodic translational motion to create asymmetric acceleration leading to a virtual force vector. The method is based on the sigmoidal relationship between perception and physical quantities (tactile and proprioceptive sensations); humans more strongly feel rapid acceleration than slow acceleration. A prototype of the haptic display that generates one-directional force using a relatively simple mechanism is fabricated and evaluated. Experiments verify the feasibility of the proposed method by examining the effect of the frequency of acceleration and amplitude of the force on the perception of the virtual force vector.

1. Introduction

Since wearable computers have a "position" variable which ordinary desktop computers do not have, many researchers have examined their application to navigation services; some of them are based on tactile sensation[1][2][3]. Force displays that used tactile and proprioceptive sensations are suitable for intuitively presenting direction information. However, previous wearable and mobile force displays can produce neither constant force nor translational force, without reaction force. Examples include GyroDisplay[4], which utilizes the gyro effect, and GyroCube[5], which presents a torque by using the change in angular momentum of a motor.

This paper introduces a method for creating an effective "virtual force vector". It involves the asymmetric acceleration created by periodic translational motion. We construct and test a prototype of a handheld haptic display based on the method that presents nonverbal direction information. While the display does not provide an actual force, due to the characteristics of human perception, the "virtual force" is effectively perceived by the user as a constant translational force.

2. Concept and implementation

We realize the haptic illusion that leads to the perception of the virtual force vector by subjecting a mass to periodic translational motion; the mass is accelerated more rapidly in one direction than the other. This method can generate a sensation of a one-directional force. Even though this force display has no fulcrum, it can generate constant force, which previous wearable and mobile force displays cannot.

The haptic illusion involves tactile and proprioceptive sensations; the underlying perception mechanism for the force display involves (1) a proprioceptive difference in reactive characteristic of muscle spindle, static and dynamic reaction [6], (2) a tactile difference in the friction force of contact surface, (3) the nonlinearity of human perception, which is known to match a psychometric function whose shape is an S-curve (sigmoid curve)[7][8], and (4) temporal masking of difference of amplitude of force.

The authors designed a mechanism to generate asymmetric acceleration by transforming a circular motion at constant speed into curvilinear motion by a swinging-block slider crank mechanism (Figure 1).

The equation of motion of the weights is given by;

$$x = r\cos\theta + \mu(d - r\cos\theta) + \sqrt{l_2^2 - \{r(\mu-1)\sin\theta\}^2} \quad (1)$$

where

$$\mu = \frac{l_1}{\sqrt{r^2 + d^2 - 2rd\cos\theta}} \quad (2)$$

x = OD, r = OB, d = OA, l_1 = BC, l_2 = CD, θ =AOB, respectively. The movement of the slider and the

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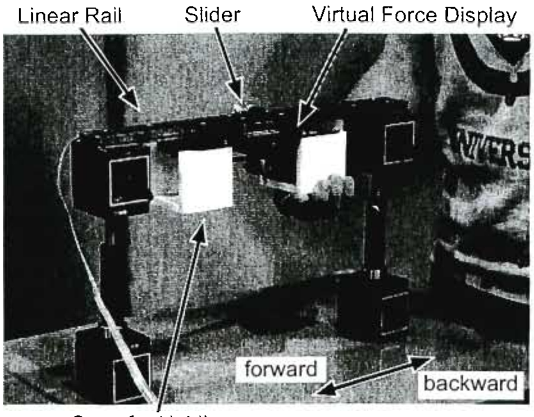


Figure 5. View of experiment

3.1.2. Apparatus. The direction of the translational motion was limited to one axis, forward and backward, by using a linear rail (LWFF; the Nippon Thompson Co., Ltd). The virtual force display was fastened to a slider on the rail; rail length was 400 mm. Two cubes made of acrylonitrile butadiene styrene (ABS) resin were attached to the virtual force display, and the subject held the closest cube with the dominant hand. Figure 5 shows the experimental setup. The method of grasping the device was constant throughout the experiment: the tips of the fingers were wrapped around the cube; subject's elbow was not fixed. The total mass of the weights on the slider in the virtual force display was 20 g.

3.1.3. Procedure. We determined how often the perceived direction of movement matched the intended direction. The rotational frequency of the motor was altered in 1 Hz steps from 5 to 11 Hz. Subjects indicated the direction of movement in ten trials at each frequency (five trials forward and five trials backward). We randomized the order of the intended direction at each frequency. The same sequence of parameters was used for all subjects. The answers were forced-choice, either "feeling forward force (pushing relative to the ground)" or "feeling backward force (pulling relative to the ground)". Subjects were not told if their answer was correct or not. In order to remove the influence of adaptation by long-term vibration, the subject was given a one-minute break every 20 trials. The stimulation was presented for approximately one second (two seconds maximum).

The subjects were required to reply with one of the directions; answers such as "I'm not sure" were not accepted. Therefore, the correct answer rate would be 50 % assuming that the subject randomly selected his replies. When the vector was unambiguous, the correct answer rate was 100 %. In most psychology experiments, the threshold is set at 75 %. Given the quantization error and the comparatively small number of trials, we set the threshold at 80 % in this experiment.

3.2. Results and discussion of Experiment 1

Table 1 shows the results of Experiment 1. Motor speeds over 10 Hz yielded correct answer rates of over 80 % for all subjects. The averages of the correct answer rate in each direction are shown in Figure 6. For backward (forward) stimulation, the average correct answer rate exceeded 80 (90) % for motor speeds over 9 (8) Hz. It is suggested that there is a threshold in terms of the rotational frequency of the motor, and the threshold differs with the direction.

In the experiment, the presentation time of stimulation was approximately one second so no unstable phase was encountered. Even with this short stimulation time, the intended virtual force vector was well perceived. This is reasonable since short term use will minimize battery consumption.

3.3. Experiment 2: which frequency or amplitude causes haptic illusion?

The rotational frequency of the motor in the force display has two parameters, the frequency of acceleration

Table 1. Correct answer rate of presented direction vs. rotational frequency of motor

		Correct Answer [%]						
		Rotational Frequency of Motor						
		5 Hz	6 Hz	7 Hz	8 Hz	9 Hz	10 Hz	11 Hz
Subject	GK	100	100	100	100	100	100	100
	TK	70	60	50	90	90	90	100
	HA	100	60	90	100	100	100	100
	IT	70	90	70	60	90	100	80
	JW	50	60	80	70	70	80	80

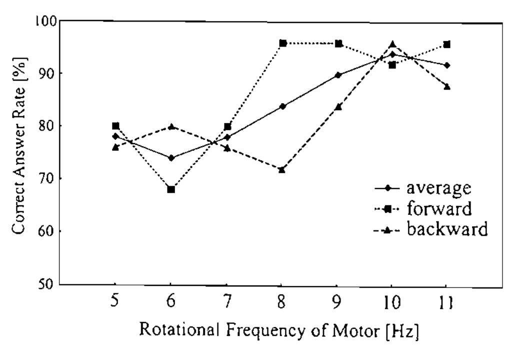


Figure 6. Direction identification performance (average for five subjects)

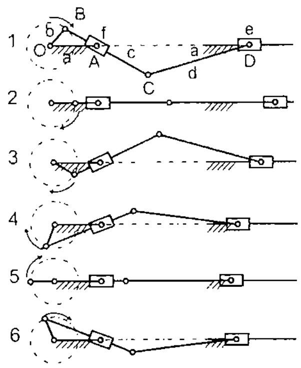


Fig.1 Motion of slider

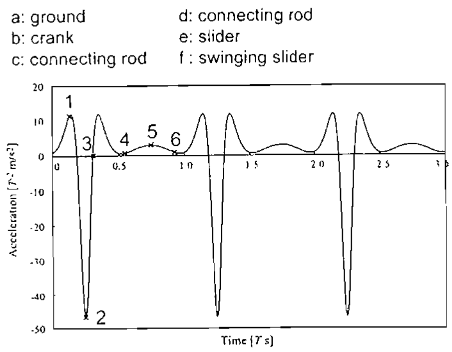


Fig.2 Theoretical acceleration value

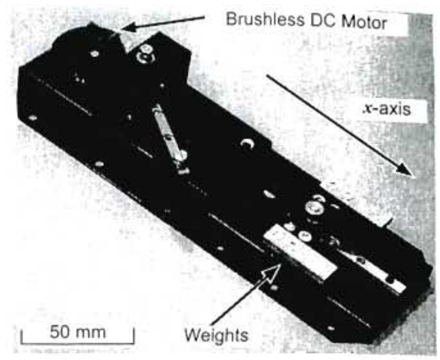


Fig.3 Overview of the haptic display

theoretical value of acceleration are described in Figures 1 and 2.

Figure 3 shows the prototype that generates asymmetric acceleration. In the prototype, rotation of the motor makes the weights slide backwards and forwards with asymmetric acceleration. The device is composed of a single DOF (degree of freedom) mechanism. Since the prototype neither accelerates nor decelerates with the motor, the energy efficiency is high. Thus the mechanism is thought to be suitable for mobile and wearable computers which have limited energy reserves. The motor in the virtual force display is a brushless DC motor (EC45 Flat motor; Maxon Motor), which has a weight of 88 g, and a maximum permissible rotation speed of 10,000 rpm. The weight of the virtual force display except weights and the motor amplifier is approximately 230 g. The display is 70 mm wide × 200 mm deep × 48 mm high.

We measured the output acceleration of the virtual force display to confirm the basic mechanical properties. An acceleration sensor whose weight, including ancillary electronic parts, was 2 g was adopted (ADXL210; Analog Devices Co.). The acceleration sensor was fixed to a weight in the virtual force display with double-sided tape, and the virtual force display was fixed to a base with double-sided tape. The mass of weights on the slider in the display was 20 g. Figure 4 shows the measured acceleration values. Mechanical friction and sensor drift generated high-frequency noise, but peak moment and time ratio of acceleration change basically matched the theoretical values.

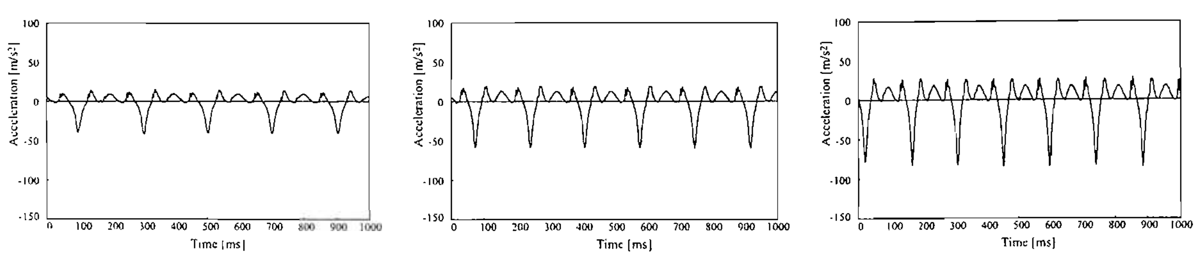
3. Evaluation of perception

First, we confirmed whether humans could perceive the virtual force or not. Next, we attempted to delineate the effect by altering the frequency of the acceleration change and the peak force value. In the experiments, subjects made a single interval two-alternative forced-choice (2AFC) judgment on the force direction.

3.1. Experiment 1: does the haptic illusion happen?

To examine whether humans could perceive the virtual force, we determined the correct answer rate at several motor rotational frequencies. The task was to judge whether the force presented was 'forward' or 'backward'.

3.1.1. Participants. The subjects were five men from 25 to 29 years of age, (average was 26.8 years). Four were right-handed and one was left-handed. Subject HA was experienced with the device and the remaining four were naive. Visuals effects were suppressed by the use of eye masks.



(a) 5 Hz (b) 6 Hz (c) 7 Hz

Figure 4. Actual value of acceleration

change and the peak value of force. The objective of Experiment 2 was to investigate the impact of these two parameters on the perception of the virtual force vector. Experiment 2 was similar to Experiment 1, but the weights were changed.

3.3.1. Participants and apparatus. The subjects were four men from Experiment 1, the average age was 26.8 years. Three were right-handed and one was left-handed. Subject HA was experienced with the device and the remaining three were naive.

The experimental apparatus of Experiment 2 was identical to that of Experiment 1.

3.3.2. Procedure. Experiment 2 followed the procedure of Experiment 1 but four combinations of mass of the weights on the slider in the display and rotational frequency of the motor were examined: (X1) 20 g & 10 Hz, (X2) 80 g & 5 Hz, (Y1) 5 g & 10 Hz, and (Y2) 20 g & 5 Hz. Pairs X1-X2 and Y1-Y2 had the same amplitude of force because the relationship between mass, m, acceleration, α, and applied force, F, is F=mα by Newton's second law of motion, and α is proportional to f^2 (f is frequency).

3.4. Results and discussion of Experiment 2

Table 2 shows the results of Experiment 2. Two subjects whose correct answer rate was under 80 % in condition Y2 had acceptable answer rates in condition Y1. Although Y1 and Y2 had the same amplitude of force, Y1 had higher frequency than Y2. Thus it is considered that the frequency of acceleration change effects perception.

There was no significant difference in the correct answer rates for X1 and X2. Although the relation between X1 and X2 is similar to that of Y1 and Y2, X1-X2 had higher force amplitudes than Y1-Y2. Thus it is considered that the amplitude of force also effects perception. A comparison of X2 and Y2, the pair with the same frequency, also indicates that the amplitude of force plays an important role in perception.

We believe that the results provide strong evidence that both the frequency of acceleration and amplitude of force influence the perception of the virtual force vector. However, our current data do not indicate which is the dominant factor.

Table 2. Correct answer rate for combinations of frequency of acceleration and mass of weights under condition of equivalent force

		Correct Answer [%]			
		Condition			
		X1 20g&10Hz	X2 80g&5Hz	Y1 5g&10Hz	Y2 20g&5Hz
Subject	GK	100	100	100	100
	TK	90	100	100	70
	HA	100	100	90	100
	IT	100	90	80	70

4. Conclusion

This paper introduced a simple haptic method that can create a virtual force vector without a fulcrum; it is based on the tactile and proprioceptive characteristics of humans. We designed and developed a prototype that implements the proposed method by using periodic translation motion to generate asymmetric acceleration changes. We examined the impact of the weights of the oscillating masses and the rotational frequency of the driving motor on the perception of short-term virtual force vectors. We found that the vector is well perceived using practical weights and rotating frequencies; results indicated that both the frequency and amplitude of acceleration play important roles in the perception of the vector. Future works include creating virtual force vectors in all directions, preventing the generation of acceleration in unintended directions, and solving the problem of the acceleration change due to gravity.

References

[1] S. Ertan *et al.*, "A Wearable Haptic Navigation System", *Proc. of the 2nd International Symposium on Wearable Computers*, pp. 164-165, 1998.

[2] D. Ross and B. Blasch, "Wearable Interfaces for Orientation and Wayfinding", *ACM Conference on Assistive Technologies*, pp. 193-200, 2000.

[3] T. Amemiya *et al.*, "Virtual Leading Blocks for the Deaf-Blind: A Real-Time Way-Finder by Verbal-Nonverbal Hybrid Interface and High-Density RFID Tag Space", *Proc. of IEEE VR 2004*, pp. 165-172, 2004.

[4] H. Yano *et al.*, "Development of a Non-Grounded Haptic Interface Using the Gyro Effect", *Proc. of HAPTICS 2003*, pp. 32-39, 2003.

[5] Y. Tanaka *et al.*, "Mobile Torque Display and Haptic Characteristics of Human Palm", *Proc. of ICAT 2001*, pp. 115-120, 2001

[6] N. Kakuda and M. Nagaoka, "Dynamic response of human muscle spindle afferents to stretch during voluntary contraction", *Journal of Physiology*, Vol. 513, pp. 621-628, 1998.

[7] P. H. Lindsay and D. A. Norman, "Human Information Processing: An Introduction to Psychology", *Academic Press*, 1977.

[8] S. S. Stevens, "Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects". *John Wiley and Sons*, 1975.