EV-Pen: Leveraging Electrovibration Haptic Feedback in Pen Interaction

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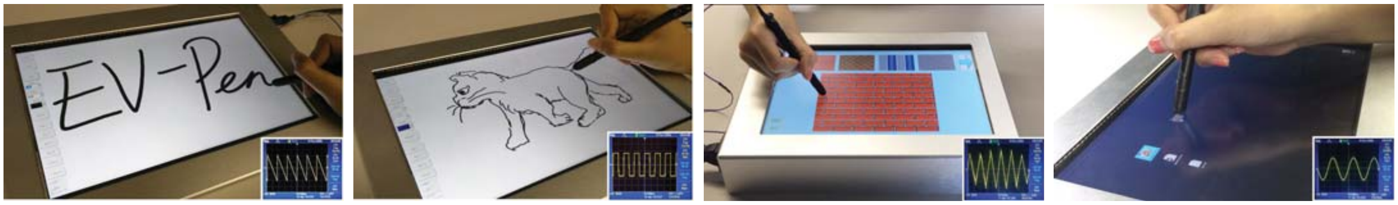

(a) Handwriting (b) Drawing (c) Texture Simulations (d) GUI Elements with Haptic Feedback

Figure 1. Demo applications with electrovibration haptic feedback created for our EV-Pen.

ABSTRACT

This paper presents an Electrovibration Pen (EV-Pen) which incorporates electrovibration technology into pen interactions. The EV-Pen has two unique characteristics: precise interaction and pen-on-paper feeling. We conducted four experiments for evaluating the EV-Pen. Experiment 1 was to determine preliminary characteristics of the EV-Pen. Experiments 2 and 3 were to evaluate precise interaction task performance through a steering task and a tracing task. We compared user performance between the EV-Pen, a mechanical-vibration pen, a normal pen without feedback and electrovibration-based finger interaction. Experimental results indicated that the EV-Pen outperformed the other devices in precise task interactions. Experiment 4 tested pen-on-paper feeling in drawing and handwriting tasks, and it was observed that the EV-Pen significantly enhances user experience. Based on the experimental results, we discuss implications and potential benefits for the design of the EV-Pen.

Author Keywords

pen; electrovibration; haptic feedback; steering task; tracing task; drawing; handwriting

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation]: User Interfaces; Haptic I/O, Input devices and strategies

INTRODUCTION

Recently, pen-based devices are widely used in computer graphics systems by designers, artists and architects [11, 13]. Pen-based interaction has also become a de-facto standard input method for large screen smartphones and tablet computers. Some pen-based products have been launched, such as the Apple Pencil, the Microsoft Surface Pen, and the Samsung S-Pen. These have shown real potential but there is room for significant improvement.

For example, currently available products do not consider feedback and material properties that could simulate a real pen-on-paper experience. To overcome this issue, pen devices with haptic feedback based on mechanical technology were developed [2, 6, 7, 12, 14, 15, 20]. However, in such pens, traditional vibrotactile feedback, which is generated by mechanical motors [5], may shake the whole pen and the hand, thus making it difficult to perform precise operations.

For performing precise operations and implementing real pen-on-paper feeling, we developed the EV-Pen by leveraging *electrovibration* technology [16] in pen interaction (Figure 1). It controls electrostatic friction [4] between the pen-tip and the touch surface to produce multisensory feedback. The EV-Pen has two unique characteristics: 1) precise interaction enhances human performance (e.g., menu navigation, tracing) because unlike conventional vibrotactile feedback pen, the EV-Pen has no mechanical actuator to disturb movement of the pen-tip; 2) pen-on-paper feeling enhances user satisfaction (e.g., drawing, handwriting) because it allows users to perceive different textures.

In this paper, we first review the related work and describe the implementation of the EV-Pen. We then present an experiment to determine preliminary characteristics of the EV-Pen (Experiment 1), and evaluate two unique characteristics (precise interaction in Experiments 2 and 3, and pen-on-paper feeling in Experiment 4). Concretely, *Experiment 1* was to determine the basic characteristics of the EV-Pen, which also provided the basic parameter values for Experiment 2, 3 and 4. *Experiment 2* was a fundamental study to look *theoretically* at whether the steering law holds well with our EV-Pen,

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i.e., whether the EV-Pen can perform basic HCI tasks. *Experiment 3* was an empirical study which *quantitatively* investigated the performance of the EV-Pen through the tracing task. *Experiment 4* was performed to *qualitatively* understand the user experience when interacting with the EV-Pen in practice through drawing and handwriting.

The experiment results confirmed that the EV-Pen has two unique characteristics: precise interaction which enhances human performance (e.g., menu navigation, tracing); pen-on-paper feeling which enhances user satisfaction (e.g., drawing, handwriting).

RELATED WORK

Our work focuses on leveraging electrovibration haptic feedback for pen interaction. This section summarizes previous studies related to haptic perception for pen and electrovibration for finger interaction.

Haptic Perception for Pen

Pen devices with haptic perception features have been explored in many studies. The works can be classified into three subcategories based on the technology used. (1) *Haptic feedback through vibration actuator*: these pen devices provided vibrotactile haptic feedback to users by augmenting different kinds of vibration actuators such as linear resonant actuators, piezo-ceramic actuators [6], vibration motors [2, 12], TouchEngine actuators [20], solenoid actuators [14, 15] and Maxon motors [7]. (2) *Haptic feedback through retractable machinery*: to provide a greater degree of freedom in pen motion apart from the feedback, researchers adopted retractable technology. By using different kinds of motors, these pen devices can be changed in length [18, 28] and shape [10] while interacting on screens. (3) *Haptic feedback through electromagnetic technology*: Wintergerst et al. [27] designed a reflective haptic pen operated through changing friction between the steel ball and a screen by the electromagnetic coil.

First, undesirable forces, vibration and noise are unavoidably produced in motors because of bearings, sliding contacts, imbalance, geared power transmissions and friction force [5]. So, when motors or some other mechanical actuators are used to provide haptic feedback, the feedback may shake the whole pen and the hand, making it difficult to perform precise operations with the pen. Furthermore, the noise produced by mechanical actuators can be annoying, causing distraction which leads to a non-immersive experience.

Second, previous works focused on haptic texture rendering and modelling [17, 22] to re-create paper-like textures with haptic pen using actuators, but they have focused less on discussing a natural pen-on-paper feeling to improve the performance of pen interaction in HCI (e.g., steering, tracing).

We have developed the EV-Pen which provides haptic feedback *without* mechanical actuator. Thus, our EV-Pen feedback is silent and does not cause disturbance because no physical motion ever happens inside the pen. Also, as the feedback of the EV-Pen is generated by controlling friction between pen-tip and touch surface, this passive (frictional) nature supports precise interactions. However, haptic feedback using a mechanical actuator is active (i.e. making energy).

Electrovibration for Finger

The effect of "electrovibration" was discovered by Mallinckrodt et al. [16] while a finger was touched on a surface with a high-voltage (110 V) AC conductor coated with a thin layer of insulation. Applications based on the electrovibration effect on a touchscreen have been developed by some researchers [3, 4, 26], such as TeslaTouch and REVEL which allowed users to feel different textures and friction between objects.

However, extreme temperatures and humidity can interfere with the sensation of electrovibration on the human body [9] when the human skin becomes moist. Furthermore, users felt numb and uncomfortable after extended use with voltages (more than 250V, 6-8 minutes). This fact was revealed through our pilot studies.

Moreover, due to "*fat finger*" problems [23], it is difficult to perform accurate movement tasks, such as drawing and gesturing [25]. For handwriting and drawing tasks, studies [21, 25] have shown that users prefer a pen over a finger.

Our EV-Pen augments electrovibration technology into the pen device, where sensation is barely influenced by extreme environments and human body. By contrast, numbness was not experienced during experiments with our EV-Pen. Participants found EV-Pen haptic feedback to be comfortable. At the same time, the EV-Pen inherits all the advantages of pen interactions, particularly in supporting precise interaction (e.g., drawing and handwriting).

In summary, no previous study has focused on electrovibration for pen interaction. Also, little study has explored possible application scenarios for effective haptic pen interaction including analyzing the task performance quality and satisfaction of the users. Thus, we leverage electrovibration into pen interactions to enhance user experience and performance.

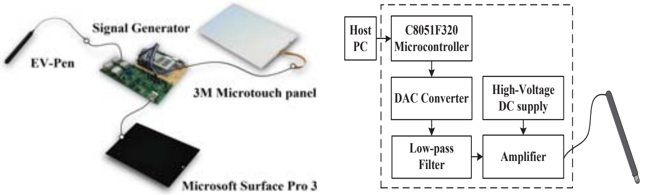
THE IMPLEMENTATION OF EV-PEN

Our prototype of the EV-Pen provides haptic feedback which is based on the primary principle of electrovibration without using any form of mechanical actuator. The system structure of the EV-Pen is shown in Figure 2a.

Prototype Design

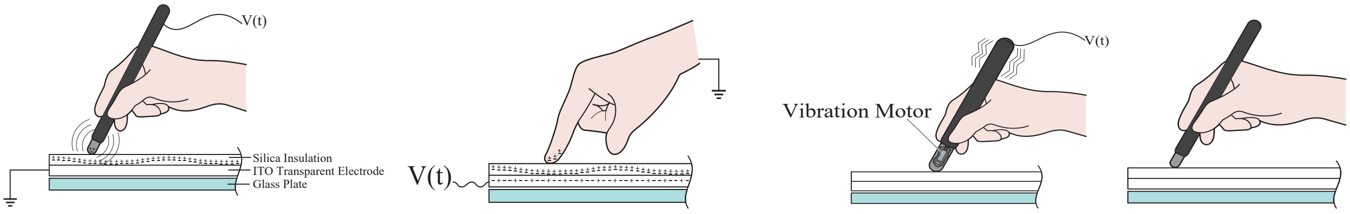
To create the EV-Pen, we modified a capacitive pen which was originally designed for capacitive-based touch surfaces. The pen is about 100mm long and 7 mm wide. The pen-tip diameter is 5 mm. We connected the tail of the pen to a signal generator. Then, the pen was covered with insulation tape.

To activate the principle of electrovibration, a 3M Microtouch panel was used (model number: $SCT3250EX$). It is composed of an ITO transparent electrode sheet applied to a glass



(a) The components of EV-Pen (b) The signal generator of EV-Pen

Figure 2. The system structure of EV-Pen.



(a) EV-Pen (b) EV-Finger (c) V-Pen (d) N-Pen

Figure 3. Four different input devices tested in experiment.

plate coated with a layer of silica insulation. The thickness of the silica insulation layer is one micron. The thickness of the ITO transparent electrode layer is 40 nanometers. The signal generator and the transparent electrode sheet of the 3M Microtouch were electrically coupled to a common ground to create a return ground path for the signal.

The signal generator provided the drive signal for the EV-Pen (Figure 2b). A Silicon $C8051F320$ microcontroller generated a low-amplitude signal using an 8 bit digital-to-analog converter ($DAC0832$). Various signal shapes were stored in the microcontroller's flash memory and their frequencies and amplitudes were controlled by the host computer. The signal was smoothed using a low-pass filter and amplified using a transistor amplifier with high-voltage DC supply. The low pass filter cutoff frequency was 3 KHz, which would scarcely distort the low-frequency wave. We tested the waveform on an oscilloscope. Finally, the signal was injected to the EV-Pen. The drive signal frequency range was 10 Hz to 1000 Hz, and the amplitude range was 0 V to 400 V. The current was limited to 0.5mA, which was considered safe.

Theory of Operation

When the EV-Pen (Figure 3a) slides over the 3M Microtouch panel, the signal generator creates various signals V(t) of sufficient amplitude to affect the pen. An electrostatic force of attraction develops between the sliding EV-Pen and the underlying electrode. The attractive force increases the dynamic friction between the EV-Pen and the 3M Microtouch surface. This friction can be controlled by modulating the waveform, amplitude and frequency of the drive signal. Thus, users can feel haptic feedback during pen motion and no feedback while the pen is stationary according to the principle of electrovibration technology.

By contrast with TeslaTouch [4], we reversed the electrovibration path: the signal was injected to the EV-Pen and the surface was grounded, which enhances haptic feedback and supports multi-point feedback.

EXPERIMENT 1: PRELIMINARY CHARACTERIZATION

Designing effective haptic interfaces based on the EV-Pen requires an understanding of the basic factors and usability characteristics of electrovibration for a pen. What are the lowest signal levels that users can feel? What about the subjective feelings of users toward our EV-Pen? To answer these questions, we conducted detection threshold pilot studies and subjective evaluation studies.

Detection Threshold Pilot Study

To judge the perception-based characteristics of the EV-Pen, it is essential to measure the absolute detection threshold. This psychological measure fixes the baseline of human sensitivity. In the case of the EV-Pen, we calculated the minimum voltage amplitude that creates a just noticeable difference at a typical frequency. We were obviously unable to consider the voltages below the detection threshold, as those are not effective in creating haptic sensations.

We estimated the detection and discrimination thresholds for seven frequencies: 50, 100, 150, 200, 250, 300 and 350 Hz. We randomized the order of frequencies to minimize the order effect. A widely used one-up/two-down adaptive staircase procedure [4] was implemented. We then estimated absolute detection thresholds by using a two-alternative forced-choice paradigm. The touchscreen canvas was split into two areas; one had haptic feedback, while the other had none. In each trial, we randomly assigned stimulus to one of the two areas and participants determined which area had haptic sensation.

Six participants (3 males, 3 females, aged from 21 to 27 years old, mean age 23.8 years old, all right handed) took part in the pilot study. They conducted between 50 and 100 trials for each of the 7 reference frequencies. Total experiment time was around 45 minutes.

Results and Discussion

The detection threshold results are shown in Figure 4. We found: (1) frequency influences the detection threshold of a sine waveform, (2) frequency barely influences the detection threshold of a square waveform, (3) the detection threshold of a square waveform is lower than that of a sine waveform, (4) the detection threshold of sine waveform for the EV-Pen is lower than that of TeslaTouch [4].

The experiment provides important guidelines for designing the EV-Pen interfaces. For example, the results inform the designer that at each frequency the applied voltage must be above the corresponding detection threshold level in order to provide a haptic sensation that a user can perceive. Also, results show that the EV-Pen is operable in low power mode, so it can be applied in mobile devices.

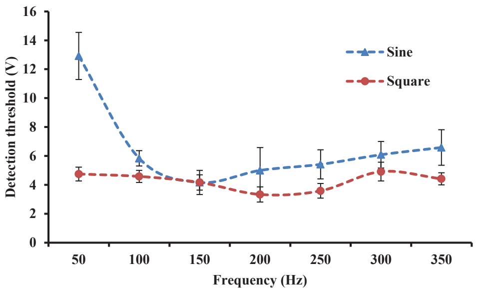


Figure 4. Mean detection threshold with standard error bars.

Parameters	Values	
Waveform	Sine	Square
Frequency	Low:50Hz	High:200Hz
Amplitude	Low:100V	High:250V

Table 1. The different parameters tested in experiment

Subjective Evaluation Study

We conducted subjective evaluation to better understand how users feel the haptic feedback produced by the EV-Pen.

Participants

Twelve volunteers (6 males, 6 females, aged from 21 to 35 years old, average age 27.6 years, all right handed) participated in the experiment. None had prior exposure to this technology and none had worked with a stylus.

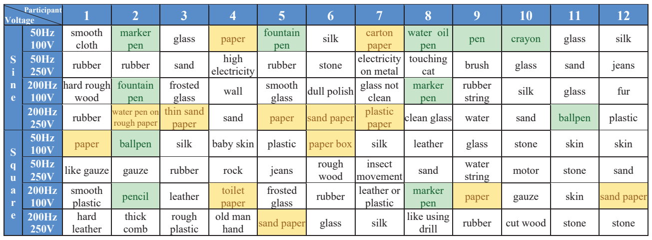
Task and Procedure

Participants felt eight kinds of haptic feedback from the EV-Pen produced by six amplitude & frequency & waveform combinations (Table 1). We chose two frequencies that are within the sensitivity range of human perception, and a low amplitude that is strong enough to be perceived, whereas the high amplitude is not so strong as to make the users uncomfortable. These were determined through pilot studies.

Participants were asked to draw the gestures for as long as they wished with each feedback type of the EV-Pen. The feedback types were presented to the user randomly. After each feedback experience, participants filled out a two-session questionnaire. In the first session, participants were asked to describe each feedback type in their own words as comprehensively as possible (e.g., the feeling is like using paper). In the second session, participants used a set of 7-point Likert scales to record their evaluations of the following characteristics: hardness ($1 =$ softness to $7 =$ hardness), roughness ($1 =$ roughness to $7 =$ smooth), friction ($1 =$ sticky to $7 =$ slippery), pleasant ($1 =$ unpleasant to $7 =$ pleasant) [4, 19]. The sessions took about 35 minutes.

Results and Discussion

First session results are as follows (Table 2). For the sine waveform with low frequency and low amplitude (50Hz, 100V), five participants described the feeling as various kinds of pen (e.g., pen, water oil pen, fountain pen) and two participants described it as various kinds of paper (e.g., paper, cardboard paper). However, for the sine waveform with high frequency and high amplitude (200Hz, 250V), five participants described it as various kinds of paper (e.g., paper, rough paper, plastic paper, sand paper). For the square waveform with low frequency and low amplitude (50Hz, 100V), three participants described the feeling as various kinds of paper or pen (e.g., paper, paper box, ballpen). However, for the square waveform with high frequency and low amplitude (200Hz, 100V), five participants described it as various kinds of paper or pen (e.g., paper, toilet paper, sand paper, pencil). Other participants described it as rubber, stone, sand and skin.



Voltage \ Participant		1	2	3	4	5	6	7	8	9	10	11	12
Sine	50Hz 100V	smooth cloth	marker pen	glass	paper	fountain pen	silk	carton paper	water oil pen	pen	crayon	glass	silk
	50Hz 250V	rubber	rubber	sand	high electricity	rubber	stone	electricity on metal	touching cat	brush	glass	sand	jeans
	200Hz 100V	hard rough wood	fountain pen	frosted glass	wall	smooth glass	dull polish	glass not clean	marker pen	rubber string	silk	glass	fur
	200Hz 250V	rubber	water pen on rough paper	thin sand paper	sand	paper	sand paper	plastic paper	clean glass	water	sand	ballpen	plastic
Square	50Hz 100V	paper	ballpen	silk	baby skin	plastic	paper box	silk	leather	glass	stone	skin	skin
	50Hz 250V	like gauze	gauze	rubber	rock	jeans	rough wood	insect movement	sand	water string	motor	stone	sand
	200Hz 100V	smooth plastic	pencil	leather	toilet paper	frosted glass	rubber	leather or plastic	marker pen	paper	gauze	skin	sand paper
	200Hz 250V	hard leather	thick comb	rough plastic	old man hand	sand paper	glass	silk	like using drill	rubber	cut wood	stone	stone

Table 2. Participants' subjective feelings of the EV-Pen.

Second session results are presented in Figure 5. Indeed, amplitude had a significant effect on perception of hardness ($\chi^2(2) = 5.33$, $p < 0.05$): low amplitudes were associated with sensations of softness, while high amplitudes felt like hardness. Amplitude had a significant effect on perception of roughness ($\chi^2(2) = 12.00$, $p < 0.01$): low amplitudes were associated with roughness sensations, while high amplitudes felt smooth. Amplitude had a significant effect on perception of friction ($\chi^2(2) = 8.33$, $p < 0.01$): low amplitudes were associated with slippery sensations, while high amplitudes felt sticky. Waveform also had a significant effect on perception of friction ($\chi^2(2) = 5.33$, $p < 0.05$): sine waveforms were associated with slippery sensations, while square waveforms felt sticky. Haptic feedback with high amplitudes were rated less pleasant than lower amplitude, with a mean rating of 4.5 versus 3.3 ($\chi^2(2) = 5.33$, $p < 0.05$).

The results of subjective evaluation studies provide important guidelines for designing the EV-Pen interfaces. For example, the square wave with high amplitude produces unpleasant feedback which may act as "*error feedback*". However, the sine waveform with low amplitude means pleasant feedback which may act as "*affirmative feedback*". Participants also expressed their feeling as real *pen-on-paper*. These kinds of natural feelings are helpful when handwriting and drawing.

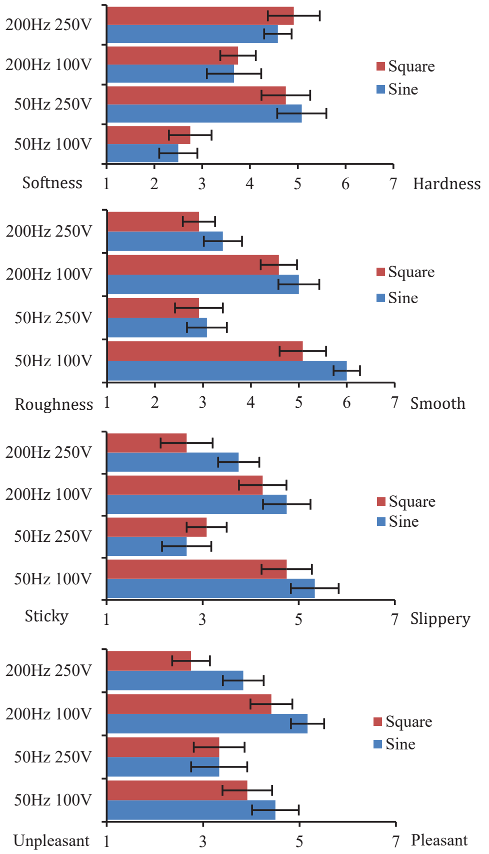


Figure 5. Ratings of hardness, roughness, friction and pleasure.

EXPERIMENT 2: STEERING TASK

To examine the effectiveness of the EV-Pen, we conducted a steering task experiment. The choice of a steering task for our experiment was based on careful consideration. Steering tasks can be used in many daily tasks like navigation in hierarchical menus and other trajectory-based manipulations. Our EV-Pen is a new device so we modeled it on the steering law which has been widely used as a theoretical framework for computer input device evaluation [1,20].

We compared the EV-Pen with two conventional haptic input modes (Table 3): mechanical-vibration pen input (V-Pen) and electrovibration-based finger input (EV-Finger). For comparison with a V-Pen, we chose a typical type of general vibration actuated V-Pen. EV-Finger and the EV-Pen are based on the same principle.

For the steering task, while the pen or finger was moving along the circular steering tunnel, haptic feedback was presented to the participants on the boundaries and outside the tunnel, i.e., we built a "*haptic tunnel wall*" to indicate that participants were inside the tunnel. Haptic feedback indicated "*error feedback*" [24] for participants.

Apparatus

The experiment was conducted on a Microsoft Surface Pro 3 tablet PC running Windows 8.1 pro. The screen size was 12-inches with a resolution of 2160×1440 pixels. The experimental software was developed in C++.

For the EV-Pen, the stimulating signal was a square wave with an amplitude of 300V, and a frequency of 120Hz. We chose these parameters based on Experiment 1 because the square wave with high amplitude provided more unpleasant feelings to users. This frequency of 120 Hz was easily detected, according to our experiment of device characteristics. This combination was therefore suitable for "error feedback". We tested the parameters through pilot studies with four participants. The feedback was easily perceived and the device was steady and comfortable to use.

For the V-Pen (Figure 3c), a vibration motor (2.0 V to 3.0 V, $LA4 - 503AC2$) was mounted in the capacitive pen body. The body of the same type of capacitive pen was used for the EV-Pen. The size of the motor was 4.3×10.7 mm. We used adhesive tape to mount the motor inside the pen, 15 mm from the pen-tip. The electrical signal was controlled by a Silicon $C8051F320$ microcontroller. For fair device comparison, the stimuli intensity with V-Pen was set as close as possible to the EV-Pen. We conducted pilot studies with four participants to determine suitable feedback parameters. As a result, the motor was supplied with 2.0 Vdc/55 mA.

Devices	EV-Pen	V-Pen	EV-Finger
Implement	Pen	Pen	Finger
Mechanism	Electrovibration	Vibration	Electrovibration
Feature	No motor inside the pen	Motor inside the pen	Visual occlusion by finger-tip
	Precise interaction	Imprecise interaction	Affected by humidity etc.

Table 3. Three input devices tested in Experiment 2.

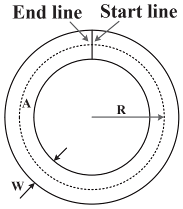


Figure 6. The steering task.

For EV-Finger (Figure 3b), it was similar to TeslaTouch [4]. The drive signal was the same as the one used in the EV-Pen.

Participants

Twelve volunteers (7 males, 5 females, aged from 22 to 37 years old, average age 31.6 years, all right handed) participated in the experiment. Only one had worked with a stylus.

Task and Procedure

We chose a non-liner steering task because the circular steering task is more complex than a straight line steering task. For a circular tunnel, the movement distance *A* was equal to the circle's circumference, i.e., $2\pi R$, where *R* is the radius. The tunnel width was *W*. According to the steering law, the *index of difficulty* for steering through a circular tunnel was $ID = A/W$. The movement time *T* could then be expressed in the formula: $T = a + bID$, where a and b are empirically determined constants.

All participants conducted the experiment in sitting postures. Participants were asked to move along a circular tunnel from the start line to the end line as accurately and as fast as possible in a clockwise direction using a pen or finger (Figure 6).

We measured the movement time *T* (time taken to move from the start line to the end line). To measure the accuracy of the trajectory produced, we calculated its lateral standard deviation *SD* (standard deviation of the distances between trajectory points and the center of the circular tunnel) and out of path movement *OPM* (percentage of trajectory points outside the tunnel boundaries). For both *SD* and *OPM*, higher values indicate lower accuracy.

After finishing the trials, the participants were asked to fill in a questionnaire to evaluate their subjective performances on 7-point Likert scales with ratings from 1 (worst) to 7 (best).

Design

The experiment employed a within-subject factorial design. The independent variables were: tunnel width W (30, 40, and 50 pixels), tunnel distance A (1000, 1500 and 1800 pixels), and three devices (EV-Pen, V-Pen, EV-Finger). Participants were exposed to three devices, whose order of appearance was balanced using a Latin square. For each device, participants were asked to perform the task in all combinations of tunnel widths and tunnel distances 3 times in random order.

The experiment consisted of: 12 participants × 3 tunnel widths × 3 tunnel distances × 3 devices × 3 repetitious = 972 trials.

The temperature in the lab was 25.0°C – 27.5°C with a relative humidity of 62.3% – 77.0% during experiments.

Results

Movement Time (T)

A repeated-measures ANOVA (analysis of variance) showed that there was no significant effect for devices on *T*. The overall means of *T* were 2.57s for the EV-Pen, 2.25s for the V-Pen and 2.23s for the EV-Finger.

The regression analysis on *T* and *ID* indicated that all three devices proved to fit the steering law with correlations greater than 0.90. The linear regression between the steering time (in s) and steering *ID* produced the following equations for each of the three input devices:

EV-Pen: $T = 0.0436ID + 0.9422\ (R^2 = 0.9322)$

V-Pen: $T = 0.0357ID + 0.9133\ (R^2 = 0.9176)$

EV-Finger: $T = 0.0301ID + 1.0957\ (R^2 = 0.9057)$

Our results showed that the steering law holds well with our EV-Pen $(R^2 = 0.93)$.

Out of Path Movement (OPM)

A repeated-measures ANOVA showed that there was a statistically significant effect for devices on *OPM* ($F_{2,22} = 22.35, p < 0.001$). The overall means of *OPM* were 8.76% for the EV-Pen, 11.84% for the V-Pen and 21.80% for the EV-Finger (Figure 7a).

Pair-wise comparison tests showed that the participants produced significantly lower *OPM* ($p < 0.05$) with the EV-Pen compared to other devices.

Standard Deviation (SD)

A repeated-measures analysis showed that there was a statistically significant effect for devices on *SD* ($F_{2,22} = 16.25, p < 0.001$). The overall means of *SD* were 15.63 for the EV-Pen, 19.06 for the V-Pen and 24.26 for the EV-Finger (Figure 7b).

Pair-wise comparison tests showed that the participants produced significantly lower *SD* ($p < 0.05$) with the EV-Pen compared to other devices.

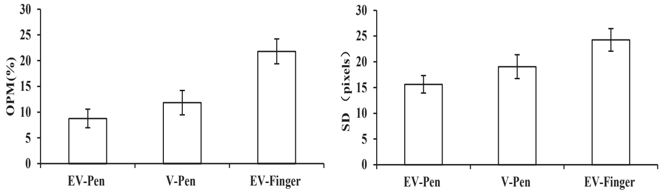
Subjective Evaluation

According to the results of the questionnaire, half of the participants ($6/12$) preferred the EV-Pen over other devices to negotiate the tunnel. The participants also commented that the haptic feedback of the EV-Pen was more comfortable than with the V-Pen. The majority of participants ($9/12$) reported that it was difficult to complete the tasks with EV-Finger.

A repeated-measures analysis showed that there was a statistically significant effect for devices on *satisfaction* ($F_{2,22} = 7.90, p < 0.05$). The overall means of *satisfaction* were 5.75 for the EV-Pen, 5.41 for the V-Pen and 4.08 for the EV-Finger. *Satisfaction* was the highest with the EV-Pen.

Discussion

The results showed that the *OPM* and the *SD* with the EV-Pen were the lowest. This indicates that participants performed the task most accurately with the EV-Pen. This is because the haptic feedback of the V-Pen comes from the body of the pen. As a result, the smooth movement of the pen is disturbed by the vibrating motor which is mounted inside the pen. By contrast, the EV-Pen produces haptic feedback from the pen-tip when the pen-tip touches the screen surface and this allows users to perform more precise interactions.



(a) Mean OPM with standard error bars. (b) Mean SD with standard error bars.

Figure 7. The results of steering task with three different input devices.

The experiment showed that *T* with the EV-Pen was slightly longer than with the others. This is caused mainly by friction between the pen and the touch surface due to the electrovibration. When participants moved outside the tunnel erroneously, the friction between the EV-Pen and touch surface increased to provide haptic feedback to indicate such errors. In other words, the EV-Pen acts as a "*brake*" and "*caution*". By contrast, the V-Pen acts only as a "*caution*".

Half of the participants preferred the EV-Pen. They stated that the EV-Pen was comfortable and easy to use. Besides, the majority of participants ($9/12$) reported that it was difficult to complete the tasks with the EV-Finger. Indeed, it is difficult to perform the task when the tunnel is narrow because of visual occlusion caused by the thickness of the finger-tip.

EV-Finger interaction is affected by the users skin properties (electric impedance), temperature and humidity [3, 9]. The temperature and humidity in our experiment constituted mild weather (temperature was $25.0°C – 27.5°C$ and humidity was $62.3\% – 77.0\%$). We could predict that if temperature and humidity became very high, the EV-Finger would not work very well. By contrast, weather conditions and human body barely affect the haptic feedback of our EV-Pen.

EXPERIMENT 3: TRACING TASK

Experiment 1 confirmed that our EV-Pen could provide haptic feedback just like pen-on-paper feeling. Experiment 2 confirmed that our EV-Pen outperformed the other input modes in precise navigation interactions. Therefore, Experiment 3 was aimed to quantitatively investigate the performance of the EV-Pen in a tracing task because tracing is also a fundamental skill for people to learn writing or drawing.

As a pen is the main device for tracing tasks, we compared our EV-Pen with two conventional pen modes: mechanical-vibration pen (V-Pen) and normal pen (N-Pen, i.e. pen without haptic feedback). By contrast with the steering task experiment, haptic feedback was presented to the participants in the tunnels to guide tracing while the pen was moving along the tracing tunnel, so the participants could feel haptic feedback most of the time. In this task, haptic feedback indicated "affirmative feedback" to the participants.

Apparatus

The apparatus for this experiment was similar to that used in Experiment 2.

Figure 8. Three different shapes tested in Experiment 3.

For the EV-Pen, the stimulating signal was a sine wave with an amplitude of 200 V, and a frequency of 120 Hz. We chose these parameters based on the results of Experiment 1 because sine waves with lower amplitudes could provide more pleasant sensations to users. This frequency of 120 Hz was easily detected according to our experiment of device characteristics. This combination was suitable for navigating the tunnel. We tested the parameters through pilot studies with four participants. The feedback was easily perceived and the device was steady and comfortable to use.

For the V-Pen (Figure 3c), the device was the same as that used in Experiment 2. For fair device comparison, the stimuli intensity with V-Pen was set as close as possible to the EV-Pen. We conducted pilot studies with four participants to determine suitable feedback parameters. As a result, the motor was supplied with 1.5 Vdc/30 mA.

For the N-Pen (Figure 3d), the same type of capacitive pen was used, but without feedback.

Participants

Twelve volunteers (6 males, 6 females, aged from 21 to 35 years old, average age 26.83 years, all right handed) participated in the experiment. None had worked with a stylus.

Task and Procedure

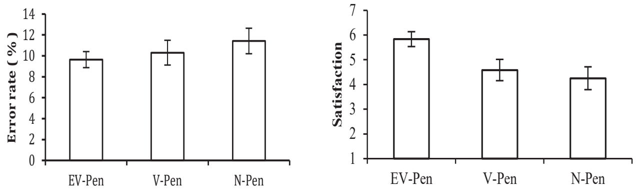
All participants conducted the experiment in sitting postures. Participants were instructed to trace over the shape in one stroke, beginning at the start line to the end line in a clockwise direction (Figure 8). They traced over the shape once for each pen, the EV-Pen, the V-Pen and the N-Pen. The participants were asked to move as accurately and as quickly as possible.

For a trial, we collected the following metrics: *Tracing time* (time taken to completely trace a shape) and *Error rate* (percentage of trajectory points outside the tunnel). We also saved a screenshot of each completed trial. After finishing the trials, participants were asked to fill in a questionnaire to evaluate their subjective performances on 7-point Likert scales with ratings from 1 (worst) to 7 (best).

Design

The experiment employed a within-subject factorial design. The independent variables were: shapes (circle, star and puzzle), tunnel width (30 and 60 pixels), and three devices (EV-Pen, V-Pen and N-Pen). The shape size was 1200 pixels. Participants were exposed to all three devices, whose order of appearance was balanced using a Latin square. For each device, participants were asked to perform the task in all combinations of shapes and tunnel widths 3 times in random order.

The experiment consisted of: 12 participants × 3 shapes × 2 tunnel widths × 3 devices × 3 repetitious = 648 trials.



(a) Mean error rate with standard error bars. (b) Mean satisfaction with standard error bars.

Figure 9. The results of tracing task with three different input devices.

Results

Tracing Time (T)

A repeated-measures ANOVA showed no significant effect for devices on *T*. The overall means of *T* were 13.96s for the EV-Pen, 14.04s for the V-Pen and 13.68s for the N-Pen.

Error rate

A repeated-measures ANOVA showed that there was a statistically significant effect for devices on *error rate* ($F_{2,22} = 3.669, p < 0.05$). The overall means of *error rate* were 9.64% for the EV-Pen, 10.29% for the V-Pen and 11.41% for the N-Pen (Figure 9a).

Pair-wise comparison tests showed that the participants produced a significantly lower *error rate* ($p < 0.05$) with the EV-Pen compared to N-Pen.

Subjective Evaluation

According to the questionnaire results, nine participants (9/12) preferred the EV-Pen to other devices to negotiate the tunnel. They also commented that the haptic feedback of the EV-Pen was more comfortable than the V-Pen.

The overall means of *satisfaction* were 5.83 for the EV-Pen, 4.58 for the V-Pen and 4.25 for the N-Pen (Figure 9b). A repeated-measures analysis showed that there a was statistically significant effect on *satisfaction* ($F_{2,22} = 4.25, p < 0.05$). *Satisfaction* with the EV-Pen was the highest.

Discussion

The experimental results showed that the *error rate* with the EV-Pen was the lowest. This indicates that participants performed the task most accurately with the EV-Pen. Furthermore, nine participants (9/12) preferred the EV-Pen over the other input devices. The feedback provided by the EV-Pen was the most pleasant of all input devices. Participants stated that the movement of the EV-Pen was easy to control and it was easy to complete the task with the EV-Pen. This is mainly because our EV-Pen produces haptic feedback from the pen-tip rather than from the pens body and this allows users to perform more precise interactions.

By contrast, the participants stated that feedback provided by the V-Pen was a little shaky. When they used it for a long time it felt unnatural and uncomfortable. This is because haptic feedback from the V-Pen comes from the body of the pen resulting in disturbed movement which requires more effort to control and to maintain accuracy tracing.

The participants stated that N-Pen was too smooth for writing on the touchscreen. They could not control it very well because there was no haptic feedback.

EXPERIMENT 4: DRAWING AND HANDWRITING

There are many touchscreen applications where the EV-Pen can be implemented to perform specific tasks. However, our EV-Pen uniquely supports applications where precise and controlled pen movements are required. Moreover, the superior waveform, frequency & amplitude range and unique characteristics of the EV-Pen yield more accurate haptic representations and allow for richer user experiences.

Therefore, to understand user experience with the EV-Pen, we chose drawing and handwriting applications to imitate real world experiences because they are common for user tasks. Also, these applications are suited to continuous feedback which can improve the quality of the artwork and user experience.

Participants

Six participants (3 males, 3 females, aged from 19 to 35 years old, average age 25 years, all right handed) took part in the drawing and handwriting applications. All of them had moderate to good sketching and illustration skills. Three of them had drawing experience on computers.

Task and Procedure

We designed drawing and handwriting applications aligned with our previous experiments. Six different kinds of haptic feedback of the EV-Pen were presented to users and users freely chose the one that best suited them. The thickness of the line could be changed, meanwhile different intensities of haptic feedback were provided.

Participants performed the experiment in the sitting posture. After training, they were asked to (1) freely experiment with the EV-Pen to create artworks of their own, and then (2) write five phrases ("Good afternoon", "Hello", "Happy Birthday", "Handwriting" and "Drawing") in the most natural way. We conducted an open-ended interview with a subjective questionnaire during the experiment. On an average, participants took 45 minutes to complete the whole experiment.

Results

Overall, participants responded positively regarding the effectiveness of our EV-Pen. All participants appreciated the unique haptic feedback of our EV-Pen.

P3: "I think it is interesting. It is difficult to tell the feeling, but I like it. The feedback made me think that I was drawing. I prefer to use it always. "

P5: "The haptic feedback is very important for drawing and handwriting because you can express the feeling from it."

P6: "The haptic experience of writing or drawing with pen now can be transferable from real pen-on-paper to the computer environment."

Drawing

Some artworks created by participants are shown in Figure 10. Participants expressed that the EV-Pen provided haptic feedback just like using a real pen to draw on real paper.

P3: "The feeling is like pencil drawing on paper. If I change the line thickness, the feedback is changed to other pencil."

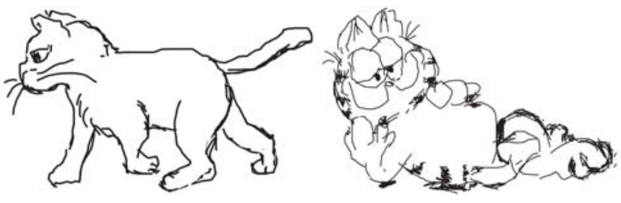

(a) (b)

Figure 10. Artworks created by participants using the EV-Pen.

They also stated that the feeling was good and it helped to improve the quality of their computer-based drawing.

P6: "It can provide the feeling of texture. The feeling is like drawing on real paper. It is better than my previous drawing experience on computers."

Handwriting

Similar to drawing, participants were satisfied with the haptic feedback as they could relate to real pen-on-paper writing.

P1: " The feeling of the friction with the pen is like a pencil sliding on real paper. This feeling is amazing."

Participants also believed that the continuous haptic feeling enriched their experience and enhanced their writing ability.

P4: " This haptic feedback makes me immersed in writing on touchscreens."

Potential Applications

Participants pointed out their desire to use our EV-Pen in a variety of applications. Also, they provided some good ideas for future enhancements.

P3: "If a professional drawing software application can provide haptic feedback like this, that will be perfect."

P4: "This can be used to teach children about sketching and writing in computers."

P6: "If different pen pressures can change the thickness of the line and the haptic feedback of the pen, that will be helpful."

Discussion

The overall experience of participants revealed their appreciation for the unique capabilities of our EV-Pen. They felt that our EV-Pen kept them engaged while drawing and handwriting. Also, participants agreed that they drew and wrote more correctly with haptic feedback. Whether the character shapes were curly, straight, mixed etc., it was easy for participants to control their pen movements on the touchscreen (just as with real pen and paper). They enjoyed the tasks and were satisfied with their experiences during the experiment. The feedback was natural and harmonious, so they were able to draw complex sketches and shaped letters easily with the system. The results showed that our EV-Pen can enhance user experience, efficiency and accuracy when drawing and handwriting.

GENERAL DISCUSSION

We designed the EV-Pen that leverages electrovibration haptic feedback in pen interaction by controlling electrostatic friction between the pen and the touch surface. Therefore, the EV-Pen can produce multisensory feedback. In other words, the electrostatic friction is controlled by the voltage, which is further parameterized by changing the waveform, amplitude and frequency. Thus, this potentially offers three channels of haptic information. Moreover, the haptic feedback can be dynamically changed according to the circumstances while the pen is moving on the surface.

Implications and Opportunities

The four experiments showed that our EV-Pen can enhance user performance and experience for precise tasks with real pen-on-paper feeling. More than that, a set of new haptic interactions can be implemented. We have implemented "*Texture Simulations*" and "*GUI Elements with Haptic Feedback*" (described below). We have further explored some interaction opportunities of the EV-Pen (shown below).

Texture Simulations (Figure 1c)

Apart from augmenting the pen device with electrovibration, we also characterized the feedback strengths which were responsible for distinct feelings. We offered three dynamic haptic feedback channels of information depending on amplitude, frequency and waveform. The results showed that our EV-Pen can simulate different kinds of haptic interaction, such as simulating friction between objects, feeling different textural patterns, implementing different feedback modes and intensities for different commands on touchscreens.

GUI Elements with Haptic Feedback (Figure 1d)

There are many interesting ways through which we can augment haptic feedback of the GUI elements for EV-Pen interaction. For example, users can feel different kinds of haptic feedback when they drag different files (e.g., doc, pdf, jpg) on touchscreens. These functions will help improve user satisfaction and experience in EV-Pen interactions.

Haptic Information Layers

In our experiments, we have tested the characterization and user feeling for some typical combinations of waveform, frequency and amplitude. The results support additional feedback channels which open up the possibility of perceiving non-visual information layers. For example, users can choose and draw on different layers with different types of haptic feedback from the EV-Pen when they work with Photoshop.

Pen Simulations

Most of the participants commented that interaction with the EV-Pen is more helpful, satisfactory, more engaging and it enhances their ability to draw or write well. This is because the feeling when drawing and writing is very similar to the physical and intimate interaction with a pen on real paper. We can further extend the user experience by simulating haptic feedback modes for different kinds of pen (e.g., pencil, ballpen, crayon, brush) on different kinds of paper.

Multi-point Haptic Feedback (Figure 11a)

More than one EV-Pen can be utilized to interact simultaneously on a multi-point touchscreen by being injected with different drive signals. For example, two EV-Pens can be injected with different drive signals providing two kinds of feedback (e.g., one for drawing and the other for handwriting), which is useful for collaborative work.

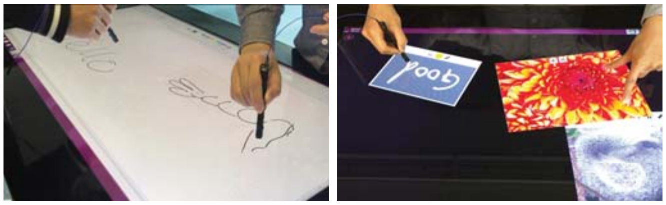

(a) Multi-point Haptic Feedback (b) Pen-Finger Simultaneous Operation

Figure 11. Interaction opportunities of the EV-Pen.

Pen-Finger Simultaneous Operation (Figure 11b)

Based on the capacity to perform multi-point haptic feedback using electrovibration, we can combine electrovibration in pen and finger technology for simultaneous operation. The EV-Pen and fingers could employ two handed operations on a single touchscreen. For example, the non-dominant hand could perform a gross manipulation with fingers, such as zoom in/out and rotating, while the dominant hand simultaneously performs a fine-grained interaction with the EV-Pen, such as gesturing, writing and drawing [8]. Both the EV-Pen and fingers can feel respective haptic feedback at the same time. This could be an interesting area for future exploration.

Limitations and Future work

Our prototype EV-Pen is wired with external hardware. To make it commercial and convenient to use, we can miniaturize the signal generator and put it inside the pen. The user's body can act as a common ground; when one hand holds the metal body of the mobile device (connected to the ground of the touch panel) and the other holds the EV-Pen (connected to the ground of the EV-Pen), the user can feel the haptic feedback. Current flow will be limited for safety.

In addition, we plan to put pressure, accelerometer and orientation sensors into the EV-Pen. Thus, haptic feedback will be controlled by pressure, tilt, rolling and azimuth of the pen [29]. Also we can dynamically change the waveform, frequency and amplitude by considering the pen location, velocity and direction, which can help simulate textures more precisely. This work will increase the interaction bandwidth and give sufficient choices to users who access the EV-Pen.

This paper focuses on pen interaction rather than presenting an entirely perceptual study. Thus, we only determined the basic detection threshold and a subjective evaluation study. Future work may include human perception (e.g., proximal stimuli, magnitude estimation) to enhance the efficiency of the EV-Pen. To make the "pen-on-paper" feeling and other textures even more realistic, we will explore more complex combinations of waveform & frequency & amplitude.

CONCLUSION

We presented the EV-Pen for touchscreens providing variable intensity electrovibration feedback without any mechanical actuator. We demonstrated the effectiveness of the EV-Pen through four experiments. The results confirmed that employing the EV-Pen enhances the user experience to perform precise tasks with real pen-on-paper feeling. We are still at an early stage in exploring electrovibration for pen interactions. We believe that this work will open up a wide range of possibilities for both electrovibration and pen interactions.

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