Enhancing Pen-based Interaction using Electrovibration and Vibration Haptic Feedback

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ABSTRACT

This paper presents the *EV^2-Pen* which leverages *electrovibration* technology and *vibration* technology in pen interaction. Electrovibration technology can produce multisensory feedback when the pen is in motion (sliding/moving on the screen), and vibration technology can provide vibrative feedback when the pen is stationary (pointing/resting on the screen). We conducted an experiment to investigate user performance with the EV^2-Pen. The results indicated that the EV^2-Pen outperformed the EV-Pen [18, 19] in pointing-steering tasks. Finally, we discuss the characteristics of the EV^2-Pen, and explore some possible applications and scenarios.

ACM Classification Keywords

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

Author Keywords

Electrovibration; vibration; haptic feedback; pen-based interaction

INTRODUCTION

Nowadays, pen devices have become popular for interactions that require precision (e.g., drawing, handwriting) on touchscreen devices like smartphones and tablet computers, many of which are commercially available in the market, e.g., Apple Pencil, Microsoft Surface Pen, Samsung S-Pen. However, their interaction efficiency is suboptimal, as they do not provide haptic feedback. This deficiency not only limits the potential of pen interactions, but also diminishes the user's satisfaction and experience when using such pen devices.

Some current pen devices provide haptic feedback based on mechanical technology [2, 5–7, 9–11, 14], where the mechanical actuators provide continuous feedback. However, traditional vibrotactile feedback, generated by some mechanical motors [4], may shake the whole pen and the hand, thereby making precise interactions difficult to perform. To improve the situation, researchers deployed electrovibration technology for pen-based interaction, i.e., EV-Pen [18, 19], providing haptic sensation without the use of mechanical actuators. However, HCI involves both trajectory (sliding/moving on the screen) and pointing tasks. The EV-Pen can only provide haptic feedback for trajectory tasks, but cannot provide haptic feedback for pointing tasks (pointing/resting on the screen).

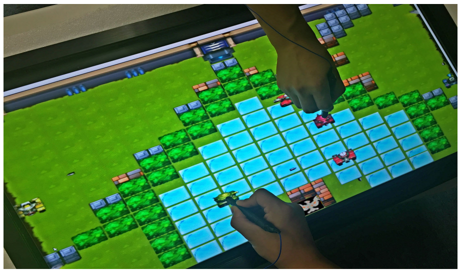

Figure 1. Playing Tank Shooting Haptic Game with the EV^2-Pen.

This paper presents an Electrovibration-Vibration Pen (EV^2-Pen) device, where users can feel continuous haptic feedback when the pen is either in motion or stationary. Here, the *electrovibration* [12] technology produces multisensory feedback (e.g. real pen-on-paper feeling [18]) as the pen slides on a touchscreen, controlling electrostatic attractive friction [3] between the pen-tip and the touch surface. Moreover, the *vibration* technology can be used to provide vibrative feedback produced by an actuator when the pen points or remains stationary on the touchscreen.

Combining these two feedback modalities has clear benefits: the EV^2-Pen enriches the information transfer, enhances human performance on touchscreen interaction by giving continuous haptic feedback for both pointing and trajectory tasks.

In this paper, we first introduce the implementation of the EV^2-Pen. We then describe a linear pointing-steering experiment that investigates user performance. Finally, we discuss the characteristics of the EV^2-Pen and explore some possible applications and scenarios (Figure 1).

RELATED WORK

There is a large body of research on pen interaction, e.g. [15] for target selection, [16] for grips and gestures, [17] for pen and finger stroke gestures. This paper mainly focuses on haptic feedback for pen interaction. These works can be broadly classified into two categories based on the technology used.

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- *Haptic feedback through mechanical actuators*: some pen devices provide vibrotactile haptic feedback by augmenting different kinds of vibration actuators such as linear resonant actuators [6], piezo-ceramic actuators [5], vibration motors [2, 9], TouchEngine actuators [14], solenoid actuators [10, 11] and Maxon motors [7]. Some other pen devices used actuators to change the length [13, 20] and shape [8] when interacting with objects on the screen.

  However, in such devices, undesirable forces, vibration and noise are unavoidably produced because of bearings, sliding contacts, imbalance, geared power transmissions and frictional forces [4]. Therefore, when mechanical actuators are used to provide haptic feedback, the feedback source may shake the whole pen and the hand, making it difficult for the user to perform precise manipulative operations.

- *Haptic feedback through electrovibration technology*: Wang et al. [18, 19] designed an electrovibration haptic pen that can simulate real pen-on-paper feelings and perform precise manipulative operations without any form of a mechanical actuator. The pen operates by changing the electrostatic attractive friction between the pen-tip and touch surface to produce various modes of haptic feedback.

  However, for providing haptic feedback through electrovibration technology, users can only feel the feedback while the pen is sliding on the screen. Because HCI involves both pointing and trajectory tasks, as the pen points or stays on the screen, no haptic feedback is provided for pointing tasks, limiting its application domains.

In summary, to extend the application range of electrovibration and vibration technology, we have developed the EV^2-Pen device which combines the advantages of electrovibration and vibration. The unique characteristics make our EV^2-Pen particularly suitable for pointing-steering tasks.

THE IMPLEMENTATION OF EV^2-PEN

Our prototype of the EV^2-Pen provides haptic feedback which is based on the primary principle of electrovibration and vibration. For the electrovibration that we used in the EV^2-Pen, the electrostatic friction between the pen-tip and the touchscreen is controlled by voltage. For the vibration that we used in the EV^2-Pen, the feedback is controlled by voltage, with different intensities of haptic feedback according to the scenarios.

The system structure of the EV^2-Pen is shown in Figure 2. For our prototype, we used a 32-inch display monitor. To capture the user's input, a 32-inch IR multi-touch panel was installed over it. The touch detection part and the voltage signal part were physically isolated, so the current setup didn't affect the performance of touch detection.

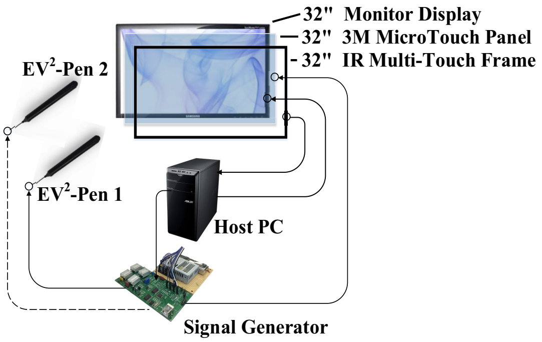


Figure 2. The system structure of EV^2-Pen.

Prototype Design

To create the EV^2-Pen, we modified a capacitive pen which was originally designed for capacitive-based touch surfaces. The pen was about 100 mm long and 7 mm wide, with a pen-tip of 5 mm in diameter .

Electrovibration feedback

For electrovibration feedback, the tail of the pen was connected to a signal generator. The pen was then covered with insulation tape. To activate electrovibration, a 3M Microtouch panel was also used (model number: $SCT3250EX$, size: 32-inch). It was composed of an ITO transparent electrode sheet applied to a glass plate coated with a layer of silica insulation. The thickness of the silica insulation layer was one micron. And the thickness of the ITO transparent electrode layer was 40 nanometers. The signal generator and the transparent electrode sheet of 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^2-Pen (Figure 3). A Silicon $C8051F320$ microcontroller generated a low-amplitude signal using an 8 bit digital-to-analog converter. Various signal shapes were stored in the microcontroller's flash memory and the 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 a high-voltage DC supply. The cutoff frequency of the low pass filter 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^2-Pen. The drive signal frequency range was 10 Hz to 1 KHz, and the amplitude range was 0 V to 400 V. The current was limited to 0.5mA, which was considered safe.

When the EV^2-Pen (Figure 4) slid over the touch panel, the signal generator would produce various signals V(t) of sufficient amplitude to drive the pen and generate a sensation for the user. An electrostatic force of attraction was also developed between the sliding EV^2-Pen and the underlying electrode, increasing the dynamic friction between the EV^2-Pen and the touch surface. This frictional force could be controlled by modulating the waveform, amplitude and frequency of the drive signal, producing haptic feedback to the user.

By contrast with TeslaTouch [3], we reversed the electrovibration path: the signal was injected to the EV^2-Pen and the

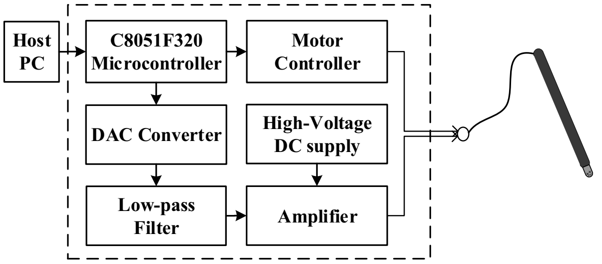


Figure 3. The signal generator of EV^2-Pen.

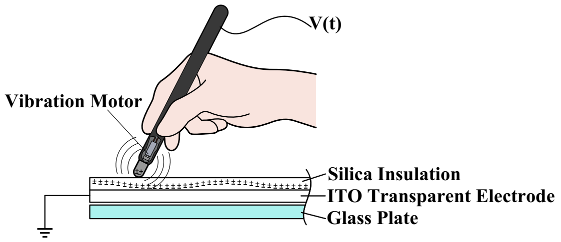


Figure 4. The schematic diagram of EV^2-Pen.

surface was grounded. This enhances the haptic feedback and it also supports multi-point feedback.

Vibration feedback

For vibrative feedback, a vibration motor (2.0 V to 3.0 V, $LA4-503AC2$) was mounted in the capacitive pen body. 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 the microcontroller.

USER STUDY

To better understand user performance of the EV^2-Pen, we conducted a linear pointing-steering based task [1] between the EV^2-Pen and electrovibration for pen (EV-Pen) [18, 19].

Task and Procedure

Twelve participants (6 males, 6 females, aged from 21 to 35 years old, $M = 26.4$, $SD = 4.6$, all right handed) took part in the experiment. After 10 minutes training, the participants were asked to select and drag a “ball” (target) from the start point to the end as quickly and as accurately as possible (Figure 5). According to the steering law [1], the *index of difficulty* for steering through a linear tunnel was $ID = A/W$. The movement time T_s could then be expressed in the formula: $T_s = a + bID$, where a and b are empirically determined constants.

For the EV^2-Pen, vibration feedback (while selecting the target and reached the destination) and electrovibration feedback (while moving in the tunnel) were provided. For electrovibration, the stimulating signal was a sine wave with an amplitude of 150 V, and a frequency of 120 Hz. For vibration, the motor was supplied with 2.0 VDC/55 mA. We chose these parameter settings because the feedback was easily perceived by the user and the vibration intensity was limited, so it barely interfered with the task. We tested and optimized these parameters through pilot studies.

For the EV-Pen, the device was the same as the EV^2-Pen but without the drive signal to activate the vibration feedback. When the pen was moving inside the tunnel, only electrovibration feedback was generated. The stimulating signal of electrovibration was the same with the EV^2-Pen.

A within-subject experimental design with repeated-measures was used. The independent variables were: target size S (3, 4 and 5 mm), tunnel width W (8 and 12 mm), tunnel distance A (150 and 250 mm), and two devices (EV^2-Pen, EV-Pen).

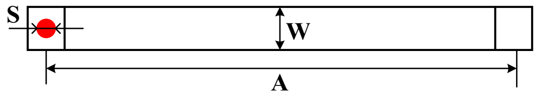
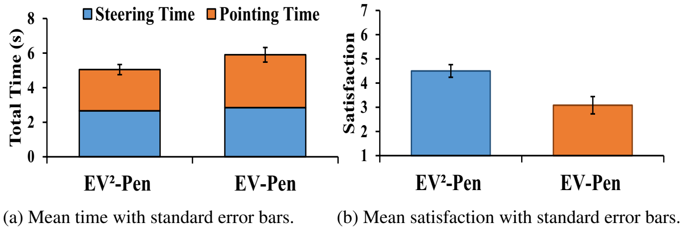


Figure 5. The linear pointing-steering based tasks.



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

Figure 6. The results of pointing-steering based task.

Participants were asked to perform the task in all combinations 3 times in random order. The experiment consisted of: 12 participants × 2 devices × 3 target sizes × 2 tunnel widths × 2 tunnel distances × 3 repetitious = 864 trials.

After the experiment, participants were asked to fill out a questionnaire to rank their satisfaction levels using Likert scale ratings from 1 (worst) to 7 (best). On average, each participant took 20 minutes to complete the whole experiment.

Results

Total Time (T)

The total time: $T = T_p + T_s$, where T_p is pointing time (i.e., time taken to select the target) and T_s is steering time (i.e., time taken to drag the target from the start point to the end).

The means of T were 5.04s ($SD = 1.01$) for the EV^2-Pen, and 5.90s ($SD = 1.46$) for the EV-Pen (Figure 6a). A repeated-measures ANOVA showed that there was a statistically significant effect for devices on T ($F_{1,11} = 14.92, p < 0.01$).

Pointing Time (T_p)

The means of T_p were 2.38s ($SD = 0.86$) for the EV^2-Pen, and 3.05s ($SD = 0.80$) for the EV-Pen (Figure 6a). A repeated-measures ANOVA showed that there was a statistically significant effect for devices on T_p ($F_{1,11} = 12.75, p < 0.01$).

Steering Time (T_s)

The means of T_s were 2.66s ($SD = 0.93$) for the EV^2-Pen, and 2.85s ($SD = 1.19$) for the EV-Pen (Figure 6a). A repeated-measures ANOVA showed that there was no significant effect for devices on T_s.

A regression analysis on T_s and ID indicated that all devices proved to fit the steering law with correlations greater than 0.90. Using linear regression between the steering time (in s) and steering ID the following equations for the devices were developed (Figure 7):

EV^2-Pen: $T_s = 0.05ID + 1.6147 \; (R^2 = 0.9101)$

EV-Pen: $T_s = 0.043ID + 2.0175 \; (R^2 = 0.9024)$

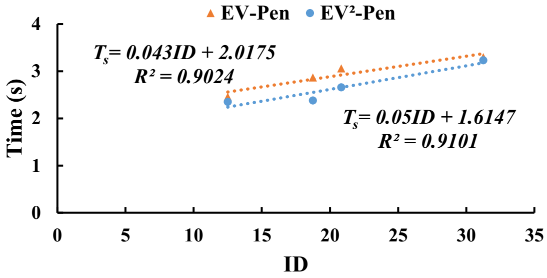
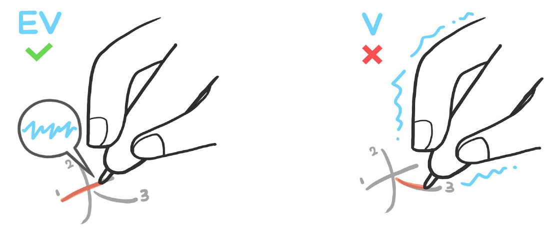


Figure 7. The steering law regression with two different input devices.



(a) Electrovibration for correct stroke order. (b) Vibration for incorrect stroke order.

Figure 8. Enhancing handwriting learning using the EV^2-Pen.

Error rate

The means of *error rate* (percentage of trajectory points outside the tunnel boundaries) were 6.67% for the EV^2-Pen, and 7.76% for the EV-Pen. A repeated-measures ANOVA showed that there was no significant effect for devices on *error rate*.

Subjective Evaluation

The questionnaire results suggested that, all participants preferred the EV^2-Pen over EV-Pen to complete the tasks. The means of *satisfaction* were 4.50 ($SD = 0.90$) for the EV^2-Pen, and 3.08 ($SD = 1.24$) for the EV-Pen (Figure 6b). Non-parametric Wilcoxon signed-rank tests showed that there was a statistically significant effect on *satisfaction* ($Z = -3.002, p = 0.003$). The participants also commented that the haptic feedback of the EV^2-Pen was very useful for selecting the target.

DISCUSSION

We have designed the EV^2-Pen to leverage both electrovibration and vibration haptic feedback in pen interaction. The results of the experiment show that the T and T_p with the EV^2-Pen were lower than EV-Pen. Taking into the account that both the EV-Pen and EV^2-Pen have the same performance based on the same mechanism for the steering task, the difference in performance is therefore attributed only to the absence/presence of the vibration feedback. This indicates that the EV^2-Pen can enhance human performance in pointing tasks in HCI, e.g., pointing at buttons, selecting menus.

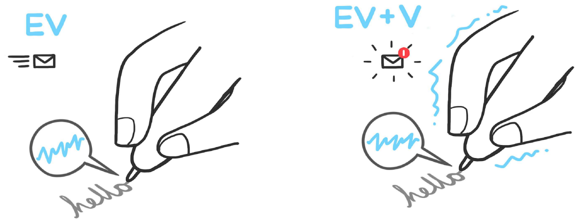
Interaction Design

The user study showed that our EV^2-Pen can enhance user performance and experience for pointing tasks in HCI. Furthermore, a set of new haptic interactions can be implemented.

Learning Handwriting

Unlike Latin alphabets, stroke-based characters (e.g., Chinese characters) are much more difficult to learn and to write. It requires a lot of effort to learn the stroke order and to control the spacing between the strokes. The EV^2-Pen can help users who are learning to write stroke-based characters more easily on touchscreens. We have also developed an application that allows users to write with haptic feedback (Figure 8).

When learners use the EV^2-Pen application system to learn handwriting, the pen can provide the pen-on-paper feeling which can enhance their writing experience by using electrovibration technology if they write it in the correct stroke order (Figure 8a). However, if the stroke order is incorrect, the EV^2-Pen will vibrate to issue an error alert (Figure 8b). By providing haptic feedback, we make the learning and practicing process easier, more effective and more efficient.



(a) Electrovibration while mail being sent. (b) Vibration while mail being received.

Figure 9. Haptic feedback for notification using the EV^2-Pen.

Feedback for Notification

The EV^2-Pen can support multiple users for face-to-face collaborative work on a multi-point touchscreen. While one or more users perform different tasks (e.g., handwriting, drawing) on the touchscreen, the EV^2-Pen can provide different haptic feedback for different users by using electrovibration technology (Figure 9a). Moreover, when one user sends a message to another person, or when an incoming notification (e.g., email, message, reminder) is received, the EV^2-Pen will vibrate to alert the user with a vibration sensation (Figure 9b). The combination of the two technologies improves the efficiency of collaborative work on multi-point touchscreens.

Haptic Game

By leveraging haptic feedback into game interaction, our EV^2-Pen can make computer games more interesting by supporting and augmenting any immersive experience. We have designed a Tank Shooting Game (Figure 1). Players can use the EV^2-Pen to control tank movements. When the tank is moving on a different terrain (e.g., grass, sand, cement, asphalt), the EV^2-Pen can provide different kinds of feedback to simulate different ground textures by using electrovibration technology. Furthermore, when the tank fires, the EV^2-Pen will vibrate to simulate the shock received by the tank.

In general, participants expressed their appreciation for the multi-sensory feedback of the EV^2-Pen with these three applications. They felt that their interaction experience with the EV^2-Pen was engaging and satisfying.

CONCLUSION

We have presented the EV^2-Pen that provides variable intensity feedback by leveraging electrovibration and vibration technology in pen-based interaction. The electrovibration technology is suitable for trajectory interaction, capable of producing different texture feedback (e.g., pen-on-paper feeling) as the pen slides on a touchscreen. In addition, the vibration technology is suitable for pointing interaction, providing vibrative feedback (e.g., hint, alert) when the pen interacts on a touchscreen.

Future work includes making the EV^2-Pen wireless and portable, and also exploring the effects of modulation of the two haptic sensations.

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