Flashpen: A High-Fidelity and High-Precision Multi-Surface Pen for Virtual Reality

Hugo Romat * Andreas Fender * Manuel Meier * Christian Holz *

Department of Computer Science
ETH Zürich, Switzerland

ABSTRACT

Digital pen interaction has become a first-class input modality for precision tasks such as writing, annotating, drawing, and 2D manipulation. The key enablers of digital inking are the capacitive or resistive sensors that are integrated in contemporary tablet devices. In Virtual Reality (VR), however, users typically provide input across large regions, hence limiting the suitability of using additional tablet devices for accurate pen input. In this paper, we present Flashpen, a digital pen for VR whose sensing principle affords accurately digitizing hand writing and intricate drawing, including small and quick turns. Flashpen re-purposes an inexpensive gaming mouse sensor that digitizes extremely fine grained motions in the micrometer range at over 8 kHz when moving on a surface. We combine Flashpen's high-fidelity relative input with the absolute tracking cues from a VR headset to enable pen interaction across a variety of VR applications. In our two-block evaluation, which consists of a tracing task and a writing task, we compare Flashpen to a professional drawing tablet (Wacom). With this, we demonstrate that Flashpen's fidelity matches the performance of state-of-the-art digitizers and approaches the fidelity of analog pens, while adding the flexibility of supporting a wide range of flat surfaces.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction devices—Graphics input devices;

Figure 1: Flashpen is a precise pen input device that can be used in a virtual reality environment (virtual reality content superimposed in this figure to visualize system usage). The device can be used on a horizontal surface like a table (left) or a vertical surface (right).

1 INTRODUCTION

Pen interaction is becoming a commodity input modality on interactive devices [5, 46], which has been shown to help externalize thoughts [36] via annotations and note-taking as well as to enhance visual thinking [54]. With the growing availability of VR applications and platforms, designers and researchers have started to explore their capability of supporting pen input for sketching [8, 23, 24, 55], to support gestures input [39], or to support mid-air techniques [6].

To register input, current VR sketching applications track the user's hands or handheld controllers through cameras built into the headset, mostly to sketch in mid-air (e.g., commercial systems like *TiltBrush*, *GravitySketch*, *Quill*, and *Logitech VR Ink Pilot*). The accuracy is thereby limited by the tracking system, i.e., the resolution and frame rate of the cameras used for registering input locations. The former is sufficient for sketching under visual control and has been shown to support an accuracy between 1 mm to around 5 mm in a dynamic configuration for the controller [16, 33]. However, it is the camera's frame rates (mostly around 65 Hz–90 Hz for current mobile or stationary headsets) and the comparatively low spatial resolution that are very limiting when reconstructing input strokes. Even static professional motion capture systems like OptiTrack require multiple perfectly calibrated cameras to reach sub-millimeter precision and to minimize (but not fully eliminate) jitter. Hence, despite such systems being well suited for high-fidelity motion capture and mid-air input, they are impractical for jitter-free fine-grained on-surface input, which requires a precision between 0.1 and 1 mm [13, 52]. Similarly, this also makes high-precision pointing and dragging tasks, which are already common on desktop interfaces (e.g., dragging points in a vector graphics program) infeasible for typical VR setups without artificially adjusting the control-display ratio. Therefore, VR interactions are typically on a larger scale than surface input (i.e., mostly contents on a room-scale, but not fine-grained interactions, e.g., on a virtual desk). Other approaches are based on using tablet interaction in VR [23] to palliate this lack of accuracy, bearing a trade-off with mobility and restricting the input surface.

We present Flashpen, a pen device that brings fine-grained near-analog pen input qualities to VR. Our prototype re-appropriates a flow sensor from high-end gaming mice that reliably registers movements of *one 226th of a millimeter* (or 4.42 micrometers). It operates at a frame rate of 8 kHz, thus digitizing pen strokes 40 × faster than state-of-the-art stylus input digitizers (e.g., Wacom [62], Microsoft Surface Pro [46]). Our prototype can be used on a flat surface (at different orientations, see Figure 1) with a wide range of supported surface materials. Our implementation combines medium-precision 6DoF camera tracking (absolute) with Flashpen's high-precision motion sensing (relative), bringing pen input to VR systems to enable fine-grained on-surface input and handwriting at high fidelity. We demonstrate Flashpen in a series of VR applications to highlight the potential of our approach. In our user evaluation we collected performance measurements, subjective data and qualitative feedback to compare Flashpen's performance to that of a professional Wacom stylus. The (subjective and objective) fidelity of Flashpen matches Wacom's precision, whereas Flashpen has the flexibility working on various different surfaces (tables, walls and more) instead of the confined area of a tablet.

*e-mail addresses: firstname.lastname@inf.ethz.ch

2 RELATED WORK

Our work builds on related efforts in pen hardware prototyping, VR devices for writing, and sketching interaction metaphors.

Input approaches for Virtual Reality: Several input devices that are designed for 2D tasks can be suitable for 3D tasks with a proper mapping [17]. Most of the sketching systems using hand input [65] that were proposed previously do not require high precision. Such use cases include quick sketches [32] or drawing *large* shapes under visual control [58], or controlling animation paths and orientations of objects [8]. In Augmented Reality, researchers have superimposed low-fidelity sketch input on top of the environment [28, 38]. All these systems have the lack of needed precision for interaction in common and were therefore suitable for the proposed techniques. For instance, conventional VR controllers [31] were used, e.g., for painting and drawing [9, 20, 57] or to create immersive data visualizations [55]. While suitable for gestures and sketching input, the resulting renderings and paintings can still remain rugged [23] and do not achieve a level of accuracy that is comparable to touchscreen devices [12, 21] without the fine-grained precision attainable with regular pens. To this end, several digital pens have been created to support the use in VR. Researchers appropriated physical pens for input in VR, such as in the Virtual Notepad [53] where a tablet digitized the handwriting and displayed it in VR. More recently, proposed devices have been augmented with additional sensors, such as reflective markers tracked by surrounding cameras [7, 23, 61, 68], which tracks pen motions during writing and pointing experiences. Others have shown that such pen input fosters the efficiency of data workers [29] and supports creativity in drawing applications [23]. Such devices still rely on external tracking systems that produce traces that do not approach analog writing. Researchers proposed alternative pen-approaches that implement their own tracking to draw curves and free-form shapes, such as FreeDrawer [63]. Other approaches for increasing input precision include a brush augmented with physical properties [35] or using haptic devices [34, 64] - also to mimic the texture of the surface [24]. For bridging 2D and 3D sketching, Symbiosis sketch [6] and VRSketchin [23] combine tablet and mid-air input to combine the precision of tablet sketching with the freedom of 3D drawing in VR. Mid-air interaction has also been investigated in the context of AR and VR by using grip-specific gestures [39] and evaluations in the context of tasks that require accuracy [10, 51].

Technology embedded in digital pens: Before describing our implementation for tracking pen input, we briefly discuss the components that enable digital pens to resolve writing and sketching input. Three main digitizer types exist:

Electromagnetic tracking: Such styli embed a printed circuit board across the entire device [62], typically situated underneath the display and its backlight. The circuit board has several planar coils that emit an electromagnetic field. As the pen approaches these fields and coils, it couples into the EM signal and adds a load, which is picked up across multiple coils from which the digitizer interpolates the position of the stylus. The field lines can emit up to 15 mm above the display, which allows for sensing hovering styli. Data is transmitted from the pen to the device (e.g., pressure and button presses) by modifying the frequency content of the load. Orientation is extrapolated from field orientations, which can be useful to remove parallax. Such pens (e.g., WACOM pen) display points at a frequency of 200Hz for the most recent devices.

Passive capacitive tracking: Passive styli are simple conductors that couple to the touch sensor through the electrostatic fields between the transmit and the receive lines of the sensor. Such styli couple to the user's hand, acting as an extension of their bodies, and are thus picked up by the touch digitizer using the transparent conductive lines in front of the display. Most inexpensive pens use this technology (e.g., Galaxy pen) at around 200 Hz.

Active capacitive sensing: Active styli started being introduced in the early 2000s. They also use the transparent sensor lines on touchscreens, but in contrast to passive pens, the pen tip injects an electrostatic signal that the touch digitizer can detect. The pen usually has a small battery on-board and emits frequency signals from the tip and the tail. Because this sensing principle naturally extends that implemented in touch devices, it has become popular and widely used (e.g., Microsoft Surface Pro 3 stylus [56]) at a frame rate of around 180 Hz.

Optical motion sensing: The sensor that we use in our Flashpen prototype is essentially a low-resolution camera comprising an array of around a thousand photodetectors. Combined with two lenses and an illuminant, the sensor tracks x and y translations from illuminated features in the images that typically stem from irregularities in the surface by comparing consecutive frames [42, 47, 50]. Illuminants typically operate in the red wavelengths, since such LEDs consume comparably little power and incur low fabrication costs [19]. Alternatives use blue LEDs to robustify tracking [15] to produce higher contrasts and work on more surfaces or infrared that penetrate surfaces deeper, making mice work on an even larger variety of surfaces. In terms of uses of mouse sensors for interactive scenarios, Soap [11] integrated one to detect relative in-hand motions and acted as a joystick. Small mouse sensors have also been embedded into miniaturized devices to detect several types of gestures [48] or worn on the body for 2D tracking [67] and for detecting several surface textures. To detect absolute positions using such sensors, fiducial markers are commonly used [37, 67]. Cook's patent application [22] is close to our approach and also proposes a flow sensor inside a digital pen to detect relative motions. Closest to our Flashpen is the family of *Anoto* pens, which embed a camera to track input locations when the pen is set down on surfaces that are covered with the systematic *Anoto* dot pattern [4]. Such kind of pen [49, 59] could be useful to support data worker activities, especially during annotation or externalization tasks in AR [40].

2D augmented digital pens: Several attempts have been made to enable styli to acquire new types of information or to increase their performance. For example, FlexStylus is a flexible stylus that uses the deformation of its shell as an additional degree of input [26]. The Multi-Touch Pen senses touch gestures of the index finger or thumb as well as a grip as a mechanism for mode switching [60]. Finally, cameras integrated into pen prototypes have also been used to detect gestures surrounding the pen and to trigger commands that act on the user's ink input. PenSight [44] embeds a downward-facing camera to detect gestures from both hands. Palm and touch gestures detected by the surface can also be used while writing to trigger several commands [45]. DodecaPen [66] uses a dodecahedron on a physical pen to capture handwriting through common cameras at 50 Hz over a 30 cm × 40 cm working area.

Role of sampling rate and accuracy: Many of the previous approaches use cameras to capture pen input (with most ranging from regular cameras at around 50Hz to OptiTrack cameras at around 120Hz). Annett et al. [2] identified some arising issues: stylus accuracy and stroke beautification. Inaccuracy [3] is often a parameter that force users to write bigger with digital pens compared to analog pens because they have more difficulty forming and terminating letters. Writing bigger increase the number of points sampled and help mimicking analog handwriting. Several researchers have developed stroke-beautification techniques [25, 41, 69] to overcome the low of number of points. Those algorithms are trying to interpolate the best curve based on several parameters such as velocity, pressure, direction that could match an analog writing curve. However, current beautification methods employed for inking do not match analog writing on paper [2]. In contrast, the strokes from our Flashpen prototype with its high sample rate and accuracy do not require any post-processing.

3 FLASHPEN: ASSEMBLY AND IMPLEMENTATION

We designed Flashpen to support fast interaction on any passive surface with the ambition to resolve pen strokes at the fidelity of analog handwriting. To that end, we designed a VR controller with the form factor of a pen. Flashpen's hinge allows the pen to adopt to comfortable postures during interaction on the surface so that users can write with it similar to a real pen but digitizing their ink in VR instead. In this section, we describe the components of our prototype and their assembly followed by the VR and camera setup including our tracking pipeline.

3.1 Device Components

As shown in Figure 3 (right), we designed Flashpen to be held like an ordinary pen. All sensors and electronics used are depicted in Figure 2. The shell of the pen is made from a 30 mm plastic tube wrapped in black electrical tape. This tube encases all hardware components except for the optical flow sensor at the tip. When writing with a regular pen, users hold the device with different hand postures. To accommodate this with Flashpen, we used a light plastic joint (*LEGO Mindstorms* hinge, Figure 2.4) that we cut so as to be as close as possible to the surface. The hinge has an angular range of 110° from left to right. Flashpen can therefore be used by left-handed as well as right-handed people and supports various grips for holding.

To track relative motions, Flashpen embeds an optical flow sensor (Pixart PMW3360) at the tip of the pen (2) whose lens and cover (3) we sanded down to be as small as possible. With its flat tip, the design is similar to the Adonit Pro 3 [1]. An inertial sensor mounted inside the shell of the pen captures rotations and accelerations (InvenSense MPU6500). All parts connect to an Expressif ESP32 microcontroller that connects to the PC through a cable to minimize the latency of input sensing and for power. Reflective markers are mounted around the pen tip (1) for tracking absolute positions using cameras. Overall, Flashpen weighs approximately 200 g. We used the shown prototype for both the study and the video accompanying the paper.

3.2 Tracking Setup

The flow sensor at Flashpen's tip captures optical reflections at 8,000 fps and derives relative motions from inter-frame differences, represented through relative motions $(\Delta x, \Delta y)$ encoded in fractions of a millimeter. We configured the flow sensor to operate in burst mode, such that Flashpen's microcontroller can report all relative motion events to the VR system at the full framerate. We complement the high-speed relative motion sensing on the tip with absolute positions from a camera system that records the reflections from Flashpen's markers. While a VR headset's built-in cameras could perform such tracking (Oculus quest establishes a world-referenced absolute coordinate system), we opted for a small but stationary tracking system for our prototype tests so as to focus on the capabilities of the

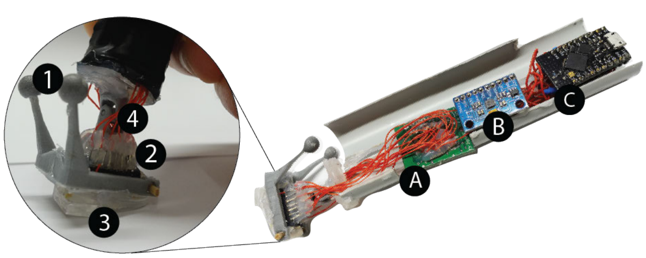

Figure 2: Prototype components: (1) markers for tracking, (2) optical flow sensor, (3) sensor lens, and (4) a plastic hinge to accommodate writing at various angles. Inside shell: (A) PMW3360 breakout board (optical flow sensor), (B) MPU6500 breakout board (IMU sensor), (C) ESP32 prototyping board (TinyPico)

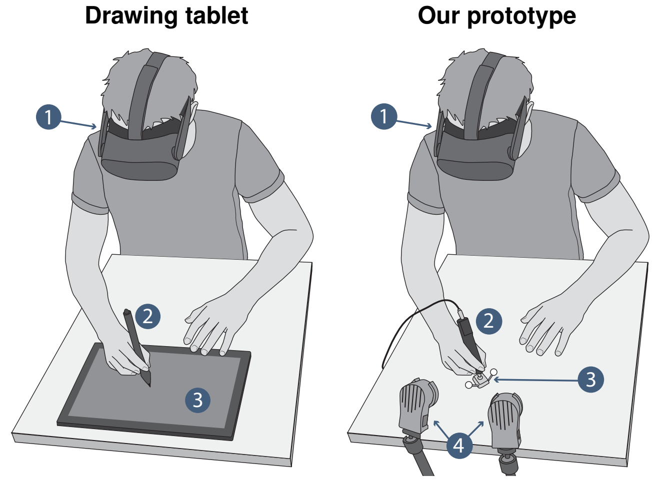

Figure 3: Virtual reality pen input based on a drawing tablet (left) versus our prototype (right). (1) Both variants use a VR headset. (2) Both, the drawing stylus (left) and our device (right) are held like a pen. (3) Conventional styli only work on the drawing tablet area (left), whereas we use a optical flow sensor that works on any surface (right). (4) We use two static OptiTrack Flex13 cameras to retrieve the absolute pen position (when in mid-air) and the pen orientation.

sensor. This removes potentially confounding factors like the VR-headset's capability to compensate head-rotation (which becomes increasingly accurate and responsive, but still might skew the results in our tests). We perform basic blob detection and line intersection in the (pre-calibrated) stereo setup to resolve the pen's position and rotation in absolute 3D space.

For inferring the pen *position*, only ever use one modality at a time (either cameras or optical flow sensor). We use the two cameras for absolute above-surface positions (i.e., when hovering) and the optical flow sensor for on-surface movements. Flashpen's flow sensor detects the presence and contrast of reflections, from which our prototype infers that it has been set down on a surface. Setting down the pen is an event that is also noticeable in the continuous signal of the inertial sensor. Once this state has been detected, the translation tracking is taken over by the pen in relative mode, starting from the last reported absolute position. Likewise, the flow sensor detects the absence (or low contrast) of reflected features, from which Flashpen infers a lift event. Whenever this event is detected, we switch the position tracking back to the camera system.

As opposed to the position, the absolute pen *orientation* is tracked by the cameras at all times (also when on the surface). This is necessary, because depending on the pen orientation around the surface normal when starting to write, the relative forward-right movements reported from the sensor do not correspond to the absolute forward-right axes from the users point of view. Similarly, users may slightly arc their writing, rotated about their elbow, thereby gradually changing the rotation of the pen and thus the perceived direction of writing. Such rotational movements amount to drift in tracked locations, if not accounted for. To incorporate the initial orientation as well as the small subconscious rotations, we combine the tracking of absolute rotation obtained from the camera system throughout, convolving potential yaw rotations into the relative movements reported from the flow sensor. In our experience, the required accuracy for adjusting the yaw is comparatively low, because users easily adapt visually, as long as the tracked yaw is not too far off or changes constantly.

We implemented the tracking and sensing pipeline in Unity (C#), whereas we used the *Velt framework* [27] (a Unity plugin) to directly process the camera streams and handle the overall dataflow. The application is executed on a PC inside the Unity Editor and rendered on an Oculus Quest 2 via Oculus Link (tethered).

4 USER STUDY

While a digital pen can be used to write and carefully annotate document, it can also be used as a precise input device and fine grained 2D input to manipulate widgets or interact with the virtual environment. To evaluate those opportunities with our prototype, we conducted a user study using a within-subject design. We split the study into two blocks: the *tracing block* and the *writing block*.

The aim of the *tracing block* was to gather quantitative data about FLASHPEN's accuracy. In this block, we examined the accuracy of pen input by measuring the user performance in tracing tasks. The patterns to replicate are variations of different connected patterns, each consisting of a repeating simple shape. With this, we deliberately focused on low-level aspects of interaction, specifically motor control during input, avoiding higher-level cognitive processes that may have added noise in our observations. In the *writing block*, we investigate investigate the impact that each of the device had on handwriting. For this, we compare the devices with each other and with an analog pen.

4.1 Study Design

For both blocks, we used the FLASHPEN sensor on an office table, whereas we used the WACOM pen on the WACOM tablet. We choose this particular setup and surfaces to adopt the best conditions for each of those devices in which they work the best. We chose VR technology to take advantages of the mobility and to have a direct mapping between the user input and the resulting strokes on large surfaces.

Block 1: Tracing: This first block uses two devices: WACOM pen and FLASHPEN. We use the WACOM pen and tablet (a high-end commercial device used by professional artists) to establish our baseline in terms of spatial resolution and frame rate. For each trial, the participants were given one out of two instructions. More specifically, participants were asked to either follow the trace AS FAST AS POSSIBLE or AS ACCURATE AS POSSIBLE. Those instructions were displayed at all times in front of participants (on top of the trace in VR) and the experimenter reminded them whenever the instructions changed between trials. Hence, we separated speed and accuracy into two conditions, because being accurate and fast are important factors depending on the specific task (e.g., fast sketching versus slow dragging when carefully manipulating 2D content). We also varied the content of the traces to follow in this block, to bring diversity in the profile of the pattern and to avoid memorization from users. We include four shapes with different levels of smoothness (see Figure 4). This includes a shape with no corners (WAVE), a round shape between two corners (half-CIRCLE) and shapes with several sharp corners (TRIANGLE and RECTANGLE). The shapes are similar to the ones from previous tracing tasks in related work [26]. We also varied the SIZE of the pattern, which was LARGE, MEDIUM or SMALL. We calibrate this factor through average handwriting size as guided by lined paper (i.e., 2 cm). Derived from this was LARGE at 3 cm and SMALL at 1 cm. Overall, we collected data from 480 trials in this block across participants:

  10 Participants
× 2 Devices (WACOM pen, Flashpen)
× 2 Instructions (ACCURATE, FAST)
× 4 Shapes (WAVE, CIRCLE, TRIANGLE, RECTANGLE)
× 3 Sizes of the trace (LARGE, MEDIUM, SMALL)
= **480 trials total** for Block 1

Block 2: Writing: In this second block we define factors to investigate real handwriting scenarios. uses the same device as the first block plus an ordinary pen on paper (ANALOG pen). We use the ANALOG pen to compare both devices with analog writing (i.e., as baseline in terms of handwriting). With each device, participants had to write eight pre-defined sentences. The sentences for the writing block originated from MacKenzie and Soukoreff's phrase set [43].
We conducted 240 trials in total in the writing block:

  10 Participants
× 8 Sentences
× 3 Devices (WACOM pen, FLASHPEN, ANALOG pen)
= **240 trials total** for Block 2

4.2 Participants & Apparatus

We recruited ten participants (4 females) from our institution. Each participant took part in both blocks (tracing and writing). All participants were daily computer users, aged 23–36 (mean=29.6, median=29). One participant was left-handed. Five participants reported being familiar with pen & touch devices and reported using them at least once a month. Seven participants mentioned being familiar with VR.

For both blocks, we used the same overall setup depending on the device (see Figure 3). The experiment was conducted on a WACOM CINTIQ with a built-in full HD screen (1920 × 1080) as the pen input surface (the built-in screen served no purpose for participants, but facilitated implementation). The VR system was an Oculus Quest and powered by a PC (i9, 32 GB RAM, RTX 2080 Ti GPU). For the two non-analog conditions (Flashpen versus WACOM pen), we use the same setups as shown in Figure 3. In the ANALOG condition during the writing block of the study, participants wrote using a black BIC Atlantis pen. The whole apparatus and all interfaces were wiped down and sanitized between participants.

4.3 Procedure

Upon entering the ventilated experiment room, participants took a seat at a table. To comply with local COVID-19 policies, participants wore their own face mask at all times and received disposable gloves to wear during the study. Participants read and signed a consent form and filled out a demographic questionnaire. The experimenter then explained the purpose of the study, showed the Flashpen prototype, the WACOM pen, and the regular pen. Participants were encouraged to take each pen device and adjust their grip for optimal and comfortable pen writing. Afterwards, participants were handed the VR headset equipped with a sanitary hygiene cover to put on. Participants familiarized themselves with the study environment in VR. The study consisted of two blocks, one to evaluate the accuracy of our prototype by following traces and the second to (visually) compare Flashpen's handwriting fidelity with that of a digital pen and ordinary paper handwriting. Trials within blocks were counterbalanced (Latin Square) across participants. Throughout the study, we record all samples from the devices at the highest frame rate (i.e., 8000 per second with Flashpen) to capture all users' motions and to be able to reproduce users' handwriting as well as spatio-temporal 2D input at a high fidelity (micrometer range). However, to not risk sacrificing responsiveness in VR, our system renders only a quarter of all recorded input locations of Flashpen (i.e., 2000 samples per second were added to the rendered stroke). In the case of the WACOM pen, we recorded and displayed all raw samples (i.e., around 190 points per second).

Procedure of block 1: Tracing: In this block, the experimenter briefly introduced the task with a short demonstration. Participants could then practice the task using both *devices*, Flashpenand the WACOM pen, This training phase lasted approximately five minutes. Afterwards, participants completed a series of 48 trials The order of those conditions was counterbalanced across participants. At the end of each sub-block, participants took a short break. Participants' strokes were displayed in real-time on the virtual canvas while they were performing the task.

Procedure of block 2: Writing: In this block, participants reproduced eight sentences using each input DEVICE, namely ANALOG pen, WACOM pen, and Flashpen. The order of the *sentences* and *devices* were counterbalanced across participants. In between sub-blocks, participants rated their experiences for each *Device* on a 5-point Likert scale on physical comfort, efficiency, cognitive load, and overall impression on their writing speed. When rating, participants also expressed their comments and thoughts. After both blocks, the experiment concluded with a debriefing where participants reported their overall impressions and reported on the pros, cons, and differences between devices. Throughout the experiment, participants were encouraged to verbally share their impressions, of which the experimenter took notes. For each input trial, our system logged all the events from each *Device*. In addition, the system captured a screenshot of each drawing at the end of each trial. Overall, the entire experiment lasted around 60 minutes per participant.

5 STUDY RESULTS

We used various metrics for analyzing our results. The measurements of the tracing block yielded mostly objective results, while the writing block mostly focused on subjective ratings, visual inspection and feedback.

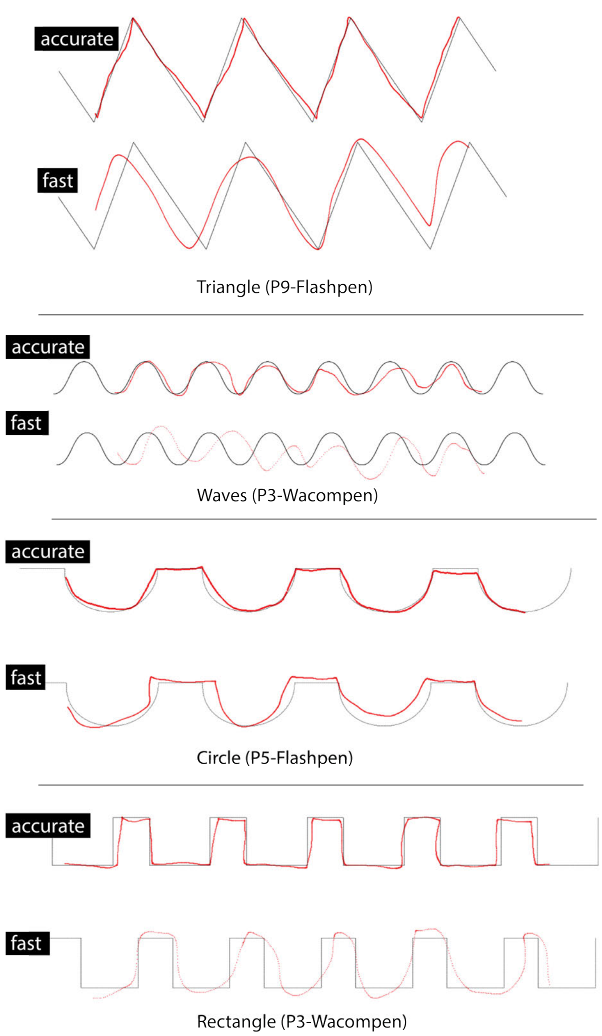

Figure 4: Patterns used in the study (WAVE, CIRCLE, TRIANGLE and RECTANGLE) with an overlaid red stroke for each to exemplify the traces drawn by participants.

5.1 Results of Block 1: Tracing

In this block, we primarily measured user performance, but also asked participants for qualitative feedback. Overall, participants enjoyed using the devices during this tracing task, commenting that *"It was so much fun using this kind of new device"* (P4), and thought they were accurate *"I found I could perfectly follow the pattern shown on screen"* (P5).

In this section, we will focus on the quantitative results of the tracing block, involving users to reproduce a repeating pattern of shapes. Our experimental software collected the points that were drawn with both devices, WACOM pen and FLASHPEN, with a timestamp for each pen-down- and pen-up-event. We computed two metrics: 1) *Velocity* is the overall distance divided by the amount of time between a pen-down-event and a pen-up-event, expressed in cm/s. 2) *Accuracy* is the shortest distance between each point of the stroke drawn by the participant and the reference pattern shown on the screen. We normalized this value by the width of a shape in a pattern for {SMALL, MEDIUM, LARGE} by {1 cm, 2 cm, 3 cm}, respectively. A repeated measure ANOVA of the four factors on the accuracy and velocity reveals some effects that we will detail in the remainder of this section.

Similar accuracy across devices: Depending on the condition, participants were instructed to do a trial either as FAST or as ACCURATE as possible. Figure 5 depicts the accuracy and the velocity by which participants reproduced the pattern with both devices depending on the INSTRUCTION. For the instruction AS ACCURATE AS POSSIBLE, we observed an overall accuracy mean of $\mu = 0.026$ and $\mu = 0.028$ respectively for the WACOM pen and the FLASHPEN. For the instruction AS FAST AS POSSIBLE, we found an overall accuracy mean of $\mu = 0.079$ and $\mu = 0.076$, respectively. As expected, the effect of INSTRUCTION is significant on the accuracy ($F_{1,9} = 43.96$, $p = 0.00009$, $\eta^2_G = 0.625$), because slower speeds allowed participants to draw the trace more carefully. Participants reported having no trouble interacting with one or the other device, and they stated that they were accurately reproducing the pattern.

This result is supported by an analysis of variance which reveals that there is no interaction effect between SPEED and DEVICE on the accuracy ($F_{1,9} = 0.80$, $p = 0.393$, $\eta^2_G = 0.003$) and the velocity ($F_{1,9} = 0.125$, $p = 0.73$, $\eta^2_G = 0.0008$). This result suggests that FLASHPEN performed well under both conditions, FAST and ACCURATE, comparable to commercial devices.

While participants did not draw the trace faster using FLASHPEN compared to using the WACOM pen, four out of ten participants mentioned that they felt they were faster with our prototype. Besides, four out of ten people commented that the difference in surface types might have changed the way they wrote with a pen. Surprisingly,

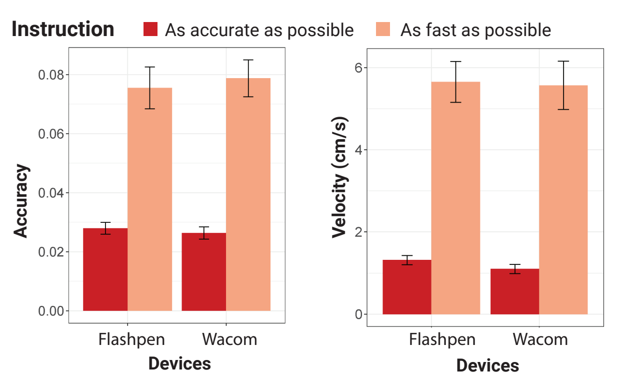

Figure 5: Accuracy and velocity for both devices FLASHPEN and WACOM pen for the two Instructions (FAST versus ACCURATE) in the tracing block.

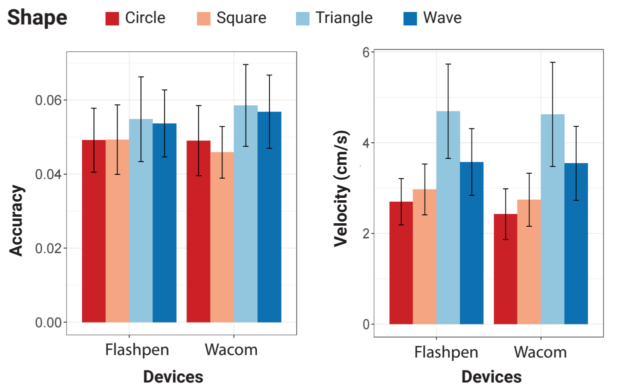

Figure 6: Accuracy and velocity for both devices (FLASHPEN and WACOM pen) for the SHAPE factor.

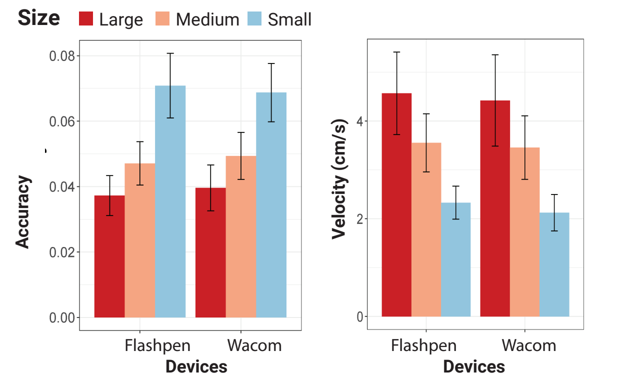

Figure 7: Accuracy and velocity for both devices (FLASHPEN and WACOM pen) for the SIZE factor.

participants also indicated that it was easier to draw the trace on the table than on the WACOM tablet, which was described as more slippery than the table by participants.

Impact of Shapes: The previous ANOVA reveals that the SHAPE has a significant effect on accuracy ($F_{3,27} = 5.69$, $p = 0.0037$, $\eta_G^2 = 0.038$) and velocity ($F_{3,27} = 35.76$, $p < 0.0001$, $\eta_G^2 = 0.34$), which means that some shapes were drawn more accurately and fast than others. By taking a closer look at the shapes, we found that CIRCLE and SQUARE had similar accuracy while the same was true for TRIANGLE and WAVE. The latter pair was drawn more accurately faster. A simple explanation is that drawing WAVE and TRIANGLE patterns are performed with a series of more natural hand motions, while the other shapes require interleaving horizontal segments, breaking the flow of handwriting (akin to handwriting in cursive vs. script). However, we did not find an interaction effect of the *shape* and *devices* on accuracy ($F_{3,27} = 1.36$, $p = 0.28$, $\eta_G^2 = 0.005$) and time ($F_{3,27} = 0.84$, $p = 0.48$, $\eta_G^2 = 0.002$), meaning that these results hold for both pens.

Impact of Size: We also found that the effect of the SIZE of the pattern was significant on both the accuracy and the velocity, with each condition significantly differing according to pairwise t-test. This means that LARGE shapes ($\mu = 0.038$) (unit normalized across pattern size to keep consistency between conditions) were more accurate than MEDIUM ($\mu = 0.048$) and SMALL ones ($\mu = 0.070$). However, LARGE ($\mu = 4.49$cm/s) shapes were drawn faster by participants than MEDIUM ($\mu = 3.51$cm.s^{-1}) and SMALL($\mu = 2.23$cm.s^{-1}) shapes on average - larger shapes requiring less meticulousness than small shape.

Participants found it hard to follow the small shapes, as the pattern to follow was tiny and led to more errors. Also, participants were faster with the small pattern, as the shape stayed in the range of the motions of their hand. This allowed them to draw the entire motif without lifting their wrist, compared to the large pattern where they had to adjust their wrist's position. Such readjustments then led to errors and sometimes caused the pen to be lifted off the surface a bit.

5.2 Results of Block 2: Writing

In this subsection, we focus only on the second block of the study, in which participants needed to write sentences with both devices and an ANALOG pen. We gathered qualitative feedback from participants about their experience when writing with the devices, during the interviews and from the Likert scale. Figure 8 illustrates the same sentence written by the three devices in our study. It is evident that the fidelity of FLASHPEN and WACOM match the fidelity of the analog pen (in terms of shape when disregarding scale). During fast movements, for example at the end of a letter's stroke points, points produced by the WACOM pen are much more spaced than using FLASHPEN. Note that the size of the points for WACOM has been enlarged 5 times more than for FLASHPEN merely for visualization purposes. Because current pens do not deliver dense enough samples of the pen positions to compose a curve, digital pen systems need to interpolate between raw points, either using a Bézier curve or using the velocity of the pen to infer the small micro-movements of the pen, Those interpolations and prediction techniques can lead to errors and a lack of precision. Due to the higher sampling rate in FLASHPEN, the interpolations are much shorter and, thus, cause the overall input to exhibit higher fidelity.

During the writing block, participants had an overall preference for the ANALOG pen over WACOM pen over FLASHPEN. From the interviews, we discovered that for some participants, it was

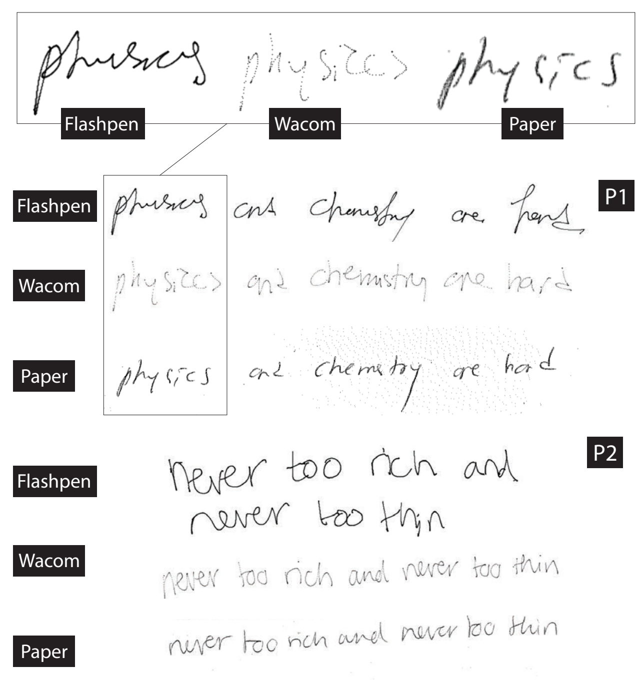

Figure 8: Same sentence written by the same participant with the three devices, respectively, the top one using the FLASHPEN, the middle one using the WACOM pen and the bottom one using an analog pen. Note: for visual clarity, we rendered the points of the WACOM pen than the points from FLASHPEN.

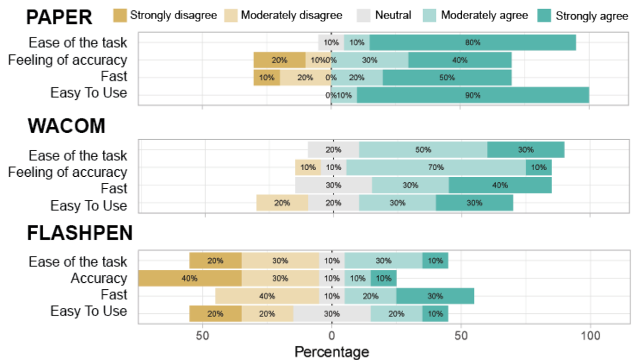

Figure 9: Likert scale of participants' ratings for the second block of the study: the sentences writing.

mostly due to the difficulty to do quick lift gestures with FLASHPEN. When lifting the pen, FLASHPEN's sensor keeps reporting for a split-second, which can sometimes lead to errors and approximations. Due to those errors, participants found FLASHPEN less accurate, found the tasks harder and the device slower. For example P2 mentioned that during the writing block with FLASHPEN: *"I have to put the pen straight to be able to lift it up correctly, and that's not something I usually do"*. However, in the the tracing block, participants experienced no such difficulties, as they adjusted their grip angle without lifting the pen during all trials. Participants overall liked that FLASHPEN's tip can be readjusted. P4 commented that *"It's really easy to readjust the tip angle, I don't feel any difference with the* WACOM *pen"*.

5.3 General Feedback

We gathered general feedback about three of the devices, regarding *the writing* and *the tracing* block. Those comments were mainly about ergonomics. Participants enjoyed the feeling of the surface when writing with FLASHPEN, which felt like they were *"writing on paper"* (P8), whereas WACOM PEN handwriting performed worse, appearing *"slippery on the surface"* (P7). Participants also felt that *"[*FLASHPEN*] provides a better ink experience as it feels I can write smoother than using a digital pen"* (P8). In contrast, from the Likert scale shown in Figure 9 and the interviews, it appears that writing on paper involves even more friction than when using the WACOM pen. This prevents users from writing fast, which might be due to the differences in surfaces and, especially, the roughness of paper in the ANALOG case.

Six participants mentioned the fact that FLASHPEN was harder to grip and less ergonomic compared to the WACOM pen. They mentioned that the main difference in ergonomics between both devices was the shape of the shell, which is cylindrical in the case of FLASHPEN and fusiform in the case of WACOM. They also commented that the lack of grip on FLASHPEN's shell made it harder to hold and they expressed the necessity to add a textured surface that can be felt by the fingers to remember where to place them. Three out of the ten participants thought that FLASHPEN's tip was not flat, but rather looked like an old pen with a bigger tip than casual ones. We found this reassuring and think that with an appropriate form factor, a future iteration of FLASHPEN can create the illusion of an authentic pen. For example, P9 said: *"I thought it was an old pen, or a really cheap pen, because it feels like the tip was really large but I did not suspect it to be flat."* Four participants commented that it was comfortable to be able to grip the pen using several postures and to orient the pen in several directions. However, because we only tracked the tip of the pen during the study to be consistent with the WACOM pen (which only tracks the tip), it was hard for some users to understand the difference of orientation between the tip of the pen and the pen itself.

6 APPLICATIONS

We designed a set of virtual reality application prototypes to showcase Flashpen's capabilities through VR interaction techniques. All applications can be seen in Figure 10 (we encourage the reader to also watch the supplemental video to see all applications in motion). For all applications, Flashpen is represented as a virtual pen to maintain functional consistency between the physical world and the virtual world. The applications can be used on any surface orientation (i.e., horizontal or vertical).

Reviewing and annotating documents: In Figure 10A, a user can browse their document library to select a specific article to review. The users can highlight important parts, jot down comments, and emphasize paragraphs of interest using Flashpen. Using a swipe gesture with the non-dominant hand (tracked with built-in hand tracking from VR headset), users can switch between pages to review several pages while immersed in a VR environment. As a future use case, we envision that such an annotation application can also be mobile (e.g., on paper or on a notebook) to support on-the-go interaction while collaborating on documents. Related to this application, we see an opportunity for Flashpen as the basis for an exploration of broader ranges of scenarios and interaction techniques that could involve pen+touch [30] in VR. With the possibilities of VR, we can also expand the work space with other types of documents (e.g., interactive content such as video) and thus support an active reading process [18].

Multi-layered map: In Figure 10B, a user explores a multi-layered map with a magic lens metaphor [14]. The map has two layers, whereas the first layer is a geologic map and the second one is a satellite view seen through a magic lens. The user can use the pen as a precise manipulation tool to drag the magic lens around

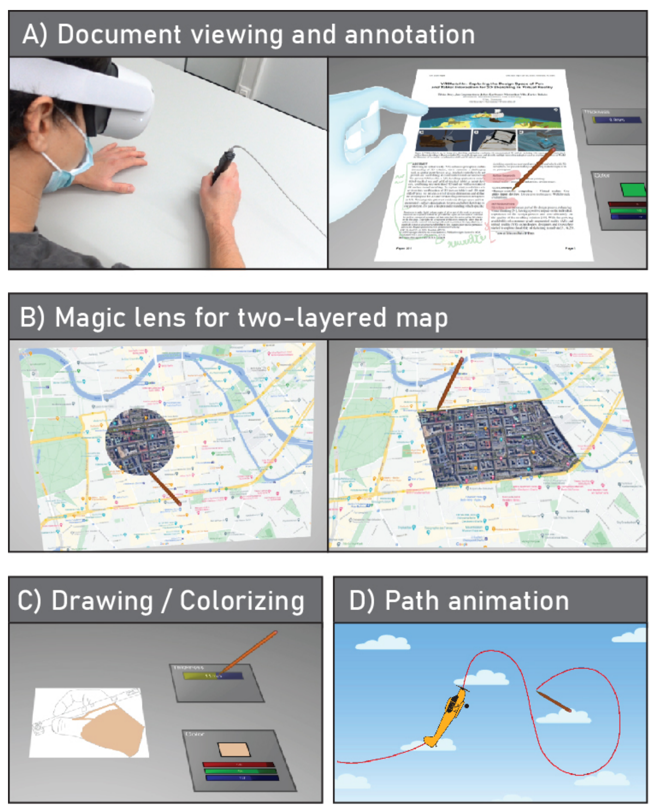

Figure 10: Virtual reality prototypes that utilize Flashpen. Each application can be used on a horizontal or vertical surface.

(Figure 10B, left), revealing the satellite layer. Instead of using a pre-defined round magic lens, the user can also precisely define a custom polygon shape (Figure 10B, right), e.g., following a road or a river. Every single vertex of the polygon can be precisely defined with Flashpen's robust registration of very small movements.

Drawing application: We also demonstrate Flashpen's precision and mobility in a painting app (Figure 10C), which allows users to accurately fill shapes and interact with widgets. Examples for such widgets are the sliders that are displayed on the right. Users can put the pen down on a value to select or to drag the slider until reaching the desired color and thickness. Once a color has been selected, they can start drawing or filling monochrome shapes with color. Only with the jitter-free high precision of the flow sensor, small corners of the drawing can be accurately filled with color without error, which would be infeasible with cameras alone. The combination of Flashpen and VR enable a practically unlimited space of pen interaction on a surface, allowing to populate the space with an unlimited amount of widgets. The drawing canvas itself can also be wider allowing to simulate a real painting canvas.

Motion path animation: As shown in Figure 10D, we use the high sample rate of Flashpen in this application to design motion experiences where the user draws strokes using varying input speeds to create a path animation of a plane. After drawing the spatiotemporal curve, the yellow plane will follow the exact same path while matching the user's velocity at every point on the curve. Thus, such motion paths simultaneously encode spatial as well as temporal information, e.g., by drawing slowly while going in a straight line and then accelerating while drawing a looping.

7 Limitations and Future Work

Flashpen is a promising prototype that showcases a principle for precise pen input in virtual reality on many surfaces. In particular, the results of the tracing block indicate great performance for on-surface interactions. However, there are several limitations that can be addressed in the future. Writing is feasible, but the results of the writing block in our study are not as strong as with tracing. Primarily, for many users, fast movements above the surface when lifting the pen might not be as accurate as with an analog pen (repeatedly releasing and establishing surface contact is required while writing with a pen). To increase hover-precision, other absolute tracking principles, such as the one implemented in the *Anoto* pen [4] can be used in a complementary manner.

Other optical flow sensors than the one we used might have potential as well in the future. Currently, Flashpen performs well on most surface types (wood, paper, plastic and many more), which could be horizontal or vertical, and which do not require a specific surface (e.g., capacitive) unlike most current pen technologies such as Wacom or Microsoft Surface. To also support challenging surfaces like glass, future iterations could utilize blue light sensors.

As mentioned earlier, the ergonomic factor of our pen, currently similar to a cylinder, might affect the way users write. As they are often used to writing with more fusiform devices, such as analog pens, this form factor has to be taken into consideration to match what currently exists on the market and to establish a user experience that is closer to what users have experience with. Similarly, the system currently relies on outside-in tracking (see Figure 34). With this, we removed tracking errors due to head motions as confounding factor and focus on the device and interaction capabilities. Based on additional engineering efforts, our research prototype can be reconfigured and be made more ergonomic as envisioned in Figure 11

Given such variations of the prototype and different (mobile) contexts, longitudinal studies will be needed to fully understand the impact of our prototype on the more general writing and 2D manipulation experience, as well as on users' comprehension.

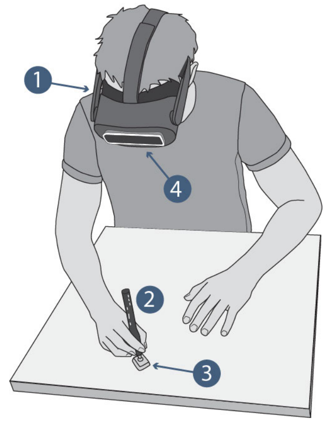

Figure 11: Envisioned lightweight setup configuration in the future. Similar to our prototype, we envision (1) a mobile VR headset, (2) the pen device (wireless, with a more ergonomic form factor), and (3) the optical flow sensor as in our prototype. (4) However, instead of using two external OptiTrack cameras, a stereo-camera built into the headset would track the pattern on the pen, similar to how mobile VR devices are already capable of tracking controllers. Combining tracking and sensor data would work the same as with our prototype, but in a mobile device configuration.

8 Conclusion

Flashpen is a novel input device that allows users to precisely sketch and draw at a high sample rate, uniquely and almost perfectly reconstructing analog pen motions. While previous devices like the Wacom pen offer a reasonable tool for reproducing handwritten annotations, they lack flexibility due to the required drawing tablet. Flashpen brings writing and fine-grained on-surface input into VR. The results of our study strongly suggest that our prototype is a promising tool for very precise 2D manipulation. Unlike drawing tablets, Flashpen works on many different surface materials, which in itself lays the groundwork for mobile use-cases in the future. Pen input in VR is an opportunity to design novel interaction techniques that go beyond the traditional controllers and hand interactions usually found in current VR applications. With this paper, we open up a rich design space that can be investigated thoroughly in the future.

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