DeltaPen: A Device with Integrated High-Precision Translation and Rotation Sensing on Passive Surfaces

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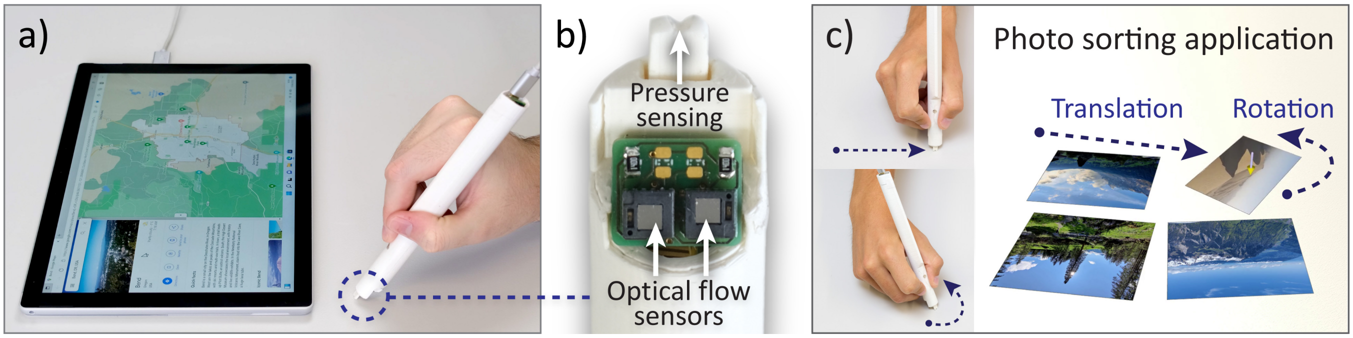

Figure 1: (a) DeltaPen is a digital pen that resolves precise translation and rotation (yaw, tilt) on uninstrumented surfaces. (b) Our device requires no surrounding cameras or specialized sensing surfaces and instead has all sensing hardware integrated. Two optical flow sensors and a pressure sensor enable high-precision pen input, which is complemented with an IMU as well as components for supporting vibrotactile feedback. (c) Besides precise translation, DeltaPen also senses rotational movements for input. In this photo sorting application example, the user can drag pictures and rotate them at the same time.

ABSTRACT

We present DeltaPen, a pen device that operates on passive surfaces without the need for external tracking systems or active sensing surfaces. DeltaPen integrates two adjacent lens-less optical flow sensors at its tip, from which it reconstructs accurate directional motion as well as yaw rotation. DeltaPen also supports tilt interaction using a built-in inertial sensor. A pressure sensor and high-fidelity haptic actuator complements our pen device while retaining a compact form factor that supports mobile use on uninstrumented surfaces. We present a processing pipeline that reliably extracts fine-grained pen translations and rotations from the two optical flow sensors. To asses the accuracy of our translation and angle estimation pipeline, we conducted a technical evaluation in which we compared our approach with ground-truth measurements of participants' pen movements during typical pen interactions. We conclude with several example applications that leverage our device's capabilities. Taken together, we demonstrate novel input dimensions with DeltaPen that have so far only existed in systems that require active sensing surfaces or external tracking.

CCS CONCEPTS

• **Human-centered computing** → **Pointing devices**; **Graphics input devices**; *Haptic devices*.

KEYWORDS

Pen input, rotation sensing, tilt interaction, haptic feedback

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1 INTRODUCTION

Stylus interaction has been an integral focus of research in Human-Computer Interaction, dating back to the beginnings of interactive screen technologies (e.g., Sketchpad [62]). Since then, research on pen computing has explored efficient input for on-screen user interfaces (e.g., sketching and note-taking [50]), precise manipulation [77], and ergonomic digital input [21]. With the advent of tablet computing in research (e.g., [23, 25, 35]) and in the commercial space, pen interaction has become established alongside touch, mouse, and keyboard input. Especially the combination with commodity touch screens has become commercially successful, such as the Surface Pen [42], Apple Pencil [4], or Galaxy Tab [57]. For professional use, `Wacom` has long optimized pen input through custom digitizers [70], allowing high-precision input for writing, sketching, and UI control on specialized tablets. Even with the advancements

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*Both authors contributed equally to this research.

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in 3D technologies, on-surface input remains a reliable means of input for 2D as well as 3D tasks [9].

Digital styli work in concert with tablet surfaces or smartphone screens, which track their input positions. While this allows users to directly and precisely interact with screen content, it limits all input to the available area on the screen. To support larger-surface interaction, so-called 'pen mice' strike a compromise–using indirect relative input on passive surfaces while retaining high precision [1, 51, 59, 63]. A common goal of pen mice is to essentially be a more ergonomic mouse input device [47], i.e., reusing the flow sensor found in optical mice and mimicking mouse use, yet in an ergonomic form factor suitable for pen input [11, 66]. Pen mice are integrated and standalone without relying on external tracking, leading to advantages for mobile interaction. However, despite the precise interaction afforded by the stylus form factor, pen mice limit input operations to mere 2D translation—much like traditional mice. This sacrifices the input dimensions that on-screen styli specifically provide to better support 'natural' pen interaction, such as pen roll (e.g., for drawing with brushes and calligraphy [20, 71] or UI manipulation [10]), tilt (e.g., for menu interaction [65] or mode switching [78]), and input pressure (e.g., for writing and sketching [73]). Research prototypes that support these input dimensions have relied on external tracking or a large form factor. A compounding problem that affects pen mice is their lack of the key component that makes traditional mice reliable: the input button. Pen mice either detect input from surface *proximity*, which causes spurious input during place-down and lift-off events [24], or they include buttons on the device, which can compromise ergonomics.

In this paper, we present DeltaPen, a novel pen device that does not require surface instrumentation and instead integrates all sensing components for accurate 2D translation, accurate 1D rotation, and accurate surface contact. This enables the utilization of large passive surface areas for relative input in mobile scenarios beyond the limits of a mobile device's screen size (Figure 1 a). The key component of DeltaPen is a sensor design that rigidly couples two adjacent high-speed lens-less 2D optical flow sensors (Figure 1 b) and one accelerometer, which together allow us to resolve spatially accurate motion. Because the lens-less sensors require no physical contact with a surface, we were able to include a proper pen tip into the physical design of our device. This allows DeltaPen to fully integrate all tracking, serve mobile use-cases, and thus achieve the light-weight form factor that is needed for precise pen computing. DeltaPen also integrates a pressure sensor to register precise surface contact as well as pressure levels. A wide-band haptic actuator complements the sensor to render haptic effects. As a result, we can finely resolve input motions that, unlike regular mice, users dominantly control through their fingertips, i.e., the end-effectors of the human kinematic chain. This affords small rotations by moving not just the arm and wrist, but also the fingertips to translate and minutely rotate the device (Figure 1 c).

We conducted a technical evaluation to assess the quality of our translation and angle estimation by measuring pen motions while participants were writing and sketching. Furthermore, to showcase the potential of DeltaPen, we demonstrate a series of user-interface applications that make use of its unique capabilities, which so far have only been possible using specialized surfaces or external (outside-in) tracking using surrounding cameras.

Taken together, in this paper we contribute:

- A novel and integrated dual-sensor approach and pipeline that registers translations and rotations along passive surfaces.
- A prototype pen that showcases the synergy of our dual-sensor design, pressure sensitivity, and haptic feedback.
- A technical evaluation to measure the quality of our translation and angle estimation pipeline including the role of individual pipeline steps.
- Several user-interface demonstrations that leverage the unique fidelity of our accurate sensing approach, especially pressure-based and rotation-based interaction with UI widgets including haptic feedback.

2 RELATED WORK

Over the years, previous researchers have explored different opportunities of pen-shaped devices [53]. In this section, we review the literature that our approach and device builds upon.

2.1 External sensing and tracking

Devices like `Wacom` tablets [70] achieve very high precision through a specialized tracking surface, i.e., the tablet surface with capacitive sensing. Most previous research on pen input similarly relies on external cameras or specialized surfaces to precisely track the pen motion [22]. For instance, Vandolo et al. built the *IntuPaint* system [68] as well as the *FluidPaint* system [67], both of which support using non-digital brushes for painting, but require a specialized setup for the interactive surface. Matulic et al. attached a wide-FoV camera to the top of a stylus in their *PenSight* system [41]. The goal is to enhance the capabilities of a tablet stylus, e.g., by enabling hand-gestures with the non-dominant hand, i.e., the pen input itself requires a tablet surface.

Many previous pen devices work on passive surfaces, but still require some external tracking (e.g., via cameras) to support more degrees of freedom (**DoF**). *Flashpen* by Romat et al. [55] is a pen-shaped device with an optical flow sensor that has a large contact area with the surface similar to a `Penclic` device [47]. However, they rely on external cameras for detecting rotations. Furthermore, while the device is used like a pen, the lack of a pen-tip can be a hindrance for fluid pen-input like writing. Wu et al. present *DodecaPen* [77], which features high-fidelity vision-based 6 DoF tracking. The *Spidar-pen* by Lin et al. [38] tracks the 2D position and 1D rotation through strings that physically connect the pen with the four corners of a screen.

While those works achieve high accuracy and extend the available DoF for input, their reliance on external sensing technology heavily impacts mobility and flexibility. We tackle the problem of bringing such capabilities to a device that works on passive surfaces without external sensing or tracking.

Pen input in Mixed Reality. Closely related to external camera tracking, many previous systems focused on sketching in Mixed Reality (**MR**), e.g., directly through mid-air input [29, 30, 74, 75, 80]. For instance, Rosales et al. [56] create manifold surfaces from coarse mid-air strokes. While direct sketching in mid-air can be expressive, it can also be challenging due to the lack of physical support or haptic feedback. Therefore, many researchers aimed to mitigate this by constraining the input to surfaces and utilizing passive or active haptic feedback [17]. Poupyrev et al. present the *Virtual Notepad* [54], a pen-based note-taking tool in VR. Similarly, Drey et al. present *VRSketchIn* [16], which utilizes a handheld pen tablet and additionally constraints the input to facilitate sketching along virtual surfaces. *ARPen* by Wacker et al. [69] is a mobile phone application, which tracks the 6 DoF of a pen in a handheld video see-through arrangement.

Besides sketching, pen input in MR can be useful for other tasks. Gesslein et al. [19] combine a tablet, a pen device and virtual reality to improve interaction with digital spreadsheets. Pham et al. [50] found out that a pen-shaped prop is the most promising selection device compared to mouse and a commercial VR controller.

While not designed for mid-air sketching, our DeltaPen device shares similar goals with regards to precision as well as active and passive feedback. Furthermore, DeltaPen can potentially be suitable for mobile MR applications or MR workspaces.

2.2 Active haptic feedback

Haptic feedback can significantly improve task performance for on-surface interaction like text input for touch keyboards [27]. Stewart et al. explore different characteristics of pressure thresholds for handheld mobile devices in connection with vibrotactile feedback [61]. *TeslaTouch* by Bau et al. [8] creates haptics sensations of textures on touch screens. Similarly, Kim et al. [31] simulate lateral friction on touch screens to create sensations of bumps.

The form factor and grip of pen-shaped devices make them suitable for similar active haptic feedback techniques with the pen itself [33] or with the surface providing force feedback. An early example for the latter is the pen-based force display by Buttolo et al. [12]. They use multiple actuators to create haptic feedback for pen input. *MH-Pen* by Chen et al. [13] is an actuated pen for vibrotactile feedback as well as force feedback and works on capacitive screens. Withana et al. present the *ImpAct* device [76]. As users push the pen against the screen, the physical pen shortens while the virtually penetrating tip is rendered so as to create the illusion of interacting inside the virtual space. Park et al. propose a stylus for touch screens with force feedback [46]. Similarly, with the *EV-Pen* [72], Wang et al. generate different friction on a capacitive touch screen levels through electric signals to simulate haptic textures (e.g., the feeling of writing on paper) and general haptic effects in GUI interaction. Arasan et al. also built a haptic stylus [5, 6], whereas their work strongly focuses on the perception of the haptic vibrations and not the pen itself as input device. Similarly, *RealPen* by Cho et al. [14] generates realistic audio signals while writing on capacitive touch screens. Mueller et al. [43] identified requirements for note-taking devices for successful adoption by users. Importantly, they found that users could not make small motions when using passive styli and hence they had to draw larger shapes or write with larger letters, respectively, compared to using paper or active styli. Teyssier et al. built a multi-modal pen input device called *VersaPen* [64]. The pen is modular, i.e., the individual parts of the pen can be hot-plugged to quickly configure the pen's capabilities. One of the modules is a vibration motor for haptic feedback.

To leverage the potential of active haptic feedback identified by previous work, we incorporated a linear resonant actuator so as to render haptic effects in conjunction with pressure sensing.

2.3 Integrated sensing

Most relevant to our work are previous approaches that integrate most (if not all) of their sensing capabilities in the device itself.

Optical flow sensing. Previous research utilized optical flow sensors [39] either for fully self-contained devices or as additional sensing capability for accurate on-surface input [45, 79].

Even though a pen has very different affordances, our approach is closely related to previous explorations of expanding the capabilities of computer mice–primarily the support for additional DoF. Researchers have long been investigating how to support additional DoF through on-surface input either through specific interaction techniques [32] or, in the case of the mouse, by creating custom mouse prototypes [48]. The *Rockin'Mouse* by Balakrishnan et al. [7] is a mouse with two additional DoF. Besides moving the mouse along the 2D surface, they map tilting movements to the third dimension. However, the form factor is still that of a mouse and the focus is on 3D interaction without support for writing and note-taking. Several works investigated using an additional optical flow sensor in a single mouse so as to track rotation and compensate for it [2, 39, 40]. An early example is the *Two-Ball Mouse* by MacKenzie et al. [40], which tracks the mouse rotation along the surface as an additional DoF. Besides mice, many commercial mouse pen devices [47, 59, 63] are fully self-contained and work on passive surfaces. The *Adonit Ink* pen for instance combines a stylus for capacitive sensing and a mouse pen in one device (it uses two different tips on both ends). However, pen mice only support 2 DoF.

While calculating the rotation is straightforward in a mouse form-factor with the two sensors always perpendicular to the surface, the problem becomes challenging in the case of a pen form factor with little space at the tip and multiple rotation axes involved during usage. To our knowledge, while those techniques have been explored thoroughly with mouse-like devices, no previous work made the dual-sensing principle work in a non-mouse form factor, where the sensors or lenses are not in contact with the surface.

Pen and paper interaction. Digital pen devices can also work in conjunction with ordinary or enhanced paper utilizing their rich passive haptic properties. *Anoto* [3] is a commercial example that utilizes specialized printed dot patterns on ordinary paper so that the digital pen can localize itself. Many previous research undertakings utilized the passive haptic properties paper for natural pen input. Nebeshima et al. present *Memo* [44], which can be used as an ordinary ball pen. The pen does not track the motion in itself, but captures the strokes drawn on paper using a CCD behind the tip. Liao et al. [37] built a prototype that provides multimodal feedback–including tactile feedback–while writing and interacting on real paper. Another approach for digital pen input is to augment the paper itself with digital capabilities–either physically or through virtual augmentations. Song et al. [60] explore different interaction techniques based on the combination of a digital pen with a projector that illuminates ordinary paper externally. *HoloDoc* by Li et al. [36] augments physical paper through an AR HMD.

While our prototype is compatible with paper as a passive surface, we seek a more general-purpose solution, i.e., having the pen entirely self-contained without the need for a specialized or augmented surface.

2.4 Related work: Summary

Pen interfaces and devices have been explored thoroughly for different use cases with different requirements, e.g., with regards to precision or form factor. Generally, there is a trade-off between precision and mobility, e.g., high-precision devices require specialized surfaces or high-performance external sensing–reducing mobility or limiting the surface area for interaction. To our knowledge, we present the first approach and prototype to bring the affordances of pen interaction including rotation to uninstrumented (passive) surfaces with all tracking capabilities built into the pen. While dual-sensor approaches have been explored for mice, we present a solution for a device that retains the affordances of a pen, meaning that the sensing needs to work on a small form factor around the tip and with different pen postures that are not always orthogonal to the surface. In the remainder of this paper, we elaborate on our lens-less dual sensor approach.

3 DELTAPEN IMPLEMENTATION

DeltaPen senses 2D translation along the surface, rotation around the axis perpendicular to the surface, and tilt. The core of our approach consists of the two adjacent lens-less optical flow sensors integrated into DeltaPen, which, in conjunction, allow us to track not only pen movements but reliably *separate* translation from rotation. We accomplish this through a signal fusion method that takes as input both optical flow measurements as well as pen tilt obtained from a 3-axis accelerometer inside the pen. Figure 1 showcases the usage of DeltaPen.

3.1 Hardware

Figure 2 shows DeltaPen's components alongside a close-up of our dual-optical sensor design. A 3D-printed shell that features an ergonomic shape for grasping encloses all pen components, including a Teensy microcontroller board that handles all sensor fusion, processing, motor actuation for haptic feedback, and communication with a host PC. As part of the case, DeltaPen includes a distinct tip that facilitates precise input and allows to smoothly rotate the pen around the up-axis originating from the point of contact with the surface. This design is possible, because our sensor does not require a fixed distance to the surface nor a specific angle of attack during interaction. The pen is 190 mm long and has a diameter of 15 mm. DeltaPen connects to a PC through USB. We use USB for communication and power supply, whereas the processing (movement and rotation estimation) is integrated in the device.

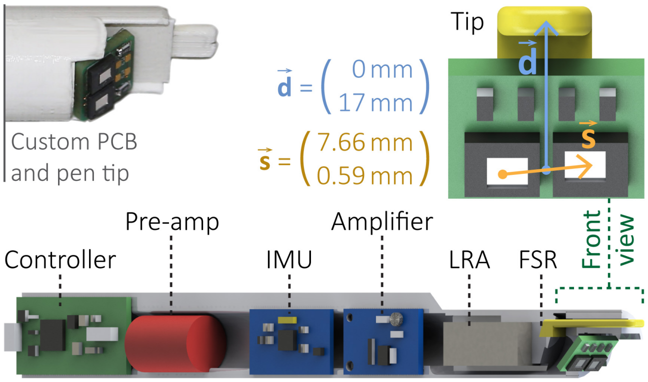

Figure 2: DeltaPen's embedded components and physical arrangement. We rotated the optical flow sensors away from each other so as to maximize distance between them within a small form factor. $\vec{s}$ is the vector from one optical center to the other. $\vec{d}$ is the vector from the midpoint between the optical centers to the center of the pen tip.

Input sensors. DeltaPen's core sensing component comprises two adjacent optical flow sensors. Our small circuit board (10 mm × 12 mm) at the tip of the pen accommodates the two lens-less optical sensors (PixArt P3040), voltage converters, and passive components. The optical centers of the sensors are not in their actual center point, so we can maximize their distance by rotating them away from each other. Individually, the sensors report movement directions at 1000 Hz, with a resolution of 6000 dpi (dots per inch). The sensor is found in commercial pen mice (e.g., Adonit [1]) and, apart from lens-less operation, it is comparable to optical flow sensors inside mice, such as a PixArt PMW3360, using similar pin outs and electrical communication protocols. For comparison, the PMW3360 operates at 12 kHz with a resolution of 12000 dpi, but mounts a lens on top of the sensor and requires the lens fixture to sit flat on the surface [55, 58]. In contrast to lens-based optical flow sensors, the P3040 operates up to a distance of 200 mm from the surface (though increasingly unreliably above a distance of 60 mm), thus tracking motions even when the pen is hovering to some extent. The sensor also records flow under varying tilt angles, for which we apply a gravity-based correction to reconstruct lateral optical flow. Our pen continuously senses acceleration using a 3-axis accelerometer as part of the InvenSense MPU9250 chip [28]. This inertial measurement unit (**IMU**) also includes a 3-axis magnetometer (AK8963) and a gyroscope. While we use the magnetometer in our sensor fusion approach, DeltaPen does not use the gyroscope. To measure the pressure applied to the pen tip, DeltaPen connects an 8 mm force sensing resistor (**FSR**) to the tip. The sensor therefore allows rapidly retrieving changes in pressure applied to the tip.

Haptic actuator. Apart from reporting immediate translation, pen rotation, and tilt for visual feedback and interaction, DeltaPen also incorporates a linear resonant actuator (**LRA**) to render tactile feedback. Specifically, we use a wide-band voice coil actuator to render high-fidelity effects, which we extracted from a `Nintendo Switch` `'JoyCon'` controller. The tactile effects that DeltaPen renders optimally couple to the user's hand and fingers as they grip the pen. The actuator can play complex actuation patterns such as a variety of simulated clicks, simulated detents during continuous input, simulated inertia during pen motion across various simulated surface materials, and more. Our embedded platform directly drives the actuator through the Teensy. The Teensy modulates a PWM output to simulate an audio signal, which we subsequently smooth with a capacitor. This signal idles at 1.65 V, we therefore pass it through an analog subtraction circuit, so that the LRA does not draw current during non-operation. This processed signal is fed into an amplifier that directly drives the motor.

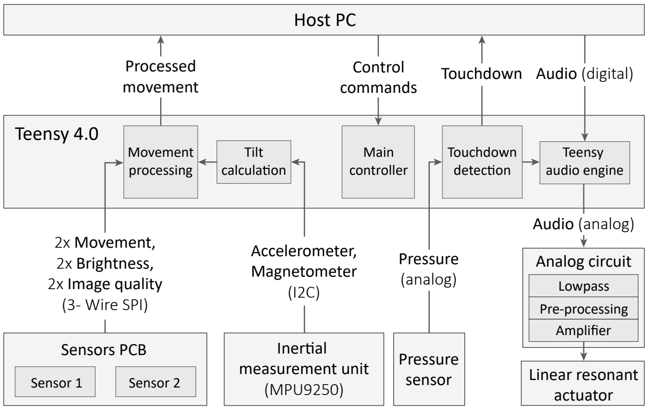

Figure 3: Overview of our architecture. DeltaPen's Teensy microcontroller reads raw values from the optical sensors, IMU, magnetometer, and pressure sensor, fuses input, and sends pen motions and rotations to the host PC. DeltaPen renders built-in haptic effects in response to touchdown events. The host PC can send additional real-time haptic signals (via audio output) to the Teensy.

3.2 Embedded processing

DeltaPen is powered by a Teensy microcontroller, which has a small enough form factor to fit inside the pen's case. The ARM Cortex-M7 600 MHz processor [52] is powerful enough to perform our geometric methods for online reconstruction of translation and rotation. All pen events are forwarded to a PC through USB, which simultaneously powers our device. The microcontroller directly communicates with the two optical flow sensors through a 3-wire SPI interface. Both sensors thereby are on the same bus, providing optical flow vectors at 1000 Hz.

IMU and magnetometer. The integrated inertial motion unit connects to the Teensy through the I2C bus. We configured the IMU to log signals at a rate of 200 Hz, internally filtered to remove noise from higher frequencies in the input data. DeltaPen regularly polls the data from the IMU's internal FIFO buffer. Using the same I2C connection, DeltaPen obtains magnetometer readings through the MPU at 100 Hz. Based on the accelerometer data, we calculate the gravity vector, which in turn allows us to derive the angle between the DeltaPen and its tracking surface (assuming a level surface).

Pressure sensor. DeltaPen samples the analog voltage output from a simple voltage divider ($R = 10\,\text{k}\Omega$), which connects to the FSR. We use the Teensy's internal 13-bit analog to digital converter and log pressure changes at 200 Hz. A simple running average integrator acts as low-pass filter for the raw measurements to remove jitter arising due to pen movement or other sensor noise. The tip inside DeltaPen is loosely mounted inside the case, but directly connects to the force sensor, which enables precise measurement of changing contact forces. The pen exhibits a subtle haptic 'click' upon touchdown, not unlike that in a Microsoft Surface pen or similar.

Touchdown detection. Apart from supporting force-based input, the purpose of the pressure sensor is to precisely detect whether DeltaPen is hovering or in contact with a surface. The force sensor thus allows us to disambiguate moments in the optical flow signal that occur just before touchdown and during lift-off, which would otherwise manifest themselves as artifacts of a pen stroke [24].

To detect proper contact, DeltaPen first analyzes the average brightness of reflected patterns reported by both optical sensors to estimate whether there is a trackable surface within reach. If there is, the pen tip is typically within 20 mm of the surface. Similarly, if the combination of brightness and reported sensor image quality indicates that there is no surface nearby, we conclude a lift-off event and stop processing input motions. This detection is not just crucial for proper pen stroke segmentation, but also enables 'clutching'–allowing users to readjust their palm positions.

Haptic actuations. DeltaPen supports playback of simulated clicks directly on the board, which our pen renders immediately upon detecting a large enough force and switching into tracking mode. This synthesized 'click' feedback thus plays with low latency to support user input with high responsiveness and without requiring round-trip communication with a host. Our embedded platform has sufficient on-board flash to store a series of haptic effects, which can be directly played back. We encode these effects using simple audio files. In addition, more complex haptic effects can also be played back through a connected host PC. Using Teensy support, DeltaPen implements an audio output interface that can be selected for operating system-level sound output on the host PC, thus facilitating playback through the USB cable from any software. We pass all audio signals through a software side amplifier to support precise volume control, which affects the intensity of haptic feedback on the wide-band voice coil actuator.

3.3 Processing pipeline

We now describe the core method of DeltaPen to disentangle 2D motion from 1D rotation using the two optical flow sensors, the accelerometer, and the magnetometer. All computations are performed on the microcontroller, which post-processes raw computations before sending them to the host PC. The end-to-end latency is comparable to the latency of a tethered computer mouse. Figure 4 shows an overview of our processing pipeline. Before deploying the pipeline on the pen, we prototyped it in the `Unity3D` engine by sending all raw values to the PC. We used the `Velt` framework [18] to implement and experiment with the data flow.

Step 1: DPI correction. The lens-less optical flow sensors inside DeltaPen track movement despite not being horizontally aligned with a tracking surface. While this is an advantage over comparable embedded optical flow sensors, it also leads to distorted reported motions depending on the angle between the sensor and surface. Therefore, we apply a simple angle-based correction to the reported raw motions from each sensor. As mentioned above, we estimate the gravity vector from the accelerations reported by the IMU (the angle θ represents the tilt in x-direction and ψ in y-direction) and apply the following formula to each sensors raw data:

$$\Delta x = x_{raw}/\cos(\theta), \qquad \Delta y = y_{raw}/\cos(\psi)$$

Step 2: Angle estimation. From the tilt-corrected raw data in Step 1, we now derive the rotational angle of the pen around the axis that is perpendicular to the surface. We use the known vector between the sensors $\vec{s}$ (Figure 2) and the measured offset $\vec{o}$ (the

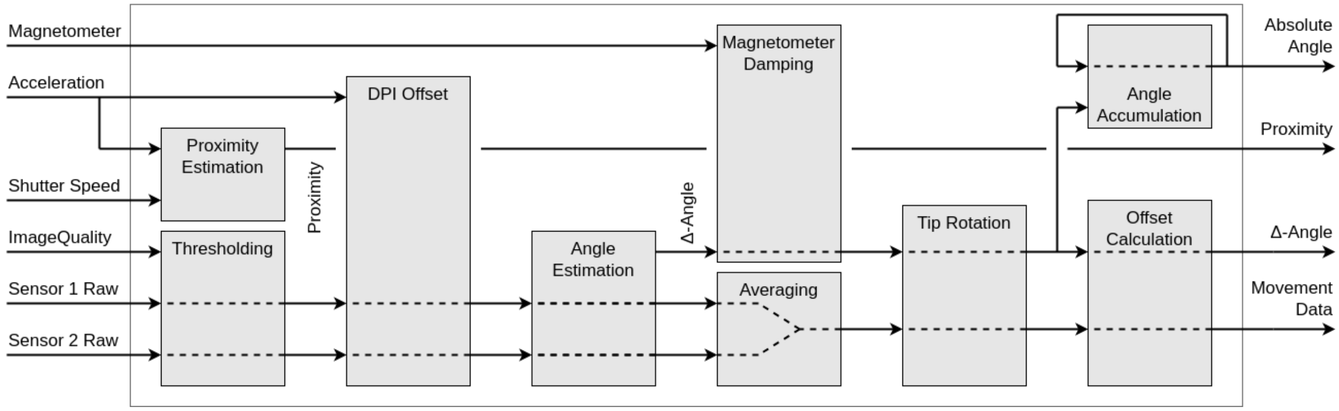

Figure 4: The full processing pipeline used to alter movement data, derive proximity and calculate the angles. Arrows indicate types of data and gray boxes are processing steps. Raw signals are coming from the left. Some processing steps transform input into new types of data (e.g., 'Proximity').

difference between the reported sensor values) to calculate $\Delta\alpha$, which describes the change in yaw rotation:

$$\vec{o} = \vec{m}_{s1} - \vec{m}_{s2}$$

$$\Delta\alpha = \arcsin\left(\frac{\vec{s} \times (\vec{s} + \vec{o})}{||\vec{s}|| * ||\vec{s} + \vec{o}||}\right)$$

Step 3: Proximity estimation. To support clutching during pen interaction, we analyze the brightness of reflections as reported by the optical sensors to estimate the proximity of a potential tracking surface. This allows the user to move the mouse cursor without contact to the surface by hovering slightly above it, or to clutch by lifting the pen further (approximately 2 cm).

Step 4: Thresholding. To account for outliers in the raw reported optical flow values, we apply a simple thresholding function to determine whether or not to process the current frame. Both sensors occasionally produce such outliers, roughly in 0.05% of all measured data points. For example, as a result from our angle estimation, in these rare cases we would obtain an angular rotation of 90° frame-to-frame (i.e., $1/200^{\text{th}}$ of a second) if we would not remove the outliers. A frame is only processed, if both of the two sensors provide valid movement values.

Step 5: Averaging. From here, we do not need the separated movement values anymore, so we combine the data of both sensors into a single value. As a side effect, using two independent sensor values for translation can reduce noise.

$$\vec{m}_{avrg} = 0.5 * (\vec{m}_{s1} + \vec{m}_{s2})$$

Step 6: Magnetometer-based damping. To improve the estimated angle, we included a damping stage based on the sensed magnetometer data. We do not fuse magnetometer measurements directly as part of our angle estimation, but instead leverage a lack of difference in frame-to-frame magnetometer observations to discard changes in our angle estimations. First, we calculate the magnitude of the magnetometer's change vector frame-to-frame. This magnitude indicates whether angular movement was present, with values that are proportional to the amount of angular movement. Since magnetometer measurements are noisy, we filter the signal with a moving average filter (averaging the last 8 values). We then use the output to scale the angular movement $\Delta\alpha$. This step reduces the negative effects of noise in the optical flow sensors and consequently also reduces drift when moving the pen over large distances without applying angular motion.

Step 7: Offset calculation. Next, because the tip of our pen extrudes from the sensor platform along the outside of the pen case, we compensate for rotations about the tip of the pen (which has an offset from the center of the sensors' measurement locations on the surface). Without this compensation, rotations about the pen tip would be falsely reported as movements. To compensate, we use the measured distance between the pen's tip and the midpoint between the sensors $\vec{d}$. Since the offset in x direction is 0, we can omit it from the calculation. We then remove this offset by applying

$$\Delta\vec{m}_{rot} = \vec{m}_{avrg} - \begin{bmatrix} sin(\Delta\alpha) * \vec{d}.y \\ cos(\Delta\alpha) * \vec{d}.y \end{bmatrix}$$

Application layer. The application in the host PC can choose how to combine the processed values. For writing tasks, we can apply the accumulated α value to the movement data to compensate for rotation. However, for other tasks such as dragging pictures in the photo sorting application (Figure 1 c), we do not use a 1:1 mapping for the rotation–we apply a rotation gain to rotate pictures more conveniently with only small rotations of the wrist.

4 TECHNICAL EVALUATION

To quantify DeltaPen's performance of angle estimation during typical pen operations such as sketching and writing, we conducted a technical evaluation with 10 participants (4 female) who were between 25 and 31 years old (mean age: 26.7). Primarily, we analyzed how close our angle estimation method is to ground-truth rotation, which we gathered using a high-precision optical tracking setup (OptiTrack). A secondary goal of this evaluation is to determine which of the optional pipeline steps contribute to an overall better angle estimation and to which extend.

4.1 Apparatus

Figure 5 shows our data collection setup. Because we wanted participants to provide pen input that is as accurate as possible, we performed this evaluation on a high-precision Wacom tablet (`Intuous` 4). To rigidly couple DeltaPen and the Wacom pen, we 3D-printed a mount to attach and align both pen tips as shown in Figure 5 bottom-left. We attached tracking markers to DeltaPen, which three surrounding `OptiTrack` infrared cameras tracked throughout operation (Figure 5 top-right). A screen in front of the participant provided visual feedback while drawing (Figure 5 bottom-right). Importantly, the rendered strokes were solely based on the Wacom pen's absolute position input. We recorded all OptiTrack, Wacom and DeltaPen data for offline analysis.

4.2 Data collection procedure

The procedure of the study was designed to capture various types of pen-input data under different levels of control. Therefore, participants' tasks comprised pre-defined motions, hand writing, as well as free motions that were not guided by the experimenter. We also included a task in which participants had to do pen motions slightly above the surface without touching it (i.e., hover). Overall, the participants completed four tasks:

(1) Participants drew various pre-defined closed shapes, such as circles and rectangles, each in a small and large version. 'Small' means that participants rested their palm on the surface and only rotated their wrist and fingers while drawing, leading to shapes with a size of 2 cm to 4 cm. 'Large' shapes where around 10 cm from top to bottom. Participants thereby repeated drawing each shape and variation for one minute in-place.
(2) Participants wrote five pre-defined sentences, each in two versions: in block letters and in cursive.
(3) Participants created a sketch, which they drew based on their own imagination for about 5 minutes.
(4) Participants repeated the first phase, drawing primitive shapes again. This time however, they were instructed to do the motion with the pen hovering slightly above the Wacom tablet.

The goal was to collect both, movements on the surface as well as slightly above. While Tasks (2) and (3) inherently contained both (i.e., participants lifted the pen between strokes), Task (4) ensured that we also have enough samples of the pen hovering above the surface. During the study, participants received visual feedback on a dedicated screen that displayed a simple canvas. Therefore, participants immediately saw the strokes they were drawing as registered by the Wacom tablet.

4.3 Data processing

After conducting the study, we cleaned the raw recordings following several criteria. We only included data points that where recorded while the OptiTrack system had a clear view on the three markers. At the same time, the pen had to be close enough to the Wacom surface so that it could accurately measure the distance and position (up to approximately 1 cm above the Wacom surface). We also removed frames at the beginning and end of each recording. While not necessarily invalid, those data points often did not include meaningful data. In total, we obtained a set of 209,986 data points across all tasks and participants.

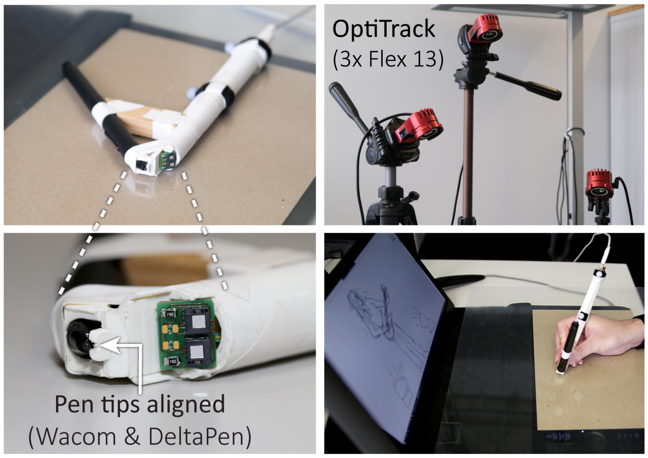

Figure 5: Setup of our data collection. Top-Left: We mounted a Wacom pen to our DeltaPen to collect ground-truth position data with a Wacom tablet. Bottom-left: The tip of the Wacom pen is aligned with the tip of DeltaPen. Top-right: We tracked the absolute angle of the pen with an OptiTrack system. Bottom-right: While drawing, users saw the output registered by the Wacom tablet on a screen.

4.4 Results

Based on our dataset consisting of DeltaPen, Wacom and Optitrack data, we analyzed the translation and angle estimation errors. Additionally, we tested how the different processing steps in our pipeline contribute the the accuracy of the pen.

Angle estimation errors. We analyzed the accuracy of our angle estimation method in comparison with the ground-truth rotations reported by the external OptiTrack system. Table 1 shows the MAE as well as the median of the absolute errors over the whole dataset depending on which of the optional pipeline steps are active. The error metrics indicate that *DPI compensation* has a negative and the *Magnetometer damping* a positive impact on the accuracy.

In order to confirm the impact of the optional pipeline steps on the angle estimation, we evaluated the statistical effect of *Pipeline step* on *Accuracy*. For this, we fitted a Generalized Linear Mixed Model (GLMM) with logistic link to the absolute angle error data because data points were not normally distributed (*Shapiro-Wilk*

Additional processing steps	Median error	Mean error
None (unprocessed angle)	$5.25 * 10^{-3}$	$9.56 * 10^{-3}$
DPI compensation	$5.60 * 10^{-3}$	$9.97 * 10^{-3}$
Magn. damping	$4.75 * 10^{-3}$	$9.19 * 10^{-3}$
DPI comp. & magn. damping	$5.06 * 10^{-3}$	$9.56 * 10^{-3}$

Table 1: The mean and median errors of the angle per 40 milliseconds over the whole dataset depending on which optional pipeline stages are enabled. 'None' means that we only calculate the angle based on the optical flow sensors without pre- or post-processing. All errors are given in radians.

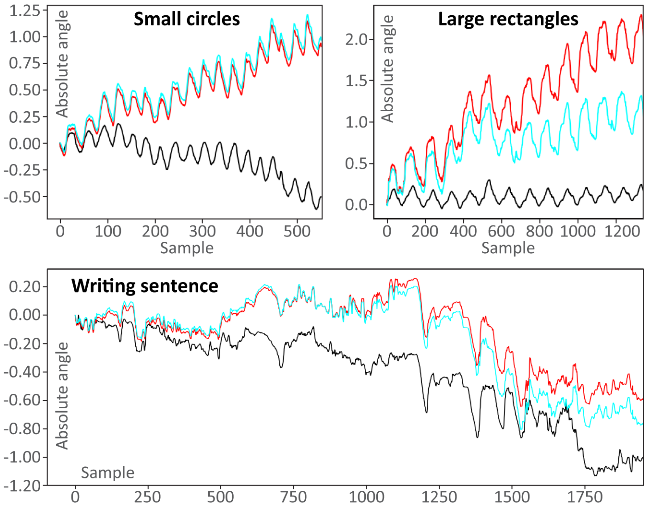

Figure 6: Three examples of absolute angles calculated from the DeltaPen sensor values (red) and with magnetometer damping enabled (cyan) in comparison to the OptiTrack baseline (black) for specific tasks and participants. All angles are given in radians.

$p < .001$). The model included the two independent variables *DPI_Scaling* and *Magnetometer* as fixed effects and participant as a random effect. We carried out the statistical tests using *glmer* of the *lme4* package[15] in the R programming language.

The GLMM showed a main effect of *DPI correction* ($p < .001$) and *Magnetometer damping* ($p < .001$), but no interaction effect between *DPI correction* and *Magnetometer damping* ($p = .95$). We found that disabling *DPI correction* led to a significantly smaller angular error ($M = .009$ compared to $M = .01$ with DPI Correction enabled). In contrast, disabling *Magnetometer damping* led to significantly higher error ($M = .01$ compared to $M = .009$ when enabled). Figure 6 top shows how the *Magnetometer damping* step provides a larger improvement when drawing longer strokes (such as in the 'Large rectangles' subfigure), compared to the smaller strokes (such as the 'Small circles' subfigure).

The results indicate that the DPI correction in our pipeline has a negative impact on the accuracy while the magnetometer damping step is indeed useful.

Angular drift. Because errors in angle estimation can accumulate when drawing or interacting for a longer period of time, we evaluated the amount of drift accumulation. Figure 6 shows the accumulated angle drift over time in comparison with ground-truth angles during various participants' drawing tasks. When calculating the absolute angle over time, we found the amount of drift to be $0.160 * 10^{-2}$ rad s^{-1} over all 209,986 collected data samples.

Idle Drift. While an idling sensor produces less noise, there is still a small drift over time. To find the idle drift, we left the pen stationary for a prolonged time, and measured the accumulating angle and translation. Our test indicates that DeltaPen's angle estimation drifts $9.07 * 10^{-5}$ rad s^{-1} and the translation drifts 0.04375 mm s^{-1} in X and Y direction (each) when idle.

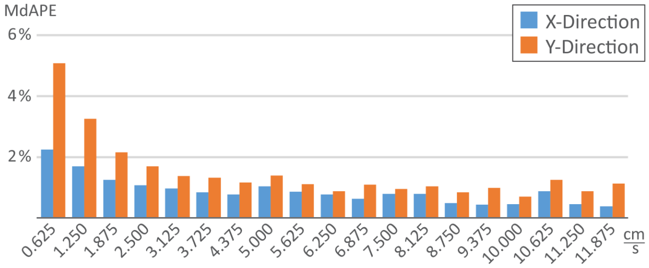

Figure 7: Relative translation errors against velocity (in cm s^{-1}) separated in X and Y translation. We assigned each sample to a 'bin' (horizontal axis) based on its velocity. Each bin contains samples that had at least the bin's minimal velocity and were slower than the velocity of the next bin. The exception is the rightmost bin, which incorporates all velocities greater than or equal to 11.875 cm s^{-1}.

Translation errors. We measured the errors of the movements of the pen versus the ground truth movement measured by taking the deltas of the Wacom tablet's reported absolute positions. When reading movements (DeltaPen) and taking the position differences (Wacom) at every 10 ms, then the *Mean Absolute Error* (**MAE**) for the magnitude of the translation is 0.0683 mm (Median = 0.0236). We additionally analyzed the translation error separated in X and Y direction. As opposed to the magnitude error above, the X and Y separation is inherently dependent of the pen rotation. Therefore, to make this analysis independent of our angle estimation error, we first compensated for the current absolute pen rotation (by rotating the sensor values in the opposite direction) when measuring the X and Y errors. Figure 7 shows the *Median Absolute Percentage Error* (**MdAPE**) for several ranges of velocity. The error in Y-direction is consistently larger than in X-direction, indicating future potential for further pipeline refinements. The relative error tends to decrease as the pen moves faster within the velocity limits of the optical flow sensors. While the sensor readings can become unstable during very fast motions, the graph also reflects that the pen movements during the data collection (i.e., while sketching and writing) where within a stable velocity range.

5 USE CASES AND WIDGETS

In this section, we describe several use cases and widgets that we implemented to showcase the haptic capabilities of DeltaPen and the use of the rotation as an additional degree of freedom. We encourage the reader to also refer to the supplemental material of this publication to see the individual applications and widgets described hereafter in motion.

5.1 Minimal use cases

Mouse cursor and mobile use. Our device can be connected and recognized by the PC as a *Human-Interface Device* (HID) and hence it can be used to control the mouse cursor of the operating system. For instance, in Figure 1 a, DeltaPen is used as mouse input on a small tablet with rotation being mapped to the mouse wheel. This points to a future in which users can utilize a table surface (e.g., in a cafe) for translation and rotation input on a small tablet or even smartphone–avoiding occlusion and additionally freeing up display space that can potentially be leveraged for complementary touch input using the non-dominant hand [26, 49].

Sketching and note-taking. The most common use case for a pen-shaped device is sketching and note-taking. Our device can be used like a conventional pen or stylus to support such interactions. Participants of our data collection could volunteer to try our device in its finished form. Figure 8 showcases some hand-written sentences and a few sketches from one of the volunteers.

Photo viewer. Figure 1 c shows our photo viewer application, which demonstrates a minimalist use case for translation and rotation input. The user can move images across the virtual surface and rotate them around the pen. This way, no separate gizmo or handle is needed to enable rotation.

5.2 Widgets

We implemented several UI widgets that utilize haptic feedback as well as rotary input (Figure 9).

Button. The most basic haptic UI component is a button that can simulate stiffness through haptic feedback [34]. We can vary the perceived stiffness simply by adjusting the pressure that the user needs to exert before feeling the button click (Figure 9 a).

Slider. We also implemented a haptic slider (Figure 9 b). Users can press down the slider and drag the cursor so as to manipulate its value. Whenever certain values are reached (rendered as small bumps on the slider at regular intervals), the user feels a small click from the pen.

Knob. Similar to a linear slider, we implemented a haptic knob (Figure 9 c) with which the user feels a click at pre-defined angles while rotating it. Instead of dragging left and right, the widget makes use of the unique rotation capabilities of our pen. Such rotation-based widgets can add flexibility to the user interface layout and potentially require less space compared to sliders, as they are a small circular shape instead of a long rectangular one. For instance, arrays of knobs in music mixing user interfaces make heavy use of this form factor, but such applications typically map translation (of the mouse cursor) to knob rotation.

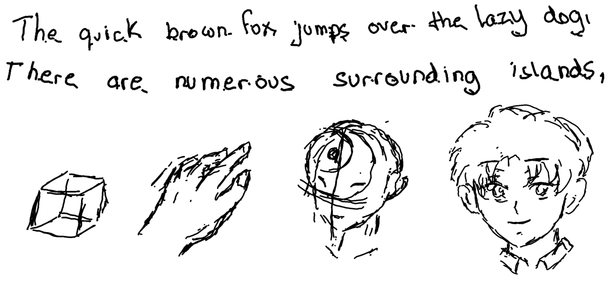

Figure 8: After the data collection, we invited users to try out the finalized pen. The sentences and sketches were made by a first-time user of our DeltaPen device on a table surface.

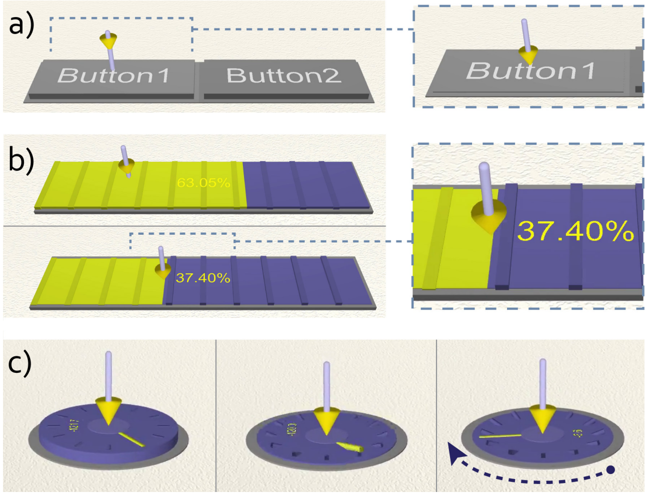

Figure 9: Basic widgets that make use of our pen's capabilities. (a) A button that features a haptic 'click' effect when applying enough pressure. (b) A slider that, once pressed down, features little bumps at key values. Users feel how those bumps get pushed in once they move the cursor across. (c) A knob that the user can rotate while applying pressure.

5.3 Painting application

We implemented a painting application that combines multiple combinations of translation and rotation input. The application features a canvas and a color palette (Figure 10). The user can freely move and rotate the palette across the canvas so as to bring the color selection close to where the user wants to paint. When picking a color from the palette, the user can additionally rotate the pen before releasing it to make the same color brighter or darker. The middle of the color palette features a preview stroke. The user can adjust the stroke's thickness, opacity and roundness all at once by pressing down on the stroke and vertically moving, horizontally moving and rotating the pen, respectively. By shaking the pen in the air, the most recent stroke is removed (undo). Lastly, by holding the pen upright while dragging, the user can move and rotate the whole canvas. Figure 11 shows virtual paintings created with DeltaPen.

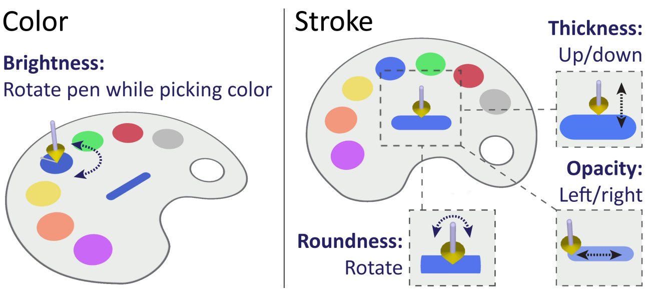

Figure 10: Color palette of our painting application. The user can pick a color, adjust its brightness as well as set the stroke thickness, opacity and roundness.

6 LIMITATIONS AND FUTURE WORK

In this work, we demonstrated the feasibility of a pen device that can precisely track translation and rotation along the surface with all sensing components integrated into the device. Our design comes with some limitations, which we plan to address in the future.

Absolute rotation. While our pen reliably senses relative rotations, an open challenge remains in finding the initial rotation of the pen upon starting an interaction. This is especially important for movement compensation. The initial rotation does not need to be as precise or as responsive as the quick relative rotations that we use the optical flow sensors for. For this, a simple solution would be a calibration step (e.g., briefly letting the user draw a short stroke to the right). However, we plan to investigate calibration-free methods, e.g., by estimating the initial rotation from the precisely sensed pen motions using machine learning.

Untethered operation. While all sensing and processing methods are fully integrated into our device, our current prototype still requires a USB connection for communication and power. In the future, we plan to make the device entirely self-contained, such as by integrating a Bluetooth low-energy (BLE) component, a battery, and a charging circuit. This will make it necessary to optimize data transfer in order to maintain the low latency transmission to the PC or mobile device.

User study on input effectiveness. In this paper, we primarily focused on the technical challenges of our integrated pen device. This opens up opportunities for exploring the human-factor perspective of pen interaction with a device such as DeltaPen in future work. While participants informally tried out our pen (Figure 8), a more formal and larger-scale evaluation will be needed to investigate the effectiveness of DeltaPen more broadly.

Mid-air interaction. One possibility for future research is to investigate how to combine high-precision on-surface input with continuous mid-air input. For instance, the IMU can potentially support continuous tracking at a lower precision whenever surface contact is lost. Similarly, in mobile situations where cameras are available (e.g., through a Mixed Reality headset), such cameras could help maintain the pen tracking when the pen is lifted. Such tracking would then be in synergy with our dual-sensor approach whenever surface contact is re-established so that the pen can be kept at a small form factor.

7 CONCLUSION

We presented DeltaPen, an integrated haptic pen input device that can sense translations, as well as its own rotation around the axis perpendicular to the surface it is used on. A particular challenge for sensing rotation with a pen-shaped device is the need for two optical flow sensors lying in the narrow space at the pen-tip. With our technical evaluation, we provided an indication that sensing the translation and rotation with our approach is close to the baseline of externally tracking the pen position as well as rotational movements. Furthermore, the evaluation helped us to make informed choices for fine-tuning the pipeline. We hope to inspire future research on high-precision pen devices that can be used on passive uninstrumented surfaces without external tracking.

Figure 11: Various example paintings created with DeltaPen on a desk surface utilizing all features of our painting application—including opacity for shading and adjusting the drawing angle by rotating the pen (e.g., for adding fur).

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