OptiBasePen: Mobile Base+Pen Input on Passive Surfaces by Sensing Relative Base Motion Plus Close-Range Pen Position

Andreas Fender
Visualization Research Center (VISUS)
University of Stuttgart
Stuttgart, Germany

Mohamed Kari
Chair for Integrated Information Systems
University of Duisburg-Essen
Essen, Germany

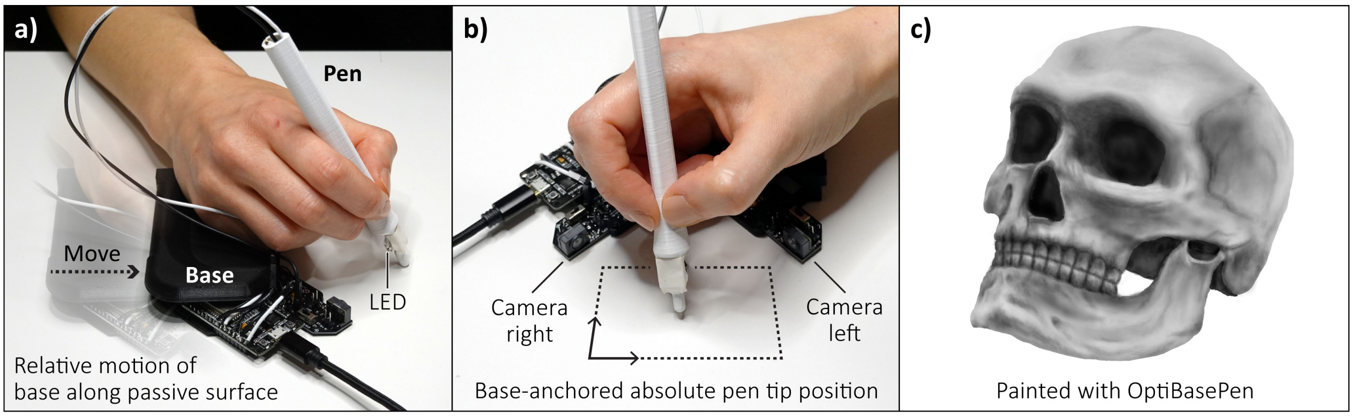

Figure 1: We present the base+pen concept and our OptiBasePen prototype. The user's moving hand rests on the *base*, which tracks its own motion along the surface using a mouse sensor (a). The base contains two cameras, which track the pen tip within the base's coordinate system (b). The cursor position results from the base movement (a) plus the base-anchored pen tip position (b). OptiBasePen enables use cases like digital painting (c) on passive surfaces on the go without external tracking.

Abstract

Digital pen input devices based on absolute pen position sensing, such as a Wacom pen, support high-fidelity pen input. However, they require specialized sensing surfaces like drawing tablets, which can have a large desk footprint, constrain the possible input area, and limit mobility. In contrast, digital pens with integrated relative sensing enable mobile use on passive surfaces, but suffer from motion artifacts or require surface contact at all times, deviating from natural pen affordances. We present OptiBasePen, a device for mobile pen input on ordinary surfaces. Our prototype consists of two parts: the "base" on which the hand rests and the pen for fine-grained input. The base features a high-precision mouse sensor to sense its own relative motion, and two infrared image sensors to track the absolute pen tip position within the base's frame of reference. This enables pen input on ordinary surfaces without external cameras while also avoiding drift from pen micro-movements. In this work, we present our prototype as well as the general base+pen concept, which combines relative and absolute sensing.

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CCS Concepts

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

Keywords

Pen input, relative input, absolute input, stylus, digital painting

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1 Introduction

Digital pens or styli have evolved into mature and popular high-precision input devices as evidenced by products such as Microsoft Surface Pen [46], Apple Pencil Pro [4], Wacom [70], Anoto Pen [3], and others. However, these examples either operate directly on the display or require specialized input surfaces like drawing tablets or paper with specific dot patterns [3]. In contrast, off-screen pens without the need of surface instrumentation, e.g., useful for mobile input on laptops, have limited commercial success due to other drawbacks. For example, pen mice feature optical flow sensors as found in ordinary mice, packaged in a stylus-like form factor [48]. However, they lack natural pen input affordances, because, just like conventional computer mice, pen mice typically require orthogonality and closeness to the surface for uninterrupted and accurate tracking. These constraints entail a hand posture that is unnatural for pen input, which in turn significantly limits tip control. This is why pen mice are mostly meant to be used as ergonomic alternatives for mice [14, 68] and have remained in a niche existence. Research prototypes have aimed to address those limitations, e.g., by adding a second optical flow sensor to sense relative rotation in addition to translation [38], but those are typically prone to the inherent limitations of relative tracking like drift. Prototype designs that employ cameras mounted on or above the table [9, 39, 71] offer precise *absolute* pen tracking without drift. However, the need for installing external cameras limits their flexibility and portability. This range of previous devices can be seen as a *mobility-vs-trackability trade-off*. Fully self-contained pens offer a compact form factor and are therefore highly mobile, but suffer from tracking artifacts and thus lack the quality that is expected by stylus users. Conversely, pen designs that require external high-resolution cameras offer high tracking quality, but lack the flexibility for mobile use.

In this paper, we present the *base+pen* concept of combining relative movement sensing with close-range absolute tracking. As an instance of this concept, we present the OptiBasePen prototype, which enables digital pen input on passive surfaces without external tracking. OptiBasePen retains the natural affordances of a pen while avoiding drift from pen micro-movements. Instead of expensive high-resolution cameras, we designed the prototype around low-cost and low-power hardware components for mobile use. Figure 1 shows an overview of our prototype (also see Video Figure A in the supplemental materials). The user's hand rests on a *base* device (Figure 1 a), which can slide along the surface together with the user's hand. Meanwhile, the base senses its *relative* motion using a built-in mouse sensor. For pen tip sensing, our base contains two low-cost image sensors for sensing an LED that we attached right above the pen tip, covering a close-range tracking area of around 6 cm × 6 cm next to the moving base (Figure 1 b). Hence, the pen tip sensing is *locally absolute* within the frame of reference of the moving base. For the final cursor, we add the LED's horizontal 2D position to the accumulated base motion, and use the LED's vertical position to detect surface contact. OptiBasePen covers different mouse or pen input use cases such as digital painting (Figure 1 c).

We argue that our base+pen approach brings together advantages of relative and absolute sensing, fundamentally enabled by the idea of leveraging the tendency of humans to position a pen tip through *hierarchical control* of the human kinematic chain. Concretely, humans tend to move their palm coarsely on the surface and then finely draw, write, or point with fine-grained finger articulation. We take advantage of this with our movable base, placed underneath the hypothenar eminence (the part of the hand that usually rests on the surface while writing). Due to the close-range absolute tracking, pen micro-movements do not lead to drift or other motion artifacts that are typical for relative-only sensing.

Taken together, we contribute:

- The **base+pen concept** of combining relative and absolute sensing for pen input.
- The **OptiBasePen prototype** serving as a reference implementation of our concept.
- A set of implemented example interactions showcasing the device's capabilities.

2 Related work

There is a wide range of existing products and research prototypes related to digital pen input. This section deals with different types of optical pen sensing approaches and describes specific examples from industry and research.

2.1 Mid-air versus on-surface

Many sketching interfaces support mid-air pen interaction in 3D space [6, 30, 34, 56, 67]. However, the lack of a physical surface often poses a challenge [20], which can be mitigated with virtual planes [7] or an additional tablet [18, 44, 52]. Furthermore, 3D sketching use cases and outputs generally differ from systems featuring pen interaction on, or right above surfaces. Therefore, the remainder of this section focuses on works that have use cases closely related to the ones of OptiBasePen. This includes systems that utilize surfaces as the primary input area and optionally the space directly above the surface as the secondary input space (i.e., hover).

2.2 Dedicated specialized sensing surfaces

2.2.1 Active sensing surfaces. Many previous commercial products and research prototypes use dedicated surface areas for pen or pen-like input, be it transparent surfaces to enable tracking from below [19, 69] or with the surface itself containing sensing components [25, 33]. A commercial example for the latter is a Wacom tablet [70], which is a sensing surface dedicated to high-precision pen input as used in digital art. Pen input is typically also supported on commodity capacitive touch screens, such as smartphone screens [64] or tablets [4]. Researchers often directly build upon such capacitive screens. For instance, the IrPen by Han et al. [25] expands the pen input to the space above a tablet by using photodiodes. VersaPen by Teyssier et al. [65] is primarily used on capacitive screens, but additional modules, e.g., containing an Inertial Measurement Unit (IMU) or input/output components (wheel, vibro-motor), can be physically attached or detached depending on the use case.

Typical drawbacks of devices based on active sensing surfaces are the desk footprint and an overall limited flexibility of the input area. This does not only impact mobility but can also be a hindrance in emerging Mixed Reality (MR) use cases, where input devices and surfaces are not always bound to specific physical locations [45].

2.2.2 Paper-based sensing. A common drawback of active sensing surfaces is their surface material, which differs from the affordances and familiarity of paper. Therefore, researchers investigated how to use paper as the input surface for digital input [35, 36]. Relevant products are the Neo Smartpen [61] and the Anoto Pen [3], both of which can track their absolute position on a printed pre-defined dot pattern, which in turn has been used for research prototypes. For example, MouseLight by Song et al. [63] built a projector and pen system that uses multiple Anoto Pens for absolute tracking. Specifically, two Anoto Pens are attached to a movable mini projector unit, which is operated with the non-dominant hand and illuminates a region of the paper. Another Anoto Pen held with the dominant hand then enables pen input, primarily inside the illuminated region. Although not a pen device, Dothraki by Schüsselbauer et al. [60] uses a pattern on a tabletop so that their tangible can track its own position similar to Anoto.

The discussed approaches have in common that they require specialized patterns on the paper. This makes them useful for special-purpose applications but less practical in generalized mobile use cases involving unprepared ordinary surfaces. Therefore, researchers have investigated alternative sensing methods for pen input that keep the input surface requirements flexible. We discuss such works in the next subsection.

2.3 Optical pen tracking on ordinary surfaces

Most previous optical pen tracking approaches, also for ordinary surfaces, can be categorized into outside-in or inside-out tracking.

2.3.1 Outside-in optical tracking. To retain the weight, form-factor, and handling of the pen device, a lot of previous works opted to use external cameras for pen tracking instead of integrating all electronics into the pen. In general, tracking objects outside-in has been researched in many areas like tabletop systems [2]. Pen input research has utilized related concepts such as marker tracking. Dodecapen by Wu et al. [71] features a passive marker at the top end of the pen to track its pose at a very high precision. Similarly, TsFPS by Xiang et al. [72] uses markers on different tools including pens. TipTrack by Maierhöfer et al. [39] uses an integrated LED that illuminates the tip from the pen's inside as well as external infrared cameras to track the pen tip and to detect surface contact.

When using outside-in tracking as in TipTrack and similar systems, the cameras are typically relatively far away from the pen. This means that the cameras need to provide high-resolution streams and the camera rigs—often table-mounted—are not intended for mobile use. In contrast, our base+pen approach allows to use low-power, low-cost cameras as they are integrated in the base and hence located very close to the pen tip.

One way in which previous works circumvent the cost and flexibility issue is to use already-available cameras depending on the use case. For instance, Kern et al. [31] attached different digital pen tips to commodity MR controllers tracked by the MR headset to enable writing and sketching on passive surfaces. This reliance on MR devices, however, makes the pen input method less flexible compared to devices that contain all sensing components. Song et al. envision a pen that integrates a small projector to augment physical paper. While they envision such a pen to be self-contained, they implemented their outside-in PenLight prototype to test this concept. Their setup uses a static projector illuminating the paper from above to simulate the behavior of a miniature projector whose projection frustum originates from the pen itself.

2.3.2 Inside-out optical tracking. Typically, inside-out-based pen devices are fully relative devices that sense motion, as they do not have a global reference. This also means that most of those devices are fully integrated without requiring special surfaces or sensing hardware installed in the environment. Most prominently, commercial pen mice [48] provide the functionality of a mouse, but with the form factor of a pen. Primarily, those devices aim to improve ergonomics compared to a typical mouse and to prevent injury [14, 68], which means their use cases largely overlap with those of an ordinary mouse. What hinders the use as a pen is the fact that such devices use mouse sensors at the pen tip, which require lenses that are perpendicular (or at least close to perpendicular) to the surface at all times, i.e., the bottom of the device needs surface contact, and buttons are used as activation triggers (e.g., holding a button to draw strokes). Those factors are opposing the affordances of pen interaction. The Adonit Ink-M [1], a hybrid device that integrates stylus and mouse functionalities in one device, only supports pen capabilities on dedicated sensing surfaces. The separate mouse functionality cannot be used at the same time and has similar limitations to other pen mice. There are previous research undertakings using inside-out tracking that aim to fully retain the affordances of a pen [47]. DeltaPen by Lüthi et al. [38] uses two small lens-less optical flow sensors to track translational and rotational movements along passive surfaces. However, as the device is purely relative, micro-movements and pen rotations around other axes than the tracked one can lead to small inaccuracies and drift. Additionally, its form factor is affected by the hardware components that need to be integrated into the pen.

2.3.3 Combining inside-out and outside-in. Flashpen by Romat et al. [55] primarily uses inside-out tracking but also has an outside-in tracking component. Concretely, a mouse sensor that has surface contact senses movements with high precision, and a secondary external OptiTrack system tracks the rotation (yaw) in order to correct the values reported by the mouse sensor. In other words, Flashpen combines two optical tracking approaches and is hence conceptually related to our approach from a high-level perspective. However, like previously discussed outside-in approaches, Flashpen requires high-resolution external cameras.

2.4 Summary of related work

Typically, outside-in and inside-out sensing corresponds to absolute and relative input, respectively (though absolute sensing can also support relative input [23]). OptiBasePen combines several techniques and properties of inside-out and outside-in tracking and can therefore not be strictly categorized. The close-range sensing is absolute within the base's frame of reference, whose translation is the accumulated relative motion of the base. To our knowledge, no previous pen input device features such a combination of a pen and a base, integrating relative and absolute sensing to support pen input on ordinary surfaces without external cameras while also avoiding drift from pen micro-movements.

This section focused on works that are closely related to our OptiBasePen prototype. We discuss further previous works that are relevant to our concept (beyond our implementation) in section 5.

3 Concept and implementation

The basic idea of the base+pen concept lies in enabling pen input on ordinary surfaces by combining relative and absolute input. While a mouse is grounded at all times (except when clutching) the same cannot be said about natural pen input. A pen undergoes continuous small movements and rotations on the surface as well as in the air. When using optical flow sensing, the scale of the sensed movement can vary as slight offsets in distance and angle of the sensor towards the surface changes the sensor readings. Therefore, we argue that the pen itself needs to be tracked in an absolute frame of reference in order to keep the cursor motion consistent and to avoid drift. Normally, this would require an external high-resolution tracking setup, an active sensing surface, or the input would be limited

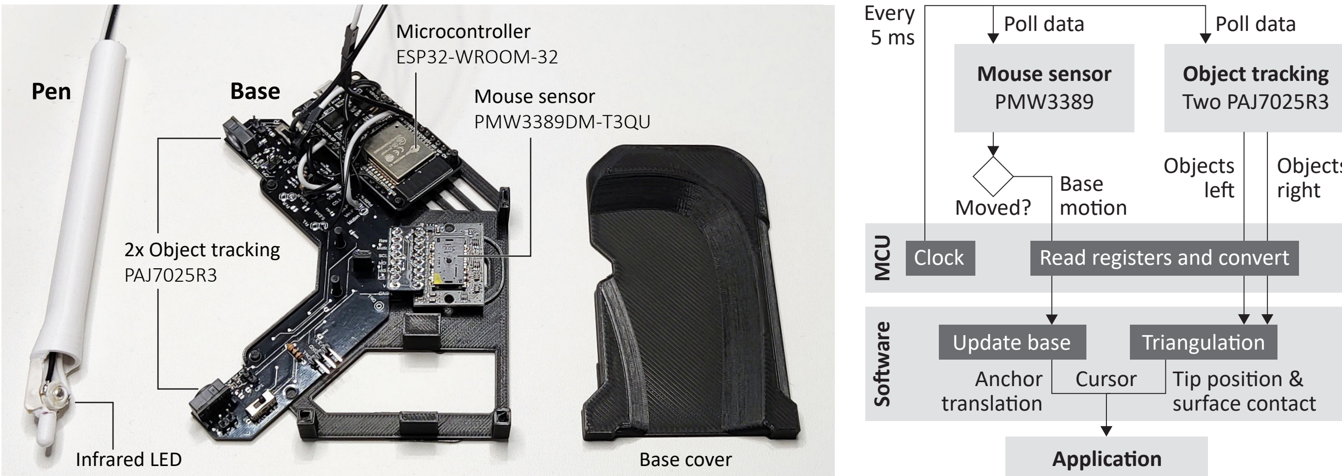

Figure 2: Hardware components and pipeline. Left: Our device consists of a pen with an infrared LED, two object tracking image sensors, a mouse sensor, and a microcontroller (MCU). The 3D printed base cover sits on top of the base (detached in picture for visibility). Right: Our pipeline including the embedded processing steps all the way to the application. The MCU polls sensor readings every 5 ms and forwards them to the PC, which combines the values into the final cursor for the application.

to a small area. We therefore additionally sense relative motion of the hand, which rests on a movable base. Because the hand is grounded and not bound to the same fine-grained motion and drift requirements of the pen itself, we can use an ordinary mouse sensor. This combination makes use of the human's hierarchical kinematic chain in unimanual input, tracking the coarse position of the hand (upper hierarchy level), which precedes the fine-grained movements of the end-effectors, i.e., the fingers holding the pen (lower hierarchy level). The pen is absolute within the area next to the moving base, i.e., while the coordinate system itself moves, the same camera readings always lead to the same locally tracked absolute pen position. The cursor is then simply the sum of the aggregated base translation and the tracked pen position within the base's tracking area. In the remainder of this section, we describe OptiBasePen, an instance of our base+pen concept.

3.1 Hardware components

Figure 2 left shows OptiBasePen's hardware components. An infrared LED is attached close to the pen tip. The base contains all of the sensing components, which we describe in the following.

The base contains a custom PCB with two infrared image sensing and processing components (PAJ7025R3 [51], denoted **PAJ** hereafter). A PAJ reports the position and other features of bright blobs in image space at up to 200 Hz. While a PAJ's native resolution is 98 pixels × 98 pixels, the image processor estimates sub pixels and maps each blob's position and radius to an upscaled coordinate system of 4095 units × 4095 units. On our custom PCB, the PAJs have a yaw angle difference of 90 degrees and a distance of 9 cm. They are arranged like this to avoid occlusion by the user's fingers that are resting between the PAJs. The two PAJs track the position of a hemispherical LED attached close to the pen tip (facing roughly towards the surface and the base). While the pen's LED could also be powered by a small battery, we decided to connect it to the base with wires to easily control the brightness in code.

The other sensing component of the base is a mouse sensor (**PMW** hereafter). The PMW needs to be at a specific physical height, different from the PCB for the PAJs. Therefore, instead of a single custom PCB for the PMW and the PAJs, we included connectors for a separate PMW breakout board. We designed the base connectors to work with an open source breakout board[1]. However, in the end, we created a simple adapter and connected our final prototype to a pre-assembled PMW3389DM-T3QU breakout board[2] as its shape is more suitable for the inside of our base.

We use an ESP32-WROOM-32 microcontroller unit (**MCU** hereafter). Notably, the chosen MCU is relatively large and hence adds to the base's footprint. Even though smaller MCUs would also be capable of the processing tasks, the number of additional pins of the ESP32-WROOM-32 were very useful for developing and testing. Furthermore, implementing debugging functionalities, such as streaming raw images from the PAJs for inspection, turned out to be easiest with this board.

A 3D printed case for the base supports the PCBs from below and a separate attachable cover allows to rest the hand on it. We glued commercial mouse feet to the bottom to reduce the friction when sliding the base along the surface.

3.2 Pipeline overview

Figure 2 right shows our overall processing pipeline. Every 5 ms (corresponding to 200 Hz) the MCU polls data from the PMW and the PAJs. The MCU sends the raw data to the PC via USB. Even though the PMW can sense motion at much higher rates, we decided to use the 200 Hz of the PAJs as the global clock and to send the PMW's accumulated motion from within those 5 ms. This way, base and pen tip are always updated at the same time.

[1]https://github.com/siderakb/pmw3360-pcb?tab=readme-ov-file
(last access: July 23, 2024)
[2]https://www.tindie.com/products/citizenjoe/pmw3389-motion-sensor/
(last access: July 23, 2024)

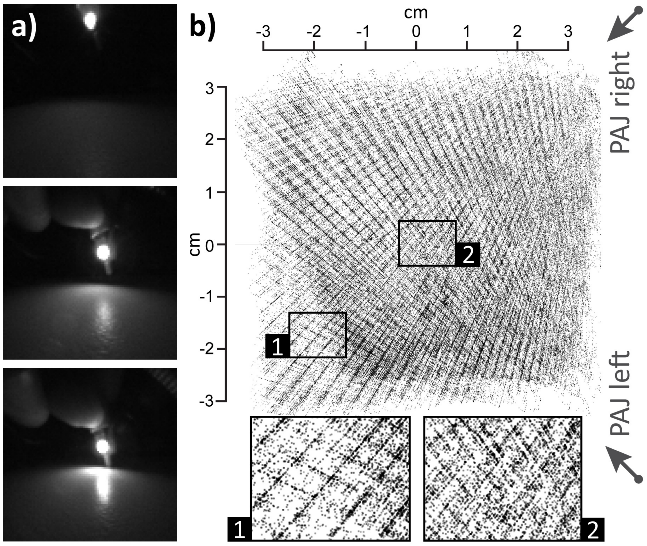

Figure 3: Inspection of the PAJ frames from the base. a) Raw frames of a PAJ. The LED creates a bright blob and an unwanted reflection. Because the LED is slightly above the tip, those two blobs are always separate. Hence, we can simply discard the lower blob (i.e., the reflection). b) Scatter plot of around 30000 samples after drawing in a 6 cm × 6 cm area.

We implemented a configurable version of the software part (“Software” in Figure 2 right) using Unity 3D and Velt [22]. For the base, we simply accumulate the received PMW values and update its virtual 2D translation. Given the extrinsics and intrinsics of the PAJs as well as the rays created from the image coordinates, we triangulate the pen tip position by finding the point that has minimal distance to both rays using a mid-point method [8]. We use ALGLIB [53] for the minimization problem.

In the end, the pen tip position is the sum of the virtual base position and the local absolute pen tip position. To distinguish between surface contact and hover, we use a threshold for the vertical position of the tracked LED. In our implementation, this threshold is 1 cm, accounting for the offset between LED and tip.

3.3 Cursor position refinement

To refine the cursor position after triangulation, we recorded and visually inspected the streams of the two PAJs with our sensor arrangement. This includes both inspecting the raw PAJ streams to assess surface reflections (Figure 3 a) as well as understanding the behavior when triangulating the reported blobs (Figure 3 b).

3.3.1 Inspecting triangulation. To investigate the triangulation, we moved the pen tip along the surface to cover the base-trackable area of about 6 cm × 6 cm and recorded around 30000 samples within this area in total. To fine-tune the PAJs’ extrinsics (due to potential misalignments when soldering), we first minimized the mean distance of the triangulated points (going from 0.8 mm to 0.5 mm after calibration). Then, we investigated the best approach to understand and deal with the low resolution as well as the sub pixel approach of the PAJs. Despite sub pixel blob coordinates, the clusters of samples tend to form lines corresponding to the PAJ’s resolution (see Figure 3 b), especially in areas close to the tracking area’s boundaries. For instance, in Figure 3 b, the clusters in area 1 (far away from tracking area center) form lines with large gaps in between compared to area 2 (close to center). Based on this, we devised our post-processing steps.

3.3.2 Post-processing: smoothing. In the following description, a *raw cursor* refers to the position that was created by triangulating two blobs—one from each PAJ. First, given a new raw cursor, we append it to the end of a list of raw cursors. If *at least one* of the two blobs of the new raw cursor still has the same image coordinates as the ones from the first item in the list, we do nothing and wait for the next raw cursor. Otherwise, we clear the list after taking its average (yielding a *pre-averaged cursor*) and proceed to the second step. Once the first step outputs a pre-averaged cursor, the second step applies a running average filter (using the current and four previous pre-averaged cursors) to create the final cursor.

3.4 Final cursor output and example usages

3.4.1 Mouse mode. Most basic, OptiBasePen can be used as an ordinary computer mouse (Video Figure B). This basically means that "Application" in Figure 2 becomes "OS cursor". At each frame, we first add the base movement to the mouse cursor position. Then, we add the movements of the pen tip position to the mouse cursor position while we store a floating point position of the cursor and only round the final pixel position at the last step before sending it to the operating system. Since many common applications do not strictly distinguish between mouse and pen input, OptiBasePen can seamlessly switch between mouse and pen usage, e.g., when annotating a PDF document (Figure 4 a). We also embedded a simplified fixed-function version of the pipeline (including “Software” part in Figure 2 right) so that it fully runs on the device without Unity. This means that OptiBasePen can act as a wireless BLE HID device, sending mouse movements directly to the operating system.

3.4.2 Painting. In a simple painting application [38, 55], users have access to a color palette and can adjust the stroke thickness as well as the opacity (Figure 4 b and Video Figure C). The skull in Figure 1 c is an example painting created with OptiBasePen.

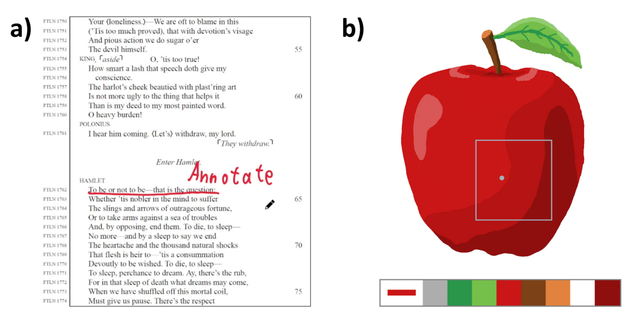

Figure 4: Example usages of OptiBasePen: as an ordinary mouse, but in a pen form factor (a), and as a digital painting device (b). The light-blue rectangle in (b) moves together with the base while the cursor inside the rectangle is mapped to the local absolute pen tip position.

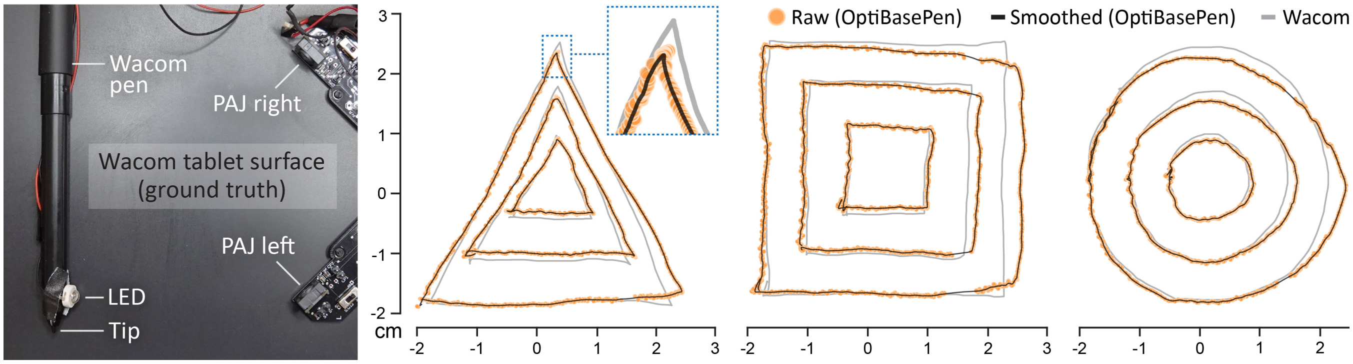

Figure 5: Apparatus of our technical evaluation together with plots. We attached an LED to a Wacom pen (left). The plots show simultaneous readings (while drawing simple shapes) of the Wacom tablet and OptiBasePen (raw and smoothed samples). The origin (0,0) is where the PAJs' forward rays meet. We aligned Wacom's and OptiBasePen's coordinate systems using ICP.

4 Technical evaluation

In addition to the initial inspection of the PAJs' readings (subsubsection 3.3.1), we conducted a technical evaluation with our final refined pipeline. This includes precision and latency measurements.

4.1 Measuring positional and angular error

4.1.1 Apparatus. We used a Wacom Intuos 4 drawing tablet as ground truth (**GT**). As seen in Figure 5 left, we removed the rubber from the Wacom pen and attached an LED close to the tip so it can be tracked by the base. The line and scatter plots in Figure 5 show data recordings from simple shapes drawn with this setup.

4.1.2 Procedure. We drew across a 6 cm × 6 cm trackable area (akin to Figure 3 b, but on the Wacom tablet surface), collecting around 25000 OptiBasePen samples. To align the coordinate systems of OptiBasePen and Wacom, we aligned 1000 sample correspondences (using ICP with manual initialization) and excluded those samples from the validation to avoid overfitting.

4.1.3 Results. The mean absolute error (**MAE**) of distance to GT using raw samples in the validation set is 1.87 mm. Our real-time smoothing (see subsubsection 3.3.2) reduces the MAE to 1.69 mm. The improvement is significant (paired t-test, Shapiro-Wilk normality > 0.98, $p \ll 0.001$, $t = 19.2$). Raw velocity vectors (deltas of samples 50 ms apart) have an angular MAE of 25.28 degrees (also see zig-zagging of raw samples in Figure 5). When smoothing, the angular MAE is 11.58 degrees, a significant improvement (paired t-test, Shapiro-Wilk normality > 0.85, $p \ll 0.001$, $t = 81.99$).

4.2 Latency

We measured the end-to-end latency on a 144 Hz screen with a 960 FPS camera. A test app receiving the cursor from OptiBasePen via serial USB reacts after around 17-22 ms (similar to Wacom in the same measurement setup). When running as a self-contained BLE HID mouse (see subsubsection 3.4.1), the operating system's cursor moves 30 − 35 ms after hitting the pen. Of this total latency, the pipeline itself on the device (i.e., one complete pipeline frame including data polling, triangulation, and smoothing) takes up around 1.3 ms (using default Arduino clock calls for measurements).

5 Discussion and future work

Our OptiBasePen prototype is based on optical sensing and only uses a single LED in order to showcase our core principle. However, there are opportunities to explore the concept in different directions with different additional input/output modules or alternative sensing approaches.

5.1 Limitations of reference implementation

In principle, the PAJ7025R3 that we use is suitable for our concept implementation because of its high frame rate, integrated image processing, and wide field of view. However, a fully realized high-precision base+pen device would benefit from a specialized tracking component with a higher horizontal resolution in relation to its field of view. Furthermore, it remains to be tested, how the device performs on different surfaces and under different lighting conditions, as some light sources can emit strong infrared lights within the range of detected wavelengths. To make the device more resilient to unwanted infrared light sources, one future approach could be to turn the LED off every n-th frame with the tracking being synchronized accordingly [40, 58]. While this would reduce the sample rate (with the lowest being 100 Hz in the case of $n = 2$), it could make the tracking more robust in bright environments.

5.2 Direct extensions of OptiBasePen

In terms of tracking and additional components, OptiBasePen can already be extended without fundamental changes to our implementation. Previously, we only used the vertical position of the pen to distinguish between contact and no contact in order to support hover as well as activation (e.g., starting a stroke) without a button. However, the PAJs can also track the continuous distance to the surface. This additional axis enables close-range mid-air interaction. Relatedly, we included two simple voltage divider circuits and connectors in our custom PCB to easily connect basic input components such as buttons or pressure sensors (**FSR** hereafter).

5.2.1 Implemented extension. As a concrete example, we implemented a first extension, featuring 3D tracking and one additional sensing component (Figure 6 and Video Figure D). We attached a small FSR to the thumb-area of the pen to enable grasping 3D

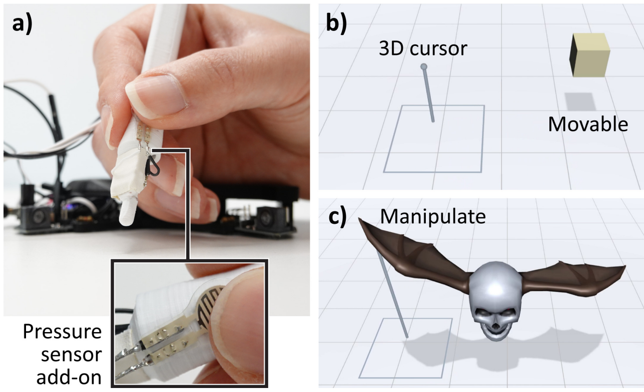

Figure 6: As a first extension of OptiBasePen, we implemented 3D cursor input. We attached a pressure sensor close to the pen tip (a). The cursor can be moved in three dimensions (b). Using the pressure sensor, the user can grasp and move objects such as the yellow cube (b right), or manipulate the joints of an articulated 3D character (c).

objects (Figure 6 a). Users control a 3D cursor to move objects (Figure 6 b) or for operations such as posing 3D characters (Figure 6 c). This also enables switching seamlessly between surface and mid-air pen interaction. Specifically, in Figure 4 b, tapping the surface while the cursor is inside the palette widget selects a color, but by hovering above it and pressing the FSR instead, the widget can be moved and re-positioned. This first extension also raises future questions about close-range mid-air interaction. For instance, future research could explore ergonomic designs of mid-air menus with this form factor, i.e., exploring how to arrange menu items. A related question could be whether the benefits of a resting surface for mid-air interaction [16] analogously apply to a hand resting on a base during close-range mid-air pen interaction.

5.2.2 Future complementary components. In principle, sensors such as FSRs can also be integrated into the pen, e.g., to enable pen tip pressure sensing [38] or for more specialized pens, e.g., with a bendable tip region [21]. An FSR could also be integrated into the base to use hand pressure as additional input [13]. Similarly, IMUs inside the pen could be used to add additional input dimensions, e.g., pen tilt [66, 73] or pen rolling [9].

Furthermore, as the pen tip does not have requirements (e.g., in terms of material), our approach can easily be combined with conventional digital pen approaches. Concretely, the tip itself could be capacitive so that the same pen can either be used on a tablet device or on a passive surface using the base, depending on what is available. Besides versatility, such a hybrid device would also allow to switch seamlessly between direct on-screen and indirect off-screen pen input. This way, modes and operations can be assigned to each, e.g., by drawing when on-screen versus selecting contents or menu items when off-screen (via indirect cursor) or vice versa.

The possible additional components are not limited to sensing. For instance, previous research has demonstrated the benefits of active haptics in pen input devices [5, 10, 15, 17, 28, 29, 32, 38, 54]. Such capabilities are orthogonal to our concept, but can greatly enhance the use and feel of our pen.

5.2.3 Additional optical tracking capabilities. The PAJs can track multiple blobs, meaning that a second or third LED could be added for tracking the pen rotation as well. In addition, the pen can potentially be made fully passive by using retroreflective markers, while LEDs illuminate them from each of the PAJs viewpoints (akin to motion capture systems like OptiTrack). During development, we experimented with an infrared laser that creates a bright spot on the surface, which can be detected by the PAJs. This would enable raycast interaction, where the physical surface acts as the plane for the ray intersection. Overall, there are already many ways to enhance the pen's capabilities without many alterations to our base.

5.3 Future alternative sensing methods

While our OptiBasePen prototype uses optical approaches for both the motion sensing and the pen tip sensing, the general concept is not limited to optical sensing. Future iterations could incorporate other sensing methods for pen tracking by using emitters and/or receivers that work particularly well with close-range sensing. This includes magnetic sensing [67] or radio frequency sensing [12]. ITrackU by Cao et al. [12] combines IMU data and ultra-wideband radio antennas for tracking a pen along a large whiteboard. Pentelligence by Schrapel et al. [59] combines IMU and acoustic sensing integrated into a pen to predict characters written on paper. The close-range sensing could also borrow from mechanical sensing approaches. For instance, Spidar-pen by Lin et al. [37] uses strings connecting the pen with the corners of the display to track the pen position. It remains to be explored how those alternative sensing methods differ in terms of precision and accuracy.

5.4 Future alternative interaction methods

There are future possibilities for base+pen interaction techniques when considering variations of our proposed concept as well as combinations with existing interaction paradigms [26].

5.4.1 Bimanual interaction. The kinematic chain for asymmetric bimanual input [24] indicates that the non-dominant hand typically precedes actions of the dominant hand and also provides a frame of reference. This has been the inspiration for many input techniques in HCI, including pen input [43, 49, 57]. With our approach, only the dominant hand is moving its frame of reference while the non-dominant hand is free. Future works could compare or combine our concept with bimanual interaction. For instance, a base-like device with relative sensing could be used with the non-dominant hand (to move to the region of interest) to then use the pen next to it. This would be similar to the interactions in MouseLight [63] but would not require a specialized surface.

5.4.2 Combination with touch or gestures. Previous research explored using the non-dominant hand for complementary touch input [27, 49, 50]. Our approach does not require to share the input surface between touch and pen input, i.e., allowing to use the capacitive sensing device for touch input only and the surface next to it for pen input. Furthermore, wide-angle cameras inside the base could specifically be used to track the hand, e.g., to enable gesture input while using the pen [11, 41, 42] or to sense the pen grip [62]. Lastly—beyond pen input—cameras at a horizontal angle as with our base could potentially detect surface touch events reliably.

6 Conclusion

We presented the base+pen concept as well as the OptiBasePen prototype, which consists of a pen and a movable base to rest the hand on. OptiBasePen enables pen input on ordinary surfaces by sensing relative motion of the base along the surface and tracking the pen tip position within the base's moving frame of reference. Our device can be used as an ordinary mouse or for digital painting. In addition, we implemented an extension that enables close-range mid-air pen interaction. Our concept and our device point to different future research directions exploring the potential of combining relative and absolute sensing for pen input.

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