Building Miniature and Standalone Haptic Wearables for Integrating into the Real World

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ABSTRACT

Haptic feedback is a key factor required to create realistic and fluid virtual & augmented interactive experiences. However, these two goals are often at odds. For instance, highly realistic haptic interfaces prioritize dexterity and haptic quality at the expense of their resulting form factor, i.e., they feel great but are usually large and cumbersome. This is the key factor why these interfaces typically find their use in virtual reality but fail to integrate into other interactive regimes such as augmented reality, where the user not only interacts with the virtual interfaces but also the physical objects in the real world—for a haptic device to be successful in augmented reality it must satisfy *both* haptic quality and small form factors that feel unencumbered to wear. Here, using examples from our own haptic interfaces, we argue that it is possible and desirable for haptics' hardware to harmonize realism (dexterity, speed, etc.) with the haptics innate to the real world (i.e., keep the user's body free to feel the world that surrounds them). We argue that this is done via a concerted effort by researchers in HCI & Haptics and that aim to engineer standalone haptic devices with minimal form-factors. We further identify that these devices share common techniques yet can easily adjusted to support various kinds of haptic feedback and that sharing device implementation (by open sourcing its hardware) accelerates the research space. Finally, we layout the core electronic circuits and mechanical design for our exemplary projects in the hope of assisting researchers in creating devices that can be integrated into our daily life.

KEYWORDS

Haptics, Interactive Devices

Introduction

Our research group, Human Computer Integration Lab[1] (University of Chicago), engineers interactive devices integrated with the human's body. One way we explore this integration is by finding new haptic sensations [2], new actuation techniques [1, 3, 8] or improving the limitations of existing actuators [5, 6]. While we have seen many recent impressive haptic devices developed by our community, we also identified that these tend to only optimize for either haptic quality or dexterity, often aimed for Virtual Reality (VR), and thus are typically large and cumbersome. While these devices make VR experiences more immersive, they fail to integrate into other interactive paradigm such as Augmented Reality, where the user not only interacts with the virtual interfaces but also the physical objects in the real world—for a haptic device to be successful in augmented reality it must satisfy *both* haptic quality and small form factors that feel unencumbered.

Here, we show many of our endeavors toward the goal of integrating haptics into daily life by minimization of haptic devices. Although these projects have different application scenarios, they share common engineering and design considerations. We made them as minimal and unintrusive, in their form factors, as possible, yet they are standalone, i.e., untethered, self-powered, and with ability to communicate to other interactive system.

In the following sections, we use examples from our own haptic interfaces and argue that it is possible and desirable for haptics' hardware to harmonize realism (dexterity, speed, etc.) with the haptics innate to the real world (i.e., keep the user's body free to feel the world that surrounds them). We layout the core electronic and mechanical design of each project. These projects include devices that are worn on the fingernail, hand-worn, and nose, which all require this minimal form factor. At its core all of these works utilized similar strategies to minimize their form factor, such as electronics designs based on a low power nRF52811 micro-controller (chosen for its small size including built-in wireless communications) or 3D printed mechanical designs that keep the user's hand maximally free.

Finally, to help readers replicate our design, we provide all the source code, 3D files, firmware, and schematics of our implementation on the website of our research group[1].

Project 1: Rendering touch in mixed reality while keeping the fingerpad free

In this first project, we show how minimizing the device can help blend haptics into our daily environment. Touch&Fold [8] is a nail-mounted foldable haptic device that provides tactile feedback to mixed reality (MR) environments by pressing against the user's fingerpad when a user touches a virtual object, yet it quickly tucks away when the user interacts with real-world objects. Its design allows it to fold back on top of the user's nail when not in use, keeping the user's fingerpad free to, for instance, manipulate handheld tools and other objects while in MR. The device can render contacts with MR surfaces, buttons, low- and high-frequency textures (Figure 1).

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[1] http://lab.plopes.org/

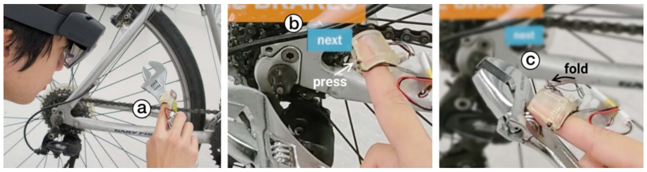

Figure 1: Touch&Fold renders touch in mixed reality without impairing sensation from physical objects. (a) The user is to fix their bike with virtual instructions, while wearing our device. (b) When the user taps on the virtual button, our device unfolds to tap the user's fingerpad, providing a sense of contact. (c) When the finger leaves the button, the device folds back onto the nail, without impairing the sensation from the wrench.

We engineered a wireless and self-contained haptic device. Figure 2 depicts our self-contained prototype, which was 3D printed using a Form Labs 3 with clear resin to minimize visual interference with the real world. Its complete footprint is 24×24×41 mm and weighs 9.5 g, including its battery. It attaches to the user's fingernail using double-sided tape. Our device unfolds using a DC motor (26:1 Sub-Micro Planetary Gearmotor 0.1 kg-cm, Pololu) mounted on our 3D printed rail drive (rack with 26 teeth and pinion with 12 teeth), driven by a low-voltage motor driver (DRV8837, Texas Instruments). A photo-interrupter (SG-105F, Kodenshi) is used to sense the retraction, and a force sensor (FSR 400, Interlink Electronics) to regulate the pressure on the fingerpad when unfolded. To increase the expressivity of our device, we embedded a linear resonant actuator (LRA C10-100, Precision Micro Drives), driven by a MOSFET (SSM3K15ACTC, Toshiba), in the cover that touches the user's finger. Our 16.8x10.3 mm PCB houses at its core a microcontroller with Bluetooth Low Energy (nRF52811, Nordic Semiconductor). To decrease its footprint, we used a ceramic chip antenna (W3008C, Pulse Larsen), instead of the traditional zig-zag PCB antennas. The device is powered by a 40 mAh LiPo battery (4.1V).

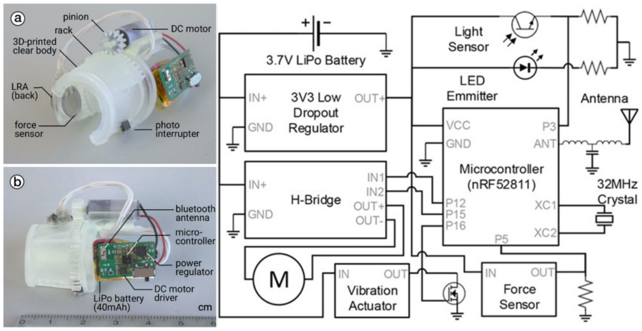

Figure 2: (a, b) Our haptic device and (c) its electronic schematics.

Project 2: Precise braking for electrical muscle stimulation pose guidance

In this project, we show how that we can extend our approach to haptic actuators in multiple channels. DextrEMS [5] is an EMS-based haptic device featuring mechanical brakes attached to each finger joint. Since EMS actuation of fingers is lack of independence and causes unwanted oscillations, how DextrEMS solved this is that while the EMS actuates the fingers, it is our mechanical brake that stops the finger in a precise position. Moreover, it is also the brakes that allow DextrEMS to select which fingers are moved by EMS, eliminating unwanted movements by preventing adjacent fingers from moving. We implemented dextrEMS as an untethered haptic device, weighing only 68g, that actuates eight finger joints independently (metacarpophalangeal and proximal interphalangeal joints for four fingers). Applications range from assisted fingerspelling, a piano tutorial, guitar tutorial, to VR games.

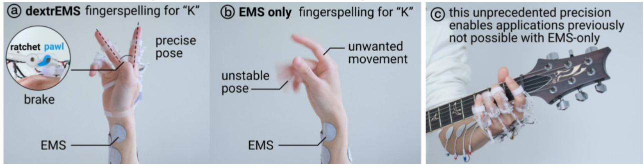

Figure 3: DextrEMS increases dexterity of EMS by combining it with brakes.

The majority of our brake mechanism was 3D printed (Form Labs 3) using clear resin, while the hinges at each joint were laser cut out of 3mm clear acrylic. The see-through materials were used to minimize visual obstruction of the real world. The mechanism of one of our brakes is a custom-made ratchet and pawl mechanism (24 teeth). Our pawl is controlled by a small DC motor (Vibration Motor 11.6×4.6×4.8mm, Polulu), which are placed at every PIP and MCP joints in all four fingers. The electronics of our device, depicted in Figure 4 are housed in our custom printed circuit board. Fitted on the back of the hand, its core is a microcontroller (nRF52811, Nordic Semiconductor) with on-chip Bluetooth Low Energy (BLE). Each of our eight DC motors is driven by a H-bridge motor driver (DRV8837, Texas Instruments). Moreover, to better visualize the action of each brake joint, we added a red or green LED parallel to the positive and negative rail output of the motor-driver, allowing us to visually see if a brake is locked or unlocked. The electronics are all powered via a 500mAh 3.7V LiPo battery. Since as soon as the pawl is jammed into the ratchet, the motor drivers release the DC motor, relying on the mechanical force to keep the lock. This solution enables our device to be power efficient.

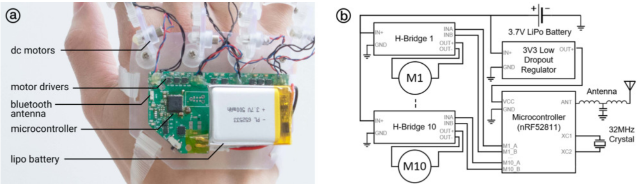

Figure 4: (a) DextrEMS components and (b) schematics.

Project 3: Ubiquitous vibration haptics

This project shows a minimized electro-magnetic actuator, which we call MagnetIO [4], that is comprised of two parts: one battery-powered voice-coil worn on the user's fingernail and any number of interactive soft patches that can be attached onto any surface (everyday objects, user's body, appliances, etc.). When the user's finger wearing our voice-coil contacts any of the interactive patches it detects its magnetic signature via magnetometer and vibrates the patch, adding haptic feedback to otherwise input-only interactions. To allow these passive patches to vibrate, we make them from silicone with regions doped with polarized neodymium powder, resulting in soft and stretchable magnets. This stretchable form-factor allows them to be wrapped to the user's body or everyday objects of various shapes (Figure 5).

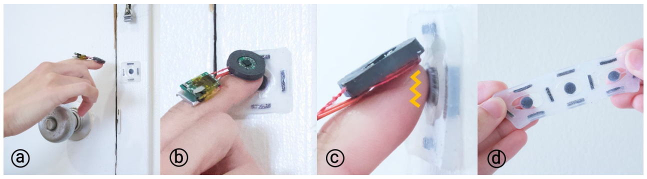

Figure 5: MagnetIO provides haptic feedback in ubiquitous environment (a, b, c) When the fingernail-worn device contacts any of the interactive patches, it detects the magnetic signature and makes the patch to vibrate. (d) The patches are flexible.

MagnetIO devices have two principal components: (1) *many* of our silicone-based interactive passive patches, which have regions doped with neodymium powder ($Nd_2Fe_{14}B$) and can be attached to surfaces; and (2) our nail-worn device, which can make our patches vibrate via its electromagnetic coil; the latter is entirely self-contained, i.e., it has input (via a 9DOF IMU), output (electromagnetic coil), processing, battery and wireless. We engineered a custom PCB for MagnetIO's finger-worn device, as shown in Figure 6. At the center of the coil, we place a 9DOF IMU (MPU-9250, 3-axis magnetometer, 3-axis gyroscope, and 3-axis accelerometer) to read the local magnetic field and sense proximity to any patch. On the user's finger, we place our PCB that houses our motor driver (DRV8850, Texas Instruments), Bluetooth enabled microcontroller (nRF52811, Nordic Semiconductor), and battery (40 mAh). The complete finger-worn device including battery weighs only 4 grams and measure 17 mm x 11 mm with 7 mm thickness.

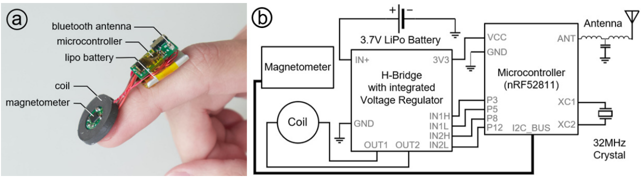

Figure 6: (a, b) Wearable device components (c) and schematics.

Project 4: Altering softness of real objects

We propose a haptic device that can make rigid objects feel softer [7]. The device works by restricting fingerpad deformation with a motor pulling a hollow frame around the fingerpad. This approach is that it leaves the center of the fingerpad free, so the users can still feel the objects they are touching; it is different from typical haptic devices, which cover the fingerpad and only render virtual haptics. We explore our device to alter the softness of rigid protrusions to serve as buttons, part of a rigid 3D printed object, or make the same VR prop changes between soft and hard state (Figure 7).

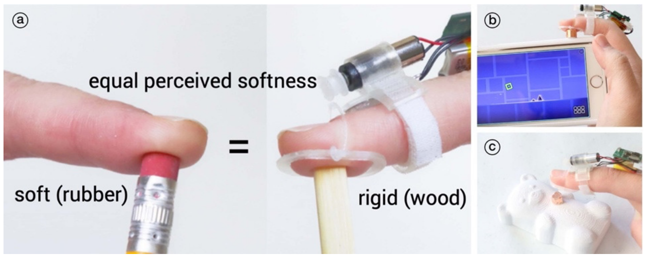

Figure 7: (a) Our haptic device can make objects feel softer. (b) This can be used to make a rigid button feel softer in games and (c) a 3D-printed bear to feel softer at its heart .

Our device actuates the hollow frame around the fingerpad using a pulley controlled by a small DC motor (136:1 Sub-Micro Planetary Gearmotor 0.55 kg-cm, Pololu), which is housed by a 3D printed casing at the first phalanx of the finger. When the motor is actuated, it pulls the frame towards the fingernail, gently squeezing the fingerpad—this restricts the fingerpad, which is key to enabling the softness illusion. Our 16.8 ×10.3 mm PCB houses (Figure 8) at its core a nRF52811 microcontroller with on-board Bluetooth Low Energy (Nordic Semiconductor). To decrease its footprint, we used a ceramic chip antenna (W3008C, Pulse Larsen), instead of the traditional zig-zag PCB antennas. We power the entire device using a 40 mAh LiPo battery. To measure the force that the frame applies on the fingerpad so that we can interactively toggle fingerpad deformation restriction on and off during use, we attached a force sensor (FSR, Taidacent) between the finger and the device. A thin silicone pad (2mm, 20 Shore A hardness) is layered on top of the FSR to ensure good contact with the skin. Then, we use a PID (proportional–integral–derivative) controller to adjust the motor to achieve a consistent restrictive force level of 60 g. The device has a total dimension of 55L × 16W × 25H mm and a weight of 5.03g.

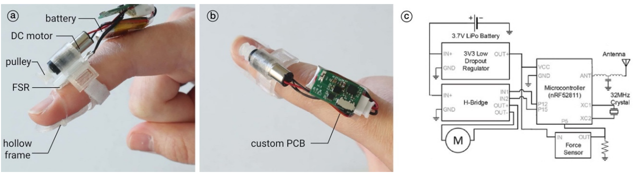

Figure 8: (a, b) Device components and (c) schematics.

Project 5: Haptics in difficult to reach locations (inside-the-nose haptics)

We propose a novel type of olfactory device that renders readings from external odor/gas sensors into trigeminal sensations by means of electrical stimulation [2]. By stimulating the trigeminal nerve, it allows for smell augmentations or substitutions without the need for implanting electrodes in the olfactory bulb. To realize this, we engineered a self-contained device that users wear across the nasal septum, it communicates with external gas sensors using Bluetooth. In this example, it enables a user to perceive the gas's direction (i.e., to their left or right) by varying the pulse-width and current polarity of the electrical impulses. The result is that this user can quickly locate their gas leak using our device as a *stereo-smell augmentation* (Figure 9).

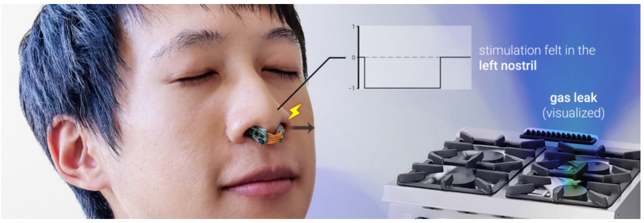

Figure 9: Our haptic device stimulates trigeminal nerves in the nose enabling stereo smell.

Figure 10 shows our complete and self-contained prototype, including its battery. It measures 10x23x5 mm in one nostril, 10x23x7 mm in the other, and weighs 3.4 g. To create the stimulation waveform, we utilize a DRV8847 (Texas Instrument), a dual h-bridge capable of outputting up to 18 Vpp in a 3x3 mm footprint. The voltage supply for the stimulation is generated from a MT3608 (Aerosemi Technology) boost-converter with adjustable voltage output, which we set at 18V. The parameters of the generated waveform (such as pulse-width or current polarity) are generated by the microcontroller by controlling the h-bridge's enable and direction. To deliver the electrical impulses from our stimulator to the user's trigeminal nerve, we utilize two silver/silver chloride (Ag-AgCl) disc electrodes, which protrude on the back side of each PCB. To allow users to feel the trigeminal sensations in a realistic manner, SG-105F reflective-type infrared photo interrupter (Kodenshi Corp) on the PCB is used to track the breathing patterns. We use two magnets to hold the device in place by attracting each other, even across the nasal septum. We power our device using a 10 mAh lithium polymer battery (PGEB201212, General Electronics Battery Co.).

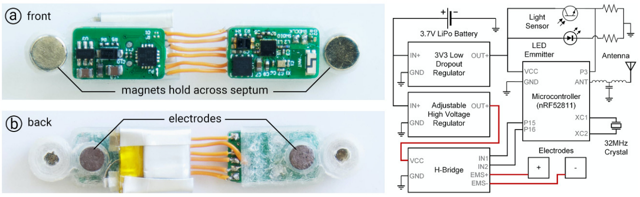

Figure 10: (a, b) Device components and (c) schematics.

Conclusion

Highly realistic haptic interfaces typically prioritize haptic quality at the expense of their resulting form factor, ending up usually large and cumbersome. Therefore, these interfaces typically find their use only in virtual reality. Instead, they fail to integrate into other interactive regimes such as augmented reality, where the user not only interacts with the virtual interfaces but also the physical objects in the real worlc—for a haptic device to be successful in augmented reality it must satisfy *both* haptic quality and small form factors that feel unencumbered to wear. In this paper, we use examples from our own haptic interfaces and argue that it is possible and desirable for haptics' hardware to harmonize realism (dexterity, speed, etc.) with the haptics innate to the real world (i.e., keep the user's body free to feel the world that surrounds them). We show examples of research work from our institute that utilize minimal yet standalone wearable devices, in the goal of integrating haptic devices into the real world. These devices share common techniques yet can easily adjusted to support various kinds of haptic feedback and that sharing device implementation (by open sourcing its hardware) accelerates the research space. We hope by showing detail implementation, it can assist researchers to build more devices in the future.

Acknowledgment

Thanks to all the authors of the projects, Jas Brooks, Alex Mazursky, Yujie Tao, Jun Nishida, Pengyu Li, Jingxuan Wen, and Joshua Fonseca.

REFERENCES

[1] Jas Brooks, Steven Nagels, and Pedro Lopes 2020. Trigeminal-based Temperature Illusions. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2020), 1–12. https://doi.org/10.1145/3313831.3376806.

[2] Jas Brooks, Shan-Yuan Teng, Jingxuan Wen, Romain Nith, Jun Nishida, and Pedro Lopes 2021. Stereo-Smell via Electrical Trigeminal Stimulation. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2021), 1–13. https://doi.org/10.1145/3411764.3445300.

[3] Jasmine Lu, Ziwei Liu, Jas Brooks, and Pedro Lopes 2021. Chemical Haptics: Rendering Haptic Sensations via Topical Stimulants. *The 34th Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, Oct. 2021), 239–257. https://doi.org/10.1145/3472749.3474747.

[4] Alex Mazursky, Shan-Yuan Teng, Romain Nith, and Pedro Lopes 2021. MagnetIO: Passive yet Interactive Soft Haptic Patches Anywhere. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2021), 1–15. https://doi.org/10.1145/3411764.3445543.

[5] Romain Nith, Shan-Yuan Teng, Pengyu Li, Yujie Tao, and Pedro Lopes 2021. DextrEMS: Increasing Dexterity in Electrical Muscle Stimulation by Combining it with Brakes. *The 34th Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, Oct. 2021), 414–430. https://doi.org/10.1145/3472749.3474759.

[6] Akifumi Takahashi, Jas Brooks, Hiroyuki Kajimoto, and Pedro Lopes Increasing Electrical Muscle Stimulation's Dexterity by means of Back of the Hand Actuation. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3411764.3445761.

[7] Yujie Tao, Shan-Yuan Teng, and Pedro Lopes 2021. Altering Perceived Softness of Real Rigid Objects by Restricting Fingerpad Deformation. *The 34th Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, Oct. 2021), 985–996. https://doi.org/10.1145/3472749.3474800.

[8] Shan-Yuan Teng, Pengyu Li, Romain Nith, Joshua Fonseca, and Pedro Lopes 2021. Touch&Fold: A Foldable Haptic Actuator for Rendering Touch in Mixed Reality. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2021), 1–14. https://doi.org/10.1145/3411764.3445099.