MagnetIO: Passive yet Interactive Soft Haptic Patches Anywhere

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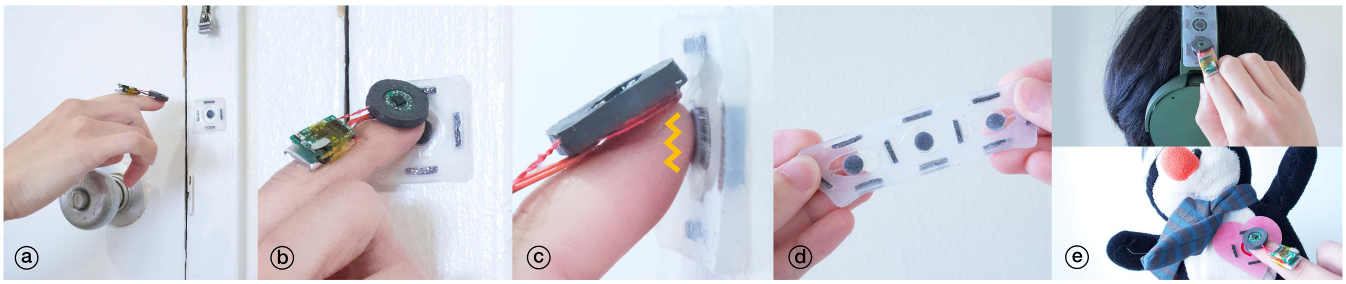

Figure 1: (a) We propose a new type of haptic actuator, which we call MagnetIO, that is comprised of two parts: *any number* of soft interactive patches that can be applied anywhere and *one* battery-powered voice-coil worn on the user's fingernail. (b) When the fingernail-worn device contacts *any* of the interactive patches it detects its magnetic signature and (c) makes the patch *vibrate.* (d) To allow these otherwise passive patches to vibrate, we make them from silicone with regions doped with neodymium powder, resulting in soft and stretchable magnets. (e) This novel decoupling of traditional vibration motors allows users to add interactive patches to their surroundings by attaching them to walls, objects or even other devices or appliances without instrumenting the object with electronics.

ABSTRACT

We propose a new type of haptic actuator, which we call MagnetIO, 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. We demonstrate how these add haptic output to many situations, such as adding haptic buttons to the walls of one's home. In our technical evaluation, we demonstrate that our interactive patches can be excited across a wide range of frequencies (0-500 Hz) and can be tuned to resonate at specific frequencies based on the patch's geometry. Furthermore, we demonstrate that MagnetIO's vibration intensity is as powerful as a typical linear resonant actuator (LRA); yet, unlike these rigid actuators, our passive patches operate as springs with multiple modes of vibration, which enables a wider band around its resonant frequency than an equivalent LRA.

CCS CONCEPTS

• **Human computer interaction (HCI)**; • **Interaction devices**; • **Haptic devices**;

KEYWORDS

soft magnets, ubiquitous haptics, fabrication

ACM Reference Format:

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1 INTRODUCTION

Today's interactive devices increasingly instrument every kind of surface, effectively adding interactive functionality even to passive everyday objects such as walls, tables, and rapidly prototyped objects [14, 28, 64, 75, 76], as well as to the user's body [35, 36, 61]. To enable sensing these interactions, researchers engineered conformable/stretchable sensing devices so that these can comfortably

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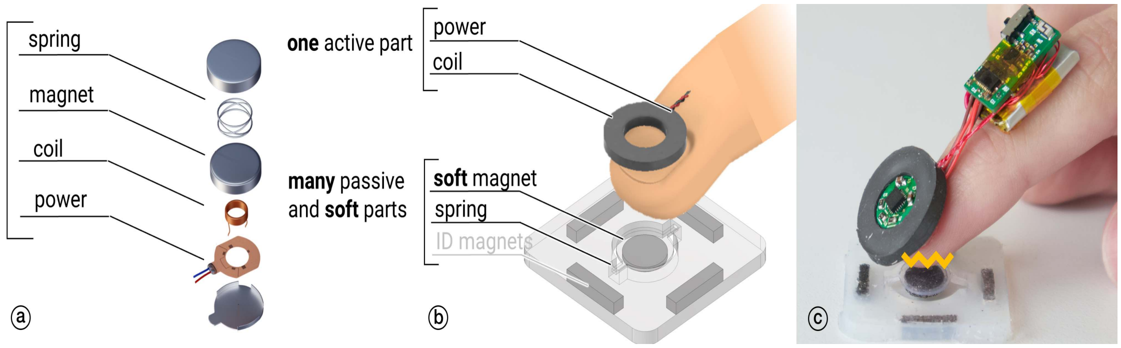

Figure 2: (a) Our device is built from the same principle as traditional linear resonant actuators (LRA), i.e., based on moving a magnetic mass using a coil and a spring. (b-c) However, our device decouples these components into two parts: *one* active element containing the coil, which the user wears on their fingernail; and, *many* passive elements, which are comprised of silicone with regions doped with neodymium powder which together realize a spring & magnet.

fit around non-planar surfaces, which is the case for everyday objects or the human body. This led to a mature field of on-body or on-object *sensing* technologies that are easy to deploy and ideal for prototyping or enabling interactions in ubiquitous settings.

However, the converse is not the case, while sensing can be done in a distributed fashion around the user and in conformable form-factor, the same is not true for *actuation*. Researchers are still looking for techniques that allow deploying large numbers of actuators without the constraints of power delivery to every single individual actuator, wireless communication across all actuators, microcontrollers, etc. As a result, while we have a range of interactive techniques to deploy sensing "patch"-like devices everywhere, these patches typically do not exhibit any form of haptic response, i.e., they can sense the user's touch (e.g., to turn on/off the user's home-alarm) but they cannot vibrate in response to that touch (e.g., to indicate the alarm is on/off), not at least, without requiring vibration motors or other haptic actuators, which in turn require batteries and circuitry. Ultimately, all these dramatically limit the ubiquitous application of these interactive patch-like devices.

In this paper, we engineered and explored a new alternative for adding haptic feedback to everyday surfaces, which is depicted in Figure 1. Our approach, which we call *MagnetIO*, introduces a new type of haptic actuator that is passive (i.e., requires no electronics, no battery, etc.) until the user's finger, which is instrumented with a wearable voice-coil, touches it, causing it to vibrate.

2 OUR APPROACH: MAGNETIO

MagnetIO is composed of *many* passive interactive patches and *one* nail-worn device, which features a miniaturized and custom-engineered voice-coil, inertial measurement unit (IMU), battery, microcontroller and wireless. MagnetIO's complete voice-coil and circuitry fits entirely on the user's fingernail, thus leaving the fingerpad unobstructed to feel interactions with the user's environment and the vibrations from our passive patches.

The design principle that enables our interactive patches to vibrate is that they are made from silicone doped with neodymium powder, resulting in stretchable magnets that are thus attracted/repelled by the wearable coil. Conceptually, we liken our approach to a linear resonant actuator (LRA, typical vibration element in most commercial mobile devices), which is comprised of a magnet attached on a spring and a coil, which we depict in Figure 2

To better illustrate our design, we make an analogy to the inner workings of an LRA: when current is supplied to the LRA's coil, it produces a magnetic field which attracts or repels the magnet. By performing this multiple times, the momentum of this *magnet-spring* assembly creates a feelable vibration (Figure 2a).

In our case, our design takes a sharp conceptual turn from that of the LRA as we *purposely decouple* the magnet-spring from the coil (Figure 2b). This allows us to scale up the output by placing *many* spring-magnet pairs everywhere, which are activated when the user's wearable coil contacts them (Figure 2c). The advantage is that our design requires only *one* coil, meaning it also only requires *one* driver circuit, *one* communication module and *one* battery. Furthermore, all our interactive patches are passive since we implement them using silicone, an elastic material that allows us to achieve the "spring" component; subsequently, some regions are doped with neodymium powder, which allows us to realize the "magnet." Therefore, our soft-magnets realize the "spring-magnet" component typical of LRAs. The result is that MagnetIO patches are easy to place anywhere because they are stretchable and soft, and yet they deliver haptic output to the user, appearing as interactive patches.

Moreover, unlike approaches that attach vibration actuators directly to the user's fingerpad, MagnetIO can trigger vibrations whenever a user touch any of our haptic patches, while simultaneously leaving the user's fingerpad free (thus, minimizing impacts to dexterity).

Note that while our main contribution is *on realizing haptic output* for these soft patches via our soft magnets, we also demonstrate one possible sensing mechanism by using the magnetic signature of the patches themselves, i.e., the user's fingernail-worn device detects the unique ID of each patch by using a 3DOF magnetometer to read each patch's unique 3D magnetic field (see details in *Implementation*). Naturally, there are several other possible passive implementations, each with their idiosyncratic pros/cons, such as RFIDs [17, 39, 60], acoustic IDs [21], optical (barcodes [24], QR codes [49, 53], Anoto pen-like patches [50]), etc.

3 RELATED WORK

The work presented in this paper builds primarily on the fields of ubiquitous interfaces, especially instrumented interactive surfaces, and haptics, with emphasis on soft and magnetic-based actuators.

3.1 Adding input to everyday objects and surfaces

To enable the vision of ubiquitous computing [62], many researchers have engineered techniques that add input to everyday objects and surfaces. A common approach to adding input to objects is to apply a flexible resistive or capacitive sheet to the surface [37, 46, 76]. For example, PrintSense [14] utilized an network of electrodes printed on a flexible substrate to add input to surfaces. Electrick [75] combined conductive materials with Electric field tomography to achieve touch input on a wider variety of objects, such as tools and toys. Similarly, ObjectSkin [16] used hydroprinting to transfer sensors and circuits onto irregular objects. Sprayable User Interfaces [64] enabled large-scale interactive surfaces via spray-on sensors. Additionally, many other techniques are available, even acoustic techniques have been used to add touch input to objects [38].

3.2 Passively adding input to everyday objects and surfaces

The key issue with the previous approaches is that they all add electronics onto the objects they are enabling. As such, we quickly reach a limit to the vision of ubiquitous interfaces, as all objects require batteries, circuits, etc. As an alternative to this, researchers have investigated *passive* input techniques. Passive input is advantageous in that it does not require instrumenting the object with electronics, but instead, typically instruments the user with sensors, such as cameras, etc. For instance, computer vision can be used to detect interaction with surroundings, as demonstrated by early works like Light Widgets [13] and more recently with depth cameras as in WorldKit [66]. Acoustic techniques can also be used for passive input: Acoustic Barcodes [21] and Scratch Input [22] both utilized the physical surface roughness of objects to detect input. Furthermore, electrical techniques are another popular method for passive input; notably Touché [45] realizes gestural detection on any electrically conductive surface and time-domain reflectometry adds multitouch to wires [65]. Finally, 3D printed ferromagnets have been used to encode information directly in 3D printed objects; allowing users to scan the object with a magnetometer, like how one would scan a conventional barcode. Here, users swipe their smartphone's magnetometer across the surface of the object to read out its unique magnetic identifier [26].

3.3 Adding haptic output to everyday objects and surfaces

When it comes to adding haptic output to everyday objects and surfaces, the most common technique to instrument objects with haptic feedback is to simply embed actuators within the device, as we do with mobile phones [41, 42, 73]. However, this approach tends to lack haptic fidelity and design flexibility. One versatile solution to this challenge was put forth by *Magtics*, which introduced a tactile array of rigid actuators inside a flexible casing that could conform to curved objects [40]. *Tactlets* also explored a flexible form factor for adding electrovibration feedback to everyday objects [15].

Evidently, when compared with adding input to the environment, adding haptics is far less explored. The limitations that we discussed for active sensing (i.e., it requires electronics & batteries on every object) become dramatic for haptic output, because haptic actuators require even more power than their sensing counterparts. To overcome this limitation, MagnetIO takes a sharp conceptual turn with respect to the traditional design of a haptic device, it decouples the device into two parts: *one* active that the user carries and *many completely passive parts*, that can be attached to objects and surfaces without the need for electronics.

Conceptually, our proposal relates to Sekiguchi et al.'s "Ubiquitous haptics" vision, in which any interactive device around the user's environment, be it a surface or an everyday object, was not only added with input capability but *also displays haptic feedback* [47]; they proposed realizing vision this using active haptic devices based on motorized actuators. We build on this concept but allow this to scale to practical uses with *many* devices. This is only possible because, instead, our concept uses *passive* patches applied ubiquitously in the user's environment, rather than requiring batteries & electronics inside every surface or object the user interacts with. For our passive patches to produce actual haptic feedback, we were inspired by two hardware techniques: (1) soft actuators and (2) magnetic actuators, which we discuss below.

3.4 Soft actuators

Advances in materials science and mechanical engineering brought soft actuators to interactive devices. A wide range of soft actuators have been developed based on different working principles: pneumatics [1, 54, 57], hydraulics [19, 20], acoustofluidics [2], electroactive polymers [9, 11, 74, 77], twisted and coiled polymers [18], gels [34], and electrorheological and magnetorheological fluids [27, 30, 31, 44, 48, 69]. Many have been adapted to realize deformable devices, shape-changing output, and so forth [3, 7, 43]. For instance, HapBead [19] added a bead in a soft microfluidic channel around the finger pad to generate tactile sensations caused by the bead moving around. HapSense [74] demonstrated a wearable electroactive polymer for tactile feedback. MagnetIO differs from the approach in *HapSense* by its decoupling between the active and passive components. Additionally, MagnetIO is made from softer materials (silicone vs. PVDF), allowing it to conform to more irregular objects and body parts.

Recently, researchers in soft robotics have become particularly interested in soft magnetic materials for sensing and actuation (note that in these mechanics-focused works, and in this paper, "soft" refers to the low-modulus of the materials involved, rather than the magnetic properties). Unlike electrically-controlled or fluid-driven systems, magnetic materials lend themselves well to *untethered* operation because they may be sensed and actuated without contact. For example, magnetic microrobots may be steered within an environment by controlling an external magnetic field [25, 68]. Additionally, magnetic skins have been used as tactile and wearable sensors with minimal need for wiring [4, 23]. Research on fabrication has demonstrated the ability to design soft magnets with custom polarity by manipulating the applied magnetic field during curing; this allows for tunable behavior when the cured magnet is exposed to a field, resulting in programmable shapes and locomotion [25, 29, 68].

3.5 Magnetic-based haptics

Magnets have been used to convey haptic feedback across a wide range of applications. Permanent magnets have been identified as a passive actuator (no electrical power required) for providing haptic feedback [52, 70–72, 78, 79]. However, permanent magnets lack control; they cannot be turned off and the intensity of their feedback can only be changed by physically displacing them. Thus, many interactive devices rely on electromagnets so that the output magnetic force is controllable [51, 55].

Many of the proposed systems are based on 2D electromagnet arrays. For example, *FingerFlux* utilized an array of electromagnets with a nail-mounted permanent magnet to provide haptics on tabletops [63]. Similarly, Actuated Workbench used magnets to move tangibles on a table [56]. More recently, *M-Hair* proposed coating the body's hair in iron powder so that it may receive haptic feedback from electromagnets moved on top of the user's skin [8]. However, the arrays of electromagnets used here are extremely bulky and prevent wearable, mobile and/or scalable form factors.

To make magnetic actuators more mobile, many devices rely on custom electromagnetic coils. For instance, *Magnetips* designed a single coil worn on the back of mobile devices for delivering feedback to a nail-worn permanent magnet [32]. *Magtics* created a flexible haptic device based on the hybrid of hard electromagnetic actuators in a flexible case [40].

Unfortunately, prior approaches to magnetic-based haptics do not easily scale to many applications because: (1) they require power; (2) the magnets are rigid, so they cannot conform to objects or the human body. To address these issues, MagnetIO uses *one* wearable coil and *many* interactive patches made from flexible silicone and stretchable magnets. The result is the first *one-to-many* system for ubiquitous vibrotactile haptics.

4 WALKTHROUGH: ADDING MAGNETIO PATCHES EVERYWHERE

To give the reader a complete picture of how MagnetIO allows a user to control their environment with ad-hoc interactive haptic patches, we describe a walkthrough via the example of a user in their home, using our MagnetIO patches to control a wide-range of interactive appliances such as internet-of-things (IoT) devices.

Figure 3a shows our user, wearing our wearable voice-coil on their index finger, walking into their home. Figure 3b shows that as they walk in, they tap a MagnetIO patch that has been attached to their door. In response to tapping the patch, they feel two consecutive vibrations (*tzzz*, pause, *tzzz*) confirming that their home-alarm is now disabled, which is depicted in Figure 3c. Note that this user can also perform this action *in the dark* (i.e., eyes-free, which we did not illustrate for the sake of visual clarity) because our MagnetIO patches are inherently haptic interfaces designed to vibrate on touch.

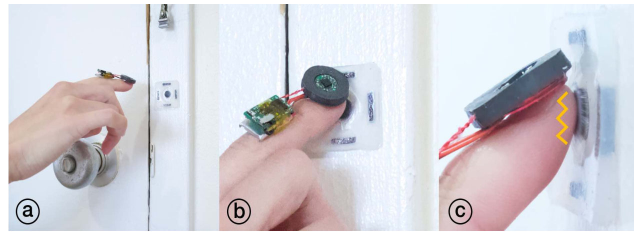

Figure 3: (a) Our user at home, wearing our coil, surrounded by surfaces with interactive patches. (b) They tap their wall, which has a passive patch that controls their home alarm. (c) The user feels the patch vibrate to indicate that their alarm is now disabled.

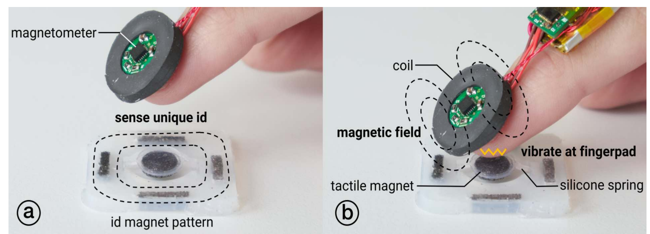

Figure 4: (a) When the user's finger approaches an interactive patch, its magnetometer reads and recognizes its unique 3D magnetic ID and (b) activates the wearable-coil, generating a magnetic field that vibrates the patch under the fingerpad.

Now that we depicted an interaction with MagnetIO from the user's perspective, let us examine what is happening from the device's perspective. In other words, we will describe how our patches work to deactivate the user's IoT home alarm. Figure 4 depicts the principle behind MagnetIO interactions. First, as depicted in Figure 4a, as the user taps on the patch to deactivate their home-alarm, the wearable-coil approaches the patch and senses its ID, i.e., the wearable-coil recognizes that the particular patch the user is touching is the "home-alarm" ON/OFF patch. To sense the ID of a patch, the wearable-coil makes use of its inertial measurement unit, which includes a 3DOF magnetometer. Using the magnetometer data, the wearable-coil detects the patch that the user is interacting with by comparing the current reading to pre-trained magnetic signatures. These magnetic signatures are just an example of one many possible ways our system could sense the ID of each patch (refer to *Implementation* for details). Alternatively, our system could utilize a wide variety of sensing mechanisms, such as RFIDs [17, 39], acoustic IDs [21], optical IDs [49, 53], etc. After the wearable-coil has identified that the user touched the "home-alarm" patch, it communicates to the user's IoT home-alarm via its Bluetooth module, informing it to switch to the "OFF" state. Finally, as depicted in Figure 4b, the home-alarm confirms the new state by sending a message to the wearable-coil, which the wearable device renders *haptically* by energizing the coil in a vibrotactile pattern. This creates a magnetic field which in turn attracts the magnetically-doped region of the interactive patch, making the patch vibrate under the user's finger.

Next, as depicted in Figure 5a, the user taps on another patch on the wall to adjust their thermostat. Figure 5b, depicts how the user slides their finger across the patches, at each step, they feel a short vibration that haptically signals each temperature level. However, as depicted in Figure 5c, when they cross the middle patch, they feel a strong vibration (a haptic detent) that indicates that this is the last used setting.

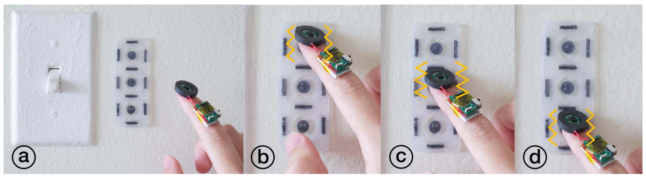

Figure 5: The user touches the top magnet and slides their finger down to the middle magnet where they feel the strongest vibration, indicating the last setting used and continue to slide down to the bottom to reset the thermostat to the lowest setting.

MagnetIO patches are versatile because they are *passive*, made from stretchable silicone. Figure 6a illustrates how our user detaches a patch from the wall and attaches it to new objects. These patches are sticky as their underside is made of a layer of skin safe adhesive, making our patches also suitable for ad-hoc on-body interfaces. In fact, MagnetIO patches are even weather-proof. For instance, Figure 6d depicts a user washing their smart kettle instrumented with an interactive patch. Because MagnetIO's patches operate via magnetism alone (for both sensing and actuation, no circuitry is inside the patch), the interaction will not be affected so long as the wearable coil remains dry.

Figure 6: (a) The user peels off the patch. Because our interactive patches are *passive* and *soft*, they can be applied to a variety of objects: (b) smartwatch bracelet, (c) water bottle, (d) and even washed (still works while wet).

Besides our sticker patch, we also implemented a strap-like patch, depicted in Figure 7, that can be wrapped around objects, such as handles, bottles, etc. These types of patches are ideal for cylindrical objects such as the gaming controller depicted in Figure 7a. In Figure 7, our user stretches the patch around the grip of the controller, which enhances its functionality by allowing them to mode-switch in their game, while keeping their eyes on the game menu; again, an eyes-free interaction.

Now, the user's partner, who is Blind, walks into the room. Despite being visually-impaired, their partner also makes use of MagnetIO patches to control their home. Since MagnetIO are interactive *haptic* patches, they can serve as useful interfaces for visually-impaired users. Especially, because MagnetIO patches are simply

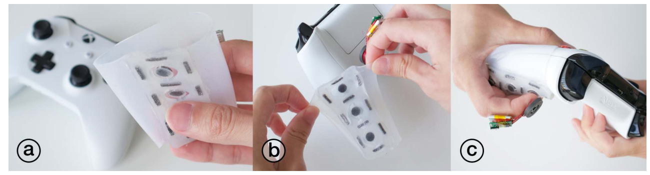

Figure 7: (a) The user holds a strap-like patch and (b) stretches it around their gaming controller, enabling (c) an eyes-free I/O space for controlling modes and menus.

cast from silicone, one can add *tactile bumps* that encode messages in Braille, as depicted in Figure 8. This allows our visually-impaired user to use the thermostat interface by adding a side patch with Braille annotations. The user then feels the Braille to know which patch this is e.g., "thermostat" or "setting 1", and so forth (Figure 8b), and then make use of MagnetIO's vibrations to know they have selected a setting on the interface (Figure 8c).

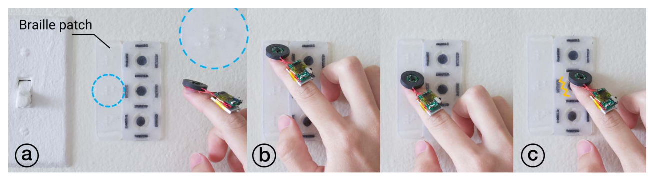

Figure 8: Since our interactive patches are made from silicone, they may easily include Braille to assist Blind users.

While our walkthrough exhibits the key principles behind how MagnetIO allows to deploy haptic patches everywhere, these do not depict an exhaustive list. We designed MagnetIO to be attached to many more objects and believe that it will inspire researchers to use, or even create, passive haptics patches that can be anywhere.

5 CONTRIBUTION AND LIMITATIONS

Our key contribution is that we propose, explore, and engineer conformable interactive patches that can be placed ubiquitously to provide touch input and more importantly haptic feedback. The conceptual result of MagnetIO is the first *one-to-many* system for ubiquitous vibrotactile haptics.

Our approach has the following benefits: (1) while traditional actuators each require their own power supply/electronic-circuits, MagnetIO decouples the powered coil component from the passive magnetic elements, allowing us to actuate *many* interactive patches using only *one* active component, resulting in haptics patches that scale; (2) our interactive skins offer a conformable I/O space that can adapt to many shapes and body parts that pose challenging to existing, rigid actuators (LRAs, etc.); (3) our nail-worn device leaves the fingerpad free to interact with one's surroundings, yet haptic sensations are still delivered directly to the fingerpad; (4) our fabrication technique enables customizable geometries, magnetic fields and even aesthetics; (5) in contrast haptic devices based solely on permanent magnets, the use of our wearable coil allows us to program custom tactile waveforms and/or turn off haptic sensations only-on demand, i.e., these are truly interactive.

Our approach is limited in that: (1) the use of soft elements has its downsides, as our actuators are subject to mechanical losses from hysteresis and yield a reduced magnetic field strength when compared to rigid, sintered magnets; (2) our approach only generates haptic sensations when the wearable-coil is on top of the soft patch, i.e., these patches cannot vibrate by themselves, which is why we believe they are useful for adding vibrations to touch based-interactions; (3) the object being instrumented with our interactive patches must be larger than the patches themselves; lastly, (4) as our approach is based on magnets it is not advised for instrumenting ferromagnetic objects, as these attract the magnets and dampen the resulting vibrations.

6 IMPLEMENTATION

To help readers replicate our design, we now provide the necessary technical details and fabrication process. Furthermore, to accelerate replication, we provide all the source code of our implementation[1].

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.

6.1 Mechanics our of passive patches that can vibrate

The key behind the design of our patches is that they embody the same mechanics that allow a linear-resonant actuator (LRA) to vibrate, yet they are stretchable and passive. In other words, they implement a mass and spring, depicted in Figure 9, that respond to applied magnetic field. Because of silicone's intrinsic elasticity, it naturally behaves like a spring. To allow the soft magnet to achieve amplitudes needed for "feelable" vibrations, we designed the spring mechanism as a long and slender beam (3.75 mm length, 0.5 mm thickness). Furthermore, we found that an optimal 1 mm for the beam-spring's width maximized feelable vibrations (see *Technical Evaluation* for details).

Moreover, as depicted in Figure 9b, we designed the hollow cutout at the center of each patch with a diameter of 9 mm, which is slightly smaller than 10-14 mm of the average fingerpad diameter [10]. Thus, as the fingerpad lands on the center of the patch, it is mostly supported by the silicone walls outside the cutout. This allows the magnet to vibrate freely in the airgap and contact the fingerpad even when the finger pushes down.

6.2 Fabrication of our soft magnets: doping silicone with magnetic powder

Our passive patches are made of two parts: a soft stretchable magnet made of silicone mixed with permanent magnetic powder ($Nd_2Fe_{14}B$) adhered to a flexible silicone mechanism that enables vibration.

[1] lab.plopes.org/#MagnetIO (software, firmware, schematics, 3D files, simulation scripts, evaluation scripts).

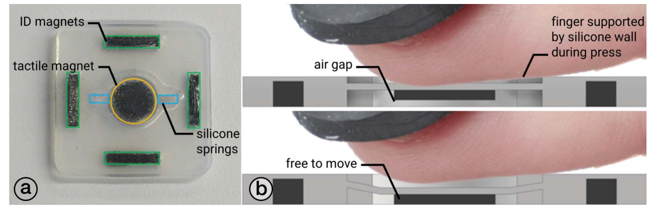

Figure 9: The key mechanism behind our soft magnets: (a) this thin beam act as a spring that connects the magnet (dark region at center) to the base (silicone around it, with cutouts). (b, c) Schematic side view depiction of our mechanics that allow the magnet to vibrate even as the user presses down; note that as the fingerpad lands on the center of the patch, it is mostly supported by the silicone walls outside the cutout.

Prior to the start of the fabrication, the magnetic powder is filtered through a 200 μm mesh. Smaller particles allow for more stretchability, as we validated in our *Technical Evaluation*.

Figure 5 illustrates our fabrication process. First, we fabricate our 1.5 mm soft magnets by mixing the silicone (Dragonskin FX Pro) and NdFeB powder. The mixture is hand-stirred for 10 minutes and cast to a 3D printed mold to shape the magnet; the process is the same for the tactile magnet (that sits at the center of our patches) and the ID magnets (that sit at the edges of the patch, solely for the purpose of shaping its magnetic signature).

The mold is held between two strong permanent magnets (N52 0.75" x 0.75", K&J Magnetics). This strong magnetic field (~1.1 T) magnetizes and aligns the polarities of the individual particles. This process results in a composite with a strong, permanent magnetic field, while remaining flexible due to the silicone holding it together. With a goal of maximizing magnetic field strength to produce strong vibrations, we use an NdFeB weight concentration of 80%.

Next, the rest of the patch, which embodies our spring-mechanism, is cast using pure silicone. For the spring mechanism, Dragonskin FX Pro silicone is used for its elasticity. The magnets and mechanism may be cured at room temperature (which takes ~40 minutes for Dragonskin FX Pro) or inside a dehydrator in a few minutes.

After both the silicone mechanism and soft magnets have cured, the interactive patch is assembled by adhering the magnets to the mechanism with silicone glue (Sil-poxy). The total thickness of a patch is 2.5 mm.

We designed MagnetIO patches to be attached to a wide variety of objects of different shapes, textures, and sizes. To adhere our patches to surfaces such as walls, objects and even skin, we add a final layer of sticky silicone adhesive (*Skin Tite*) to the back of our patches. Other types of patches can be made with longer straps of silicone (as used in Figure 7 around the gaming controller) or even in custom shapes (e.g., smartphone sleeve made from silicone with our magnets embedded or a beating heart for a child's toy, shown later in *Envisioned Examples*).

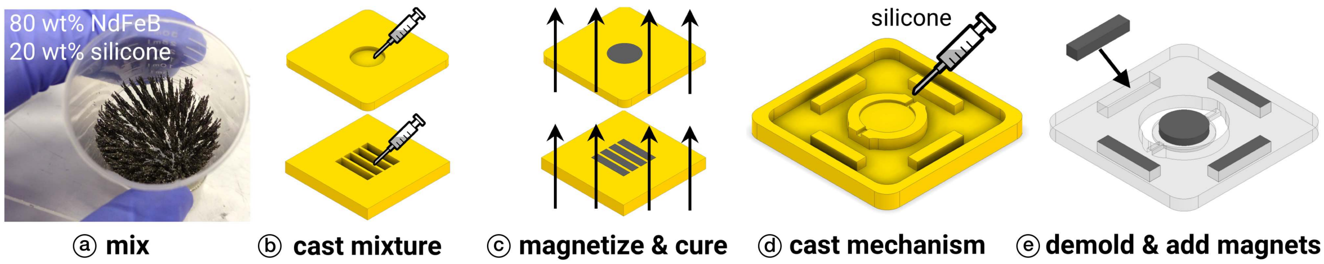

Figure 10: We fabricate our devices by: (a) doping silicone with magnetic powder, (b) casting the doped silicone mixture into 3D printed molds of desired shape, (c) curing the mixture in a strong, external magnetic field, (d) casting our mechanism out of silicone, and (e) adhering the soft magnets to the silicone mechanism.

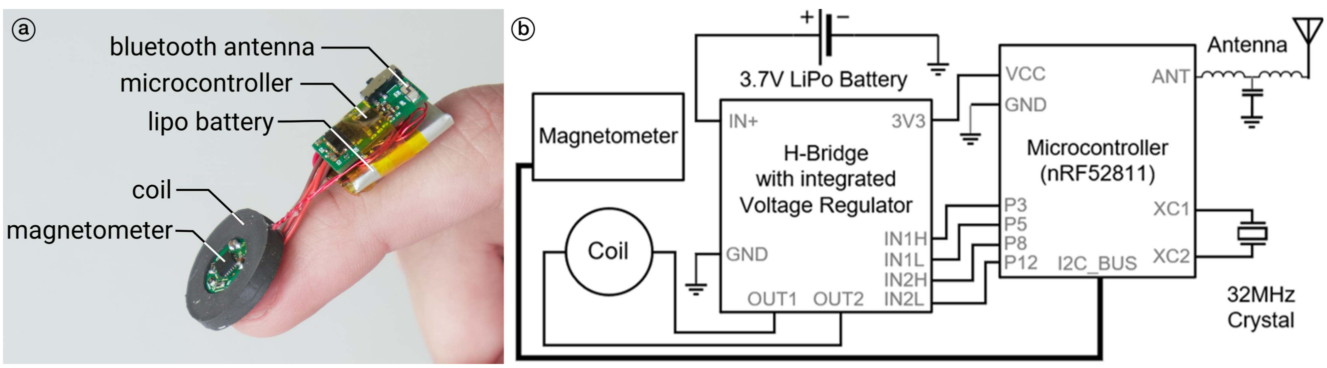

Figure 11: (a) Components used in our device; (b) Circuit diagram of our implementation.

6.3 Engineering our nail-worn device

Our nail-worn device is comprised of a voice-coil and PCBs for processing sensing and actuation, shown in Figure 11. Our voice-coil is optimized to provide strong magnetic forces while maintaining a compact, lightweight footprint that does not occlude the user's fingerpad, allowing the user to still touch objects and feel the haptics of their surroundings.

The coil in our voice-coil is made from copper enameled wire (28 AWG wound for 42 turns. To concentrate the coil's magnetic field, we designed a ferromagnetic core to fit around the windings. To make the core comfortable to wear and to bias its magnetic field downwards to the fingerpad, we designed a computationally-optimized ferromagnetic core made from silicone doped with iron powder (70 wt% iron powder, 30 wt% silicone). We describe this optimization process in our *Technical Evaluation*. The final coil design weighs 2 grams.

We engineered a custom PCB for MagnetIO's finger-worn device, as shown in Figure 11. 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 motor driver can provide up to 5 A of current, but typically 1 A is sufficient to cause a haptic patch to vibrate. With this one small battery, our device allows for only ~100 haptic interactions. Yet, one can triple its battery-life by adding a second 80mAh battery on the first finger phalanx. The complete finger-worn device including battery weighs **only 4 grams.** The coil measures **18.25 mm** in diameter and 3 mm thick, while the wearable controller and battery measure **17 mm x 11 mm** with 7 mm thickness.

6.4 Sensing by means of detecting the magnetic signature of a patch

While the focus of our paper *is on the vibrations produced by our novel soft patches*, these only become interactive when the loop is closed, i.e., only when they exhibit both output and input. We acknowledge that detecting touch and/or the ID of the interactive patch that the user's finger is contacting with can be achieved using a variety of methods previously explored, such as radio [17, 39], acoustic [21], or optical [53, 53] IDs.

However, for the sake of completeness, we also implemented an input identification technique that relies solely on the magnetic properties of a patch. To achieve this, as depicted in Figure 12, we added four small bar magnets (which we call ID magnets) around the main vibration magnet, which we call the tactile magnet. All four rectangular magnets are also soft and were produced using the same method as the tactile magnet. The purpose of these rectangular magnets is to encode an *ID* by means of shaping the 3D magnetic field such that each patch exhibits a different magnetic field when read by the 3DOF magnetometer, which is featured on our wearable nail-worn coil.

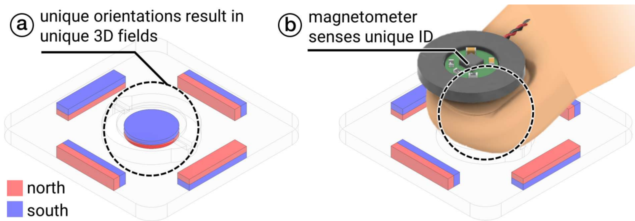

Figure 12: (a) Each patch has one central tactile magnet surrounded (the one that vibrates) and four small bar magnets whose orientation shapes the 3-D magnetic field. (b) When a user touches a patch, the magnetometer reads the patch's unique magnetic field to recognize; thus, enabling the input side of the interaction.

The principle behind our encoding system is as follows: by varying the orientation of the ID magnets, unique 3D magnetic fields can be produced; the number of combinations achieved by this technique is obviously limited but other sensing techniques are also possible. Furthermore, the tactile magnet can also exhibit two polarities, which contributes to a larger number of combinations. Each of the four ID magnets may be oriented in one of four ways (north facing up, down, left, or right). The magnetic fields of each individual magnet interact at the center of the patch and the net magnetic field is read by the magnetometer. As we demonstrate in detail in our *Technical Evaluation,* we can reliably identify eight patches at 99.06% accuracy just using simple threshold-based identification (if-then-else) based on the physical principles that guide magnetism. Certainly, one could alternatively feed the magnetometer data into a more sophisticated classifier (e.g., SVM, DNN, and so forth) to potentially expand both in accuracy and sample size or even fuse the 9DOF of the IMU for more rich data.

7 TECHNICAL EVALUATIONS

We characterized the performance of our proposed device in five technical evaluations. To aid the reader in understanding the different validations we performed, we present an overview of our evaluations with a preview of their respective results:

1. **Impact of particle size on elasticity**: we found that our choice of doping silicone with small particles (<200 μm) improved stretchability, a key feature since we want our patches to stretch and conform around objects.
2. **Measuring & optimizing the vibration response of our soft patches**: we found that (1) a 1 mm spring width and (2) a magnet diameter of 7.5 mm optimizes the resulting vibrations to the feelable range of the human skin; and (3) that placing magnets at least 5 mm apart from each other minimizes any interference from the magnetic field of adjacent magnets.
3. **Measuring & optimizing the magnetic field of our coil**: we found that we could tune the shape of the magnetic field of our coil by (1) computationally simulating it; and (2) adding an iron-doped silicone. The result is that unlike conventional magnets that radiate in a symmetric pattern, our field is biased towards the fingerpad. We also found that most of MagnetIO's vibrations happen at the patch, which vibrates 16x stronger than the coil.
4. **Comparing MagnetIO's vibration to a Linear Resonant Actuator**: we found that our device vibrates with a similar intensity as an LRA driven at 4V with a wider frequency bandwidth due to its soft spring.
5. **Identifying patches by means of magnetic signatures**: while the entire focus of our paper is on the haptic vibrations we produce via our soft patches, for the sake of completeness, we also evaluated our straightforward sensing method that identifies patches based on their magnetic signature. We found that this can identify eight patches with an accuracy of 99.06%.

7.1 Technical Evaluation 1. Impact of particle size on elasticity

To enable our patches to fit around different surfaces, especially those that are non-planar such as the everyday objects or the human body, it is critical that they allow for deformations, i.e., these should *stretch.* Our choice of implementing our interactive patches from silicone allows for this. However, as one dopes the silicone with neodymium powder to enable them to vibrate as a response to our coil, it decreases the elasticity (i.e., an increase in elastic modulus as found by [4]). Thus, to maximize the elasticity of our soft magnets, we explored refining the neodymium powder particle size using a simple mesh filter. Figure 13 depicts the results of a simple elongation test of two soft magnets with comparable properties (size, volume, mass, 80 wt% particle concentration) under 25 grams of load, except that the soft magnet represented by the orange data is made by doping silicone with particles <200 μm; conversely the other soft magnet is made from particles >200 μm.

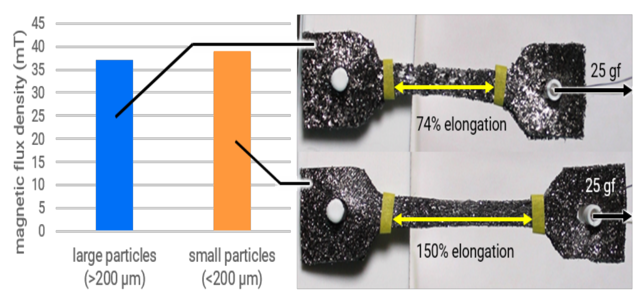

Figure 13: Comparison of soft magnets made with large (>200 μm) and small particles (<200 μm): magnetic flux density (left) and elongation under 25 grams of load (right).

Our results show that fabricating soft magnets using particles smaller than 200 μm allows elongation up to 150% of the original size. Furthermore, not only a smaller particle size improves elasticity, it also slightly increases the magnetic field, which in turn increases haptic performance. As a takeaway from this evaluation, we recommend researchers and practitioners use our approach to quickly improve the quality of their devices by refining the neodymium particle size using a simple mesh filter.

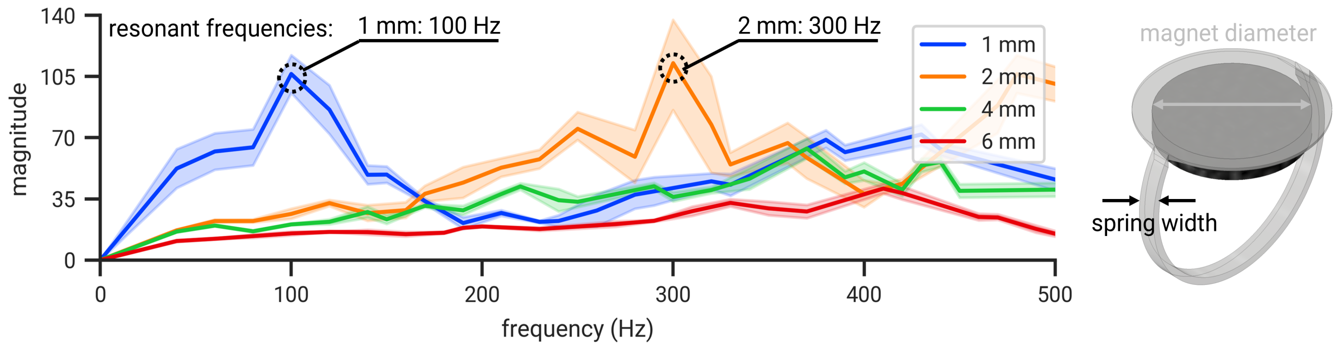

Figure 14: Magnitude of vibrations of the *same* soft magnets but with four varying spring widths. Frequency was swept between 0 to 500 Hz (in 20 Hz steps). Shaded regions depict a 90% confidence interval.

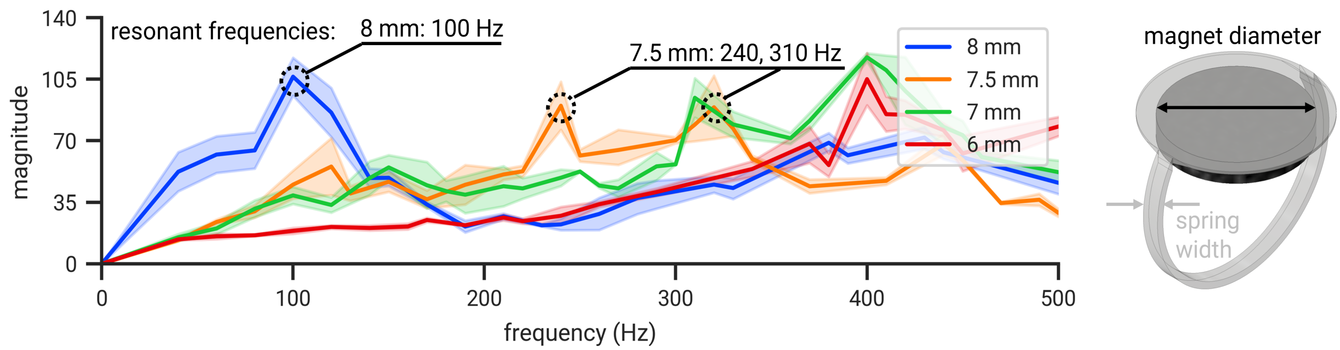

Figure 15: Magnitude of vibrations for four soft magnets with varying diameters of the region that is doped with neodymium (same spring widths of 1 mm). Frequency was swept between 0 to 500 Hz (in 20 Hz steps).

7.2 Technical Evaluation 2. Measuring & optimizing the vibration response of our soft patches

To understand the haptic response of our soft magnets we conducted an experimental evaluation aimed at measuring the impact that each design factor has on the resulting vibration. We measured the impact of: (1) the width of our beam-springs, (2) the magnet's diameter, and (3) interference from any adjacent magnets. To measure the vibration generated, we placed a piezoelectric vibration sensor (AB1070B-LW100-R) below each patch. The coil was held stationary directly above the patch at 6 mm away. Data was recorded at 3300 Hz and processed using a Fast Fourier Transform to examine the frequency response. In our plots, "magnitude" denotes the actual analog reading as measured by our piezoelectric sensor.

7.2.1 Impact of the spring width's in resulting vibration profile. In all our haptic patches, the *spring width* is a major factor that determines the amount of resulting vibration over a range of frequencies. As such, we measured the vibration of four of the same magnets (8 mm diameter, 1.25 mm thick, 34.1±3.2 mT measured at surface) when attached via four different spring widths (1 mm, 2 mm, 4 mm, and 6 mm). To gather insights about a wide range of frequencies, we swept our coil in a square wave pattern from 0 to 500 Hz in steps of 20 Hz. Three repetitions were performed for each magnet.

Figure 14 depicts our results for the measured magnitude of the vibrations of these four different spring widths, over a wide range of frequencies (0-500 Hz). By examining the resonant frequencies (sharp peaks in the response) we found that increasing the spring's width increases the resonant frequency. This is in line with simple vibrational theory, where increasing the spring constant increases the natural frequency. We found that the thicker springs (4 mm or 6 mm) dampen the resulting vibrations. Conversely, we found that the thinner springs (1 and 2 mm) result in a strong vibration. In fact, the 1 mm spring exhibits a maximum vibration a lower frequency peak of ~100 Hz when compared to the 2 mm spring, which resonates maximally at ~300 Hz.

As a takeaway from this evaluation, we recommend researchers and practitioners use a spring width of 1 mm, resulting in a soft magnet design with a resonant frequency at ~100 Hz. From here on, all our soft magnets will utilize a spring width of 1 mm. Note that, depending on the type of application, it might be also worth utilizing also the 2 mm spring which vibrates maximally at a higher frequency of ~300 Hz.

7.2.2 Impact of the magnet's diameter on resulting vibration profile. The next factor that impacts the resulting vibration is the *diameter* of the magnetic region doped with neodymium. As such, using the same apparatus, we measured the vibrations of four soft magnets with varying diameters (6 mm, 7 mm, 7.5 mm, and 8 mm). We fixed the spring width at 1 mm according to the findings of our previous experiment.

Figure 15 depicts the results for the magnitude of the vibrations of these four magnets with varying diameters, as they vibrate over a wide range of frequencies (0-500 Hz). This is again aligned with what is expected by vibrational theory, where increasing the mass decreases the natural frequency. We found that the larger diameter magnet at 8 mm provides mostly only one resonant mode, i.e., it vibrates maximally at ~100 Hz. Then, for diameters below 8 mm, we found a wider range of frequency modes, i.e., these magnets have a few frequencies at which they can vibrate strongly. For instance, soft magnets with a diameter of 6 mm or 7 mm vibrate the strongest at ~400 Hz. Lastly, at a diameter of 7.5 mm, the soft magnet's strongest vibrations occur at 240 Hz and 310 Hz.

As a takeaway from this evaluation, we recommend researchers and practitioners to use a diameter of 7.5 mm, resulting in a soft magnet design with a resonant frequency at ~240 Hz, which leverages the fact that the human skin is very sensitive at those frequencies [58]. From here on, all our soft magnets will utilize a diameter of 7.5 mm with spring width of 1 mm. Note that, the larger 8 mm diameter might be worth exploring for applications requiring a lower frequency ~100 Hz. However, we advise against using soft magnets with diameters below 7.5 mm for haptic applications (with 1 mm spring width), as these resonate at higher frequencies (~400 Hz) at which the human skin is not particularly sensitive [58].

7.2.3 Impact of adjacent magnets in resulting vibration magnitude. Next, because our approach allows users to easily attach these soft interactive patches to objects and the environment to create simple interfaces, the soft magnets may end up neighboring each other. Since this meant that adjacent magnets could potentially interfere with each other's magnetic fields and decrease the vibrations, we decided to measure it. We utilized the same apparatus as in our previous experiments, but attached three consecutive magnets separated by 5 mm. As we were interested in measuring the impact of each magnet's field on the adjacent magnet, we attached the magnets to individual stands connected only at the base; allowing us to measure the impact of the field strength independently of vibrations that propagate through the apparatus (these depend on the material that the magnets are attached to and is a known problem in any vibration-based interface [12]). Then, we proceeded to vibrate, using our coil (at the resonant frequency of 240 Hz), each magnet, one at a time, but measured not only the magnitude of this magnet but also its two adjacent neighbors.

Figure 16 depicts our results of the magnitude of the vibrations (normalized to the maximum) of the soft magnet being excited as well as its two neighbors. As expected, the adjacent magnets exhibit a minute vibration, since their permanent magnetic fields interact with that of the coil and vibrate in response. However, we also found that these vibrations are very small, i.e., ~10% of the maximum at the nearest neighbor and less than 1% of the maximum at the further neighbor. A straightforward empirical test (placing another person's finger over the adjacent magnets) did not reveal that one could confidently feel these vibrations in adjacent magnets.

As a takeaway from this evaluation, we recommend researchers and practitioners to keep adjacent soft patches at least at 5 mm of each other.

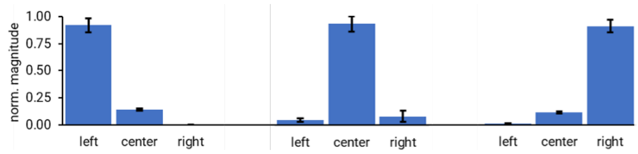

Figure 16: Magnitude of vibration (at resonant frequency) of three adjacent soft magnet placed at 5 mm of each other. As observed, there is very little influence of permanent magnetic field of the adjacent magnets

7.3 Technical Evaluation 3. Measuring & optimizing the magnetic field of our coil

While in our previous evaluations we characterized the vibration of our soft magnets to precisely optimize their frequency/intensity, we now turn our attention toward optimizing & evaluating our wearable coil. The objective is simple: maximize the field strength at the user's fingerpad without increasing the coil size. First, we performed finite element simulations to design an iron-doped core with a geometry that concentrates the field at the user's fingerpad. Then, we experimentally confirmed that it improved the magnetic field strength by 40%.

7.3.1 Impact of an iron core on the resulting magnetic field. Electromagnets are comprised of a coiled wire spun around a magnetic core made from a ferromagnetic material such as iron [33]; this ferromagnetic core concentrates the magnetic flux and results in a more powerful magnet. This is commonly seen in various types haptic devices, e.g., DC motors, solenoids, etc. Inspired by this principle, we engineered our wearable coil to benefit from a ferromagnetic core. However, because our electromagnet is nail-worn, a pure iron core would be heavy and not ergonomically follow the shape of the fingernail. Therefore, we engineered a silicone doped with iron, which increases magnetic field, yet is soft.

We evaluated the effect of an iron-doped silicone core by means of: (1) a simulation, which enable us to determine in detail the advantages of our design; and (2) an empirical validation with a Gaussmeter, which we present later, that provides confirmation of the advantage but displays less resolution than the former simulation.

First, we performed a finite element method (FEM) simulation to compare the magnetic flux density between our initial coil design against our coil design with an added iron-doped core. As with any other materials of this paper (e.g., software, firmware, circuits, 3D models) the simulation files are provided to assist researchers with replication or building on top of our design[1]. All our simulations were conducted using *Finite Element Method Magnetics* (FEMM), a computational solver for magnetics, electrostatics, etc., widely used in physics [5]. Our simulations were set to match our physical coil and are defined as follows: inner and outer diameter of 11 and 16.75 mm, respectively; thickness of 2.5 mm, which provided enough space for 42 turns of 28 AWG enameled copper wire. The coil was excited with 4.8 A to match our benchtop power supply. For the iron-doped silicone core model, the coil was encased in a composite (70 wt% iron powder, 30 wt% silicone) and a magnetization curve for the material was imported to capture the core's ferromagnetic

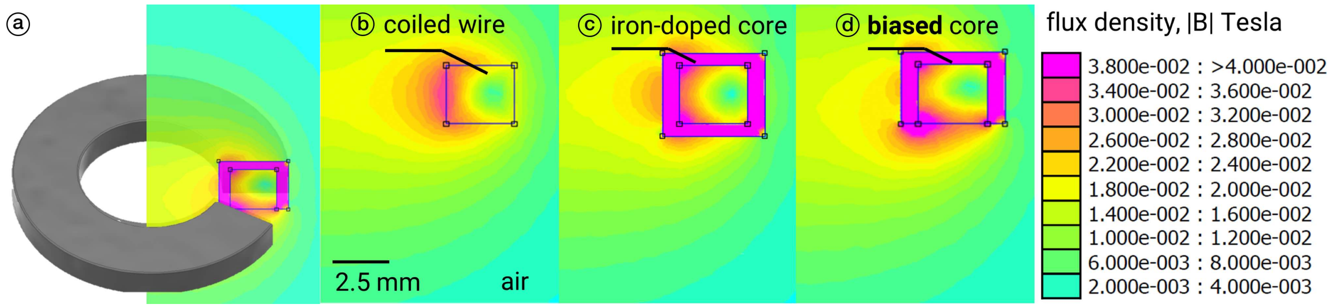

Figure 17: (a) Our simulation is run as a slice of the coil. The magnetic flux contour was calculated for (b) a coil without a core (c) the same coil with a silicone-iron composite core and (d) the same coil but with a core that biases the field to one face of the coil.

behavior [67]. Since our coil's geometry is symmetrical, we simulate only its cross-section (Figure 17a).

Our simulation results are depicted in Figure 17b,c, as a slice of the cross-section. We confirmed that adding a silicone-iron core increased the magnetic field produced by concentrating the flux within the core.

7.3.2 Impact of core geometry in the shape on the resulting magnetic field. Having confirmed that adding a ferromagnetic core concentrates the magnetic field, we explored whether the ferromagnetic core's geometry would allow us to design a wearable electromagnet that exhibits an asymmetric magnetic field, i.e., concentrates the magnetic field *at the fingerpad*, where it is needed for haptic interactions.

Our resulting design is a "pot"-shaped ferromagnetic core (Figure 17d). By means of FEM simulation, we found that leaving one of the faces open "forces" the magnetic field lines to "jump the gap", thus concentrating the field along that face. This effectively biases the magnetic field to one side, making it asymmetric towards the user's fingerpad.

7.3.3 Experimental validation of core design. Finally, we empirically evaluated our coil design by fabricating two coils: a coil with our silicone-iron doped core and pot-shaped geometry; and he same coil but without a core (baseline). Then, we powered the coils by connecting them to our MagnetIO device one at a time. Using a gaussmeter (TD8620) mounted on a caliper, we measured the magnetic field strength as a function of distance (from 0 mm to 12 mm away from the coil; <12 mm being the thickness of a typical finger [59]. Because we hypothesized that the field in our custom coil is asymmetric (biased towards the fingerpad) we measured the field strength in two locations: (a) at the center of the coil, and (b) at the edge of the coil, where we expected the field to concentrate.

Figure 18 depicts our results of the magnetic field strength (in mT) measured at increasing distance from the surface of the coil where the field has been biased. Overall, we found that at any distance, our custom coil (with its soft-iron core and asymmetric magnetic field) produces stronger fields, which is critical since magnetic force rapidly decays over distance. Importantly, when measured directly at a finger's thickness away (12 mm) at the center of the coil, the field strength is 40% greater for the coil with a ferromagnetic core compared to no core.

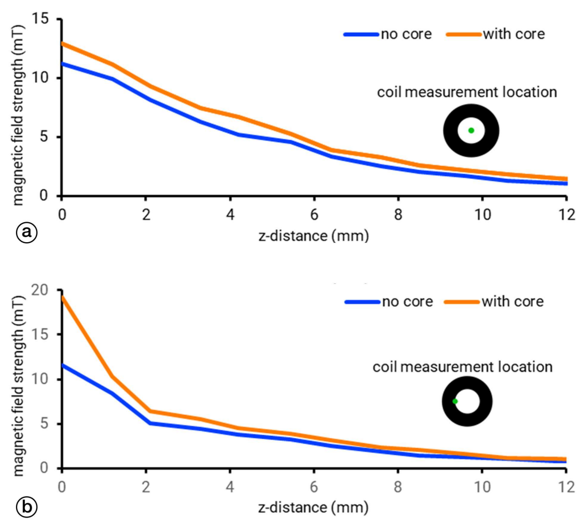

Figure 18: The addition of a ferromagnetic core increased the magnetic field strength at (a) the coil's center as well as at (b) the coil's inner diameter.

As a takeaway from this evaluation, we recommend researchers and practitioners to optimize their wearable electromagnets to direct the magnetic field where it is most useful for the haptic effects. We have not seen this much in the design of interactive devices and believe it might enable improvements in existing interactive devices that are based on electromagnets, such as Magnetips [32] or Magtics [40] just to cite a few.

7.3.4 Measuring the vibrations at the patch vs. vibrations at the coil. Last, since the electromagnetic forces act equally and opposite to each other on the interactive patch and wearable coil, *both* the patch and coil vibrate when excited. To determine the degree to which the coil and magnet vibrate, we placed a piezoelectric sensor beneath each of them and excited the patch at its resonant frequency. We found that the patches vibrate 16x more than the coil, likely due to the coil's greater mass and constraints. Thus, we found that the tactile sensation is greater at the patch, as intended for any haptic application.

7.4 Technical Evaluation 4. Comparing MagnetIO's vibration to a Linear Resonant Actuator

To put our results into perspective, we compare our chosen soft magnet (1 mm spring width; 7.5 mm diameter) with a conventional linear resonant actuator (LRA). As we established, the LRA is the most similar haptic device to our approach, except that its inner workings are rigid and thus not stretchable. For this comparison we used the C10-100, which was driven using a function generator and its driver at a nominal 4 V.

Figure 19 depicts our results for the magnitude of the vibrations of our soft magnet vs. the LRA, as they vibrate over a wide range of frequencies (0-400 Hz). As expected, the LRA resonates at 150 Hz, which is consistent with its specifications. Also as expected, our soft magnet (with 7.5 mm diameter and a spring of 1mm) resonates at both 240 Hz and 310 Hz. Surprisingly, when comparing the magnitudes of each device at their resonating frequency, these are comparable, i.e., our soft magnets vibrates as much as an LRA. Note that our device does this while remaining stretchable. Furthermore, our interactive patches operate consistently over a wider range of frequencies than an LRA; this may be attributed to the larger degrees of freedom that arise from the fact that our patches are made from soft materials [6].

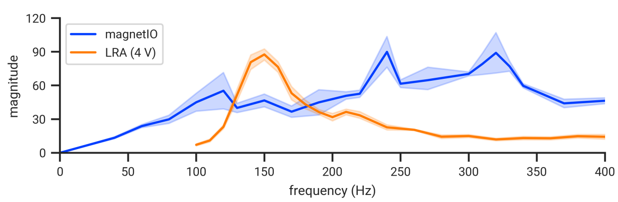

Figure 19: Magnitude of vibrations for our soft magnet design (MagnetIO) vs. a traditional LRA (C10-100 at 4 V).

7.5 Technical Evaluation 5. Identifying patches' ID by means of magnetic signatures

Lastly, to test the accuracy of our simplistic identification based solely on magnetic signatures of the patches, we fabricated eight interactive patches, each with a *random* orientation of their ID magnets. It is extremely important to note that these patches were not custom made. We simply fabricated 32 bar magnets (the small ID magnets) and randomly placed these on each patch without even checking their orientation; this depicts the worse-case scenario for our simple approach. Then, while wearing our nail-worn device with magnetometer, we recorded the 3-axis magnetic field when touching each patch. The readings were converted into a simple rule-based classifier (if-then-else) that classified each patch based on the incoming magnetometer readings. Then, to evaluate the sensing accuracy, one participant touched each patch in a previously randomized ordering (320 touches, 40 touches per patch). For each touch, we recorded the ID predicted by our classifier.

Figure 20 depicts the resulting confusion matrix. We found the overall accuracy across all trials to be 99.06%. This is a sufficient result for simple interactive use, despite using random orientations of the small ID magnets.

While this approach to identifying the interactive patch is relatively simple, i.e., a series of rules based on the physical principles that shape magnetic fields, one could alternatively feed the magnetometer data into a more sophisticated classifier (e.g., SVM, DNN, and so forth) to potentially expand in accuracy and sample size. Lastly, note that we purposely used *only* the 3DOF of magnetometer data for identification to understand the magnetic-only approach; however, our IMU provides an extra 6DOF (3DOF from gyroscope and 3DOF from accelerometer) which can be fused with the magnetometer data for a more sophisticated identification approach.

8 ENVISIONED APPLICATIONS ENABLED BY MAGNETIO

To illustrate the versatility of our approach we demonstrate a wide range of applications, where we utilize MagnetIO patches attached to a variety of objects to propose new interactions with haptic feedback. Broadly speaking, we organize our proposed applications into four categories: (1) ad-hoc & ubiquitous haptics; (2) eyes-free use; (3) adding interactivity to everyday objects; and (4) adding interactivity everywhere, even to outdoor objects, exposed to weather conditions.

8.1 Benefit#1: Scalability—enabling ubiquitous ad-hoc haptic interfaces

Figure 21 depicts an example of how a user might instrument their living room using six MagnetIO patches, to create ad-hoc interfaces that fit their own needs, such as (a) haptic buttons for their e-reader; (b) haptic controls for their smart-dehumidifier, (c) volume control with haptic detents on their armchair; (d) additional settings with haptic feedback on their smart thermostat; (e) haptic feedback as they touch their plant's pot to select the amount of water from their watering system; and, (f) controls for their fan with haptics when they touch the "eco" setting.

Additionally, MagnetIO patches can weave interactivity into playful everyday objects. Figure 22 shows how patches can (a) add dynamic interaction to a children's coloring book; (b) add tactile cues to board games; and (c) add play, stop, record buttons with haptic feedback for their guitar's looper.

8.2 Benefit#2: Conformability—adding MagnetIO patches to non-planar objects, outdoors, etc.

Furthermore, we believe MagnetIO patches are especially useful for realizing interfaces attached to objects that are not planar, which is depicted in Figure 23. For instance, (a) music player control on their headphones; (b) additional buttons with haptic feedback for a gamepad; and (c) added to one's favorite toy to feel its heartbeat.

More interestingly, Figure 24 depicts how our patches can provide interactions in extreme environments, such as contexts where significant forces are applied or drastic weather changes. Figure 24a depicts a user who has instrumented their bike handle with MagnetIO patches to receive turning signals from their phone's GPS navigation application. When the user wants to check driving

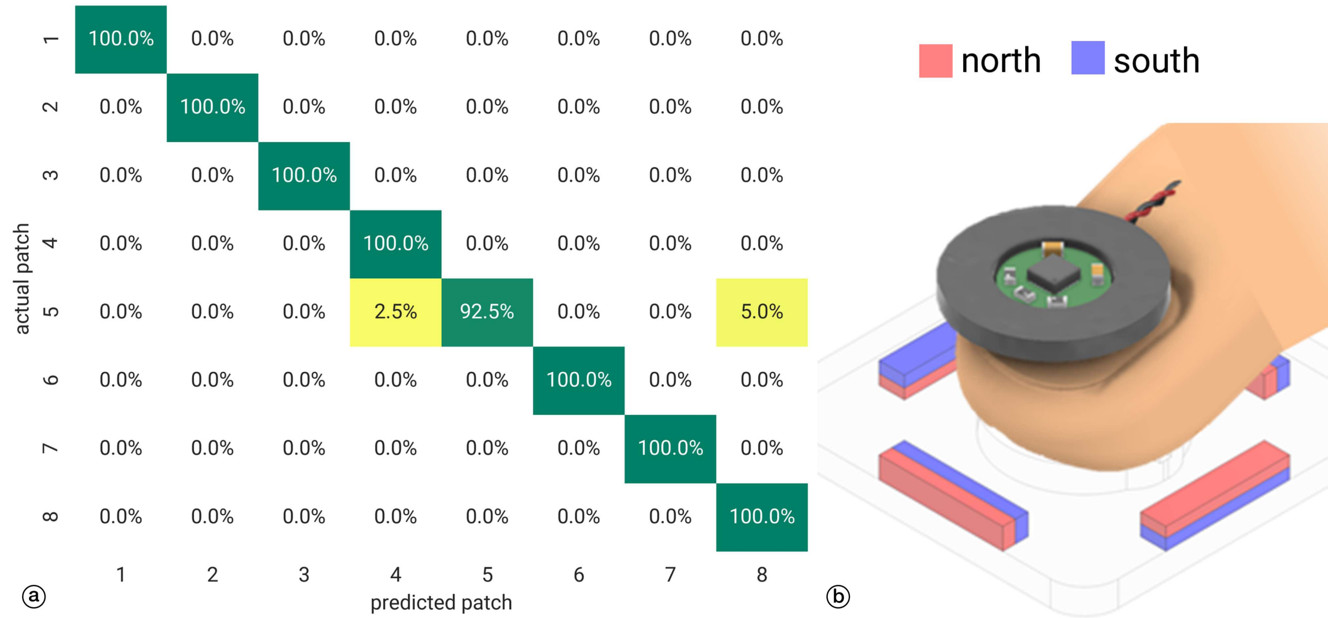

Figure 20: Interactive patch confusion matrix across 320 trials.

Figure 21: An example of an envisioned ad-hoc interface created by a user for their living room using six patches .

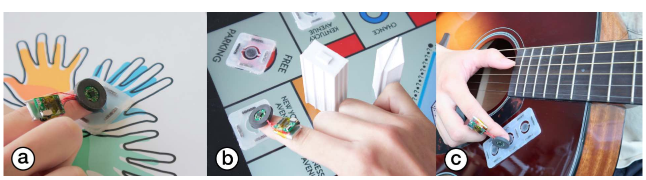

Figure 22: Examples of how MagnetIO can enhance everyday objects by creating an ad-hoc I/O space; these objects can now sense touch interactions and vibrate in response.

directions, they place their fingers on a MagnetIO patch that buzzes once or twice, in response to the navigation-application's messages, to notify them to turn on the next intersection to the left or right, respectively. Here, the MagnetIO patches survive adverse weather conditions because they are completely *passive*.

9 CONCLUSION

We presented MagnetIO, a new type of haptic actuator comprised of two parts: *one* battery-powered voice-coil worn on the user's

Figure 23: Examples of how MagnetIO patches can conform to objects of various shapes.

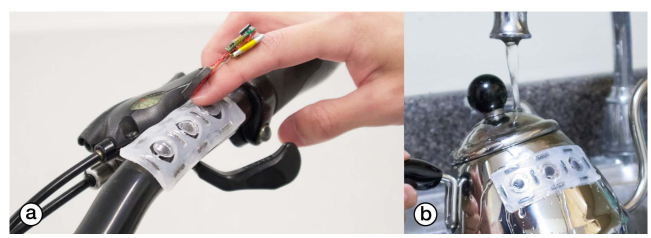

Figure 24: Two examples of applying MagnetIO patches in extreme contexts with significant forces or weather changes, such as this bike's handle; however, because our patches are passive and soft, they resist these adverse conditions.

fingernail and *many* 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 coil contacts any of the interactive patches it detects its magnetic signature via magnetometer and makes the patch vibrate, adding haptic feedback to otherwise input-only interactions. To allow these passive patches to vibrate, we fabricated them from silicone with regions doped with polarized neodymium powder, resulting in soft and stretchable magnets. This stretchable form-factor allows our patches to be wrapped to the user's body or everyday objects of various shapes.

It is this novel technical implementation, based on the decomposing the inner-workings of a linear resonant actuator, that gives rise to MagnetIO's unique feature, it is a *one-to-many haptic device*, i.e., *one* active part (an electromagnetic-coil worn the fingernail) powers *many* passive actuators.

We demonstrated a range of applications that make use of MagnetIO's patches to realize ubiquitous haptics, i.e., surfaces and objects around the user can now exhibit interactive behavior (they can vibrate upon touch).

Furthermore, in our technical evaluation, we demonstrated that our interactive patches can be excited across a wide range of frequencies and can be tuned to resonate at specific frequencies based on the patch's geometry. Furthermore, we demonstrate that MagnetIO's vibration intensity is as powerful as a typical linear resonant actuator (LRA); yet, unlike these rigid actuators, MagnetIO's patches operate as springs with multiple modes of vibration, which enables a wider band around its resonant frequency than an LRA.

We tend to think of MagnetIO not as an end-product but as a hardware & fabrication technique that will inspire the creation of a new type of passive-haptic interactive devices that can even unlock new use cases. As such, we plan to publish the detailed fabrication process, hardware schematics and code as open-source to accelerate future research.

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