Reconfigurable Tactile Micro-Elements: Electromagnetic Actuation and Sensing for Dynamic Affordances and Mobile Interaction Techniques

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Figure 1: Reconfigurable tactile micro-elements (shown in arrows) for interaction on a mobile device. Left to right: a flexible PCB utilizing micro-coils for magnetic actuation of tactile elements, a mobile prototype using the PCB micro-coil technique, a mobile prototype using low-power switchable permanent magnet actuation, a game played using reconfigurable tactile controls, a wearable band with tactile elements for display and interaction.

ABSTRACT

Currently, virtual (i.e. touchscreen) controls are dynamic, but lack the advantageous tactile feedback of physical controls. Similarly, devices may also have dedicated physical controls, but they lack the flexibility to adapt for different contexts and applications. On mobile devices in particular, space constraints further limit our input and output capabilities. We propose utilizing reconfigurable tactile micro-elements around the edge of a mobile device to enable dynamic physical controls and feedback. These tactile micro-elements can be used for physical touch input and output, and can reposition according to the application both around the edge of and hidden within the device. We present two implementations of such a system which use magnetic locomotion as means of actuation. One approach utilizes PCB-manufactured electromagnetic coils, and the other uses switchable permanent magnets. We perform a technical evaluation of these prototypes and compare their advantages in various applications. Finally, we demonstrate several mobile applications which leverage these systems to create novel mobile interactions.

ACM Classification Keywords

H.5.2. User Interfaces: Graphical user interfaces (GUI), Haptic I/O, Input devices and strategies

Author Keywords

Mobile Haptics; Tactile Display; Dynamic Affordance; Magnetically-actuated Buttons

INTRODUCTION

Current mobile devices allow users to choose from millions of applications. However, due to the convergence of hardware for smartphones and tablets, interaction with these different applications is generally limited to the same means of physical input—a touch screen and a few physical buttons. This greatly limits interaction, especially when the user cannot visually attend to the display, which is a common scenario when users multi-task in a mobile context, but also an everyday reality for the visually impaired. Thus, we seek to use actuation to expand the capabilities of mobile I/O without radically changing the form factor or functionality of these devices. In particular we asked ourselves: What if the physical interface elements of a mobile device could reconfigure on the device to fit the application and user needs?

In this paper, we propose a new approach to mobile physical interaction: reconfigurable tactile micro-elements (RTMEs) which can travel on the exterior of traditional mobile and wearable devices. We specifically explore RTMEs on the edges of mobile devices, resulting in a smartphone prototype which can dynamically surface, move, and hide discrete physical controls along its edge. These RTMEs can both provide haptic feedback and enable expressive input methods utilizing the dominant or non-dominant hand. As discrete, movable tactile elements, RTMEs permit a number of interactions on a mobile interface, such as shear input and tactile display. They enable context-dependent physical controls for applications, and introduce new tactile notifications that allow a user to "glance" at information through touch. Because these RTMEs operate on the edges of the device, interactions do not occlude the screen can work in tandem with the graphical display.

In selecting an implementation to realize the tactile micro-elements, we chose to explore magnetic actuation with the goal of a small, lightweight, low cost design with few moving parts which could be integrated into mobile devices (phones and tablets), wearables (e.g. smart watches), and automobile dashboard interfaces or steering wheels. Magnetic actuation utilizing an array of electromagnetic coils and passive RTMEs also enables the system to scale towards a high number of elements, in contrast to mechanical actuation methods. This paper examines the strengths and weaknesses of two different magnetic actuation techniques and the prototypes built to explore them. The first utilizes thin electromagnetic micro-coils integrated into flexible printed circuit boards, inspired by previous work [26, 27, 7]. These boards can be designed and fabricated with traditional Printed Circuit Board (PCB) techniques, making it ideal for applications requiring thin form factors and low cost. The second system uses a bi-stable design through switchable permanent magnets, which have a larger footprint and are more rigid, but potentially result in significantly lower power consumption. These systems have been integrated into two form factors. The first positions RTMEs on the edges of a mobile device, the second utilizes the thin form factor of the Flexible Micro Coil system to be integrated into a wearable wristband.

Contributions

- The concept of Reconfigurable Tactile Micro-Element Interfaces to enable dynamic affordances and haptic feedback on the physical surfaces of devices.

- Two mobile implementations of such an interface which leverage the electromagnetic actuation of neodymium micro-elements:

  - *Flexible Micro-Coil System* based on thin, flexible PCB with micro-coils for arbitrarily curved surfaces and minimal footprint in small devices.
  - *Switchable Permanent Magnet System* that enables bi-stability and low power magnetic actuation.

- A technical evaluation of the electrical characteristics and magnetic properties of our prototypes, discussing their suitability for mobile hardware.

- Novel applications and mobile interaction techniques for a Reconfigurable Tactile Micro-Element Interface that enable context-specific controls, self-adjusting interface elements, physical extensions of the GUI, and rich haptic notifications.

RELATED WORK

Mobile Tactile Interaction

Much research attention has focused on expanding the physical output modalities of mobile devices. In addition to actuating the entire device through vibration, there are broadly two classes of approach: 1) systems that provide surface haptics co-located directly on a touch screen display, and 2) tactile feedback on the periphery (e.g. edge or back) of the device. Haptic feedback can be added directly to GUI interactions through vibration [28, 5, 21], electrostatic friction [2] or reconfigurable elements emerging from the display (e.g. by pneumatics [11], hydraulics [8], or actuation [10, 29]).

Other contributions have utilized the periphery of mobile devices, exploring touch on the back [3], sides [4, 13] and surrounding regions [6]. Mobile devices also often include passive physical controls near the edges, and one line of research involves increasing the dynamic nature of these elements. Hemmert et al. created a single dynamic button for mobile interactions [12], and Pasquero et al. created a button with an array of piezo actuators to provide skin stretch directly to the user's thumb [23]. More recently, Jang et al. augmented a mobile device with an array of linear actuators to create dynamic affordances. [16].

Also related is the Eone Bradley tactile watch [33]. This watch uses two magnetic ball bearings in grooves to display the time both visually and tactually. This system has no input capabilities, and is limited to two tactors on different surfaces due to its use of a motorized actuation system.

While mobile tactile feedback as a whole has received much research attention, we believe that RTME Interfaces have a number of key distinctions from prior work, such as the ability to support lateral displacement for feedback and user input.

Reconfigurable and Actuated Input Devices

Researchers have also explored user reconfigurable physical input devices. Some work, such as that of Jansen and colleagues, customizes a traditional device with passive physical widgets that can be sensed for input [17, 37]. Villar and Gellersen used pushpin-style connectors and flexible circuit membranes [34]. In the mobile space, the MagGetz system used magnetic sensing to allow users to reposition physical input elements which were sensed by a mobile device's magnetometer [14]. These systems require the user to manually reconfigure the device, which makes them low-cost.

Outside of a mobile context, there has been much work in creating actuated table top interfaces with reconfigurable tangible elements [1, 22, 25, 30]. Researchers have also explored how users perceive these moving physical affordances by leveraging patterns of motion and shape change [32]. Many of these systems use arrays of electromagnets to induce magnetic fields and move permanent magnets [22, 24, 35, 36]. However, such systems require large electromagnets, making them ill-suited to mobile applications. To address the size and power constraints of mobile devices, we require an alternative design. Furthermore, our system must work in various orientations and configurations. Our goal is to reduce the cost, size, and power consumption of such a system, and to develop meaningful interactions to work in the mobile context.

Le Goc et al. recently described the Swarm User Interface, in which interactive swarm robots combine to form a reconfigurable interface. The swarm interface is, however, limited to a flat surface and requires a fixed projector setup [20].

Magnetic Locomotion

Since at least the 1990s, researchers have been exploring magnetically levitated and controlled micro robots for manufacturing [9, 26]. These devices are fabricated using traditional PCB techniques [27] and utilize diamagnetic materials to levitate the magnets to reduce friction. Many of these systems use a row and column approach to drive the magnetic field. However, this presents challenges for independent control of multiple robots, leading to the exploration of alternative approaches [7, 18]. Inspired by this work, we aim to apply a similar technology to mobile user interfaces, with the additional challenges posed by interaction and display, such as the need for integrated sensing.

RECONFIGURABLE TACTILE MICRO-ELEMENTS

We propose a new class of I/O for providing dynamic physical affordances on mobile devices called the Reconfigurable Tactile Micro-Element Interface. In these interfaces the physical elements can reconfigure their positions on a device to adapt to different applications or provide haptic feedback. While these elements can be perceived visually, their main function is in tactile interaction, and thus we chose not to explore integrated visual display elements such as LEDs.

Design Space

There are a number of parameters to be considered when designing a RTME Interface. These parameters affect the ways in which RTMEs are used for display and interaction, as well as the size and power consumption of its components. We explore this design space in the section below.

Size. The size of a RTME changes how the user interacts with it much like a static button. Fitt's Law and ergonomic guidelines should be used to determine the ideal size. Smaller elements could be combined to form larger compound elements.

Number. The number of elements supported by the system has a large impact on its interactions and applications. A single RTME enables simple interactions with a single interface element, such as a scroll bar. With more RTMEs, more complex interfaces can be generated, and more expressive tactile display can be achieved. Multiple elements could be attached together to form larger elements, and then split apart.

Dimensionality. This paper focuses on 1D actuation. However, RTMEs could operate in 2D on a given surface, or stack to create elements of different heights.

Location. The RTMEs can be located on different areas of an interactive device. RTMEs could be located on the 2D visual display of a device, or on the back of the device. Here we explore interaction on the edges of the device.

Homogeneous vs. Heterogeneous. RTMEs can all be the same shape and size, or they could be comprised of a set of differing geometries. For example, a larger button could be used as a camera shutter, whereas smaller buttons could form zoom controls. This could also enable the use of Phicons [15].

Visibility and Accessibility. RTMEs could be exposed at all times. Alternatively, RTMEs could be stored out of sight of the user in a reservoir. Because they are physical elements and cannot instantaneously appear/disappear, it is important to help the user to distinguish when the RTME is actively displaying information and when it is moving into a position.

Force. The amount of force a RTME can impart largely affects its use in feedback. Low force suggests that it can mostly be used for locomotion of the RTME. However, a RTME with higher force could impart force on a user and induce a haptic sensation, either by hitting the side of their finger, vibrating underneath it, or even moving the finger.

User Input. RTMEs can be touch sensitive, either by integrating sensing into the RTME or elsewhere in the device. This touch could also be pressure sensitive to provide analog input. If the RTMEs are backdriveable or loosely coupled to the actuation (i.e. through magnetic fields), it is possible for the user to reposition the RTME. In this mode, the RTME can be used for shear input through its lateral displacement, provided that there is appropriate position sensing.

Interaction

The RTME Interface consists of a number of passive RTMEs that can be actuated to assume different positions and roles around the edge of a device. These elements can, for example, act as physical controls, haptic notifications, or tactile displays. They can emerge from a hidden state within the device itself, assume a given function on the device, and then return back into concealment when the interaction completes. Multiple elements can be actuated at once.

RTMEs can be interacted with in a static state, wherein they assume a particular form when an application is launched and act like traditional physical controls. Alternatively, RTMEs can use their ability to dynamically reposition to provide more active affordances. For example, a button moving quickly in an erratic pattern might imply that users should not touch it.

These RTMEs can be controlled in coordination with the primary graphical display of the device. As such, there are different paradigms by which to design these joint interactions: By *mirroring*, RTMEs can display the same interface elements as displayed on the graphical display, such as physical buttons near existing virtual buttons. By *complementing*, RTMEs can display a spatially relevant interface element in addition to the graphical display, such as a scroll bar for text. Finally, by *extending*, RTMEs can render information not represented on the primary display, such as a notification.

We describe below some of the main interaction primitives of the RTME Interface:

- *Buttons.* A RTME becomes a dynamic, touch responsive button on the edge of the device. Because it can be located easily via the sense of touch, the button is more readily recognized than a virtual button when attempting input.

- *Sliders.* A RTME acts as a linear slider, allowing the user to scroll through content by moving a physical control down the side of the device.
- *Toggles.* A RTME becomes a switch, where a tap causes it to toggle the value for a parameter, and correspondingly move to a new position that represents the updated value.
- *Pinch controls.* A pair of RTMEs operate to form a pinch-gesture interaction with physical feedback, e.g. for zooming. Users can slide the RTMEs closer together or further apart to adjust along a continuous scale.

In addition to generating these input elements, RTMEs are also capable of providing feedback to the user through a number of techniques:

- *Haptic notifications.* RTMEs can be used to "bump" into the user's hand as it grips the device, alerting them of new information in a discreet fashion.
- *Physical information display.* RTMEs can represent discrete chunks of information, such as unread notifications or members of a conversation, which can be perceived both visually and haptically by the user. Further, motion of the RTME can also be used for information display, such as rendering a loading bar, or a playback head for a music player.
- *Haptic detents in lateral interaction.* The device can create regions of varying force, such that a user moving an interface element along the device feels haptic pulls or resistance to their action.

IMPLEMENTATION

Technical Considerations

There are many actuation approaches that could be used to implement RTME Interfaces, including belt/cable driven tactors, linear actuators (motor driven, S.M.A, pneumatic, hydraulic, etc.), electrostatic actuation, magnetic actuation, or self-actuated elements (such as microrobots). We considered a number of factors in the design of our RTME system, towards the goal of creating a system suitable for mobile and wearable applications:

Size. Size is a chief concern in mobile and wearable devices. Ideally, the actuation technology is thin and light, so as not to add thickness or weight to a mobile or wearable device. The length of the active area and max linear displacement of RTMEs was also an important consideration, as we wanted to allow for interaction on multiple sides of the device.

Multiple Elements. Our goal was to support several elements simultaneously. This scaling issue limits the feasible technical solutions, as many technologies would make it difficult to drive RTMEs along a single track. For example, if linear actuators were used they may physically collide or not have enough space, unless stacked. Cable driven systems could support more elements, but still run into space constraints. Magnetic drive systems could theoretically support many RTMEs simultaneously, approaching the number of magnetic coils present.

Force. The force of the RTMEs is important both for haptic feedback and for the robustness of the system. Stronger lateral forces allow us to create greater haptic sensations, and a stronger normal force helps to keep the RTME from dislodging from its target position. The amount of force varies greatly with the chosen actuation mechanism. For example, large forces are most easily achieved via motor-driven systems.

Cost. The cost per RTME is also a consideration. Small motors and linear actuators generally have relatively high parts costs, so it is rare to find multiple of them in one consumer product. Often, components that can be easily fabricated with existing PCB technology can be low cost, due to the optimization and scale of this fabrication process.

Reduced number of moving parts. Lowering the number of moving parts that can be broken by users or external forces is a key consideration. Many linear actuators are not compliant or backdrivable, which would cause them to potentially break. Magnetic action provides compliance and robustness to high forces, as the RTME can just slide freely if a high external force exceeds the magnetic force.

Power Consumption. Power consumption for mobile devices is extremely important. Some technologies only use power to move elements (most linear actuators, switchable magnets), however others require power to hold a steady state (e.g. shape-memory alloys and electromagnets).

Implementation Design Selection

Prioritizing the goal of independently controlling a number of RTMEs along the edges of a mobile device or wearable, we decided to utilize a magnetic approach to actuation, as opposed to mechanical alternatives such as linear actuators or belts beneath the edge of the device. We chose to explore two different approaches to magnetic actuation - thin and flexible elements that could be low cost to produce, and secondly, lower power consumption using switchable magnets. Both of these systems share a number of benefits including the reduced number of moving parts and overall low cost to actuate many RTMEs, with the trade-off of a relatively low output force. Our implementation provides enough force to allow for haptic feedback in the form of "taps" on the side of the finger, but not enough to physically displace the user's finger.

In the sections that follow, we refer to our specific implementations of a RTME Interface, noting that other implementations could facilitate somewhat different interactions and applications.

FLEXIBLE MICRO COIL SYSTEM

In our first prototype, the RTMEs are actuated by a flexible multilayer PCB with patterned copper traces. To drive magnetic elements, we require only a thin, flexible strip of small coils, which can be manufactured through standard PCB fabrication techniques. Further, a single strip can be folded around to cover the entire perimeter of the device, simplifying the transition between edges. By continuing this strip beyond the

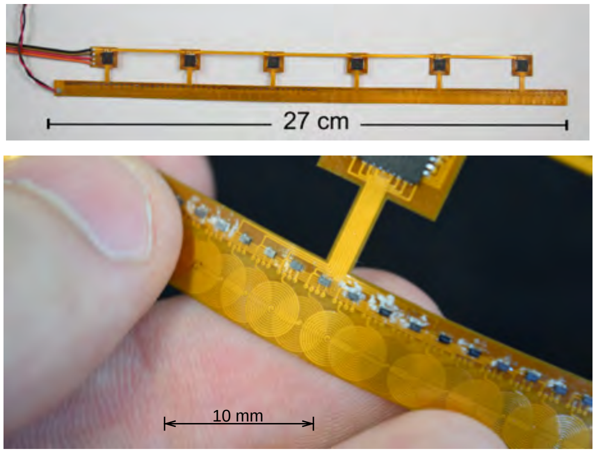


Figure 2: Interleaved micro-coils on a flexible PCB. Top: The total length of the PCB is 27 cm, allowing it to operate on all sides of a mobile device. Bottom: Close up of coils and transistors. Coils have a radius of 2.5 mm. Each transistor controls a single coil.

exposed area, we create a reservoir area where RTMEs can be stored in a “hidden” state when unused.

Running current through the circuit layers creates magnetic fields and imparts forces on the RTMEs, causing the RTMEs to move in a controlled direction. In addition to the lateral movement, the effect also creates a strong normal force which keeps the RTMEs attached to the circuit surface even when vertical. Each layer of the PCB contains a series of micro-coils (see Figure 2). The circuit layers are patterned identically, but are offset so that as the layers are driven independently, the magnets are pushed and pulled to the next position. The RTMEs are driven in open-loop control via microstepping—i.e. the activation of a given coil is increased and decreased by adjusting PWM pulse widths.

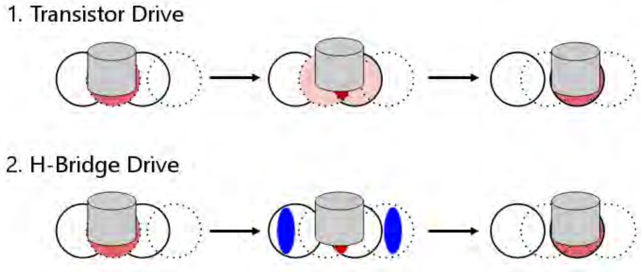


Figure 3: Single-transistor drive versus H-Bridge drive for our interleaved micro-coil setup. With a single transistor, a microstep involves transferring power from one coil to the next, shifting the attractive force. With an H-bridge, coils beneath the RTME produce an attractive force (red), while coils bordering the RTME produce a repelling force (blue).

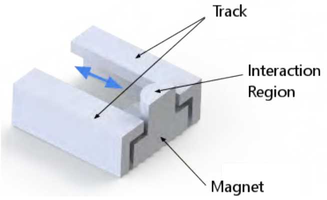


Figure 4: A mechanical track constrains the motion of the RTME, while exposing one end for user interaction.

In similar systems such as [7], a combination of repulsive and attractive forces have been used to create smooth motion of the travelling magnet. However, creating both attractive and repulsive forces from the same set of coils requires switching with an H-bridge configuration for each coil, drastically increasing the cost, complexity, and size of the circuitry. Instead, by solely leveraging attractive forces, we can switch each coil with a single transistor. The differences in drive patterns in the single transistor and H-bridge configurations are shown in Figure 3.

While a normal force is generated in the drive process to keep the RTME atop the PCB coils, we additionally mechanically constrain the motion of the RTME by fixing it to travel within a fixed track along the side of the device (as shown in Figure 4). The magnetic base of the RTME slides along the coils beneath the track, and a 3D-printed cap on the magnet protrudes as a region for user interaction. This keeps the RTME from escaping even when powered off, and helps prevent dislodging in the event of bumps or drops.

Coil Design

The first consideration in designing the PCB is the layout and number of coils. By interleaving multiple sets of coils offset in phase, we can achieve a smoother travel in either direction than with a single set of coils of the same radius. However, assuming the same force per coil, powering additional coils results in increased power consumption as well as an increased number of transistors required over the same length. Our prototype uses two sets of coils positioned 180 degrees out of phase, which can optionally be run using just a single set.

Secondly, we consider the design of each individual coil. Based on the work of Cappelleri et al., we utilize a spiral-shaped micro-coil, to maximize the field in the region beneath the cylindrical magnet in the planar PCB layer [7]. Our parameters include the radius of the coil, the thickness of the trace, and the number of turns. To inform our designs, we used finite element analysis (FEMM) to explore the effect of various parameters on the resulting output force. We approximate our spiral shape as a series of concentric circles for the purposes of simulation. The simulation geometry is shown in Figure 5.

Given that the traces are relatively short and contribute minimal resistance, we can vary the trace width and assume a constant current without much error. The results of varying the number of turns in tandem with trace width are shown in Figure 6. As expected, a tightly wound spiral with thin traces produces the largest force on the RTME, so our coils

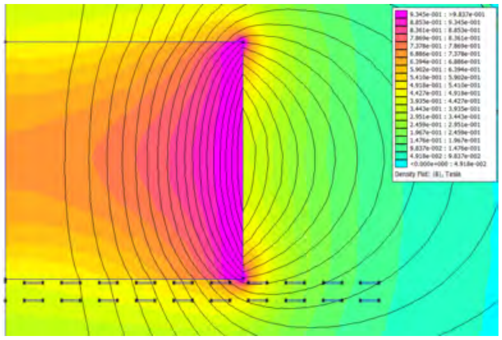


Figure 5: Axisymmetric finite element analysis showing the flux density of our magnetic RTME atop a single powered 2-layer, 10-turn coil.

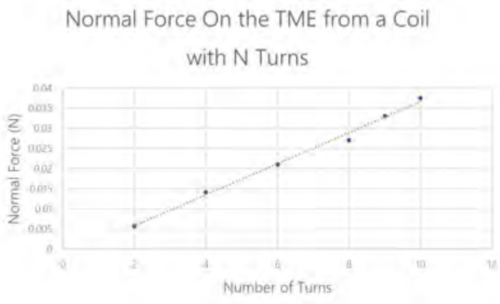


Figure 6: The normal force experienced by a RTME located directly above a single coil powered at 1A. As the number of turns are increased, the trace width is decreased to fill the same 5 mm diameter radius with a constant .125mm separation between turns. Normal forces were calculated using block integral stress tensors.

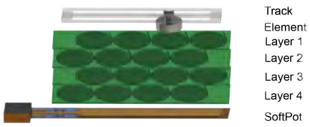


Figure 7: Exploded view of the PCB micro-coil system, consisting of a RTME, a linear track, flexible circuit layers containing interleaved electromagnetic coils, and a soft potentiometer.

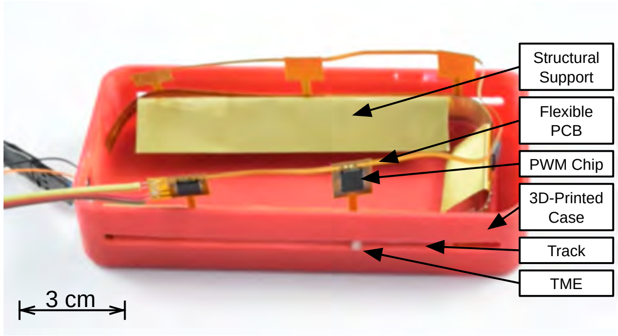


Figure 8: Prototype mobile device system using a 4-layer flexible PCB. The 3D printed case has integrated tracks for the RTME to slide in.

are designed with the minimum trace width/separation per the manufacturer (0.125 mm), and the maximum number of turns (10) in an empirically chosen radius (2.5 mm).

Magnet Selection

Magnet Grade

Our prototypes utilize N52 Neodymium magnets as the RTME base. The N52 grade is one of the highest available, and Neodymium magnets are particularly suitable for translations on flat circuits given their high surface magnetic field.

Magnet Dimensions

The dimensions of our magnets take into consideration both the constraints of actuation as well as the ideal form for user interaction. While magnetic field strength increases with both thickness and diameter and enables greater attractive forces, increased dimensions also increase the weight of the RTME, which has a net decrease in performance. Thus, the ideal magnet for our system has the smallest dimensions while still being large enough to permit user interactions.

We settled on a 1/16" (1.59 mm) magnet thickness, and a 1/8" (3.18 mm) magnet diameter. The diameter allows us to constrain the motion of the RTME within the mechanical track, while still presenting a milli-scale interaction region to the user. The thickness is sufficient to provide stability to the section of the RTME within the track, allowing it to resist torque resulting from the weight of the 3D-printed cap.

The mass of the magnet is 0.09 g, and the printed cap adds an extra 0.04 g, for a total of 0.13 g.

System Design

Our final design (Figure 2) uses a four-layer flexible PCB, with one coil set in layers 1 and 3, and the other set in layers 2 and 4. A via connects each of two paired coils between layers to make a continuous trace, effectively increasing the number of turns in the same radius. The two sets are offset 180 degrees out of phase. Each coil has 10 turns in each layer, for a total of 20 turns, equating to roughly 1Ω of resistance.

An Arduino Uno microcontroller controls the coils using PCA9685 PWM ICs over I^{2}C communication. Each IC is capable of driving 16 coils, and each coil is switched with a CSD13383F4T transistor. In addition, a linear soft potentiometer behind the PCB is used to sense pressure and to calculate the input position when a user pushes a button into the track. An exploded view of the layers of the system is shown in Figure 7.

Mechanical Design

To test our prototype with an existing mobile device, we 3D printed a case to house the electronics alongside an iPod Touch (Figure 8). The case features a linear track to constrain the motion of the RTMEs, and has interior room for RTMEs to

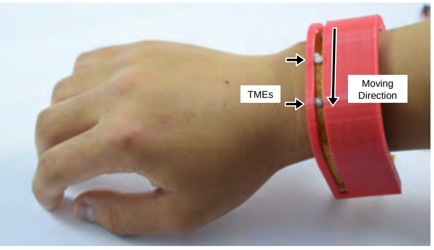


Figure 9: The wristband wearable device with RTMEs. This prototype utilizes a 3D printed case and the Flexible Microcoil array to actuate magnetic RTMEs.

"disappear" when not used in a given application. We utilize a Bluetooth Low-Energy UART chip from Adafruit Industries to communicate with the iPod Touch, enabling interactive applications.

We also designed a wearable form factor utilizing a wristband-style device, see Figure 9. A 3D-printed case encloses the device and again has an integrated a linear track. The RTMEs can travel around the wrist to display information to the user. While the current prototype does not have a coordinated graphical display or touch sensing, those could be added as for the mobile device.

Technical Evaluation

The prototype runs at 1.1V and draws a steady 0.5 A of current per RTME, regardless of whether the RTME is moving or stationary. RTMEs can be actuated at speeds up to 80 mm/s. An individual RTME can be positioned to a resolution of $\approx$1 mm. Because of magnetic interactions between RTMEs in close proximity, a minimum separation of 15 mm is required between adjacent RTMEs.

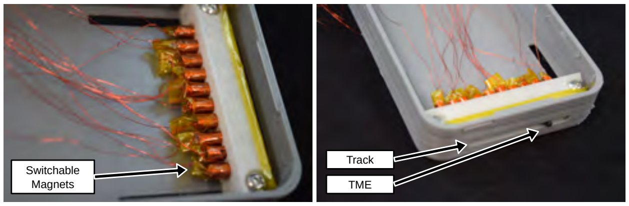


Figure 10: A prototype system utilizing a switchable permanent magnet drive.

SWITCHABLE PERMANENT MAGNET SYSTEM

In many applications, RTMEs remain in static positions for significant periods of time. With our current design, holding this position requires continuous power. To demonstrate an alternative design with greater power efficiency, we prototyped a second version of the system (Figure 10) which leverages switchable electromagnet actuators to generate the magnetic field. We use a magnet design similar to that described by Strasnick and Follmer, with Grade 6 AlNiCo magnets wrapped in a solenoid [31]. Because of the low coercivity of the AlNiCo magnet, when current is briefly pulsed through the wire, the polarity of the magnet is permanently changed. This allows us to maintain an attractive force on the RTME without continuous power.

We use the same N52 neodymium magnets for the RTMEs. Switchable permanent magnets are lined up along the edge of the device (Figure 10). Each AlNiCo magnet is wound with $N = 140$ turns of 36 AWG wire, yielding a radius of 1.9 mm. Rather than traveling directly atop the AlNiCo magnets, RTMEs travel along a spacing surface. The width of this spacer (2.275 mm) was chosen to be thick enough for the AlNiCo magnets to switch easily in the presence of the RTMEs magnetic field, yet thin enough to still impart significant forces on the RTME. As in the previous system design, we add a linear track to the outside of the case to additionally constrain the motion of the RTMEs.

We also use a similar PWM-based microstepping approach to generate smooth motion of the micro-robot. However, since we cannot interleave coils as in the flexible PCB variant, we utilize MOSFETs in an H-bridge configuration on each AlNiCo magnet to create variable strength attractive and repulsive forces (Figure 11). The combination of repulsive and attractive forces to create a motion vector is similar to the translation motion primitive described in [7]. Thus, when the magnet is moving, at most 2 AlNiCo magnets are being switched. When the magnet is at rest, power is completely disconnected.

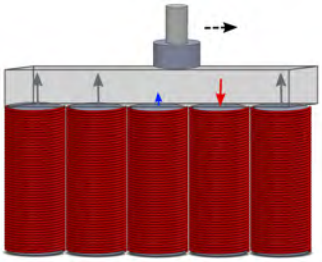


Figure 11: Microstepping a tactile micro-element towards the right across a surface by using switchable permanent magnet actuators. Grey arrows represent magnets which are not being switched, but remain in the maximally repulsive state. The blue arrow (an increasing repulsive force) and the red arrow (a decreasing attractive force) constitute the microstep.

Though the system operates at 29V to allow for large current spikes, these spikes are brief and infrequent, resulting in a low amortized current. 100uF capacitors are charged up and discharged when switching a magnet to prevent large current draws from the power supply. Our prototype was driven atwith a 100 μs pulse length and a PWM frequency of 500kHz, empirically determined to be the minimal pulse length to reliably switch the permanent magnet using our components.

Technical Evaluation

The switchable permanent magnet variation exhibits a linear average power response with respect to the traveling speed,

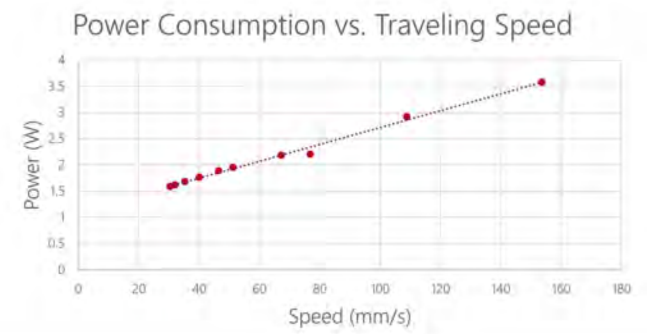


Figure 12: Average power consumption of the switchable permanent magnet variant while moving a single RTME, as a function of its speed.

controlled by adjusting the delay between microsteps (Figure 12). While the system draws more power when moving RTMEs than the coil-based prototype, we can amortize its cost over time spent with RTMEs in a static position to find a break-even point at which the switchable permanent magnet variation becomes efficient. Examining the single RTME case, let T_m be the time spent moving the RTME, and T_s be the time spent with the RTME stationary. P_s is the power consumption for a stationary RTME, P_m is the consumption for a moving RTME, and P is the total power consumption. Then:

$$P = \frac{P_s * T_s + P_m * T_m}{T_s + T_m}$$

For the PCB-coil version, $P_s = P_m = 0.55W$. For the switchable permanent magnet variant, $P_s = 0$, and P_m is a function of v, the traveling speed of the magnet in mm/s: $P_{m[switch]} = 0.0161v + 1.109$ Setting these equations equal for the two prototypes, and substituting in the empirically measured power consumptions, we can determine the point at which the switchable magnet variation becomes power efficient:

$$\frac{T_m}{T_s + T_m} = \frac{0.55}{P_{m[switch]}} = \frac{0.55}{0.0161v + 1.109}$$

This equation shows the break-even percentage of time spent moving for power consumption between the two systems, as a function of the speed of the switchable magnet variation. That is, if the RTME is moving for more than $\frac{0.55}{P_{m[switch]}}$ of the total time of operation, then the switchable permanent magnet version is more power efficient. The break-even ratio is plotted as a function of speed in Figure 13. For example, at a speed of 50 mm/s, the switchable magnet variation is more efficient if the RTME is moving less than 28.7% of the time. This implies that the ideal drive mechanism (from a power perspective) is dependent upon the characteristics of the target application. A technical comparison of the two prototypes is presented in Table 1.

APPLICATIONS

The proposed RTME interface enables a wide range of mobile interactions that can leverage dynamic interface elements, tactile notifications, and rich haptic feedback. Here we describe a number of applications, see examples in Figure 14, primarily for the mobile device with integrated Reconfigurable RTMEs, though many could be extended to a wearable band style device as well.

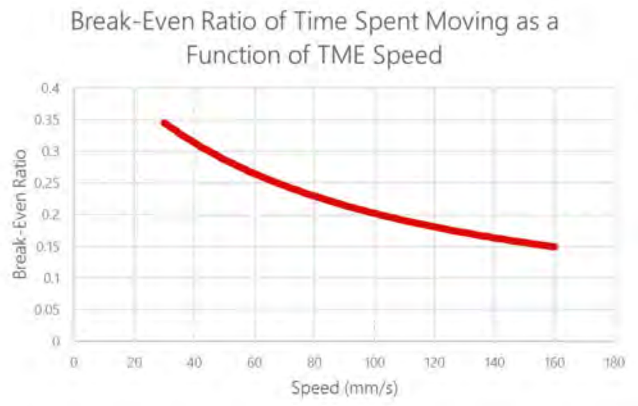


Figure 13: The fraction of total operation spent moving a RTME below which the switchable permanent magnet system is more power efficient than the micro-coil version. This break-even point is lower when moving the magnet at greater speeds on the switchable magnet system.

	PCB Micro-Coil	Switchable Magnet
Depth*	0.125 mm	9.9 mm
Flexibility	Yes	No
Power (stationary)	0.55 W	0 W
Power (moving)	0.55 W	0.0161v + 1.109**
Maximum speed	80 mm/s	160 mm/s
Maximum lateral force	<1 g	<1 g

* Protrusion into device, RTME not included
** v is the speed of the RTME in mm/s

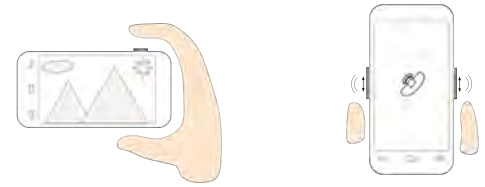
Table 1: Comparison between the two implemented RTME interface prototypes. Power consumption is per RTME.

Context-Specific Controls

Physical controls have a number of advantages over touchscreen interactions in many applications. As an example interaction, when the user starts a game on the mobile device, two shoulder buttons emerge to become the interface elements (See Figure 15). The elements could also dynamically move in correspondence with game elements, such as acting as physical paddles in a game of Pong.

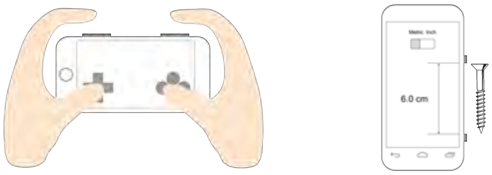
Self-Adjusting Interface Elements

Interface elements can adjust to accommodate new modes or states. For example, when the user opens a camera application, a physical shutter button appears, to allow the taking of photos without the need to locate a graphical button on the screen. Further, when the device is rotated, the button can adjust to ensure that the control always remains in the user's preferred position (e.g. top right). We can similarly have physical



(a) A physical camera button which adjusts according to orientation

(b) Haptic notifications which tap the user's finger during an alert



(c) Physical game controls

(d) Using a dynamic physical tool in the form of interactive calipers to measure the external world.

Figure 14: Example applications leveraging the RTME system.

scrollbars or other indicators which adjust to render the state of the application.

Increasing Effective Screen Space

Because of their small size, mobile devices have limited space for interaction. In particular, interface elements rendered on the screen can subtract from real estate otherwise used for display, since the display is necessarily occluded by the user's hands when they interact with on-screen controls. By creating controls on the sides of the device, we can free up the entire screen for display, and enable interactions without occluding the screen. For example, we can provide a video player which has a scrubber/playback slider on one side of the device, and volume controls on another side. This allows the video to play in full-screen without GUI elements. Figure 16 shows a scrollbar RTME that moves with the current document position.

Rich Haptic Notifications

There are numerous situations in which users cannot necessarily devote their visual attention to their mobile device, e.g., due to safety (e.g. while riding a bike), inappropriate for social reasons (such as at a dinner or in the cinema), or due to lighting conditions (strong sunlight). In such cases, we can convey notifications and other information haptically, such as representing unread notifications as the number of tactile elements lining the side of the device, or by altering their position, as shown in Figure 17.

LIMITATIONS AND FUTURE WORK

Though the use of magnetic actuation has numerous advantages, our current designs do have some limitations.

While our system is significantly more power efficient than traditional shape displays, power consumption could be further optimized to increase suitability for mobile and wearable devices. The thin, flexible micro-coil version uses power not only to move the RTMEs, but also to keep them in a steady state.

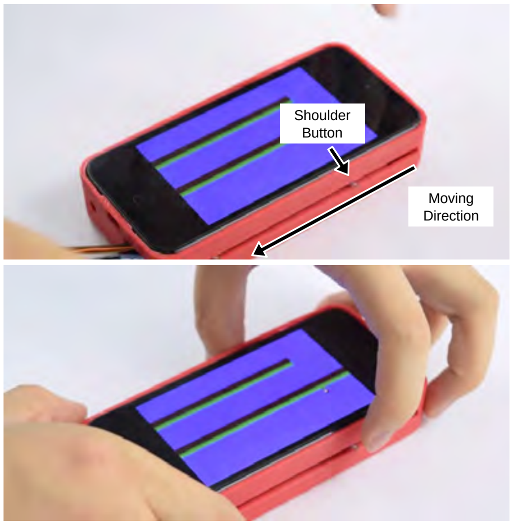


Figure 15: Two tactile micro-elements appear as dynamic, physical shoulder buttons with touch input for a mobile video game.

Figure 16: A tactile micro-element represents the current position while scrolling through a document. Touching the element bookmarks the position

We envision adding a mechanical clutch to lock all RTMEs in their current location at once, allowing us to effectively unpower all but the sensing subsystems while the RTMEs are stationary. Rather than completely locking the elements, the clutch could provide a high friction force, holding the RTMEs in place while still allowing users to reposition them for input. Another approach would be to add ferromagnetic material beneath the PCB, such that the RTME is passively attracted with a normal force, even when power is not supplied.

The system is currently limited to low forces, which precludes more advanced haptic interactions with the ability to apply larger force to the user's fingers. The use of electro-permanent magnets [19], which are similar to our bistable magnets but can generate higher magnetic fields (at the cost of the ability of changing polarity), could allow us to generate stronger forces. In addition, with our current implementations, when a user places the device into a pocket, the RTMEs would likely be dislodged from their target positions from strong contact forces. By implementing closed-loop control, we could potentially

Figure 17: A tactile micro-element changes position based on the number of e-mails available for subtle, tactile notifications.

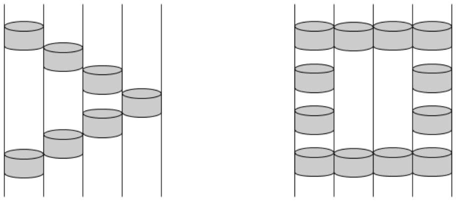


Figure 18: Future iterations could combine multiple rows of RTME tracks to allow for the display of more complex shapes, such as these playback controls.

detect these unintentional movements and return the RTMEs to their previous positions when the resistance is removed.

As previously described, the neodymium magnets require a minimum separation to maintain stability, which prevents current applications from having several RTMEs in close proximity. When RTMEs approach a certain distance, they snap together and need to be mechanically separated as the system's dynamic magnetic fields are not strong enough to pull apart the strong N52 magnets. We are currently exploring magnetic shielding materials on the exterior of the RTMEs. While our early efforts significantly decreased the minimum separation, shielding adds additional weight to the RTME, and thus additional tuning of the dimensions and materials is required to maintain the performance of the system. Future versions could also introduce a small linear actuator with a simple wedge to separate RTMEs, thus allowing for different lengths of RTMEs to be ejected. Currently, there is also a limited number of RTMEs that can be stored in the "hidden" state, due to the minimum spacing required between RTMEs. Further sophistication of the reservoir where the RTMEs are stored is needed.

Magnetic fields external to the device could interfere with normal operation, and the magnetic activity from the device could also cause problems for other magnetically sensitive devices, such as a magnetometer or credit card. In simulations using our neodymium magnets, we find that the problematic distance at which demagnetization of a standard credit card becomes likely is far less than the minimum possible separation (due to the casing of the device). However, since we have not tested these effects directly, they remain an open concern.

An additional technical issue arises due to eddy currents generated within the neodymium magnet. As the micro-element moves through a magnetic field, the induced current causes heating, which can become problematically hot over long periods of operation in our current prototype. In addition to damaging other internals within the device and possibly causing harm to the user, a RTME left in a high-temperature state for too long could lose its magnetization. This issue can be addressed by refining our choice of magnet. An RTME consisting of a laminated magnet or a magnet with a high electrical resistance would have significantly reduced eddy currents.

Furthermore, our use of a single soft potentiometer for registering input precludes us from recognizing multi-touch input. This means that multi-touch techniques (such as pinch input) require additional sensing. While we are currently using the system in an open loop configuration, we envision that a hall effect sensor array would improve performance and also make the system more robust to disturbances. Using a pressure-sensitive soft potentiometer, we hope to enable multi-stage touch interaction. For example, in a camera shutter application, a light touch on the RTME could initiate auto-focusing and illumination, while a solid press would then take the photo.

There are also limitations inherent to RTME interfaces in general, one of which is the inability to instantaneously "display" a RTME. Unlike the rendering of a pixel, the RTME takes a finite time to travel to its intended location. In a 1D implementation this poses a critical path planning problem if there are heterogeneous RTMEs. In addition, it could be hard for a user to discriminate between preparatory motion of an RTME into position and intentional motion for display. By better utilizing (or increasing) the thickness of the device, we can implement parallel rows for RTME display. With an added method of changing tracks, we could move RTMEs into position along the hidden tracks, then bring them to the surface for interaction. In addition, this would create a 2D tactile display along the edges of the device, enabling the rendering of more complex shapes. For example, in a music player application, the play, fast-forward, and rewind functions could be rendered as tactile shapes, that could be recognized via the sense of touch, (see Figure 18).

CONCLUSION

We have presented a novel approach to mobile and wearable haptics in the form of the Reconfigurable Tactile Micro-Element Interface, which seeks to augment existing devices with dynamic physical controls and feedback, without altering the existing form factor. We have shown two possible implementations of such a system, and discussed their technical tradeoffs and limitations. We have also explored the design considerations for interactions of a RTME Interface, and presented a number of example applications which leverage the advantages of dynamically reconfigurable tactile micro-elements on a mobile device.

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