TacTiles: Dual-Mode Low-Power Electromagnetic Actuators for Rendering Continuous Contact and Spatial Haptic Patterns in VR

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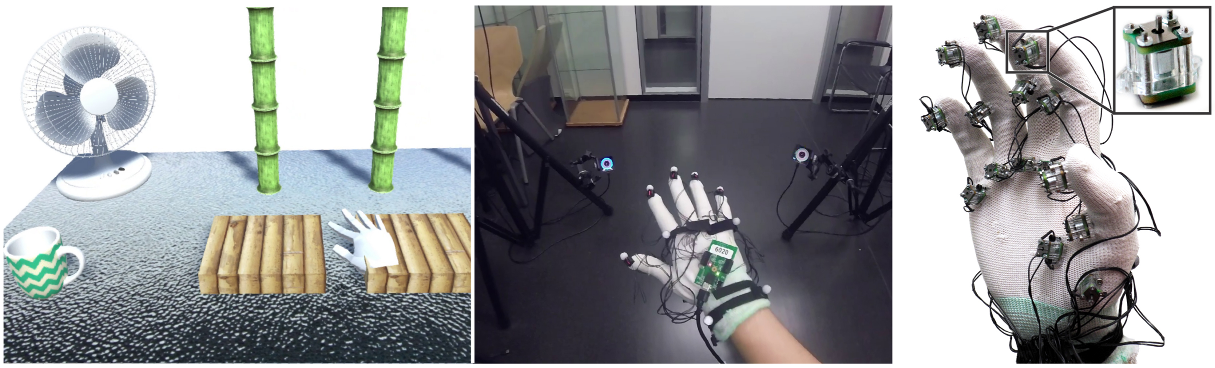

Figure 1: TacTiles are small and light form factor tactile elements that can be placed anywhere on the hand to render contact with virtual objects and enable haptic surface exploration. An individual TacTile is able to produce 200 mN of holding force on the finger without any power draw and is dampened on one side to minimize release vibrations.

Abstract

We introduce TacTiles, light (1.8g), low-power (130 mW), and small form-factor (1cm^3) electromagnetic actuators that can form a flexible haptic array to provide localized tactile feedback. Our novel hardware design uses a custom 8-layer PCB, dampening materials, and asymmetric latching, enabling two distinct modes of actuation: contact and pulse mode. We leverage these modes in Virtual Reality (VR) to render continuous contact with objects and the exploration of object surfaces and volumes with spatial haptic patterns. Results from a series of experiments show that users are able to localize feedback, discriminate between modes with high accuracy, and differentiate objects from haptic surfaces and volumes even without looking at them.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction devices—Haptic devices; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality;

1 Introduction

When interacting with objects in real life, we make use of our sense of touch to recover properties such as objects' shape, size, and texture [10, 21]. Allowing for similar haptic-based scene exploration in Virtual Reality (VR) is desirable as it can increase realism [13] and enhance our interactive capabilities [12, 14]. In particular, we seek to leverage the Palmar surface of the hand which contains the highest density of touch receptors [15] and is the most natural place to provide tactile feedback.

Designing a hand-based cutaneous feedback system for use in VR poses significant challenges as it must be i) *wearable* – to allow the hand to move freely and to ensure skin conformity, (ii) *high-fidelity* in terms of density and the ability to render different modes of actuation (e.g. contact events and continuous touch) and yet (iii) *low-power* – to prevent overheating during frequent actuation typical in VR. Even at the single actuator level, these design challenges are at odds with each other, and become even more complex to integrate in a system designed for the whole surface of the hand.

The most common actuator design is based on vibrotactile feedback such as those built into VR controllers (e.g. Oculus Touch) and in a glove form factor such as the Cybertouch [6] and the Hi5 VR Glove. However, as vibrotactile feedback is only able to stimulate high frequency mechanoreceptors [15], it can not convincingly render discrete touch events or the continuous sensation of touch required for high-fidelity and localized feedback.

Increasing fidelity is possible by using mechanically-driven tilting platforms and high resolution pin arrays [1, 25, 31]. More complex actuators, however, make it difficult to integrate and place them flexibly around the hand. Another strategy is to use simple actuators with external driving mechanisms, for example using servo motors [32], or pneumatic inflation [11]. This allows the integration of multiple actuators on the hand, however, at the cost of additional bulky hardware which limits freedom of movement in VR. More recently, actuators have been proposed based on electromagnetic latching [27] and direct electrotactile stimulation [35]. While these devices present promising developments, they must carefully balance power-draw, force-generation capabilities, and skin conformity in order to avoid overheating during demanding VR usage.

To address the diverging requirements of form factor, power envelope, and rendering fidelity we propose a novel type of multi-mode actuator, called TacTiles, which can be placed anywhere on the hand, and comes in a form factor and power envelope which is closer to current vibrotactile actuators. Each TacTile is self-contained and includes the actuation mechanism capable of rendering discrete contact events, continuous contact, and short high-frequency bursts. This allows an array of TacTiles to seamlessly transition between object surface exploration and object enclosure in a single interaction.

Similar to our earlier work on MagTics [27], TacTiles utilizes a bi-stable electromagnetic latching mechanism, but takes up half the physical space and reduces power consumption by a factor of four, while maintaining a high holding force of 200 mN. This is enabled by a novel hardware design consisting of 4-layer latching plates

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and custom-designed 8-layer printed circuit boards (PCBs). The small form factor (1 cm^3) and low weight (1.8 g) of the actuators allows for denser and more flexible arrangements on the hand. The low power consumption (130 mW on average, pulsed activation at 5 V and 3.6 A) allows for continuous activation without overheating, which in turn enables the actuator to render a high dynamic range of frequencies. To avoid undesired haptic sensations from actuator recoil when disengaging (e. g. releasing contact with a virtual object), we furthermore propose adding dampening material into the magnet chamber which drastically reduces the perceived recoil. We experimentally show that the dampening is effective across a wide frequency band.

These results are used to build a 15 actuator array of TacTiles, which is mounted on a glove and tested under various scenarios including discriminating haptic pattern frequencies and haptic surface and object exploration in VR. We experimentally confirm that users can discriminate the location and mode of individual TacTiles with an average accuracy of 78.7%. Furthermore, we show that participants can discriminate the frequency of different haptic patterns with a just-noticeable-difference of 6% on average. TacTiles enable a wide range of applications, which we show in a first experience test in VR. When users were shown multiple different haptic patterns and objects for exploration, they were able to discriminate objects from haptic patterns, different patterns, and could detect objects on virtual surfaces even without looking at the objects.

2 Related Work

We focus on wearable tactile feedback devices most relevant to TacTiles. For a full review of haptic devices designed for AR and VR, we refer readers to the work of Bermejo et al. [2].

Wearable vibrotactile displays. Wearable haptic devices are a natural fit for VR as they are always-available and at the user's fingertips. The most commonly used haptic technology in such devices is based on vibrotactile actuators which can render contact on different parts of the hand [6, 22] and are common in commercial gloves designed for VR [24, 29]. Vibrotactile feedback harnesses the piezoelectric effect to efficiently convert electrical current into vibrating mechanical energy. However, such feedback is primarily capable of stimulating Pacinian mechanoreceptors responsible for high-frequency sensations [15]. While vibrotactile actuators lack the rendering fidelity to create a sensation of localized touch, they are well suited to rendering textures which have natural vibratory patterns [4]. Recent advances in asymmetric vibrotactile actuation allow rendering directional cues on the fingertips [5, 19, 30]. An important design goal of TacTiles is to retain the small form-factor and power-envelope of vibrotactile actuators, while expanding on the types of modes it can render.

High-fidelity haptic feedback. Several types of haptic devices for VR have been proposed to increase fidelity. The high receptor density of the fingertips makes them an ideal place for high resolution feedback [16]. Benko et al. proposed two devices, *NormalTouch* and *TextureTouch* based on a handheld mechanically-tilting platform and a 4×4 articulated pin array respectively [1]. They found that both platforms increased tracing and pointing task accuracy, however, the high resolution pin-array did not perform better than the tilting platform. Whitmire et al. [34] proposed an articulated and interchangeable haptic wheel that could accurately render 1D shear forces. Surprisingly, they found that wheel spin direction had little impact on realism. Multi-DOF devices have also been proposed in a more wearable form-factor where the articulated platform is driven by small motors mounted on top of the finger [18, 25, 31, 37] and are capable of rendering contact angles and varying degrees of pressure to the fingertips. These devices are typically characterized by mechanical actuation and because of their form-factor, are not designed to cover arbitrary parts of the hand.

Integrating tactile feedback on to the whole hand can also be accomplished by offloading the driving mechanisms. Son and Park [32] proposed a tactile device to provide feedback at 10 locations on the user's palm, however, it requires attaching the relatively large motor-pack directly onto the user's hand. Gloves based on pneumatics use valves to activate tactile pixels on the hand [11]. However, these require complex routing and pumps to activate which may limit wearability. Since each TacTile is designed to be a self-contained unit and does not require surface area beyond its immediate footprint, it can be placed anywhere on the hand without restricting range-of-motion. When configured in such an array, TacTiles can provide higher fidelity localized feedback to render interactions such as object enclosure and surface exploration.

Low-power actuation mechanisms. Power draw is crucial in the context of VR, where activations are frequent and sessions can last a long time. Therefore, we consider two actuation technologies with low-power draw, but with the potential to render multiple modes of actuation: electrotactile and electromagnetic.

Electrotactile actuation directly stimulates mechanoreceptors in the hand to render touch in VR [14, 37]. To be most effective, such devices require high conformity to the skin and typically use clipping systems that limit placement to the fingertips. Recent work has addressed this problem by embedding electrotactile tactors in a flexible substrate [35] that can adhere to the skin. Rendering continuous contact with electrotactile actuation is still problematic as it requires a constant power-draw. Yem et al. also found mechanical skin displacement to be a better approximator of properties such as hardness and macro roughness [37].

Electromagnetic actuation was used by Yang et al. in a 3×3 tactile array driven by embedded solenoids and returned to resting states by springs [36]. The measured force output was rated at 5.6 mN which is an order of magnitude less than TacTiles. It also requires continuous power output to provide feedback. Improving on this design, Pece et al. proposed MagTics, a flexible tactile device using a bi-stable latching mechanism that provides continuous force output without the need for further power [27]. Despite many appealing properties, the device cannot sustain continuous usage in VR due to its power draw of 140W per activation. In addition, when disengaging from the skin, the bi-stable actuator causes an unwanted haptic vibration as the pin hits the wall of the chamber. More recently, Duvernoy et al. showed a stationary conformal haptic interface interface using a braking mechanism based on magnetic force repulsion [8].

We base the core design of a single TacTile on the power-efficient MagTics actuator, but make key improvements by significantly reducing power consumption, adding damping to reduce unwanted feedback, and reducing the size, thus enabling a multi-mode actuator that is suitable for continuous and demanding use in VR.

3 System Overview

The aim of our work is to provide a tactile feedback system for VR that is capable of rendering realistic tactile information when touching virtual shapes and exploring object surfaces. Given the design considerations of *wearability*, *high-fidelity*, and *low-power*, we select the bi-stable electromagnetic latching actuator used in MagTics [27] and make several key improvements that significantly decrease it's form-factor, harness the full mode capabilities of the actuator, and lower its power usage by a factor of four. We further integrate 15 of these actuators in a dense arrangement on a textile glove, exploiting a large part of the Palmar surface of the hand. Together, these improvements enable it's use under high-stress and continuous usage scenarios in VR and open up new types of interaction. The proposed system called TacTiles, is shown in Figure 2.

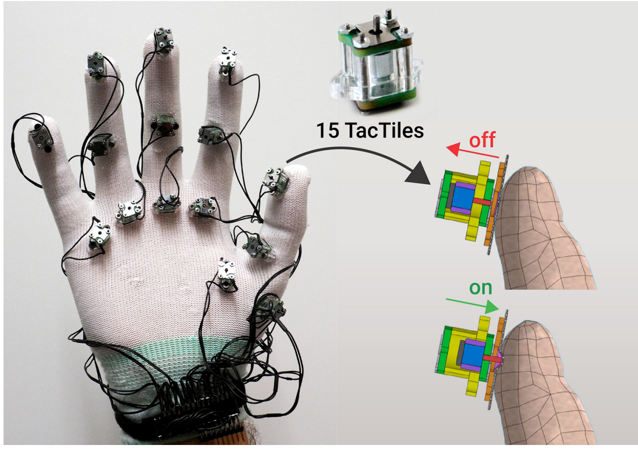

Figure 2: The final array of 15 TacTiles mounted on a glove. Each actuator can be controlled individually, rendering a haptic sensation by making contact to the skin with a retractable pin (red).

3.1 Principle of Operation

We employ the same principle of operation as MagTics, which is based on a bi-stable electromagnetic latching mechanism. This consists of a moving permanent magnet switching between two stable positions via application of short pulses of electrical current (see Figure 3.b). The magnet moves inside a cylinder, covered by coils on a PCB to deliver the switching impulse. The magnet stays in any of the stable positions due to attraction to the latching plates mounted in parallel to the PCBs. Once latched, the mechanism consumes *no further power* until switching again. The magnets are laterally shielded to avoid the magnetic cross-talk between neighbouring actuators. A pin attached to to the magnetic side facing the skin can transmit the movement and deliver contact/no-contact sensation to the user. The original design achieved a holding force of up to 200 *mN* with a stroke of 2 *mm*, values that were shown to provide a convincing and distinguishable tactile feedback [27].

3.2 Design for VR

The design in MagTics has several drawbacks that limit its applicability to fine-grained VR interaction, which we overcome in this paper. First, 140 *W* of pulsed power were required over a time span of 20 *ms* for switching. This large amount of Joule heating limits the switching frequency, as the heat is accumulated faster than the device can dissipate it. This limitation renders active surface and texture exploration infeasible, which requires high-frequency and continuous activation. Second, the symmetric by-stable design leads to strong sensation during both engagement and disengagement with the skin. In our preliminary tests, we found that this is perceived as highly unnatural. It is therefore desirable to have strong impact force but no sensation during disengagement. Finally, MagTics require a pitch of 1.7 *cm* between actuators, making it difficult to arrange them densely.

We alleviate these main limitations of MagTics through 1) asymmetric latching, 2) smaller form factor, 3) new electronic PCBs consuming far less power, resulting in less heat, 4) faster fabrication and much easier assembly and re-configuration, 5) a damping mechanism to reduce feedback during disengagement.

The resulting improvements allow TacTiles to perform an average of 120 switches per minute without overheating, enough for demanding VR interactions such as exploring a haptic surface. TacTiles can also be activated in short bursts of 50 *ms* at up to 200 *Hz*, giving it a wide dynamic range. Asymmetric latching and damping address the unwanted sensations when disengaging from the skin. The reduced form-factor enables denser arrays allowing for glove integration.

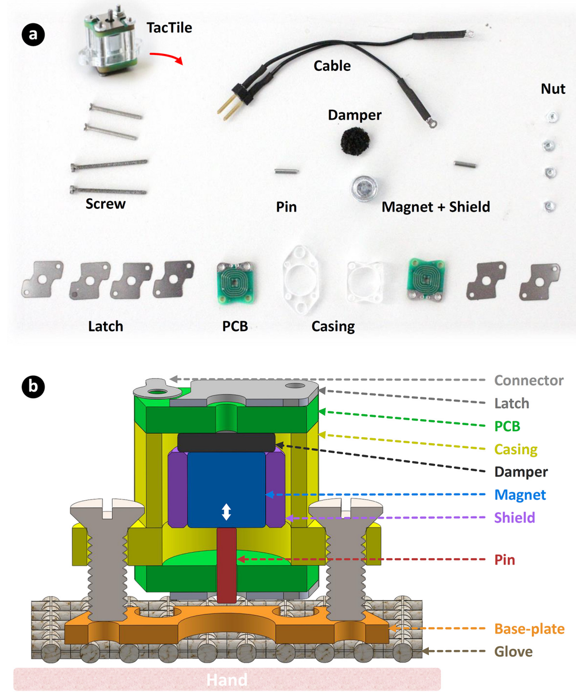

Figure 3: TacTiles parts and structure. A) Pre-assembly view of the TacTiles parts and B) schematic of TacTiles assembly.

4 Hardware Design

4.1 Materials and Assembly

TacTiles are haptic feedback cells designed to be created with a simple and reliable fabrication process. They only require parts that are readily available (e. g. in modern FabLabs), shown in Figure 3.a. Latching plates are made from low carbon laser-cut steel and plastic parts are made of laser-cut acrylic (PMMA). Screws, nuts, pins, magnets and shields are standard elements and the PCBs can be ordered online. The PCBs are symmetrical and electrical contacts are established by exerting pressure only. This allows for quick assembly, reconfiguration and tuning of parameters (e. g. adding PCB layers to increase latching force).

4.2 Form Factor

While actuators need to be compact, the force provided by electromagnetic actuators scales with the volume of the magnet. This leads to a trade off between actuator size and perceived force.

To achieve a higher actuator density while maintaining a high force profile, we reduced the footprint by 41.6%, compared to MagTics. By employing a PCB technology with thicker and larger number of layers, we were able to improve the power consumption and make the coil more compact. A single TacTile measures 8×9.5 *mm* (i. e. footprint of only 71.5 mm^2). Using mostly plastics reduced its weight by 45.5% to 1.8 *g*. This weight reduction is crucial for comfort when the actuators are worn on the fingertips with no perceivable sagging of the glove's fabric even when the user's hand is facing down.

4.3 Power Envelope

While bistability allows persistent haptic contact/no-contact sensation without drawing power, power consumption during switching must be low enough to allow switching at higher frequencies without failure due to excessive heating. Our design only requires a square voltage pulse of maximum 5 *V* and 10 *ms* to switch the actuators, depending on travel time and travel distance. *Once latched, the* *actuator does not consume any power*. The power consumption is further improved by leveraging a denser PCB design, composed of six 105 μm thick copper layers inside and two 75 μm thick copper layers above the PCB. Each layer contains five turns of 220 μm wide tracks. Compared to MagTics, we thus increase the amount of copper per PCB by 390%. However, the PCBs' total thickness increases only from 1.2 *mm* to 1.4 *mm*. As a result, the new PCBs have twice as many turns while having the same total electrical resistance of $1.38 \pm 0.1 \Omega$. Our design is 7 times more power efficient and requires pulses of only 18 *W* to switch reliably, compared to 140 *W* reported for MagTics. During our user studies, we recorded a mean rate of 44 switches per minute in each actuator. This represents an average power of only 130 *mW* on each TacTile under usual operation and thus a large reduction in heat generation (see Section 5.2).

4.4 Asymmetric Latching and Damping

Touch interaction in VR can be broken down into three separate events that the user feels: 1) the initial contact, 2) the continuous sensation of pressure on the finger, and 3) disengaging from the object. In the real world, we naturally integrate these three events. At each stage there is a particular expectations as to how they feel. For example, when sliding the finger over an object we expect to feel pressure, whereas on object release, we expect minimal output (unless the object surface is sticky). When designing our actuators for VR gloves we experimentally found that during the actuator recoil, the vibration created by the magnet latching to the 'off' state may be perceived as an additional impact, leading to an unnatural sensation when releasing contact with virtual objects. We therefore introduce an asymmetric latching mechanism, that can maintain force generation on the skin, while reducing the recoil sensation. We found that an asymmetric latching plate of 400 μm thickness on the side facing the skin, and of 200 μm thickness respectively, gave the best results in terms of force generation, i. e. a strong contact force while maintaining a soft landing when retracting the actuator. When the magnets hits the PCB it produces an acceleration peak of 10 g, followed by a phase of magnet bounce, which is perceived as high frequency vibration (Figure 4). Adding dampening materials between the magnet and the 'off' latching plate drastically reduces this effect (Figure 4, dotted green and orange line).

4.5 Modes of Actuation

Due to its ability to provide actuation with high frequency, we propose two different modes of actuation. In *contact mode*, the pin of an actuator moves towards the skin until it makes contact, i. e. the skin gets stimulated directly by the pin. From our damping tests, we know that this requires a movement time of 6 *ms* (see Figure 4). The pin then rests on the skin (using the bistability of the device) until disengagement is triggered (e. g. a user ending a collision with a virtual object). In *pulse mode*, the pin moves towards the skin for only 3 *ms*, and then retracts immediately. Therefore, while users feel a pulse, the skin is not directly stimulated by the pin but the indirect movement of the whole actuator. This is comparable to the haptic feedback of piezo actuators, but only a single vibration. Pulse mode can also be fired in successive fashion using a 2 *ms* pulse towards the skin, and a 3 *ms* pulse in the reverse direction to render vibration sensations. In our experiments in VR, we use the *contact mode* for rendering collisions with objects and the *pulse mode* for rendering spatial haptic patterns.

4.6 Integration of the Actuators into a VR Glove

Compact and lightweight actuators are the first step towards a comfortable haptic glove. Electromagnetic actuators must also be able to be placed arbitrarily in order to coincide with areas of high mechanoreceptor density on the user's hand. We hence chose to forgo a monolithic approach in favor of a distributed, reconfigurable array of actuators. Based on the work by Murakami et al. [23], we

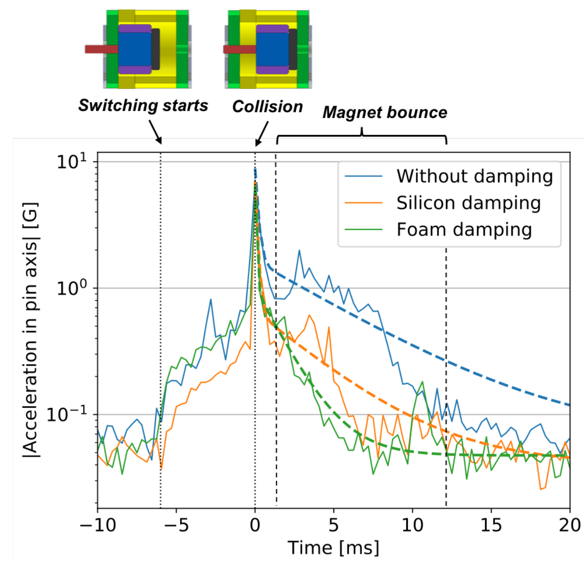

Figure 4: Acceleration switching profiles with and without damping (log-scale). Each curve is the average over 20 switches measured with an accelerometer *ADXL345*, previously aligned in the time domain. At time = 0 the magnet hits the 'off' state (max acceleration due to the collision $10g$). Dashed lines show exponential decay fit (see text).

choose the most relevant locations to provide tactile information when manipulating objects, as shown in Figure 2. These locations cover the five fingertips, four intermediate phalanges (little finger excluded), five palm locations close to each finger (reverse of each knuckle), and the exterior of the palm below the thumb. We use a commercial textile glove as starting point for our system and glue a 2 *mm* thick base-plate with 2 threads to the textile in the desired locations. This way, the actuators can be mounted quickly by simply screwing them onto the base-plates (see Figure 3).

5 System Evaluation

We evaluate key parameters of the hardware design: the effect of additional dampening, and the thermal behaviour of the actuators.

5.1 Effect of Damping

During switching, the magnet is accelerated from being in contact with one latching plate to the other (2 *mm* travel distance). Due to the high acceleration, the magnet bounces and generates high-frequency vibrations which are perceived as being unnatural. We evaluated different damping materials to alleviate this effect. We compared discs of 5 *mm* in diameter and 1 *mm* thickness made of two different materials: PDMS silicone and foam. We expect that silicone will present an elastic bounce combined with damping, while for the foam we expect the damping to be the dominant.

To experimentally verify the accelerations during switching, we attached differently damped TacTiles to a one meter long pendulum of 40 *g* mass with an accelerometer *ADXL345* attached to it. We sampled the acceleration at a rate of 3200 *Hz* over 20 switches. Figure 4 shows the acceleration profile for the three different cases over time: no damping, silicone damping and foam damping. The time axis (t) was offset so the collision with the latching plate corresponds to 0 *ms* (maximum acceleration). The acceleration axis is in log scale. Two regimes can be distinguished: a switching period from $t = -6$ *ms* up to the collision, and a second period of magnet bounce from $t > 0$ until it reaches the resting position. We observe that the vibrations during the bouncing period decay much faster in the case of using damping compared to the baseline. Furthermore, foam appears to be more promising since the accelerations decay fastest. An exponential decay fit (dashed lines) confirms this: $\tau_{no-damped} = 5.9$ ms; $\tau_{silicone} = 4.1$ ms; $\tau_{foam} = 1.8$ ms. Based on this result, we built our VR glove with 15 TacTiles using foam as damping material.

5.2 Experimental Test of Heat

The Joule heat generated on electromagnetic actuators is a well known limitation when using them intensively. TacTiles benefits from the latching mechanism that requires only power for switching, added to the improved coil design described in Section 4.3. We measured the actuator heating under an intense switching rate to test the thermal behaviour of the device. Figure 5 shows the temperature as a function of time when read from a thermocouple placed between the latching plates and the PCB of the device. For this experiment we switch the actuator continuously for 6 minutes at 2 Hz (average power $P_{av} = 0.36$ W). Then we let the device cool down under natural convection with no power applied. The curve of temperature vs. time is well described by Newton's law of cooling and its heating equivalent,

$$\begin{aligned} T_{heating}(t) &= T_{room} + \Delta T_{max}\left(1 - e^{-(t-t_0)/\tau_{therm}}\right) \\ T_{cooling}(t) &= T_{room} + \Delta T_0\, e^{-(t-t_0)/\tau_{therm}}, \end{aligned}$$

where T represents temperature and t time. These equations describe how temperature rises and decreases always with a characteristic time τ_{therm}. The asymptotic value of the temperature reached in 3 to 5 τ_{therm} is proportional to the average power applied, that means $\Delta T_{max} = c * P_{av}$. According to the measured values $\tau_{therm} = 102 \pm 5$ seconds and $c = 69 \pm 10$ °C/W for our device.

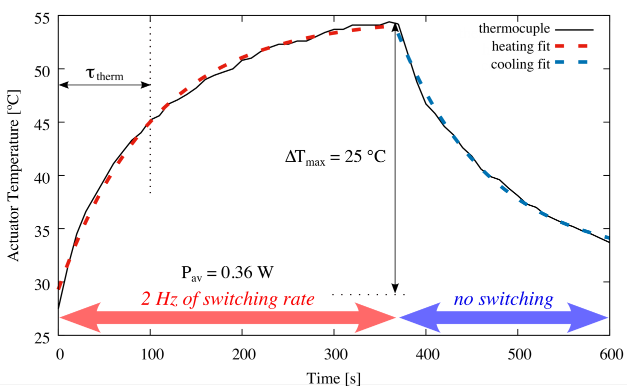

Figure 5: Heating (6 min at 2 Hz, red arrow region) and cooling temperature curve (blue arrow region) of a single TacTiles actuator. Dashed lines indicate the exponential fit according to the Newton's law of cooling/heating. We obtain the values $\tau_{therm} = 102 \pm 5$ seconds and $\Delta T_{max} = 25$ °C/W, when actuating with an average of 120 switches per minute ($P_{av} = 0.36$ W).

Thermally speaking, we can consider the actuator as a mass able to accumulate heat and then dissipated it into the environment. Only the mean power matters, i. e. the average number of switches occurred in the past 3 to 5 τ_{therm}. As shown in Figure 5, we can ensure TacTiles are kept in a safe temperature range if the average switching rate is below the 120 switches per minute (2 Hz). This does not impact the maximum speed of activation, which is constrained only by the amount of time required to move a single pin. For example, it is possible to render repeated *pulses* at up to 200 Hz in short 50 ms bursts on average every 5 seconds without overheating. For real-use testing, we recorded activations for each actuator on the hand during study 3, which constitutes a demanding haptic environment, and found that the actuators were on average switched between 38 and 49 times per minute. Using the upper bound, this can be translated in a temperature increase over room temperature of only $\Delta T = 10.1$°C. The increase in temperature was also not noticed by participants, likely due to thermal insulation from the glove. This shows that TacTiles are able to be go under intense use without any overheating problems.

6 User Evaluation

To better understand the efficacy of TacTiles and its possible applications, we conducted 3 studies with studies 1 and 2 focusing on quantitative aspects and study 3 exploring qualitative aspects. The studies were designed to answer the following research questions:

- **RQ1:** How well can participants localize individual actuators on their hand when using TacTiles?
- **RQ2:** How well can participants discriminate the two modes (i. e. contact mode and pulse mode) of TacTiles?
- **RQ3:** What is the *just noticeable difference* (JND) of frequency for spatial haptic patterns with TacTiles?
- **RQ4:** How well can participants perceive differences in *direction* and *frequency* between visual and corresponding haptic spatial patterns with TacTiles, and what is the effect this has on realism?

6.1 Study 1: Mode Discrimination and Localization

The aim of this study was to understand how well participants can 1) localize individual actuators on their hand and 2) differentiate between different modes of tactile feedback. TacTiles supports two modes of tactile feedback: direct skin contact (*contact mode*) and pulse without skin contact (*pulse mode*). For each actuation, participants were tasked to answer at which locations they felt the feedback, and which mode they felt.

6.1.1 Participants

We recruited 10 unpaid participants (age M = 28.3 years; SD = 3.1; 3 female) from the local university campus. 8 participants had used VR equipment before, 7 had experienced haptic feedback devices, based on self-reports. Each participant signed an informed consent form prior to the study informing them about the data we recorded and the possibility to interrupt or end the study at any time.

Figure 6: Apparatus for the study 1 and 2. *Left*: a participant in part 1 (localization and mode). They were asked to indicate the position and mode of the stimulus and not look at the device during actuation. *Right* shows a participants in part 2 (JND) wearing a VR headset.

6.1.2 Procedure and Tasks

The study was conducted in a quiet experimental room. Participants were equipped with the TacTiles glove on their right hand, shown in Figure 6 (*left*). They were introduced to the device and completed a short training. During the training, five individual TacTiles were actuated in both modes (i. e. 10 training trials). Participants were informed about the mode and were allowed to look at the device during actuation. During the study, participants wore noise-canceling headphones through which white noise was played. This was done to mask any auditory sensation of the magnetic actuators.

Participants were asked *not to look at the device* but an instruction sheet showing the locations of the individual TacTiles (Figure 6, *left*). Based on a predefined random order, individual TacTiles were actuated with a random mode. Participants were asked to state the location of the actuated TacTile and its mode. A trial consisted of rendering a single mode of feedback at one of 15 locations on the hand. Each mode was played back once at each location for a total of 30 trials per participant. There was no time limit set for answering, and participants could ask for an actuation to be repeated once. This experiment lasted approximately 15 minutes per participant.

6.1.3 Results

Participants were able to correctly identify the location and mode of individual TacTiles with an accuracy of 78.7% (*SD* = 11.2%). Looking at localization only revealed an accuracy of *M* = 87.7% (*SD* = 8.6%). Participants were able to discriminate the mode in *M* = 87.0% (*SD* = 7.6%) of trials. Figure 7 shows the results in more detail.

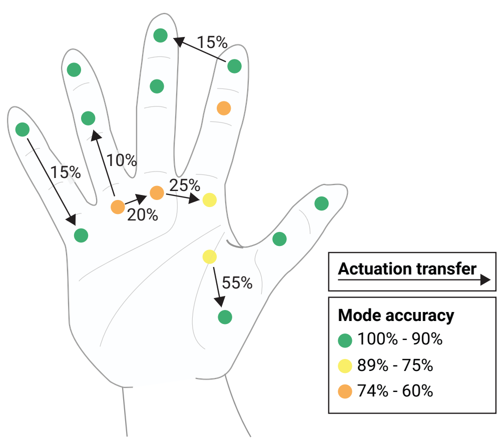

Figure 7: Breakdown of mode errors and localization errors. Colored dots indicate actuator positions and their mode accuracy. Arrows and number indicate how often an actuator (arrow start) was mistaken for another actuator (end arrow). Localization errors below 5% (i. e. 1 out of 20) were omitted from this figure.

6.2 Study 2: JND of Spatial Haptic Patterns

While several studies have been conducted to understand the influence of a single actuator on the perception of parameters such as softness (e. g. Perez et al. [28]) or edge sharpness (e. g. Park et al. [26]), we were interested in perceptual effects of our multi-actuator device. Specifically, we were interested in participants' ability to discriminate *frequencies* of different spatial haptic patterns.

6.2.1 Stimuli

We chose 4 different spatial patterns from literature [7] (see Figure 8) that were replayed to participants as long as they moved their hand over a virtual object. Each pattern is encoded in the time domain by setting the mode of each actuator to render a *pulse* at discrete time points. Although the participant moves their hand to trigger the patterns, each pattern is played back at a fixed speed to avoid the confounding variable of hand speed. This allows us to render haptic patterns on the hand in a repeatable and controllable manner (i. e. separate frequency and movement velocity). The presentation order of the patterns was counterbalanced using a Latin square.

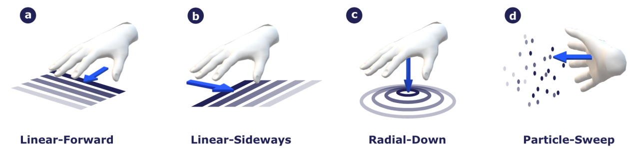

Figure 8: Spatial haptic patterns coupled to their respective hand movements: a) Linear pattern as the hand moves forward, b: Linear pattern as the hand moves sideways, c: Radial pattern as the hand sweeps down, c: Particle pattern as the hand sweeps sideways. Each line, ring, or set of dots is rendered once as it propagates through the hand. Opacity represents, i. e. lines rendered later are have less opacity.

6.2.2 Procedure and Tasks

In this second study, participants were wearing a VR headset and the TacTiles glove on their right hand, shown in Figure 6 (*right*). Since this study was conducted immediately after study 1, the same set of participants stayed in the same room and were given a new set of instructions and tasks. During the study, participants wore noise-canceling headphones through which white noise was played. Participants' hand posture and position was tracked using a Leap Motion controller that was mounted to the front of the headset. The experimental software was programmed in Unity 2017. The virtual environment consisted of two cubes with a side length of 30 *cm*, with a horizontal distance of 15 *cm*. When touching an object, a spatial haptic pattern with a specific frequency was played back. Participants were asked to decide which of the two objects exhibited a higher frequency. Based on pilot studies, we select the reference stimuli of the four patterns to be one second long in total. The line patterns (a and b in Figure 8) refresh five times during a stimuli, giving 5 Hz reference patterns. The radial pattern (Figure 8.c) refreshes 4 times, while the particle pattern (Figure 8.d) refreshes 10 times within a stimuli. This gives 4 Hz and 10 Hz of reference frequency for the radial and the particle patterns, respectively. In all cases, we chose a variable step size with an initial value of 5%. In each trial, participants touched both objects (i. e. experienced both frequencies). They were asked to move their hand across the objects to reflect the direction of the pattern, e. g. sweep from the back to the front of the object for the first linear pattern in Figure 8. For one object, the reference frequency was played back. For the other object, the approaching frequency was played back. Participants were unaware which frequency was used and were allowed to touch each object an unlimited number of times. The assignment of frequency to object was randomized every time participants provided an answer. The initial value for the reference frequency was always +15% of the reference frequency. We only used a positive values to decrease the total time needed for the experiment given that positive and negative JND approaches are typically symmetric [9]. After each trial, we asked participants to identify which of the two frequencies was perceived higher. A correct response brought the frequency in the next trial a step size towards the reference frequency, and vice versa [3]. The step size was decreased to 1% once participants hit an absolute delta of 5%. We chose this procedure in order to get higher accuracy after the initial approach. The procedure was repeated until the direction was reversed 3 times and the reversal points were averaged to get the JND of each pattern. The experiment lasted approximately 30 minutes per participant.

6.2.3 Results

Participants were able to adequately sense a difference in frequency of *M* = 6% (*SD* = 4.5%). Figure 9 illustrates the results. Note that lower JND is better. For the vertical and horizontal linear pattern, the JND was *M* = 6.2% (*SD* = 2.9%) and *M* = 6.0% (*SD* = 4.6%), respectively. The radial pattern exhibited the lowest JND, *M* = 3.2%

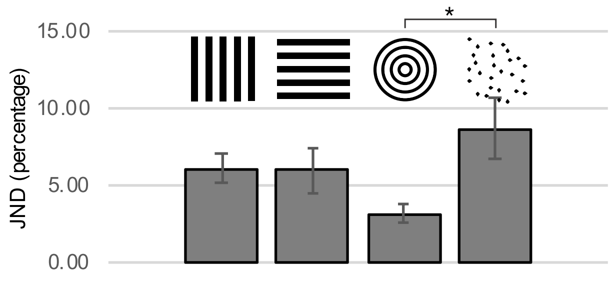

Figure 9: Results of the JND experiment. Error bars indicate standard error.

(SD = 2.1%). The particle pattern, exhibiting no distinct structure, had the highest JND of M = 8.7% (SD = 6.2%).

A Kruskal-Wallis test revealed a statistical main effect between the four patterns, $\chi^2(3) = 9.498$, $p = 0.023$. A series of post-hoc t-tests revealed that only the difference between the radial and the particle pattern was statistically significant, t=2.879, p = 0.04.

This shows that for distinct patterns (e. g. linear or radial), participant can distinguish very small differences in frequencies, and even for patterns that lack this structure, these noticeable differences are well below 10%.

6.3 Study 3: Experience Test

To gather more insights into the usage of TacTiles in VR, we performed an experiential study where participants were seated in front of a virtual desk (see Figure 10) containing multiple objects with different visual and spatial haptic patterns. We were interested in the realism of interactions when augmented with TacTiles, as well as the influence of spatial haptic pattern frequency and direction on the participant's sensation. We furthermore wanted to know participants reaction to the two modes and their combination in a single scene.

6.3.1 Participants and Apparatus

We re-invited 6 unpaid participants from the first study to participate (age M = 29 years; SD = 2.7; 2 female) in the experiential study. The study took place one day after the first. We decided against performing all 3 studies in one session to avoid fatigue.

In this study, we replaced the Leap Motion controller used for hand tracking with an OptiTrack setup (Motive:Tracker 2.1, 10 Prime3 cameras) to increase the hand pose tracking stability during 3D scene exploration. The TacTiles glove was augmented with 4 passive infrared markers and 5 active LED tags at the fingers to enable hand pose tracking. The coordinate systems were aligned via the built-in calibration procedure in the Motive:Tracker software.

6.3.2 Environment and Procedure

We designed a simple virtual environment (Figure 10) with 5 different types of objects: a table exhibiting a particle type haptic pattern; 3 bamboo segments and 3 wood blocks with a linear pattern that a) matched the visual texture direction and frequency b) matched the direction but had twice the frequency, or c) matched the frequency but not the direction; a fan that rendered a radial haptic pattern in mid-air, the frequency of which increased with proximity to the object; a cup and a computer mouse, that would render continuous (permanent) contact rather than pulses (i. e. contact mode triggered on collision). Spatial haptic patterns were rendered during collisions between the hand mesh and the object, while continuous contact mode activated a predefined set of actuators for that object.

Participants were familiarized with the setup and guided through the environment. The experimenter asked them to explore the wood blocks by gliding their hands horizontally over their surfaces, and similarly, by exploring the bamboo segments by moving from the

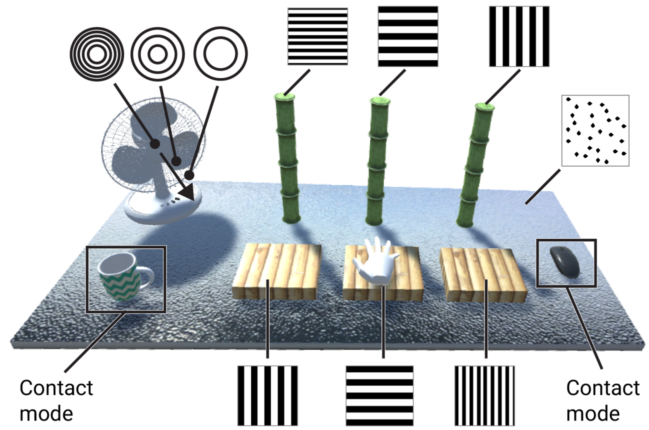

Figure 10: Environment with objects and haptic surfaces used in our experience test.

top to the bottom of the segment. Participants were asked to pay attention to how well the spatial patterns they felt on their hands matched the object's visual texture and based on this, select the object which they perceived had the closest match. Next, participants were asked to localize the mouse by touch alone, first by placing their hand on the table and then moving towards the mouse until they felt the contact mode engage on the actuators. After completing the tasks, participants could interact with any object in the scene and comment on the realism of the interaction. The study lasted approximately 25 minutes per participant.

6.3.3 Results

Overall, the virtual objects with matching visual and haptic direction and frequency were the rated as the best matched, with three out of six participants choosing the first wood block and again, three out of six choosing the second bamboo segment. All six participants could easily tell the difference between the two modes of interaction.

Sensitivity to frequency and direction of patterns. All participants were able to discriminate the object in the set of three with higher frequency than the others. However, for directionality, only two participants noticed that the second wood block texture was not matching, while four out of six participants noticed that the third bamboo segment texture did not match. Participants often commented when they perceived a mismatch between visual and haptic patterns, for example, when referring to the visual bump frequency on the middle bamboo: *"The middle one is more confusing. There is a mismatch."* (P3) and *"The middle one is random bumps. They don't correspond to what I'm seeing visually."* (P2). Referring to the in the middle wood block, one participant correctly perceived that it was direction that was mismatched: *"It's rotated. If I imagine it being rotated it would align nicely."* (P4). Some participants noted that the visual sense could override their haptic sensation: *"I had a feeling they all matched the visuals. Maybe because I am so focused on the visuals. I had the feeling that they all go from bottom to top."* (P1).

Contact and pulse mode. Since in the previous study, contact mode was only rendered for brief periods at a single location, participants were surprised that the actuators had the capability to continuously push against their skin, which was magnified by the combined effect of the array. Participants considered the effect of touching an object both distinct and convincing: *"With the cup I feel that I've made contact with the object."* (P2) and *" The feeling is very penetrating, but very convincing. You cannot miss the cup."* (P1). While not explicitly asked to do so, many stated a preference for the contact mode over the pulse mode used for spatial patterns: *"Purely just* *in terms of touch, it more closely resembles what I would expect."* (P6) and *"At least with the feedback I can feel when I've made the contact with the cup, but I don't with the block. So I like the cup better."* (P2).

Realism of feedback. In regards to realism, the effect of 3D geometry played a heightened role in the expectations of users: *"The bamboo has the extrusions - which I should feel. The wood blocks are flat, so I should feel a shear, not a travelling bump."* (P3). However, for the wooden blocks, the tactile feedback did not match the flat visual appearance: *"I see wood, and I am expecting it to be a coarse surface. Not smooth."* (P6) On the other hand, participants felt the spatial particle pattern on the table was a good match for the visually bumpy surface: *"I like the table though. Its meant to be textured. The table is great."* (P3).

Eyes-free localization. Four of the six participants could localize the mouse on their first attempt without explicitly looking at it by gliding their hand over the desk. While having tactile feedback was an effective aid, it was not as efficient as it could be due to the lack of grounded feedback: *"If you're on the right plane, then it's very easy. But you can go through the table."* (P4).

7 Discussion

The main contribution of our work is a novel design of an electromagnetic tactile actuator that exhibits a small form factor, low power consumption, low heat generation, and a strong holding force. By introducing a dampening material directly in the actuators, we were able to mitigate the transfer of unwanted vibrations onto the hand. We further characterized the thermal behavior of a single actuator and found that even in a demanding haptic environment the heat generation was at most 10.1°C above room temperature. To cover a large set of mechanoreceptors on the hand, we carefully chose the placement of 15 actuators and integrated them into a wearable form factor, i. e. a haptic glove that can be used in VR. By introducing two different modes of actuation, TacTiles can render both haptic surface information (see Figure 8) and the distinct sensation of touching an object. Taken together, these contributions allow TacTiles to satisfy the proposed design guidelines of *wearability*, *low-power*, and *high-fidelity*.

In our first experiment on mode discrimination and localization, participants achieved 87.0% and 87.7% accuracy respectively. One actuator on the palm exhibited comparably poor localization of 55%, indicating that at this specific location, a single actuator instead of two might have been sufficient. This goes in line with findings from neurobiology on the sensitivity of different areas of the human hand due to differently distributed mechanoreceptors [16, 33]. Actuators along the base of the fingers exhibited higher localization, although they were closer together (between 1.5 *cm* and 2 *cm*). This needs to be considered for rendering haptic sensations, for example, by increasing the density of haptic actuators near the fingertips, while spreading them out near the palm. However, it should also be taken into account that it's even possible to confuse localization between two fingertips [17]. Increased density at the fingertips may exacerbate this effect.

We also found that participants were able to easily distinguish differences in the frequencies of spatial haptic patterns of 3% to 6%. Even for quasi-random patterns, participants were able to distinguish frequencies with a difference of only 8.7%. Pairing this with visual feedback from our second experience test, we believe that TacTiles enables a very rich set of haptic rendering capabilities.

In our experience test, participants confirmed the importance of a *correct correspondence* between a visual and haptic representations of patterns. Previous work on rendering tactile feedback to the fingertip in VR has shown a high tolerance for directional mismatch between visual texture and haptic patterns (e. g. Haptic Revolver [34]). In our experiments, however, when rendering feedback to the whole hand, we found that participants were able to perceive both orientation differences and frequency differences. Thus, while full-hand tactile rendering affords richer experiences in VR, the directional and frequency compatibility between visual and haptic patterns should be considered carefully.

In terms of realism, in pulse mode, the haptic sensations produced by TacTiles would be more appropriate to render 3D features rather than 2D visual textures. Participants were also more sensitive to directional mismatches when presented with 3D features, such as in the bamboo segments. Conversely, the bump-mapped table surface has both 3D features and matched t Enclosing or grasping objects triggered contact mode. Participants commented that this more closely resembles their expectations in terms of haptic feeling. This mode could additionally provide information about the location and state (i. e. grasped) of an object which could be used in more interactive scenarios.

Providing both contact and haptic surface rendering capabilities in a single device is desirable as we use these modes routinely in everyday life, for example, during object identification tasks [20]. With TacTiles, we show that by combining both modes in a single device, we can enable new forms of interaction in VR such as the localization of objects that are out of sight by touch alone.

7.1 Limitations and Future Work

While the 15 actuators of TacTiles are able to render haptic feedback to key regions on the fingers and palm, the full haptic surface of the hand still has much room before its fully saturated. In addition, areas on the hand such as the sides of the fingers are difficult to exploit, as the size of the actuator can physically impede finger flexion and abduction. Future work can address this by further reducing the size of TacTiles and placing them in even denser arrangements.

Another area which could improve VR realism is providing different levels of contact pressure which could be based on the levels of penetration into an object.

Going beyond purely tactile feedback, it would be a fruitful direction of future research to combine tactile arrays with kinesthetic haptic devices such as our recently introduced device DextrES [12] in order to increase realism of touching *and* holding objects (cf. user comment on muscle tension).

We believe that TacTiles has the potential to serve as haptic feedback device beyond the current form factor as a glove, for example, in an forearm sleeve. TacTiles enable the design of novel, larger scale devices due to its low power consumption and low heat generation. This may enable so far unexplored rendering of tactile sensations in VR.

8 Conclusions

We presented TacTiles, a novel type of haptic device that integrates an array of electromagnetic actuators. TacTiles come in a small form factor (1 cm^3, 1.8 *g*), consume little power (130 *mW*) and produce a low amount of heat. This makes them suitable for prolonged use in VR scenarios. By including two different actuation modes, i. e. *pulse* and *contact* mode, they can produce different sensations on users' hands. They are re-configurable, allowing for a wide range of possible device configurations. We show that users can successfully localize actuation and discriminate the two modes. A experiential study showed that TacTiles can convincingly render continuous touch with an object, convey haptic surface information, and even allows users to localize objects in a scene without looking at them. We see TacTiles as an enabling technology that allows researchers to push the boundary of feedback in VR scenarios, thus ultimately improving the usefulness and applicability of VR.

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