MagKnitic: Machine-knitted Passive and Interactive Haptic Textiles with Integrated Binary Sensing

Yiyue Luo
yiyueluo@mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

Junyi Zhu
junyizhu@mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

Kui Wu
kwwu@global.tencent.com
LightSpeed Studios
Los Angeles, California, USA

Cedric Honnet
honnet@media.mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

Stefanie Mueller
stefanie.mueller@mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

Wojciech Matusik
wojciech@csail.mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

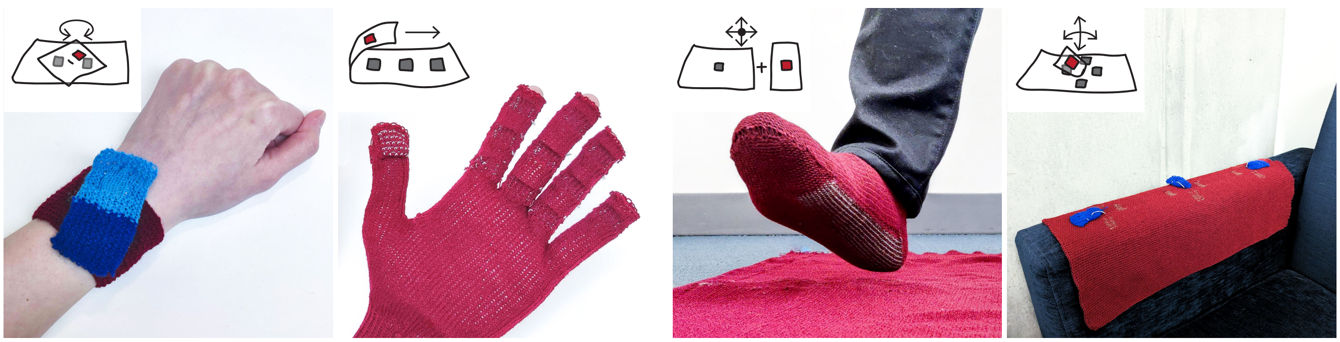

Figure 1: Example applications of *MagKnitic*. From left to right, a rotary wristband, a glove numpad, VR socks, and a sofa covering, offering passive haptic feedback during users interactions.

ABSTRACT

In this paper, we introduce *MagKnitic*, a novel approach to integrate passive force feedback and binary sensing into fabrics via digital machine knitting. Our approach utilizes digital fabrication technology to enable haptic interfaces that are soft, flexible, lightweight, and conform to the user's body shape. Despite these characteristics, our interfaces provide diverse, interactive, and responsive force feedback, expanding the design space for haptic experiences. *MagKnitic* provides scalable and customizable passive haptic sensations by utilizing the attractive force between ferromagnetic yarns and permanent magnets, both of which are seamlessly integrated into knitted fabrics. Moreover, we present a binary sensing capability based on the resistance drop resulting from the activated electrical path between the integrated magnets and ferromagnetic yarn upon direct contact. We offer parametric design templates for users to customize *MagKnitic* layouts and patterns. With various design layouts and combinations, *MagKnitic* supports passive haptics interactions of linear, polar, angular, planar, radial, and user-defined motions. We perform a technical evaluation of the passive force feedback and the binary sensing capabilities with different machine knitting layouts and patterns, embedded magnet sizes, and interaction distances. In addition, we conduct two user studies to validate the effectiveness of *MagKnitic*. Finally, we demonstrate various application scenarios, including wearable input interfaces, game controllers, passive VR/AR wearables, and interactive furniture coverings.

KEYWORDS

Passive Haptics; eTextiles; Machine knitting; Personal Fabrication; Rapid Function Prototyping

ACM Reference Format:
Yiyue Luo, Junyi Zhu, Kui Wu, Cedric Honnet, Stefanie Mueller, and Wojciech Matusik. 2023. MagKnitic: Machine-knitted Passive and Interactive Haptic Textiles with Integrated Binary Sensing. In *The 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23), October 29–November 01, 2023, San Francisco, CA, USA.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3586183.3606765

UIST '23, October 29–November 01, 2023, San Francisco, CA, USA

ACM ISBN 979-8-4007-0132-0/23/10.
https://doi.org/10.1145/3586183.3606765

1 INTRODUCTION

Haptics is a critical component in designing interactive systems for tangible digital interfaces. Haptic interaction and feedback can be categorized into two primary types, active and passive. Passive haptics, in contrast to active haptics, utilizes non-powered or non-motorized interfaces, such as physical props and textured surfaces, to provide tactile sensations to users during their active movement. These passive interfaces require minimal power consumption, have a lower cost, and are less complex to design [6]. Such features make passive haptics a great fit for large-scale deployment and portable environments [40].

Conventional passive haptic devices rely on mechanical structures such as buttons, springs, and gears to generate haptic feedback. However, these devices are often rigid and inflexible, which poses a challenge when integrating them with the user's body form or wearable devices. To address this challenge, researchers have been investigating new approaches to create flexible and stretchable passive haptic interfaces by leveraging soft and stretchable materials, such as elastomers and hydrogels [25]. However, such soft passive haptic interfaces are usually fabricated manually with complex and time-consuming procedures.

To overcome these drawbacks, we propose *MagKnitic*, a novel design and fabrication pipeline for textile-based passive haptic interfaces with integrated binary sensing via digital machine knitting. Digital machine knitting is a highly versatile fabrication method that can create lightweight and stretchable fabrics with conformal shapes in a customizable, scalable, and programmable manner. Knitting is also compatible with a rich material library of functional yarns for various mechanical and electrical features. To convert users' interaction with *MagKnitic* as passive force feedback, we integrate commercially available permanent magnets and ferromagnetic yarns into fabrics by digital machine knitting seamlessly. Our approach expands the design space for haptic experiences through digital fabrication technology, enabling haptic interfaces that are soft, lightweight, and conform to the user's body shape while providing strong, interactive, and responsive force feedback.

MagKnitic supports fully programmable and customizable designs, which enable precise control of the placement and density of the magnets and ferromagnetic yarns within the fabric through a parametric design pipeline. Six design templates for passive haptic interactions enable fast prototyping, including linear, polar, angular, planar, radial, and free motions. In addition, *MagKnitic* enables further programming of passive force sensations through post-fabrication techniques such as embroidering and altering the arrangement of the permanent magnets. This feature provides a high degree of customization and adaptability, allowing users to fine-tune the haptic feedback to their specific needs and preferences. In addition to providing passive force feedback, *MagKnitic* can also integrate resistive binary sensing capability via the high conductivity of integrated ferromagnetic yarn and permanent magnets. Such a sensing mechanism works in tandem with the passive force feedback generation, enabling interface designs with both input and output capabilities.

In this paper, we contribute the following:

- A programmable fabrication pipeline for textile-based passive haptic interfaces with integrated resistive binary sensing capability using industrial digital knitting machine and commercially available functional yarns.
- Interactive parametric design templates for fast prototyping and customization on designs, enabling passive force feedback for linear, polar, angular, planar, radial, and free interactions, as well as binary sensing capability.
- Technical evaluations on passive haptic feedback and sensing capability of *MagKnitic* with different ferromagnetic knitted patterns and layouts.
- Preliminary user studies on the effectiveness of *MagKnitic* for the passive haptics feedback.
- Demonstrations of various *MagKnitic* prototypes across diverse interactive application scenarios.

2 RELATED WORK

We briefly review related works on passive haptics, machine-knitted smart textiles, as well as magnetic interactions in HCI.

2.1 Passive Haptics

Passive haptics provides users with indirect feedback about their interactions with virtual objects, with the use of non-powered or non-motorized devices [6]. Traditionally, passive haptics feedback is generated by rigid mechanical structures, such as buttons, springs, and joysticks, as well as material-specific properties that can dissipate and redirect forces during interactions, like elastic and magnetic materials [18]. Researchers have explored integrating structure-driven approaches with various devices and interfaces, such as *MagGetz* [8] and *shiftIO* [42] for mobile phones, and *FlexMarker* [43] for interactive surfaces. Another commonly employed approach that leverages structure-driven design is based on Origami and kirigami-based structures. For example, *Foldio* [33] and *Sensing Kirigami* [56] provided binary haptics feedback with foldable paper structures, and *Kirigami Haptic Swatches* [4] further enabled quantitatively adjustable passive haptics feedbacks of four types of kirigami buttons. For material-driven passive haptics, *Ogata et al.* implemented linear and planar feedbacks with embedded permanent magnets [31, 32], *Yasu et al.* also worked on multiple projects utilizing magnetic rubber sheets, including rubbing over [48] or overlaying one or multiple magnetic sheets [49, 50], for passive haptics over 2D surfaces.

More recently, with the development of rapid prototype techniques like 3D printers, functional inkjet printing and computational knitting machines, complicated structures with integrated electronic functions became easier to design and fabricate [58, 59], along with newly available materials, which led to advances in both structure-driven and material-driven passive haptics feedback design. For instance, with structure-driven passive haptics, *FlexHaptics* [19] introduced passive haptic input interfaces utilizing planar compliant structures, *Shape-Haptics* [57] investigated planar & passive haptics feedback with "click" structures, and *Ondulé* [7] with spring structures. *Rivera et al.* and *Ion et al.* expanded on material-driven approaches, with embedded elastic textiles [39] and 3d printable metamaterials [9], respectively. The affordances of surface gestures and passive haptics on diverse textile user interfaces have also been investigated [21, 28, 34].

Inspired by both structure-driven (i.e. programmable knitting structures) and material-driven (i.e. ferromagnetic & conductive yarns) approaches, we propose *MagKnitic*, a novel textile-based passive haptic interfaces integrated binary sensing via a highly-customizable digital fabrication technique, digital machine knitting.

2.2 Machine-knitted Smart Textiles

Digital machine knitting is a widely used textile manufacturing method that enables the automated and programmable production of textiles by creating interlocked-loop structures (stitches). Knitted textiles possess desirable attributes such as softness, flexibility, and conformability. In this work, all samples are fabricated using a v-bed weft digital knitting machine. The machine comprised a front and a back needle bed. By utilizing combinations of various needle operations such as knits, transfers, and tucks, digital knitting machines allow for the customization of textiles with unique features such as color, texture, pattern, and properties [45].

Advances in computational design tools for digital machine knitting promote an accessible, interactive, and rapid design process. McCann et al. [27] introduced Knitout [26], a compiler that translates high-level shape primitives into low-level knitting machine instructions. This design pipeline was subsequently expanded to an interactive design interface [51]. Similarly, based on high-level primitives, Kaspar et al. [11, 13] introduced an interactive web-based knitting design interface. [52] introduced the stitch meshes framework, which built yarn-level models and served as an effective 3D design and modeling interface for editing at the stitch level. Such frameworks were later applied to machine knitting design [29, 47]. The design process could be further expedited by a machine learning-based pipeline [12], which converted visual patterns into low-level knitting instructions. We leveraged Knitout compiler for the interactive designs of MagKnitic.

Sensing capabilities can be seamlessly integrated into textiles by digital machine knitting through the integration of functional materials. Full-sized knitted garments such as socks, vests, and gloves with embedded resistive pressure sensing matrices were presented through the scalable and seamless integration of coaxial piezoresistive fibers using a digital knitting machine. This integration enables real-time human-environment interactions and human-robot interactions [22, 60]. Similarly, Wicaksono et al. [46] demonstrated the use of knitted conductive traces as electrodes for resistive sensing matrices and presented activity recognition and monitoring through knitted tactile sensing socks and carpets. Leveraging the unique geometries and structures of the knitted textiles, conductive yarns were also integrated into knitted textiles by plating and short-rows to enable resistive and capacitive sensing for programmable interactive user interfaces [23, 35]. Aigner et al. [1] stepped further to integrate piezoresistive yarn as a spacer through digital machine knitting for continuous pressure sensing.

Previous works have also demonstrated actuation in knitted textiles for assistive wearables, interactive user interfaces, and soft robotics. Albaugh et al. [2] leveraged the knitting technique of inlaying, where a yarn was inserted across the knitting structure as the cable for actuation. Actuation was also performed in knitted textiles through memory alloy, which was seamlessly integrated into the knitted fabric and generated deformation during heating [5, 15]. Coupling with a pneumatic system, Luo et al. [24] leveraged the anisotropic behaviors of knitting covers, which constrain the motion of tubular objects as pre-defined and induce bending-based deformation. Similarly, integrating fluidic fibers into knitted textiles enables dynamic motion through pneumatic actuation [14, 16].

Harnessing the programmable and customizable properties of digital machine knitting, as well as its compatibility with a diverse range of materials, we seamlessly integrate passive force feedback with binary sensing into textiles. Our approach is both scalable and cost-effective while remaining highly portable.

2.3 Magnetic Interactions in HCI

There are three types of magnets: permanent magnets, temporary magnets, and electromagnets [20]. Permanent magnets emit a magnetic field without the need for any external source of magnetism or electrical power. Temporary magnets, also with no external power needed, behave as magnets only while near something that emits a magnetic field and lose these characteristics when the magnetic field is removed. Electromagnets, on the other hand, require electrical power in order to behave as a magnet. Magnetic interactions generated by these three types of the magnets, individually or in combinations, have been explored in various HCI applications, including wearable haptic feedback, interactive displays, and physical inputs. Electromagnets, for example, have been used for generating dynamic and wearable haptic feedbacks [36], tangible displays [3, 38, 53], as well as fabricating programmable interfaces when combined with permanent magnets matrices [30] Permanent magnets, including soft magnets and magnetic sheets, have also been explored for haptic feedback [25, 49, 50] and macrotexture designs [48]. More recently, researchers have investigated integrating magnets to 3D printed objects, combined with electromagnets and temporary magnets, for making 3D printed objects interactive [37], providing force feedbacks [31, 55], objects assembly [44], and electronic prototyping [41]. Furthermore, magnetic force feedback has been studied computationally [32], which allows for the design of magnetic force feedback based on user-defined parameters.

MagKnitic utilizes the strong magnetic field generated by permanent magnets, and integrates with highly versatile machine knittable temporary magnets (i.e. ferromagnetic yarn), which results in a a customizable, scalable, and programmable haptic interfaces with high force-to-weight ratio. We choose permanent magnet over electromagnet because embedded permanent magnet has higher magnetic flux per square unit on textiles compared to embroidered copper coils, and is safer and more comfortable for users (no external electrical power and no additional current-generating hardware).

3 MAGKNITIC

3.1 Principle

The passive force feedback in *MagKnitic* was generated through the interaction between permanent magnets and ferromagnetic yarns. The ferromagnetic yarn (Filix) is made of stainless steel fiber, which comprises iron and exhibits the unique ability to interact with a magnetic field and get magnetized. A typical passive haptic unit is made of knitted fabric with plated ferromagnetic patches and another knitted fabric with a split pocket for the permanent commercial magnet (K&J, Neodymium, N52, axially magnetized) insertion. When the permanent magnet approaches a knitted fabric integrated with ferromagnetic yarn caused by a human's motion, an attractive force between two pieces of fabric is generated and transmitted to the user through the fabric, providing them with customized feedback (Figure 2 left). Our force feedback mechanism operates with zero energy consumption. Unlike active haptics, our passive haptic design eliminates wiring, batteries, and driving circuits. This not only conserves energy, but also facilitates seamless integration into wearable devices, enabling unobtrusive passive force feedback during user interactions.

We further augment *MagKnitic* with a binary sensing capability by utilizing the high conductivity of ferromagnetic yarn and the

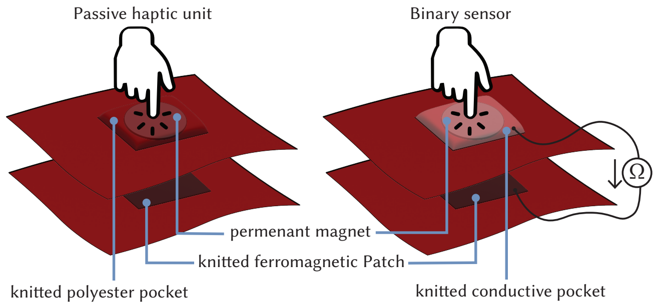

Figure 2: Principles of *MagKnitic*. In general, *MagKnitic* comprises an integrated ferromagnetic patch and a split pocket for permanent magnet placement. Left, As the user moves, bringing the inserted permanent magnet closer to the integrated ferromagnetic yarn, an attractive force is generated and transmitted to the user as a passive force feedback to a specific interaction. Right, to enable binary sensing, we further integrate commercial conductive yarn into the split pocket. Thanks to the high conductivity of permanent magnet and ferromagnetic yarn, as the user's motion brings the plated conductive pocket with inserted magnet into contact with the integrated ferromagnetic yarn, active electrical paths form and the measured resistance significantly drops, enabling binary sensing on the user's interaction accompanied by the passive haptic feedback to the user.

permanent magnet. We achieve this by placing the permanent magnet in a split pocket plated with conductive yarn (Figure 2 right). As the user brings the pocket with inserted magnet into direct contact with the ferromagnetic patch, the resistance drops significantly due to the activated electrical paths. This drop in resistance allows us to detect the presence of user motion or interaction by measuring the resistance between the knitted pocket with inserted magnet and the integrated ferromagnetic patches. In this work, we focus on passive force feedback that provides a single instantaneous response to the user upon interaction with the interface. Therefore, binary sensing, which detects the presence or absence of interaction, is preferable over continuous monitoring of the applied force level. Note, unlike passive haptic, power supply is needed for sensing signal serialization and visualization.

3.2 Designs for Various Motions

Inspired by previous works on magnet-based passive haptic interactions [55], we propose designs for six different passive haptic interactions that involve linear, polar, angular, planar, radial, and free motions (Figure 3). Here, we describe their interaction principle and how we leverage machine knitting to fabricate them.

Linear motion. Interacting with linear motion involves pushing or pulling along a straight path, which was often implemented as a slider. *MagKnitic* featuring passive force feedback during linear motion is knitted as a flat sheet, with plated ferromagnetic patches and a split pocket for magnet placement in a linear arrangement.

Polar motion. Interacting with polar motion involves spinning or rotating around a fixed point or axis, which was often implemented as a knob. *MagKnitic* featuring passive force feedback during polar motion is implemented as a double sheet structure by knitting on both the front and back beds. The front sheet obtains a split pocket for magnet placement, and the back sheet obtains plated ferromagnetic patches at desired locations. The two knits are interconnected by transferring two stitches at the center from the front bed to the back bed, which serves as the spinning fixed axial point.

Angular motion. Interacting with angular motion involves flipping around an axis within a two-dimensional plane, which was often implemented as a switch. *MagKnitic* featuring passive force feedback during polar motion is fabricated by knitting on both beds. The out-of-plane flipping patch with the split pocket for magnet placement is knitted on the front bed, while the base structure with plated ferromagnetic patches is knitted on the back bed. All stitches from the front knitted flipping patch is transferred and merged to the base structure on the back bed. The merged seam serves as the flipping axis. The integrated ferromagnetic patches are arranged linearly and separated by the merged seam of the flipping patch, offering passive force feedback during the angular flipping interactions.

Planar motion. Interacting with planar motion involves panning along a two-dimensional plane, often implemented as a thumbstick interface. *MagKnitic* featuring passive force feedback during planar motion is based on tubular knitting with an enclosed bottom and top. During tubular knitting, stitches are made across both the front and back beds. The split pocket is integrated into the front knits, and the plated ferromagnetic patches are integrated into the back knits at desired locations. Note that the tubular knitted structures as the essential shape primitive of knitting is also supported by our planar motion intersection. In that case, two encased tubes can move freely along the axis direction and rotate to enable the passive haptic feedback.

Radial motion. Interacting with radial motion involves adjusting the angle and direction along a circular path with the combination of rotating and flipping motion, often implemented as a joystick. *MagKnitic* featuring passive force feedback during radial motion obtains similar designs to the one featuring angular motion. The radial patch with the split pocket for magnet placement is knitted on the front bed, while the base structure with plated ferromagnetic patches is knitted on the back bed. Stitches from the front knitted radial patch first decrease into two stitches and are transferred and merged to the base structure on the back bed. Since there are only a few interconnected stitches, the out-of-plane knit could be flipped and rotated, enabling radial interactions.

Free motion. Interacting with free motion involves controlling the movement in a three-dimensional space. *MagKnitic* featuring passive force feedback during radial motion is enabled with two separated fabrics, one flat sheet with plated ferromagnetic patches knitted on the front bed and another flat sheet or tubular structure with split pockets for magnet placement.

MagKnitic offers passive haptic feedback for each interaction through the machine-knitted textile interface without requiring any external power source or electronic components, allowing for accessible, natural, and comfortable user input, control, and interactions.

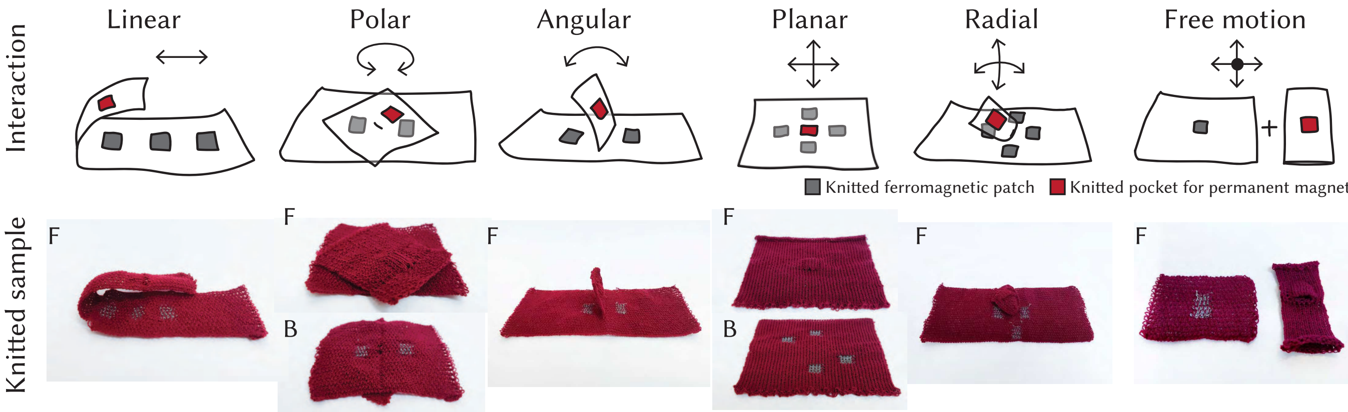

Figure 3: *MagKnitic* enables passive haptics during linear, polar, angular, planar, radial, and free interactions.

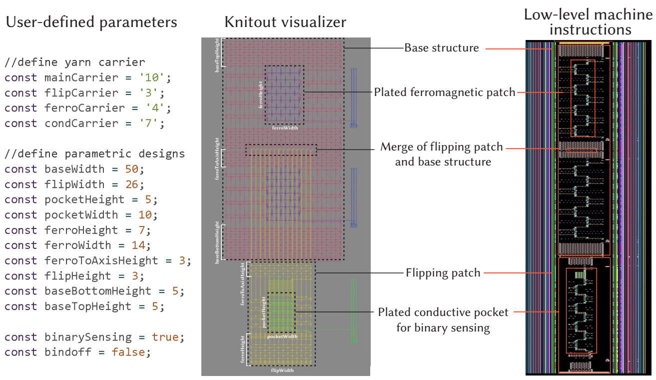

Figure 4: Example parametric design template for a *MagKnitic* design enabling passive haptic feedback during angular interactions. Users were able to define design-specific parameters, such as the dimensions of the flipping patch and base structure, as well as the placement of plated ferromagnetic patches, and split pockets. In the middle Knitout visualization, the user-defined parameters are in white. With the user-defined parameters, our pre-programmed design templates output the corresponding .DAT file on the right using the Knitout compiler, encoding low-level knitting machine instructions and can be imported to the machine for automatic fabrication.

3.3 Parametric Templates

We offer interactive parametric design templates for *MagKnitic* designs featuring passive haptic feedback during each interaction. Our design templates are compiled and visualized based on .Knitout [26, 51]. Figure 4 shows an example template on a design enabling angular interaction. Users can define various parameters, including which yarn carrier to use, with or without the integration of conductive yarns for binary sensing, the size of the base structure, the placement of ferromagnetic patches, and so on. Our templates take all user-defined parameters to the .Knitout compiler, which outputs the corresponding low-level machine instructions (.DAT files). The digital knitting machine is able to fabricate the defined designs automatically after importing the output machine instructions. All templates can be found in Supplementary Materials.

3.4 Fabrication

MagKnitic can be fabricated automatically using a digital machine knitting (Shima Seiki SWG091N2G, 14 gauge). The digital knitting machine comprises a front and a back needle back (Figure 5), which enables the fabricating of full-sized garments, e.g., socks, and gloves in a single machine run. Fabrics of different geometries, patterns, and textures are generated using the different operations of needles, including knits, purls, tucks, and so on. The fabrication of *MagKnitic* leverages the knitting technique of *splitting* and *plating*. Splitting is a technique to extend a second sheet from the base sheet. This technique creates pockets or separates fabric sections from the base designs. Plating is a technique of using two different yarns together in the knitting process to create a single layer of fabric. In plating, one yarn is knitted on the front of the fabric, while the other is knitted on the back. Plating can combine different colors or properties in a single layer of fabric. We use 1-ply acrylic knitting yarn (Uppingham) for the base structures, stainless steel yarn (Filix) as ferromagnetic yarn and polyester yarn with 20% micro stainless steel fiber as conductive yarn. All samples are knitted using half-gauge, meaning every other needle is used during the knitting.

Conductive pocket for magnet placement. A pocket for permanent magnet placement can be created by splitting a second knitted layer from one side of the needle bed at specific locations. This is achieved with a sequence of transferring and tucking. To further enable binary sensing, conductive yarn is integrated into the split pocket by plating (Figure 6 left).

Ferromagnetic patch. The ferromagnetic yarn is compatible with all needle operations so can be knitted, plated, transferred, and inlaid by the industrial knitting machine. The ferromagnetic patches are incorporated into the knitted fabric at predetermined locations by plating the ferromagnetic yarn with the standard acrylic knitting yarn at specific needles (Figure 6 right).

After the samples are knitted, we manually place the commercial permanent magnets into the corresponding knitted pocket. To enable binary sensing, electrical connections are established by entangling read-out cables with the plated conductive yarns in the split pocket and the ferromagnetic patch.

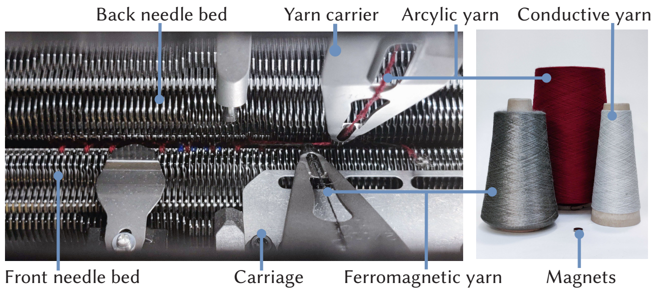

Figure 5: Materials and fabrication. *MagKnitic* is made of acrylic yarn, ferromagnetic yarn, conductive yarn, and permanent magnets. All specimens are automatically fabricated by an industrial digital knitting machine.

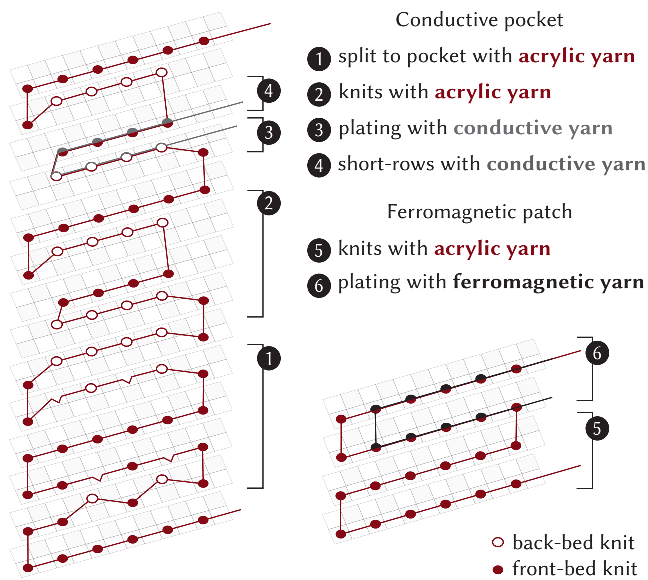

Figure 6: Knitting structures. The knitting machine bed-view of the knitting structure of the conductive pocket for permanent magnet placement and the ferromagnetic patch.

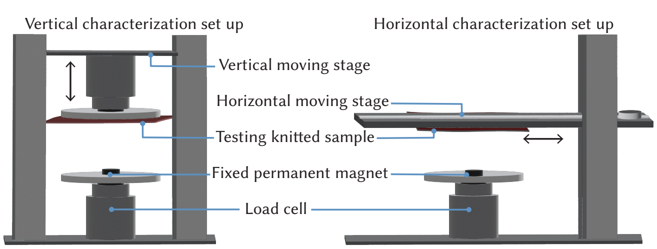

Figure 7: Characterization schematics. The customized characterization schematics featuring Left, vertical motion and Right, horizontal motion.

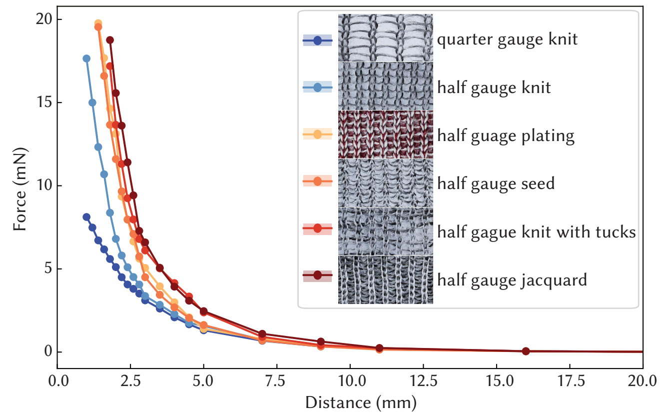

Figure 8: Force response of ferromagnetic patches with different knitting patterns along vertical displacement towards a fixed permanent magnet.

4 TECHNICAL EVALUATION

4.1 Passive Force Feedback

The passive haptic feedback is affected by both the amount of integrated ferromagnetic yarn, which varies based on the knitting designs, and the magnitude of the applied magnetic field, which is determined mainly by the size of the integrated permanent magnet.

We characterized the effectiveness of various knitting patterns by approximating the force generated between knitted ferromagnetic patches with varying designs and a fixed magnet. The measurement was done on a customized mechanical testing setup, where a permanent magnet was fixed on the bottom plate integrated with a load cell, and the ferromagnetic knitted patches were fixed on the top plate. The top plate can move vertically, where the distance between the two plates and the reading from the load cells can be recorded simultaneously (Figure 7 left). As demonstrated in Figure 8, patterns with higher ferromagnetic yarn compositions, such as seed, knit with tucks, and jacquard knits, obtain steeper force response curves, indicating stronger force feedback. On the other hand, the quarter gauge knit obtains the weakest force response due to its lower ferromagnetic yarn composition. In this work, we opt for a stronger force response; to further optimize for the knitting complexity, we select seeds for most of our ferromagnetic patch designs. Figure 9 shows the force response between a plated ferromagnetic patch and permanent magnets of different sizes (diameters of 1/4", 1/2", and 1", the thickness of 1/16"). A larger magnet generates a stronger force response due to the introduction of a stronger magnetic field. However, we also note that larger magnets are heavier, which must be taken into consideration for real-life applications.

Moreover, we evaluated the dynamic force responses of *MagKnitic* during coaxial interaction. The characterization was performed on a similar setup with a single or an array of permanent magnets fixed on a bottom plate with an integrated load cell and the knitted ferromagnetic textiles fixed on the top plate. The top plate can be moved horizontally (Figure 7 right). We measured the force response curves from a knitted fabric with patterned ferromagnetic patches as it moved horizontally across a fixed magnet (Figure 10), as well as the force response curves from a single knitted ferromagnetic

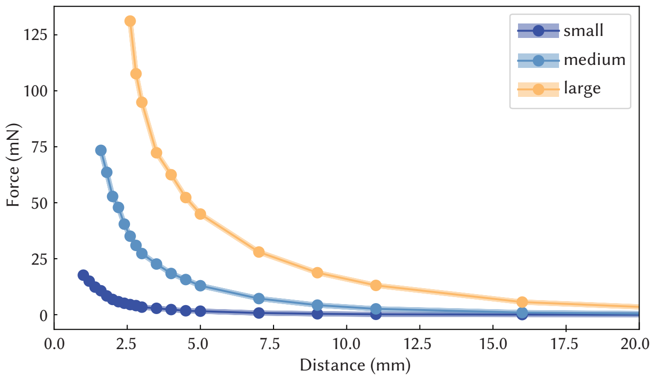

Figure 9: Force response of a ferromagnetic patch (half gauge knit) along vertical displacement towards the fixed permanent magnets with different sizes.

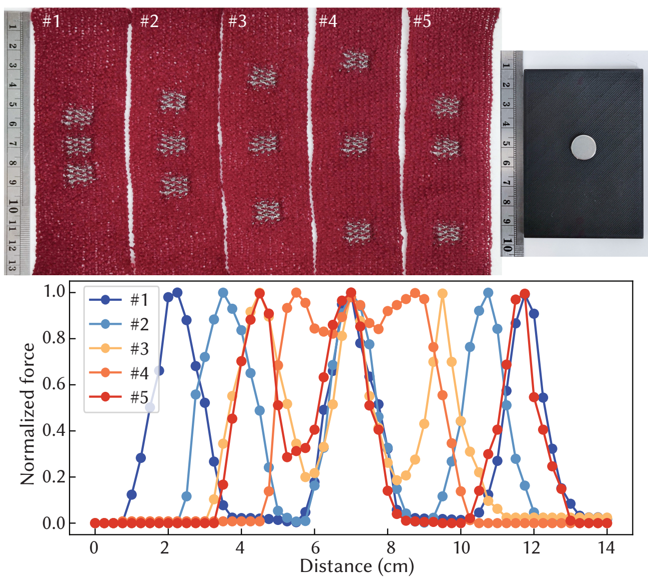

Figure 10: Force response of linear ferromagnetic knits with different arrangements along horizontal displacement towards a fixed permanent magnet.

patch moving horizontally across a defined magnet array (Figure 11). Diverse force characteristics can be obtained by varying arrangements of the plated ferromagnetic patch or the inserted permanent magnets, demonstrating possibilities for creating a wide range of passive haptic sensations and force feedback using our approach.

4.2 Binary Sensing

Within the context of passive interactive haptics, we specifically focus on binary sensing in this work. Coupling passive haptic feedback with binary sensing, which enables the detection of the presence or absence of an interaction, we are able to create a more sophisticated and versatile interactive system.

We evaluated the binary sensing performance with different commercial conductive yarns, including ferromagnetic yarn (50 Ω/m), polyester yarn with 20% dispersed stainless steel fiber (4000 Ω/m),

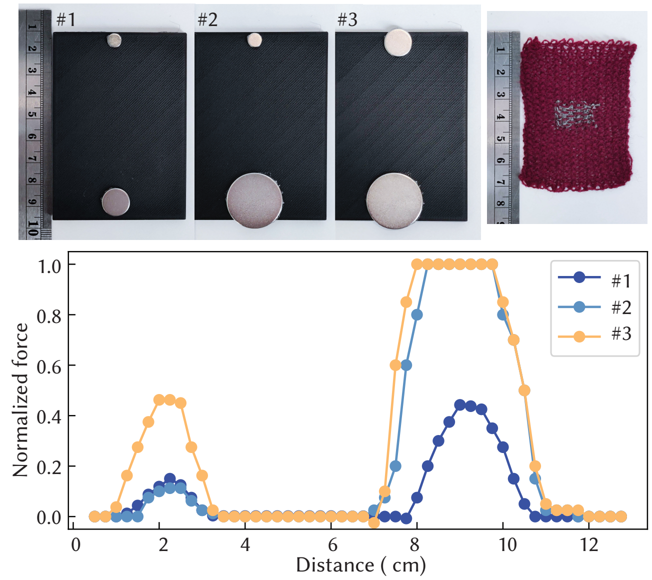

Figure 11: Force response of a ferromagnetic knit along horizontal displacement towards different permanent magnet arrangements.

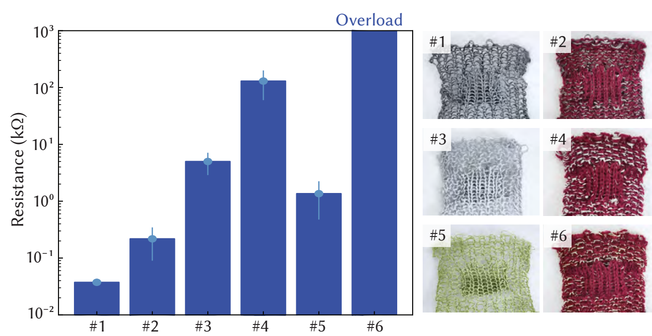

Figure 12: Binary sensing characterization. The resistance between the conductive pocket with different knitting structures and materials and ferromagnetic patch upon contact.

and silk yarn with intertwined single stainless steel thread (700 Ω/m). To quantify the performance, we focused on the angular interaction mode. The out-of-plane flipping knits were machine-knitted using three different conductive yarns in pure or plated designs. Resistance was measured between the flipping knits with inserted permanent magnet and the ferromagnetic patch during the characterization. The resistance is overloaded when the flipping knits are not in contact with the ferromagnetic. On the other hand, when the flipping knits come into contact with the ferromagnetic patch during the angular interactions, the measured resistance drops dramatically due to the formed electrical paths (Figure 12). Compared with designs made of plated conductive yarn, designs with pure conductive knits enable larger contact areas for electrical paths and hence obtain lower resistance during the interaction. Since ferromagnetic yarn has the lowest resistance, designs made of ferromagnetic yarn obtain the lowest resistance when the interaction occurs. It is also interesting to note that designs with plated silk-based conductive yarns are overloaded

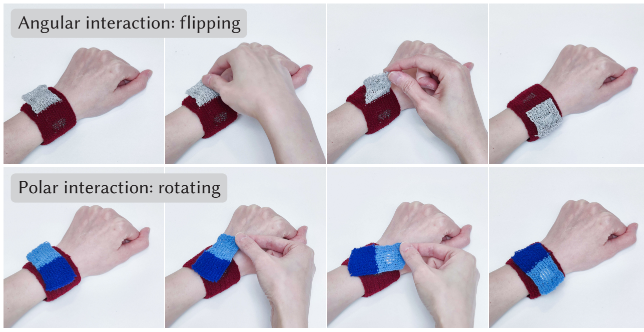

Figure 13: *MagKnitic* in wristbands. Knitted wristbands with haptic feedback as wearable input interfaces, enabling angular and polar interactions.

Figure 14: Glove-based T9 text input device with haptic feedback.

Figure 15: Sleeve-based shape input device and an interactive hat with haptic feedback for music control.

during the interactions; this is because the intertwined structure in silk-based conductive yarn and the plating structure limit the exposed area of the conductive stainless steel thread and restricts the stable electrical interactions between the flipping knits and ferromagnetic passive haptic patches.

In this work, we select plated polyester yarn with 20% dispersed stainless steel fiber (design #4). Its distinct change in resistance range (overload to kΩ range) makes it effective for binary sensing. Additionally, unlike ferromagnetic yarn, the polyester-based yarn does not interfere with the designed passive force feedback. Moreover, plating is a straightforward technique for integrating functional yarn into textiles, which made it a practical choice for our implementation.

5 APPLICATION

Thanks to the digital design and fabrication pipeline, we are able to integrate *MagKnitic* into textiles spanning from compact wearables to full-sized furniture coverings and carpets in a seamless and salable manner. In this section, we discuss applications of *MagKnitic* in passive yet interactive textile-based input wearables, soft game controllers, and large-scale objects like furniture coverings. All examples are built with our parametric design templates and fabricated in one go.

5.1 Input Wearables

MagKnitic is uniquely suitable for integration into full-sized garments due to its compatibility with the industrial textile manufacturing process. As demonstrated in Figure 13, wristbands embedded with *MagKnitic* enable angular and polar interactions, which can serve as a customizable flip and rotary interface for wearable devices, such as for mode switch controls (focus, driving modes etc.) on mobile devices.

Coupling with binary sensing, *MagKnitic* offers solutions for wearable input interfaces with programmable haptic feedback. For example, we developed a custom text input device in the form of a glove (Figure 14). The digitally knitted glove includes 10 ferromagnetic patches along the index, middle, ring, and pinky fingers, as well as a conductive pocket with an embedded magnet on the thumb. Each of the ferromagnetic patches is designed as one key of the T9 predictive text input, plus one patch for the space & delete key. Together it can serve as a wearable keypad for user input. The user can perform input by getting the thumb tips towards a specific ferromagnetic patch, which causes the resistance to drop dramatically between the pocket and the patch, indicating the press input from the user. At the same time, the user receives haptic feedback through the generated attractive force as a confirmation of successful recordings of the input.

This setup can also be incorporated similarly into a sleeve and a hat with various ferromagnetic patch layouts as wearable shape input or music control interfaces for mobile devices (Figure 15). By wearing a glove with a conductive pocket for an embedded magnet at the index fingertip, users will be able to input commands through different finger movements while perceiving tactile feedback that enhances their experience with the wearable input interface. These eyes-free interactions [10, 54] can be important for safety and convenience in various situations. For example, users can control their music or make phone calls while they are driving or walking in the street.

Figure 16: Knitted soft game controller.

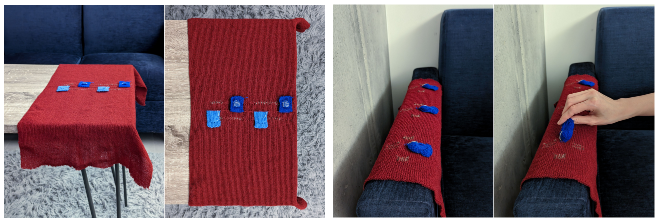

Figure 17: Furniture covering. Leveraging digital design and fabrication pipeline, *MagKnitic* can be integrated into furniture coverings, including table cloth, and sofa coverings, for diverse user interactions with passive haptic feedback. Using scenarios include tangible and interactive task checklists, ubiquitous user input interfaces, and so on.

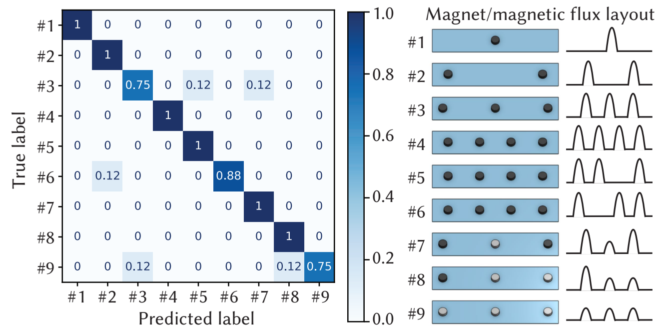

Figure 18: User classification on force feedback generated by diverse magnet arrangements. The magnet flux layouts generated from different magnetic amplitudes and spacing are plotted on the right.

5.2 Soft Game Controller

To demonstrate *MagKnitic*'s capability for planar interactions, we implement a textile-based thumbstick-like game controller interface (Figure 16). This soft custom controller is designed for adolescents or users with small hands, for whom the conventional game controllers are too big. Integrated with four ferromagnetic patches, this soft and flexible controller enables binary directional sensing, allowing users to input through planar motion. In addition, it provides passive haptic feedback that enhances the users' sense of immersion during their planar interaction.

5.3 Furniture Coverings

Unlike traditional passive haptic technologies that require rigid mechanical components and are challenging to be scaled up, *MagKnitic* can be seamlessly integrated into large-scale objects, such as furniture coverings. For example, it could be used to create interactive tablecloths and sofa coverings (Figure 17) that provide users with both comfort and aesthetic appeal and an immersive and tactile user interface with passive haptic feedback.

6 PRELIMINARY USER EVALUATION

In this section, we discuss preliminary user evaluation on *MagKnitic*, with two user studies on the effectiveness of the generated passive haptic feedback. Both studies are evaluated and approved by The Committee on the Use of Humans as Experimental Subjects of our institute.

6.1 User Study #1

In our first user study, we investigated the effectiveness of our passive haptic feedback by evaluating users' perceptions toward diverse force feedback characteristics generated by *MagKnitic*.

Participants. We recruited 8 participants (3 female, 5 male) aged 24-32 years (M=27.37, SD=3). All participants were right-handed and used their non-dominant hands for the study.

Study procedure. During the study, participants wore a machine-knitted glove with an integrated ferromagnetic patch at the index fingertip. Participants first got the opportunity to experience the passive haptic feedback generated via MagKnitic by approaching a permanent magnet. Then, they were asked to identify the predefined 9 textured surfaces by hovering their index fingertip above different permanent magnet layouts. The magnet layouts varied in each magnet's magnetic flux density and spacing, which were expected to create different force curves during the participant's finger movement. A piece of paper was placed on top of the magnet layouts so they were invisible to the participants. Participants were free to interact with the surface until they were confident about their answers. We recorded the participants' answers once they confirmed their selections.

Results. Figure 18 demonstrated the confusion matrix depicting the identification of experienced force curves by participants, which were generated by different magnet layouts. In general, participants achieved 93.1% accuracy in identifying the textured surfaces. Accuracy is almost perfect except for designs #3 and #9. This suggests that users had a distinct perception of the presence of passive force feedback, the spacing between every single peak of the provided force feedback, and the intensity of the force feedback when a reference was provided (i.e., when both the strong and weak feedback were provided).

6.2 User Study #2

In this user study, we investigated the effectiveness of MagKnitic for user input.

Participants. We recruited 6 participants (3 female, 3 male) aged 24-27 years (M=25.75, SD=1.26). All participants were right-handed and used both hands for the study.

Study procedure. In this study, the participants were asked to interact with a swatch enabling polar interactions. The swatch was integrated with two ferromagnetic patches at the bottom layer and a pocket for permanent magnet insertion at the top. Before the study, we let the participants experience the generated haptic feedback when they rotated the top layer. During the study, the participants were asked to rotate the top layer 30, 60, 90, 120, and 150 degrees, respectively, to the target position, where the integrated ferromagnetic patch was located. The same procedure was performed both with and without the permanent magnet inserted to provide haptic feedback. Participants were free to interact with the swatch until they felt confident that they had rotated to the target position. We

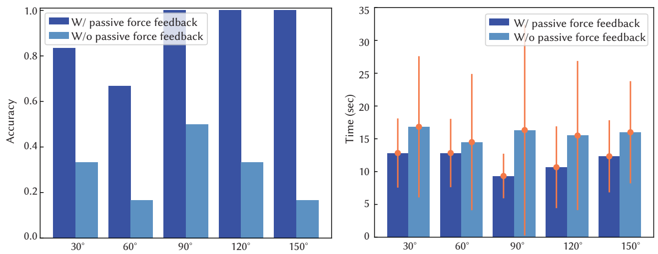

Figure 19: Time consumption and input accuracy featuring polar interactions with and without *MagKnitic* passive haptic feedback.

recorded the time each participant took to complete the task and their accuracy.

Results. Overall, participants reported experiencing higher resistance during rotation when the inserted magnet aligned with the ferromagnetic patches. As shown in Figure 19, the integration of passive force feedback results in higher accuracy on the rotation task. This is because the passive force feedback gave users a tactile cue to indicate whether they were reaching the target position. It is also noted that in the absence of integrated force feedback, participants achieved the highest accuracy when performing 90-degree rotations. This is because the 90-degree rotation is a more familiar and intuitive task for the participants. We have also observed that, on average, it takes users a long time to complete the rotation. However, 2 out of 6 participants performed the rotation faster when passive force feedback was not integrated. According to the 2 participants, without integrated force feedback, they lacked a means of determining whether their actions were correct. Consequently, they had to perform the task randomly, which may be efficient but not accurate.

The high accuracy exhibited by users in distinguishing between various force feedback characteristics and the improved accuracy observed in rotation tasks confirms the effectiveness and capability of MagKnitic, reiterating its potential for real-world applications.

7 DISCUSSION

7.1 Use of Permanent Magnets

In this work, we used permanent magnets rather than electromagnets to provide a magnetic field for force feedback due to several reasons. First of all, conventional electromagnets are based on coil structures, which are not feasible through digital machine knitting. While electromagnets are feasible through digital embroidery, another scalable textile manufacturing technique (Figure 20), the magnetic flux generated by an embroidered electromagnet powered by a 3.7 V battery is more than 1000 times weaker than that produced by a permanent magnet of the same size. Additionally, although electromagnets offer the advantage of programmable and active haptic feedback, they also raise concerns about safety due to the current and generated heat. They are also subject to significant energy consumption. These limitations make textile-based electromagnets less practical for wearable applications.

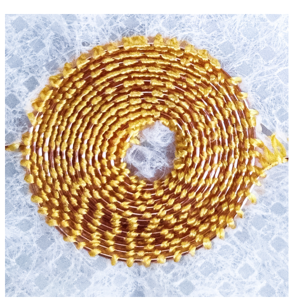

Figure 20: Digitally embroidered electromagnet.

Taking into account the constraints of electromagnets in textile-based wearable applications, we opted to use permanent magnets for their simplicity, reliability, and energy efficiency. Our integrated permanent magnets are comparable in size to rigid buttons and zippers commonly found on garments (radius < 1/2" and thickness < 1/16"). Despite adding a non-textile-based component to the systems, the small permanent magnets provide a strong and constant magnetic field without adding significant stiffness to the textile substrate. In the future, we also plan to explore the integration of polymer-based magnets [25] with textiles to enable a fully soft interface.

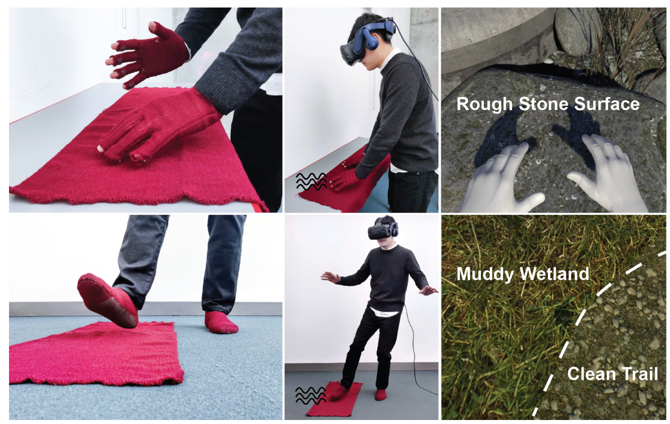

Figure 21: Potential application of passive yet interactive gloves and socks for surface textures rendering in VR environments.

7.2 Potential Applications in Virtual Texture Rendering

Passive haptic provides a natural and comfortable experience for VR/AR applications while keeping the cost and complexity of the device at a minimum. We propose potential applications of *MagKnitic* as easily integrated into AR/VR wearables, providing a subtle and realistic tactile sensation to the user and enhancing the sense of presence and immersion in the virtual environment in a passive manner. For instance, by wearing the socks and stepping towards a floor area or a knitted carpet with embedded magnets arrays, users will experience the sensation of walking on the muddy wetland, feeling the resistance and texture of the surface (Figure 21 bottom). Similarly, wearing the gloves and moving across a magnet array, users will experience touching a rough stone surface and feeling the bumps and irregularities of the texture (Figure 21 top). As demonstrated in preliminary user evaluation, our passive haptic feedback allows the user to feel the differences between various magnet layouts and magnetic flux densities, which demonstrate potential for embodying different textures in VR, e.g. mudding wetland, clean trial, and rough stone surface, in a soft, flexible, conformal, and natural form factor.

More user studies will be planned to validate users' sensation over *MagKnitic* in VR environments.

7.3 Limitations

MagKnitic is a passive interface that benefits from being scalable, portable, low-cost, and low-power. However, it also suffers from common limitations of passive haptics, the lack of specificity and real-time response. *MagKnitic* needs to be pre-programmed and does not respond to real-time changes. This may limit the realism and effectiveness of the haptic feedback in high-speed or unpredictable environments, especially for AR/VR applications. Also, because ferromagnetic materials can only be attracted to the magnetic field, *MagKnitic* can only utilize the attractive force between the ferromagnetic yarn and the magnet. This means that the system is limited to providing passive haptic feedback in a single direction, namely towards the magnet. While this may be sufficient for most applications for tangible user interfaces, it may not be ideal for more complex interactions that require feedback in multiple directions. Also, the spatial resolution of passive haptic units and binary sensors are inherently constrained by the resolution of knitting structures.

7.4 Future Work

Our approach can be extended to a bigger design space and even to active haptics. With the fast advances in materials science, we speculate the possibility of integrating programmable magnetic materials into fibers or textiles. This will introduce both attractive and repulsive force responses to the current system and expand the design space. Additionally, we plan to investigate the integration of miniaturized electro-permanent magnet systems [17], which could transform our system into an active haptics system capable of real-time interactivity and programmable active haptic responses. Extending or combining the current fabrication pipeline to different textile manufacturing methods, such as weaving and embroidery, is also an interesting avenue for future research.

Although *MagKnitic* supports various passive haptic interactions, we have not verified whether users can distinguish these haptics. We plan to conduct comprehensive user studies to validate users' perception during their interactions with various *MagKnitic* designs, which will help us further explore the potential applications of our passive haptic designs.

8 CONCLUSION

We present *MagKnitic*, which integrates passive force feedback and resistive sensing into fabrics via digital machine knitting. With its soft, flexible, and lightweight nature, *MagKnitic* conforms to the human body and provides unique and natural tactile sensations, as well as perceivable haptic feedback during users' interactions and motions. Coupling with the complementary binary sensing feature, which detects users' interactions, *MagKnitic* provides users with tangible cues to interact with physical interfaces in diverse ways. We also provide parametric design templates for users to customize *MagKnitic* layouts and patterns, which support passive haptic interactions featuring 6 different motions. Technical evaluations and user studies validate the effectiveness of our approach. Finally, various application scenarios at different scales, from wearable input interfaces like glove-based text input and sleeve-based shape input devices, soft game controllers, to passive haptics systems for VR/AR environments, and large scale objects like interactive furniture coverings, demonstrate the potential of *MagKnitic* in different domains. This research opens up new possibilities for incorporating passive haptic feedback into fabrics, paving the way for the development of innovative and more immersive interactive systems.

ACKNOWLEDGMENTS

We thank Filix for providing the ferromagnetic thread used in this project. We thank AFFOA for generously allowing us access the digital knitting machine for sample testing. We would also like to give special thanks to MJ Schmuhl for her assistance with communication and expertise in operating the equipment. This work is supported by MIT College of Computing Google Fellowship and the National Science Foundation under Grant No. 2008116.

REFERENCES

[1] Roland Aigner, Mira Alida Haberfellner, and Michael Haller. 2022. SpaceR: Knitting Ready-Made, Tactile, and Highly Responsive Spacer-Fabric Force Sensors for Continuous Input. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 68, 15 pages.

[2] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13.

[3] Andrea Bianchi and Ian Oakley. 2013. Designing Tangible Magnetic Appcessories. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 255–258.

[4] Zekun Chang, Tung D. Ta, Koya Narumi, Heeju Kim, Fuminori Okuya, Dongchi Li, Kunihiro Kato, Jie Qi, Yoshinobu Miyamoto, Kazuya Saito, and Yoshihiro Kawahara. 2020. Kirigami Haptic Swatches: Design Methods for Cut-and-Fold Haptic Feedback Mechanisms. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12.

[5] Min-Woo Han and Sung-Hoon Ahn. 2017. Blooming knit flowers: Loop-linked soft morphing structures for soft robotics. *Advanced materials* 29, 13 (2017), 1606580.

[6] Vincent Hayward, O Ashley, Cruz Hernandez, Danny Grant, and Gabriel Robles-De-La-Torre. 2004. Haptic interfaces and devices. *Sensor Review* 24 (03 2004), 16–29.

[7] Liang He, Huaishu Peng, Michelle Lin, Ravikanth Konjeti, François Guimbretière, and Jon E. Froehlich. 2019. Ondulé: Designing and Controlling 3D Printable Springs. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 739–750.

[8] Sungjae Hwang, Myungwook Ahn, and Kwang-yun Wohn. 2013. MagGetz: Customizable Passive Tangible Controllers on and around Conventional Mobile Devices. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13)*. Association for Computing Machinery, New York, NY, USA, 411–416.

[9] Alexandra Ion, David Lindlbauer, Philipp Herholz, Marc Alexa, and Patrick Baudisch. 2019. Understanding Metamaterial Mechanisms. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–14.

[10] Thorsten Karrer, Moritz Wittenhagen, Leonhard Lichtschlag, Florian Heller, and Jan Borchers. 2011. Pinstripe: Eyes-Free Continuous Input on Interactive Clothing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 1313–1322.

[11] Alexandre Kaspar, Liane Makatura, and Wojciech Matusik. 2019. Knitting Skeletons: A Computer-Aided Design Tool for Shaping and Patterning of Knitted Garments. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 53–65.

[12] Alexandre Kaspar, Tae-Hyun Oh, Liane Makatura, Petr Kellnhofer, and Wojciech Matusik. 2019. Neural Inverse Knitting: From Images to Manufacturing Instructions. In *Proceedings of the 36th International Conference on Machine Learning (Proceedings of Machine Learning Research, Vol. 97)*, Kamalika Chaudhuri and Ruslan Salakhutdinov (Eds.). PMLR, Long Beach, California, USA, 3272–3281.

[13] Alexandre Kaspar, Kui Wu, Yiyue Luo, Liane Makatura, and Wojciech Matusik. 2021. Knit sketching: from cut & sew patterns to machine-knit garments. *ACM Transactions on Graphics (TOG)* 40, 4 (2021), 1–15.

[14] Ozgun Kilic Afsar, Ali Shtarbanov, Hila Mor, Ken Nakagaki, Jack Forman, Karen Modrei, Seung Hee Jeong, Klas Hjort, Kristina Höök, and Hiroshi Ishii. 2021. OmniFiber: Integrated Fluidic Fiber Actuators for Weaving Movement Based Interactions into the 'Fabric of Everyday Life'. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1010–1026.

[15] Jin Hee (Heather) Kim, Kunpeng Huang, Simone White, Melissa Conroy, and Cindy Hsin-Liu Kao. 2021. KnitDermis: Fabricating Tactile On-Body Interfaces Through Machine Knitting. In *Designing Interactive Systems Conference 2021* (Virtual Event, USA) *(DIS '21)*. Association for Computing Machinery, New York, NY, USA, 1183–1200.

[16] Jin Hee (Heather) Kim, Shreyas Dilip Patil, Sarina Matson, Melissa Conroy, and Cindy Hsin-Liu Kao. 2022. KnitSkin: Machine-Knitted Scaled Skin for Locomotion. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 391, 15 pages.

[17] Ara Nerses Knaian. 2010. *Electropermanent magnetic connectors and actuators: devices and their application in programmable matter*. Ph. D. Dissertation. Massachusetts Institute of Technology.

[18] Susan Lederman and Roberta Klatzky. 2009. Haptic Perception: A Tutorial. *Attention, perception & psychophysics* 71 (10 2009), 1439–59.

[19] Hongnan Lin, Liang He, Fangli Song, Yifan Li, Tingyu Cheng, Clement Zheng, Wei Wang, and HyunJoo Oh. 2022. FlexHaptics: A Design Method for Passive Haptic Inputs Using Planar Compliant Structures. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 169, 13 pages.

[20] James D. Livingston. 1996. Driving Force: The Natural Magic of Magnets. *American Journal of Physics* 64, 12 (1996), 1532–1532.

[21] Yiyue Luo, Evelina Barhudarian, and Teddy Seyed. 2023. Project Mihr: Enabling Gestural Interactions on a Keyboard Using a Graphene-Based Fabric. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI EA '23)*. Association for Computing Machinery, New York, NY, USA, Article 236, 7 pages.

[22] Yiyue Luo, Yunzhu Li, Pratyusha Sharma, Wan Shou, Kui Wu, Michael Foshey, Beichen Li, Tomás Palacios, Antonio Torralba, and Wojciech Matusik. 2021. Learning human–environment interactions using conformal tactile textiles. *Nature Electronics* 4, 3 (2021), 193–201.

[23] Yiyue Luo, Kui Wu, Tomás Palacios, and Wojciech Matusik. 2021. KnitUI: Fabricating Interactive and Sensing Textiles with Machine Knitting. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 668, 12 pages.

[24] Yiyue Luo, Kui Wu, Andrew Spielberg, Michael Foshey, Daniela Rus, Tomás Palacios, and Wojciech Matusik. 2022. Digital Fabrication of Pneumatic Actuators with Integrated Sensing by Machine Knitting. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 175, 13 pages.

[25] Alex Mazursky, Shan-Yuan Teng, Romain Nith, and Pedro Lopes. 2021. MagnetIO: Passive yet Interactive Soft Haptic Patches Anywhere. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 213, 15 pages.

[26] James McCann. 2017. The "Knitout" (.k) File Format. [Online]. Available from: https://textiles-lab.github.io/knitout/knitout.html.

[27] James McCann, Lea Albaugh, Vidya Narayanan, April Grow, Wojciech Matusik, Jennifer Mankoff, and Jessica Hodgins. 2016. A compiler for 3D machine knitting. *ACM Transactions on Graphics (TOG)* 35, 4 (2016), 1–11.

[28] Sara Mlakar, Mira Alida Haberfellner, Hans-Christian Jetter, and Michael Haller. 2021. Exploring Affordances of Surface Gestures on Textile User Interfaces. In *Designing Interactive Systems Conference 2021* (Virtual Event, USA) *(DIS '21)*. Association for Computing Machinery, New York, NY, USA, 1159–1170.

[29] Vidya Narayanan, Kui Wu, Cem Yuksel, and James McCann. 2019. Visual knitting machine programming. *ACM Transactions on Graphics (TOG)* 38, 4 (2019), 1–13.

[30] Martin Nisser, Yashaswini Makaram, Lucian Covarrubias, Amadou Yaye Bah, Faraz Faruqi, Ryo Suzuki, and Stefanie Mueller. 2022. Mixels: Fabricating Interfaces Using Programmable Magnetic Pixels. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 8, 12 pages.

[31] Masa Ogata. 2018. Magneto-Haptics: Embedding Magnetic Force Feedback for Physical Interactions. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 737–743.

[32] Masa Ogata and Yuki Koyama. 2021. A Computational Approach to Magnetic Force Feedback Design. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 284, 12 pages.

[33] Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and Jürgen Steimle. 2015. Foldio: Digital Fabrication of Interactive and Shape-Changing Objects With Foldable Printed Electronics. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 223–232.

[34] Alex Olwal, Jon Moeller, Greg Priest-Dorman, Thad Starner, and Ben Carroll. 2018. I/O Braid: Scalable Touch-Sensitive Lighted Cords Using Spiraling, Repeating Sensing Textiles and Fiber Optics. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 485–497.

[35] Jifei Ou, Daniel Oran, Don Derek Haddad, Joseph Paradiso, and Hiroshi Ishii. 2019. SensorKnit: architecting textile sensors with machine knitting. *3D Printing and Additive Manufacturing* 6, 1 (2019), 1–11.

[36] Fabrizio Pece, Juan Jose Zarate, Velko Vechev, Nadine Besse, Olexandr Gudozhnik, Herbert Shea, and Otmar Hilliges. 2017. MagTics: Flexible and Thin Form Factor Magnetic Actuators for Dynamic and Wearable Haptic Feedback. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 143–154.

[37] Huaishu Peng, François Guimbretière, James McCann, and Scott Hudson. 2016. A 3D Printer for Interactive Electromagnetic Devices. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 553–562. https://doi.org/10.1145/2984511.2984523

[38] Hayes Raffle, James Tichenor, and Hiroshi Ishii. 2004. Super Cilia skin: A textural interface. *Textile* 2, 3 (2004), 328–347.

[39] Michael L. Rivera, Melissa Moukperian, Daniel Ashbrook, Jennifer Mankoff, and Scott E. Hudson. 2017. Stretching the Bounds of 3D Printing with Embedded Textiles. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 497–508.

[40] José-Luis Rodríguez, Ramiro Velázquez, Carolina Del-Valle-Soto, Sebastián Gutiérrez, Jorge Varona, and Josué Enríquez-Zarate. 2019. Active and Passive Haptic Perception of Shape: Passive Haptics Can Support Navigation. *Electronics* 8, 3 (2019), 12 pages. https://www.mdpi.com/2079-9292/8/3/355

[41] Martin Schmitz, Jan Riemann, Florian Müller, Steffen Kreis, and Max Mühlhäuser. 2021. Oh, Snap! A Fabrication Pipeline to Magnetically Connect Conventional and 3D-Printed Electronics. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 420, 11 pages. https://doi.org/10.1145/3411764.3445641

[42] Evan Strasnick, Jackie Yang, Kesler Tanner, Alex Olwal, and Sean Follmer. 2017. ShiftIO: Reconfigurable Tactile Elements for Dynamic Affordances and Mobile Interaction. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 5075–5086.

[43] Ryo Suzuki, Abigale Stangl, Mark D. Gross, and Tom Yeh. 2017. FluxMarker: Enhancing Tactile Graphics with Dynamic Tactile Markers. In *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility* (Baltimore, Maryland, USA) *(ASSETS '17)*. Association for Computing Machinery, New York, NY, USA, 190–199.

[44] Ryo Suzuki, Junichi Yamaoka, Daniel Leithinger, Tom Yeh, Mark D. Gross, Yoshihiro Kawahara, and Yasuaki Kakehi. 2018. Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 99–111. https://doi.org/10.1145/3242587.3242659

[45] Jenny Underwood. 2009. *The design of 3D shape knitted preforms*. Ph. D. Dissertation. RMIT University.

[46] Irmandy Wicaksono, Peter G Hwang, Samir Droubi, Franny Xi Wu, Allison N Serio, Wei Yan, and Joseph A Paradiso. 2022. 3DKnITS: Three-dimensional Digital Knitting of Intelligent Textile Sensor for Activity Recognition and Biomechanical Monitoring. In *2022 44th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*. IEEE, IEEE Computer Society, Los Alamitos, CA, USA, 2403–2409.

[47] Kui Wu, Marco Tarini, Cem Yuksel, Jim McCann, and Xifeng Gao. 2021. Wearable 3D Machine Knitting: Automatic Generation of Shaped Knit Sheets to Cover Real-World Objects. *IEEE Transactions on Visualization & Computer Graphics* 1, 01 (feb 2021), 1–1.

[48] Kentaro Yasu. 2017. Magnetic Plotter: A Macrotexture Design Method Using Magnetic Rubber Sheets. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4983–4993.

[49] Kentaro Yasu. 2019. Magnetact: Magnetic-Sheet-Based Haptic Interfaces for Touch Devices. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–8.

[50] Kentaro Yasu. 2020. MagneLayer: Force Field Fabrication by Layered Magnetic Sheets. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–9.

[51] Tianhong Catherine Yu and James McCann. 2020. Coupling Programs and Visualization for Machine Knitting. In *Proceedings of the 5th Annual ACM Symposium on Computational Fabrication* (Virtual Event, USA) *(SCF '20)*. Association for Computing Machinery, New York, NY, USA, Article 7, 10 pages.

[52] Cem Yuksel, Jonathan M. Kaldor, Doug L. James, and Steve Marschner. 2012. Stitch Meshes for Modeling Knitted Clothing with Yarn-level Detail. *ACM Trans. Graph. (Proceedings of SIGGRAPH 2012)* 31, 3, Article 37 (2012), 12 pages.

[53] Juan Jose Zarate, Olexandr Gudozhnik, Anthony Sébastien Ruch, and Herbert Shea. 2017. Keep in Touch: Portable Haptic Display with 192 High Speed Taxels. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI EA '17)*. Association for Computing Machinery, New York, NY, USA, 349–352.

[54] Shengdong Zhao, Pierre Dragicevic, Mark Chignell, Ravin Balakrishnan, and Patrick Baudisch. 2007. Earpod: Eyes-Free Menu Selection Using Touch Input and Reactive Audio Feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '07)*. Association for Computing Machinery, New York, NY, USA, 1395–1404.

[55] Clement Zheng, Jeeeun Kim, Daniel Leithinger, Mark D. Gross, and Ellen Yi-Luen Do. 2019. Mechamagnets: Designing and Fabricating Haptic and Functional Physical Inputs with Embedded Magnets. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 325–334.

[56] Clement Zheng, HyunJoo Oh, Laura Devendorf, and Ellen Yi-Luen Do. 2019. Sensing Kirigami. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 921–934.

[57] Clement Zheng, Zhen Zhou Yong, Hongnan Lin, HyunJoo Oh, and Ching Chiuan Yen. 2022. Shape-Haptics: Planar & Passive Force Feedback Mechanisms for Physical Interfaces. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 171, 15 pages.

[58] Junyi Zhu, Lotta-Gili Blumberg, Yunyi Zhu, Martin Nisser, Ethan Levi Carlson, Xin Wen, Kevin Shum, Jessica Ayeley Quaye, and Stefanie Mueller. 2020. CurveBoards: Integrating Breadboards into Physical Objects to Prototype Function in the Context of Form. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13.

[59] Junyi Zhu, Yunyi Zhu, Jiaming Cui, Leon Cheng, Jackson Snowden, Mark Chounlakone, Michael Wessely, and Stefanie Mueller. 2020. MorphSensor: A 3D Electronic Design Tool for Reforming Sensor Modules. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 541–553. https://doi.org/10.1145/3379337.3415898

[60] Lara Zlokapa, Yiyue Luo, Jie Xu, Michael Foshey, Kui Wu, Pulkit Agrawal, and Wojciech Matusik. 2022. An Integrated Design Pipeline for Tactile Sensing Robotic Manipulators. In *2022 International Conference on Robotics and Automation (ICRA)*. IEEE, IEEE Computer Society, Los Alamitos, CA, USA, 3136–3142.