Democratizing Magnetic Soft Materials Fabrication

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ABSTRACT

While the last decade of HCI research has seen a rapid increase in stimuli-responsive materials and soft devices, few works have leveraged magnetic soft materials despite their range of benefits for both sensing and actuation. They are inherently compliant (a benefit to wearability and shape-change), can readily operate untethered (unlike similar soft mechanisms, e.g., pneumatics, tendon-driven actuators, etc.), and are relatively easy to control via magnetic fields. Moreover, magnetic soft materials can be made with a relatively simple fabrication process: simply doping silicone with magnetic powder, such as neodymium, and curing in a strong magnetic field. In this paper, we distill techniques for fabricating magnetic soft materials and devices to make them more accessible to HCI researchers and designers.

Author Keywords

soft magnets; fabrication; soft robotics

INTRODUCTION

Motivated by promises of better compatibility with the human body, the development of soft robots has advanced rapidly in recent years. For example, soft robots can now walk and run [6, 22], climb [23], swim [8, 21], grip [4, 27], and more. In parallel, the field of human-computer interaction (HCI) has adopted and developed interactive devices based on soft robotics and materials principles. For example, pneumatics has been used to realize deployable and variable stiffness interfaces in works like PneUI [28], Pupop [24], Jamming UIs [11], and JamSheets [20]. Other works have directly used stimuli-responsive materials for shape-change and haptics, such as ModiFiber [12], MimicTile [19], and HapSense [29], just to name a few.

Despite the clear advantages of mechanical compliance, soft devices still face a significant challenge that limits their practical use: conventional soft actuators that are driven by fluids (pneumatics and hydraulics), wire tendons, or high-power electronics often must be tethered to pumps and power sources. While there have been growing advances in creating soft pumps [5] and energy sources [2, 25] to overcome these challenges, these have yet to mature to a point of easy adoption for users beyond material scientists due to their own challenges, such as high voltages and/or complex electrochemistry. In contrast, other soft robotics efforts have centered around soft materials that respond to magnetic fields. Unlike electrically-controlled or fluid-driven systems, magnetic materials naturally lend themselves well to *untethered* operation because they may be sensed and actuated without contact. For example, magnetic microrobots may be steered within an environment by controlling an external magnetic field [16, 26]. Additionally, magnetic skins have been used as tactile and wearable sensors with minimal need for wiring [1, 14]. Research on fabrication has demonstrated the ability to design soft magnets with custom polarity by manipulating the applied magnetic field during curing; this allows for tunable behavior when the cured magnet is exposed to a field, resulting in programmable shapes and locomotion [16, 17, 26].

Still, magnetic soft materials have yet to see wide adoption within the HCI community. In our CHI 2021 work, MagnetIO [18], we developed a haptic device based on soft and stretchable magnets. MagnetIO is composed of two components: (1) a miniaturized electromagnetic coil worn on the user's fingernail and (2) silicone patches with regions of magnetic soft material that, when touched by the finger equipped with the coil, vibrate back against the user's fingerpad for tactile feedback. Notably, our magnetic soft patches are entirely passive; they only respond when attracted and repelled by the user's coil. The result is that many patches can be placed within an environment to enable ubiquitous haptics without concern for tethering to power or needing to replace many batteries. While our main contribution is on realizing haptic output for these passive patches via magnets, we also demonstrate one possible sensing mechanism by using the magnetic signature of the patches themselves, i.e., the user's fingernail-worn device detects the unique ID of each patch by using a magnetometer to read each patch's unique 3D magnetic field.

We believe MagnetIO to be just a first step in a potentially rich direction for HCI research involving magnetic soft materials. Thus, in this paper, we detail fabrication techniques for magnetic soft materials and devices as well as our experiences when developing MagnetIO to make these promising materials more accessible to HCI researchers and designers. Moreover, we open-source our hardware to accelerate replication[1].

FABRICATION METHODS

Magnetic soft materials consist of two parts: (1) a polymer matrix and (2) embedded magnetic particles. The polymer component contributes to the material's elasticity and the magnetic particles dictate the material's response to applied

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[1] https://github.com/humancomputerintegration/MagnetIO

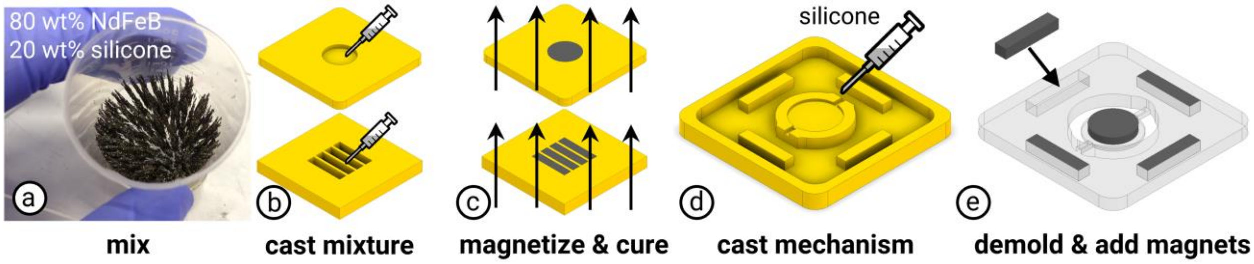

Figure 1. We fabricate MagnetIO patches by: (a) doping silicone with magnetic powder, (b) casting the doped silicone mixture into 3D printed molds of the desired shape, (c) curing the mixture in a strong, external magnetic field, (d) casting our mechanism out of silicone, and (e) adhering the soft magnets to the silicone mechanism

fields. Polymer matrices can be made from elastomers or gels. Most commonly, silicone has been used for its relatively easy fabrication process (simply mixing two liquid components and waiting for it to cure into an elastomer). In the case of MagnetIO, we used Dragonskin FX Pro as the polymer matrix for its fast cure time (40 mins, can be accelerated by curing in a dehydrator, making it ideal for rapid prototyping). Note that if the elasticity of the magnetic soft material is of great importance to the end application (e.g., for shape change), then it is important to choose a polymer with a corresponding modulus of elasticity.

Magnetic particles can generally be categorized into two groups: hard magnetic particles and soft magnetic particles, where hardness here refers to the magnetic notion of hardness rather than the mechanical notion. Hard magnetic materials can become stable, permanent magnets after being magnetized due to their high coercivity and high remanence. For MagnetIO, we used neodymium powder ($Nd_2Fe_{14}B$) for its particularly high remanence; having a stronger permanent magnet meant a stronger response to a given electromagnet. Hard magnetic materials can be sourced from scientific suppliers (e.g., Sigma Aldrich, Magnequench, etc.), but can also be found at a lower cost per quantity from Alibaba if purity is less critical. Alternatively, hard magnetic powder can easily be created by crushing commercial neodymium magnets (N52 grade for the highest strength) – they are rather brittle and can be ground by hand with a hammer. Note that the powder is already magnetized in this case but can be useful for prototyping with magnetic powder.

Conversely, soft magnetic particles are characterized by high magnetic susceptibility and saturation magnetization, but relatively low remanence and coercivity. This means that soft magnetic materials are strongly attracted to magnets and magnetize easily, but easily demagnetize as well. Common examples of soft magnetic materials are carbonyl iron and iron oxide powders. Soft magnetic materials are generally used for applications needing magnetostriction (deformation under magnetic field) or magnetorheological effects (stiffening under magnetic field) [3]. We experimented with soft magnetic materials for MagnetIO's patches but found the required field strength to induce an effect to be much greater than that of hard magnetic materials (which contribute their own field). This did not lend itself well to miniaturization and mobilization but may be of use for interactive devices that are grounded or have tighter magnetic coupling [7, 15]. However, we did use a soft magnetic material when designing our wearable electromagnetic coil, not for its stimuli-response, but to act as a ferrite core to concentrate the coil's magnetic field (see MagnetIO [18] for details).

Fabricating magnetic soft materials can be done in just a few simple steps. Before the start of the fabrication, we recommend filtering the magnetic powder through a mesh to remove any large particles that may increase the modulus of the material. **Error! Reference source not found.** illustrates the fabrication process used in MagnetIO to make soft magnetic patches. First, we mix the silicone (Dragonskin FX Pro) and NdFeB powder. The mixture is hand-stirred for 10 minutes and cast into a 3D printed mold to shape the magnet. The mold is then held between two strong permanent magnets (N52 0.75” x 0.75”, K&J Magnetics). This strong magnetic field (~1.1 T, handle these magnets with care for safety, i.e., wearing goggles, ensuring the magnets cannot slam together, avoiding placing any fingers between the magnets) magnetizes and aligns the polarities of the individual particles. This process results in a composite with a strong, permanent magnetic field while remaining flexible due to the silicone holding it together. Intending to maximize magnetic field strength to produce strong vibrations, we use an NdFeB weight concentration of 80%. Note that increasing the concentration of magnetic powder increases the stiffness of the resulting composite [1]. After the magnetic composite has cured, it may be removed from the mold. While the magnet may be stiff initially, it may be softened via stress softening (i.e., stretching, bending, etc.), i.e., the Mullins effect [9].

In the case of MagnetIO, we also make a mechanism using pure silicone, which embodies a spring. After both the silicone mechanism and soft magnets have cured, the interactive patch is assembled by adhering the magnets to the mechanism with silicone glue (Sil-Poxy). The total thickness of a patch is 2.5 mm. We designed MagnetIO patches to be attached to a wide variety of objects of different shapes, textures, and sizes. To adhere our patches to surfaces such as walls, objects, and even skin, we add a final layer of sticky silicone adhesive (Skin Tite) to the back of our patches.

Importantly, these fabrication techniques are simple relative to synthesizing other smart materials. Beyond the raw materials, permanent magnets, and a scale, all that is needed is a method to make molds, such as 3D printing which has become ubiquitous in maker spaces. It is important to review materials safety data sheets; in the case of magnetic powder, the greatest concerns arise from risks of inhalation and ingestion. Most of MagnetIO's development was done in a home-lab (due to COVID-19 precautions, but also a testament to the ease of making soft magnetic materials,).

DISCUSSION

We tend to think of MagnetIO not as an end-product but as a hardware & fabrication technique that will inspire the creation of a new type of passive-haptic interactive devices that may even unlock new use cases. For example, MagnetIO only explored ubiquitous haptics via vibrotactile feedback, a small subset of our tactile experience. It may be possible to create a range of other stimuli such as pressure and skin-stretch through similar mechanisms based on soft magnetic materials. Moreover, MagnetIO only examined magnets with one degree of polarity about the vertical axis, whereas it is possible to create programmable continuous deformations by programming multiple polarities into the material. Other mechanisms from the field of soft robotics, such as bistability, may be leveraged to create magnetically-triggered devices. In addition to actuation, soft magnetic materials may aid in the wearability of magnet-based sensors (such as Abracadabra [13]) owing to their ability to conform and stretch with our skin.

Soft magnetic materials are not without limitations, and whether soft magnetic materials are appropriate will depend on the end application. For instance, soft magnetic materials yield a reduced magnetic field strength when compared to rigid, sintered magnets. Thus, it can take additional power (a potential detriment to untethered use) or clever engineering to get responses equivalent to their rigid counterpart. Additionally, their field strength decays rapidly over distance; the application must naturally afford for the magnets to interact closely. For example, in MagnetIO, our approach only generates haptic sensations when the finger wearing the coil touches the interactive patch (12 mm from the coil to the patch), i.e., these patches cannot vibrate by themselves, though other works have integrated soft and stretchable coils into their designs [10].

CONCLUSION

Advances in the fields of smart materials and soft robotics have led to a wide range of sensors and actuators that lend themselves to interactive devices that can integrate with our bodies and environments. In MagnetIO, we leveraged magnetic soft materials to instrument surfaces with passive yet interactive patches – a step toward ubiquitous haptics. We believe magnetic soft materials offer a rich space for interactive devices that can circumvent challenges associated with conventional soft robotic approaches by being untethered and easy to fabricate. That said, magnetic materials do come with their own limitations; for instance, while they can be actuated at a distance via magnetic fields, the strength of the actuation drastically decays as the distance is increased. Therefore, choosing the right material will continue to depend on the end application. We hope that by elaborating upon techniques for fabricating magnetic soft materials and devices, we may inspire HCI researchers and designers to unlock new interaction possibilities through emerging, programmable materials.

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