

Mechamagnets: Designing and Fabricating Haptic and Functional Physical Inputs with Embedded Magnets

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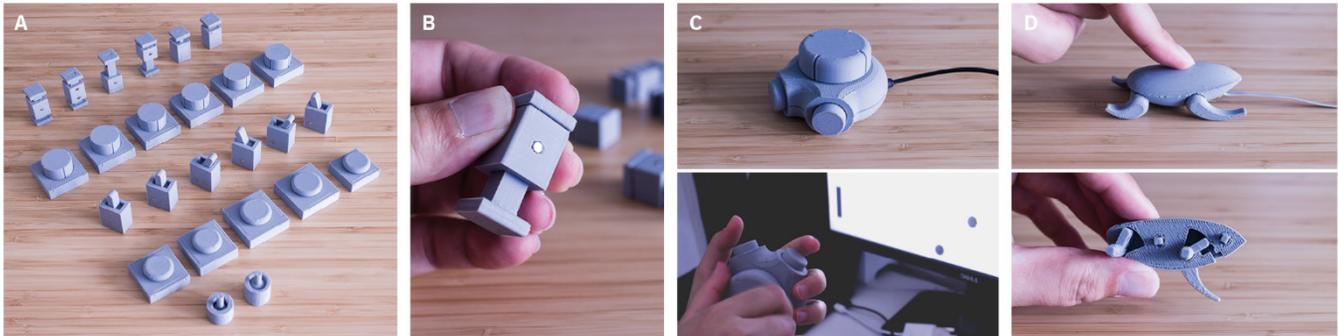


Figure 1. A) 3D printed *Mechamagnets* taxonomy. B) Exploring the *linear X attracting-center* input model. C) Ergonomic game controller designed with *Mechamagnets*. D) “Springy” legs by embedding the *angular X rotating-end* model in the toy frog’s body.

ABSTRACT

We present *Mechamagnets*, a technique for facilitating the design and fabrication of haptic and functional inputs for physical interfaces. This technique consists of a set of 3D printed spatial constraints which facilitate different physical movements, as well as unpowered haptic profiles created by embedding static magnets in 3D printed parts. We propose the *Mechamagnets* taxonomy to map the design space of this technique for designers and makers. Furthermore, we leverage the use of magnets by instrumenting these objects with linear Hall effect sensors to create functional digital inputs. We showcase *Mechamagnets* with a series of novel physical interfaces made with this technique.

Author Keywords

Prototyping; Haptics; Magnets; 3D Printing; Fabrication.

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INTRODUCTION

Affordable digital fabrication enables designers and makers to rapidly design and fabricate unique physical forms, while embedded electronic platforms, such as the *Arduino* ecosystem, facilitate the exploration of functional physical systems. These facilitate the creation of robust and interactive prototypes, particularly during the early stages of a design process. However, when creating such prototypes, designers must contend with off-the-shelf parts, constraining them to predefined geometries and mechanisms. In particular, designers of physical interfaces are often limited by prefabricated input components (such as push buttons). It is a challenge to comprehensively and freely specify features such as visual affordance, mechanical behavior and haptic feedback of physical interfaces when designing with off-the-shelf parts.

Haptic feedback is an integral part of our interactions with physical interfaces. It facilitates task performance, like in robot-assisted surgery [19]; and it also contributes to the satisfaction of an experience, evident in the wide variety of custom controllers and “tactile” keyboards for gaming [21]. In addition, prototyping bespoke physical interfaces is an important process within product design. Notably, BMW’s dedicated haptics team specifies the form, feel, and function of every physical input that goes into the car [2].

Our goal is to facilitate the design and fabrication of haptic and functional physical interfaces in a holistic and economical manner. In this paper, we build on previous work [23] and describe *Mechamagnets* as a technique for

creating bespoke physical input components. Our technique supports designers and makers who use computer-aided design (CAD) and digital fabrication, and it leverages the use of commodity 3D printers in design studios and makerspaces. In this paper, we detail the three core parts of the *Mechamagnets* technique. First, physical interactions are defined using simple spatial (physical) constraints which we identified by deconstructing existing physical inputs (Table 1); for instance, constraining a body to move linearly along a hollow track. Second, static magnets are configured and embedded in the fabricated parts to define the mechanical behavior of physical inputs, as well as deliver haptic feedback during interaction (Figure 4). Third, linear Hall effect sensors are placed in the fabricated input to read and communicate its state (Figure 6). We provide a taxonomy to illustrate basic input models afforded by *Mechamagnets*, and to map the design space of this technique for designers and makers (Figure 5).

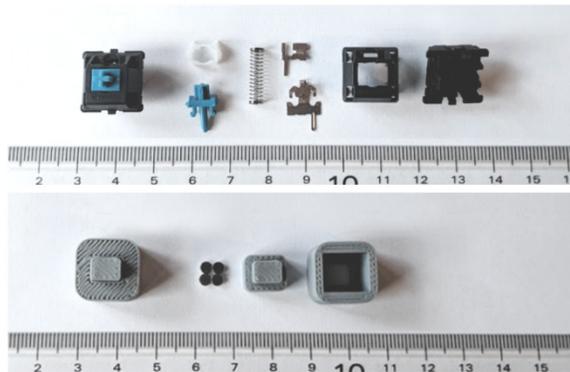


Figure 2. Assembled and disassembled. Top: Cherry MX Blue switch. Bottom: *Mechamagnets* switch with similar haptic feedback and mechanical behavior.

RELATED WORK

Embedding materials and mechanisms into 3D printed objects

3D printers, particularly fused deposition modeling (FDM) machines, are restricted to printing using a small set of materials. This, in turn, limits the material properties of parts that can be fabricated via additive manufacturing. Researchers have proposed a variety of techniques to address this constraint. *Medley* [3] is a design tool that facilitates compositing external materials in 3D printed parts. It offers a library of common materials with different functional properties, such as bendable florists' wire and soft sponge. In the same vein, *Reprise* [4] supports customizing existing products with 3D printed attachments. Researchers have also explored creating metamaterial mechanisms [10] by 3D printing internal microstructures that vary the properties of a material within a part. While no external materials are used, here the limitation is size: the fabrication resolution of 3D printers affects the scale of microstructures, which places minimum size constraints on parts needed to deliver a mechanism.

Mechamagnets extends this research by investigating the affordances of static magnets embedded in 3D printed parts. With a simple inventory, we demonstrate a variety of unpowered haptic profiles that work across different types of physical inputs that move within several degrees of freedom.

Generating haptic feedback with static magnets

Other projects have investigated static magnets for haptic interaction, as they produce force-feedback without external power when moved relative to one another. Static magnets also come in simple physical forms like cylinders and cuboids. As such, they are an ideal material to embed in physical parts to generate haptic feedback. *Haptic Cues* [20] enables users to feel an invisible texture through the force produced by moving magnets sandwiched across a textured plastic surface. *Magnetic Plotter* [22] explores haptic patterns through drawing variable patterns on a soft magnetic sheet. When two sheets are rubbed together, the patterns create different vibratory feedback. *GaussBricks* [13] investigates elastic textures afforded by a chain of static magnets; including clicking, bending, stretching and squeezing. In *Mechamagnets*, we demonstrate how embedding static magnets in 3D printed parts can deliver haptic feedback and the mechanical behavior of physical inputs in tandem.

Creating functional physical inputs

Electronic platforms and toolkits such as *Arduino* [24], *Phidgets* [8], *Calder* [12], and *Makers' Marks* [17] facilitate prototyping functional physical interfaces. However, these systems limit designers to prefabricated components. Other systems support designing and fabricating functional physical inputs with digital fabrication. In *Sauron* [16], computer vision senses the state of 3D printed physical inputs. *Lamello* [18] utilizes a microphone to read an input by parsing the audio signal generated by 3D printed tines. These systems minimize the electronics needed for instrumenting the fabricated input. *Sauron* requires embedding a camera into the fabricated object, while *Lamello* requires additional 3D printed structures for passive sound generation. With *Mechamagnets*, small static (neodymium) magnets are employed to deliver haptic feedback. We embed these magnets in combination with individual linear Hall effect sensors to create functional 3D printed inputs. These sensors are inexpensive, and come in small and simple physical packages. They are used to sense the position and orientation of physical parts in many commercial applications, such as car steering and machine controls. The design of tangible interfaces has also explored this method of instrumentation. For example, *MagGetz* [9] and *MagnID* [1] employs the magnetometer (a 3-axis linear Hall effect sensor) built into smart devices to detect the states of physical inputs and positions of tangible tokens respectively. *GaussBricks* employs a surface instrumented with a grid of Hall effect sensors to detect the position and configuration of models composed of a magnet-based construction assembly kit.

Type	Linear	Polar	Angular	Planar	Radial
Diagram					
Related Actions & Examples	push, pull, slide push button, slider	turn, twist, scroll dial, knob, scroll wheel	flip switch, lever	slide, pan thumbstick, gear shift	tilt joystick, trackball

Table 1: Five spatial constraints, with related actions and examples

MECHAMAGNETS

There are three core aspects to the *Mechamagnets* technique: 1) designing the form and function of physical interactions through spatial constraints, 2) designing mechanical behavior and haptic feedback with embedded magnets, and 3) instrumenting input components into functional devices with linear Hall effect sensors. We unpack each aspect in the following sections and describe how they interact.

Form and function via spatial constraints

Mechamagnets applies to any plastic additive manufacturing process, however, we focused on the capabilities of desktop FDM machines due to their pervasive use in studios and makerspaces. Mass-produced physical inputs typically employ injection molding and automated assembly lines. Their designs rely on a high degree of manufacturing tolerance that is unattainable with FDM (Figure 2 top). As such, rather than mimic the construction of commercial components, we developed *Mechamagnets* by deconstructing existing physical inputs into simpler models.

We can characterize many existing physical inputs by constraining the movements of a pair of 3D bodies with different cavity shapes. *Mechamagnets* proposes five types of spatial constraints (Table 1). Although this is not an exhaustive set of possible physical interactions, it addresses a wide range of movements found in existing physical inputs. Mackinlay and colleagues proposed a taxonomy [14] that describes physical inputs as transducers of linear or rotary movements, in any of the six spatial Cartesian degrees of freedom. We build on this work by demonstrating solid geometries for 3D printing that afford different degrees of linear and rotary movements.

Linear spatial constraint: to move along a linear track. Commonly associated interactions are pushing and pulling.

Polar spatial constraint: to rotate about an axis. Commonly associated interactions are turning, twisting and scrolling.

Angular spatial constraint: to pivot on a point, typically in the form of an extended arm. Flipping is a common interaction associated with this model.

Planar spatial constraint: to slide along a two dimensional plane. Commonly associated interactions include sliding and panning.

Radial spatial constraint: to pitch and roll around a point. Tilting and rolling are commonly associated interactions.

These spatial constraints abstract input interactions into different classes of physical movements, and create opportunity for designers to specify input components in relation to the rest of a physical interface (Figure 8A, 8D). These models also serve as building blocks for constructing more complex physical interactions and unconventional inputs; such as by compounding similar movements (Figure 8B), or blending different movements (Figure 8C). Furthermore, the deconstructed models offer other advantages. The spatial constraints are straightforward to create in 3D CAD programs through a “subtraction” operation and do not require high resolution fabrication, thus optimizing parts for FDM. They also simplify embedding magnets and sensors into parts; two important aspects of this technique that will be discussed below.

Haptic feedback and mechanical behavior via static magnets

Commercial inputs rely on an assembly of different components to deliver haptic feedback and mechanical behavior. For instance, a mechanical keyboard button uses contact leaves to generate a “click” when it is pressed (haptic feedback), and a spring to push it back to its original position (mechanical behavior) (Figure 2 top). In *Mechamagnets*, we investigated using only static magnets and 3D printing (Figure 2 bottom) to specify different unpowered haptic feedback as well as mechanical behaviors of inputs. To inform our development of these mechanisms, we first characterized the forces generated by magnets as they move relative to each other. With this characterization, we propose six different haptic profiles for physical inputs by embedding static magnets.

Magnet-movement interactions

Haptic feedback is broadly categorized into *kinesthetic* and *tactile* feedback. Kinesthetic feedback results from forces felt due to body movement, whereas tactile feedback results from stimulation to the skin [6]. Physical input components provide both kinesthetic and tactile feedback, and Kim et al.

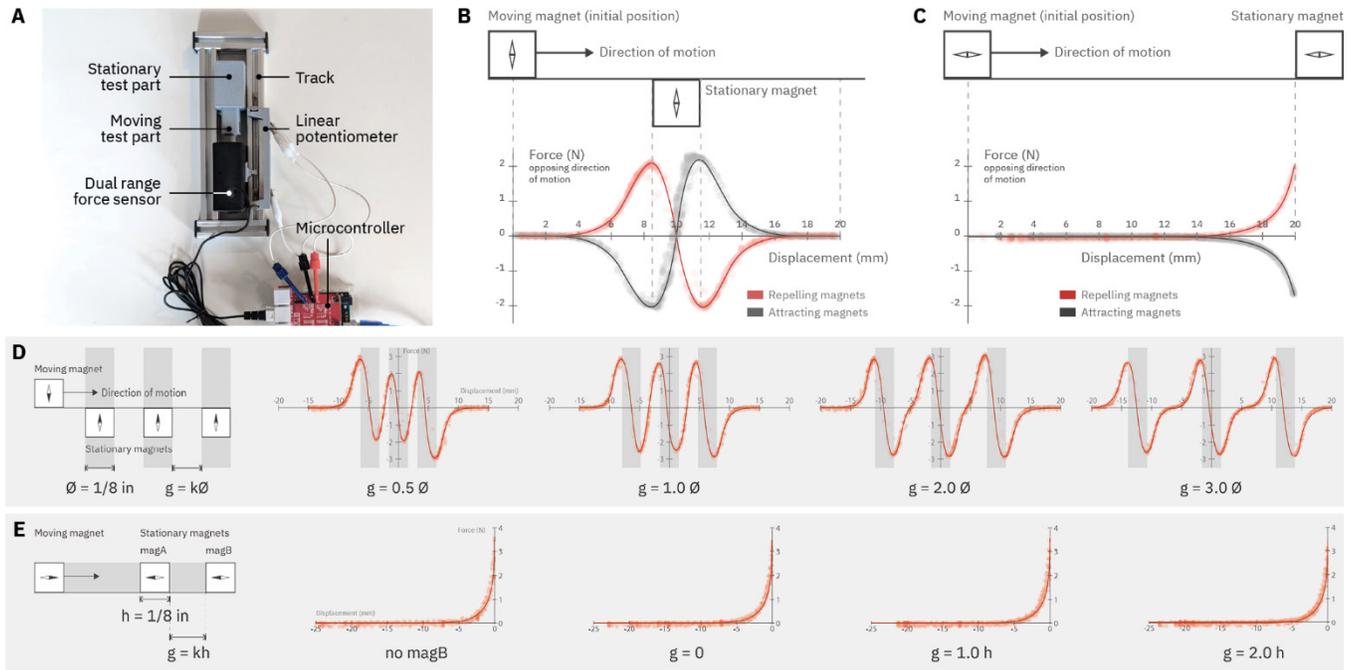


Figure 3. A: Force measurement rig. B: Force-displacement curves of magnets moving perpendicularly, C: coaxially. D: Inter-magnet interactions test of magnets moving perpendicularly, E: coaxially.

demonstrated the usefulness of force-displacement curves to quantify and simulate the haptic feedback of such inputs [11]. We employ the same measurement to characterize the unpowered haptic feedback provided by moving static magnets relative to each other.

We organize magnet-movement interactions based on their attraction / repulsion, and their relative movements (perpendicular / coaxial). Perpendicular magnets travel in a direction normal to their polar axis; while in coaxial movement, magnets travel in line with their poles. We constructed a rig to measure the force-displacement curves of these four interactions (Figure 3A). It consists of a dual-range force sensor [25] physically coupled to a linear potentiometer to measure displacement. This force sensor pushes and pulls a 3D printed part relative to a stationary part. We tested 1/8" by 1/8" N48 cylindrical neodymium magnets embedded in FDM-printed parts to account for forces, such as friction, that might result from physical inputs fabricated with 3D printing. Using this rig, we plotted more than a thousand force-displacement

measurements distributed across a 20mm range. Figure 3 illustrates the magnets' setup, and the corresponding measurements for each magnet-movement interaction. From these measurements, we generated four different force-displacement curves (Figure 3B/C). We use these curves to visualize the haptic feedback generated by moving static magnets to develop different feedback profiles for physical inputs.

In addition, we explored inter-magnet interactions with the same rig. The force-displacement curves of a 1/8" by 1/8" N48 cylindrical neodymium magnet moving perpendicularly across three laterally spaced similar magnets were measured (Figure 3D). Two insights emerged from these measurements. First, while discrete "steps" are still observed at $g=0.5\text{Ø}$ (1/16"), inter-magnet interactions are apparent as indicated by the diminished forces measured while traversing the middle magnet. Second, as the gap increases, we noticed a flattening of the curves between magnets. At $g=3.0\text{Ø}$ (3/8"), this curve is completely flat between magnets. This suggests that, as a heuristic, the

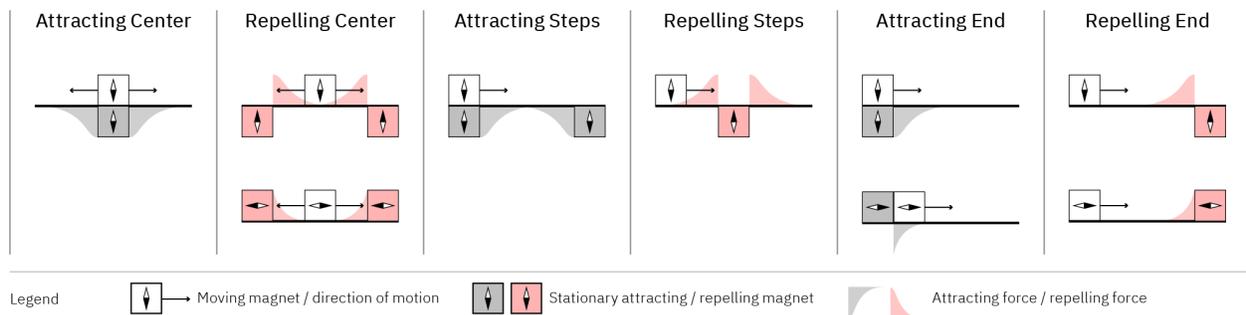


Figure 4: Six haptic feedback profiles for physical inputs through embedding static magnets in 3D printed parts.

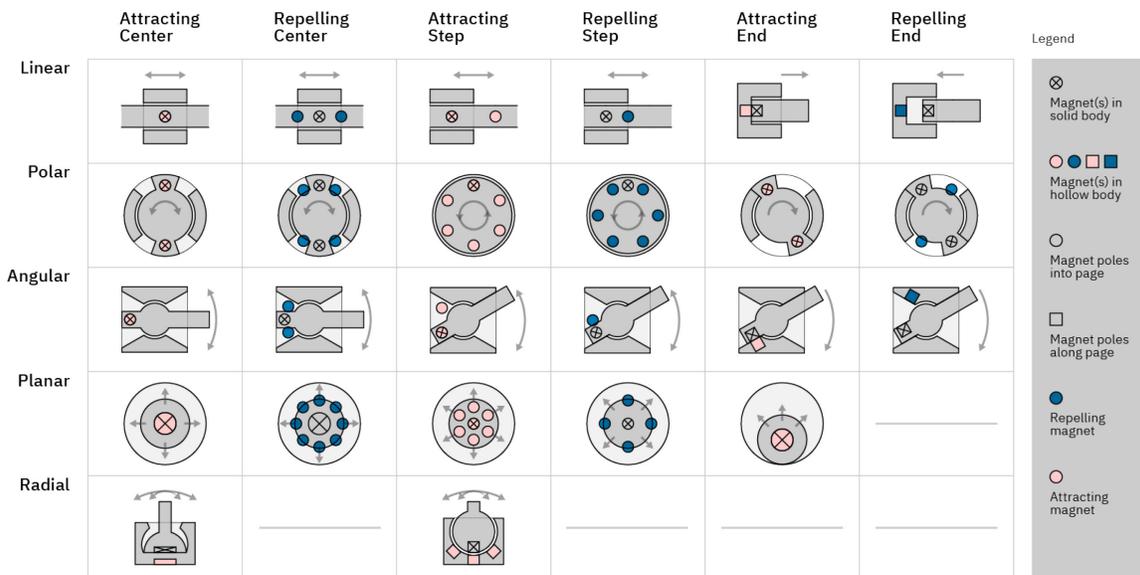


Figure 5. Mechamagnets Taxonomy.

magnetic fields on the surface of 1/8" neodymium magnets with a lateral separation of 3/8" have negligible influence on each other. We conducted the same test for coaxially arranged magnets, and found negligible inter-magnet interaction even when stacked pole-to-pole (Figure 3E).

Unpowered haptic profiles

Building on these magnet-movement interactions, we define six basic unpowered haptic feedback profiles for physical inputs, realized by embedding static magnets in 3D printed parts. We describe these haptic profiles through the magnetic forces at play, and the mechanical behavior they provide during interaction. Figure 4 illustrates these six profiles. We use the force-displacement curves from the previous section, and visualize them in terms of attraction or repulsion. The slope of the curves indicates the direction of force—an inclining slope means that magnets oppose movement; a declining slope indicates that the magnets augment movement.

Attracting / Repelling Center: This pair of profiles encourages a stable “center”; magnets push the input component to a central position during interaction; for example, in a joystick. For attracting center, users experience a larger initial force opposing their movements, which weakens over distance. For repelling center, an increasing force opposes movements as distance from the center increases.

Attracting / Repelling Steps: This pair of profiles introduces “steps” along the interaction path of an input. For attracting magnets, steps are stable locations that the input “snaps” to. Repelling magnets act in reverse; steps oppose movement, and users must exert more force to “push over” a step. Detented inputs such as rotary encoders with discrete “ticks” are examples of such mechanisms.

Attracting / Repelling End: This pair of profiles encourages a stable “end”. For attracting end, users overcome a larger initial force to move the input, and this force weakens over distance. For repelling end, users experience an increasing opposing force as they move the input. Push buttons and pull cords are examples of mechanisms with a stable end.

Mechamagnets Taxonomy

By crossing the five spatial constraints and six haptic profiles, we developed a *Mechamagnets* taxonomy to map the possibilities for other designers and makers. It contains 25 basic input models¹ (Figure 5). Each model illustrates spatial constraints through a “hollow” and “solid” body, as well as the configuration of magnets within these bodies for different haptic profiles.

Each diagram in the taxonomy presents one instance of combining a spatial constraint with a haptic profile; and it is important to note that parameters can be varied for each model. For instance, in the *angular X repelling-step* model, designers can vary its degree of rotation by changing the angle between the stops in its hollow body. Designers can also add steps by embedding more repelling magnets along the input’s interaction path. Magnets are press fit into recesses printed in the parts. In developing this taxonomy, we constrained the magnets used to 1/8" by 1/8" N48 neodymium magnets; except for *radial X attracting-center*, *planar X attracting-center*, *planar X repelling-center*, and *planar X attracting-end*, where we used 1/4" by 1/16" N48 neodymium magnets.

¹ Not 30, as certain categories of haptic profiles are not applicable to the planar and radial spatial constraints; the friction generated between moving bodies will render the mechanism ineffective.

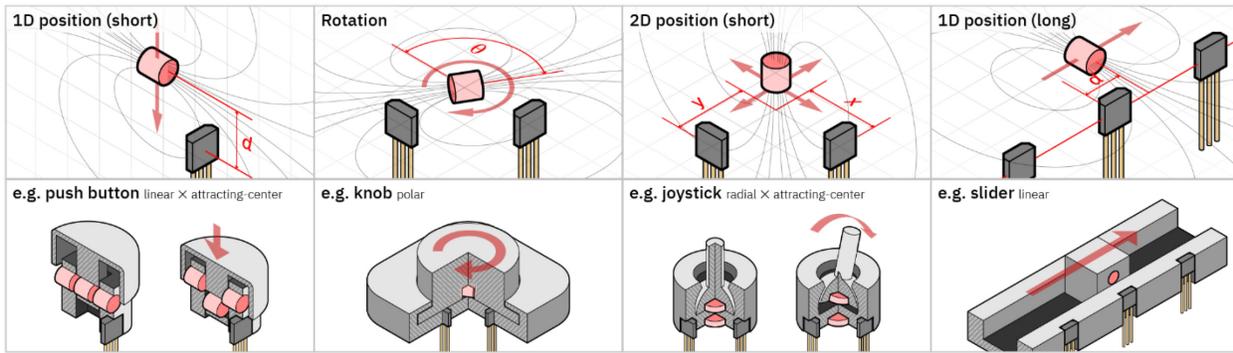


Figure 6. Four sensor configurations for detecting different types of magnet positions, and example uses for each configuration.

The models illustrated in this taxonomy were abstracted to be independent from specific 3D modeling applications. Besides the schematics in Figure 5, we further demonstrate each model in this taxonomy through *Fusion 360* parametric files, and STL files optimized for FDM fabrication. These are available through an online repository², and in this paper’s supplementary materials (Figure 1A/B).

Instrumentation via Linear Hall Effect Sensors

We instrument *Mechamagnet* components with linear Hall effect sensors to make functional input devices. A linear Hall effect sensor gives a continuous signal range from 0V to the supplied voltage, based on the strength and polarity of the magnetic field around it. Any microcontroller with an analog to digital converter can parse this signal. For our prototypes, we employed linear Hall effect sensors with sensitivities equal or less than 5mV/G to minimize external influences such as geomagnetism or magnetic fields generated by other objects.

Gaussbricks demonstrates using an external grid of linear Hall effect sensors to detect the state of magnetic tangible interfaces [13]. We extend this work by investigating instrumentation with individual Hall effect sensors for integrated and portable physical interfaces where multiple *Mechamagnet* inputs operate with different movement axes in an object (Figure 8). We embed these sensors into *Mechamagnet* components by fitting them into recesses modelled inside 3D printed parts. As analog devices, instrumenting *Mechamagnet* components with linear Hall effect sensors provides designers with more interaction information than conventional off-the-shelf inputs. For instance, designers can customize the activation point of an input. Sensors can also report variables such as the speed or force of human interaction. These measurements add nuance to simple input components like a push button. We use two variations of linear Hall effect sensors depending on the magnet’s strength, both with an effective sensing radius of approximately 10mm (see Table 2). We develop four sensor configurations for instrumenting different models in the *Mechamagnets* taxonomy. Figure 6 illustrates

the different configurations and example uses for each configuration. Depending on the type of input, we can either use magnets already employed for haptic feedback (see Figure 6 push button and joystick), or embed an additional magnet dedicated to sensing (see Figure 6 knob and slider). A single sensor can detect the proximity of nearby magnets (see technical document [7]). This configuration can detect interactions that travel a short distance, such as pressing a button, flipping a switch, or twisting a knob. Two sensors can be positioned at a right angle to detect the rotation of a magnet (see technical document [5]), such as in a continuous dial. The same two-sensor setup can also detect the 2D position of a magnet within a short range, as in sliding thumbsticks or joysticks. Multiple sensors can be arranged along a path for sensing the position of a magnet across a longer distance, useful for instrumenting inputs like linear sliders.

	Allegro A1324LUA-T	Allegro A1308KUA-1-T
Size	4 x 3 x 1.5mm	4 x 3 x 1.5mm
Sensitivity	5.0mV/G	1.3mV/G
Suggested magnet type	1/8" by 1/8" N48 neodymium magnets	1/4" by 1/16" N48 neodymium magnets

Table 2. Linear Hall effect sensor details.

To support this instrumentation method, we developed a library of scripts to calibrate sensor measurements for different input types. Not all magnets in a *Mechamagnet* component move and contribute to sensing; and the calibration scripts serve to establish a baseline from the component’s overall magnetic field. For example, the calibration script for 1D position identifies the minimum and maximum sensor reading; while the script for rotation identifies the center of rotation and zero-angle direction. These scripts are also open sourced through the online *Mechamagnets* repository.

DESIGNING WITH MECHAMAGNETS

Mechamagnets facilitates creating bespoke physical inputs with 3D printing, static magnets, and linear Hall effect sensors. It can be incorporated into the workflow (Figure 7) of prototyping physical interfaces with digital fabrication:

² <https://github.com/clementzheng/mechamagnets>

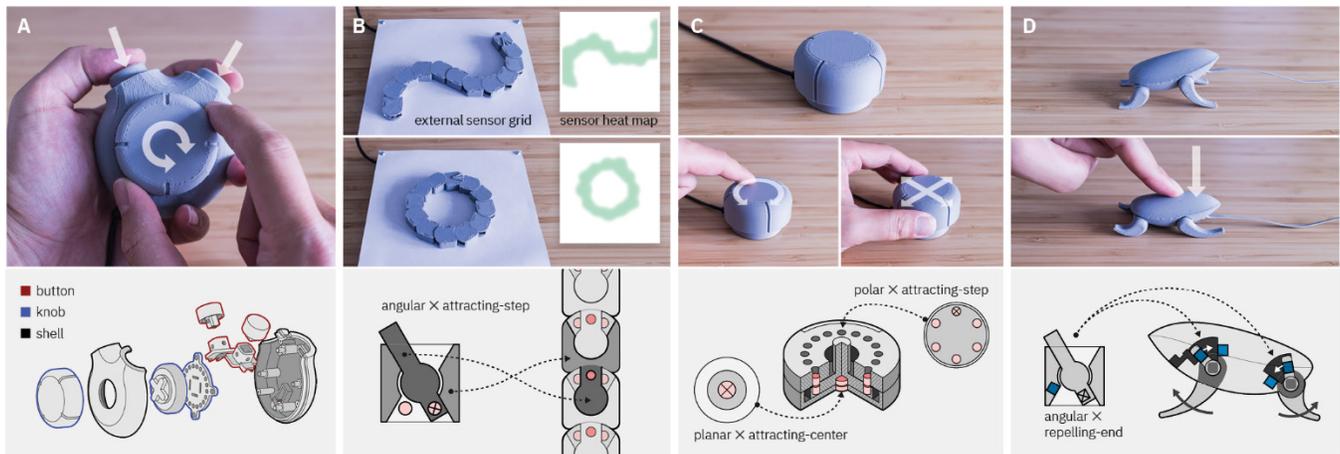


Figure 8. Physical interfaces designed with *Mechamagnets*: A) Ergonomic Game Controller, B) Switch Snake, C) Sliding Dial, and D) Toy Frog Button.

First, inputs are designed in CAD along with the other parts of a physical interface (Figure 7A); at this stage, the haptic profile is also specified and recesses are created for static magnets and linear Hall effect sensors. Second, the parts are fabricated with 3D printing (Figure 7B). Magnets and sensors are then inserted into these 3D printed parts (Figure 7C). Third, the parts are assembled to form the physical interface, and sensors are connected to a microcontroller (Figure 7D). We demonstrate this workflow and the capabilities of this technique through a series of novel physical interfaces designed with *Mechamagnets*.

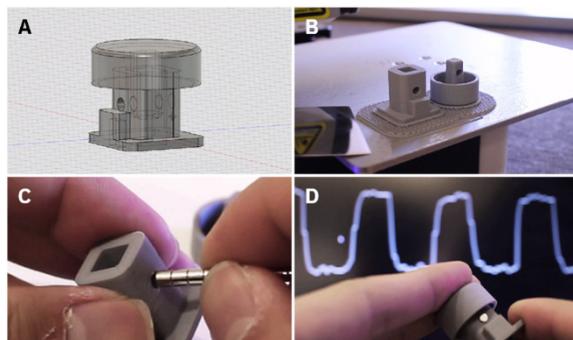


Figure 7. Mechamagnets workflow: A) Modelling in CAD, B) fabricating parts with FDM printing, C) embedding magnets, and D) embedding and calibrating linear Hall effect sensors.

Creating a new physical interface:
Ergonomic Game Controller

Physical interface design is an important part of the gaming industry. For example, video game company *Nintendo* [26] has released a myriad of game platforms with unique physical controllers, such as the *Wii*, *3DS*, *Switch* and its *Labo* construction kit extension. We demonstrate how *Mechamagnets* supports the industrial design of such interfaces by creating a set of physical game controllers for a *Pong*-like game (Figure 1C, 8A). The game controllers were designed based on the hand size measurements of one of the authors. Push buttons were created by adding end caps to the *linear X attracting-center* input model, and the

knob employs the *polar X attracting-step* input model. Inputs were positioned for easy access by the user. Each button was instrumented with a single linear Hall effect sensor, while the knob has two sensors to measure angle of rotation. *Mechamagnet's* input models enabled us to explore and specify haptic profiles its specific application. For instance, the game's main interaction is turning the knob, and we investigated different step intervals for this interaction's haptic feedback. We settled on 16 steps to create a satisfying sequence of light "bumps" when turning the knob. In addition, we were able to rapidly experiment with different actuation thresholds for the push button, till we found a point that the user felt was most responsive.

Compounding similar inputs: Switch Snake

The *Mechamagnets* taxonomy offers a range of basic input models on which designers can build and extend. The Switch Snake demonstrates how we compound an input model to create a novel physical interface. It comprises a chain of twelve *angular X attracting-step* modules. Each module has three steps separated at a 30° angle, which turn relative to one other. The schematic in Figure 8B shows how we connected multiple *angular X attracting-step* inputs by combining their solid and hollow bodies in a staggered fashion. Switch Snake is designed as a tangible interface where users manipulate its shape, and its modularity enables it to scale up to any length. Rather than embed sensors into 3D printed parts, we used an external grid of linear Hall effect sensors [13,27] to recognize the shape and position of this object (as shown in Figure 8B).

Blending different interactions: Sliding Dial

Mechamagnet's simple spatial constraints and haptic profiles also facilitate designers to blend different input types. We demonstrate this with the Sliding Dial (Figure 8C). This physical interface combines the *planar X attracting-center* input with the *polar X attracting-step* input to create a hybrid input that affords both sliding and turning. We first modelled a spatial constraint in the form of a hollow disc that supports sliding freely along its plane

and turning about its axis. We embedded the mechanism for the turning interaction in the top surface of this cavity, and mechanism for the sliding interaction in the bottom surface. Four linear Hall effect sensors instrument this interface: two for the turning interaction to measure angle of rotation, and two for the sliding interaction to measure displacement. We demonstrate how the Sliding Dial supports manipulating multi-dimensional controls for applications such as sound editing or graphic design.

Embedding Haptic and Functional Movements: Toy Frog Buttons

The input models offered by *Mechamagnets* can apply beyond conventional input components to create haptic and functional movements in a physical user interface. To demonstrate this, we put ourselves in the shoes of a toy designer and created a set of toy frogs (Figure 8D). We articulated the front and back legs of each toy frog with the *angular X repelling-step* input model. When the frog is pressed and released, its legs snap back with enough force to propel it into a different position. We embedded a linear Hall effect sensor in each toy frog, which measures the proximity of the magnets in the front mechanism. This transforms the toy frogs into a set of unconventional push buttons that hop around, and we use them to control a *Froger*-like game.

LIMITATIONS & FUTURE WORK

Taxonomy limitations

The *Mechamagnets* taxonomy illustrates the design space of basic physical input models possible with this technique, and we expect that designers can extend these inputs to create many new physical interfaces. However, this taxonomy certainly does not completely cover all types of physical inputs. We proposed five spatial constraints as building blocks for designers to compose different physical inputs. These are limited to inputs with active moving components afforded by these spatial constraints. In particular, it excludes inputs that do not involve moving a physical part, such as touchpads and trackpads.

Size constraints

The size of magnets and 3D printing resolution constrains the minimum size of interfaces composed of *Mechamagnet* components. In this paper, we explored using only 1/8" by 1/8" or 1/4" by 1/16" neodymium magnets, and commodity desktop FDM machines to fabricate *Mechamagnet* components. By keeping the inventory and process simple, we aimed to create an accessible technique for other designs and makers. For future work, we aim to create manual and automated tools that assist inserting differently sized (including smaller) magnets, as well as higher resolution additive manufacturing processes. Inter-magnet interactions also affect the distance between *Mechamagnet* components; placing components close to each other influences the haptic profiles (Figure 3D), and might trigger false positives when using embedded Hall effect sensors. Our heuristic, at this moment of writing, is to keep a

minimum lateral separation of 3/8" between components when using 1/8" by 1/8" neodymium magnets. The Hall effect sensors we employ for the two sizes of magnets used (Table 2) has an effective sensing radius of 10mm. By extension, the magnets participating in sensing a component should be at least 10mm apart for the sensors in another component. A tool that simulates the resultant 3D magnetic field generated by multiple *Mechamagnet* components can optimize the placement of components and sensors. *Magneto-haptics* [15] not only offers an efficient method to compute this, but also an approach of designing more complex haptic profiles with static magnets along a movement path. Future work will explore incorporating the *Magneto-haptics* simulation to inform the design of assemblies with *Mechamagnet* components.

Sensing constraints

We are interested in developing a technique to make integrated and portable prototypes of physical interfaces. As such, we investigated how to spatially arrange individual linear Hall effect sensors to detect different magnet movements. However, embedding these individual sensors for every single *Mechamagnet* component can be a time-consuming process. Such an approach also requires the interface to be physically tethered by wires to power the sensors as well as for data communication. For tabletop *Mechamagnet* interfaces (such as Figure 8C and D), an external sensor grid (see [13] and Figure 8B) can easily replace the embedded sensors, and thus free the interface from a physical tether. We plan to explore this external sensing approach in more depth for future work with surface-based interfaces. For portable applications, we aim to develop a physical computing kit, including breakout boards with pre-configured sensor arrangements, which easily "plug" into 3D printed parts.

CAD & design assistance

In this paper, we focused on generalizing this technique to make it applicable to different CAD and embedded electronics platforms. However, this also expects designers and makers be reasonably proficient in these practices to use *Mechamagnets* effectively. As mentioned above, we aim to develop a physical computing kit for *Mechamagnets* that facilitates placing and computing data from embedded Hall effect sensors. We also plan to further develop the current taxonomy into an interactive application. This interactive taxonomy will enable other designers to explore and customize each model based on different parameters, as well as simulate haptic feedback profiles and inform sensor placement. Designers can then download these customized models for further work in a CAD application they are comfortable with.

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