Freezing the Field

Robotic Extrusion Techniques Using Magnetic Fields

ABSTRACT

The introduction of robotics into the field of 3D printing allows designers and fabricators to truly print in three dimensions, focusing more on the volumetric properties of the extrusion rather than two-dimensional slicing and, furthermore, introducing forces that can defy gravity. This paper introduces a new method of robotic extrusion using magnetic fields to construct ferrostructures. Using a custom tool and ferromagnetic material, the research develops a construction process utilizing the off-plane toolpaths of a 6-axis industrial robotic arm to pull, attract, and repel material into a hardened structure. The ferromagnetic liquid forms spikes and connections around the invisible magnetic fields, and upon hardening, freezes the field into a new physical artifact. This extrusion process allows a fabrication that defies gravity. The robotic fabrication process allows microextrusions to build off of one another, scaling the result to approach an architectural scale and bringing a new freedom to the designer and the fabricator.
INTRODUCTION
Ferromagnetic materials are based off the principles of ferrofluids, a colloidal dispersion of nano-ferromagnetic particles suspended in a carrier liquid that reacts to permanent and electromagnets by forming into spikes along the force lines of the magnetic field (Odenbach 2009). Upon removal of the magnet, the fluid returns to a flat liquid state in the form of the container that it is held in (Figure 2). Introducing multiple magnets causes the liquid to jump and bifurcate along overlapping fields, creating nodes of spikes and suspended liquid in between, seemingly defying gravity as it reacts more to the magnetic field than to gravitational force (Figure 3).

While this fluid typically reacts and is understood to move in an unpredictable way, it can be influenced and controlled through magnetism. We looked specifically at Zelf Koelman’s project “Ferrolic” (2015), which examined the natural dynamics and structural possibilities of this fluid, not just for its aesthetic value. Koelman details how, in addition to the natural flow of the material as a clock, Ferrolic is used to form recognizable shapes and written characters. Using design paths by turning a grid of electromagnets on and off, Ferrolic uses both information layers in parallel in order to display scenes and transitions in a choreographed way. As ferrofluid is inherently impermanent, with the shapes and structures existing solely in the presence of a magnet, we sought to freeze that field by developing a material that could harden the ferrofluid form into a solid state. As Koelman capitalizes on the fluid’s malleability to choreograph stories, we want to choreograph a metallic material’s malleability by controlling the inherent forces and forms of a magnetic field as the ferrostructure’s main structural element.

The addition of a custom tool and robotic toolpaths allows for a repeatable and reliable formwork that shapes both the volumetric unit of nodes and connections as well as the aggregate of those nodes into a larger structure. We employed two methods of introducing the material to the magnetic field within the tool. The first is a pull method that attracts the material from a flat pool, a method influenced by the Gravity Tool and Stool and experiments of artist Jólan van der Wiel (2011). Van der Wiel’s art sandwiches a pool of ferromaterial between two large stacks of ceramic magnets, one of which is cranked up on a 1-axis winch, pulling a structure up to bench height. We began utilizing this pull method, replacing the winched magnet with a magnetic end effector for the robot, affording us more axes of motion. After scale limitations and awkward connection details, we developed a second method, the drip method, for which we redesigned the tool, and will continue to use.

Robotic 3D printing is redefining a new range of construction materials specific to robotic fabrication, materials that can form off-plane, subject to forces other than gravity, and be hardened in situ in mid-air. Ferrostructures take advantage of robotic toolpaths to sculpt and construct a material that has agency to create a new freedom of construction for designers and fabricators.

METHODS
The methods of this research have so far defined parameters of the process: the material, the magnets, the tool, and the extrusion method. Each has influenced the selection and design of the others, and though the work is still in progress, we made decisions based on the desire to ultimately achieve a larger scale with certain weight limits from magnets and our KUKA KR AGILUS robotic arm’s payload.

The development of the ferroresin material occurred simultaneously with the optimization of numbers, sizes, shapes, and strengths of the magnets. We started by mixing black iron oxide with castable materials like plaster and concrete, but the mixes were too blobby and heavy to create spikes. We next chose a fast-curing epoxy resin, which proved the best material in terms of a short pot life, a mix malleability to jump between magnets.
and a pre- and post-cure strength to form and keep the distinct spiky form. The ratio of the mixture was determined by these variables—too much iron content made for a gummy putty-like material too difficult to form and too little iron made for a lower viscosity that would not fully form structural spikes. Furthermore, different ratios caused the iron oxide to separate from the resin, creating color and strength differences throughout the structure. This ultimately led to a 2:3 iron oxide to epoxy resin ratio.

Similarly, the magnets were tested on which produced the most distinct spikes and which would later allow for connections between nodes. Van der Wiel used large stacks of ceramic magnets, but this was too heavy for our robot’s payload. Koelman used electromagnets, and though they provide the ability to turn forces on and off, they proved too weak to form spikes. The best magnet was a neodymium magnet, as it provided the highest strength for the lowest weight for the robot. Its relatively small size allows for the greatest control and sculpting of the material.

After choosing a magnet and a mix, we could develop a set of tools based on two different methods of material introduction to the build environment. The first was a pull method that attracted ferroresin out of a pool base to a single magnet holder. The ferroresin jumped to the magnets, surrounding the tool and taking its form (Figure 4).

We introduced a metal bowl as a buffer in between the magnet and the pool of material for ease of demolding. Multiple plates and bowls held at various angles caused different bifurcations and jumps (Figures 5 and 6).

With the bowls proving too bulky, we substituted the buffer for an acrylic plate. The plate led to a design of an acrylic grid to house multiple magnets along a plane behind an acrylic plate. The pattern of magnets in the grid produced various field conditions that would attract and repel the ferroresin in the pool. The pull method created the beginnings of a truss structure, but was limited both in the distance of the pull and the angle between the base pool and the plane (Figure 7).

The pull method also creates an issue in scaling up. With a set height that is determined by the amount of ferroresin in the pool and the strength of the magnetic field, the ferrostructure cannot grow in size unless multiple separate pieces are built on top of one another. We attempted to add height by continuing in a column structure, but it created issues of seams, awkward joints, and difficult environments upon which to add more resin as the structure grows (Figure 8).

To overcome the limitations of pulling from the base pool, we switched to introducing the ferroresin by a drip method applied between two plates that are mounted to the robot perpendicularly to the toolpath motion (Figures 9 and 10). The space...
between the plates became our microextrusion volume through which to introduce resin by dripping it out of a silicone frosting bag (Figure 11).

The ferroresin attracted between the magnets, connecting nodes through a series of spikes and bridges. Once the resin was hardened, the robot moved further along its vertical toolpath, and the microextrusions build on top of one another seamlessly, unlike the forced connections with the pull method (Figure 12).

Though the drip method incorporated hand dripping and pouring through various cake frosting bags and nozzles, the constant addition of the material solidified a number of parameters for future experiments. The placement of the magnets, the amount of material needed to make and strengthen connections, and the reliability of the spike pattern allowed us to push the possibilities of the robotic toolpaths. The tool was able to move off plane in multiple axes and maintain the ongoing truss-like structure.

RESULTS

By turning the tool perpendicular to the robotic toolpath, we expanded our possibilities of building and scaling up, joining together aggregations of microextrusions, and making structural prototypes at a 1:1 scale given our tool, material, and robot. In the final artifacts using the drip method, we can see how seamlessly the addition of material built up an aggregation of nodes and bridges, leaving the trace of magnetic fields along a robotic toolpath (Figure 13).
In order to achieve a smooth robotic movement, a plastic sleeve was added between the tool and the build space to allow the motion along a path without adhesion. A base magnet was added below the table from which the tool began its toolpath, creating a flat bottom that could be designed to adhere to a foundation. Currently, each microextrusion takes 5 minutes to harden before moving to the next location on the toolpath.

While we left the magnets at the same place in the grid within each test, the magnets could be moved to allow for multiple bridge patterns. Moving the magnets within one grid on one side of the tool created more spindle-like bridge connections, while magnets far apart from each other from one side of the tool to the other created a weaker field and needed more material to make a bridge. Connections would occur at the most prominent spikes from each side and then create a strong core around which more material would thicken and flow towards each node. These connections would often overcome the force of gravity to cantilever and support the material being dripped on top of it, even when the material was still in the liquid state (Figure 14).

The structures are now at a scale that can be load tested. Techniques based on different magnet patterns, as well as varying robotic toolpaths, can be dialed in to control the thickness of bridges, the location of nodes, and the angles off-plane.

CONCLUSION
Ferrostructures, in their current state of development, can be used to create small- to medium-sized truss-like structures in multiple directions utilizing off-plane tool paths. Future development of this project involves the parameters that define the method, such as the magnets, tool, material, and scale.

Magnets: The current tool is designed around the use and constraints of square neodymium magnets. Future development of the project includes further research into the use of electromagnets, as it adds the ability to turn the magnetic field on and off, creating new implications for the robotic toolpath and structure design.

Scale: With the success of the ongoing truss-like structure, this project is capable of reaching a much larger scale with enough material and space. Further research into the shape of the final structure using trusses can be examined and implemented.

Tool: Tool design iterations continue to develop as further research into materials and magnets are done. Future tool development includes lighter and stronger plates around the magnets for safety as the magnets get closer together, as well as the development of more efficient ways to move or remove magnets mid-toolpath in the grids.

Material: The current ferroresin recipe is still in development. While it currently meets a baseline to create the truss-like structure, structural testing of the composition and strength of the material will be done to determine use in construction processes. Alternate ratios of the material may allow for further bridge development and design.
This new extrusion technique using robotics and magnetic fields opens up a new set of forces for construction. As we develop the aforementioned parameters, we are looking for patterns that emerge inherent to magnetic fields. As with a catenary arch to its inherent forces, a different set of inherent structures may materialize as we freeze the magnetic field. New forms give designers and fabricators new freedoms for choreographing and constructing with metallic materials using robotic fabrication.

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REFERENCES


IMAGE CREDITS

All figures are by the authors and the project team.

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Carolina Myers graduated in 2017 from the University of Virginia with her B.A in Media Studies and a minor in Technology Entrepreneurship. She is a Masters of Commerce candidate at the University of Virginia to be conferred in June 2018. In college, she began focusing on fabrication and robotics, leading research groups dedicated to studying Ferrofluids. Her research focuses on the intersection of robotics, material science, computational design, and digital fabrication, and applying that knowledge to structures on multiple scales.