A 3D Printer for Interactive Electromagnetic Devices

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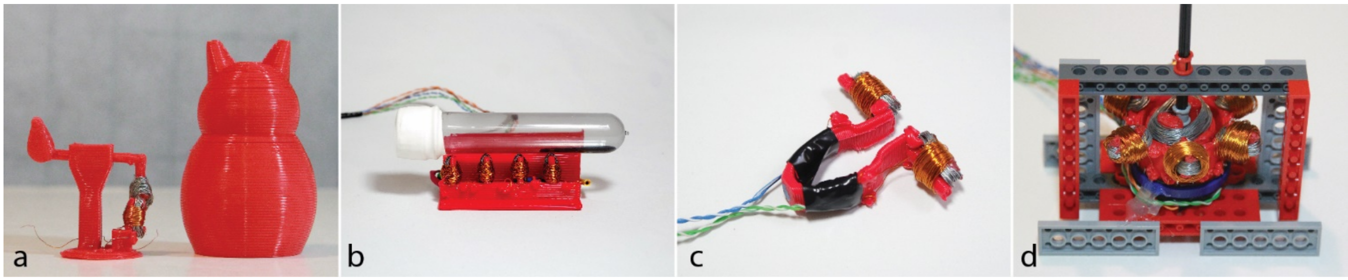

Figure 1. 3D printed electromagnetic devices. a) Solenoid used to actuate the cat hand; b) A Ferrofluid display; c) A movement sensor based on coupling strength; d) The stator and the rotor of a reluctance motor. The electromagnetic components are printed with a soft iron core, wound in place, and multiple layer of copper wire.

ABSTRACT

We introduce a new form of low-cost 3D printer to print interactive electromechanical objects with *wound in place* coils. At the heart of this printer is a mechanism for depositing wire within a five degree of freedom (*5DOF*) fused deposition modeling (FDM) 3D printer. Copper wire can be used with this mechanism to form coils which induce magnetic fields as a current is passed through them. Soft iron wire can additionally be used to form components with high magnetic permeability which are thus able to shape and direct these magnetic fields to where they are needed. When fabricated with structural plastic elements, this allows simple but complete custom electromagnetic devices to be 3D printed. As examples, we demonstrate the fabrication of a solenoid actuator for the arm of a *Lucky Cat* figurine, a 6-pole motor stepper stator, a reluctance motor rotor and a Ferrofluid display. In addition, we show how printed coils which generate small currents in response to user actions can be used as input sensors in interactive devices.

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INTRODUCTION

3D printing technology has moved beyond simply instantiating 3D geometries to printing functional and interactive objects. Recent work has considered how a range of functional objects might be fabricated, including 3D printed optical components [30], speakers [11], hydraulic robots [14], and pneumatic devices for haptic feedback [28]. By using conductive filament, ink, or fabric sheets, several projects also explored embedding three-dimensional conductive traces inside printed objects to create simple electronic devices [24, 29, 17]. This opens the possibility of eventually using 3D printing for the on-demand fabrication of highly custom interactive devices, as well as greatly expanding our ability to rapidly prototype sophisticated devices. However, to date we have not been able to directly fabricate most functional devices needing actuators, but instead these required either assembly with, or addition of, pre-manufactured parts into a print.

In this paper, we introduce a new type of 3D printer that can print interactive objects with embedded electromagnetic coil components such as those illustrated in Figure 1, including a solenoid actuator for the arm of a *Lucky Cat* figurine (Figure 1a), a Ferrofluid display (Figure 1b), an electromagnetic input sensor (Figure 1c), and both the stator and rotor for an electric motor (Figure 1d). Coils have been widely used as the fundamental component to convert electric current to a magnetic field in order to apply forces and create mechanical motions on demand. Being able to build electromagnetic components directly into a 3D printed object brings us one step closer to the vision of fully printing one-off interactive objects proposed by Willis et.al. [30]. However, production of electromagnetic coils requires very high conductivity material (most typically supplied by long strands of metal wire) which can be tightly spaced and configured with many turns, along with complex 3D wiring layouts which are not easily combined with the layer at a time process normally used in nearly all 3D printing.

Our printer design overcomes these difficulties by embedding continuous strands of wire inside a 3D printed object across printed layers. Structural parts consisting of conventional printed plastic can be (partially) created first. Using the 5DOF nature of our printer, wiring (including coils) can be placed around these parts. Finally, additional conventional plastic printing can continue (again possibly using the 5DOF nature of our printer in order to remove the normal "horizontal layers only" restriction on FDM printing).

To handle wire as an additive manufacturing material, we developed a custom print head (as shown in Figure 2) with two wire feeders, which can rotate around the center conventional FDM filament extruder tip indefinitely. The wire feeder can feed the wire to the center of the extruder tip, can cut wires, and re-deliver new wire segments on demand during the printing process.

To make a simple coil, the print head anchors the start of the wire with extruded filament, and then preforms a circular motion around an already printed *winding jig* to create a 3D coil. To strengthen the magnetic field, the second wire feeder can first lay down high permeability soft iron wire to serve as a magnetic core for the coil wound around it. To expand coiling flexibility, we installed the print head on to a five degree-of-freedom (*5DOF*) delta printer [18], which further allows us to coil at various positions and orientations, and allows FDM printing after coil creation to occur at whatever orientations are required.

In the following material, we detail our printer design and our explorations of printing electromechanical objects with the printer. We showcase several interactive examples printed with our printer and offer design guidelines for this new type of 3D printing technology.

RELATED WORK

Our work builds upon and extends a body of work on fabrication of functional objects as well as techniques for embedding wiring inside 3D printing.

Fabrication of Functional Objects

Fabrication of functional and interactive objects is a recently emerging research area. One approach to this topic is to embed off-the-shelf sensors inside a printed object. Savage et al. [22] show how rapid prototyping with 3D printed objects can be made interactive by embedding cameras to recognize motions of input components and map these to functions. Hook et al. [10] use wireless accelerometers to map functions to 3D printed cases. RevoMaker [8] allows the user to insert premade circuits inside a box and then prints around them while Makers' Marks [23] allows the recognition of marks and tags placed on a physical model surface made from e.g., molding clay, and translation of them into the geometry necessary for mounting sensors and electronics on a corresponding 3D printable model.

Another approach to creating interactive objects is to include the fabrication of sensing and actuation parts (mostly) during the printing process. Researchers have looked into printing interactive objects with, for example, printed light pipes [30], speakers [11], pneumatic controls [28], hydraulic robots [14] and capacitive sensors [24]. By printing electric traces with conductive inks as well as embedding electronic components like off-the-shelf motors, Voxel8 [29] has achieved complex functional objects such as a printed drone.

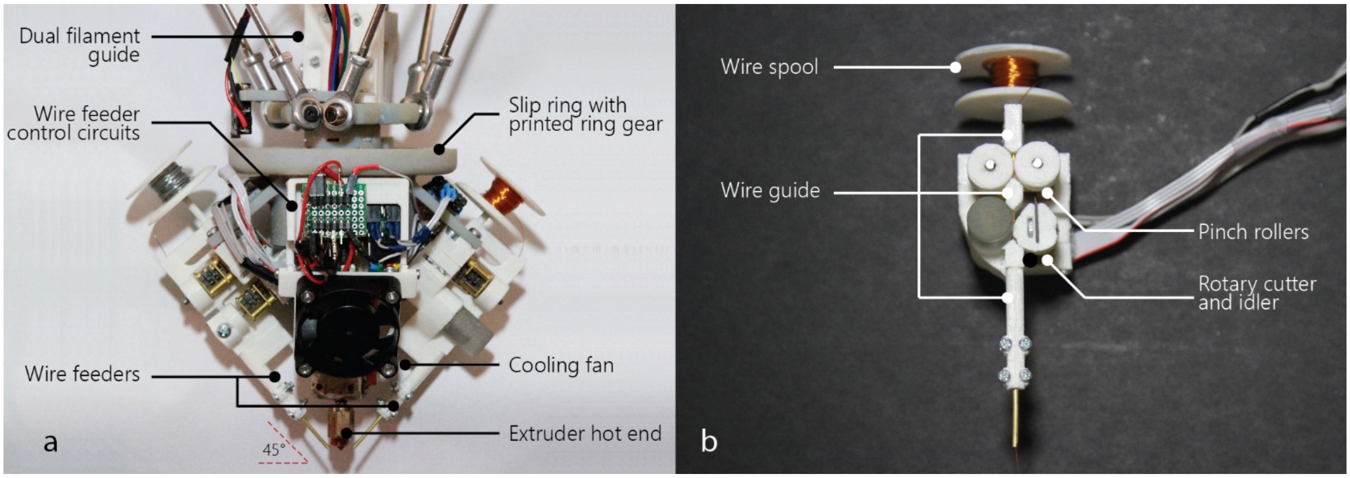


Figure 2. Print head design overview. a) The print head contains a pair of motor driven wire delivery mechanisms, and a rotary cutting mechanism. b) This pair of wire feeders is installed on a rotary slip ring centered around a conventional FDM extruder.

Our contribution to printing interactive objects is a new type of 3D printer capable of printing electromagnet components – constructs capable of generating dynamically changeable magnetic fields controlled by electrical current – inside a specified 3D geometry. This allows us to create programmable mechanical motions within a potentially monolithically printed object.

Fabrication of Custom Coils and Wiring Paths

Since coils are a very common electrical component, spindle driven coil winding machines have been widely seen in both manufacturing industries and consumer level markets. These coil winders can make high quality coils but serve only one purpose.

Recently in the 3D printing community, people have started to explore different ways to insert wires into 3D printed geometry, making it possible to create some kinds of coils in situ. Kim et.al. [12] showed early results on attaching wires to the surface of an FDM built part using ultrasonic bonding. Bayless et.al. [2] explored embedding wire using a mechanical pencil mechanism with limited early printed results. Bas [4] used a rotary ring to orient wire and the extruded filament as coating and a gluing method for the wire, and showed examples of single layer wiring prints. Skylar-Scott et.al. [26] introduced a technique to print metallic wire in midair to create structures like helical springs at the microscale. Finally, Saari et.al. [21] showed a technique for embedding wires into 3D printed objects with extruded filament as encapsulation. The printed result achieves high printing resolution, but coiling direction is restricted to remain always vertical, with no automatic feeding and cutting mechanism. In addition to supporting arbitrary coil orientations, our method uses insulated wire, and can feed and cut in situ. This allows our printer to achieve high density coils without worrying about insulation issues. Further, our printer can produce more efficient coils with a type of soft iron core.

A HYBRID FDM / WIRE PRINTER

Embedding a coil is different from laying down wires in a plane in that the wire needs to be shaped into a series of concentric loops placed very close to each other. For example, coils in motors are usually made with one continuous wire formed into hundreds of concentric circles as close to each other as possible, but electrically separated with insulation.

To support winding dense coils inside a 3D model, we use thin insulated magnet wire as our coil building material. The benefit of using insulated wire is that there is no need to print insulation for each of the turn of the coil, which simplifies the coiling mechanism and allows us to print coils with very high density. The insulating coating around wire leads can be easily removed after print using sand paper.

The coiling process can be divided into two main steps: printing a jig to wind the coil around, and coiling the wire. This winding jig is a 3D printed structure used as the structural support for a coil. Printing of this jig is done using a conventional FDM printing process. After the jig is printed, the machine can then coil wire around it. Insulated wire is delivered to the center of the print head through a wire feeder. The wire feeder assembly is free to rotate around the extruder center (without this rotation, the wire would twist and eventually break). By programming the print head to move around a printed jig and having the wire feeder rotate accordingly, the wire can be naturally coiled onto the printed object.

Nearly all 3D printers work in a layered fashion moving with only three degrees of freedom and depositing material only in one horizontal layer at a time. However, because the magnetic field created by a coil may need to be oriented in a specific direction, printing coils in only one orientation (e.g., only in a vertical orientation) would significantly limit the electromagnetic mechanisms that could be printed. To avoid this limitation, our print head is placed within a 5DOF FDM printer [18], which allows the addition of material in various orientations, not limited to a single horizontal plain at a time. This feature allows us to print coils at various positions and orientations.

In addition, the use of a 5DOF print platform makes it possible to lay down a second type of wire in an orthogonal orientation to a coil. We can use this ability to create a core of high magnetic permeability material inside the coil (soft iron wire, in our case). Materials with high permeability support the formation of a magnetic field within them more readily than low permeability materials (such as air or plastic). Thus a high permeability material will direct magnetic flux lines to be within the material itself and so are capable of directing and concentrating the magnetic field generated by a coil in an efficient manner.

Print Head Design

Figure 2a shows the print head design. At the center of the design is a six conductor slip ring connector [27] for power and data distribution to the rotating wire feed heads. This connects a dual filament guide at the top, an off-the-shelf filament extruder hot end at the bottom, and also serves as the platform for bolting wire feeders and a hot end cooling fan at the side. The slip ring also delivers power to control the wire feeders while rotating. The slip ring has a 12.7mm inner bore and a 56mm diameter outer ring. The inner bore provides an internal channel to guide non-rotational components between the top and the bottom of the entire print head assembly, including plastic filament, the hot end temperature sensor line, and the heating cartridge cable. The outer ring, together with a pair of wire feeders and the hot end cooling fan form the rotatable components. These are free to continuously revolve concentric to the print head center line. Rotation is driven by a small stepper motor which seated next to the filament guide at the upper part of the print head. The shaft of the stepper is mated to a 3D printed 50 tooth ring gear at the skirt of the outer ring to drive the rotary motion.

Wire Feeder Design

Each wire feeder (Figure 2b) is a 35×50×120mm module installed on the side of the outer slip ring at an angle of 45 degrees, aimed toward the center of the extruder tip. From top to bottom, the wire feeder consists of a wire spool, a pair of pinch rollers, a rotary cutter with its counterpart cylindrical idler, and a 100 mm wire guide with a copper tube in the end towards the center of the extruder tip. Guiding structures are placed between the spool and the upper part of the pinch roller, and between the bottom part of the pinch roller and the wire cutter. Wire at the spool is delivered down through the tubing structure to the end of the wire guide. A pair of 13mm diameter pinch rollers are used to deliver wires both actively and passively. Two pinch rollers are installed on a small one-way clutch [9] and are driven by a 1000:1 miniature gear motor [1]. The one-way clutch allows the pinch roller to passively rotate in one direction but not in the opposite direction. Thus, when the wire needs to be delivered passively, the gear motor is stopped so that the wire can slip between the two rollers. When the system needs to actively drive the wire, the gear motor is activated.

Below the pair of pinch rollers is the rotary wire cutter and its counterpart roller. The rotary wire cutter achieves wire guiding and wire cutting in a compact form factor. This is achieved by a water drop shape with one end made of a 13.5×7 mm blade and a guiding half on the side of the shape. This assembly is installed on a 1000:1 gear motor [1] with a shaft encoder [16]. The rotary cutter can rotate 360 degrees. During the wire coiling process, the cutter is positioned with the cutting blade pointed to the top (Figure 3a) allowing the wire to move freely through the guiding side and past the counterpart pinch roller. To cut, the rotary cutter is rotated towards the roller (rotating 360 degrees). Because the cutting blade has a longer radius, when it rotates to the pinch roller it presses the wire against the roller and subsequently cuts it (Figure 3b). The strong torque from the high ratio gear motor guarantees the cutter does not get stuck while passing the counterpart roller.

Right after the rotary cutter is the wire guide tube. The wire will be delivered through the tube towards the center of the extruder tip. This allows the wire to pass through to the extruder tip at all times.

The wire feeder is designed to cooperate with thin wires that is commonly to find in the market. Specifically, the copper wire we used is 30 AWG and the soft iron wire is 32 AWG. Note that it is possible to coil with other thickness (i.e. 26 AWG or 34 AWG) with a change of the wire guide diameter and the distance between the pinch rollers accordingly.

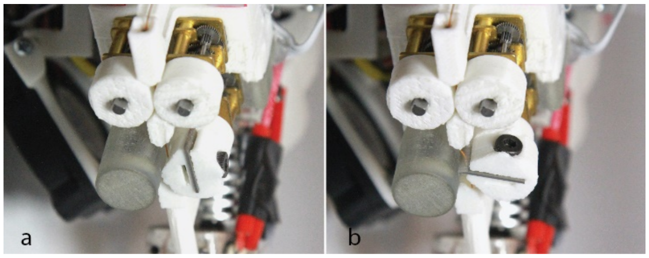


Figure 3. Cutting mechanism in action.

Hardware Controller

Using the same mechanism as the printer described in [18], the core of the printer controller is a Beagle Bone Black [3] with a CRAMPS 2.0 cape module [5]. However, to support the additional stepper motors needed to drive the wire feeders' motion, we add one CRAMPS3 add-on [6] on top of the cape, supporting control of up to 9 stepper motor motions at the same time. The gear motors for both of the wire feeders are directly controlled from a teensy controller within the rotating assembly, which receives control signals from the Beagle Bone Black mother board though the slip ring data line.

PRINTING COILS

In this section we introduce the steps needed to print a basic cylindrical coil in a vertical orientation (with respect to the print head, but not necessarily with respect to the printed part). This serves as the fundamental building block for printing interactive electromechanical objects.

Printing an Air Coil

Anchoring the wire

After printing a winding jig in plastic using the FDM print head, the printer can start to print a coil. The first step to print a coil is to anchor the wire at the starting point. To achieve this, the pinch rollers first actively feed the wire past the center of the extruder tip. The print head, together with the wire below, then moves above a flat surface (either the build platform, or a printed surface) with a 2mm gap. The filament extruder tip then starts to extrude melted plastic. The 2mm gap leaves room for melted plastic to form a small dot large enough to cover the top of the wire and fix it in place. We discovered that extruding 40 mm of 1.75mm diameter plastic filament can guarantee full coverage of the wire while leaving a relatively small anchor structure on the surface. To ensure a firm connection, after plastic extrusion, the print head presses down to the surface and pushes the extruded

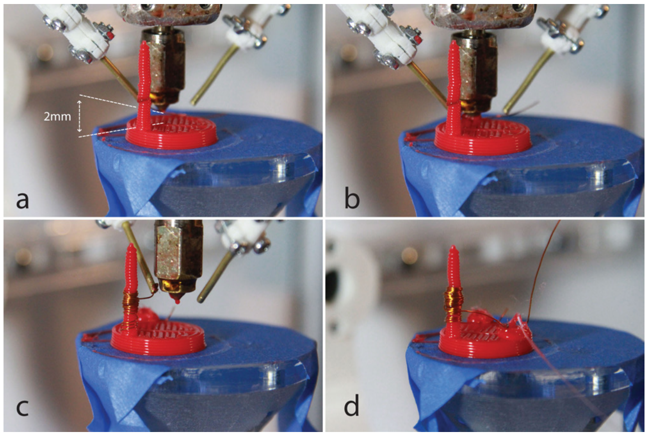


Figure 4. Printing a simple coil: a) Print head stopped 2mm above the printing surface; b) Extruding filament to create the anchor point; c) Coiling; d) Printed result.

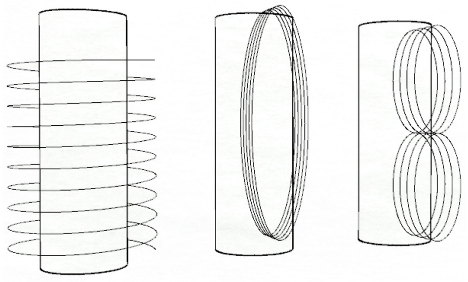


Figure 5. Three different way to create a magnetic core: Left: Coiling along the main axis. Middle: coiling perpendicular to the main axis; Right: coiling perpendicular to the main axis using a Figure 8 pattern.

filament to have a full contact with the embedded wire. The extruder tip then cools down to 150°C before moving above to perform coil placement. This cooling allows the anchor structure to solidify and secures the wire prior to coiling. Figure 4a and b shows the printer anchoring the wire.

Coiling the wire and anchoring the end

As long as the wire is anchored, wire can be delivered passively. Instead of driving the wire with the drive pinch rollers, wire is pulled from the spool as the print head moves around the winding jig. As the print head moves along the path around the jig, the wire feeder positions itself so that the wire guide is always tangent to the jig. The movement necessary to produce the desired number of turns for the coil is controlled by G-code which is generated using a custom plugin (introduced in a later section). Based on our tests, for single layer coils we can get the coil circle equally distributed with 0.2 mm between each turn. Figure 4c shows a basic coiling motion. After coiling, the end of the coil will be anchored using the same anchoring procedure introduced above.

Cutting and restart

Finally, once the wire end is anchored, it is safe to cut the wire (if that is desired) and restart the next length of wire. To do this, the cutter assembly rotates to press the blade against the counterpart roller, pinching the wire and cutting it into two pieces. The print head moves upwards with the end of the wire sliding out of the wire guide naturally. To restart the next length of wire, the pinch rollers actively drive the wire to deliver it to the extruder tip, ready for the next coil. Figure 4d shows the printed vertical coil with 1 layer of 30 turns. Removing the insulating coating from cut wire leads is performed as a post-processing step via manual sanding.

Printing a Coil with a Soft Iron Core

Using the method above to print coils with an air core, our printer can 3D print devices with, for example wireless power transmission functions. However, to create electromagnets and other mechanisms for mechanical motion, a more concentrated magnetic field than can be easily achieved with an air core coil is often needed. To achieve this, a core of high permeability material is normally needed inside the coil to direct and concentrate the flux lines of the generated field. Our preliminary tests showed that Magnetic Iron PLA [20] was nearly identical to having and air core (Figure 6), so to create this core we make use of our second wire feed mechanism loaded with an uninsulated soft iron wire.

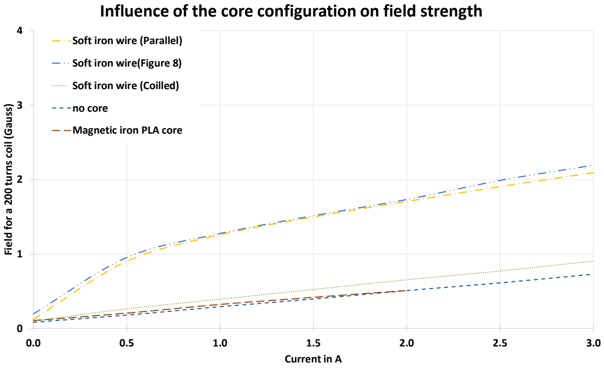


Figure 6. Magnetic field measurement of the three tested configurations. Magnetic iron PLA core is used as a reference and is nearly identical to no core.

We considered three configurations that the iron core can be constructed in. The first and simplest is to print the iron core the same way as we print the copper coils. A series of concentric soft iron loops are first wound around the center plastic jig to as the core, with copper coils wrapped around that core (Figure 5 left). The second configuration is to print the iron wire around two posts to create series of long ellipse shapes. This structure is easy to produce and could be made with very short height (Figure 5 center). The third option is to use the same two posts as the scaffold, but create figure-eight shaped windings instead of ellipses (Figure 5 right). Comparing to configuration 2, the crossing in found in this configuration places more wire at the center of the core and thus could potentially direct the magnetic flux better.

To compare these potential soft iron core configurations, we produced three corresponding electromagnets and measured the magnetic fields they produced. The test electromagnets were made with a plastic jig with a height of 22mm with 200 turns of copper coils. Configuration 2 is wound with 5 turns of a parallel ellipse. Configuration 3 is wound with 5 turns of figure-eight shaped winding, and configuration 1 is wound with concentric coil using the same total length of the soft iron wire as in configurations 2 and 3. We measured magnetic field strength using an HMC5983 magnetometer. To avoid saturation of the magnetometer (which has a range of ±8 Gauss) for the higher intensity tests, we placed each coil 23mm above the electromagnet. Figure 6 shows the test results. Both configuration 2 and 3 generate comparable magnetic fields while configuration 1 has much less flux density, most likely because the core wires are oriented in a non-optimal direction. Based on these results, we have adopted configuration 2 – elliptical core coils – for our printed examples.

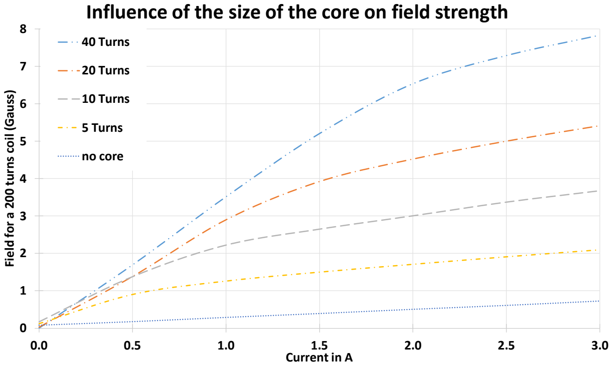


Figure 7. Magnetic field generated with coils printed with air core, and a range number of soft iron core layers.

With configuration 2, we then ran another measurement to understand the relationship between the number of loops used by cores and the magnetic field strength. Figure 7 shows one set of measurements including the magnetic field of a plastic core and a set of soft iron wire cores with different numbers of layers. We can conclude that more soft iron wire layers result in a stronger magnetic field. However, in printing practice, the size of the overall coil will increase correspondingly to the number of core loops as well. For most of our examples, we used soft iron cores with 30-40 loops of iron wire, which could generate enough magnetic field to pick up steel parts and create potential physical motions.

To produce these cores with our printer, we print a vertical winding jig as in the procedure for printing an air core coil, and add to this jig posts at the top and bottom of the coil. Note that the core winding posts are horizontal with respect to the nominally vertical coil. However, we can make use of the 5DOF printing platform to print them in a temporarily vertical orientation without the need for added support material. After printing the core, the rest of the coiling procedure is the same as in the air coil process. Figure 8 shows a printed coil with a soft iron core. It is printed with a 30 turn soft iron core and 200 turns of copper coil in total. With a current of 2.3A it produces a magnetic field that is strong enough to pick up a 1.2g 18mm M3 steel screw at the distance of 3mm. After being picked up, the current can be dropped to a minimum of 0.26A to hold the screw in place with less magnetic field. Note that we used a current limit power supply for all our examples and measurements. Current will adapt to the change of coil resistance caused by the temperature.

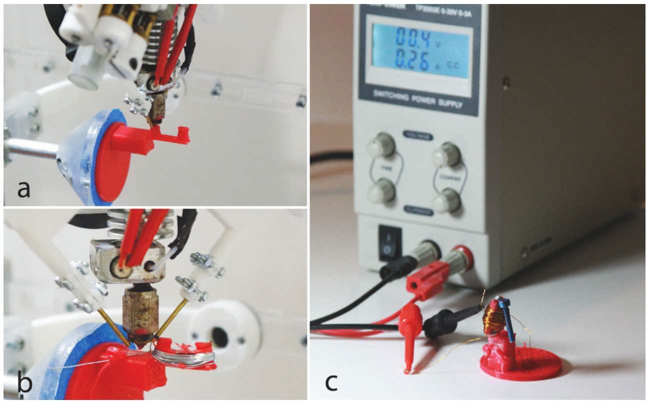


Figure 8. Printing a soft iron core: a) Creation of the pillars printed without support; b) Coiling iron core in an ellipse shape; c) Printed coil magnetically holding a steel bolt.

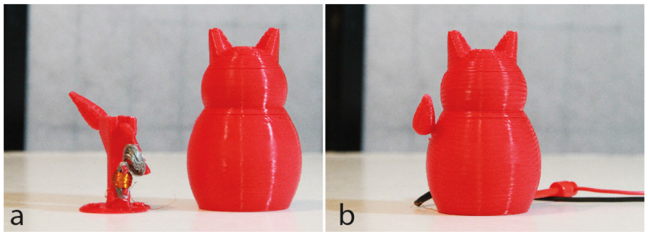


Figure 9. a) A printed *Lucky Cat* figurine; b) Arm is activated with a printed coil.

Printing Coils in Tight Configurations

Our print head design uses wire feeders at the two sides of the plastic extruder placed 2mm above the extruder tip at 45 degree angle. Thus at a height of 10mm above the print head tip, the widest dimension of the print head assembly is 50mm wide. Without special procedures (i.e., using the print procedure as outlined below) this would indicate that coils must be printed at least 50mm apart in order for the print head to always safely move between them. To reduce this distance, we can produce a specialized motion path which aligns the two wire feeders in the direction of motion while moving in a straight line past any narrow gaps. This allows us to pass through gaps as small as the width of the end of the extruder (10mm for our standard extruder tip).

Note that in the coil section using this special low-profile winding configuration, the wire is not being fed tangent to the coil. As a result, it is not necessarily pulled tight. However, after passing through the narrow gap, returning to the normal print procedure rotates the head back into a tangent position and tightens the small potentially loose section of the coil. Figure 11c shows the actual motion when the extruder tip moves between the coils and Figure 11d shows the retightening of the wire after the print head moves back to its normal coiling configuration.

PRINTING ELECTROMECANICAL OBJECTS

In this section we demonstrate several 3D printed examples with embedded coil(s). We show that our printer design and our method of coiling can support variety of design situations and can be used for both interactive input and output devices.

Example 1: Printing an Actuator with One Vertical Coil

Figure 9 shows a printed *Lucky Cat* figurine example, with which the arm can rotate by actuating a printed coil. When the user increases the input current, the magnetic field of the coil becomes stronger and pulls the arm upwards. When the input current is off, the weight of the arm lowers itself back to its original place.

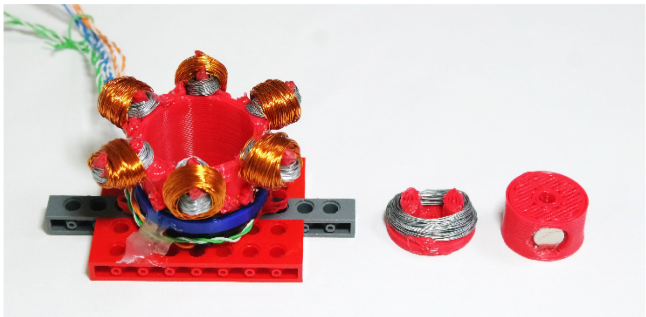


Figure 10. 3D printed motor elements: Left: stator with 6 poles; middle: a reluctance rotor printed on our printer; Right a magnet holder rotor (the magnets were not printed).

This example is printed in three parts. The main part is the base with one vertical coil with soft iron core inserted. After printed the coil, we print a Y-shape branch structure next to the coil to hold the rotation arm part. The rotation arm part has one end with soft iron core and can be placed inside the Y-shape branch for rotation. Finally, the cat case, seating on top of the base structure, has a hole on its side which allows the rotation arm part to stick out.

Example 2: Motor Stator Using 6 Coils with Different Orientations

In this example, we printed a 6 coils motor stator structure (Figure 10 left) that can create a rotating magnetic field to spin a 2-magnet motor rotor (Figure 10 right). As a closer step towards printed entire motor, we also printed a reluctance rotor with the soft iron core (Figure 10 middle), which can rotate at 50RPM activated with our printed 6 coils stator. The coils were controlled through an L298 full bridge driver with a teensy microcontroller.

Unlike the first example, this stator structure consists of multiple coils, which are positioned on a horizontal platform. To print this example, we first print the circular base vertically. We then rotate the base with one surface facing upwards to print a coil jig. The model is then moved into the original position facing upwards, and two winding posts are printed on top of the coil jig. The soft iron wire is then wound on these posts to provide a coil core. After that, the model is posed with the coil jig upwards again to coil copper wire. This process is repeated for the remaining five coils.

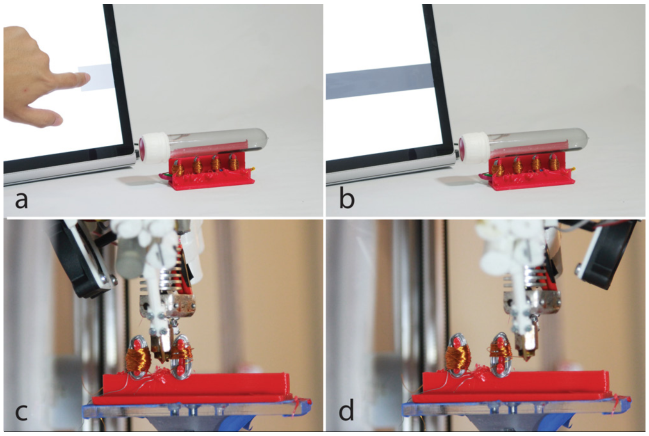


Figure 11. Printed Ferrofluid display. a, b) Energizing different coils moves the FerroFluid; c, d) Our system can wind coils about 5mm apart. In that setting the wire is tighten after the turn around.

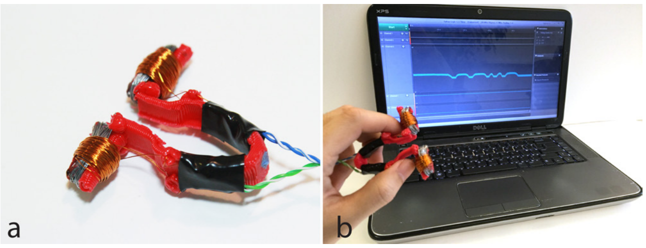


Figure 12. A printed coupling sensor. a) The sensor is made by printing two coils next to each other; b) By driving one coil with a square wave, we can infer distance between the two coils by observing the coupling strength.

Example 3: Physical Progress Bar with Ferrofluid

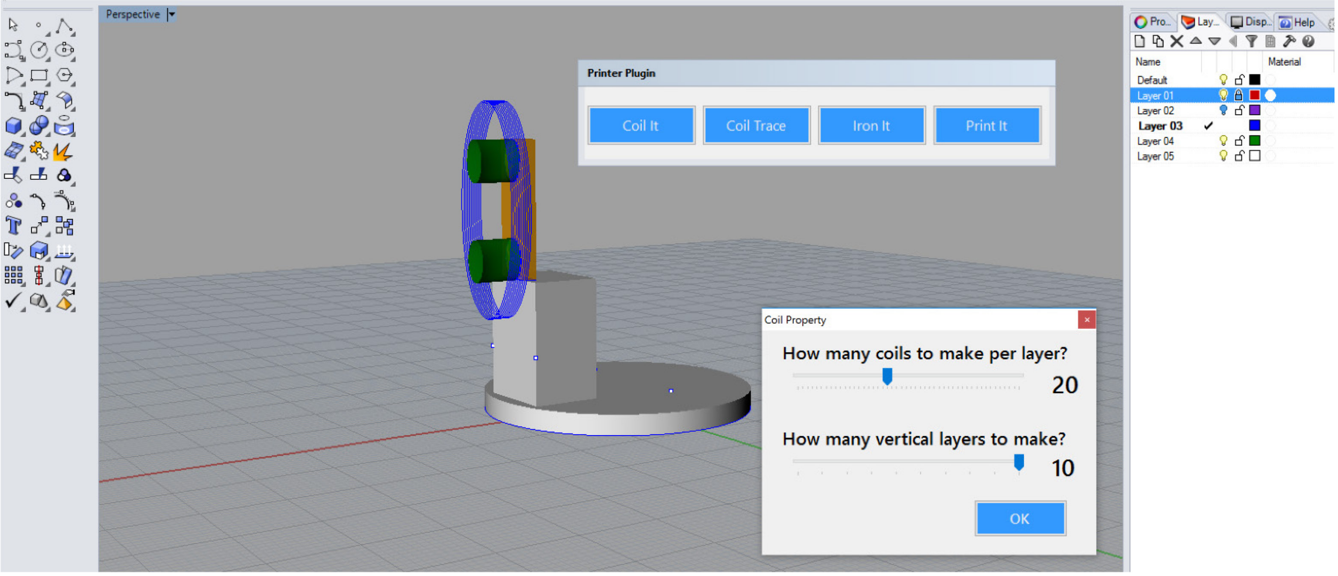
Printing electromagnets inside a 3D printed model allows us to interact with a variety of metallic objects in the environment. In this example we printed a tube holder with electromagnets to control the flow of a Ferrofluid inside to create a physical progress bar. (A *Ferrofluid* is a liquid – typically an oil – with suspended ferrous nano-particles making it a fluid magnetic material which can flow under the influence of a magnetic field.) As shown in Figure 11 a and b, as the user drags the slider on the screen, the Ferrofluid in the tube moves from one spot to the next, in response to the changing magnetic field inside the holder induced from the several coils printed below it. This example is inspired by, and could also be considered as the simple version of, the Ferrofluid Clock [7]. However, we are able to 3D print nearly all the components using our hybrid printing technique. The printing process of this example is similar to Example 2. However, to have fine control over the flow of the Ferrofluid, we print coils in a closely packed arrangement using the tight printing technique introduced in previous section.

Example 4: An Input Sensor

Beyond generating output, printed coils can also be used as a sensing component for an interactive input device. In this example we printed a customized motion sensor in the shape of a clamp. Two electromagnets are printed on each side of the clamp branches. With one side of the coil powered with an AC current, a corresponding current is induced in the other coil. The strength of the induced current is dependent on the distance between the coils. When the clamp is pressed down the activated coil moves towards the sensing coil. The small increase in the current produced can then be easily sensed by a microcontroller (Figure 12).

COIL GENERATION AND CONTROL SOFTWARE

Two specialized software components are used in conjunction with our printer: the printer control software itself and a custom plugin to generate the print G-code which is interpreted by this control software.



How many coils to make per layer? 20

How many vertical layers to make? 10

Figure 13 Plugin Interface with visualization of coils and core.

The main control software for the printer is based on the open source LinuxCNC system [13] running on Machinekit images [15]. We modified the software control files so that it can accept custom G-code to control printer motions. In our case, we need to extend beyond the traditional G1 {X, Y, Z, A, B, C} as we need six degrees of freedom to control XYZ motions, filament extrusion, and the two additional degrees of freedom for platform rotation, plus a seventh degree of freedom for wire feeder rotation (for which we use a custom "V" axis). We also defined a list of custom M codes from 110 to 114, mapping to wire feeder delivery and cutting behaviors. With these modifications, all machine actions can be written in G-code and execute without human assistance.

G-code Generation Plugin

We developed a plugin for the Rhino CAD package [19] to support generating the G-code which coordinates our high degree of freedom printer motions and supports printing both soft iron cores and coiling motions (Figure 13). The plugin has 4 basic functions: printing traditional solid structure; printing a generic coil; printing a coil with a custom defined path and printing a soft iron core. The user can freely design 3D structures inside the Rhino CAD system, and achieve each individual function by clicking the corresponding button, and then selecting the part that needs to be printed in that way.

To print a traditional solid form, the user first clicks the "Print It" button, and then selects the structure to be printed. The structure is then converted to an STL file in the background. The Slic3r slicing program [26] is then invoked using its command line API to slice the geometry. Slic3r slicer only supports 3DOF horizontal slicing, so after the Slic3r G-code is generated, our plugin inserts G-code do any necessary rotational transition of the 5DOF print bed automatically, and finally generates ready-to-print G-code.

To print a coil, the user first clicks the "Coil It" button, and then selects the structure which serves as the jig to coil around. The user is also asked to define the starting and ending anchor points. A window then pops up, asking the user how many turns of coil and how many layers of coil they'd like to print. The maximum number of turns is based on the selected geometry height. Figure 13 shows the pop up coil setting window. Once the coil property is specified, our software generates motion commands for a circular path centered at the center of the selected geometry, with the radius calculated based on both the geometry of the jig and the print head diameter. The wire feeder's angle is also calculated and written into the G-code (using the custom G1 {V} command), together with codes for motions to implement anchoring, delivery of the wire, and cutting actions. Our software also supports a simple visualization function, showing the actual print head motions with color coded lines.

Generating a coil with a custom path is very similar to the "Coil It" function with the only difference being that the printing path is based on a custom path provided by the user. We use this function to print coils close to each other as is shown in the Example 3. Printing soft iron cores is also similar to printing air coils in the software interface, but the user is asked to choose two more points as the two winding post positions. The geometry of the posts is then generated automatically with corresponding G-code. Figure 12 shows the visualization of the generated core and coil.

Although at present our plugin has a limited set of automated functions, it is sufficient to generate the G-code needed to print a wide variety of electromagnetic components on demand.

DISCUSSION AND FUTURE WORK

Printed Coil Performance

We discussed the magnetic field strength in the previous section. Here we report our additional exploration on the characteristic and performance of the printed coil with soft iron core.

Temperature

Because activating coils with high current may generate heat that affects the plastic coiling structure, we ran the following experiments to understand the temperature and coil durability. For a 200 turns coil, we energized it with 1 Amp for 30s and the temperature rose from 26C to 35C. We then tested it for a continuous 15min activation and the temperature reached a plateau of 90C. Although we were not able to do industrial-level long term test, this suggests at least a Class-Y coil. We repeated the measurement at 2Amps. The coil reached 103C at 30 seconds and the plastic structure started to deform after 1 minute. Therefore, at high current the solenoid is not suitable for long term activation, but it is still possible for quick motion activation.

Consistency

To test printed coils consistency, we measured the 6 coils printed for the motor stator (Figure 10 left, with the same number of turns for both soft iron core and copper coils) using the same method as in Figure 6 and 7. At 1Amp, the 6 coil's magnetic fields are 3.70, 3.59, 3.72, 3.60, 3.82, 3.60 Gauss respectively with the max percentage deviation at +4/-2.2% around the mean.

Printing time

With our non-optimized prototype, the current coiling speed for a 20 turn soft iron core, 200 turn coil is less than 20 minutes. The speed could be further improved with stronger steppers and better hardware design.

Core Geometry

It is often the case that the poles of magnets and motors need to be shaped in a very specific configuration to be effective. Yet our current system is creating relatively simple geometry. Creating more complex geometry is possible if one prints pegs to hold the wire in a specific configuration. This will require a more complex path generation and the use of thinner, more flexible iron core wire.

Automated Insulation Removal Mechanism

Our current printer design doesn't consider a wire coating removal mechanism. This is not a difficult issue in our printed examples, as coating on the coil leads can be readily removed using sand paper after prints. However, this could be a potential challenge if connection between separate wires is needed inside an encapsulated print. In the future, we could improve our rotary cutter design by adding a sanding function to it. To do this, we would install a coarse sanding paper on the bottom side of our water drop shaped cutter. To strip the wire, the sanding side of the cutter/sander assembly could then be positioned against the counterpart roller, leaving a very small gap in between. The wire would then be dragged in between to remove the insulating coating. However, further investigation is needed to confirm this design.

Placing Wire Structures into 3D Print

Although not our main focus of this paper, during the exploration use of the printer, we found that embedding wires into 3D printing in general could open exciting new design opportunities. Using wires with different stiffness or weaving wires into particular patterns could potentially create sophisticated structures to either strengthen certain printed parts, or to create mechanical structures, such as an axle and suspension structure. Our printer could also support different types of wires, such as shape memory alloy, to create printed shape changing objects.

CONCLUSION

In this paper we have presented a new type of low-cost printer that can integrate electromagnetic components into a 3D printed structure. This is achieved with a pair of wire feeders which can rotate while centered on a conventional FDM print head. By employing one wire feeder with insulated magnetic wire and the other wire feeder with soft iron wire, our printer can print both a high permeability core and high density copper coils in one automated process. With a 5DOF printing platform, our printed coils can be positioned at various positions and orientations as needed by a particular mechanism or application. We demonstrated a set of examples with printed coils serving as both actuators and sensors to create interactive 3D printed objects.

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