

# Reprinting the Telegraph: Replicating the Vail Register using Multi-materials 3D Printing

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## Abstract

Solid Freeform Fabrication is a family of manufacturing processes that create three-dimensional objects by depositing material, layer-by-layer. Traditionally, this technology has been used to fabricate passive parts, but recently it has been used for producing active components such as batteries and soft-polymer actuators. In this paper we demonstrate the ability of this process to fabricate a complete, active electromechanical system. Using only SFF processes, we reproduced the 1844 Vail register - a landmark in digital communications history. With the techniques developed in this research, a range of solenoid devices can be fabricated and embedded into freeform fabricated devices. This could enable the realization of novel and otherwise difficult to manufacture electromechanical designs.

*Keywords: telegraph, solid freeform fabrication, electromagnet, electromechanical, deposition, rapid prototyping, magnetic, assembly.*

## Introduction

Solid Freeform Fabrication (SFF) refers to a family of computer-aided manufacturing (CAM) processes in which material is robotically deposited, layer-by-layer, to build 3-dimensional objects. In recent years, SFF processes have been extended from their original range of applications, namely the fabrication of purely mechanical parts, to the fabrication of active, functional devices, including complete batteries (Malone et al. 2004), electrical wiring (IBID), fully assembled mechanisms (Prinz and Weiss, 1998), living tissue and tissue engineering (Cohen et al. 2004), and even soft polymer actuators (Malone and Lipson, 2007). Our group produced the above products with a single, multi-material SFF system, which suggests that complete electromechanical devices can be made entirely by printing with a single fabrication system. Our approach primarily employs polymeric materials, and low temperature processes, we did not expect it to be suited to manufacture “traditional” electromechanical devices, in particular those involving electromagnetic actuators, but rather expected to develop new types of devices, such as biomedical implants or biomimetic robots. To test this assumption, we attempted to construct a working replica of a key innovation of the 19<sup>th</sup> century – the electromechanical telegraph.

It is common for mechanical systems to utilize solenoids for mechanical motion and electronic control. Hence, attempts have been made to fabricate them. Coils and non-traditional actuators were produced using Ink-Jet printing in combination with non-SFF processes like sintering, but electromagnetic actuation was not realized (Fuller et al. 2002). Using a full range of Micro Electro Mechanical Systems (MEMS) fabrication techniques, functional electromagnets were produced for MEMS devices by Sadler (1997) and others. However, the manufacturing steps to produce MEMS electromagnets do not represent SFF manufacturing steps and include

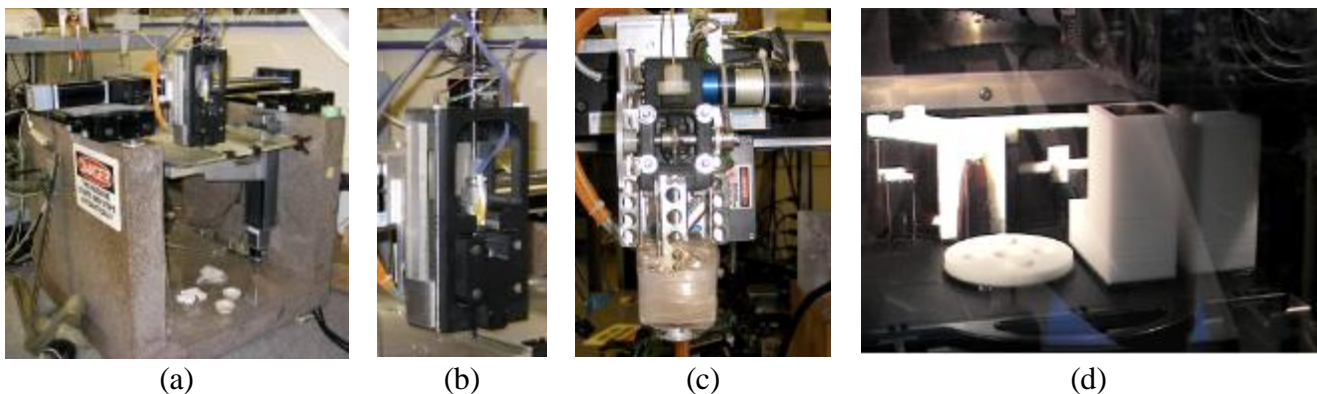
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chemical vapor deposition and evaporation, electroplating, and photolithography. This paper presents a method of producing complete electromagnets from common materials entirely within a single SFF system, and then demonstrates their utility in a printed and functional complex electromechanical device - a replica of a landmark integrated telegraph receiver and recorder. While the replica was made with SFF, three components were added post manufacturing. This included a power source and connections, ink tip for printing, and counterweights on the recording arm.

## Background

In 1844, Samuel Morse and Alfred Vail used the Vail register (Casale 2001), the landmark integrated telegraph receiver and recorder, to receive the Morse coded, electronically transmitted message “What Hath God Wrought”. This breakthrough arguably marks the start of the digital communications era. The Vail register contains four components: a structural base and frame, a clock mechanism to feed paper, a lever mechanism for printing, and two electromagnets for actuation. Its construction included wood, brass, and ~16 gage copper wire. In its original construction, the mechanical components were machined using steam powered lathes and mills. The electromagnets and batteries were made by hand as described by Vail (1845), which included manual winding and insulation of the wire. This early digital device was on the forefront of technology during a time when electricity was still a new concept, as Vail (1845) describes in his details of the register. We therefore consider replicating the register as a fitting challenge for the emerging digital technology of Solid Freeform Fabrication of complete electromechanical devices.

We employed two SFF systems in this research. The first is a multi-material and multi-process system *Figure 1(A)*, purpose-built in our laboratory for research into SFF of complete functional devices. It includes a syringe tool and molten extrusion (FDM) tool. The syringe tool, *Figure 1(B)*, typically deposits semi-fluid materials that form a solid after curing, in streams that can be varied from .25-2mm in diameter. The FDM tool, *Figure 1(C)*, feeds 3.125mm wire materials into a heated nozzle at up to 325°C, depositing a ~.25mm diameter filament. The second is a commercial SFF machine, the Stratasys Dimension SST 768 Series (*Figure 1(D)*, Stratasys, Inc.), which also utilizes FDM to deposit acrylonitrile-butadiene-styrene (ABS) plastic, *Figure 1(E)*.

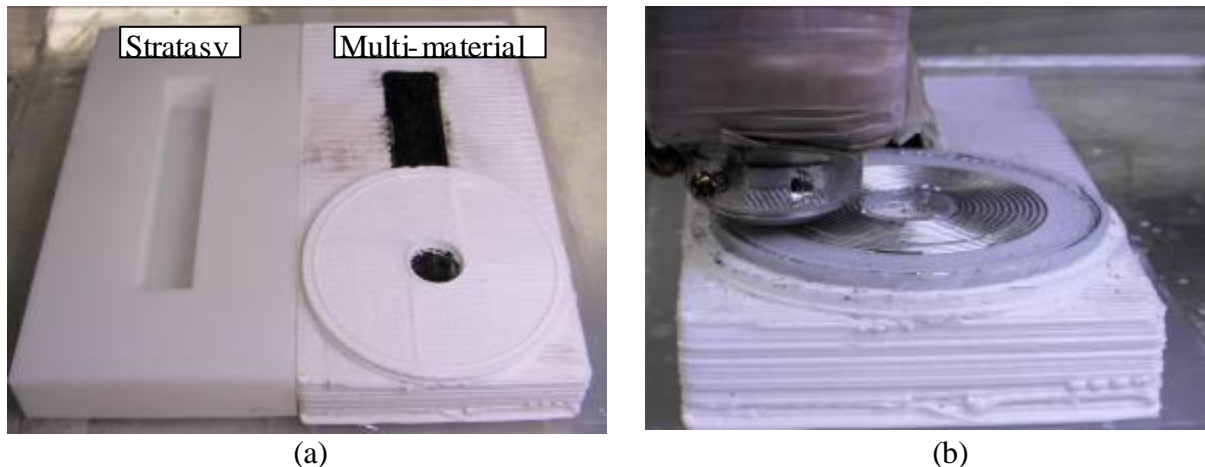


**Figure 1: 3D-Printing Tools:** (a) Multi-material SFF platform comprising a Cartesian gantry with deposition tools; (b) Syringe deposition tool (c) wire-feed deposition tool (d), Stratasys Dimension internal print chamber.

## Freeform Fabrication Experiment

The emphasis of this research was to demonstrate that freeform fabrication could produce a functional replica of a complex electromechanical device originally manufactured via traditional processes. The most significant challenge was freeform fabricating a complete electromagnet capable of macroscopic actuation force – something never before achieved, requiring a multi-material SFF system. We decomposed this challenge into the identification and formulation of materials that are compatible with our multi-material research system while retaining electromagnetic functionality and tuning manufacturing process parameters to achieve the design requirements.

The initial intent of this project was to fabricate the entire register with only the multi-material research system. Preliminary versions of the components were produced using this system as demonstrated in *Figure 2* by the base structure, core material deposition, the electromagnet base layer, and with the electromagnetic coil added. Since the SFF of the electromagnet is of greater research significance, it was decided to dedicate the multi-material research system to that goal, and therefore the majority of the structural and mechanical mechanisms (e.g. clock mechanism for paper feed) were produced using the Stratasys. The components made by the two systems were then manually assembled into the final device.



**Figure 2: Printed components:** (a) Base structure of the Vail register replica as printed by the Stratasys and the multi-material fabricator; (b) Three-layer electromagnet during construction

## Material Selection and Formulation

Electromagnets require at least three material types: a conductor to make the coils which carry current and generate the magnetic field, an insulator to allow the coils to be densely packed without shorting, and a ferromagnetic core material to focus and amplify the magnetic field. Materials were selected based on compatibility with one of the two deposition processes (molten extrusion using wire feedstock and ambient-temperature syringe deposition) available in our SFF research system, functional performance, mutual thermal and chemical compatibility, and health and safety considerations.

Sn-Sb alloy (95% tin, 5% antimony) solder was chosen as the conductive material because it is available in wire form, it has a melting point (240°C) compatible with our molten

extrusion tool, it has a high electrical conductivity relative to polymer-based conductive materials and inks, and has reduced health risks compared to lead solders. The presence of antimony also increases the material's ductility, allowing it to endure high strain. It was anticipated that this would aid in the continuous deposition process.

GE Silicone II – a commercial 1-part room-temperature vulcanizing (RTV) silicone elastomer, was selected as an insulating material. This material works very well with syringe deposition, and is chemically inert, an excellent electrical insulator, and tolerates high temperatures (200°C). The solder also adheres very well to the silicone. Its drawbacks for this application are that it has low stiffness when cured, cure time of about 30 minutes every few layers and the production of ammonia and methanol during curing.

A ferromagnetic core material was formulated using iron powder that was manually mixed in lithium grease. The grease acted as a carrier fluid and allowed the iron to be deposited. Tests of syringe deposition and magnetic force generation revealed that the preferred formulation is 80.5% iron by weight. A higher concentration of iron yields higher magnetic force generation, but the viscosity becomes too large for the syringe deposition tool to dispense the material reliably.

All other components not essential to the electromagnetic actuation were created by the Stratasys system with ABS plastic.

## **Fabrication Methods**

The Vail register replica was fabricated in multiple steps, which demonstrated several achievements. The first step was producing a complete electromagnet, which begins with the deposition of a layer of coiled wire. Initial attempts to deposit within predefined silicone groves, which had the potential to create thin wires, were unsuccessful because the positional accuracy of the machine was affected during tool changes. During replica fabrication, we were also unsuccessful in printing directly on the ABS plastic because the solder does not adhere to this material. The end result was for the wire to be deposited on flat layers of silicone. A large number of design variations and deposition system parameter adjustments were required to eventually achieve a continuous coil.

The next challenge was stacking coil layers. This was achieved by laying down a layer of silicone over a printed coil with a designated area left bare for layer-to-layer connection. Then a joining layer of solder was added at the outer or inner ring of the coil depending on the orientation of the previous layer. The joining layer was added to increase the likelihood of the solder producing contact early in its deposition stage. Two more layers of silicone were deposited to ensure isolation of layers and then a new solder layer was deposited with the same winding direction but opposite radial direction of the previous layer (e.g. always counter-clockwise, but outside to inside, then inside to outside). This was repeated as necessary. Due to inconsistencies during the tool change procedure, for a failed printed coil layer, the z-direction was manually tuned until a successful layer was produced. After stacking and connecting the layers, ferromagnetic material is deposited into the center of the coil stack, and then the entire electromagnet is sealed with a layer of silicone, *Figure 3(A)*.

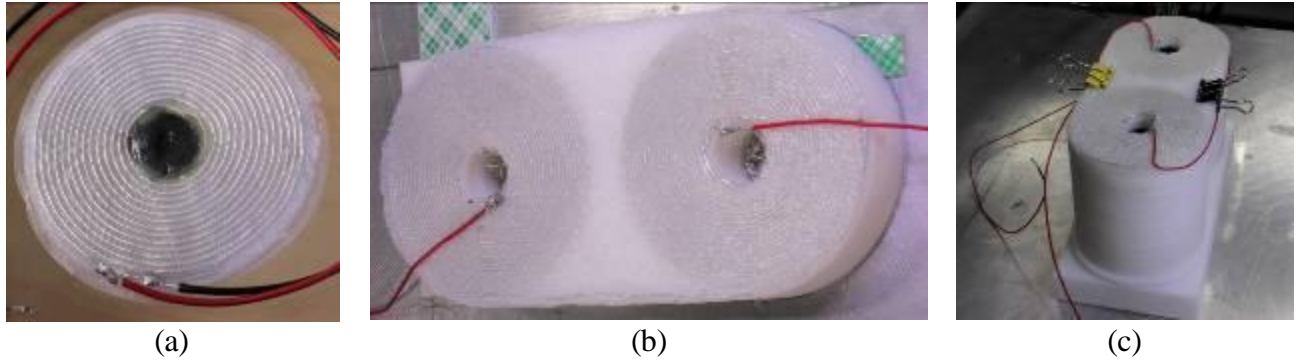
Due to interlayer connection reliability issues, and because three-layer coils generate sufficient force to actuate the register, we elected to complete this first replica of the register with fewer coils than the original. To maintain the same geometry for the overall machine, and to position our freeform fabricated coils adjacent to the lever mechanism, we deposit the

electromagnet for the finished machine atop a stack of “false coils” – hollow ABS cylinders containing only ferromagnetic core material. *Figure 3(C)* shows the result of this endeavor. The “false” electromagnetic coils were stacked on the multi-material research system, which was then used to deposit core material into them to maintain a continuous core. The silicone, solder, and core material were then printed on the ABS to form the electromagnet as in *Figure 3(B)*. In order to create structural components suitable for magnetic attraction, the multiple material research system deposited material on components produced by the Stratysis. Silicone and core material were printed by the multi-material research system directly onto the ABS lever mechanism as shown in *Figure 4(C)*. The silicone coupled very well with the ABS material. To finish the device, the Stratysis-produced clock mechanism was hand assembled together with the electromagnet and lever mechanisms, wire leads were soldered to the electromagnet to allow connection to a power supply, and a Q-tip soaked in food coloring was inserted into the lever. Small permanent magnets were added to the lever mechanism to adjust its balance point. A roll of paper was cut with a lathe and knife to use in the machine as described by Alfred Vail (1845).

## Results and Discussion

Functional electromagnets were created with a range of 14 to 20-turns with a wire diameter from .5 mm to .8 mm in layers of 11.44 cm<sup>2</sup>. *Figure 3 (A)* demonstrates a 14-turn electromagnet. The longest length of continuous wire printed was two 20-turn layers printed side by side, which resulted in an estimated 4.3m of wire as shown in *Figure 3(B)*. This was estimated from a failed 20-turn coil producing 2.14m of wire. The coil was able to lift 2.5 grams with 7 amps applied.

The best electromagnet produced was three consecutively stacked layers of 20 turns each. This device had a total resistance of 11.4Ω. It should be noted that the connection was prone to breaking from heavy movement, twisting, and bending of the coil. Reliable connections were achieved at different instances, but in general the machine was not tuned to make reliable connections. This could be achieved with proper temperature, tool, and material tuning. The largest difficulty for both the connecting layers and single layers was controlling the z-height of the machine tool. The joining layer was added to correct this issue. Without this layer, it is unlikely for a wire to form until contact with the silicone. This relates to the molten metal properties, at a far distance from a build surface the material will bead before contacting the build substrate. This pooling of material prevents the solder from losing heat fast enough to form a wire, causing the device to appear to have a lower feed rate than required.

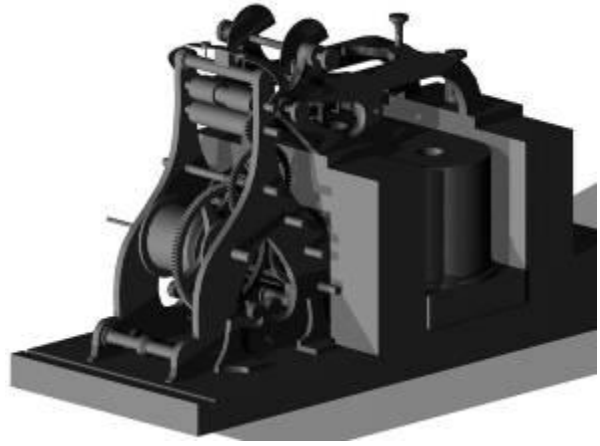


**Figure 3: Printed coils:** (a) Electromagnet consisting of 14 turns of .6-.7 mm diameter wire; (b) Demonstration of length, approximately 4.3m of coil with 0.5-0.7mm diameter wire; (c) Stacked ABS components with core material printed during stacking.

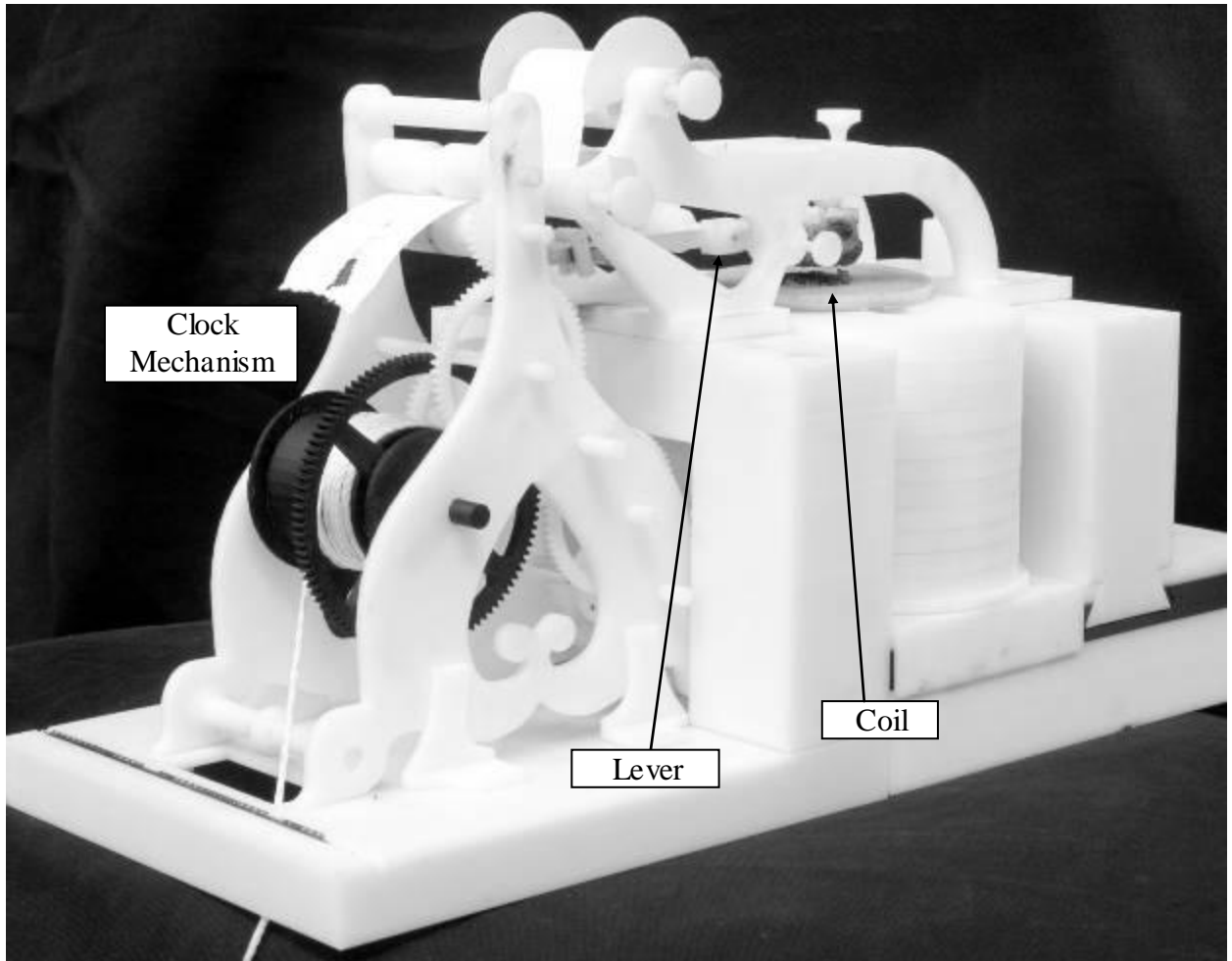
While in terms of length, the coil printed in *Fig 3b* was a significant build achievement, the coil printed in *Fig 2b* was removed and selected for telegraph actuation for its superior actuation characteristics. Current was then applied and the machine was actuated with an antique telegraph key, which controlled the flow of current to the electromagnet in order to send a message. The gear mechanism – originally intended to be gravity fed - was manually cranked, as sufficient weight control was not available. The modeled version and printed version of the machine is shown in *Figure 4*. The machine printed “What Hath God Wrought” in Morse code as shown in *Figure 5*.



(a)

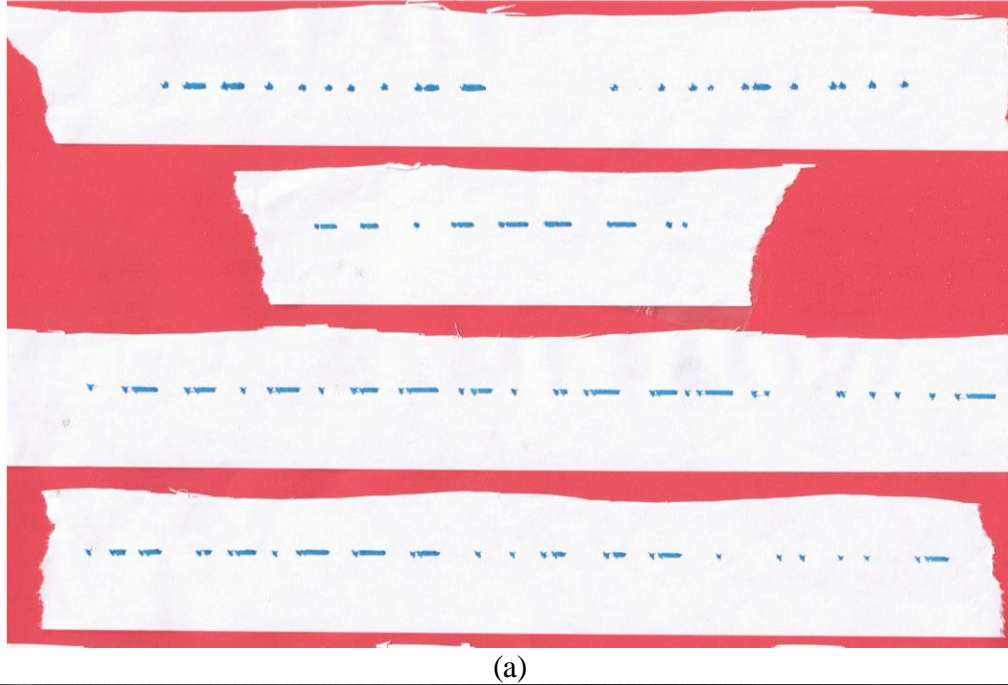


(b)

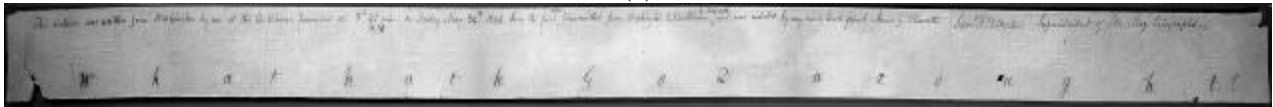


(c)

Figure 4: **The Vail Register:** (a) Original device; (b) Modeled in CAD; (c) 3D-printed.



(a)



(b)

**Figure 5: Transmitted messages:** (a) message transmitted on printed machine, reading “What Hath God Wrought” from left to right, with “Wrought” repeated; (b) The original message received in Baltimore by Alfred Vail from Samuel Morse in Washington reading:

“..... .- - | ..... .- - .... | -. -.. -.. | .- .- .- .- -. ....”

## Conclusion

In conclusion, a traditional electromagnetic actuator and complex electromechanical device has been fabricated using SFF. This is the first time a macroscopic electromagnet has been produced. An inexpensive freeform fabrication technique has been demonstrated to print freeform actuators. With this new development, we are one step closer to machines being able to design and print themselves as envisioned by Lipson (2005). We now know it can be done; the last challenge is making the machine that can do reliably. In the same way that the Vail register marked the transition to a new age of communication, the advent of classical electromechanical devices to the list of systems capable of being fabricated by SFF may help generate the transition from mass production to mass customization and fabrication of truly unique devices.

## Acknowledgments

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