

3DHI & Additive Manufacturing

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In-situ Magnetization of Additively Manufactured, Permanent Magnets

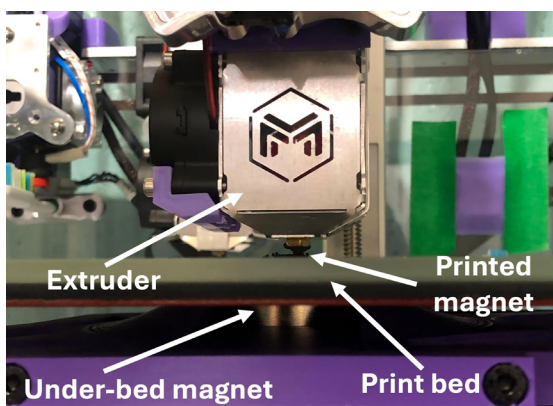
Z. Bigelow, L. F. Velásquez-García
Sponsorship: Empiriko Corporation

Hard ferrite magnets are widely used due to their low cost, chemical stability, and resistance to demagnetization, making them attractive for applications in motors, sensors, and consumer electronics. However, traditional fabrication methods are limited to predefined shapes and rely on post-processing magnetization steps, restricting design freedom and integration into complex devices.

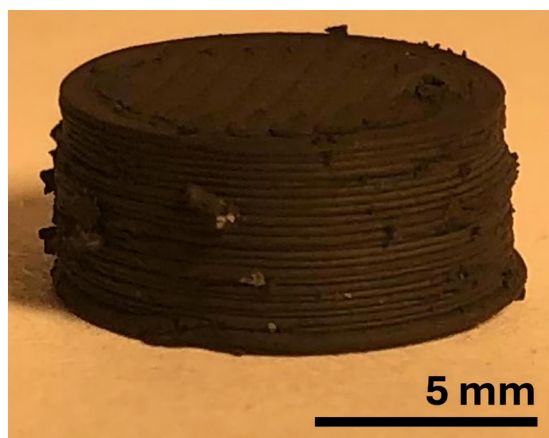
In this project, we explore the in-situ magnetization of ferrite-based composites during the printing process itself—a feat not previously demonstrated, to our knowledge. Our work represents a departure from conventional post-print magnetization techniques and

opens the door to freeform fabrication of functional, magnetic architectures, particularly in applications where shape complexity and miniaturization are critical.

By placing a high-strength, permanent magnet beneath the printer bed (Figure 1), we successfully magnetized ferrite-doped, Nylon 12 feedstock as it was extruded and cooled (Figure 2). This process resulted in a net surface magnetic field on the printed part—a significant step toward additive manufacturing of magnetized components. Current research efforts focus on feedstock optimization, magnetization direction control, and magnetic strength optimization.



▲ Figure 1: Side view of magnet secured beneath printer bed.



▲ Figure 2: 3D-printed, hard ferrite magnet.

FURTHER READING

- A. P. Taylor, J. Izquierdo-Reyes, and L. F. Velásquez-García, "Compact, Magnetically Actuated, Additively Manufactured Pumps for Liquids and Gases," *J. of Physics D – Applied Physics*, vol. 53, no. 35, 355002, Aug. 2020. DOI: 10.1088/1361-6463/ab8de8
- A. P. Taylor, C. Vélez Cuervo, D. Arnold, and L. F. Velásquez-García, "Fully 3D-Printed, Monolithic, Mini Magnetic Actuators for Low-Cost, Compact Systems," *J. of Microelectromechanical Systems*, vol. 28, no. 3, pp. 481-493, Jun. 2019. DOI: 10.1109/JMEMS.2019.2910215
- J. Cañada, H. Kim, and L. F. Velásquez-García, "Three-dimensional, Soft Magnetic-cored Solenoids via Monolithic, Multi-Material Extrusion," *Virtual and Physical Prototyping*, vol. 19, no. 1, e2310046, Feb. 2024. DOI: 10.1080/17452759.2024.2310046

Fully 3D-printed, Soft Magnetic Cores Via Material Extrusion

J. Cañada, L. F. Velásquez-García

Sponsorship: Empiriko Corporation, “la Caixa” Foundation

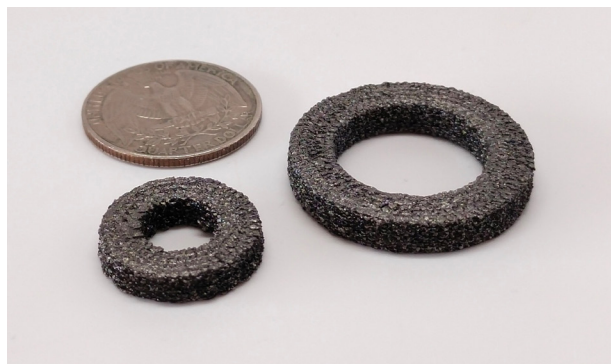
Electrical machines are the key elements in the generation, distribution, and utilization of electrical energy. Recently reported works demonstrate that additive manufacturing (AM) technologies can produce all the parts involved in the fabrication of electrical machines including magnetic cores, conductive coils, permanent magnets, and mechanical couplings. By harnessing the virtues of AM (e.g., multi-material fabrication, waste reduction, feasibility to create freeform, geometrically complex structures), the fabrication of electrical machines can become cheaper and easier, and their performance can be improved.

The performance of electrical machines is closely tied to that of their magnetic cores, which are made of soft magnetic materials. Multiple studies have reported on the development of AM-compatible, soft magnetic feedstock. However, the performance of most of the proposed materials is poor, exhibiting relative magnetic permeabilities of 2-3. Processes that yield parts with higher magnetic permeabilities (up to ~600) have been reported, but they rely on heat post-processing at temperatures close to 1000 °C, which is incompatible with thermoplastics-based, multi-

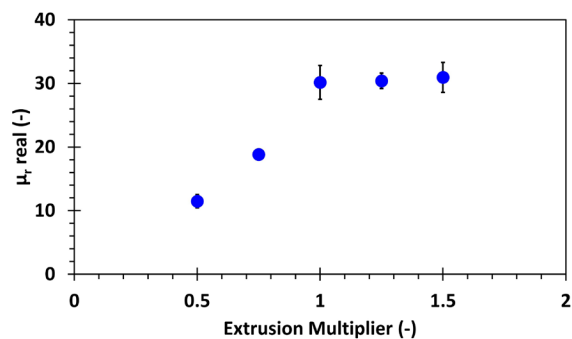
material three-dimensional (3D) printing and often introduces geometrical distortions on the fabricated components.

This work reports the single-step 3D printing of soft magnetic cores that attain relative magnetic permeabilities above 30, while not requiring heat post-processing (Figure 1). The 3D-printed cores exhibit a narrow hysteresis loop and negligible electrical conductivity—qualities desirable for the fabrication of soft magnetic cores for electrical machines. Furthermore, the magnetic permeability of the cores can be modulated by tuning specific 3D printing parameters (Figure 2), enabling the monolithic fabrication of multi-permeability cores.

The cores are fabricated from pellets of FeSiAl-doped nylon using a multi-material extrusion 3D printer capable of handling other functional materials (e.g., electrically conductive, elastic). This feat entails significant progress towards the monolithic AM of electrical machines and has immediate relevance for the on-site fabrication of electromechanical devices in remote areas.



▲ Figure 1: 3D-printed toroidal cores of different sizes made in FeSiAl-doped nylon next to a US quarter.



▲ Figure 2: Real component of the relative magnetic permeability of 3D-printed cores at 1 MHz versus the “extrusion multiplier” 3D printing parameter.

FURTHER READING

- J. Cañada, S. F. Nagle, N. Vidal, J. M. López-Villegas, and L. F. Velásquez-García, “3D-Printed Soft Magnetic Cores for Compact Electromechanical Devices Via Material Extrusion,” *2024 IEEE 23rd International Conference on Micro and Miniature Power Systems, Self-Powered Sensors and Energy Autonomous Devices (PowerMEMS)*, Tonsberg, Norway, 2024, pp. 255-258. DOI: 10.1109/PowerMEMS63147.2024.10814238
- J. Cañada, H. Kim, and L. F. Velásquez-García, “Three-dimensional, Soft Magnetic-cored Solenoids via Multi-material Extrusion,” *Virtual and Physical Prototyping*, vol. 19, no. 1, 2024. DOI: 10.1080/17452759.2024.2310046
- A. P. Taylor, J. Izquierdo-Reyes, and L. F. Velásquez-García, “Compact, Magnetically Actuated, Additively Manufactured Pumps for Liquids and Gases,” *J. of Physics D – Applied Physics*, vol. 53, no. 35, p. 355002 August 2020. DOI: 10.1088/1361-6463/ab8de8

Semiconductor-Free, Fully 3D-printed Logic Gates

J. Cañada, L. F. Velásquez-García

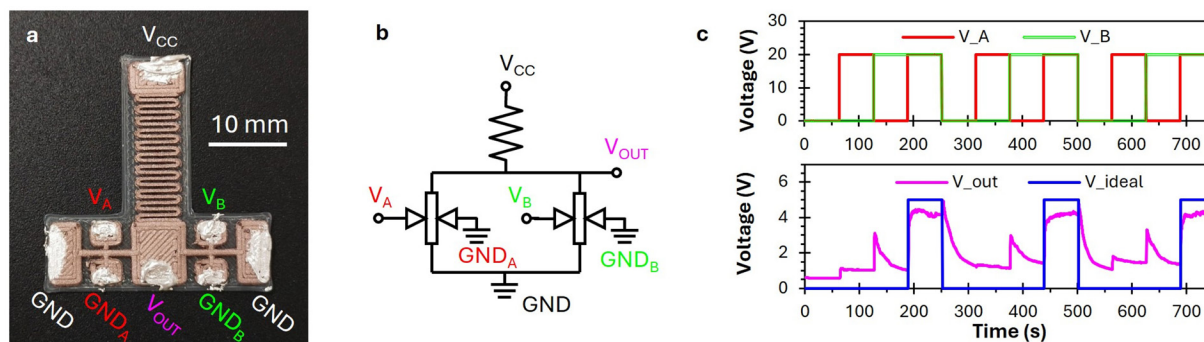
Sponsorship: Empiriko Corporation, “la Caixa” Foundation

Additive manufacturing (AM) has the potential to enable the inexpensive, single-step fabrication of fully functional electromechanical devices. However, while the three-dimensional (3D) printing of mechanical parts and passive electrical components is well developed, the fabrication of fully 3D-printed active electronics, which are the cornerstone of intelligent devices, remains a challenge. Existing examples of 3D-printed active electronics show potential but lack integrability and accessibility.

This work reports the first instance of active electronics fully 3D-printed via material extrusion. Material extrusion is one of the most accessible and versatile additive manufacturing technologies, and it is among the few techniques capable of monolithic multi-material fabrication. The proposed devices harness a polymeric positive temperature coefficient phenomenon observed in thin 3D-printed traces of copper-reinforced polylactic acid. This phenomenon, which entails a temperature-driven, reversible, and repeatable spike in resistivity, can be leveraged for

the implementation of 3D-printed electrical switches. The proposed switches behave as normally closed switches, and their combination with other 3D-printed components (e.g., resistors) enables the fabrication of fully 3D-printed integrated circuits. This capability is demonstrated through the implementation of the first fully 3D-printed, semiconductor-free, solid-state logic gates (Figure 1). The devices are fabricated in a single operation using commercially available hardware and materials.

Although the reported switches and logic gates do not perform competitively against semiconductor-enabled integrated circuits, the customizability and accessibility intrinsic to material extrusion make this technology promisingly disruptive. Furthermore, the combination of the proposed control devices with the ability of material extrusion to fabricate electromagnetic devices and mechanically functional components can enable the single-step fabrication of complex hardware, such as functionalized prostheses and robots.



▲ Figure 1: Fully 3D-printed AND gate: picture of fabricated device (a), schematic (b), and input-output characteristics with V_{cc} set to 5 V (c)

FURTHER READING

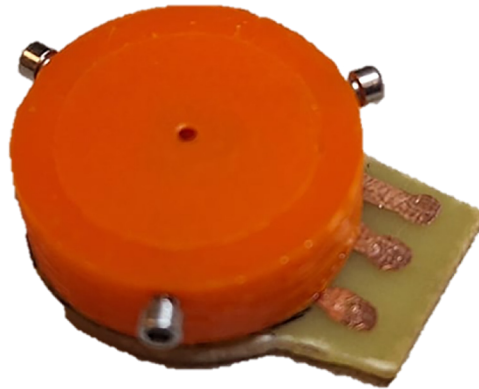
- J. Cañada and L. F. Velásquez-García, “Semiconductor-free, Monolithically 3D-printed Logic Gates and Resettable Fuses,” *Virtual and Physical Prototyping*, vol. 19, no. 1, 2024. DOI: 10.1080/17452759.2024.2404157
- J. Cañada, H. Kim, and L. F. Velásquez-García, “Three-dimensional, Soft Magnetic-cored Solenoids via Multi-material Extrusion,” *Virtual and Physical Prototyping*, vol. 19, no. 1, 2024. DOI: 10.1080/17452759.2024.2310046
- A. P. Taylor, J. Izquierdo-Reyes, and L. F. Velásquez-García, “Compact, Magnetically Actuated, Additively Manufactured Pumps for Liquids and Gases,” *J. of Physics D – Applied Physics*, vol. 53, no. 35, p. 355002 Aug. 2020. DOI: 10.1088/1361-6463/ab8de8

Miniaturized, 3D-printed Retarding Potential Analyzer

B. I. Quintanar, Z. Bigelow, L. F. Velásquez-García
Sponsorship: Lam Research

Retarding potential analyzers (RPAs) are gridded instruments that estimate the energy distribution of plasma ions; the information is important for optimizing plasma-based processes in fields such as semiconductor manufacturing, materials processing, and fusion energy research. This project aims at conducting a proof-of-concept demonstration of an additively manufactured RPA capable of measuring cold, dense plasmas, which have associated a small Debye length. The fabrication of the RPAs uses a combination of two different

vat-photopolymerization techniques: two-photon polymerization for the grids and digital light projection for the housing, allowing for precise control over the device's geometry and dimensions while minimizing the printing time. Computational fluid dynamics simulations using COMSOL Multiphysics have guided the design of the RPA. Current efforts focus on fabricating the devices and testing them in experimental plasmas of relevance.



▲ Figure 1: Miniaturized RPA, showing the active zone at the top and a PCB for electrical connections at the bottom.

FURTHER READING

- J. Izquierdo-Reyes, Z. Bigelow, N. Lubinsky, and L. F. Velásquez-García, "Compact Retarding Potential Analyzers Enabled by Glass-ceramic vat Polymerization for CubeSat and Laboratory Plasma Diagnostics," *Additive Manufacturing*, vol. 58, p. 103034, Jul. 2022. DOI: 10.1016/j.addma.2022.103034
- E. V. Heubel and L. F. Velásquez-García, "Microfabricated Retarding Potential Analyzers with Enforced Aperture Alignment for Improved Ion Energy Measurements in Plasmas," *J. of Microelectromechanical Systems*, vol. 24, no. 5, pp. 1355-1369, Oct. 2015. DOI: 10.1109/JMEMS.2015.2399373
- L. F. Velásquez-García, J. Izquierdo-Reyes, and H. Kim, "Review of in-space Plasma Diagnostics for Studying the Earth's Ionosphere," *J. of Physics D – Applied Physics*, vol. 55, no. 26, pp. 263001-263027, Jun. 2022. DOI: 10.1088/1361-6463/ac520a

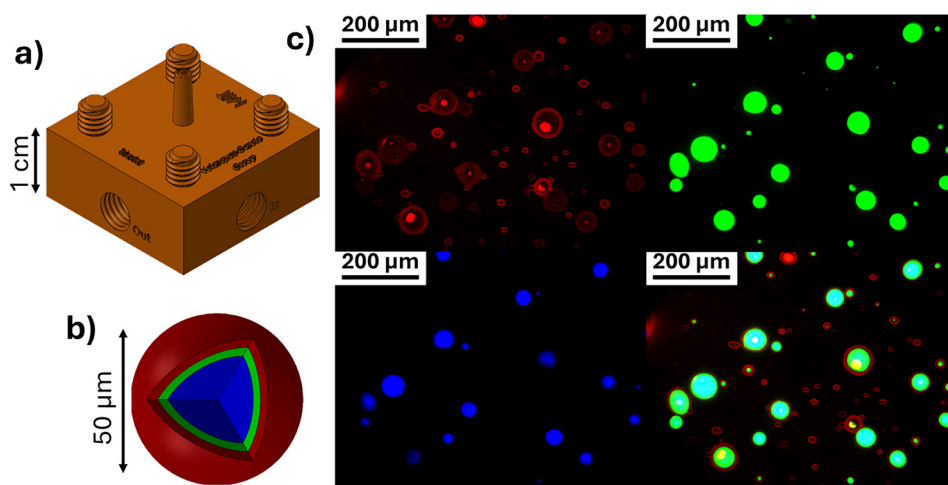
3D-printed Triaxial Electro spray Devices

B. I. Quintanar, L. F. Velásquez-García

Sponsorship: Monterrey Tec - MIT Nanotechnology Program

Electrospraying is a versatile technique that utilizes electrostatic forces to atomize liquids into fine droplets, enabling the encapsulation of a wide range of materials, including sensitive bioactive agents, drugs, and food ingredients. This project reports the proof-of-concept demonstration of the first three-dimensional (3D)-printed, triaxial electro spray microparticle generators. Made via vat photopolymerization, the devices' spouts have three concentric microchannels that facil-

itate the simultaneous and controlled release of multiple solutions, generating structured, multi-layered (core-shell-shell), compound microparticles (Figure 1). The compound particles have applications in drug delivery, self-healing materials, and micro- and nano-reinforced composites. Current research efforts focus on increasing the throughput of the devices by implementing arrays of emitters that uniformly operate in parallel.



▲ Figure 1: a) CAD of a 3D-printed, triaxial electro spray device; b) Core-shell-shell particle schematic identifying with colors its layers (red – outer shell, green – inner shell, and blue – core), c) Fluorescent microscopy images of compound particles generated by the 3D-printed devices (from left to right and from top to bottom): outer shell, inner shell, core, superposition.

FURTHER READING

- D. Olvera-Trejo and L. F. Velásquez-García, "Additively Manufactured MEMS Multiplexed Coaxial Electro spray Sources for High-throughput, Uniform Generation of Core-shell Microparticles," *Lab on a Chip*, vol. 16, no. 21, Jan. 2016. DOI: 10.1039/c6lc00729e
- H. Kim and L. F. Velásquez-García, "High-impulse, Modular, 3D-printed CubeSat Electro spray Thrusters Throttleable via Pressure and Voltage Control," *Advanced Science*, vol. 12, no. 13, pp. 2413706-2413719 Apr. 2025. DOI: 10.1002/advs.202413706
- B. Garcia-Farrera and L. F. Velásquez-García, "Ultrathin Ceramic Piezoelectric Films via Room-temperature Electro spray Deposition of ZnO Nanoparticles for Printed GHz Devices," *ACS Applied Materials & Interfaces*, vol. 11, no. 32, pp. 29167-29176, Aug. 2019. DOI: 10.1021/acsami.9b09563

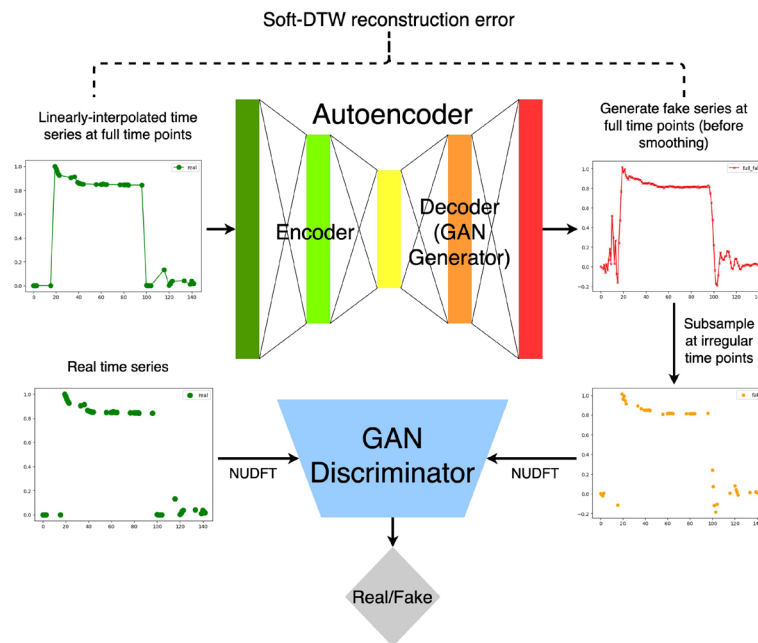
Unsupervised Anomaly Detection on Irregular Time Series Data

F.-K. Sun, R. K. Owens, D. S. Boning
Sponsorship: Analog Devices

Anomaly detection in semiconductor manufacturing is essential for maintaining production quality and efficiency. However, data from semiconductor equipment sensors can form irregular (i.e. unevenly-spaced) time series due to sporadic instabilities, which challenge the regularity assumption in most machine learning algorithms.

Our anomaly detection uses an autoencoder as its backbone. To address time shifts commonly seen in signals, we compute the reconstruction error using Soft-Dynamic Time Warping (Soft-DTW), a technique

resilient to temporal misalignments. We also employ the Non-Uniform Discrete Fourier Transform (NUDFT) to convert irregular time series into fixed-size representations in the frequency domain, making the data suitable for processing. To further enhance the ability to reconstruct realistic series, even with irregular timing, we integrate a Generative Adversarial Network. This combined approach enables robust anomaly detection in irregular time series without performance degradation.



▲ Figure 1: Overall model architecture.

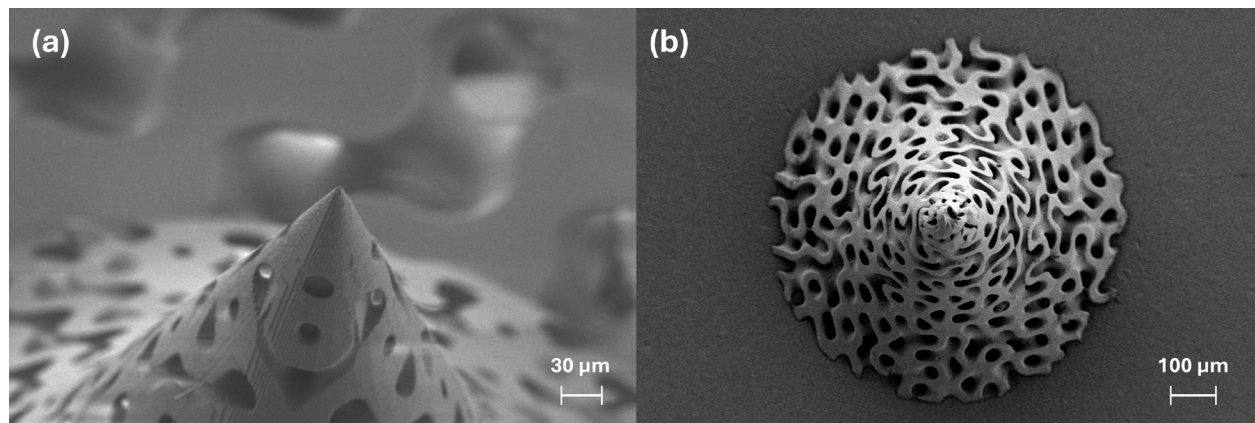
Additive Manufacturing of Hybrid Electrospray Emitter Geometries via Two-Photon Polymerization

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Sponsorship: NASA Space Technology Graduate Research Opportunities Grant

Electric propulsion provides precise, in-space propulsion with mass savings and high specific impulse. Electrospray propulsion, using microfluidics and electrostatics to accelerate ions and droplets, has low-thrust applications and can scale to larger systems. Key failure modes are dependent on the propellant wetting properties and emitter geometry.

Current manufacturing methods face challenges in creating precise, repeatable emitter geometries, leading to long development times and unstable performance.

This work aims to improve individual emitter accuracy with nanoscale additive manufacturing and tailor wetting properties via dielectric atomic layer deposition. Single emitters are printed including triply periodic minimal surfaces (TPMS) to achieve uniform porosity, followed by alumina coating to adjust wetting. Key electrospray performance parameters are estimated, revealing the potential for convenient, repeatable emitter fabrication and tailored geometries for specific applications.



▲ Figure 1: Scanning electron microscope (SEM) images of additively-manufactured (a) Schwarz diamond TPMS electrospray emitter, (b) and alumina-coated gyroid TPMS electrospray emitter.

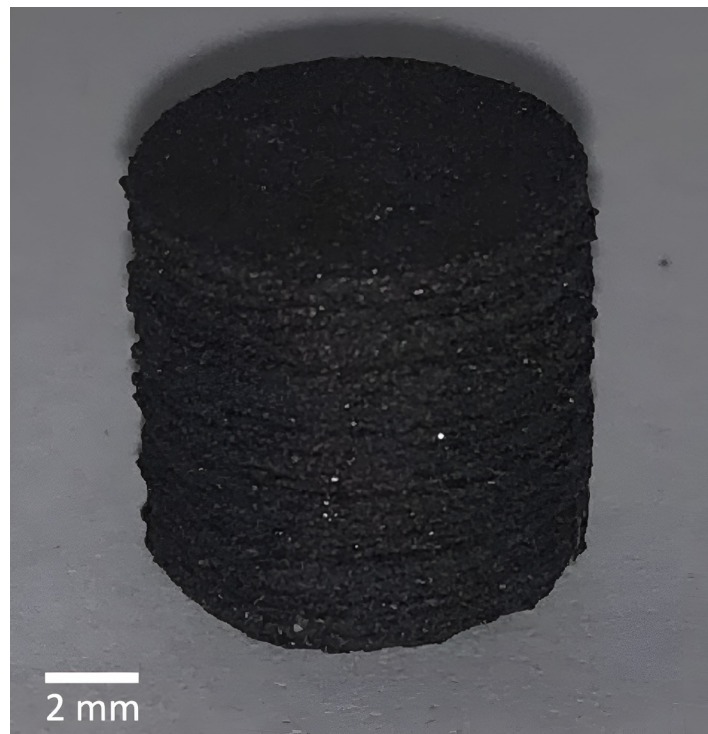
3D-Printed Hard Magnets

Z. Bigelow, L. F. Velásquez-García
Sponsorship: Empiriko Corporation

Hard magnets are extensively used across numerous industries, including electronics, automotive, renewable energy, healthcare, and consumer goods. However, conventional methods for producing these magnets are limited to simple shapes and require assembly, leading to increased production costs and constrained geometries and devices.

We present a novel 3D printing process capable of producing hard magnets using micro- and nano-reinforced materials, thereby expanding the scope of their practical applications. Our research is focused on the fabrication of isotropic magnets at a miniature

scale, typically ranging in size from a few millimeters. The material composition utilized in our printing process consists of a blend comprising 75% NdFeB and 25% Nylon 12 by volume. This work demonstrates the feasibility of 3D printing hard magnets and underscores the potential for fine-tuning magnetic properties through additive manufacturing techniques. These advancements offer precise control over magnet geometry and performance, presenting significant opportunities for industries seeking tailored magnetic solutions.



▲ Figure 1: 3D printed 75% NdFeB magnet.