High-temperature compatible, monolithic, 3D-printed magnetic actuators

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Abstract. We report the design, fabrication, and characterization of the first miniature 3D-printed, monolithic magnetic actuators that are compatible with high temperature (>200 °C) operation. The actuator is a cylindrical frame that holds a coil and a 24 mm diameter, 150 μm-thick membrane connected at its center to a piston with a cavity containing an embedded SmCo magnet. The fused filament fabrication (FFF) method is used to print the non-magnetic portion of the actuator out of pure nylon 12. The displacement of a single-layer membrane actuator is characterized for various coil bias voltages; a maximum displacement equal to 302 μm was obtained with 20V DC applied to the driving coil. Data analysis demonstrates that the magnetic force is proportional to the square of the current drawn by the coil –as expected from theory.

1. Introduction

Various PowerMEMS devices require large displacement and large force actuation to be efficient, e.g., diaphragm vacuum pumps [1],[2]. However, hardware made with standard i.e., cleanroom, microfabrication typically cannot deliver such performance without the added device complexity of hydraulic amplification of large-force, small-displacement actuation, e.g., piezoelectric [3]. Magnetic actuation is an attractive choice to deliver large displacement and large force in a compact form factor [4]; nonetheless, state-of-the-art magnetic actuation for microsystems focuses on monolithic integration of the fabrication of the magnets within the cleanroom-bound process flow of the microsystem [5], highly constraining the choice of materials, geometries, and substrates.

Additive manufacturing, i.e., the layer-by-layer fabrication of objects using a computer-aided design (CAD) file [6], has recently been explored as a processing toolbox for MEMS; researchers have reported 3-D printed microsystems with performance on par or better than counterparts made with standard microfabrication [7], as well as demonstrated microsystem designs not previously implemented due to fabrication complexity or inherent system three-dimensionality [8],[9]. Proof-of-concept stereolithography 3D-printed valves with NdFeB magnets have been reported [10], but the devices required a large external electromagnet for actuation, had magnets inserted after printing, and the NdFeB magnets should demagnetize at temperatures above ~80 °C. In this work, miniature actuators were printed in pure nylon 12 –a high-performance plastic, using the fused filament fabrication (FFF) method –where a thermoplastic filament is extruded from a hot nozzle to create layer by layer a solid object. The actuators have embedded SmCo magnets that are not demagnetized by the heated nozzle (@ 250 °C) while being sealed in place midstream in the printing process.
2. Characterization of printing method and feedstock
A CreatBot model DX Plus 3D printer (Henan Suwei Electronics Tech., Zhengzhou City, China) was used to manufacture test structures and devices in nylon 12 (Orbi-Tech, Leichlingen, Germany) with a 600 μm-diameter stainless steel nozzle extruding feedstock at 250 °C. The printer has a glass bed that was coated with a thin layer of PVA-based adhesive before printing to promote adhesion of the object to the bed. Nylon is hydrophilic and water absorption adversely impacts FFF printing; therefore, to minimize filament moisture content, the spooled filament was baked at 80 °C for 2 hours in a vacuum oven prior to use, and the printer was housed in a 3DPrintClean Model 600 enclosure (Mountainside, NJ) with recirculating HEPA filtration.

To FFF-print an object, a CAD model in .stl format is created (SolidWorks 2015, Dassault Systemes, Waltham, MA) and exported to a slicer software (Simplify3D), which transforms the 3-D model into a set of horizontal cuts, i.e., slices, creating a gcode file that contains the traveling path that rasters each slice with associated conditions (e.g., nozzle temperature, bed temperature, feedstock feed rate, nozzle speed). The gcode file is transferred to the 3-D printer using a flash memory card, to then print the object by following the instructions of the gcode file. By trial and error, it was determined that the thinnest single-layer membranes that were repeatable, robust, and appeared leak tight had a nominal thickness equal to 150 μm. In addition, it was also determined by trial and error that the thinnest layers that could reliably be printed with the setup had a nominal thickness equal to 38 μm.

Step pyramids were printed and characterized to assess the capabilities of the printing process and printer; the objects were printed in either 38 μm-thick or 150 μm-thick layers. In these experiments X and Y correspond to the in-plane dimensions (i.e., across the glass bed), while Z corresponds to the out-of-plane dimension; the size of any in-plane feature is a multiple of the layer height. Metrology of the structures conducted with a white light interferometer shows good correspondence between differential measurements in the printed object and the CAD file (Figure 1). The offset in Z is on the order of a few microns, while the offsets in X and Y are around 360 μm; the X and Y offsets can be easily compensated for when generating the gcode file used to run the printing job.

Knowing the elastic properties of the printed material is essential to model the structural performance of the actuator. Uniaxial tension tests were conducted with a PASCO Materials Testing Machine ME-8236 (Pasco, Roseville, CA) on five coupons to characterize the Young’s modulus and tensile strength of test structures printed in 150 μm thick layers with one 600 μm-wide outer shell and infill layers printed at alternating angles of -45° and +45° with respect to the major-axis, creating a crosshatch pattern. The structures are 1.3 mm thick, have a narrow 2 mm wide beam in the center, and have tabs at either end with ridges that interface with the flat coupon fixture Pasco ME-8238. The tests were conducted at 8 mm/min constant pulling rate and 20 Hz sampling frequency. From data analysis, the Young’s modulus of the crosshatched FFF-printed nylon 12 is estimated at 606 ± 10 MPa (R²=0.99) and the tensile strength is estimated at 37.9 ± 3.5 MPa. It is anticipated that the crosshatched structure is more flexible than the bulk material; the calculated Young’s modulus is about half the lower bound reported in the literature (1270 MPa [11]); nonetheless, the estimated tensile strength is close to the reported minimum value in the same reference.

![Figure 1. In-plane (X, Y) and out-of-plane (Z) printed features vs. corresponding CAD features for FFF-printed objects in nylon 12 using 38 μm-thick and 150 μm-thick layers. For objects printed with 150 μm layers there is a ~2% mismatch between the dimensions of a printed object and those of the corresponding CAD file (in-plane printed features are larger than those in the CAD model, while out-of-plane printed features are smaller than those in the CAD model).](image-url)
3. Device design and characterization
The actuator is a frame that holds a coil (from an Omron LY2-DC24 relay, iron core removed) and a 24 mm diameter, 150 μm-thick membrane connected at its center to a 12.4 mm diameter piston with a 9.5 mm diameter cavity containing the embedded magnet (Figure 2); a 150 μm-thick layer secures the magnet in place, with a 600 μm wide lip around the edge. Finite element analysis of the actuator (SolidWorks 2015, Dassault Systemes, Waltham, MA) predicts that a force of 0.12 N on the piston results in a 302 μm maximum membrane displacement (i.e., at the center, where the piston holding the magnet is connected) and a maximum stress equal to 1.9 MPa (Figure 3)—which is well below the limit for fatigue infinite life of nylon 12 (~19 MPa) [12].

To print an actuator, the printer bed is heated at 60 °C and then coated with a thin layer of adhesive. After that, the temperature of the bed is raised to 80 °C and the membrane is printed directly onto the adhesive film, followed by the piston and frame. Single 600 μm-wide inner and outer shells are defined, and the infill layers are printed alternately at ±45° with respect to the X-axis of the printer until completion. A SmCo magnet 3/8” in diameter and 1/8” thick from Dura Magnetics Inc. (Sylvania, OH; part # SC3712-500, 26 MGOe maximum energy product) is embedded into the cavity formed within the piston while the printer is paused, right before printing the sealing lip on top of the magnet to hold it in place. Once completed, the actuator is removed from the printer bed and cleaned with isopropanol to remove any remaining adhesive. Four holes printed in the frame are tapped with 6-32 threads so nylon set screws can be attached to grip the coil. The design sets the distance between the closest coil windings and the top surface of the embedded magnet in the piston at 1.85 mm, i.e., there is a 0.85 mm air gap and 1 mm-thick nylon part comprising a spool plate holding the windings in place. The membrane of the devices tested were made of one 150 μm-thick layer (Figure 4, right).

![Figure 2. Cross-section of magnetic actuator with FFF-printed nylon 12 body, embedded SmCo magnet, and off-the-shelf driving coil.](image1)

![Figure 3. Finite element solution of the actuator's stress field while a 0.12 N force is applied to the piston.](image2)

![Figure 4. A single-layer, 150 μm-thick membrane actuator while being tested (left) and close-up of the membrane showing the striations due to the rastering of the nozzle (right).](image3)

4. Experimental results
The displacement of a single-layer membrane actuator was characterized for various coil bias voltages in a Dektak stylus profilometer with ± 500 μm vertical range (Figure 4, left); the maximum displacement recorded was 302 μm with 20V DC applied to the driving coil (Figure 5). Both negative and positive voltages were applied to the coil; the shape of the displaced membrane was approximately symmetric. The magnetic force versus the square of the current drawn by the coil was estimated from current and displacement measurements in the Dektak experiments and finite element analysis (Figure 6); a linear fit to the data indicates that the magnetic force generated by the coil is proportional to the square of the coil current—as expected from theory.
Figure 5. Membrane displacement vs. radial position from the edge for various DC bias coil voltages for an actuator with a 150 µm-thick single-layer membrane. The membrane sags at 0V due to the weight of the magnet.

Figure 6. Magnetic force acting on the SmCo magnet (from finite element simulations) versus the square of the current drawn by the driving coil (from experimental measurements).

5. Conclusions
We have demonstrated the first miniature, 3D-printed, monolithic magnetic actuators that are compatible with high temperature (>200 °C) operation. The displacement of a 150 µm-thick, single-layer membrane actuator is characterized for various DC coil bias voltages, resulting in a maximum membrane displacement equal to 302 µm when 20V DC are biased across the driving coil. Current research efforts focus on achieving larger stroke actuation and higher force.

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