Low-cost, monolithically 3D-printed, miniature high-flow rate liquid pump

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Abstract. We report the design, fabrication, and characterization of the first monolithically 3D-printed, high-flow rate miniature liquid pumps in the literature. Our low-cost, leak-tight, miniature devices are microfabricated using 150 to 300 μm layers in pure Nylon 12 via fused filament fabrication with a multi-step printing process that monolithically creates all key features with <13 μm in-plane misalignment. Each pump has a rigid frame, a 21 mm-diameter, 150 μm-thick membrane connected at its center to a piston with an embedded magnet, a chamber, passive ball valves, and two barbed fluidic connectors. Pump fabrication under 2 hours and costs less than $4.65 (about $0.65 in printable feedstock). Finite element analysis of the actuator predicts a maximum stress of 18.7 MPa @ 2 mm deflection, i.e., about the fatigue limit of Nylon 12 for infinite life (i.e., 19 MPa). A maximum water flow rate of 1.37 ml/min at 15.1 Hz actuation frequency is calculated –comparable to reported values of miniature liquid pumps with up to two orders of magnitude higher actuation frequency.

1. Introduction

Many compact systems use pumps to precisely set flow rates of liquid or, in general, to manipulate small liquid volumes to achieve effective mass transport, cooling, or momentum transfer [1]. In particular, numerous microfabricated positive displacement pumps for liquids with chamber volumes that are cycled using passive and active valves have been proposed [2]. However, liquid pumps made via standard (i.e., cleanroom) microfabrication typically cannot deliver large flow rates without integrating hydraulic amplification [3] or operating at high frequency to compensate for their small pump chamber [4]. Magnetic actuation is an attractive choice to deliver large displacement and force in a compact form factor [5]; 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 [6], highly constraining the choice of materials, geometries, and substrates.

Additive manufacturing, i.e., the layer-by-layer fabrication of objects using as template a computer-aided design (CAD) model [7], has recently been explored as a processing toolbox for microsystems [8]-[14]; in particular, researchers have reported 3D-printed pumps for liquids and gases with performance on par or better than counterparts made with standard microfabrication [15],[16]. Proof-of-concept stereolithography 3D-printed valves with NdFeB magnets have been reported [17]; however, these devices have the magnets integrated after printing, and the NdFeB magnet should demagnetize at ~80 °C.

In this work, building upon earlier work on printed MEMS magnetic actuators [18], we report
miniature liquid pumps printed in pure Nylon 12 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 pumps have embedded SmCo magnets that are not demagnetized by the heated nozzle (@ 250 °C) while being sealed in place midstream in the printing process. The actuators drive a long-stroke chamber without hydraulic amplifiers, and employ passive valves to greatly simplify their operation.

2. Device design
Each pump is composed of a rigid frame, a 21 mm-diameter, 150 µm-thick membrane connected at its center to a piston with an embedded SmCo magnet, a displacement chamber, two passive nitrile ball valves, and two barbed fluidic connectors (Figure 1). The passive valves are designed to switch as the piston moves back and forth across the chamber, resulting in one-directional movement of pockets of liquid that can generate a wide range of flow rates by controlling the frequency of actuation of the piston.

The valve on the left-hand side of the pump in Figure 1 is for liquid intake and seals when the nitrile ball seats on the top of the valve body; likewise, the valve on the right is for outlet liquid flow and seals when the ball seats on the bottom. The valves were originally designed with identical geometries; however, from sealing integrity tests it was determined that it is more difficult to form a seal between a ball and the top of a valve body surface (intake valve) compared to forming a seal between a ball and the bottom of a valve body (outlet valve). Therefore, the intake valve geometry was altered until sealing was satisfactorily achieved.

3D finite element simulations of the actuator were conducted using SolidWorks 2015 (Dassault Systèmes, Waltham MA, USA). In these simulations, Nylon 12 was modeled as an elastic, isotropic material with a Young’s modulus equal to 606 MPa (from uniaxial tests) and Poisson ratio equal to 0.30. The simulation results predict a maximum stress of 18.7 MPa @ 2mm deflection (Figure 2), which is about the fatigue limit for infinite life (19 MPa) [19].

Figure 1. Clockwise from top left: cross-section of pump CAD model; side view of printed pump; bottom view of printed pump showing embedded SmCo magnet; top view of pump membrane (the piston is visible behind it; the picture was taken before printing the rest of the pump). The magnet and valve balls are added during printing of the Nylon 12 body of the pump, creating a monolithic device.

Figure 2. Finite element simulation of the pump actuator at 2 mm piston displacement (a 1 to 2 mm displacement of the actuator was observed during the experiments). Due to the specifics of the fabrication process flow (see Section 3), the unactuated membrane is bowed instead of flat, which was corrected for in the simulation.
3. Device fabrication

The pump fabrication employs a novel multi-step printing process that monolithically creates all critical features with <13 µm in-plane misalignment. Pump fabrication takes under 2 hours and costs less than $4.65, with less than $0.65 in printable feedstock. To print an object via FFF, a CAD model in stl format is created using SolidWorks 2015 and exported to a slicer software (Simplify3D, Cincinnati OH, USA) that 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). In general, the Simplify3D software makes possible to have a different set of conditions for every slice. The gcode file is transferred to the 3-D printer, which creates the object following the instructions of the gcode file. By trial and error, it was determined that the thinnest single-layer membranes with repeatable fabrication that were robust and leak tight had a nominal thickness equal to 150 µm.

A CreatBot model DX Plus 3D printer (Henan Suwei Electronics Tech., Zhengzhou City, China) was used to manufacture devices in Nylon 12 (Orbi-Tech, Leichlingen, Germany) with a 600 µm-diameter stainless steel nozzle extruding feedstock at ~250 °C. The printer was housed in a 3DPrintClean Model 600 enclosure (Mountainside NJ, USA) with recirculating HEPA filtration. Fabrication of the pump starts by heating the printer bed at 60 °C and coating its surface with a thin layer of polyvinyl acetate (PVA) adhesive. The temperature of the bed is then raised to 80 °C and several 23.4 mm diameter, 150 µm thick priming pads are extruded onto the PVA-coated build platform; this step ensures a stable flow of Nylon 12 leaving the print nozzle just prior to printing the 23.4 mm diameter, 150 µm thick membrane—the first critical component of the liquid pump. Then, the first layer of the piston is printed at the center of the membrane; this layer has a diameter of 4.2 mm, i.e., the smallest diameter empirically found to reliably adhere to the membrane. This is followed by extruding the first layer of the frame comprised of two 600 µm-wide inner and outer shells; the first layer of the frame reduces the diameter of the membrane by 2.4 mm, leaving a 21 mm diameter supported membrane. Subsequently, 150 µm thick layers of the piston and frame are printed until the base of the piston is complete; a cavity is formed in the piston and a 3/8” diameter, 1/8” thick SmCo magnet (Dura Magnetics Inc., Sylvania OH, USA) is embedded into the cavity while the printer is

Figure 3. Process flow of FFF-printed pump: a) pump membrane (red), piston (blue), and partial frame (green) are printed; printer is paused and magnet (grey) is inserted. b) Magnet is embedded and frame is completed; c) PVA film (yellow) is applied on membrane using a shadow mask (purple). d) Mandrel (orange) is printed; e) partially printed pump is pressed onto mandrel and fasten in place. f) Pump chamber (light blue), inlet valve grid (red hatch), and bottom half of valves are printed; printer is paused and balls (black) are placed into valves. g) Printing of valves, outlet valve grid (red hatch) and barbed fittings is completed; h) PVA film is dissolved.

Figure 4. Experimental setup to characterize the FFF-printed pumps. In the apparatus, the pump is mounted on a solenoid actuated by a controller, a relay, and a power supply, and graduated cylinders filled-in with water are installed on the pump ports and; upon actuation, water flows from inlet to outlet.
paused, right before printing the sealing lip on top of the magnet to hold it in place (Figure 3a). Once
the lip and the frame are completed (Figure 3b), the partially printed pump is removed from the printer
bed and cleaned with isopropanol to remove any remaining adhesive. Next, four holes printed in the
frame are tapped with 6-32 threads so Nylon set screws can be used to fasten the part in place for
subsequent processing. After that, a thin PVA layer is applied to the membrane using a shadow mask
to prevent adhesion between the membrane and the next-to-be-printed chamber ceiling (Figure 3c).
Then, a mandrel is printed (Figure 3d) and the lower half of the pump is pressed and fastened onto it
with the Nylon set screws (Figure 3e), leaving the membrane stretched in a convex shape displaced by
2 mm at the center from its relaxed position. Afterwards, the chamber, valve channels, inlet valve grid
(to prevent the inlet valve from sealing during the down strokes), and half of the valve bodies are
printed on top of the stretched membrane, which is permanently deformed by the heat from the
extrusion nozzle. Printing is paused, and a 3/32” diameter nitrile ball (Rubber Mill, Liberty NC, USA)
is placed inside each valve cavity (Figure 3f). Afterwards, the top halves of the valves, outlet valve
grid (to prevent the outlet valve from sealing during the up strokes), and barbed fittings are printed
(Figure 3g). Finally, the membrane is pulled down and the PVA film is removed from the pump
chamber with solvents (Figure 3h).

Printing fine features and/or small parts via FFF is seldom successfully accomplished when using
the parameters that satisfactorily create a larger part because unwanted effects would take place, e.g.,
melting, stress cracking, under-extrusion, over extrusion. Consequently, a total of five customized
recipes are required to manufacture a functional pump, i.e., recipes for printing (i) the membrane,
frame, and piston; (ii) the chamber ceiling with valve channels; (iii) the intake valve grid; (iv) the
valve bases and outlet valve grid; and (v) the barbed fittings. All recipes use 150 μm-thick layers,
except for the barbed fittings that were printed with 300 μm-thick layers. Each recipe has a unique set
of parameters including nozzle temperature, feedstock flow rate, rastering speed, infill percentage, and
retraction settings.

4. Experimental results

Pump performance was characterized with the apparatus shown in Figure 4. The pump is mounted in a
fixture on top of a 24V DC solenoid (20 N maximum force) with the iron armature coupled to the
magnet. A microcontroller and relay switch a 24V DC power supply at different actuation frequencies.
Graduated cylinders are mounted vertically on the pump ports; water is introduced into the system
with the chamber open, up to the 5 ml mark on both cylinders. Upon pump actuation (i) the membrane
and valve balls move up and down, (ii) water flows from the inlet to the outlet, and (iii) time and
displaced volume above the equilibrium level in the outlet cylinder are measured. An exponential fit to
the water volume versus time data at an actuation frequency of 15.1 Hz asymptotically approaches 5.9
ml (Figure 5), suggesting that a maximum of 5.9 ml of water is displaced against gravity, which is

![Figure 5](image_url)

Figure 5. Displaced water volume above equilibrium at the outlet port versus time for an actuation frequency equal to 15.1 Hz. An exponential fit satisfactorily describes the data.

![Figure 6](image_url)

Figure 6. Water flow rate versus actuation frequency. Flow rate is calculated by taking the slope of the first four data points in Figure 5 where the behaviour is linear with time ($R^2 > 0.995$).
equivalent to a pressure of 32.7 kPa in the 1.5 mm diameter channel between the chamber and outlet valve; similar data were collected at different frequencies. On each data set, the flow rate was calculated by taking the slopes of the linear portions of the curves (t ~ 0); the data plotted versus frequency is shown in Figure 6. The maximum flow rate calculated is equal to 1.37 ml/min and took place while actuating the device at 15.1 Hz; the maximum flow rate is comparable to the maximum flow rate reported from miniature non-microfabricated [20] and microfabricated pumps [21] with up to two orders of magnitude faster actuation frequency. The drop off in performance above 15.1 Hz actuation observed in Figure 6 suggests that the valves are not able to seal effectively at the higher actuation frequencies. This may be caused by insufficient time for the balls to travel from the open to closed states inside the intake and outlet valve bodies in each cycle, as this time shortens with increased frequency of actuation. Altering the designs of the intake and outlet valves to establish if this is the case and whether a better design can be implemented should be investigated in future work.

5. Conclusions
We reported the design, fabrication, and characterization of the first monolithically 3D-printed, high-flow rate miniature liquid pumps in the literature. Pump fabrication takes under 2 hours and costs less than $4.65 (less than $0.65 in printable feedstock). Finite element analysis of the actuator predicts a maximum stress of 18.7 MPa @ 2mm deflection, i.e., about the fatigue limit of Nylon 12 for infinite life (i.e., 19 MPa). Water flow rate up to 1.37 ml/min is estimated at an actuation frequency of 15.1 Hz. Future work altering the design of the intake and outlet ball valves may lead to greater performance of these miniature liquid pumps.

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