Compact, magnetically actuated, additively manufactured pumps for liquids and gases

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Abstract

We report the proof-of-concept demonstration of novel, valve-less, and magnetically actuated miniature (~1 cm3) positive displacement pumps for liquids and gases—both single-material-printed pumps with embedded sintered magnets and the first monolithic, fully 3D-printed, multi-material magnetic pumps in the literature; a valve-less design greatly simplifies the pump’s operation and consumes less power compared to designs with active valves, and is less prone to clogging than designs with passive valves. The miniature diaphragm pumps are fabricated using 150 µm-thick to 225 µm-thick layers via fused filament fabrication; the structural parts are printed in pure Nylon 12, while the magnet that makes possible the actuation of the pump chamber is either monolithically printed in Nylon 12 embedded with NdFeB micro-particles or press-fit into the pump after single-material printing of the enclosing piston. The fabrication of the pumps employs a novel multi-material-compatible 3D printing process flow that monolithically creates all features with less than 13 µm of in-plane misalignment. Pump fabrication takes below 75 min to complete and costs under $3.89 in materials. The devices are driven by a rotating magnet and can deliver liquid flow rates as large as 7.88 ml min−1 at 198 Hz for sintered magnet pumps (N35 grade) and 1.68 ml min−1 at 204 Hz for the devices with monolithically 3D-printed magnets (~N4 grade); the results surpass state-of-the-art, 3D-printed miniature liquid pumps. Actuation of a pump in excess of 14.4 million cycles shows no evidence of degradation, e.g. leaks. A pump with sintered magnet (N48 grade) was characterized as a vacuum pump using air as working fluid, achieving an ultimate pressure of 540 Torr in a 0.61 ml pumping volume and up to 9.3 ml min−1 flow rate at 230 Hz actuation; the results compare well with miniature, commercial, non-3D-printed vacuum pumps.

Keywords: 3D-printed MEMS, magnetic actuation, microfluidics, miniature pumps, printed magnets, vacuum technology

(Some figures may appear in colour only in the online journal)

1. Introduction

Miniaturized pumps supply precise flow rates of liquids and gases, or provide vacuum, in numerous compact microfluidic systems. A great variety of microfabricated positive displacement pumps, i.e. devices that cyclically displace pockets of fluid using actuated chambers, have been reported [1, 2].
Compact positive displacement pumps made via standard (i.e. cleanroom) microfabrication typically employ electrostatic or piezoelectric actuators, which can exert large forces but cannot deliver large flow rates without involving hydraulic amplifiers (i.e. structures that trade-off force for displacement) and high-frequency (>1 kHz) actuation [3, 4]. Both pneumatic and hydraulic actuators can achieve large displacement and significant force [5]; nonetheless, they require an external source of pressurized fluid, restricting their portability, and also lag in actuation speed—potentially limiting the flow rate they can deliver. Magnetic actuation is an attractive approach to deliver both large force and large displacement in a compact form factor [6].

The great majority of the reported miniaturized positive displacement pumps have valves that are either passive (i.e. actuate by direct influence of the flow they control, e.g. check valves [7]) or active (i.e. actuate due to a signal that is independent of the flow they control, e.g. Quake-style valves [8]) [9]. However, a valve-less design greatly simplifies the pump’s operation and consumes less power compared to designs with active valves, and is less prone to clogging than designs with passive valves [10].

Cleanroom-microfabricated positive displacement pumps often involve complex, multi-substrate process flows (e.g. [4, 11]), limiting their fabrication yield and increasing their manufacturing cost. Additive manufacturing, i.e. the layer-by-layer, maskless fabrication of solid objects using a computer-aided design (CAD) model [12], has recently been explored as a fabrication toolbox for Microsystems, looking to circumvent the limitations of traditional microfabrication, e.g. high prototyping cost, small pool of compatible materials, geometries constrained to planar features [13–20]; in particular, researchers have reported 3D-printed positive displacement pumps for liquids and gases with performance on par or better than counterparts made with standard microfabrication [21–24]. In addition, proof-of-concept digital light projection (DLP)-printed valves with after-printing-embedded NdFeB magnets have been reported [25]. These demonstrations have been possible due to the availability of low-cost, commercial 3D printers with tens-of-micrometres voxels that can resolve freeform features of interest in miniaturized systems, and of printable feedstock of practical interest, e.g. engineering plastics.

In this study, building upon earlier work on 3D-printed liquid pumps [26] and magnetic actuators [27], we report the proof-of-concept demonstration of compact, valve-less, and magnetically actuated positive displacement pumps for liquids and gases, specifically, novel single-material-printed pumps with press-fit sintered magnets and the first monolithic, fully 3D-printed, multi-material positive displacement pumps in the literature. The devices are made via the fused filament fabrication (FFF) method—in which one or more thermoplastic filaments are extruded from hot nozzles to create solid objects by rastering, layer by layer, a volume defined by a CAD file [12]. The structural parts of our pumps are printed in pure Nylon 12, while the magnet that makes possible the actuation of the pump chamber is either press-fit into the pump after single-material printing of the enclosing piston, or printed in Nylon 12 embedded with NdFeB micro-particles (the printed magnets are magnetized after the multi-material printing process is completed using a 1.4 T external magnetic field). NdFeB magnets are the most powerful permanent magnets available [28], e.g. they exhibit up to 1.6 T saturation magnetization [29]. Sintered magnets are the strongest [30], followed by bonded magnets [31] (i.e. magnetic composites made of a polymer matrix with magnetic microparticle filler), and then by FFF-printed magnets (i.e. magnetic composites whose formulation (polymer matrix, magnetic microparticle density) is compatible with additive manufacturing methods, e.g. FFF [32]). Isotropic magnetic powders are typically made via rapid quenching techniques, while NdFeB powders for anisotropic magnets are manufactured via hydrogenation, decomposition, desorption, recombination (HDDR) [28, 33]. Although the majority of the work on additively manufactured magnets has focused on printing large-scale structures [34, 35], there are recent reports of FFF-printed bonded hard magnets using NdFeB microparticles embedded in Nylon 11 and 12 [27, 32, 36]. Formulation of magnetic materials, e.g. Fe-based metal glasses (Fe-based solid alloys that are not crystalline) to satisfy new applications, is an active line of research [37].

Our pumps are driven by a non-contact rotating magnet and employ diffusers instead of valves to greatly simplify their operation. The piston of the pump is magnetically coupled to the rotating magnet, instead of physically coupled, and the movement of the piston is only constrained by the membrane, which is compliant, allowing the piston to move in multiple ways at the same time (the interaction between the piston and the membrane can be described as a pivoted support that allows side-to-side movement in all directions and moderate movement in and out of the socket). Pump configurations with different membrane thickness and kinds of magnet employed (sintered, printed) were designed, fabricated, and characterized while pumping water (i.e. as liquid pump) and air (i.e. as vacuum pump) as the working fluid; the experimental results as liquid pumps surpass the state of the art of 3D-printed miniature devices, while the experimental results as vacuum pumps compare well with miniature, commercial, non-3D-printed vacuum pumps.

2. Device design

The pumps were not developed with an application in mind, but as proof-of-concept demonstration. Each pump (figure 1) has a cylindrical, rigid frame with 11.2 mm outer diameter (OD) and 8.8 mm inner diameter (ID) that is attached at one of its ends to the outer edge of a 150 µm–thick or 225 µm–thick, ring-shaped membrane. The body of the pump piston is a cylinder with 8 mm height, 6.4 mm OD, and 4 mm ID that houses a printed/sintered NdFeB magnet; the piston cylinder tapers into a 2.4 mm diameter contact area, where is attached to the inner side of the membrane. The pump chamber is right on top of the membrane, immediately below a block with two diffusers and fluidic connectors that have an internal, concentric, protruding lip to facilitate connecting Tygon pipes via press
fitting. During the manufacturing process, the membrane is plastically deformed and displaced by 1 mm, creating a dome shape (see section 4). The diffusers are 1.95 mm-long hollow cones with a 0.65 mm diameter hole on the narrower side and a 1.80 mm diameter hole on the wider side; in each pump, one diffuser is placed with the larger opening connected to the chamber and the narrower opening connected to a microfluidic port, while the other diffuser is placed with the smaller opening closest to the chamber and the larger opening connected to the other microfluidic port.

All structural parts of the pumps are FFF-printed in Nylon 12, while the magnet can be either sintered (press-fit into the piston cavity) or FFF-printed in Nylon 12 embedded with NdFeB microparticles using the densest composite formulation we could FFF print—about 55% by volume NdFeB [27]; the optimization of the formulation of the FFF-printable magnetic material is reported elsewhere [27]. Nylon 12 was chosen as base material because it has excellent structural performance (Nylon 12 is an engineering plastic), can be used as matrix in a composite with high concentration of filler (e.g. the printed bonded magnet), can be printed using most commercially available FFF printers (Nylon 12 is the polyimide with the lowest melting temperature), has good dimensional stability (e.g. low water absorption) and good chemical resistance, and is insensitive to stress cracking. It would be challenging to use different base materials for the structure and the bonded magnet because of processing compatibility issues (e.g. different extrusion temperatures, differences in the printing method) and inter-material issues (e.g. adhesion); for example we tried to make the membrane of the pumps in plasticized copolyimide thermoplastic elastomer (PCTPE, Taulman3D, Saint Peters, MO, USA), but the membranes did not stick well to the Nylon 12 pump frames, yielding non-working pumps.

The sintered magnets are commercial and fully dense, and are significantly stronger magnets compared to the printed counterparts; consequently, the experimental data (see section 5) show that the pumps that use sintered magnets are more capable than the fully 3D-printed pumps. However, an all-printed pump is, conceptually, a more versatile design that can be print-to-print customized in real time, with only a CAD file, printable feedstock, and a means to magnetize the printed magnets required for its creation.

The dimensions of the different components of the pump reflect the capabilities of the printer and printing method employed (see section 4), as well as the optimization of such dimensions via iteration (e.g. pumps with narrower frames or narrower frame walls could not be reliably made, or would not be sturdy enough to withstand prolonged operation of the pump).

The pumps do not actuate as standard positive displacement hardware, i.e. the piston does not go up and down along the axis of the chamber; instead, the piston swings back and forth while moving a pocket of fluid within the chamber through the diffusers, resulting in movement of fluid that can generate a wide range of flow rates by controlling the frequency of actuation of the piston (see section 5).

3. Device modelling

3D finite element simulations of the pumps were conducted using SolidWorks 2019 (Dassault Systèmes, Waltham, MA, USA). Three kinds of studies were implemented:

- **static studies** to determine the maximum von Mises stress at maximum membrane displacement (the von Mises stress is the criterion for failure for a ductile material such as Nylon 12),
- **frequency studies** to determine the natural frequencies and oscillation modes of the different pump designs, and
- **dynamic studies** using sinusoidal loads with amplitudes equal to the loads used in the static studies to estimate the maximum dynamic von Mises stress in the range of frequencies tested (110 Hz to 210 Hz, see section 5) and compare it with the fatigue limit for Nylon 12. In these simulations, the frequency was varied in steps of 1 Hz.
In these studies:

- 3D simulations of the full pump structure and fluid were conducted; the finite element simulation result plots shown in this work are 2D cuts/surfaces of the 3D solution.
- SolidWorks’ Fast Finite Element (FFEPplus) solver was utilized, which is iterative and uses an implicit integration method. This solver is recommended when having many degrees of freedom and no non-linearities (Nylon 12 was modelled as an elastic, isotropic material with a Young’s modulus equal to 606 MPa, from uniaxial tests of 3D-printed samples, and a Poisson ratio equal to 0.30; the displacement of the membrane is smaller than the thickness of the membrane, which is the threshold at which non-linearities appear due to large deformation [38]).
- Curvature-based solid meshing with quadratic elements (4 Jacobian points) was implemented, with element sizes between 35 \(\mu\)m and 705 \(\mu\)m (99.8% of the elements have an aspect ratio < 3, the maximum aspect ratio is 5). The meshing approach automatically adjusts the size of the finite elements based on the topology of the object being simulated. The meshing approach created over 32 000 finite elements to discretize each pump configuration.
- Each simulation was performed using the p-adaptive method, in which the energy in the stress–strain field is estimated, and the mesh is improved until the difference between two sequential cases is less than a certain threshold (set at 0.1% in our simulations). The subsequent improvement is not in the number of finite elements, but in the order of the polynomials used to approximate the displacement field.
- The displacements of the outer vertical surface of the frame were constrained, letting the piston and membrane have full freedom of movement; the loads were applied through the centroid of the piston magnet, causing side-to-side, up-and-down, or combined side-to-side and up-and-down movement.

Three different pump configurations were modelled: (i) a configuration with a 150 \(\mu\)m-thick membrane and a sintered magnet, (ii) a configuration with a 225 \(\mu\)m-thick membrane and a sintered magnet, and (iii) a configuration with a 225 \(\mu\)m-thick membrane and a Nylon composite magnet; in the three pump configurations, the unactuated position of the membrane was 150 \(\mu\)m from the chamber ceiling (see section 4). We modelled the interaction of the pump with vacuum, air, and water inside the pump; the results between the three cases are very similar, within the error of the FFEPPlus method (a few percent); we believe this is due to the low damping caused by the fluid, which was confirmed experimentally (see section 5). The finite element simulation results included in this study are 2D cuts/surfaces of the 3D solutions for the cases simulated with water as working fluid.

The simulation estimates of the frequency of the first three oscillation modes for the three pump configurations are listed in table 1. The first two modes (figure 2), labelled \(x\)z and \(y\)z, are back-and-forth swing motions along orthogonal directions in the plane of the printed layers; the third mode, labelled \(z\), is an up-and-down motion at a much higher frequency than the

| Magnet Type | Membrane Thickness | \(f_{xz}\) | \(f_{yz}\) | \(f_z\) |
|-------------|--------------------|-----------|-----------|---------|
| Sintered    | 150 \(\mu\)m       | 160.3     | 169.7     | 738.5   |
| Sintered    | 225 \(\mu\)m       | 218.5     | 224.3     | 943.6   |
| Printed     | 225 \(\mu\)m       | 282.6     | 290.1     | 1215.5  |

Figure 2. Schematic of the first three natural vibration modes of the pumps studied; the first two modes (\(xz\) and \(yz\)) are orthogonal to one another and make the piston swing, while the third mode (\(z\)) makes the piston move up and down. An outline of the pump is superimposed onto the images to show the position of the deformed membrane in relation to the chamber ceiling and valve openings.

The pump is actuated with a side-by-side action, where the piston and membrane move pockets of liquid from one port in the chamber ceiling to the other port. Only a fraction of the liquid within the chamber is transferred during each stroke. Using the CAD model of the pump, the volume of a packet of liquid displaced by moving the membrane up from its unactuated position was estimated for different displacements; at a 100 \(\mu\)m displacement, the volume displaced is 1510 nl, while at 25 \(\mu\)m it is 460 nl (figure 3). From the liquid flow rate experimental values obtained (see section 5.1) it is estimated that the pump membrane was displaced by 21 \(\mu\)m (14% full stroke) from the unactuated position in configuration (i); similarly, from the vacuum pump down characteristics measured (see section 5.2), it is estimated that the membrane is displaced during actuation by 41 \(\mu\)m (27% full stroke) from the unactuated position. Based upon this information, we used a value of 100 \(\mu\)m displacement to conduct the stress estimations as an upper bound for the displacement in the \(z\)-direction—this is nearly a fivefold increase in maximum displacement for water pumping and more than a twofold increase in maximum displacement for air (vacuum) pumping. The simulations also predict that about 80% of the stresses are due to

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Table 1. Simulated first three natural frequencies of the pump configurations studied.
Figure 3. Estimated volume displaced in the pump chamber from its unactuated position versus membrane displacement.

Figure 4. Static stress field finite element solution for a pump with 225 µm-thick membrane, where the piston is displaced 100 µm in the z-direction and swung in the xz plane so that its bottom edge almost touches the inner vertical side of the frame: (a) stress field on the top surface of the membrane and (b) 2D cut through the piston axis of the 3D finite element solution.

Figure 5. Dynamic stress field finite element solution for a pump with 225 µm-thick membrane, where the piston is displaced 100 µm in the z-direction and swung in the xz plane so that its bottom edge almost touches the inner vertical side of the frame: (a) stress field on the top surface of the membrane and (b) 2D cut through the piston axis of the 3D finite element solution. The pressure exerted by the fluid on the membrane is below 0.1 MPa.

4. Device fabrication

The miniature pumps are fabricated either by (i) a multi-material FFF printing process where a composite NdFeB magnet is monolithically printed with the rest of the pump and magnetized afterwards using a strong external magnetic field, or by (ii) a single-material FFF printing process where a sintered magnet is press-fit post-printing. In both cases, a novel multi-step printing process flow that monolithically creates all critical features with less than 13 µm in-plane misalignment was employed (the design is invariant to rotations at the points the printing steps are switched; the quoted misalignment refers to the off-axis offset between the printed layers, and reflects the limitations of the positioning system of the printer used to create the devices). The time it takes to fabricate a pump with sintered magnet is about the same time it takes to create a pump with 3D-printed magnet—75 min. However, the associated cost of each kind of pump is significantly different: a pump with sintered magnet costs $0.88 in materials, while a pump with 3D-printed magnet costs $3.89 in materials—the majority of the cost is the custom-made, NdFeB-embedded Nylon 12 feedstock [27]. To print an object
via FFF, a CAD model in STL format is created (Dassault Systèmes, Waltham, MA, USA) 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 G-code file that contains the traveling path that rasterars each slice with associated conditions (e.g. nozzle temperature, bed temperature, feedstock feed rate, nozzle speed). The software Simplify3D allows having a different set of conditions for every slice, greatly facilitating the optimization of the G-code. The G-code file is then transferred to the 3D printer, which creates the object following the instructions of the G-code file.

A CreatBot model DX Plus 3D printer (Henan Suwei Electronics Tech., Zhengzhou City, China) was used to manufacture devices. The FFF printer has three 600 µm-diameter stainless steel nozzles arranged in a straight line for multi-material printing. Commercially available Nylon 12 filament (Orbi-Tech, Leichlingen, Germany) and custom-made Nylon 12 filament embedded with NbFeB micro-particles \[27\] were extruded from two of the three nozzles at about 250 °C. The printer was housed in a 3DPrintClean Model 600 enclosure (Mountainside, NJ, USA) with recirculating HEPA filtration.

The fabrication process flow of a fully 3D-printed pump (figure 6) starts by heating the printer bed at 60 °C and coating its surface with a thin layer of polyvinyl acetate (PVAc) adhesive. The temperature of the bed is then raised to 80 °C, and several one-layer thick Nylon 12 and NdFeB-embedded Nylon 12 priming pads are extruded onto the PVAc-coated build platform; this step ensures stable flow of feedstock leaving the printing nozzles. The membrane is the first part of the pump to be printed, at a thickness of either 150 µm or 225 µm. By trial and error, it was determined that a 150 µm-thick Nylon 12 membrane would eventually fail under actuation; however, 225 µm-thick membranes do not have this issue (see section 5.1). The subsequent layers comprising the bulk of the pump are printed with a thickness of 150 µm. After the membrane is printed, the first layers of printing pillars of both materials are extruded on top of the printing pillars.
pads; this continues in between the printing of each layer of the device to keep the thermoplastics flowing well throughout the process (most FFF printers control the flow of feedstock in open loop, e.g. one needs to make provisions to ensure that the required feedstock is flowing when needed by printing layers of dummy structures right before printing layers of device structures; when printing one material, the dummy structures usually are pads printed at the very beginning of the printing job, while for printing multiple materials, priming pillars are also needed to ensure that feedstock flows uniformly every time the material active is switched). The piston, magnet, and frame are then printed (figure 6(a)). The partially printed pump is removed from the printer bed, and, while still hot, is press-fit to a previously FFF-printed mandrel (mandrel 1), stretching the pump membrane and creating a sealed, domed surface (figure 6(b)). Next, a second mandrel (mandrel 2) is printed on the printer bed; the partially printed pump is detached from mandrel 1 and press-fit to mandrel 2 (figure 6(c)). After that, a thin PVAc layer is applied to the membrane dome using a shadow mask to prevent adhesion between the membrane and the next-to-be-printed chamber ceiling (figure 6(d)). Then, the mask is removed, and a 150 µm-thick, 1.2 mm wide ring of Nylon 12 is printed on the circumference of the part, surrounding the PVAc layer; then, the chamber ceiling, diffusers, and tube connectors are printed, completing all structural features of the pump (figure 6(e)). The printed pump is then detached from the mandrel 2. Afterwards, the membrane is released by removing the PVAc film using solvents (figure 6(f)), leaving a 150 µm gap between the ceiling of the chamber and the top of the piston (this is the unactuated position of the piston). The pump fabrication is completed by magnetizing the printed magnet along its axis using a strong (1.4 T) external magnetic field.

Fabrication of a pump using a single printable material and a press-fit sintered magnet is simpler than the multi-material printing process; although Nylon 12 priming pads are still required to ensure a stable flow of material at the beginning of the process, no priming pillars are required because only one material is being used. The process flow (figure 7) is identical to that of the multi-material print minus the printing of the magnet at the same time the piston is printed shown in figure 6(a); instead, the piston is printed with an inner cavity (figure 7(a)) that is filled-in with a press-fit sintered magnet after the printing job is completed (figure 7(f)).

Printing fine features 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, or over-extrusion. Consequently, a total of three customized Nylon 12 recipes were developed to successfully manufacture a functional pump, i.e. recipes for printing (i) the membrane, (ii) the frame, piston, chamber ceiling, and valve channels, and (iii) the tube fittings. Only one NdFeB microparticle-embedded Nylon 12 recipe was required create the printed magnet. Each recipe has a unique set of parameters including nozzle temperature, feedstock flow rate, rastering speed, infill percentage, and retraction settings.

5. Experimental characterization and discussion

The 3D-printed devices were experimentally characterized as liquid pumps—using water as the working fluid, and as vacuum pumps—using air as the working fluid. In both cases, the experiments were conducted at room temperature and atmospheric pressure as environmental conditions. The temperature of operation of the pumps is limited by the temperature of demagnetization of the NdFeB bonded magnet (Curie temperature ~80 °C) and the upper and lower bound temperatures at which the mechanical properties of Nylon 12 significantly change, e.g. Young’s modulus (~50 °C–50 °C) [39, 41]; consequently, the data reported in this study are representative of operating the devices in the ~50 °C–50 °C temperature range. The relative humidity (RH) at which the devices are operated is not an issue when pumping water; when creating and maintaining vacuum, the RH can be 0% to 100% because the saturation pressure of water in the ~50 °C–50 °C range is up to 92 Torr [42, 43], which is about an order of magnitude smaller than the ultimate pressure attained by our pumps (see section 5.2).

5.1. Liquid pumping

The performance of the miniature, 3D-printed positive displacement pumps was experimentally characterized using water as working liquid in a home-built apparatus (figure 8). The devices were mounted in a clamp and driven by a diametrically magnetized N42-strength NdFeB ring magnet R424DIA (K&J Magnetics, Pipersville, PA, USA) with ¼" OD, ¾" ID, and ¼" length. The magnet is spun around its axis by a miniature electric motor that is 7 mm in diameter and 16 mm long (Makefire, Shenzhen, China) so that the axis of rotation is the normal of the plane passing through the middle of the pump ports (figure 8(a)); a current limit of 400 mA, determined experimentally, was enforced during the experiments to ensure that the motor would not overheat during continuous operation. As the ring magnet rotates, it attracts and repels the magnet within the piston, producing a swing motion of the piston perpendicular to the axis of the rotating magnet (this is the swing motion xz in figure 2). The actuation frequency was set using a pulse-width modulator motor speed controller RR-PWM-15V (RioRand, China) and measured with a coil that is part of a reed relay 22RD5 (RSR Electronics, Rahway, NJ, USA) via an oscilloscope Rigol model DS6000 (Rigol USA, Beaverton, OR, USA). The coil is mounted near the rotating magnet, symmetrically on the opposite side of the pump, and experiences a magnetic field equivalent to that acting on the piston. The electrical signal of the coil that monitors the movement of the rotating magnet is made of multiple harmonics (the trace is visible on the oscilloscope in figure 8(b)), evidencing that the driving force acting on the piston has a plurality of harmonics. The motor is designed to operate at a maximum frequency of around 500 Hz when driving a light weight (<0.5 g), 55 mm-diameter micro-drone propeller. However, when loaded with the magnet weighing 1.1 g, the motor begins to spin at a minimum frequency near 100 Hz and tops out at a maximum frequency of about 250 Hz when


Figure 8. (a) Schematic of the method used to actuate the pump: a diametrically magnetized ring magnet spins around its axis; its interaction with an axially magnetized magnet embedded in the piston results in a swing motion of the piston, causing fluid to move from one pump port to the other; in the figure, the coil used to monitor the rotating magnet would be on the left of the rotating magnet, symmetrically mounted on the opposite side of the pump. (b) Experimental setup for characterizing the devices as liquid pumps. The pump is actuated by a magnet that is spun by an electric motor; a coil is used to sense the rotation rate of the magnet. The inlet reservoir supplies water to the pump; the outlet reservoir (on top of a balance with data logger), collects the water coming out of the pump.

The rotating ring magnet causes the pumps to mainly oscillate in the swing mode xz. However, the swing mode yz is also present in the actuation, although is mildly excited (it is a second-order effect from the wobbling of the rotating magnet). The swing mode yz is perpendicular to the swing mode xz, and, to first order, given the orientation of the pump ports in our setup, it does not contribute to the flow rate. The up-and-down mode z is also present in the actuation, but, given that the pump is a lot stiffer in that mode (the resonant frequency is \( \sim 1 \) kHz, about a fourfold the swing modes—see table 1), it is also mildly excited in the range of frequencies used in our experiments (110 Hz to 210 Hz).

Three pump configurations were tested: (i) pumps with a 150 \( \mu \)m-thick membrane and a N35-grade sintered NdFeB magnet; (ii) pumps with a 225 \( \mu \)m-thick membrane and a N48-grade sintered NdFeB magnet; and (iii) pumps with a 225 \( \mu \)m-thick membrane and an FFF-printed NdFeB magnet made of 55% by volume feedstock (the most concentrated feedstock we could extrude into a filament and FFF print [27]—equivalent to a strength near grade N4). The flow rate-versus-actuation frequency of the three pump configurations is shown in figure 9; in all cases, the least-squares fitting of the data shows a linear dependence between flow rate and actuation frequency—as expected for a positive displacement pump. The maximum measured flow rate is equal to \( 7.88 \text{ ml min}^{-1} \) at 198 Hz, i.e. over 11 times the maximum flow rate reported in [23] for a single-material, FFF-printed peristaltic pump (i.e. \( 0.71 \text{ ml min}^{-1} \)), and 5.75 times the maximum flow rate of our much larger (over a fourfold the volume) earlier pumps with ball valves [26] (i.e. \( 1.37 \text{ ml min}^{-1} \)). At a flow rate of \( 7.88 \text{ ml min}^{-1} \) while cycling 198 times a second, the volume of liquid moved each cycle is 663 nl, equivalent to an estimated membrane displacement of about 50 \( \mu \)m from the chamber ceiling. The maximum flow rate delivered by our pumps surpasses reported values from state-of-the-art 3D-printed pumps for liquids [23] (table 2), including DLP-printed Quake-style peristaltic pumps with up to \( 0.02 \text{ ml min}^{-1} \) flow rate [24], stereolithography (SLA)-printed, pneumatically actuated pumps with active valves that can deliver up to \( 0.68 \text{ ml min}^{-1} \) flow rate [44], and FFF-printed peristaltic pumps made of TPE with up to \( 0.71 \text{ ml min}^{-1} \) flow rate [45].

The pump design with the thinner (i.e. 150 \( \mu \)m-thick) membrane and the weaker (i.e. N35 grade) NdFeB sintered magnet yielded the greatest performance of the pumps tested. However, after actuating for approximately 719,000 cycles, this pump began to leak; other pumps with 150 \( \mu \)m-thick membranes also degraded after less than 1-million cycles actuated. The flow rates of these pumps also became unstable from about 150 Hz to 170 Hz, in the range where the first two resonant frequencies are predicted to exist (see section 3) and confirming that the working fluid (water) causes a mild damping of the pump chamber movement. Once above 170 Hz, the pump flow rate continued to rise in a linear fashion with frequency, until the current limit was reached and the maximum flow rate was measured.

The pump design with the 225 \( \mu \)m-thick membrane and the stronger (N48 grade) NdFeB magnet performed second best of the three designs, with a maximum flow rate of \( 4.32 \text{ ml min}^{-1} \) at 200 Hz, when the current limit of the motor was reached. No instabilities were noticed over the range of frequencies tested, all of which were less than the predicted natural vibration
Table 2. 3D printing method, pump type, materials, actuation method, membrane thickness, actuation frequency, maximum flow rate, and power at maximum flow rate of reported 3D-printed liquid pumps.

| 3D printing method | Pump type          | Materials                                | Actuation method | Membrane thickness (µm) | Actuation Frequency (Hz) | Maximum flow rate (ml min⁻¹) | Power at max. flow rate (W) | Reference |
|--------------------|--------------------|------------------------------------------|------------------|--------------------------|--------------------------|-----------------------------|----------------------------|-----------|
| FFF, single material | Diaphragm, valveless | Nylon 12, sintered NdFeB magnet          | Rotating magnet  | 150                      | 198                      | 7.88                        | 0.65                       | This work |
| FFF, single material | Diaphragm, valveless | Nylon 12, sintered NdFeB magnet          | Rotating magnet  | 225                      | 200                      | 4.32                        | 0.67                       | This work |
| FFF, multi material | Diaphragm, valveless | Nylon 12, Nylon 12 + NdFeB magnet        | Rotating magnet  | 225                      | 204                      | 1.68                        | 0.69                       | This work |
| FFF, single material | Diaphragm, ball valves | Nylon 12, sintered SmCo magnet          | Solenoid         | 150                      | 15.1                     | 1.37                        | N/A                        | [26]      |
| FFF, single material | Peristaltic         | Thermoplastic elastomer                  | Pneumatic        | 400                      | 8                        | 0.71                        | N/A                        | [45]      |
| SLA                | Peristaltic         | Watershed                                | Pneumatic        | 100                      | 6.7                      | 0.68                        | N/A                        | [44]      |
| DLP                | Quake               | PEG-DA-258                                | Pneumatic        | 10                       | 20                       | 0.02                        | N/A                        | [24]      |
used to push water out of the chamber, leaving a small amount of water; afterwards, a dry bulb syringe containing just air was used to seal during actuation. This was accomplished by pushing with a small amount of water, which enables the diffusers (i.e. be used as a vacuum pump) if they are first moistened to achieve large vacuum generation.

We experimentally determined that the same devices that can be used as a pump for liquids can create and maintain a vacuum frequencies of the device (table 1). This pump was also actuated for approximately 14.5-million cycles over the course of about 23 h with no signs of leaking or degradation (table 3).

The pump design with the 225 \( \mu \)m-thick membrane and the printed NdFeB composite magnet delivered the lowest flow rate for a given frequency, reaching a maximum flow rate of 1.68 ml min \(^{-1}\) at 204 Hz, but still significantly larger than the maximum flow rate reported for the 3D-printed pumps previously referenced [23, 24, 44, 45]. The water experimental data of this pump configuration did not show any resonance in the 110 Hz to 210 Hz range—in agreement with modelling (table 1).

Power consumption of the three styles of pumps follows a lognormal curve with frequency, reaching maximum values ranging between 0.65 W and 0.69 W when the current limit of the electric motor is reached in each case (figure 10).

5.2. Vacuum pumping

We experimentally determined that the same devices that can be used as a pump for liquids can create and maintain a vacuum (i.e. be used as a vacuum pump) if they are first moistened with a small amount of water, which enables the diffusers to seal during actuation. This was accomplished by pushing water into the pump chamber with a bulb syringe filled with water; afterwards, a dry bulb syringe containing just air was used to push water out of the chamber, leaving a small amount of residual water on the chamber and membrane surfaces. The apparatus in figure 8(b) was modified to characterize the performance of the devices as vacuum pumps by removing the water reservoirs and mass balance, and by adding a pressure gauge at the pump inlet and leaving the PUMP outlet open to atmosphere. The pressure gauge used in the experiments had an accuracy of \( \pm 0.15 \) Torr and a response time of 20 ms (pressure gauge model TDI31, vacuum to 15 psi range; Transducers Direct, Cincinnati, OH, USA).

Figure 11 shows the inlet pressure versus time for a pump with an N48-grade NdFeB magnet and a 225 \( \mu \)m-thick membrane. The effective vacuum chamber volume is 0.61 cm \(^3\); this estimate includes the pressure transducer and tube volumes. The pump achieves an ultimate pressure of 540 Torr in the vacuum chamber at an operating frequency of 230 Hz; in other words, the pump achieved a pressure of 220 Torr (29 kPa or 4.25 psi) below atmospheric pressure. The ultimate pressure achieved is close to values reported for commercially available, non-microfabricated, miniature diaphragm pumps with diaphragm diameters near 10 mm (table 4) including the KNF model NMP03 pump with a 460 Torr ultimate pressure [46] (KNF Neuberg, Inc. Trenton NJ, USA), the Parkennanifein model T2-05 pump with a 486 Torr ultimate pressure [47] (Parker Hannifin Corporation, Cleveland OH, USA), and the TCS Micropumps model D200BL pump with a 346 Torr ultimate pressure [48] (TCS Micropumps, Ltd., Faversham, Kent, UK). The vacuum level reached by the TCS micropump is significantly smaller than the 110 Torr ultimate pressure reached by our single-chamber, polyjet-printed miniature vacuum pump reported in [21]; however, the polyjet-printed pump is pneumatically actuated and is made of a highly compliant material (Tango Black—a family of acrylate-based UV curable photopolymers commercially available for polyjet printing with large maximum elongation [49]) that greatly facilitates attaining a large compression ratio (i.e. ratio between the maximum and minimum volume that is being pumped), which is essential for a positive displacement pump to achieve large vacuum generation. 

**Table 3.** Working fluid, actuation time, average actuation frequency, and number of cycles completed during the characterization of a pump with 225 \( \mu \)m-thick membrane and a sintered N48 strength NdFeB magnet reported in figures 9–11.

| Working fluid | Time (min) | Avg. Freq. (Hz) | Cycles |
|---------------|------------|----------------|--------|
| Water         | 1554       | 150.87         | 14067 118 |
| Air           | 41         | 170.0          | 418 200 |
| Total         |            |                | 14 485 318 |

**Figure 9.** Water flow rate versus actuation frequency of the three pumps configurations: (i) 150 \( \mu \)m-thick membrane and a N35-grade sintered NdFeB magnet (red points, blue line); (ii) 225 \( \mu \)m-thick membrane and a N48-grade sintered NdFeB magnet (orange points, green line); and (iii) 225 \( \mu \)m-thick membrane and FFF-printed magnet with near N4-grade strength (light blue points, red line). The maximum flow rate is limited by the maximum frequency achievable by the electric motor used in this study.

**Figure 10.** Water flow rate versus power consumption from the data shown in figure 8. The flow rate follows a lognormal curve with power.
We reported novel, compact, magnetically actuated, and valve-less pumps for liquids and gases, specifically, novel single-material-printed pumps with press-fit sintered magnets and the first fully 3D-printed, monolithic, multi-material pumps in the literature; a valve-less design greatly simplifies the pump’s operation and consumes less power compared to designs with active valves, and is less prone to clogging than designs with passive valves. The structural parts of our pumps are FFF-printed in pure Nylon 12, while the magnet that makes possible the actuation of the pump chamber is either monolithically FFF-printed in Nylon 12 embedded with NdFeB microparticles, or press-fit into the pump after single-material printing of the enclosing piston. Pumps are ~1 cm tall, high-aspect-ratio channels used in many reported counterparts, and 1 000 000 times less damping than a 1 µm gap (typical maximum chamber opening in many reported counterparts), and 1 000 000 times less damping than a 1 µm gap (typical gap for a surface-micromachined comb drive actuator).

6. Conclusions

In our pumps, the hydraulic structures that connect the chamber to the fluidic ports are a lot wider and have a significantly smaller aspect-ratio than those in reported counterparts, resulting in a far smaller hydraulic resistance [53]. Specifically, in our pumps the diffusers are 1.95 mm-long hollow cones with a 0.65 mm diameter hole on the narrower side and a 1.80 mm diameter hole on the wider side (see section 2)—in striking contrast with the typical ~ 100 µm tall, high-aspect-ratio channels used in many reported counterparts.

In each of our pumps, the chamber is open 150 µm when not actuated (see section 4); the experimental data for water and air show that the piston only actuates up to 27% of the full chamber stroke, leaving at least a 109 µm gap between the piston and the ceiling. The squeeze film damping coefficient is proportional to the inverse of the cube of the gap height [53]; therefore, for everything else constant, a 100 µm gap in the pump chamber causes 1000 times less damping than a 10 µm gap (typical maximum chamber opening in many reported counterparts), and 1 000 000 times less damping than a 1 µm gap (typical gap for a surface-micromachined comb drive actuator).

In a diaphragm pump, the pressure \( p \) versus time \( t \) characteristic is an exponential decay given by [50]

\[
p(t) = p_f + (p_o - p_f)e^{-(-\frac{V}{S}t)},
\]

where \( p(t \to \infty) = p_f \) is the ultimate pressure, \( p(t = 0) = p_o \) is the starting pressure (e.g. 1 atmosphere), \( V \) is the volume being pumped down, and \( S \) is the effective pumping speed. The data shown in figure 11 are closely fit to an exponential decay with effective pumping speed equal to 0.155 cm\(^3\) s\(^{-1}\), \( p_f = 542.74 \) Torr, and \( (p_o - p_f) = 227.87 \) Torr. We speculate that by changing the design to increase the compression ratio, and by FFF-printing a more flexible and compliant material, e.g. in TPE, should yield to a better vacuum pump, e.g. lower ultimate pressure.

Solving for the internal pump volume displaced in each cycle by setting the effective pumping speed equal to the pump volume times the actuation frequency yields a value of 674 nl at 230 Hz, which is 29% larger than the value of 524 nl per cycle at 230 Hz actuation frequency estimated for the liquid pump with the same (225 µm-thick) membrane and strength NdFeB magnet (N48), at the same actuation frequency. Consequently, the difference between the maximum flow rates for air and water is not large, supporting the modelling results (see section 3); however, such behaviour is contrary to that of many reported miniature/micropumps [2, 51, 52]. The striking difference in performance can be explained by the different configuration and actuation of our pumps. Unlike many reported positive displacement miniature/micro pumps, our pumps do not use long and narrow microchannels to interface with the pump chamber or conduct a full stroke of the chamber, resulting in mild damping for either water or air as working fluid:

- In our pumps, the hydraulic structures that connect the chamber to the fluidic ports are a lot wider and have a significantly smaller aspect-ratio than those in reported counterparts, resulting in a far smaller hydraulic resistance [53]. Specifically, in our pumps the diffusers are 1.95 mm-long hollow cones with a 0.65 mm diameter hole on the narrower side and a 1.80 mm diameter hole on the wider side (see section 2)—in striking contrast with the typical ~ 100 µm tall, high-aspect-ratio channels used in many reported counterparts.

Table 4. Developer, development status, actuation method, and ultimate pressure of reported miniature vacuum pumps with diaphragm diameter near 10 mm.

| Developer | Development status | Manufacturing method | Actuation method | Ultimate pressure (Torr) | Reference |
|-----------|-------------------|----------------------|-----------------|--------------------------|-----------|
| MIT—Edwards | Proof-of-concept demonstration | FFF 3D printed | Rotating magnet | 540 | This work |
| MIT—Edwards | Proof-of-concept demonstration | Polyjet 3D printed | Pneumatic | 110 | [21] |
| KNF | Commercial (NMP03) | Non-microfabricated | Rotating motor | 460 | [46] |
| Parker Hannifin | Commercial (T2-05) | Non-microfabricated | Rotating motor | 486 | [47] |
| TCS | Commercial (D200BL) | Non-microfabricated | Rotating motor | 346 | [48] |

Figure 11. Pressure versus time characteristic of a pump with a 225 µm-thick membrane and a sintered N48 strength NdFeB magnet. Data in blue, exponential curve fit in red.
surpass the state of the art of 3D-printed miniature devices. The performance is limited by the electric motor and magnet strengths selected for the study; higher performance is expected for systems with larger motors and/or stronger magnets. Actuation of a pump in excess of 14.4-million cycles shows no evidence of leaks or degradation—in agreement with keeping the stresses below the fatigue limit of the material. A device with sintered magnet was characterized as a vacuum pump using air as working fluid, achieving an ultimate pressure of 540 Torr in a 0.61 ml pumping volume and a maximum air flow rate of 0.155 ml sec$^{-1}$ (9.3 ml min$^{-1}$) at atmospheric pressure; these results compare well with miniature, commercial, non-3D-printed vacuum pumps with comparable diaphragm diameter.

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