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A novel monolithic microactuator fabricated by 3D rapid direct manufacture

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Abstract

In this paper we present the world's first micropump entirely fabricated using a 3D direct manufacture process based on microstereolithography. The device employs a single pneumatically actuated membrane, with flow rectification provided by a nozzle/diffuser arrangement. A maximum flow rate of just over 2,000 µl/min was achieved with a pneumatic pressure of 2 PSIG and a stroke rate of 96 Hz. The fabrication of actuator components using stereolithography apparatus (SLA) is a potentially major step towards the realisation of low-cost, disposable, rapid manufactured and fully integrated micro total analysis systems (µTAS).

Keywords: stereolithography, micropump, direct manufacture

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1. Introduction

There have been a large number of micropump designs published in the literature, with a number of potential applications and routes to future commercialisation. Many early devices employed macroscale machining techniques, but the focus of micropump research soon shifted to silicon micromachining [1,2]. More recently devices have been produced using polymeric materials such as polyimide and PMMA. However, the majority of devices published in the last decade use multilayer soft lithography to manipulate polydimethylsiloxane (PDMS), a silicone rubber compound. This technique has become almost ubiquitous since its first demonstration by Unger *et al* [3]. It uses temporary photoresist patterns on the surface of a silicon substrate as a micromould for multiple layers of PDMS, allowing the fabrication of complex 3D microstructures with features sizes in the micron scale. Although soft lithography has many advantages, it is potentially time consuming for larger structures, and is not a viable mass-production technique. Microstereolithography has potential as an automated rapid manufacture technique with similar output characteristics to soft lithography. There are a growing range of SLA systems and materials available commercially, using a variety of additive processes to create complex 3D structures. Although in the past many of these machines have been referred to as "rapid prototyping" systems, advances in both the technology and properties of the additive materials have made the direct rapid manufacture of plastic components for real-world use a realistic option. Despite this, only a small number of microfluidic devices have been fabricated using SLA systems, and these examples have used additional techniques and materials [4,5]. The only micropump is found in Carozza *et al* [6], who used an SLA system with a 300 µm resolution to create the device body and fluidics. Our micropump design is constructed entirely using the EnvisonTEC Perfactory® Mini SLA system.

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A number of actuation techniques were considered before pneumatic actuation was selected. This actuation technique is advantageous as it does not require any integrated electronics. However, it does require an external pressure source such as an air line or macroscale pump, with the pressure being controlled by a macroscale valve. Pneumatic actuation normally has a lower stroke rate than that used with other actuators (e.g. piezoelectric devices normally operate in the kHz range). This is compensated by an increased stroke volume, taking advantage of the plastic membrane's flexibility. The lack of integrated electronics allows our device to be fabricated quickly, allowing multiple variations to be tested using the same actuation setup, and easing potential mass production.

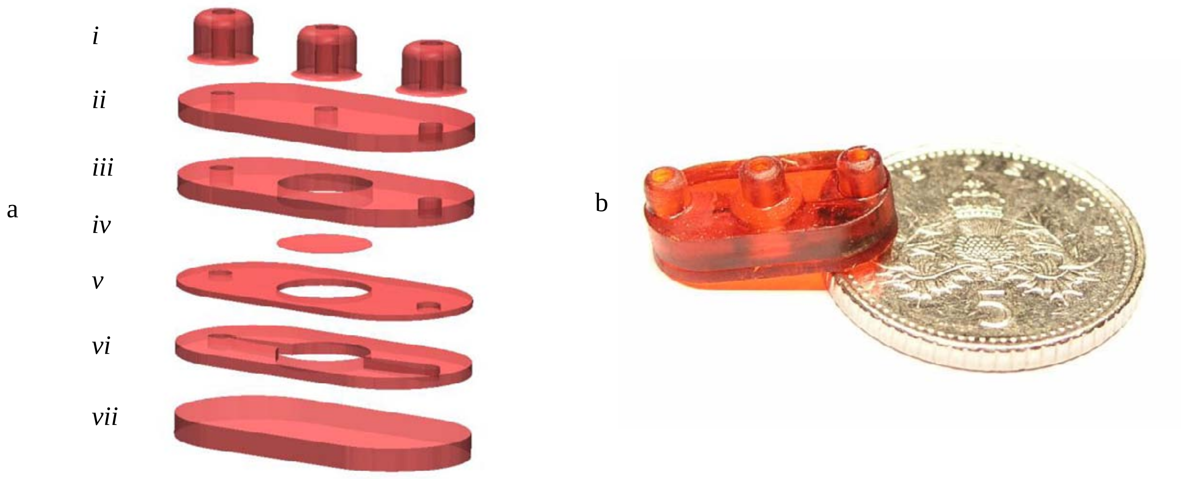

Fig. 1. (a) Exploded view of the device, showing the design features of our device, including *i*: 3 fully integrated pipe fittings (inlet, outlet, and a pneumatic port for membrane actuation); *ii-vi*: integrated 1 mm diameter fluidic channels; *iii*: a 0.75 mm deep pneumatic chamber above a 70 µm thick 4 mm diameter pump membrane (*iv*); *v-vi*: a 0.75 mm deep pump chamber flanked by a pair of 0.5 mm deep nozzle/diffuser elements (200 µm inlet to 1 mm outlet, 8º divergence from centreline) on top of a 0.75 mm thick base (*vii*). Note that the layers shown in the diagram are for visualisation only, and do not represent the layers used during fabrication. b) Photograph of the micropump with a UK 5 pence piece (18 mm diameter) for scale. The device body measures 13.63 × 7 × 3.28 mm (l/w/h); the pipe fittings measure 2.5 mm diameter and are 2 mm tall.

2. Design and fabrication

The overall layout of our micropump is defined by the inclusion of two main design elements: the pneumatic membrane and the nozzle/diffuser structures. In our device, the pump membrane is 4 mm in diameter, and separates a pneumatic and a working fluid chamber. Nozzle/diffuser elements were first reported in a paper by Stemme and Stemme [7]. These microfluidic structures are used to rectify flow passively in reciprocating displacement micropump designs, by making fluid flow preferential in one direction. The divergence angle of the nozzle/diffuser structures is critical in the efficiency of the device; an angle of 8° was taken from Kar *et al* [8] as a starting point. The final micropump design was realised using the Solidworks® 2008 3D computer assisted design (CAD) package. An exploded view of the device is shown in *Figure 1a*. The 3D CAD file was processed using the EnvisionTEC RP software suite into a proprietary library file, containing the mask files for each layer to be fabricated. The EnvisionTEC Perfactory® Mini SLA system consists of a projector, which is focused through the bottom of a transparent tray that holds the liquid acrylate resin (EnvisionTEC R11). Above this is a glass block, mounted parallel to the resin tray on a z-mobile stage. The glass block lowers to trap a 25 µm thick layer of the resin between itself and the resin tray. This layer is cured by the masked output of the projector. The maximum projector area is 28.57 × 21.94 mm, with an SXGA+ projector resolution of 1400 × 1050 pixels giving an X/Y resolution of 20 µm. The cured resin sticks to the glass block, and the z-stage moves up, creating a new layer of uncured resin. Up to 6 individual micropumps of the design shown in *Figure 1a* can be produced in a single build cycle, and the SLA system can produce the 5.28 mm tall structures in less than 2 and a half hours. The monolithic device is shown in *Figure 1b*. A number of test membranes were also fabricated in order to study the long-term performance of the membrane elements, using the same procedures and techniques described.

3. Results

Long-term tests were carried out to determine the reliability of the SLA-fabricated membranes. Pressure from an air line was controlled using a pneumatic 3-way valve (Clippard ESO-3W-12-1), which allowed the switching of the membrane-side port from a port at atmospheric pressure to another connected to the air line. The pressure was measured using a Honeywell 26PC series pressure sensor, connected to a National Instruments NI-DAQ 6009 USB data acquisition device. The valve was driven at a constant frequency of 2 Hz with a 50% duty cycle using a signal generator. Batches of 3 identical membranes were subjected to 1,000,000 on/off cycles over 6 days at both 1 and 2 PSIG without any reliability problems. *Figure 2a* shows the deflection achieved with 2 PSIG applied to a membrane previously used in these tests. *Figure 2b* shows a plot of maximum deflection versus pressure for a freshly built test membrane.

Flow rate data was collected for the micropump using a capacitive system. A stretch of 1.58 mm internal diameter rubber tubing (Cole-Palmer Clear C-FLEX®) was flanked by a pair of capacitive plates, created from printed circuit boards. The capacitive potential of these plates was compared to a reference capacitor via a bridge circuit. The measurement area was connected via the micropump to a reservoir containing deionised water. As water is introduced into the measurement area, the capacitance of the measurement capacitor will change due to the change in its dielectric properties relative to the always dry reference. It was found that this change was linear compared to the position of the fluid front within the area of the measurement capacitor. The pneumatic setup was as described in the long-term tests, except the frequency was controlled by an output voltage from the NI-DAQ 6009 via a voltage to frequency convertor circuit. This circuit was set up to produce a 50% duty cycle square wave signal, from 0 Hz at a 0 V output to 120 Hz at a 5 V output.

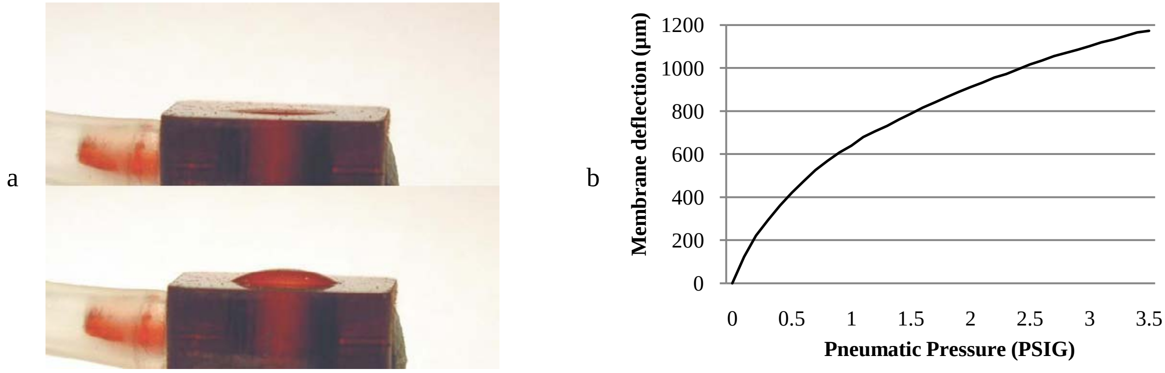

Fig. 2. (a) Photograph showing deflection of 5 mm diameter test membrane at atmospheric pressure (top) and 2 PSIG (bottom). The test membrane had been run for over 1,000,000 on/off cycles of 2 PSIG. The deflection achieved was around 800 µm. (b) Plot of deflection vs. Applied pneumatic pressure for a freshly-built test membrane, measured using a Tallysurf stylus surface profiler.

The output from the capacitive bridge circuit was amplified before being read by the NI-DAQ 6009 and written to file by a LabView program, along with time, pressure and output frequency data. The capacitive system was calibrated by taking a baseline reading with and without water. To start the test, deionised water was primed into the measurement area. All measurements were taken with zero backpressure. The NI-DAQ 6009 was instructed to sweep from 0 to 5 V over a period of around 30 seconds, actuating the micropump from between 0 and 120 Hz at a set pneumatic pressure. The raw capacitive voltage was converted into a series of flow rates for each 2 Hz step, as seen in *Figure 3*.

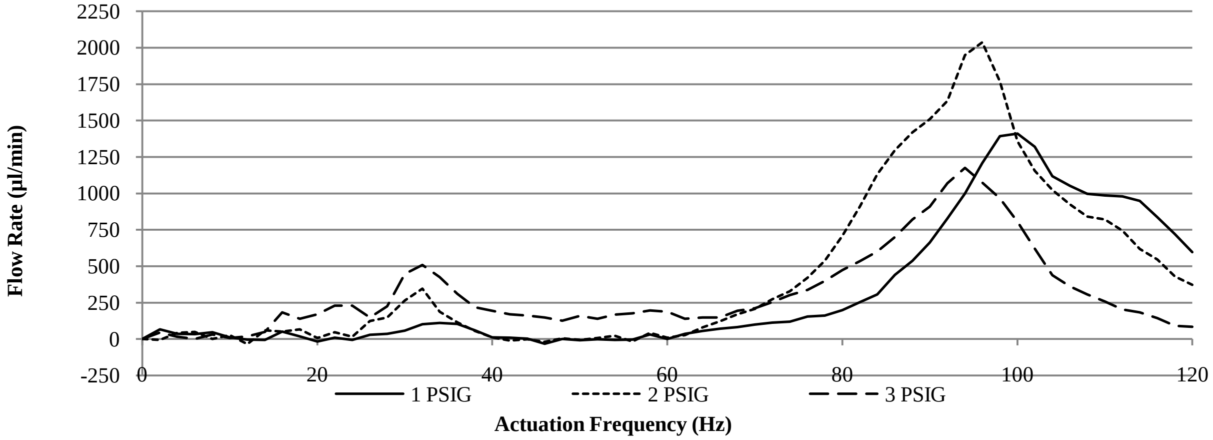

Fig. 3. Plot of pump frequency vs. flow rate for our device, with deionised water as the working fluid and zero back pressure. Actuation pressures of 1, 2 and 3 PSIG were tested across a range of actuator frequencies from 0 to 120 Hz. The driver duty cycle was set at 50%.

4. Conclusions

In this paper we have demonstrated a novel microactuator entirely fabricated using microstereolithography. A maximum flow rate of just over 2,000 µl/min was measured with an actuator frequency of 96 Hz and a pressure of 2 PSIG. Some interesting flow characteristics can be seen in the data presented in *Figure 3*. Although 3 PSIG was most efficient at the lower frequency peak, it was the least efficient compared to 1 and 2 PSIG at higher stroke rates. The effects observed are potentially caused by the actuator frequency moving in and out of phase with the membrane resonant frequencies. An additional factor is probably the precise design of the nozzle/diffuser elements, which are yet to be optimised. It is hoped future work will provide greater efficiency, along with the development of other forms of micropump using the SLA system. SLA technology has potential in the nascent field of micro total analysis (µTAS) systems, and the micropump presented has potential for direct integration into such devices.

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