Programmable Three-Dimensional Microfluidic Fabrication by Direct-Write Assembly

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ABSTRACT

In this paper, we describe the implementation method of three-dimensional microfluidic structures by direct-write assembly for potential Laboratory-On-Chip applications. We investigate the different aspects of the programmability of this technique based on the design and implementation of three microscale architectures. Also, we demonstrate a conic microreservoir precisely fabricated in epoxy resin.

Keywords: Three-dimensional microfluidic, direct-write assembly, programmability, microreservoir, epoxy resin.

1 INTRODUCTION

There are increasing needs for 3D microfluidic components such as microchannels, micromixers or micropumps for Laboratory-on-chip systems. To date, several efficient, but expensive and complex techniques such as LIGA and micro-stereo-lithography [1] have been developed to fabricate such fluidic structures. Direct-write fabrication process (DWFP) is a robotic deposition technique used to produce layer-by-layer microscale structures composed of filaments with either cylindrical, hexagonal or square cross sections [2-3]. The filaments are formed during the extrusion of a paste-like material through a micronozzle and deposited on a substrate in order to build planar or three-dimensional (3D) structures. This technique was used to fabricate multi-layers scaffold resulting in complex polymer-based 3D microfluidic structures [4-5]. DWFP is a high efficiency, low complexity and CMOS compatible technique, and can be used to fabricate 3D microfluidics or the integration of microfluidic or microelectronic chips from different technologies. We recently reported high capacitive microelectronic sensors dedicated to in-channel bioparticle detection and compatible with DWFP [6-8]. In this paper, we explain the programming concept of the direct-write assembly technique where the laborious fabrication steps are broken down to a few simple numerical algorithms. Finally, we demonstrate experimental results through the fabrication of a 3D conic microreservoir.

2 DIRECT-WRITE FABRICATION PROCESS

DWFP consists of three primary steps: ink deposition, epoxy encapsulation and ink removal as shown in figure 1. The robotically-controlled deposition of a fugitive ink filament onto a substrate as the first step of this process is illustrated in figure2 and in figures 3a and 3b, the microscope images of microchannel fabricated by direct-write assembly before and after the ink removal are shown [6]. Also, the main required equipment and material used in this project are listed in table 1.

Fabrication parameters such as data point coordinates of the deposition trajectory (X, Y, Z) and velocity (V) are initially loaded on the microrobot's control program. Under pressure, the ink is extruded at constant flow rate through a micronozzle and 3D structures are achieved using a layer-by-layer sequence. Once the deposition is completed, an uncured polymer resin is poured over the deposited ink structure and cross-linked at a specific time and temperature. Finally, at moderate temperature, the ink is melted and extracted under a light vacuum.

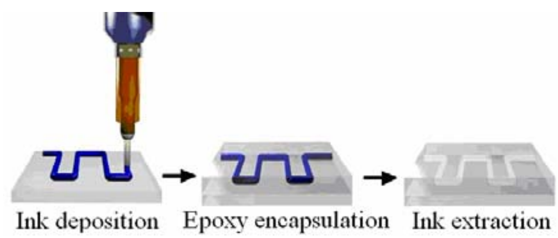

Figure 1. Illustration of three steps of DWFP.

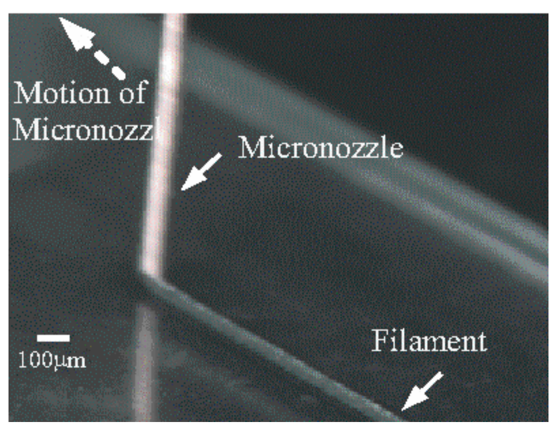

Figure 2. Microscopic image of a micro-nozzle during the deposition of fugitive ink.

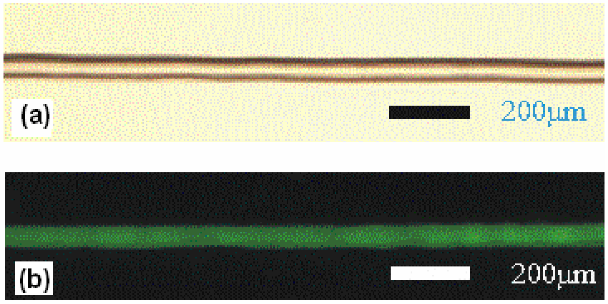

Figure 3. Microscopic image of (a) ink filament covered by epoxy resin, (b) microchannel filled by fluorescent dye.

Equipment/material	Model
Robotic apparatus	I&J 2200, I&J FISNAR Inc.
Dispensing system	2400, EFD Inc.
Epoxy resin	Epoxide 835, Epoxitech Inc.
Fugitive ink	Petroleum jelly 75% microcrystalline 25 %

Table 1. Required equipment and material for the DWFP

3 PROGRAMMING CONCEPTS OF DIRECT-WRITE ASSEMBLY

The adequate deposition of a specific ink (*M*), extruded through a micronozzle with inner diameter (*D*) over ΔL (distance between two adjacent points $A(x_0,y_0)$ - $B(x_1,y_1)$) requires a few experimentally-determined parameters such as the micronozzle height (*Z*), the extrusion pressure (*P*) and the microrobot velocity (*V*) which is assumed to be constant over ΔL. For the deposition of a 3D conic microreservoir (see Fig. 4), 340 points (ΔLs) were defined and distributed over 8 layers using the Arc function of the control program (JR Points, IJ FISNAR Inc.).

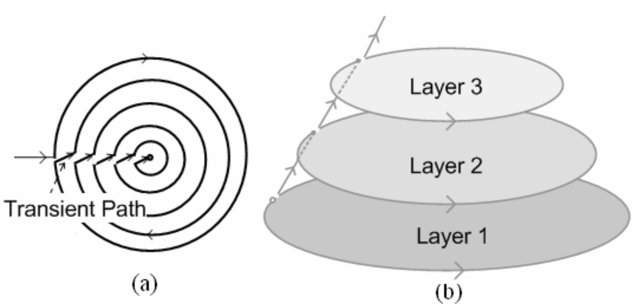

Figure 4. Implementation of a conic architecture by DWFP: illustration of the deposition path (a) on the first layer, (b) between three stacked layers.

The experimental manipulation to determine the optimal *H* and *V* for the deposition is time consuming and the resultant parameters are not optimum. The design of a smart program will enable the optimization of these manipulations and the calibration of the fabrication parameters based on previous results. A powerful algorithm such as artificial neural network (ANN) is required in order to compensate for the system nonlinearities such as ink rheological behavior and transient state of the microrobot motion. In figure 5, a typical artificial neural network ($f_{ANN} : P \to A$) is depicted where P_i and a_i are i-th component of input and output vector, respectively. The matrix weight function $W_{R\times S}$, bias values b_i's and motive function f, shown in this figure are chosen in a network depending on application. The network adapts changing the weight by an amount proportional to the difference between the desired output and the actual output. This is called the “Perceptron Learning Rule”.

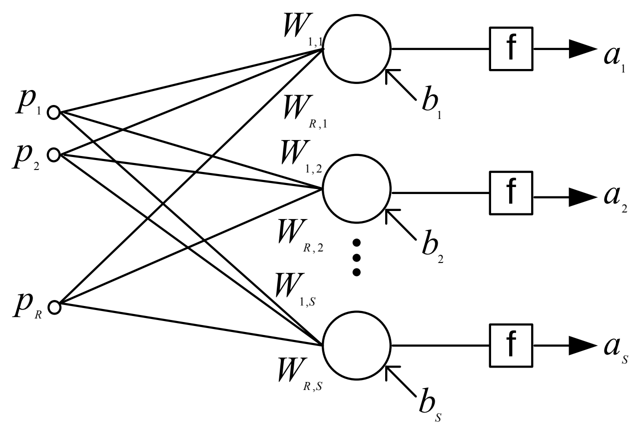

Figure 5. Simplified diagram of a Perceptron neural network

In DWFP, the main outputs for such neural network are as follow:

$$a_1 = V \quad (1)$$

$$a_2 = Z \quad (2)$$

and, the actual inputs are:

$$P_1 = M \quad (3)$$

$$P_2 = D \quad (4)$$

$$P_{3-5} = \Delta L \quad (5)$$

$$P_6 = T \quad (6)$$

$$P_7 = L_N \quad (7)$$

$$P_7 = C \quad (8)$$

where T, L_N , C and ΔL are the environment temperature, the length of nozzle, a code number indication the shape of nozzle’s cross section and a vector with three components in Cartesian space, respectively. Each new experience can add a row to the learning table of this network which is necessary for self-calibration and initializing the system to start a deposition process.

In addition to estimation of optimum values of already mentioned parameters using ANN, we introduce another aspect of the programmability of direct-write in this section. The identification of the best deposition trajectory using an artificial intelligence algorithm (AIA) is another important objective of the fabrication programming. Two basic rules of such intelligence program are recognized as:

(a) Avoiding frequent stops and starts of the micro-robot or dispensing system
(b) Implementing mechanically stable architectures in the face of epoxy coating process.

Based on our experiences, the programming of microrobot to deposit fugitive ink on start and stop points is very complicated probably resulting from a nonlinear rheological model of extrusion system in these two points. In experimental results section, this problem is indicated in the stop point of architecture.

The stability of architecture is an important issue, because the deformation of the architecture deposited impact the microfluidic structure. The creation of a stable architecture depends on many parameters such as the shape of cross section of nozzle.

For example: for the cylindrical filament ink which has been used in this work, the model shown in figure 6a is more stable than one indicated in figure 6b. Because the layers shown in figure 6b, slid on each other due to exerted force from the epoxy resin. Stacked layers shown in figure 6a results in a conic structure depicted in figure 4b whereas a cylindrical structure (figure 6c) results from the model shown in figure 6b.

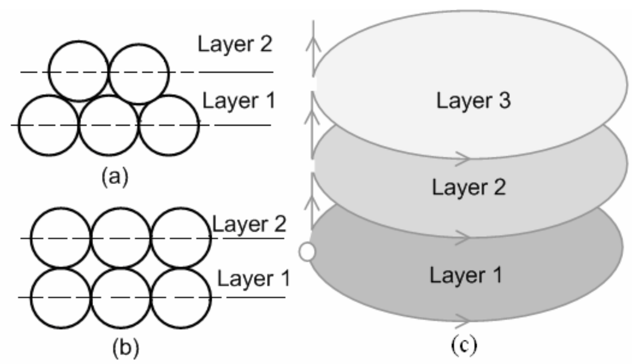

Figure 6. Schematic representative of (a) stacked layers used for the fabrication of cylindrical structure and (b) conic structure, (c) cylindrical structure results from 6b.

4 FABRICATION RESULTS AND DISCUSSION

A stable cone-shaped and a non-stable cylindrical-shaped architecture are illustrated in figure 7a and 7b, respectively. Figure 8 shows the implementation of hollow cylindrical shape architecture. The already mentioned stop point of deposition is shown in this figure. The conic-shaped architectures were used for the deposition of 3D conic microreservoirs shown in figure 9. These figures show fluorescent microscope images of 3D conic micro-reservoirs from a top view perspective. The fabrication resolution of the direct-write approach is principally function of the micronozzle inner diameter and the microrobot positioning resolution.

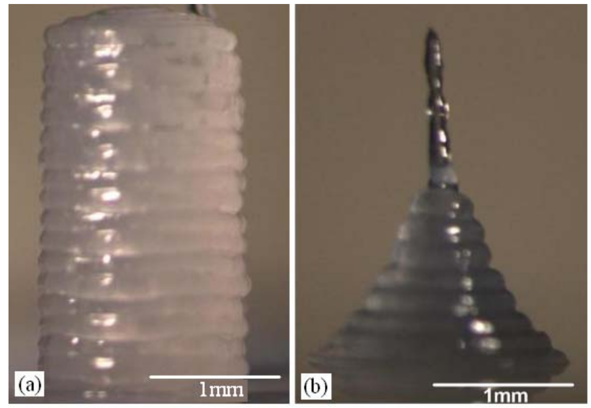

Figure 7. Optical microscopic images of (a) cylindrical shape, (b) conic shape architecture.

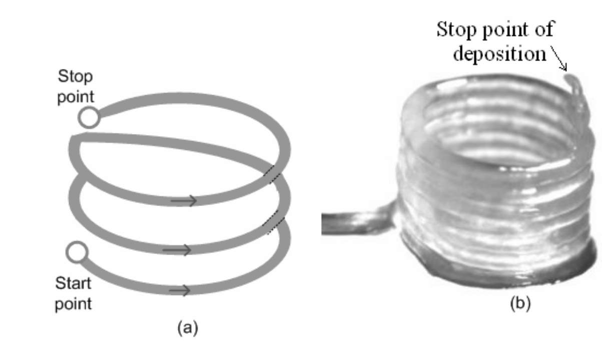

Figure 8. Hollow cylindrical architecture: (a), the rout of deposition (b) optical image of implemented architecture.

5 CONCLUSION

For the first time, we introduced the smart programming concepts of DWFP and based on experimental results we indicated how these concepts can improve the process. We believe the design of an intelligence control program and novel fugitive inks for the direct-write approach will enable the fabrication of more complex 3D microfluidic components and lead to an economic, large-scale production manufacturing method for Lab-on-Chip devices.

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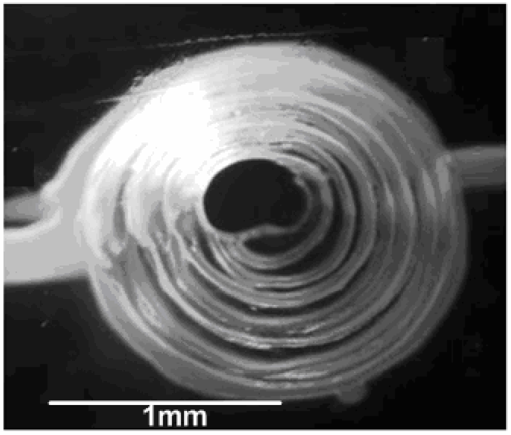

Figure 9. Ultra-violet microscopic images of a microreservoir partially filled with fluorescence dye.

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