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Development of a Projection Stereolithography 3D Printing System for Rapid Prototyping of Microfluidic Devices

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Point-of-care (POC) diagnostic devices are essential for the management of most diseases. Microfluidic devices are being used nowadays as part of the POC ecosystem due to their high level of precision. However, fabrication of these devices is often complicated, time consuming, requires expensive equipment and sophisticated cleanroom facilities. Hence, a rapid prototyping process in the form of a portable 3D printing system is proposed to enable medical practioners to print these devices on-demand. This project involved developing a projection stereolithography (SL) 3D printing system which can print microchannel structures of the microfluidic devices. The proposed system is based on the process of projecting 2D sliced image onto a UV curable resin in a layer-by-layer approach. The projection optics has been designed in which a projected pixel size of 6X the original DMD chip pixel size of 10 μm has been obtained. The system, based on a top-down design is developed and assembled using off-the-shelf optics and optomechanical components. The developed projection SL 3D printng system is able to print micro channels of the microfluidic devices with sizes down to 1000 micrometer.

Keywords: 3D printing, microfluidics, projection stereolithography, rapid prototyping

I. INTRODUCTION

The ability to diagnose a patient quickly and accurately is of paramount importance in the management of most diseases. In the developed world, accurate diagnosis can often be achieved, especially in hospitals and large clinics where sophisticated equipment and trained laboratory staff are available (Yager *et al.*, 2006). However, in low-resource settings, clinics are equipped with only minimal infrastructure, and sometimes do not have access to highly trained personnel (Yager *et al.,* 2008). Hence, there is an urgent need for affordable diagnostics that can be used at the point of care (POC) of the patient. Diagnostic techniques are often resource-intensive, requiring climate controlled usage and storage, frequent calibration, reliable electrical power, and trained personnel (Weigl *et al.*, 2009). Currently, there are many point-of-care (POC) diagnostic tests on the market. One of the POC diagnostics being sought for on the market is the microfluidics-based tests (Buser *et al.*, 2015).

Microfluidics are devices which have been designed to carry out disease diagnostics in POC settings, with a precisely controllable microenvironment, and examine chemical and biological processes with a high level of precision (Lee *et al.*, 2015). However, fabrication of microfluidic devices is often complicated, time consuming and requires expensive equipment and sophisticated cleanroom facilities (Chan *et al.*, 2015). Three-dimensional (3D) printing process presents a promising alternative to traditional techniques such as lithography and PDMS-glass bonding, not only by enabling rapid design iterations in the development stage, but also by reducing the costs associated with infrastructure, equipment installation, maintenance, and physical space (Amin *et al.*, 2016).

With the recent advancements in 3D printing technologies, highly complex microfluidic devices can be

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fabricated via single-step, rapid, and cost-effective protocols, making microfluidics more accessible to users. Suitable 3D printing approaches that have been used successfully include inkjet 3D printing (i3DP), fused deposition modeling (FDM), stereolithography (SLA) and two photon polymerisation (2PP) (He *et al.*, 2016; Walbaur *et al.*, 2011).

In this project, a projection stereolithography (SL) 3D printing system has been designed and developed for printing microfluidics devices. The microfluidics device is a polymeric cytometer-based device used for biomedical application (Selamat *et al.*, 2017). The projection SL process is based on projecting 2D images of a 3D object onto a UV curable resin. This project involved designing the 3D printing system which includes the projection optics for the DLP light projector that can project images with magnification of 1:1 at 92 mm working distance and a pixel size of 60 µm. The system has been developed based on top down design in which the images are projected from the top and down to the built platform at the bottom. Several test structures and devices have been successfully 3D printed. The printed parts are then characterized for their geometrical features.

II. MATERIALS AND METHOD

The design of the 3D printing system is based on the top down approach. Figure 1 shows the CAD design for the proposed 3D printing system. In this figure, the 3D printing system can be divided into two major parts. The projector and projection optics of the DLP projector and the optomechanical system and linear stage controller.

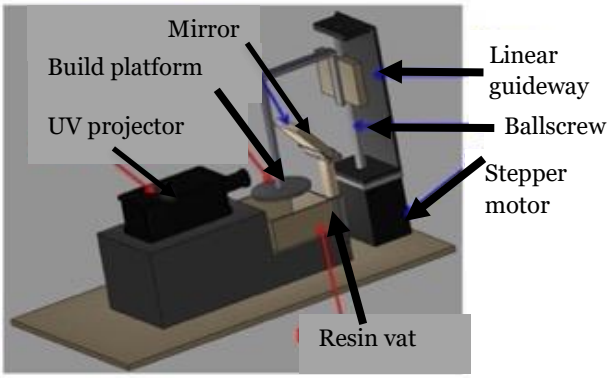


Figure 1. Top-down design for the projection SL 3D printing system

A. Projection and Imaging Optics

The core of the projection stereolithography system is the DLP light projector. The light engine of the DLP projector is the DLP 4500 lightcrafter module. The DMD chip used in the DLP 4500 lightcrafter module has a pixel size of 10.8 µm and the entrance pupil diameter (EPD) of 15 mm. The size of the DMD active area is given as 9.855 mm x 6.161 mm. The diagonal projected image size without a projection optics is about 83 cm (Texas Instruments, 2015). In this project, the projection optics is designed in order to obtain at least a 5X projected image size magnification as compared to the original DMD pixel size. The targeted projected pixel size will be around 60 µm which is smaller than the commercial-based DLP projector image size of 100 µm.

The design process will start with simple geometrical first order optics in order to find some basic parameters. Using Figure 1, we can identify the focal length of the system. Similarly, the system magnification can be calculated.

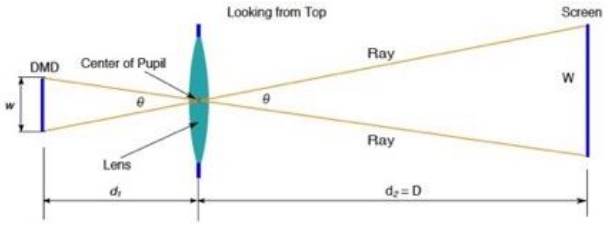


Figure 2. First order optics layout for DLP projector

If the targeted projected pixel size is 60 µm and DMD pixel size is 10.8 µm, then the system magnification, M can be obtained by using the relationship below (Texas Instruments, 2013):

$$\text{Projected pixel size} = \text{DMD pixel size} \times M \quad [1]$$

$$M = 60 / 10.8 = 5.5 \text{ times}$$

Based on this M value, we can determine the maximum paraxial image height. From Figure 2, the magnification of the projection system is given by the followings.

M = -W/w, where w = 9.855 mm (Negative sign means the image is inverted). Hence, we can calculate W which is the max paraxial image height.

W = 54 mm (5.5 x 9.855)

The second step in the design is to use a sequential ray tracing analysis software, Zemax to design the projection optics part. For the ease of design, a known microprojection lens design has been utilized. The initial design is based on the 24X microprojection lens which composes of 6 optical elements. Based on this reference design, sequential ray tracing with optimization method was used to obtain the best lens configuration that will give the lowest merit numbers. The initial design parameters that need to be input into the simulator are the aperture size (EPD) = 15 mm, wavelengths = 405 nm, max paraxial image size (half field height) = 54/2 = 27 mm. These values are the initial parameters. Here, we assume the input fields are parallel as the lights from the DMD are collimated.

B. Optomechanical System and Linear Stage Controller

The actual system is developed and constructed using off-the-shelf components and custom made parts. Based on Figure 1, a first surface UV mirror (positioned 45° facing downward) has been integrated in order to allow the system to have a small build area. This enables the DLP projector to be laid horizontally in which the projected image from the projector is beamed down to the built platform, attached to a linear guideway stage holder. A resin vat is used to store the UV curable resin. The optomechanical setup for the design is shown in Figure 3. The working distance between the output beam from the projector and the screen is about 92 mm. The layer thickness designed at 100 μm is obtained by programming the stepper motor to move in microstep. The system is designed using Arduino-based microcontroller whereas the stepper motor is controlled using a stepper motor driver.

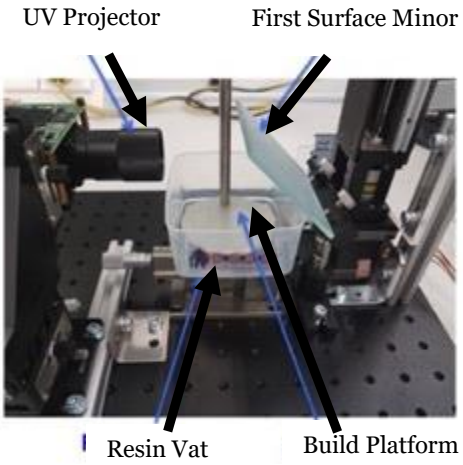


Figure 3. Optomechanical setup for the top down design

C. System Integration

The integration of the sub-assembly components includes the projector, the optomechanical parts, the linear stage controller and the controller software. The projector and the linear stage controller must be integrated and synchronized to allow the projected images to beam correctly at the right sequence. A 3D printing opensource software, *Creation Workshop* software has been utilized in which it allows the control of the projected beam from the DLP projector using graphical user interface (GUI). The synchronization between the projected beam from the projector and the linear stage controller requires additional interface program. In this case, a *G-code* program has been used ito convert the the arduino program for controlling the linear stage controller before uploading to the 3D printing software. This allows full integration and synchronization between the projected image from the projector and the linear movement sequence of the linear stage controller.

Figure 4 illustrates a three dimensional (3D) CAD image of a polymeric device. The CAD design is first converted to STL formatted file before being sliced into individual layer. The slicing of the CAD image is performed using the built in slicing tool in *Creation Workshop*. Figure 5 shows the sliced images of the CAD design for the device. Once the slice images have been obtained, the 3D printing software can project the sliced images onto the UV resin.

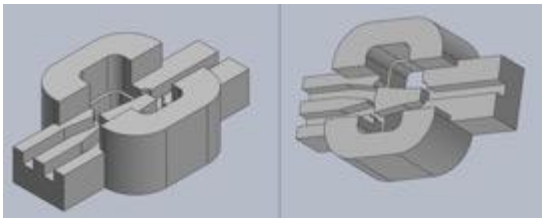


Figure 4. 3D CAD image of a polymeric device

Figure 5. Sample of sliced images for the polymeric device

C. RESULTS AND DISCUSSION

A. Projection and Imaging Optics

The ray tracing result for the projection optics is shown in Figure 6 showing the three designated fields with max field height of 54 mm and with six optical elements. Total aberration obtained composed of the spherical, astigmatism, field curvature and distortion. Low spherical aberration shows that the system is able to focus effectively whereas higher field curvature and distortion means the position of the focus is not on the paraxial image plane where the chief ray has fallen onto. The performance of the system is summarized in the Seidel (aberration) diagram, shown in Figure 7.

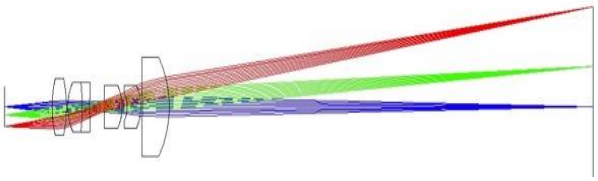


Figure 6: 2D ray tracing of projection optics

The lens data design has been provided to the lens optics manufacturer in which a prototype projection optics has been developed. The optical elements are based on stock lens as it allows reduction cost compare to custom lens. The actual projection optics parameters are compared with both design and simulated results as shown in Table 1.

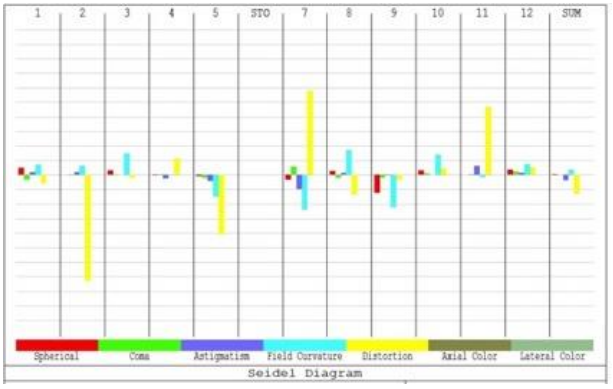


Figure 7. Seidel diagram for the projection optics

Table 1. Comparison of projection optics parameters

Parameters	Design	Simulated	Actual
F/#	2.1	2.4	2.4
Magnification	5.5	5.0	6.6
Pixel size	60 µm	54 µm	71 µm

B. 3D Printing System

The design of the system which is based on the top down approach is finalized and the system has been integrated and assembled. Figure 8 shows the final prototype of the projection SL system. The system is enclosed in a yellow acrylic case in order to protect the printing process from external visible light. Figure 9 shows the close up view of the major components of the system. The devices are printed using the UV polymer resin from *Venus Creator*. Figure 10 illustrates the printing process which shows the projected image is beamed onto the build platform.

Figure 8. Prototype of the projection SL system

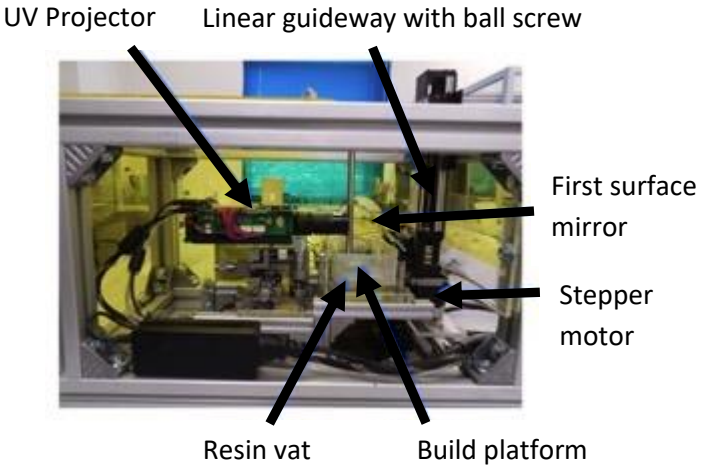


Figure 9. Close up view of the major components of the developed system

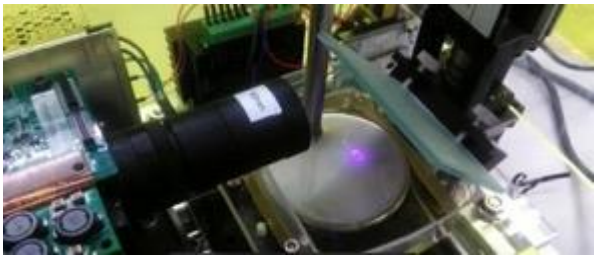
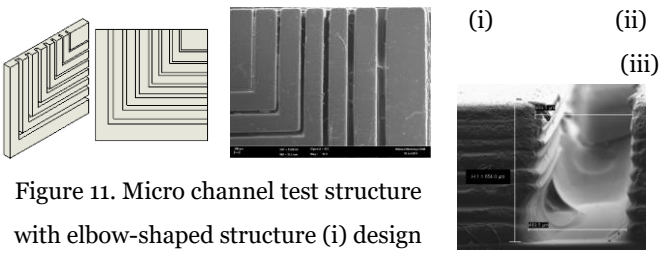


Figure 10. Projected image on the build platform

C. 3D Printed Parts

The projection SL system has been characterized by printing several test structures and devices. Geometrical characterization has been performed on the printed test structures using an optical microscope and scanning electron microscope (SEM). The first test structure being used is the elbow-shaped structure in which micro channels of various sizes with 90° bends are printed and characterized using SEM. Figure 11 (i) shows the design of the first test structure, (ii) the SEM image of the micro channels and (iv) SEM cross section view of a micro channel structure – 500 µm in height and 450 µm in depth



(i) (ii) (iii)

Figure 11. Micro channel test structure with elbow-shaped structure (i) design (ii) top view and (iii) cross section view

The second test structure being used are the micro pillars, both circular and rectangular shaped pillars. Figure 12 shows the test structure used in the second test in which circular and rectangular micro pillars with diameters of 500 µm have been used. Figure 12(i) is the design structure, whereas Figure 12(ii) and (iii) are the SEM images of the printed pillars for circular and rectangular shaped respectively.

(i) (ii) (iii)

Figure 12. Micro pillar test structure (i) design (ii) circular shaped (iii) rectangular shaped

Prototypes of the microflow cytometer devices have been printed using the 3D printing system and the results are shown in Figure 13. Figure 13(i) shows 3D printed microfluidics devices with different channel sizes and whereas Figure 13(ii) shows the 3D printed device with test liquid injected into the channel for leaking test. The result showed that the printed micro channels are able to sustain the flow of liquid inside the channel without fluid leakage. The smallest circular channel that was successfully printed measured at 1030 µm which is slightly bigger than the design value of 1000 µm. Unfortunately, the smaller sized micro channels could not sustain the injected fluid inside the micro channels. Finally, Figure 14 shows the cross section of a circular cross section micro channel showing the actual shape of the channel.

(i) (ii)

Figure 13. 3D printed microflow cytometer device (i) device with different channel size (ii) red liquid injected into channels

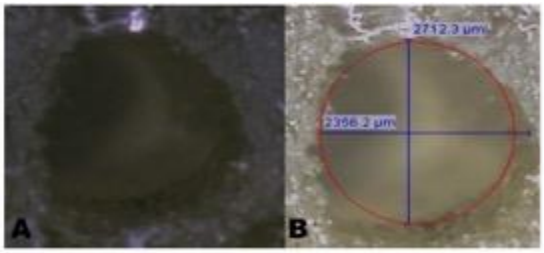


Figure 14. SEM cross section image of a circular-type micro channel

D. CONCLUSION

A projection stereolithography 3D printing system has been developed. The projection SL 3D printer is designed and developed for printing microfluidics devices. The design of the 3D printing system includes the projection optics for the DLP light projector that can project images with magnification of 1:1 at 92 mm working distance and a pixel size of 60 µm. The system based on top down design enables images to be projected from the top and down to the built platform at the bottom. Characterization of the printed devices have been performed but were limited to visual characterization using optical microscope and SEM. The results shows that the microflow cytometer devices can be 3D printed but are limited in channel sizes. Functional microflow cytometer design can be 3D printed and is able to sustain injected fluids but further study need to be conducted in order to allow micro channel sizes to be printed with precise geometrical features.

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