Characterization of a Custom-Made Digital Light Processing Stereolithographic Printer Based on a Slanted Groove Micromixer Geometry

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A custom-made stereolithographic printer using a digital light processing optical (DLP) system based on a digital micromirror device (DMD) was characterized. Several sizes of slanted grooved micromixers (SGM) were produced and typical dimensions were measured and compared to nominal values. The results show that the developed SLA printer is precise enough to be used for prototyping of larger microfluidic devices. The lateral geometries of the smallest printed micromixer designs deviated less than 20 μm from the nominal values and related feature depths deviated for less than 15 μm. However, further modifications are needed in order to improve the repeatability, accuracy, and printing resolution. [DOI: 10.1115/1.4046044]

Keywords: DLP stereolithography, 3D printer characterization, micromixer

1 Introduction
Additive manufacturing (AM) is a formal expression for what used to be called rapid prototyping (RP) technology. Several other terms are, or used to be, in use as well: automated fabrication, freeform fabrication, solid freeform fabrication, layer-based manufacturing, and 3D printing. Standard ISO/ASTM 52900 [1] classifies AM into seven groups. Stereolithography (SLA) belongs to the vat photopolymerization group. It is a liquid-based AM process, where 3D parts are made by curing a photosensitive polymer kept in a vat. Various light sources are used for photopolymerization, namely, gamma rays, X-rays, electron beams, ultraviolet (UV), and visible light source [2]. Controlled light irradiation induces a curing reaction, forming a highly cross-linked polymer.

In the last years, the resolutions of digital light processing (DLP) projectors have been significantly improved due to the use of new cost-effective digital micromirror devices (DMD). Compared to other light sources, the use of a DLP projector or LCD display enables building the whole layer at the same time.

A printing resolution that can be achieved by DLP stereolithography depends on the size of micromirrors in DMD and an optical system. In general, higher printing resolution requires a smaller size of the printing layer. The control of the thickness of the layer that is cured is essential. For a given resin, the cure depth is determined by the energy and wavelength of light to which the resin is exposed. The smallest details that can be printed depend also on the size of molecules forming a photopolymer and thus, the smallest feature that can be produced depends on the resin, too.

Recently, additive technologies have been downsized so they can be used for microfluidic device fabrication [3]. Micromixers are important microfluidic functional units. Their main task is to mix different reactants in submillimeter channels where the laminar flow regime is commonly present. One of the established designs is the bottom-grooved micromixer (for geometry visualization see Sec. 2.4) [4]. The grooves on the bottom of the channel laterally transport the fluids and induce fluid mixing.

In this article, the results of an upgraded custom-made SLA desktop printer are presented. The reference geometry produced is a bottom-grooved micromixer, which is commonly applied in microfluidic systems. The capabilities of the SLA printer setup were studied with respect to its printing accuracy. Crucial micromixer geometries were printed and dimensions measured using an optical digital microscope.

2 Materials and Methods

2.1 Custom-Made Three-Dimensional Printer. A custom-made desktop DLP stereolithographic printer consists of an optical system, printing bed, stepper motor, two threaded spindles, and microcontrollers as shown in Fig. 1. Photopolymerization was initiated by a Vitalux STAR-065 EVM Type A monochromatic (UV) DLP-projector. Projector uses 405 nm wavelength light with power up to 25 W/cm² and resolution of 1920 × 1080 pixels. In order to increase the projector accuracy (reduce the pixel size) a 15 mm long spacer was mounted between the light source and projector lens (Fig. 2). This reduced the printing distance from 340 to 80 mm and decreased pixel size from 80 to 20 μm. The projector was mounted on a custom-made casing directly below the tank since a better printing precision is obtained when the photopolymer is illuminated through a transparent bottom of the vat (constrained-surface method) compared to illumination from the top (free-surface method) [5].

To obtain a good precision of layer thickness on the given printer, the movement in the z-axis was enhanced by an accurate actuator Stand88MT1675-25 LS (Lithuania). The actuator covers movements of a maximum of 25 mm with a resolution of 1.25 μm. The new system allows speeds up to 6 mm/s. The load can be up to 30 kg in the horizontal direction and up to 7 kg in the vertical direction, which is more than enough for the given application.
The feed system movement is controlled by the 8SMC5-USB controller of the same manufacturer.

2.2 Printing Parameters. The following printing parameters were used: projector illumination power of 100%, the thickness of the printed layer 5 μm, layer illumination time 50 ms, bottom layer illumination time 300 ms, number of bottom layers 8, and height of table lifting 3 mm. Adequate printing process parameters were obtained experimentally by printing a reference part with the smallest micromixer geometry used in this investigation. The layer thickness was set to 5 μm to keep the precision of the printed parts in the z-axis. The illumination power of the Vialux projector was set to maximum (100%) to enable the shortest illumination time for the curing of individual layers. Eight bottom layers and bottom layer illumination time of 300 ms guaranteed that the part would stick to the print bed. Adequate layer illumination time was determined by incrementally increasing it and visually inspecting the printed part. For lower illumination times (<50 ms) some features of the micromixer geometry were missing due to insufficient curing of the layers. For longer illumination times, we noticed that the micromixer grooves were filled with cured photopolymer probably from the exposition of the scattered light from receding layers. Three millimeters printing bed lift after each curing cycled enabled sufficient stirring of the photopolymer beneath the printing area. The photopolymer used in this research was 3D OKAY UV LED/LCD resin. 3D printer control software Creation Workshop was used. All micromixers were printed using the same printing parameters (Table 1).

2.3 Photopolymer Handling. In previous micromixer printing tests, several photopolymers were already tested: black and clear Monocure 3D Rapid and 3D OKAY UV LED/LCD resin. In preliminary experiments, it was observed that greater details were printed with resin that had lower viscosity and for that reason, all tests presented in this article are conducted using that resin (3D OKAY UV LED/LCD resin). Prior to printing, the resin was vacuumed and stirred for several minutes to extract as much microbubbles of air as possible. The length of polymer molecules in the photopolymer defines the “resin resolution,” that is, the smallest feature that is possible to build from the resin. The “resolution” of the resin is not provided by the resin manufacturer, but the results given latter in the article indicate that it is less than the resolution of the optical system used. After the printing process, the prints

Table 1 Printing parameters used for printing reference geometry (micromixer)

| Parameter                                           | Value  |
|-----------------------------------------------------|--------|
| Layer thickness                                     | 5 μm   |
| Illumination power                                  | 100%   |
| Bottom layer illumination time                      | 300 ms |
| Number of bottom layers                             | 8      |
| Layer illumination time                              | 50 ms  |
| Height of table lifting                             | 3 mm   |
| Printing resin                                      | 3D OKAY UV LED/LCD |
were rinsed for several minutes in isopropanol in two stages. The first stage was designed to remove the liquid photopolymer that was still present on the micromixer after it was taken from the vat. In the second stage, new isopropanol was used to clean any remaining resin from micromixer channels. The micromixers were then cured by UV light.

2.4 Micromixer Geometry. Most of the bottom-grooved micromixer realizations reported in literature were made using soft lithography techniques [7]. Thus, shallow grooves were implemented. Many studies were performed in order to find optimal groove dimensions [4,8]. It was found that groove depth has the highest influence on mixing performance following the rule deeper is better. On the other hand, deep grooves render so-called dead volumes, where fluid flows extremely slow and significantly increases the residence time of the reactants. Optimal groove geometry depends also on the cross section of the main channel. It was shown that the optimal groove dimensions for \( h = 0.05 \text{ mm} \) and \( w = 0.2 \text{ mm} \) are \( a = 0.1 \) and \( d = 0.1 \text{ mm} \) [4]. For this reason, the aspect ratio of groove dimensions defined by \( d/a \) was fixed to 1, with the exception of the shallow-small design, where \( d/a = 0.5 \) was implemented.

Four micromixers (for the schematic presentation of geometry see Fig. 3) of various dimensions were produced, that is, large, medium, small, and shallow-small, to test the performance of the 3D printer. The dimensions of each micromixer are given in Table 2. All dimensions given in the table were also measured on the produced parts as explained below.

2.5 Measurements. Dimensional measurements were conducted on a Keyence VHX-6000 digital microscope. The specimen was placed on the table and then the lighting was set in order to get as much details on a surface as possible. The lighting that enabled that was full coaxial. The surface was then measured using depth composition function. This function scans the height profile of a surface in a user-defined height area (from the bottom of the channel to the upper surface of micromixer) with a manually determined pitch. The pitch was selected to get a good resolution. This was about 1/100 of a nominal channel depth. After the scanning, the dimensions were acquired by 3D measurement tools, where the edges were detected by line-to-line function and consequently the distance between the lines was determined (Fig. 4). Every feature was measured three times, thus, altogether 48 measurements were analyzed.

3 Results and Discussion

The accuracy of the printed micromixers was determined by digital microscope measurements of critical dimensions: channel width \( w \), channel depth \( h \), groove width \( a \), and groove depth \( d \). At this point, it should be noted that all micromixers were printed using the same printing parameters, which were previously adjusted for the precision of the smallest features, namely, groove dimensions of small and shallow-small designs.

First, measurements of the main channel dimensions of the four micromixers are presented (Fig. 5). The printing resolution in the \( x-y \) plane depends on the resolution of the projected light (pixel size of 20 \( \mu \text{m} \)) and “resin resolution.” The width of the micromixer main channel lies in the \( x-y \) plane. Figure 5(a) shows the difference between measured and nominal values of the width of the main channel. One can observe that the wider channels (of large and medium design) deviate largely from the nominal values. On the other hand, narrower channels (of small and shallow-small design) have expected deviation from nominal values considering the pixel size of DLP light used for curing the photopolymer layers. Average widths for small and shallow-small designs deviate less than 20 \( \mu \text{m} \) from the nominal value. Most probably, the calibration of the optical system should be adjusted when printing larger features. This should significantly reduce the lateral errors.

Additional explanation for bigger lateral deviations for larger micromixer designs may be due to so-called container effect. The container effect occurs at narrow features due to surface tension of the photopolymer and causes sticking of the raisin to the surfaces [9]. The smaller the feature the bigger the effect will be. Since suitable process parameters were obtained by investigation of printing accuracy for the smallest micromixer designs this effect was more prominent in comparison when printing larger designs. This explanation is also the rationale behind the idea of rescaling the \( x-y \) projection plane when printing larger micromixer designs. Standard deviations for all channel widths (given as error bars) are within the expected range of \( \pm 20 \mu \text{m} \) considering the pixel and raisin resolutions.

The printing resolution in the \( z \)-axis depends on the performance of the Standa high-precision actuator (declared factory accuracy is 1.25 \( \mu \text{m} \)) and the flatness and tension of the fluorinated ethylene propylene (FEP) foil on the bottom of the vat. The parameters related to the FEP foil were not monitored during printing. The depth of the main channel was measured in the \( z \)-axis. Figure 5(b) shows differences between measured and nominal main channel depths. Similar to lateral channel dimensions, the differences are larger for deeper channels (large and medium design). The calibration of the optical system has no influence on dimensions in the \( z \)-axis. A probable cause for lower printing accuracy in \( z \)-direction could be in the tension of the FEP foil. During experiments, it was observed that when lifting the table, the foil was slightly moved in the same direction as the table and then moved back. This could add up inaccuracies through more layers that are cured. This explanation is also in line with rather small deviations for shallower channels where average depth differs from nominal value for less than 5 \( \mu \text{m} \).

The dimensions of the grooves on the bottom of the main channel were analyzed in the same manner as the main channel. Figure 6(a) shows the difference between measured and nominal groove widths whereas Fig. 6(b) shows the difference between measured and nominal groove depths. Similar observations as for channel

![Fig. 3 A schematic representation of a slanted groove micromixer (SGM). The curved lines denote streamlines due to helical motion along the main channel caused by fluid lateral displacement by the grooves.](https://example.com/fig3.png)
dimensions can be extrapolated for printed grooves. Namely, the greater the nominal dimension greater will be the difference between the measured and nominal value. Again, a plausible explanation for observed lateral dimension deviations may lie in the container effect. Lateral error should be reduced by recalibrating the projected area in the \(x, y\)-plane. Standard deviations for groove widths (shown as error bars) are within the expected range, considering lateral resolution of the printer.

Unlike measured depths of the main channel (Fig. 5(b)), the larger grooves are deeper than specified (Fig. 6(b)), despite high-precision Standa stepper motor. As the grooves are printed before the channel, it is possible that FEP foil stretched during the printing process thus resulting in deeper grooves and shallower channels.

Standard deviations of groove depths (below 4 \(\mu m\)), compared to related channel depth (below 13 \(\mu m\)), are considerably smaller for the large and medium design. This observation again indicates that the error in the \(z\)-axis accumulates as the number of layers rises. As for small and shallow-small designs, the standard deviations for groove depths \(d\) are below 2 \(\mu m\) and for related channel depths below 4 \(\mu m\), which shows a good precision of printing in the \(z\)-axis.

4 Conclusions

Based on the results presented in this article and observations during experimental work the following conclusions can be drawn.

- A custom-made DLP stereolithographic printer using an optical system with 20 \(\mu m\) pixel size can produce microfeatures of which dimensions have a standard deviation in the same range, thus the printer with such optical system is in general able to produce microfeatures down to 50 \(\mu m\).
- The differences between measured and nominal values in the \(x-y\) plane depend on the nominal value, which indicates the illumination system of the printer was not properly
calibrated. For smaller designs, the average channel widths deviate less than 20 \( \mu \text{m} \).

- The differences between measured and nominal values in the \( z \)-axis also depend on the nominal values. One of the possible reasons lies in the number of layers that need to be cured. Thus, error per layer adds up as the number of layers increase for thicker microfeatures. This explanation is also in line with rather small deviations for shallower channels and grooves where average depth varies from nominal depth for less than 5 \( \mu \text{m} \). We assume that the main reason for error lies in the microscopic movement of FEP foil.

- It was observed that the light source generates uneven light exposure over the whole working area. Thus, the micro-mixers were printed as close as possible to the center of the vat. Thus, uneven light exposure could have an influence on printing accuracy.
In future work, the optical system will be recalibrated to achieve better precision in the x,y-plane. Also, a software solution to create a mask to achieve even illumination on the whole working area will be implemented and the pixel size will be reduced even further in order to be able to produce even smaller features.

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