Fast Micro-Stereolithography Process based on Bottom-up Projection for Complex Geometry

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ABSTRACT
The Mask Image Projection based Micro-Stereolithography technology (MIP-uSL) has many advantages for micro-scale manufacturing. This paper presents a recoating method based on the bottom-up projection to significantly improve the fabrication speed of the MIP-uSL processes. The paper also presents a novel support generation algorithm to significantly improve the capability of the MIP-uSL processes in fabricating complex geometries. Analytical models are established to predict the separation force and to minimize the fabrication time. A prototype MIP-uSL system and a support generation software system are developed for fabricating three-dimensional (3D) digital models with micro-scale features. Multiple test cases are performed to verify the effectiveness and efficiency of the presented approaches.

INTRODUCTION
The Mask Image Projection based Micro-Stereolithography technology (MIP-uSL) is a micro-scale manufacturing approach for fabricating complicated 3D microstructures, especially high aspect ratio microstructures [1-5]. Compared to other micro-scale fabrication methods such as Lithography Gavolnoforming Abforming (LIGA), MIP-uSL has the merits of simpler processing, faster building speed, and lower cost. As a layer based additive manufacturing process, a 3-dimensional (3D) CAD model of an object is first sliced by a set of horizontal planes. Liquid resin of each thin sliced layer is then cured by the irradiation defined by a mask image generated by a Digital Micromirror Device (DMD). Since a DMD enables one to simultaneously control ~1 million small mirrors to turn on or off a pixel at over 5KHZ, the MIP-uSL process is significantly faster than the laser-based micro-Stereolithography technology [6, 7]. Finally a 3D object can be fabricated by stacking such 2-dimensional (2D) layers.

Several MIP-uSL systems have been reported before [1-5]. The smallest feature reported by the DMD-based uSL process is 0.6 um [4]. Most MIP-uSL systems use a top-down projection approach. A schematic diagram of the related MIP-SL system is shown in Fig. 1a. A good property of the top-down projection approach is that one side of the cured layers is free such that a new layer of liquid resin can be added. However, it is difficult to form a thin layer of liquid resin due to liquid viscosity and surface tension. A recoating process based on a sweeper is usually required to flatten the top surface. For resin with low viscosity, a deep-dip recoating approach with a long waiting time can also be used to replace the surface sweeping process.

In comparison, a schematic diagram of the bottom-up projection based MIP-SL system is shown in Fig. 1b. Only a few literatures decades ago [8] were reported to fabricate micro structures based on such an approach. However, as a cured layer is constrained by the tank surface, it is found that the separation of the cured part is a big issue. The fabricated 3D structures are broken frequently during the separation process. Thus the bottom-up projection based micro-Stereolithography system has not been widely used.

Fig. 1: A schematic diagram of MIP-uSL system. (a) top-down projection; (b) bottom-up projection.

In this paper, we present a recoating approach for the bottom-up projection based MIP-SL system. We analyze the separation forces and the liquid flow filling process in the recoating process. Mathematical models and experimental tests are performed to gain better understanding of both micro- and meso-scale fabrication requirements. A fast micro-Stereolithography process has been developed based on moving the Z stage only one layer up. Hence each layer
can be fabricated in a few seconds. In addition, a novel support generation algorithm has been developed for the MIP-SL process to enable the fabrication of complex microstructures. Appropriated parameters for support generation are identified. The fast recoating approach and intelligent support generation method have been verified by various test cases.

**RECOATING PROCESS IN BOTTOM-UP PROJECTION**

In the bottom-up projection process, a cured layer is sandwiched between the previous layer and the resin vat. The solidified material may adhere strongly to the solidification substrate. To separate the cured part from the vat, the build platform may up in the Z axis or sliding in the X axis. Governing equations of both direct pull-up and sliding are derived in order to understand the related separation forces and recoating time.

**A. FORCES IN PULLING-UP AND SLIDING PROCESS**

After a layer is cured, the Z stage is moved up to separate the cured layer from the vat surface. A gap between the cured layer and the vat surface is formed and the liquid flow will fill the gap during the process. As shown in Fig. 2, a pulling-up force \( F_z \) occurs during the separation process for a given velocity \( V_z \) (velocity in the X axis \( V_x = 0 \)). Huang and Jiang [9] identified the pulling-up force is a function of the area of the cured part. He further suggested that the force can be predicted by the pulling coefficient of the vat surface, and the value of plane-strain crack initiation toughness. The force is varied with geometry of the cured part and the curing time while the relationship is complicated. The study is mainly based on physical experiments without establishing such relationship.

To simplify the model, we analyze the separation force in the pulling-up process. As shown in Fig. 2, the cured part needs to overcome force \( F_z \), which is related to the pressure difference and pulling up viscosity. To analyze the model, we assume: (1) the process can be simplified as a 1-dimensional problem; (2) the vat surface and the cured layer are smooth; (3) the tank is big enough such that the flow in the X direction is infinity.

The pulling-up force \( F_z \) consists of a suction force \( (F_p) \) due to the pressure difference and a drag force \( (F_D) \) due to \( V_z \):

\[
F_z = F_D + F_p = \frac{1}{2} \rho V_z^2 C_D \times A + \Delta P \times A' \tag{1}
\]

\( F_D \) is the drag force mainly caused by the liquid viscosity. It is calculated by the area \( A \), drag coefficient \( C_D \), density of the fluid \( \rho \), and relative velocity of the fluid \( V \).

![Fig. 2: Forces during moving up process and sliding process](image)

The drag coefficient \( C_D \) is a dimensionless quantity that is not a constant but varies as a function of parameters including object size, fluid viscosity and object geometry. \( C_D \) is an experimentally calibrated parameter. In our experiments, a very slow velocity \( V \) (0.002 in/s) and a small acceleration (0.0002 in/s) are applied. For the material used in the experiments (EnvisionTEC Si500), it has a viscosity with 180 cP at 30 °C, and a density with 1.10 g / cm³ at 25°C. (compared to water: 0.798 cP at 30°C). The drag force coefficient is within 10. With the set parameters, the drag force is negligible. Thus the major contributor to the pulling-up force \( F_z \) is the suction force \( F_p \), which is caused by pressure difference \( \Delta P \) and the vacuum area \( A' \):

\[
F_z \approx F_p = \Delta P \times A' \tag{2}
\]

Assume the flow can be considered as time-independent, fully developed and one dimensional parallel flow. Its momentum equation and boundary conditions can be written as:

\[
\rho \frac{\partial \vec{V}}{\partial t} = - \nabla P + \nabla \cdot \vec{t} \tag{3}
\]

\[
\frac{\partial \rho}{\partial t} = 0; \frac{\partial v_x}{\partial x} = \frac{\partial v_y}{\partial y} = 0 \tag{4}
\]

\[
v_x|z=\pm h/2 = v_x|z=-h/2 = 0 \tag{5}
\]

where \( \rho, \vec{v}, \vec{F}, \nabla P \) and \( \vec{t} \) are density, velocity, body forces and stress tensor, respectively. Thus substituting Equation (4) and (5) into Equation (3) leads to:

\[
- \frac{\partial P}{\partial x} + \mu \frac{\partial^2 v_x}{\partial x^2} = \frac{\partial \rho V_x}{\partial t} = 0 \tag{6}
\]

Using Equation (5), the velocity of the flow front can be derived by taking the average of the velocity in the \( X \) direction:

\[
\frac{dx}{dt} = u = \frac{1}{h} \int_{-h/2}^{h/2} v_x dz \tag{7}
\]

Combining Equation (6) and (7) yields:

\[
\frac{\partial P}{\partial x} = \mu \frac{\partial^2 v_x}{\partial x^2} = \frac{12 \mu}{h^2} \frac{dA}{dt} \tag{8}
\]

where the gradient of pressure is formed by the capillary pressure drop \( \Delta P \), and the pressure difference \( \Delta P_d \) between the inlet and the outlet. \( \Delta P_s \) is given by:

\[
\Delta P_s = \frac{2 \sigma \cos \theta}{h} \tag{9}
\]

where the gap distance \( h \) is a function of time, \( \sigma \) is surface tension. Hence substituting (9) into (8), the filling rate in \( X \) direction and thus the vacuum area \( A' \) can be derived:

\[
\frac{dA}{dt} = \left( \frac{\sigma \cos \theta - \Delta P}{6 \mu} h(t) + \frac{\Delta P}{12 \mu} h(t)^2 \right) \times \frac{1}{A} = \frac{K_1 \times h(t) + K_2 \times h(t)^2}{A} \tag{10}
\]

\[
A' = A - \int_0^T \frac{dA}{dt} dt = A - \frac{K_1 \times h + K_2 \times h^2}{A} \tag{11}
\]

Substituting Equation (11) into Equation (2), we get:

\[
F_z \approx F_p = \Delta P \times \left( A - \frac{K_1 \times h + K_2 \times h^2}{A} \right) \tag{12}
\]

Note that the separation force \( F_z \) is nonlinear with the part size \( A \):

\[
F_z \propto (A - \frac{K}{A}) \tag{13}
\]

In comparison, the \( Z \) stage can also be moved in the \( X \) axis before moving up in order to separate the cured layer from
the vat surface [10]. During the sliding process, the shearing force in the X axis mainly comes from the viscosity, which can be modeled as:

$$F_X = \int (\mu \frac{\partial v}{\partial x}) dx; \text{ hence, } F_X \propto A.$$  \hfill (14)

Note that the shearing force $F_X$ is linear with the part size $A$.

**B. MAXIMALLY ALLOWED FORCES IN THE X AND Z AXES**

To prevent the detachment of a cured layer from the built part, the separation force $F_z$ in the pulling-up process should be less than the bonding force of the cured layer and the built part. Otherwise, the cured layer will be detached and the related features will not be shaped. Fig. 3a shows some examples of failed pillars. For them, the force required to reach the break point can be modeled as:

$$F_p = \sigma_i \times b^2$$ \hfill (15)

where $\sigma_i$ is the tensile strength of the material and $b$ is the beam section size. Hence the maximally allowed separation force $F_z$ before breaking follows:

$$F_{\text{Max}, z} \propto A$$ \hfill (16)

In comparison, the shearing force in the X axis can be modeled as the bending force for a beam (refer to Fig. 3b):

$$F_B = \frac{\sigma_o b^3}{6L}$$ \hfill (17)

where $\sigma_o$ is the flexural strength and $L$ is the length of the beam. Therefore, the maximum shearing force in the X axis follows:

$$F_{\text{Max}, X} \propto A^{1.5}$$ \hfill (18)

As shown in the above equations, the separation force and the maximally allowed forces along the Z and X directions have different relationships with the surface area $A$.

(a) $F_z \propto (A - \frac{K}{r})$ and $F_{\text{Max}, z} \propto A$ when the cured part is moved in the Z axis;

(b) $F_x \propto A$ and $F_{\text{Max}, x} \propto A^{1.5}$ when the cured part slides along the X direction.

Accordingly, the trends of the forces along the Z and X directions are shown in Fig. 4. For a decreasing part size $A$, the maximally allowed force $F_{\text{Max}, X}$ decreases much faster than the separation force $F_z$; while the separation force $F_z$ decreases much faster than the maximally allowed force $F_{\text{Max}, z}$. Consequently, a recoating method based on the sliding movement in the X axis is preferred for the meso- and macro-scale MIP-SL process [10]. In contrast, a recoating method based on the direct pulling up-down in the Z axis is preferred for the micro-scale MIP-SL process.

**A FAST MIP-uSL PROCESS DESIGN**

Based on the aforementioned analysis result, a pulling-up movement design is used in developing a fast MIP-uSL process. A thin layer of Polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning) is coated on the vat surface. This is mainly based on the ability of PDMS in inhibiting free-radical polymerization near its surface [11]. Thus a very thin oxygen-aided inhibition layer (~2.5 μm) is formed near the PDMS film to prevent the bonding between the cured layer and the film. After a mask image is exposed, the platform is moved up slowly in the Z axis by a certain distance. Enough waiting time is necessary to ensure the complete filling of liquid resin in the gap. The mask image of a new layer can then be projected to cure the next layer.

Since a significant portion of the MIP-uSL fabrication time is spent on the resin recoating, the process parameters including the moving-up distance and the delay time are investigated in order to achieve a fast building process.

**A. EXPERIMENTAL STUDY OF PARAMETERS SETTINGS**

A long waiting time and a big moving distance would guarantee the complete filling of liquid resin in the gap. However, it is desired to identify a short waiting time and a small moving distance in order to achieve a fast fabrication speed. A set of experiments based on different moving distances and surface areas have been performed to identify such parameter settings. In the experiments, cubes with various sizes are built by using different waiting time and moving distances. Fig. 5 shows a cube of 6.96 × 6.96 × 2 mm. If the built part has holes or deep shadows under a microscope, the waiting time is considered to be insufficient. Accordingly a longer waiting time will be used in rebuilding the part. A critical waiting time for void-free curing is identified for different Z moving distances (hs). By changing the cube dimension, a new critical waiting time can be identified. Fig. 6 shows the relation between the critical waiting time, the cube size and the Z movement.

**Fig. 3:** Illustrations of built pillars. (a) Failed pillars in the Z axis due to insufficiently curing; (b) a comparison of built pillars using the sliding (left) and up-down motions (right).

**Fig. 4:** The relation of separation forces and area size. (a) Moving part in the Z axis; (b) moving part in the X axis.
distance. In all the tests a same speed (0.002 in/s) is used in moving up the platform. It can be observed from Fig. 6 that: (1) for the same gap height, the minimum waiting time increases with the dimensional size; (2) bigger gap height results in less minimum waiting time; (3) no waiting time is needed for a gap distance larger than 12 μm and a dimensional size smaller than 6 mm.

B. BUILDING TIME OF A LAYER

The building time of a layer is the sum of all the aforementioned steps:

\[ T_{layer} = T_{projection} + T_{wait\_projection} + T_i + T_{wait\_z}, \]

in which, \( T_{projection} \) and \( T_{wait\_projection} \) are related to the curing characteristics of the photopolymer resins and the light intensity of the light source used in the system; \( T_i \) is the time required for moving the platform one layer up in the Z axis; and \( T_{wait\_z} \) is the minimum waiting time in order for resin to fill the one layer gap.

After an image is exposed for \( T_{projection} \), a waiting time \( T_{wait\_projection} \) is required before the layer being moved up by one layer thickness. Such a waiting time is critical for the acrylate resin to complete the solidification process and gain sufficient strength for the Z movement. Otherwise, the building process may fail. Due to the fast photocuring speed of the acrylate resin, \( T_{wait\_projection} \) in our system is short (~300 milliseconds in our tests). \( T_{wait\_z} \) is related to the gap distance, filling area size, moving velocity and conditions of the PDMS coating. A minimum of 0.1 second can be used to ensure the liquid resin to stay still. For various conditions, a minimum delay time can be added based on the fitted models as shown in Fig. 6.

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**AUTOMATIC SUPPORT GENERATION**

Supports structures in the SLA process are similar to fixtures in machining or scaffolds in construction. They are important for building parts with complex geometries. Appropriate support structures are especially critical for the bottom-up projection based MIP-μSL process since all the parts are built upside-down in the fabrication process. Each cured layer needs to be securely anchored to previous layers; otherwise the building process would fail. In addition, note that the part sizes of the μSL process are tens to hundreds times smaller than those of the macro-scale SLA process; however, the sizes of a support anchor in the μSL process (e.g. 50μm rods are used in our experiment) can only be several times smaller than those in the macro-scale SLA process (e.g. 100-150μm rods are usually used). Consequently it is important to identify appropriate anchor positions for a given geometry and add a minimum amount of supports to avoid the support structures are too dense.

No literature on the support generation for the μSL process was found. For the macro-scale SLA process, most previous work on the support generation is based on direct processing of polygonal models. A dominant support generation approach is to compare the orientation angle of a triangle in a polygonal model with a minimum supporting angle specified by a user and accordingly identify supporting regions [12-14]. However, the accordingly generated supports are usually dense since the approach does not take advantage of the self-supporting property of geometric features. For example, no supports are needed for a vaulted overhand or a small overhang as all the layers of such geometric features can be anchored to previously built layers in the building process. A contour-based support generation method and related algorithms have been developed for the MIP-μSL process. Instead of analyzing polygonal triangles, our method is based on systematically analyzing the shape of sliced 2D layers and accordingly identifying support regions. Our method fully utilizes the self-supporting property of a geometric feature and can significantly reduce the number of supports that are required in the building process.

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**Fig. 5:** Test results for identifying the minimum moving distance and delay time. (a) CAD model; (b) built part with insufficient waiting time; (c) void-free part; (d) surface with a hole; (e) shadows due to incomplete filling; (f) void-free surface.

**Fig. 6:** The flow filling time with different gap height.

**Fig. 7:** An illustration of the contour-based support generation method. (a) Given layers; (b) Layer analysis result.

A. **PRINCIPLE**

The MIP-μSL processes build physical objects layer-by-layer. Accordingly, the principle of our support generation
approach is to analyze the sliced contours layer-by-layer for determining the required supports in the building process. Fig. 7 shows a simple 1-dimensional example to illustrate the contour-based support generation method. Suppose the relative sizes and positions of a current layer and its previous layer are known. All the previous layers have been built when the current layer is to be built. Obviously the portions of the current layer that directly contact the previous layer have been supported. In addition, certain neighboring areas are also supported by the previous layer (i.e. enlarging the previous layer by Dist_{self, support} as shown in Fig. 7b). The value Dist_{self, support} of a region may be experimentally determined related to the size of the region. For the remaining portions of the current layer that have not been anchored by the previous layer (i.e. regions ii in Fig. 7b), supports are required in order for them to be anchored. The additional pins that are added under a given part are called anchor supports in the paper. Such anchors have been fixed on the building platform or previously built layers when the current layer is to be built. Assume when an anchor is added at position P, the circular region centered at P with a radius of Dist_{anchor} can be safely built. Accordingly all the regions (ii) are fully supported after a certain number of anchors have been added. The value of Dist_{anchor} can also be experimentally determined for anchors with given shapes and sizes. After all the layers of a 3D model have been analyzed, the CAD model of related supports including bases and reinforcements can be computed. Consequently the building process of given CAD models will be successful since all the layers are fully anchored either by the previous layer or the added anchor supports.

B. MAIN ALGORITHMS

There are three main 2D operations in the aforementioned contour-based support generation method including offsetting, Boolean, and region covering. The operations need to be robust and general for automatic processing of sliced contours of a 3D model.

Offsetting a solid S by a distance r into a grown or shrunken version of S has been precisely defined for point sets in Euclidean space $E^2$ or $E^3$. Although the offsetting operation is mathematically well defined, computing an offset model for a given solid has proven to be difficult. We developed a novel offsetting method based on a point representation named the Layered Depth-Normal Image (LDNI) for an input polygonal model and an offset distance [15]. The offsetting method is based on: (1) directly computing offset boundary; (2) converting the boundary into structurally sampled points; (3) accordingly filtering the sampling points; and (4) reconstructing offset contour from the filtered points. The key benefits of the method are that the related geometric operation can be general, robust, and efficient.

A LDNI model consists of a set of well-organized one-dimensional (1D) volumes defined by the even number of depth-normal samples stored in each pixel of the LDNI model. Consequently, the Boolean operations on LDNI models can be converted into the Boolean operations on 1D segment [16]. After Boolean operations, the computed LDNI model is an implicit representation of a solid defined by the geometric operation. A contouring method can then be used to reconstruct a polygonal model from the LDNI model [17].

Fig. 8 presents an example taken from the sliced contours of a CAD model. Two consecutive layers (#106 and #107) are shown in Fig. 8a and 8b, respectively. The computed offset contours of Layer #106 are shown in Fig. 8c. The subtraction between the current layer and the offset contour is computed. The Boolean operation result is the regions that are to be supported by anchor supports.

The layout of anchors in a computed support region can be formulated as a 2D region covering problem. The region covering problem has been well studied [18]. A modified Delaunay triangulation method is developed for finding a small amount of anchors that can sufficiently cover an arbitrarily given 2D region. The main algorithm of the method is given as follows.

1. Triangulate a contour $L_i$ into a 2D region $R_i$;
2. Compute an initial number of supports based on $Num_{anchor} = A_{Pi} / A_{anchor}$;
3. Randomly place $N_{anchor}$ points at $Pos_{anchor}$ in $R_i$;
4. Create Delaunay triangulation of $R_i$ based on current $Pos_{anchor}$ and find the related centroid points;
5. Move $Pos_{anchor}$ to the computed centroid points;
6. Repeat from (4) until $Pos_{anchor}$ converges to centroid points of the Voroni partition;
7. Check the length of all the partition edges. If any edge length is bigger than Dist_{anchor}, increase $N_{anchor}$ to a larger value and repeat from (3).

The computed $N_{anchor}$ and related $Pos_{anchor}$ can be used as the layout for adding related anchor supports. The added anchor supports are cylindrical rods with appropriate sizes (refer to Fig. 9). The tip of anchor supports are rods with a diameter of 50um and the bottom of anchor supports are rods with a diameter of 100um. In addition, neighboring
anchor supports are connected for an increased stability. The bottom portions of the anchor supports are also connected with a base such that the supports can be securely attached to the building platform. The computed anchor supports for a gear example are shown in Fig. 9.

**Fig. 9: A support generation example-support structures of a gear.**

**EXPERIMENTAL SETTING**

A prototype system has been built to verify the presented process. The hardware setup is shown in Fig. 10. An optical system is designed to focus the mask image of a DMD onto the building plane with an envelope size of 12.7x8 mm. The DMD resolution is 1024x768. A blue light filter (410nm) is used for the tested resin (Perfactory™ SI500 from EnvisionTec Inc.). A linear stage from Aerotech Inc. (Pittsburgh, PA) with 1µm resolution is used as an elevator in the Z axis. The layer thickness in our tests is between 10 to 20µm. A 4-axis motion controller with 28 Bi-directional I/O pins from Dynomotion Inc. (Calabasas, CA) is used to drive the linear stage and to synchronize the movement and projection. The resin tank is a clear glass Petri dish with PDMS coating on the bottom. In addition, a mask planning software system has been developed using the C++ language. It integrates the geometry slicing, image planning and projection, and motion controlling.

**Fig. 10: Hardware setup**

**EXPERIMENTAL RESULTS AND DISCUSSION**

Various tests have been performed to verify the capability of the developed process and the benefits of support structures have also been tested.

**A. MICRO-FABRICATION CAPABILITY**

Several simple tests were carried out to verify the capability of the system on building micro structures or meso-scale parts with micro features. Two of the test cases are shown in Fig. 11a and 11d. In the first test case, a set of pillars are designed between a top and bottom plate. The sizes of the pillars are gradually decreasing from left to right. With the aid of the top and bottom plates, any successful built pillars can be kept after the post processing process. The test case is to identify the smallest pillars the prototype system can build reliably. In the second test case, a plate has a small gap in its center. A set of such plates with different gap sizes were built to identify the smallest gap sizes the prototype system can build successfully. Fig. 11b and 11e shows two built objects with the microscopic images of the thinnest pillar (50 µm) and the smallest gap (110 µm).

A test case of a gear was used to verify the capability of the MIP-µSL system in fabricating micro-scale curved surfaces. The CAD model of a gear with a diameter of 3mm is shown in Fig. 12a. The built physical object is shown in Fig. 12b. The microscopic image of some gear teeth is given in Fig. 12c, which shows nice curvatures of the pitch surfaces.

A test case of a hearing-aid shell was used to test the capability of the MIP-µSL system in fabricating micro-scale shell structures. Fig. 13a shows the CAD model of the hearing aid shell and related support structures constructed by our support generation algorithm. Fig. 13b shows the built physical object including the added support structures. As shown in Fig. 13c, the curved shell with desired thickness (~80 µm) was successfully built. A designed venting hole in the left side was also successfully fabricated.

**Fig. 11: Fabrication capability tests. (a)-(c): pillars; (d)-(f): gaps.**

**Fig. 12: A gear with micro-scale features. (a) CAD model; (b) built object; (c) microscopic image of gear teeth.**
The tests as shown in Fig. 11-13 illustrate that our MIP-μSL system can build parts with micro-features. Furthermore, in order to ensure the success rate and mechanical strength of built parts, (1) solid structures need to have at least 50 μm thickness; (2) solid shells need to have at least 60 μm thickness; and (3) holes or gaps need to have at least 110 μm diameters or distances.

B. TESTS ON OBJECTS WITH MICRO-FEATURES

CAD models with more complex features were tested. The experimental results verify that, with proper supports constructed by the support generation system, all the micro-scale features that satisfy the aforementioned constraints can be successfully fabricated by our MIP-μSL system.

Fig. 14: A threaded pipe. (a) CAD model of the pipe and constructed supports; (b)-(e) built physical object.

Fig. 15: A turbo fan. (a) CAD model of the fan and constructed supports; (b)-(f) built physical object.

Fig. 16: A test case on surface stiction problem. (a) A CAD model with no supports; (b) built object after pulling out from liquid resin; (c) built object after cleaning; (d) a CAD model with supports; (d) built object after cleaning; (e) built object after removing supports.

D. BUILDING TIME STATISTICS

Table 1 shows the building time of our MIP-μSL system in fabricating the related test parts. The developed process
can build a layer in <5 seconds. Hence a CAD model with micro-scale features can be fabricated in minutes instead of hours. Such fabrication speed is much faster than all the previously reported µSL work.

Table 1. Performance of our new developed MIP-uSL system.

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<td>653</td>
<td>378</td>
<td>292</td>
</tr>
<tr>
<td>( T_{\text{total,building}} ) (min)</td>
<td>4.504</td>
<td>46.27</td>
<td>17.97</td>
<td>21.93</td>
</tr>
</tbody>
</table>

* Note: although the X dimensional sizes of the parts are bigger than 6mm, the flow filling area is actually small. So \( T_z \) is still set as 0.1 second.

CONCLUSION

A novel MIP-uSL process has been presented for fabricating 3D micro-scale structures with fast building speed and complex geometries. The proposed approach is based on the bottom-up projection approach. The separation forces in the Z and X movements have been modeled and experimentally tested. It is found that the maximally allowed bending force in the X axis and the suction force in the Z axis are all dramatically reduced with a decreasing curing area size. Hence, separating cured parts from the vat surface by moving the parts in the Z axis is more appropriate for the MIP-uSL process. Furthermore, no waiting time is required for a cured area that is smaller than 6×6 mm² and a gap of 20µm. The building time of each layer can be significantly reduced. The experiments show that the building time of a layer is about 2–4 seconds in our system, which is significantly faster than other systems reported in literatures.

A novel supports generation method based on analyzing sliced contours has also been developed to facilitate the fabrication of complex geometries such as various overhanging features. The supports can also address the stiction problem of micro-scale beams and plates that is caused by surface tension. The experimental results illustrate that the newly developed MIP-uSL process can successfully fabricate complex 3D objects with micro-scale features with satisfactory quality in a reasonably short time.

Some future work we are investigating includes: (1) improving the resolution of the MIP-SL system; (2) integrating multi-scale MIP-SL systems; and (3) investigating automatic support removing processes.

REFERENCE


