1. Introduction

Most current additive manufacturing (AM) processes are layer-based [1] [2]. For example, in the laser-based or projection-based stereolithography (SL) processes, a three-dimensional (3D) object is fabricated by using light source (i.e. a laser dot or a projection image) to build layers. After one layer has been fabricated, a recoating process is required in order to distribute a thin layer of liquid resin on the previously built layers before the next layer can be solidified. The recoating process is time-consuming. For example, for the projection-based SL process with short curing time, the recoating process can take 50–90% of the total building time. Hence the fabrication speed can be 2–10 times faster if the recoating time could be reduced or eliminated. This is the core idea of our ultra-fast MIP-SL process [3] and Carbon3D’s Continuous Liquid Interface Product (CLIP) approach [1].

In addition to the recoating time of each layer, another critical issue in the SL process is the large separation force if the layer size is large. In the bottom-up projection based approach, the traditional “pulling up” separation leads to a large suction force between the cured layer and the resin tank. To address the problem of the large separation force, Zhou et al. [4] used the sliding motion along the X axis for layer separation. Similarly, Pan et al. [5] used the sliding along the shearing force direction to significantly speed up the building process of the projection-based SL process. The approach has also been adopted in the laser-based SL process [6]. However, even with the sliding mechanism, the separation between the cured layers and the resin tank is still challenging if their contact area is large. Such difficulty can be significantly reduced if the contact area during the separation can be reduced to a smaller area such as a line segment.

In our previous work, Chen et al. [7] presented a non-layer-based 3D printing process called CNC accumulation (CNC-A). The CNC-A process uses an optical fiber as the material accumulation tool and immerses the tool in liquid photocurable resin. Essentially, the process uses a point-based material deposition approach to build a 3D object. Due to the small contact area in the point-based accumulation process, the aforementioned resin recoating and layer separation problems can be effectively addressed. Based on the CNC-A process, Pan et al. [8] further demonstrated the point-based accumulation tools can have various sizes and shapes. However, the CNC-A process is relatively slow due to the point-based accumulation tool. In comparison, a new CNC-A process is presented in the paper by extending the point-based accumulation to a...
line-based accumulation approach. The new AM process is named linear immersed sweeping accumulation (LISA). Its fabrication speed is 100 times faster than the point-based CNC-A process. At the same time, LISA can effectively address the resin refilling and layer separation problems due to the small contact area in the building process.

The paper is organized as follows. Section 2 discusses the hardware design of the LISA process. Section 3 discusses the tool path planning and encoding of the line-based AM process. Section 4 presents the theoretical material accumulation model and analyzes the separation force in the LISA process. Section 5 presents several test cases in order to demonstrate the capabilities of LISA in fabricating both layer-based and non-layer-based shapes. Finally, Section 6 concludes the paper with a discussion on future research.

2. Process hardware

An AM process by forming a 3D object line by line has been developed to solve the recoating and separation challenges in the projection-based SL process and to increase the fabrication speed of the point-based CNC-A process. The line-based material accumulation approach can achieve a good balance between fast building speed and easy layer separation. The accumulation tool used in the LISA process is a laser scanner that is moved by a multi-axis CNC stage (including both XYZ linear motions and ABC rotations). Compared to the multi-axis CNC machining process, the LISA process has a material accumulation tool rather than a material removing tool. This section discusses the overall hardware design of a LISA system and the detailed design of a line-based accumulation tool as well as the related laser scanning system.

2.1. Hardware setup overview

Fig. 1 shows the main hardware components of the LISA system including a multi-axis CNC stage and a laser optical system. The CNC stage is used to move the laser-based accumulation tool, and the laser optical system is used to dynamically scan line segments.

Various multi-axis motion configurations can be used to achieve the relative motion between the immersed accumulation tool and the building platform that is mounted on the resin tank. One of such configurations is shown in Fig. 1(a). A laser scanning system consisting of a laser and two gyro mirrors is used in the LISA system. Although only one axis scanning is required for the laser scanning in LISA, we used two gyro mirrors to enable the adjustment of the laser beam such that it can pass through the small opening of the tool tip. In addition to the CNC stage and related motion controller, a tank filled with photocurable resin is required such that the linear accumulation tool can be immersed inside liquid resin during the fabrication process.

2.2. Linear light source

In the LISA process the accumulation tool can provide a linear light source to its tool tip. Fig. 2 shows an accumulation tool design. A linear light source can be achieved by incorporating a laser scanning system that is widely used in the laser-based SLA systems (e.g. Form 1 from Formlabs and Viper from 3D Systems). Based on it, we can dynamically draw a line segment within 1 millisecond. The scanned laser line will pass through a small opening at the tool tip. The opening size can be ranged from 0.1 mm to 1 mm depending on the building resolution of the system. A high power laser diode is used as the energy source. A collimated lens and a convex lens are used to focus the laser beam into a small spot at the tool tip. A two-axis gyro-mirror system is installed to scan the input laser beam into line segments to selectively cure liquid resin that pass through the tool tip at any moment. The components that are used in our system are shown in Table 1.

The scanned laser beam is required to pass through a small opening at the bottom of the linear accumulation tool. Consequently, a laser beam adjustment approach is required to guarantee the scanned laser beam can pass through the small opening even with the machining and assembly errors during the hardware construction. Compared to the optical path (~60 mm length), such a

![Fig. 1. LISA hardware design. (a) The scheme of a LISA system; (b) photo of a prototype system.](image-url)
gap is relatively small. It is difficult to use mechanical adjustment approaches to achieve the purpose. In our study, we adopted an optical adjustment approach by using a two-axis gyro-mirror system. As shown in Fig. 2(a), we can easily fine-tune the position of the scanned laser line by changing the positions of the two ends of the laser line (i.e. End₁ and End₂). Using the control software of the gyro-mirror system, the position of the laser scan line can be accurately adjusted to align with the tool tip opening.

2.3. Immersed accumulation tool

A compact structure as shown in Fig. 3(a) is designed to encapsulate all the laser optics in order to move the laser scanning system in the fabrication process. The accumulation tool has opaque sidewalls to prevent the laser beam from exposing to liquid resin that is not immediately below the bottom opening. In addition, the tool tip needs to be sealed by some transparent film such that no resin will be able to get inside the tool when the accumulation tool is immersed in liquid resin.

The following two main functions need to be considered in the tool tip design: (1) providing a linear light source to the liquid resin, and (2) reducing the separation force between the tool tip and the photo-cured line segments. The first main function requires a transparent tool tip opening to enable laser beam to pass through the tool tip. One of such designs is shown in Fig. 3(a). The second main function requires the tool tip to have a small separation force between the newly cured line segments and the film coated on the tool tip. As shown by Chen et al. [7], the coating material on the tool tip plays a significant role on reducing the separation force. It is desired to use Teflon film or some other coating materials with similar properties to ensure the newly cured line segments will detach from the tool tip and attach to the previously cured layers. Hence, a 3D object can be continuously fabricated line by line.

Fig. 3(b) shows a tool tip design based on Teflon film. The tool tip design is critical in the LISA process. The following design parameters need to be considered.

- Proper opening gap size d: This opening gap is designed to pass the laser beam. It can also physically regulate the laser beam size, i.e. the gap can play the role of an aperture. In our experiment, we have tried the gap size from 0.5 mm to 7 mm, and found that the 0.5 mm can largely reduce the diffraction of laser and generate a better surface finish.
- Gap coating: The gap should be coated with Teflon or PDMS to reduce the attaching force between the cured line segments and the tool tip surface. In our experiments, Teflon has smaller attaching force and longer lifetime.
- Body angles θ₁, θ₂: Smaller body angles provide more working space for the tool tip to tilted and rotate, while larger angels makes the tool tip stronger. In our experiment, the angels are set within 30°–45° to get a strong and flexible tool tip.
3. Software system

The designed accumulation tool is a moving laser scanning system that can control the material accumulation of line segments along the tool tip opening. Accordingly, the process planning problem is how to plan linear tool paths for given computer-aided design (CAD) models, i.e. how the line segments are cured sequentially in the fabrication process. The tool path planning for the CNC machining has been extensively studied. For such a subtractive manufacturing process, researchers have developed a large number of tool path generation algorithms based on given geometry and cutter shapes, e.g. [9,10]. The performance of different tool path generation algorithms can be compared in terms of quality (small scallop height), efficiency (building time) and robustness [9]. However, these methods only consider the material removing process based on cutters. Much less research addresses the tool path generation for material accumulation processes. Most additive manufacturing research focuses on the layer-based fused deposition modeling (FDM) [11–13] and the powder-based AM processes [14] using the point-based material accumulation approach. For the line-based tool path planning, electrical discharge machining (EDM) has similar line-based machining process based on wire-cutting [15]; however, the EDM wire-cutting has more limitations than the line-like LISA process such as working space and machining interference.

Inspired by the CNC machining process [8], a general tool path planning approach for the line-based material accumulation process has been developed. The software system is to coordinate the CNC tool motion, gyro-mirror rotation, and laser ON/OFF status during the fabrication process. Given a 3D CAD model, the tool sweeping paths need to be generated such that they can be used to control the hardware system in order to build the 3D object. To use a general format to describe the linear sweeping paths, we extend the G-code to encode the required CNC motion, gyro-mirror scanning, and laser ON/OFF status. Accordingly, a G-Code-like format named A-code is developed. Based on it, a Computer-Aided Manufacturing (CAM) software system can be developed to automate the linear path generation and control.

3.1. Tool sweeping path

Compared to CNC machining, the layer-based additive manufacturing is straightforward on its tool path planning. This is because for a given layer, the XY plane of the slicing layer is determined along a given building direction. Hence the 3D tool path considered in CNC machining can be simplified into a two-dimensional (2D) problem. For example, for the projection-based SL process, mask images can be planned for simultaneously building layers [16,17]. For the point-based SL process or the nozzle-based FDM process [18], the point-based tool paths are planned to control the material accumulation in the XY plane. In the LISA process, the basic tool path element is a set of line segments. Accordingly, a tool path generation algorithm based on linear sweeping needs to be developed.

A basic algorithm to generate the tool paths for LISA is shown in Table 2. The key idea is to slice the model into a set of layers, and then convert the interior regions of each layer into a set of line segments. The generated line segments can then be used to control the ON/OFF status of the laser. The algorithm can be illustrated by an example as shown in Fig. 4. The layer is formed by a set of line segments, each one has two ends related to laser ON and OFF.

3.2. Accumulation code

To encode the linear sweeping tool path of the LISA process, the accumulation-based G Code (called A Code) is introduced by extending the G Code, which has been widely used in the CNC machining. Besides the common commands used in the G Code, several special commands added in the A Code include:

- L: Stands for laser motion. The numbers followed by “L” indicates the laser spot position.
- M03: Stands for laser on;
- M05: Stands for laser off.

The main idea of A Code is to record the moving laser in a fixed axis (defined as the Y axis) with a set of laser ON/OFF status. Table 3 shows an A Code example generated for a simple test case. From the point of view of A Code, LISA is essentially a combination of additive manufacturing and CNC motion control.

4. Process modeling and analysis

In order to improve the fabrication performance of the LISA process and to guide the process parameter settings, the material accumulation and part separation force models are discussed in this section. Such models can help us to better understand the limitations and improvements of the LISA process.
Table 3
An example of A-Code.

<table>
<thead>
<tr>
<th>Line</th>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>G21 G00</td>
<td>Mm units. Absolute mode</td>
</tr>
<tr>
<td>N2</td>
<td>G00 Z0.2</td>
<td>Move Z up with one layer thickness</td>
</tr>
<tr>
<td>N3</td>
<td>G00 X0</td>
<td>Rapid position: Move X to home</td>
</tr>
<tr>
<td>N4</td>
<td>G01 X0 F3</td>
<td>Turn off laser, and move laser to line start point</td>
</tr>
<tr>
<td>N5</td>
<td>M05 G01 L8.40519 F0.09</td>
<td></td>
</tr>
<tr>
<td>N6</td>
<td>M03 G01 L7.59481 F0.09</td>
<td>Turn on laser, and scan the first segment</td>
</tr>
<tr>
<td>N7</td>
<td>M05</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>N43</td>
<td>M05</td>
<td></td>
</tr>
<tr>
<td>N44</td>
<td>G01 X2 F3</td>
<td>Move X to next line position</td>
</tr>
<tr>
<td>N45</td>
<td>M05 G01 L13.2888 F0.09</td>
<td></td>
</tr>
<tr>
<td>N46</td>
<td>M03 G01 L8.92986 F0.09</td>
<td>Turn on laser, and scan the first segment</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>N403</td>
<td>M05</td>
<td>End of one layer</td>
</tr>
<tr>
<td>N404</td>
<td>G00 Z0.4</td>
<td>Move Z to next layer</td>
</tr>
<tr>
<td>N405</td>
<td>G00 X0</td>
<td>Begin to build this layer</td>
</tr>
<tr>
<td>N406</td>
<td>G01 X0 F3</td>
<td></td>
</tr>
<tr>
<td>N407</td>
<td>M05 G01 L8.40519 F0.09</td>
<td></td>
</tr>
<tr>
<td>N408</td>
<td>M03 G01 L7.59481 F0.09</td>
<td></td>
</tr>
<tr>
<td>N409</td>
<td>M05</td>
<td></td>
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<td>...</td>
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</tr>
</tbody>
</table>

4.1. Part accumulation model

In the LISA process, the fabricated object grows line by line. Accordingly, a line-based material accumulation model is needed to analyze the developed AM process. As shown in Fig. 5, suppose the fabricated object is accumulated line by line in the Y direction (i.e., the laser scan direction) at a speed of \( v_y \), and the lines pile up along the X direction (i.e., the tool moving direction) at a speed of \( v_x \). After one layer is finished, the tool tip will move up to a new layer with certain layer thickness \( \delta \). The line-scanning process will be repeated to accumulate another layer.

(1) Cure line growth model and fabrication speed

According to [19], the cure depth in the SLA process can be modeled as

\[
c_d(t) = D_p \ln \left( \frac{E}{E_c} \right), \tag{1}
\]

where \( D_p \) is the depth of penetration of resin, \( E \) is the input energy exposure, and \( E_c \) is the critical energy of the photocurable resin. Both \( D_p \) and \( E_c \) are material-related properties. By adjusting \( E \), the cure depth can be controlled. This equation is a general principle that can be applied to the photocurable resin solidification. The photocuring in the LISA process also follows the equation, and a key issue is to identify the equivalent exposure energy \( E \).

Assume the laser diode used in the LISA system can uniformly output energy during the fabrication process. When the tool tip moves at a constant speed and the gap between two neighboring lines is smaller than the laser beam width, the energy exposure for the whole layer is uniform. Assume the laser power is denoted as \( \phi \), which is in the unit of \( mJ/s \). With the assumption that the photo flux are uniformly deposited to the whole layer, the equivalent energy exposure is total energy \( \phi t \) divided by the area of whole layer \( (L \times v_x t) \), i.e.

\[
E = \frac{\phi t}{Lv_x t} = \frac{\phi}{Lv_x}, \tag{2}
\]

where \( t \) is the fabrication time for a layer, \( L \) is the length of linear light source, and \( v_x \) is the moving speed of linear light source. Thus, the cure depth of the LISA process is:

\[
c_d = D_p \ln \left( \frac{\phi}{E_cLv_x} \right). \tag{3}
\]

To guarantee the newly cured line segments can attach to the previous layers, the layer thickness should be smaller than the cure depth, which can be defined as:

\[
\delta = \eta_\delta c_d, \tag{4}
\]

where \( \eta_\delta \) is an effective coefficient considering the overlap between two layers \((0 < \eta_\delta < 1)\).

As shown in Fig. 5, the fabrication speed can be formulated as

\[
\text{speed} = v_x L \delta = v_x L \eta_\delta c_d = v_x L \eta_\delta D_p \ln \left( \frac{\phi}{E_cLv_x} \right) = \eta_\delta D_p L v_x \ln \left( \frac{\phi}{E_cLv_x} \right) \tag{5}
\]

(2) Discussion on the accumulation model

Eq. (5) provides a general formula to calculate the fabrication speed related to LISA’s parameter settings. The process parameters include linear light source \( (\phi, L) \), material property \( (E_c, D_p) \), light source moving speed \( v_x \), and part quality \( (\eta_\delta) \). Among the parameters, the light source moving speed can be dynamically adjusted and controlled. Hence, we can derive the optimal light source moving speed as

\[
\tilde{v}_x = \arg \max_{v_x} (\text{speed}) = \arg \max_{v_x} \left( \eta_\delta D_p L v_x \ln \left( \frac{\phi}{E_cLv_x} \right) \right) = e^{-1} \frac{\phi}{E_c} \tag{6}
\]

And the corresponding maximum fabrication speed is

\[
\text{speed}_{\text{max}} = e^{-1} \eta_\delta D_p \frac{\phi}{E_c}. \tag{7}
\]

Note this optimal speed is similar to the CLIP process [1]. But, our proposed method eliminates the problem of resin refilling for parts with large surface areas. Also, this result indicates that the maximum fabrication speed is linear with the input laser power. From this point of view, the LISA process is to restrict the input photon distribution from 2D mask image to one dimensional line. Similarly, compared with the laser-based SL process, the LISA process extends the spot distribution of the input photon into line distribution. In such a way, the LISA process can achieve a good balance between fast building speed and high flexibility of moving accumulation tools. It can also enable multiple-axis fabrication process, which is demonstrated in Section 5.2.
Methods to increase the fabrication speed

Based on Eq. (7), the following methods can be used to increase the fabrication speed:

- Increase the power rate $\phi$, which will increase the fabrication speed linearly;
- Increase the depth of penetration of resin $D_p$;
- Decrease the critical exposure dosage $E_c$;
- Increase the effective coefficient $\eta$.

However, increasing the fabrication speed may decrease geometry resolution and mechanical property, which is discussed as follows.

Fabrication speed vs. geometry resolution

In the LISA process, the resolution along each fabrication direction is related to the fabrication speed. As shown in Table 4, the laser scanning resolution is $v_s = \frac{dt}{\cos \theta}$, where $v_s$ is the scan speed, and $dt$ is responding time for laser to switch ON/OFF. When increasing power rate $\phi$ and decreasing the critical energy exposure $E_c$, the gap between two successive lines will enlarge. Similarly, larger penetration depth yields higher fabrication speed; however, it will also lead to larger layer thickness.

(3) Validation of the accumulation model

As shown in Eq. (3), cure depth is directly related to three factors: laser power, moving speed of light source, and length of light source. The laser used in our setup is a laser diode with 405 nm wavelength and 300 mW power. The photocurable resin in our experiment is SLS00 from EnvisionTec. To explore a large range of parameters setting, twelve different moving speeds, ranging from 0.35 mm/s to 16 mm/s, and four different lengths of linear light source, ranging from 2 mm to 32 mm, are tested. The averaged results are shown in Fig. 6(a).

The experimental results reveal that the parameter settings in the left-bottom in Fig. 6a (i.e. smaller length of light source and lower moving speed) have the largest cure depth. On the contrary, the right-top parameter setting (i.e. longer light source and faster moving speed) gives us the smallest cure depth. In addition, lower moving speed and smaller length of light source will generate larger cure depth.

After measuring the cure depth for each parameter setting, a regression model fitted in Matlab is shown in Fig. 6(b). It can be seen from the figure that the data fits the proposed cure depth model well. The fitted model also verifies our uniform energy exposure assumption. According to the line curing model and the test results, the cure depth in our setup can be rewritten as:

$$c_d = 117.9 \ln \left( \frac{\phi}{0.166 v_s L} \right).$$

The established cured depth model enables us to predict the curing performance and to adjust the process parameters. An advantage of this model is that it explicitly expresses the curing characteristics using the length and speed of linear light source, which is the basic building element of LISA. The model can also be generalized to the scenarios of using variable scanning and moving speeds.

4.2. Separation force analysis

The LISA process is designed to concurrently cure liquid resin, refill additional resin, and to separate the cured line segments from the tool tip. Consequently, the extra separation and recoating time can be eliminated. In addition, the separation force in the LISA process is greatly reduced when compared with the projection-based SL process. In the LISA process, two kinds of separation motions may exist in order to detach the cured part from the tool tip. One separation motion occurs when sliding the tool tip along the X axis in the layer-based building process; and another motion is pulling the tool tip up along the Z axis during the multi-axis material accumulation process. Fig. 7 shows the two separation forces as $F_x$ and $F_z$, respectively.

4.2.1. Layer sliding separation force analysis

During the fabrication of a layer, the tool tip moves from one side to another side along the X axis (refer to Fig. 7). After one scan line is cured on the PDMS coating, an inhibition zone (~2.5 μm) between the tool tip and the newly cured part exists. Hence when the tool tip is sliding, the liquid resin in the gap will follow the movement. Thus, the sliding separation force $F_x$ can be modeled as the friction between the resin and the sliding tool tip as:

$$F_x = \mu \frac{v_s}{h} A$$

where $\mu$ is the dynamic viscosity of resin, $v_s$ is the slicing speed of the tool tip, $h$ is the inhibition zone between the tool tip and the
The newly cured part, and \( A \) is the contact area. Eq. (9) shows that the slicing force is proportional to contact area \( A \). Because at any building moment, only the newly cured line is contacting the tool tip, the contact area in the LISA process is the line opening width \( d \) the line opening length \( e.g. 0.4\text{mm} \times 50\text{mm} \). This area is less than 1% the contact area of a mask projection image \( e.g. 50\text{mm} \times 50\text{mm} \) in other SL processes. Therefore, the sliding separation force in the LISA process is largely reduced.

### 4.2.2. Pulling up separation force analysis

When the tool tip moves up in the \( Z \) axis for non-layer-based motions, it generates a pulling up separation force \( F_z \). As shown in Fig. 7, the force is a suction force that drives the resin to flow into the gap between the tool tip and the cured part. The Hele-Shaw flow can be used to model this pulling up separation. As the flow is symmetric, we can only consider the right side flow. The pressure driven flow can be quantified as

\[
Q = \frac{h^3}{12 \mu} \frac{dp}{dx} L. \tag{10}
\]

The flow generated by pulling up is

\[
Q' = L \times x \times v_z. \tag{11}
\]

Assuming the resin is incompressible fluid, we have \( Q \approx Q' \), and obtain

\[
dp = \frac{12\mu v_z}{h^3} x dx. \tag{12}
\]

Integrating the pressure over the pressure field leads to:

\[
p_0 - p(x) = \int_0^{d/2} \frac{12\mu v_z}{h^3} x dx = \frac{6\mu v_z}{h^3} \left( \frac{d}{2}^2 - x^2 \right). \tag{13}
\]

The total separation force is the integral of the pressure on the newly cured line

\[
F_z = 2 \int_0^{d/2} (p_0 - p(x)) L dx = \frac{\mu v_z a^3 L}{h^3}, \tag{14}
\]

where, \( p_0 \) is the atmosphere pressure, \( h \) is the gap between cured part and tool tip, \( v_z \) is the moving up speed, \( d \) and \( L \) are the width and length of the newly cured line respectively, \( \mu \) is the resin viscosity. In LISA, the line width is around 0.4 mm. Eq. (14) shows that the separation force is a three-order relationship with the curing line width \( d \), which means our pulling up force is only \((0.4/4)^3 = 0.1\%\) of the separation force that exists in the conventional layer-based SL process with large separation area.

In summary, both the layer sliding and pulling up separation forces in the LISA process are largely reduced. Hence the tool tip could be moved smoothly and quickly since the built line segments are continuously released from the tool tip during the fabrication process.

### 5. Experimental results

CAD models with various geometries have been designed and built to test the capability of the LISA process.

#### 5.1. Tests of various 3D geometries using the layer-based approach

Various geometries including some basic shapes and complex freeform shapes have been built.

**1) Test cases with basic shapes**

Fig. 8 shows two simple parts that are built by the LISA process. The purpose of the test cases is to verify the aforementioned process pipeline, i.e. starting from a CAD model, to the toolpath generation, to CNC motion, and eventually to the line accumulation process. The parameters for the building process is \( v_z = 2 \text{mm/s}, L = 16 \text{mm}, \phi = 300\text{mW} \). Fig. 8(a–c) is a single-layer part; Fig. 8(d–f) is a multi-layer part whose layer thickness is set as 0.1 mm.

The successful fabrication of the two CAD models demonstrates that the LISA process can accumulate materials using the linear accumulation tool immersed inside liquid resin. Notice that the top surface of the parts is quite smooth, while their side surfaces are rough. We believe the rough side surfaces are mainly due to the vibration of the laser optic system during its movement. We constructed the prototype LISA system based on a low-cost FDM printer. We plan to improve rigidity of the linear motion system in our future work.

Fig. 8. Test cases with basic shapes. (a)–(c) A test case with a single layer; (d)–(f) a test case with multiple layers. Notice that the red lines to show the tool paths are down-sampled for illustration.
(2) **3D complex test case**

To demonstrate the feasibility of using LISA to fabricate freeform shapes, a turbine with curved blades is printed as shown in Fig. 9. The red lines in Fig. 9(b) are the tool path for the linear light source. In each layer, the linear light source sweeps from left (i.e., the X-axis) to right (the X+ axis) at the speed \( v_x = 1.42 \text{ mm/s} \); the scanned lines accumulate materials to form the turbine blade. As shown in Fig. 9(c), the side surface quality of the built turbine blade is relatively poor. We believe it is mainly due to the poor linear motion resolution and the overcure between layers. We will investigate how to improve the side surface quality in our future research.

5.2. **Building ruled surface using the non-layer-based approach**

A surface \( S \) is ruled (also called a scroll) if through every point of \( S \) there is a straight line that lies on \( S \), which can be represented as \( S(u, v) = p(u) + v \cdot r(u) \). This parametric representation of ruled surface is very suitable for the LISA process, which is a line-based additive manufacturing process. Fig. 10 maps LISA’s tool path and the representation of ruled surface. Hence, the tool path for building a ruled surface is mainly to move the tool tip along its representation. This requires a 5-axis CNC stage is used in the LISA system to move the accumulation tool such that a general ruled surface can be fabricated. Two test cases with ruled surfaces have been built to demonstrate the capability of the LISA process on building-around-inserts.

(1) **Smoothen layer-based surfaces with stair-stepping defect**

The layer-based AM processes suffer from the stair-stepping defect when the part has a sloped surface. Such defect will significantly reduce the smoothness of the sloped surface. The ruled surface can be smoothened by the LISA process since its tool tip can be tilted such that the linear light source can sweep along the sloped surface. Fig. 11 shows a test case of a previously built object with a sloped ruled surface. The 3D object was fabricated using the projection-based SL process. To smoothen the sloped surface, the tool tip is moved to be parallel to the slope surface and is then slid on it to fabricate a conformal layer on the surface. Comparing the surface with and without the modification, the ruled surfaces of an inserted object can be smoothened by the LISA process.

(2) **Build texture on ruled surface**

Due to the multi-axis capability of the LISA process, we can fabricate various textures on a ruled surface of a given object. Fig. 12 shows a test case of adding texts “USC fight on” on a cone, which is a typical ruled surface. Such fabrication is infeasible for the layer-based AM processes. The planned tool path is shown in Fig. 12(a). Such tool path requires the use of a 5-axis motion system. To achieve the designed tool path, a rotation stage is used to move the tool tip, and another rotation stage is used to rotate the cone that is fixed on the tank (refer to Fig. 12b). The building result is shown in Fig. 12(d). The added textures can be fabricated using the same or different materials.

6. **Discussion**

The test results have demonstrated the LISA’s capability on fabricating various 3D shapes. They also verify the LISA process can be extendable to multi-axis fabrication for performances that cannot be achieved by the traditional layer-based SL processes. In addition,
the line-based material deposition approach can have unique benefits on speed and separation when compared to the surface-based and point-based material deposition approaches. In summary, the LISA process has the following advantages:

- **Fast building speed:** The curing speed of LISA using a line-based light source is between the surface-based and point-based light sources; however, the recoating time of LISA is dramatically reduced and can be eliminated (similar to CLIP). Note that the resin curing in the LISA process is accomplished at the same time as the recoating process. Hence the LISA process can have fast building speed (around 10 second per layer in our setup). Table 5 shows the superior speed performance of LISA. The total time per layer $T_{layer}$ in traditional laser-based SL process consists of curing time $T_{cure}$ and material recoating time $T_{recoat}$. On the contrary, the total time per layer for LISA is only the curing time $T_{cure}$. Therefore, our proposed LISA could achieve $T_{cure}/T_{recoat}$ times faster than the conventional laser-based SL process.

- **Multiple directions:** The LISA process uses the line-based accumulation tool that is immersed in liquid resin. By tilting and rotating the linear light source, LISA could achieve multi-directional fabrication. This multi-axis motion provides LISA with three potentials: (1) building-around-inserts: LISA can be used to modify objects that have been fabricated by other manufacturing processes such as injection molding; hence additional features can be added to any 3D ruled surfaces of the objects; (2) the capability of building ruled surface using non-layered-based approach, and we have developed the ruled surface representation in order to move LISA’s tool tip; (3) the possibility of enhancing surface finish or mechanical strength of some geometric shapes. For example, in Section 5.2, we have shown that the text “USC Fight On” can be added to the existing object. And a slop surface with stair-cases can be smoothed by taking the advantage of LISA’s smooth top surface. The mechanical strength of some geometric shapes such as shells can also benefit from the continuous movement of LISA, by reducing the stair-cased defects in the layer-based additive manufacturing process.

- **Large building area:** Currently, due to the focusing issue in a large field, the traditional SL process (e.g. Form 1 from Formlabs and Viper from 3D Systems) has limited building area (e.g. $125 \text{mm} \times 125 \text{mm}$). By incorporating a CNC stage, the linear accumulation tool can reach a very large building volume especially in the X axis. Generally, the building area of LISA is solely dependent on the working space of the CNC stage. Our current setup can easily achieve a $200 \text{mm} \times 240 \text{mm}$ building area.

## 7. Conclusion and future work

This paper presents a novel additive manufacturing process called Linear Immersed Sweeping Accumulation (LISA). Unlike the surface-based or point-based SL processes, LISA is line-based Stereolithography process, whose basic fabrication element is line segment. By immersing the linear light source in liquid resin, LISA can continuously fabricate layers of 3D models without additional recoating time. This novel AM process has advantages both in building time and flexibility. By eliminating the recoating and separation time, the building time of LISA can be reduced to $20–50\%$ of the traditional laser-based SL process. The concurrent recoating is enabled by immersing the linear light source in the resin, and the concurrent separation is guaranteed by the significantly reduced separation force that is less than $1\%$ of the separation force observed in the traditional SL process. Another advantage of LISA is its building flexibility, since its linear light source is attached to a multi-axis CNC stage. Compared with the layer-based additive manufacturing processes, LISA can achieve multi-directional fabrication by tilting and rotating the linear light source. Such multi-directional fabrication provides LISA with the capability of adding features on inserted objects and reaching a large building volume. The feasibility and capability of the LISA process have been verified by various test cases.

The LISA process is still in its initial development stage. Some of the future research include: (1) improving hardware construction. We plan to construct more rigid linear motion system and to reduce the laser spot size of the linear light source; and (2) developing sweeping path generation algorithm to address more complex shapes including general multi-directional ruled surfaces.
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References