Fast Speed, Multi-Scale Additive Manufacturing Process based on Dynamic Resolution Control Approach

BY

CHINTAN RAJESH DAGLI
B.E. Mechanical Engineering
University of Mumbai, 2013

THESIS

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Defense Committee:

Dr. Yayue Pan, Chair and Advisor
Dr. Houshang Darabi
Dr. Mengqi Hu
This thesis is dedicated to my family
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>NUMBER</th>
<th>CHAPTER</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td><strong>INTRODUCTION.</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1</td>
<td>Motivation and Aim.</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Conventional Mask Image Projection System.</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>Novelty and Contribution.</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td><strong>DYNAMIC RESOLUTION CONTROL MIP-SL SYSTEM.</strong></td>
<td>9</td>
</tr>
<tr>
<td>2.1</td>
<td>Overview of the system.</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Hardware Setup.</td>
<td>13</td>
</tr>
<tr>
<td>2.3</td>
<td>Software Setup.</td>
<td>14</td>
</tr>
<tr>
<td>2.4</td>
<td>Material.</td>
<td>15</td>
</tr>
<tr>
<td>3.</td>
<td><strong>PROCESS PLANNING.</strong></td>
<td>16</td>
</tr>
<tr>
<td>3.1</td>
<td>Mask Image Planning.</td>
<td>16</td>
</tr>
<tr>
<td>3.2</td>
<td>Parametric Dependence Quantification.</td>
<td>20</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Dependence of Build Area and Planar Resolution on Focal Length.</td>
<td>21</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Dependence of Vertical Resolution on Focal Length.</td>
<td>22</td>
</tr>
<tr>
<td>4.</td>
<td><strong>EXPERIMENTAL RESULTS AND DISCUSSION.</strong></td>
<td>26</td>
</tr>
<tr>
<td>4.1</td>
<td>Large Area Fabrication with Resolution R81.</td>
<td>26</td>
</tr>
<tr>
<td>4.2</td>
<td>Small Area Fabrication with Resolution R30.</td>
<td>28</td>
</tr>
<tr>
<td>4.3</td>
<td>Multi-Scale Fabrication with Resolution R41, R61 and R81.</td>
<td>30</td>
</tr>
<tr>
<td>4.4</td>
<td>Continuous Resolution Control Fabrication with R41-R61.</td>
<td>34</td>
</tr>
<tr>
<td>4.5</td>
<td>Building Performance Statistics.</td>
<td>36</td>
</tr>
<tr>
<td>4.6</td>
<td>Build Speed Analysis.</td>
<td>37</td>
</tr>
<tr>
<td>4.7</td>
<td>Part Quality Analysis.</td>
<td>38</td>
</tr>
<tr>
<td>5.</td>
<td><strong>TEXTBOOK-SIZE 3D PRINTING SETUP.</strong></td>
<td>41</td>
</tr>
<tr>
<td>5.1</td>
<td>Portable and Compact Hardware Setup.</td>
<td>41</td>
</tr>
<tr>
<td>5.2</td>
<td>Software Setup and Controls.</td>
<td>43</td>
</tr>
<tr>
<td>6.</td>
<td><strong>CONCLUSION.</strong></td>
<td>45</td>
</tr>
<tr>
<td>7.</td>
<td><strong>REFERENCES.</strong></td>
<td>47</td>
</tr>
<tr>
<td></td>
<td><strong>APPENDIX.</strong></td>
<td>53</td>
</tr>
<tr>
<td></td>
<td><strong>VITA.</strong></td>
<td>54</td>
</tr>
</tbody>
</table>
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Statistics of all test cases.</td>
<td>36</td>
</tr>
<tr>
<td>2. Geometrical accuracy of multi scale gear test case.</td>
<td>39</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Schematic illustration of conventional MIP-SL system.</td>
<td>4</td>
</tr>
<tr>
<td>2. Trade-off between pixel size and build area in conventional SL related AM: (a) Without optical lens; (b) With optical lens.</td>
<td>5</td>
</tr>
<tr>
<td>3. A comparison of conventional stitching approaches and the proposed approach: (a) Illustration of approaches based on a light source that is movable along X and Y axes; (b) Curing and stitching of pieces with a single resolution; (c) Illustration of proposed approach based on a laser projector which is movable along X, Y and Z axes; (d) Curing and stitching of pieces with multiple resolutions.</td>
<td>7</td>
</tr>
<tr>
<td>4. Laser Projector unique properties: (a) Stays focus when changing focal length; (b) Project on any shape surface.</td>
<td>9</td>
</tr>
<tr>
<td>5. A Laser Projection based SL system with dynamic resolution control.</td>
<td>11</td>
</tr>
<tr>
<td>6. Flowchart of the working of Laser Projection based SL system.</td>
<td>12</td>
</tr>
<tr>
<td>7. The prototype hardware system for the laser projection SL process with dynamic resolution control.</td>
<td>14</td>
</tr>
<tr>
<td>8. GUI of the control software.</td>
<td>15</td>
</tr>
<tr>
<td>9. Example Model: (a) STL model; (b) Transfer rays along rows and columns of a binary sliced layered image; (c) Sectional view highlighting object and boundary detection; (d) Macro image; (e) Micro image.</td>
<td>18</td>
</tr>
<tr>
<td>10. Graphical relationship between focal length, build area and planar resolution.</td>
<td>22</td>
</tr>
<tr>
<td>11. Graphical relationship between exposure energy and cure depth.</td>
<td>23</td>
</tr>
<tr>
<td>12. Graphical relationship between focal length and cure depth.</td>
<td>25</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES (Continued)

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>13. Spur gear test case: (a) Isometric view of STL model; (b) Isometric view of built part; (c) Top view.</td>
<td>27</td>
</tr>
<tr>
<td>14. Hollow ball test case: (a) Isometric view of STL model; (b) Microscopic image of the front view; (c) Microscopic image of the top view.</td>
<td>29</td>
</tr>
<tr>
<td>15. Multi-scale gear test case: (a) Isometric view of STL model; (b) Isometric view of built part; (c) Top view; (d) Microscopic image of top gear.</td>
<td>32</td>
</tr>
<tr>
<td>16. Frame test case: (a) STL model; (b) Front view of built part; (c) Microscopic image of the tooth.</td>
<td>33</td>
</tr>
<tr>
<td>17. Titled edges triangular surface: (a) Isometric view of STL model; (b) Isometric view of built part; (c) Microscopic image of the fabricated layers.</td>
<td>35</td>
</tr>
<tr>
<td>18. Schematic of stitching approach.</td>
<td>37</td>
</tr>
<tr>
<td>19. Surface roughness vs length, part with resolution R81.</td>
<td>40</td>
</tr>
<tr>
<td>20. Surface roughness vs length, part with resolution R41.</td>
<td>40</td>
</tr>
<tr>
<td>21. CAD model of portable and compact setup: (a) Isometric view; (b) Front view.</td>
<td>41</td>
</tr>
<tr>
<td>22. Portable MIP-SL setup based on laser projector and IPhone: (a) Setup with annotation; (b) Highlighting compact size.</td>
<td>43</td>
</tr>
</tbody>
</table>
SUMMARY

Additive Manufacturing (AM) is a class of technologies that possess formation of 3D parts in a layer-by-layer fashion. Mask Image Projection Stereolithography (MIP-SL) is a sub-branch of AM in which parts are fabricated by curing photopolymer liquid resin using sliced digital mask images. Compared to other polymer Additive Manufacturing technologies, MIP-SL process has many advantages. For example, the fabricated surface is usually very smooth compared to extrusion-based process. Besides, by focusing the light beam to a small image, it is able to achieve a high resolution. In the conventional system, a bulb is usually used as the light source, and a Digital Micromirror device and optical lenses are used to pattern the light and focus it on the build surface. Therefore, in these systems, once the machine is set up, the focus length is fixed. As a result, the build size together with resolution are determined and cannot be changed any more. In MIP-SL the smaller the pixel size, higher is the resolution. In order to fabricate part with detailed features, the build area must be reduced. Thus, in a conventional MIP-SL system, due to this unadaptable characteristic, there is an ultimate conflict between the build area and resolution. Current approaches to address this conflict are based on stitching methods, in which a large layer is formed by curing and stitching multiple small areas in a sequential order by moving the projection unit or platform. However, such stitching approaches elongate the overall build time of the part and may affect the mechanical properties of the fabricated parts.
SUMMARY (Continued)

To address the challenge without sacrificing the build speed, a novel AM system with dynamic resolution control capability is designed and developed in this project. A laser projection system that has unique properties including focus free operation and capability to produce dynamic mask image irrespective of any surface (flat or curved) is used as the light projection source in this study. By translating the projector along the building direction, the pixel size can be adjusted dynamically within a certain range. Consequently, the build area and resolution could be tuned dynamically in the testbed. Besides, a Layered-Depth-Image algorithm is proposed to construct mask images with varied resolutions. The curing characteristics under various resolution settings are quantified. Accordingly, a process planning approach for fabricating models with dynamically controlled resolutions is developed. To test the efficiency of the proposed dynamic resolution control based MIP-SL process, a testbed is developed and models with various surface areas, feature sizes, and structures are built with single resolution, multiple resolutions and continuous changing resolutions. Moreover, to fully utilize the benefits of the compact laser projector, a portable, compact size, and low-cost 3D printer with an added feature of using a smart phone has been designed and constructed. The dimension of the prototype machine is 7.8 x 7.0 inch, smaller than the paper size. An IPhone is used as the source to transfer the sliced images to the laser projector.

To conclude, this research contributes to the advancement of AM by addressing the historical dilemma of the resolution and build size, without sacrificing the build speed and part quality. Furthermore, a paper-sized Mask Projection Stereolithography has been developed with a laser projector and a smart phone.
List of Abbreviations

AM = Additive Manufacturing
SFF = Solid Freeform Fabrication
3D = Three-Dimensional
SL = Stereolithography
MEMS = Micro-Electro-Mechanical Systems
DMD = Digital Micromirror Device
MIP-SL = Mask Image Projection Stereolithography
VPS = Virtual Pixel Synthesis
PDMS = Polydimethylsiloxane
LDI = Layered Depth Image
LDNI = Layered Depth-Normal Images
\( C_d \) = Cure Depth
\( D_p \) = Penetration Depth
\( E_c \) = Critical Exposure
\( R_a \) = Average Roughness
FDM = Fused Deposition Modeling
ABS = Acrylonitrile-Butadiene-Styrene
1. INTRODUCTION


1.1 Motivation and Aim:

Additive Manufacturing (AM), often referred to as Solid Freeform Fabrication (SFF) or 3D Printing or Rapid Prototyping, has evolved tremendously over the years. It is a class of technologies that fabricates three-dimensional (3D) parts directly from computer models by accumulating material together, usually in a layer-by-layer way. The advent of Additive Manufacturing has eradicated fabrication restrictions and manufacturing complex parts as the conventional machines are not able to fabricate parts with such design complexities. This technology finds its applications as a rapid prototyping technology in a wide variety of fields such as industrial design, automotive, aerospace, military, engineering, medical, fashion, jewelry and education [1-3].

Intensive research attempts have been made to improve the performance of AM systems in the past decades, in terms of build speed [4-6], surface quality [7-10], material property[11-14], process reliability [12, 15-17], development of multi-material parts [18] etc. However, many limitations still exist in AM and hinder its application in fabricating end-use products, including size and resolution limitations, limited choices of materials, low through-put, etc. [19]. In this research, we focus on working to overcome one of its primary drawbacks: build size and resolution limitations in a stereolithography (SL) related AM system. Stereolithography (SL) is a sub-class of Additive Manufacturing that fabricates 3D part by selectively curing photopolymer liquid resin using light energy, usually in a layer-by-layer way.
As of today, SL has entered the mainstream of 3D printing industry with a variety of commercial 3D printers offering a wide range of resolutions from 20 ~ 200 µm and build envelope diagonal size of 30 ~ 500 mm. SL can be broadly classified into two categories: laser scanning based and projection based technologies. In the early stage, laser beam was used in SL system to cure liquid resin path by path to form one layer. With the advancement in Micro-Electro-Mechanical Systems (MEMS), projection based SL process became more popular due to their dynamic mask generation capability. In a projection based SL system, a digital micromirror device (DMD) is usually used to pattern the light. A DMD is a micro-electro-mechanical system (MEMS) device that enables one to simultaneously control ~1 million small mirrors to turn on or off a pixel each at over 5 KHz [20]. Using this technology, a light projection device can project a dynamically defined mask image onto a resin surface to selectively cure liquid resin into layers of the object. Consequently, the related AM process, Mask Image Projection Stereolithography (MIP-SL), can be much faster than the laser scanning based SL process by simultaneously forming the shape of a whole layer. The MIP-SL process can achieve a much higher resolution by having a big number of micro-mirrors and focusing each pixel in a small area. Many research groups demonstrated micro-manufacturing capability with micron or even sub-micron scale resolution in MIP-SL systems [8, 10, 21-23].

Despite the advancement of SL related AM technologies, conflict between the build size and resolution is a historically inherent manufacturing dilemma. In order to achieve higher resolution, a smaller laser beam spot is required for beam scanning based SL process whereas for MIP-SL process a smaller pixel size is desired, in turn, a smaller build area will be created. Due to the conflicting goals between build size and resolution, fabrication of a part with large surface and small features is difficult.
Many attempts have been made to solve this dilemma. Emami et al. proposed a stitching approach, where multiple images were projected using a bulb and DMD in different positions sequentially and stitched to fabricate a big layer [24]. Lee et al. [25] proposed a similar approach by using laser beam and DMD. In addition, some researchers proposed a combination of laser scanning and projection to realize large area building with micro resolution [16, 26-28]. However, all these approaches will lengthen the build time greatly and make the process much more complicated. Challenges including alignment and bonding strength have been identified. In all those approaches, the pixel size of digital masks or laser dot size cannot be altered and hence the printing resolution is fixed. As a result, the build time is still lengthened and there is no flexibility to optimize the combination of resolution, build size and build speed.

Against this background, the thrust of this research is to minimize number of stitches or even avoid stitches to fabricate parts with multi-scale resolution without sacrificing build speed and part quality. To achieve this goal, a dynamic resolution control approach by using a laser projection technology is investigated in this paper. Unlike current technologies that use fixed-sized pixels, the pixel size in this research could change dynamically and continuously throughout a layer and across layers. Due to this fundamental difference, this new approach is capable of fabricating complex parts with desired fine features in shortest time and with fewest stitches.

1.2 Conventional Mask Image Projection System:

In a conventional MIP-SL system, a 3D CAD design is generated in the format of a STL file. This STL file is sliced layer-by-layer using a 3D printing software, which further generates mask images. The sliced image is then transferred to a projection unit, which usually uses a bulb as a light source and a DMD chip to pattern the light, as represented in Figure 1. Optical lens is used to focus the patterned light onto a liquid resin surface. The liquid resin is cured after its
received light energy surpassed a certain amount. The platform moves up and down to refresh a new layer of liquid resin for next layer curing. The process continues to cure layers one after the other, thereby forming a 3D model. Then the formed 3D object usually undergoes post processing to remove the uncured resin and supports. Compared to other polymer additive manufacturing techniques, the MIP-SL system in general is capable of producing parts with high precision, high surface finish and high resolution.

Figure 1: Schematic illustration of conventional MIP-SL system

1.3. Novelty and Contribution:

In a conventional MIP-SL system as discussed in Section 1.2, the focal length is fixed and thereby the build size and pixel size are fixed. Thus, the system does not have any flexibility to cure a layer with different build size and resolution. For example, as shown in Figure 2, suppose the build size is 300 mm in x direction and there are 1000 pixels along x direction, the smallest feature that can be built would be constrained by the pixel size, which is 300 µm. In order to
fabricate features smaller than 300 µm, e.g., 30 µm, the optics in the system needs to be modified to focus the light into a smaller image. The build area will be greatly reduced as a result.

![Diagram showing the trade-off between pixel size and build area in conventional SL related AM.](a) Without optical lens; (b) With optical lens

Figure 2: Trade-off between pixel size and build area in conventional SL related AM: (a) Without optical lens; (b) With optical lens

Current approaches to building large area with small features are based on projecting multiple images and stitching these areas together, as illustrated in Figure 3(a) and 3(b). To build a large layer, the projection unit moves along X and Y directions to project images and cure resins in Pos 1~9 sequentially, as shown in Figure 3(b). In these approaches, the number of stitched images to form a certain layer is determined by the resolution. With a higher resolution, more stitches, longer build time and probably lower mechanical strength will be resulted.
To address this problem, a dynamic and continuous resolution control approach for MIP-SL systems is developed in this research. In contrast to conventional MIP-SL system design, a laser projector is used as a light source and it could move along the build direction in the proposed approach, as shown in Figure 3(c). The projection unit moves along Z-axis and the resulted projection image is always in focus. Accordingly, the resolution could be tuned dynamically in a certain range by moving the projector along Z-axis. As a result, the number of stitches could be optimized and therefore the build time could be much shorter than any current approaches. As shown in Figure 3(d), suppose that there is no small feature in Pos 1, Pos 2 contains small features and Pos 3 contains even smaller features, three images with low, median, and high resolutions could be planned to cure Pos 1, Pos 2 and Pos 3 sequentially to form the entire layer. Comparing to the conventional approach in Figure 3(b), which needs nine stitches, the build time of the new approach would be much shorter and the part quality would probably be better due to less aligning and stitching operations.

(a) Existing approach: hardware setup  
(b) Existing approach: single resolution image stitching
Figure 3: A comparison of conventional stitching approaches and the proposed approach: (a) Illustration of approaches based on a light source that is movable along X and Y axes; (b) Curing and stitching of pieces with a single resolution; (c) Illustration of proposed approach based on a laser projector which is movable along X, Y and Z axes; (d) Curing and stitching of pieces with multiple resolutions

With the proposed approach, the pixel size can be adjusted dynamically during a single building task, reducing the overall build time and making the process faster. The system offers a wide range of resolution for the given focal length. Consequently, the flexibility attained with the proposed approach is more as compared to the conventional approach.

This novel dynamic resolution control approach is presented in the following sections. Section 2.1 presents an overview of a novel Laser-Projection based Stereolithography (SL) System with the resolution control approach along with its flowchart explaining the working of the system. The hardware setup and the software used to control the motion is presented in Section 2.2 and 2.3 respectively, along with the material used in the experiment in Section 2.4. A mask image planning for dynamic resolution control is presented in Section 3.1, followed with a parametric dependence quantification process investigated in Section 3.2. Multiple test cases are demonstrated and
analyzed in Chapter 4. It is shown that parts with varying layer sizes and feature sizes could be fabricated with desired resolutions by using this approach. In addition, in Chapter 5, an attempt has been made to develop a portable, compact and low-cost 3D printing setup that uses an IPhone to transfer mask image to the laser projector instead of using a computer. Finally, conclusions are made in Chapter 6.
2. DYNAMIC RESOLUTION CONTROL MIP-SL SYSTEM


2.1 Overview of the System:

Instead of a bulb, a pocket-size laser projector ‘Showwx VGA Dock Pico Laser Projector’ by Microvision Inc is used as a projection light source in this setup. The laser projector has unique properties including focus free operation, capability to produce dynamic mask image irrespective of any surface (flat or curved) as shown in Figure 4. Last but not the least is its compact size that makes it easy to be adopted and integrated into the additive manufacturing system. These unique characteristics of laser projector eventually provide a distinct capability to change the projection image size and resolution easily.

![Laser Projector unique properties](image)

(a) (b)

Figure 4: Laser Projector unique properties: (a) Stays focus when changing focal length; (b) Project on any shape surface

The laser projector is a class 2 laser product and has a native resolution of 848 × 480 (WVGA), it also supports other resolutions like 800 × 400 (WVGA2) and 640 × 480 (VGA) [29].
It is composed of one red, one green, and one blue laser and a MEMS scanner. The light from the three lasers is combined with dichroic element into a single white beam [30]. This white beam is then relayed onto a biaxial MEMS scanning mirror that scans the beam in a pattern. A projected image is created by modulating these three lasers synchronously with the position of scanned beam [30]. The projected beam directly leaves the MEMS scanner and creates a sharp image irrespective of any surface (flat or curved) it is shone upon [30]. The essence of the design is that all the three lasers are driven simultaneously to create the proper color mix for each pixel, thereby producing brilliant images. The lasers are only ON at a level needed for each pixel and are completely OFF for black pixel, thereby maximizing efficiency. To avoid optical distortions and enable brightness uniformity, a Virtual Pixel Synthesis (VPS) engine is adopted in the laser projector design. The VPS uses a high-resolution interpolation to map the input pixels onto a high-resolution virtual coordinate grid. Through an adaptive laser drive system that uses closed-loop control, the spot size grows at a rate matched to the growth of a single pixel [30, 31].

A schematic diagram of the Laser Projection based SL system design is shown in Figure 5 below. A bottom-up projection based SL process is adopted in the following sets of experiments to constrict the size of the platform and resin vat. The light source, i.e., the laser projector is positioned at the bottom of resin vat that transmits mask image on platform. After the resin is cured, the projector moves up by one layer. The cured layer is sandwiched between the platform and Polydimethylsiloxane (PDMS) layer.
The PDMS is a transparent silicone rubber compound, applied on the resin vat since the cured layer may adhere strongly to the corresponding resin vat. The PDMS acts as a cushioning layer between the platform and the resin vat that helps to avoid breaking of the cured parts when the platform moves up. The PDMS has a property to form thin oxygen inhibition layer during polymerization process that results in preventing the cured layer to be attached to the PDMS film [32]. Even with the intermediate material, the separation force can still be relatively large and different geometries have different separation force [33, 5]. In addition, this separation force has been further examined in a Finite Element Model developed using ABAQUS software by Liravi et al. [34].

The flowchart in Figure 6 explains the working of the entire system. Similar to the conventional approach, we start from a CAD model. However, instead of slicing the STL file with a certain predefined resolution setting, we first analyze feature sizes of the CAD model, and then
set a resolution for each layer. After that, mask images will be generated by slicing each layer with the desired resolution setting. These mask images are transferred to the laser projector for layer-by-layer fabrication. The laser projector then moves to a corresponding position to cure that layer with the desired resolution and simultaneously the pixel size changes dynamically according to the position of laser projector. Thus, when the projector moves closer to the platform the focal length changes and the pixel size reduces which means higher resolution. The reverse scenario occurs when the projector moves away from the platform which results in lower resolution but bigger build area. Because of this focus free property of laser projector, the layer that has a large surface area, focal length is large, whereas for the part that has minute detailing focal length is reduced. Therefore, in this dynamic resolution control manufacturing process the mask image planning and projection location are the most important steps.

Figure 6: Flowchart of the working of Laser Projection based SL system
Correspondingly, two fundamental research questions need to be answered:

Q1. How to determine a proper set of resolutions for each layer to achieve best part quality and fastest build speed.

Q2. How to move projector to a proper position to gain the required resolution.

Question 1 will be answered in Section 3.1 by exploring a mask image planning algorithm to filter features with different resolution requirements. Question 2 will be investigated in Section 3.2 by quantifying the parametric dependence of resolution and build size on manufacturing process parameters.

2.2 Hardware Setup:

A prototype system has been built to verify the developed process. A hardware setup of the laser projection based SL system is shown in Figure 7. In the designed system, an off-the-shelf laser projector (SHOWWX+) from MicroVision was used. It has a native resolution of 848 x 480 while it supports other resolutions like 800 x 400 and 640 x 480 [29]. Due to its compact size and light weight, it can move along Z-axis rapidly. Also, its unique focus free property allows changing resolution dynamically and continuously. Various projection settings, including aspect ratio, key stone rectification, brightness, and contrast were adjusted to achieve a sharp projection image on the designed projection plane and within the focal length designed in this project. Two precise linear stages from Velmex (Bloomfield, NY) are used as an elevator for driving the platform in the Z-axis. As this is a prototype testbed to show the dynamic resolution control approach, X and Y stages for moving the platform around are not incorporated in the prototype. A high performance 4-axis motion control board with 28 bidirectional I/O pins from Dynomotion Inc. (Calabasas, CA) is used for driving the linear stages. The system uses bottom up projection based SL process. A
flat and clear glass Petri dish is used as resin tank/vat. After a layer is cured, the projector elevates up by a layer thickness to refresh the resin for the next layer. The Petri dish is clamped to the structure, helping it to stay firm during the separation force that is created between the cured layer and resin vat, when the platform moves up. A PDMS film (Sylgard 184, Dow Corning) is coated on the resin vat to protect the cured layer.

![Prototype hardware system for laser projection SL process](image)

Figure 7: The prototype hardware system for the laser projection SL process with dynamic resolution control

### 2.3 Software Setup:

A mask planning testbed has been developed using the C++ language with Microsoft Visual C++ compiler. The testbed integrates the geometry slicing with varied resolution settings, and the motion controlling of Z-stage 1 and Z-stage 2. The software also synchronizes the image
projection with the platform and projector movements. The graphical user interface of the developed software system is shown in Figure 8.

![GUI of the control software](image)

**Figure 8: GUI of the control software**

### 2.4 Material:

Perfactory Acryl R5 (red) from EnvisionTEC Inc. (Ferndale, MI), was used in testing the developed Dynamic Resolution Fabrication process. The Perfactory Acryl R5 resin is a product that consists a mixture of acrylic acid esters and photoinitiator (0.1 – 5 %) with a density of 1.12 – 1.13 gm/cm³ [35]. The material offers superior chemical resistance, a wide processing latitude, and excellent tolerance to a broad temperature and humidity range during and after build [36]. Parts created from R5 exhibit superior tensile strength of 31 – 39 MPa, strong memory retention, and high quality up-facing and down-facing surfaces [36].
3. PROCESS PLANNING


3.1 Mask Image Planning:

An image process planning algorithm is necessary to determine proper set of resolution for each layer, as it is necessary to segment the image with minute detailing contained in a large image to obtain best quality part. An image is composed of tiny square blocks called ‘pixel’ in each rows and columns. In addition, the sliced image used for all the following experiments in this paper is a binary image and has pixel value either 1 (white color) or 0 (black color), where 1 is the object pixel and 0 is the background pixel. In this study, a Layered Depth Image (LDI) algorithm is utilized to answer the first question for determining proper set of resolutions for each layer. LDI is generally used for 2-dimensional images that can be extended further to Layered Depth-Normal Images (LDNI) [37]. For easy understanding, in the following section, we use "micro feature" or "micro image" to denote an area that has to use a high resolution and "macro feature" or "macro image" to denote an area that could use a low resolution.

An example illustrating a simple sliced image for a single layer that contains micro feature in a large area is highlighted in Figure 9. If the sliced layer as shown in the example is fabricated with a single resolution, the part quality of the 4 tooth might be distorted. It is for this reason, the micro features from the macro part has to be segmented, to build these small features with higher resolution highlighting its intricate details. Let \(V\) comprises of the entire image having \(i\) pixels along X-direction and \(j\) pixels along Y-direction. This can be represented as \((X_i, Y_j) \in V\) for a single layer that can be extended to the 3rd dimension identifying the \(K^{th}\) sliced layer. Thus the overall
equation can be represented as \((X_i, Y_j) \in V_{Layer,K}\). The LDI algorithm is used to identify the object pixels from the entire image, which is then used to separate micro feature in a large image. The algorithm works in the following manner:

Rays are transmitted along the row pixel first and when it identifies a pixel that has its neighboring pixel of different intensity, it shall be marked as the boundary of the object. A loop is run for each row pixel and then for each column pixel to filter the object pixel. The section that has minute detailing and requires high resolution is then segmented from the large image.

To further explain the image segmentation, a sectional part is highlighted in the following figure to show the working of the process. The system identifies the object pixel and marks the boundary pixel at the respective position as \(X_{i,n}\), where \(i\) is the pixel location and \(n\) is the number of times the pixel color changes in each row or column. The value of \(n\) starts from 0 and changes to 1 immediately when it finds the 1st boundary pixel and then proceeds with an increment whenever it encounters a change in pixel color. Thus, the next boundary will have \(X_{i+p,n+1}\), where \(i + p\) is the pixel location where it finds change in pixel color. The distance between any two boundaries of an object can be generalized as \(d|X_{i+p,n_{\text{even}}}-X_{i,(n_{\text{even}})-1}|\), except when \(n\) is 0. A threshold feature size, defined by a variable \(T\), is set based on the resolution. For example in the test case below, if the distance between two neighboring boundary pixels is less than the threshold \(T\) of 2500 microns, the area between these two boundary pixels will be counted as micro-scale feature which needs to be fabricated by using higher resolutions, whereas if the distance between the boundary object pixels is more than the threshold it will be fabricated as macro-scale part using resolution R61. The notation R# referred here and in the following sections is the build feature of part where R stands for resolution and # is the size of a pixel in microns. Thus, R61 indicates that the part has been fabricated with a resolution of 61 micron/pixel.
Figure 9: Example Model: (a) STL model; (b) Transfer rays along rows and columns of a binary sliced layered image; (c) Sectional view highlighting object and boundary detection; (d) Macro image; (e) Micro image

For example, the sectional image in Figure 9(c), the ray transmitted along the row starts with \( n \) as 0 and then ends with \( n \) as 6, thus the row has 6 boundaries and 3 objects. It is identified that the \( d|X_{15,2} - X_{5,1}| \) and \( d|X_{59,6} - X_{49,5}| \) is greater than the threshold \( T \), thus identified as macro scale features and will be cured by an image of R61. On the contrary, the other object is micro scale features since the \( d|X_{35,4} - X_{29,3}| \) is less than \( T \) and it will be cured by an image of R41. After identifying the micro-scale features, it will set all the micro scale pixel object area to zero and generate a new image. For better efficiency, we then run this loop for all columns pixels on the new image and again the identified micro objects are set zero forming a modified image. The
modified image thus obtained is the macro image and subtracting this modified image from the initial image will give out a micro image.

The macro image, used for fabricating the related part shown in Figure 9(d) is built by using R61. The micro features separated from the original sliced image, a higher resolution R61-\(\triangle\) (denoting a resolution of 61-\(\triangle\) microns per pixel) is used to regenerate an image for the micro features. A value of 20 is used for \(\triangle\) in the example. Then the regenerated image is used as the input image and is processed the same way to determine a proper resolution for it.

**Image planning process for the example in Figure 9:**

**INPUT**

A sliced binary image, \(V\) of \(K^{th}\) layer

\(T=2500;\)

**OUTPUT**

1. Image 1 with resolution R61

2. Image 2 with resolution R41

**STEPS**

1. Transfer rays from \(Y_j\) till \(Y_{j+w}\), where \(j=0 \rightarrow w\) and \(w = \) number of pixels along Y-axis

2. For each row find boundary pixel, \(X_{i,n}\), where \(i=0 \rightarrow v\) and \(v=\) number of pixels along X-axis and \(n=\) change in pixel intensity

3. If \(d|X_{i+p,n_{even}}-X_{i,(n_{even})-1}| \geq T\), macro image else micro-image

4. If \(d|X_{i+p,n_{even}}-X_{i,(n_{even})-1}| < T\), set \(d|X_{i+p,n_{even}}-X_{i,(n_{even})-1}| = 0\)
5. New image as V_row

6. Repeat above steps for column rays on V_row

7. Store the modified image V_mac

8. V_mic = V - V_mac

RESULT

V_mac as macro image, which will be used to fabricate big features of that layer using resolution R61

V_mic as micro image, which will be used to fabricate small features of that layer using resolution R41

3.2 Parametric Dependence Quantification:

After determining proper set of resolution for each layer, the next challenge is to move the laser projector to its corresponding position so as to obtain the desired resolution setting. A process planning approach is therefore essential for smooth functioning of the system [38]. This is quantified by the dependence of pixel size and build size on the focal length. By moving the laser projector up and down using Z-stage 2 as shown in Figure 5, the digital mask image exposed on the liquid resin will have changing resolution and build size. More specifically if the laser projector is moved away from the platform the pixel size increases which means lower resolution but bigger build area. For example, the micro scale structures could be segmented and fabricated with a small focal length and hence higher resolution, while the meso or macro scale structures in the model could be fabricated with a bigger focal length and hence larger curing area. The following section shows the relationship between pixel size and build size on the focal length.
3.2.1 Dependence of Build Area and Planar Resolution on Focal Length:

Due to the laser projector’s property of producing focus free masks irrespective of any focal distance, it provides a wide variety of resolution depending upon its distance from the resin vat. Therefore, it is essential for determining the position of projector so as to obtain the required resolution for each layer. First, experiments were performed to calibrate the working range of focal length. As shown in Figure 10, the projector provides a good flexibility with a focal length ranging from 20.0 mm to 70.0 mm, leading to a resolution from 36.55 micron/pixel to 86.08 micron/pixel, and a build area from 31.0 mm to 73.0 mm along X-axis, whereas along Y-axis it is from 17.54 mm to 41.32 mm. The laser projector has a display aspect ratio of 16:9 that results in different building area along its X and Y axis. The graph highlighted in red is the relation between the focal length, $f$ (mm) and resolution, $R$ (micron/pixel), whereas the graphs in blue (dashed line) and orange (round dotted line) are associated to the focal length and building sizes along X-axis, $A_x$ (mm) and Y-axis, $A_y$ (mm) respectively.

Because of the straight projection light path, both the resolution and build area are related to the focal length linearly [31]. To validate the linear relationship, the build sizes and resolution at the middle point of the working range, that is, $f=45$ mm, were measured. The linear relationship between build area and focal length could be formulated as the following:

$$A_x = 0.8 \times f + 14.1333 \quad \text{build size along X-axis}$$

$$A_y = 0.4756 \times f + 7.9913 \quad \text{build size along Y-axis}$$

whereas, resolution and focal length is described by:

$$R = 0.9906 \times f + 16.6597$$
From the above equations, it is obvious that for producing parts with high resolution the focal length between the laser projector and resin vat should be small, conversely for the development of parts with large area its focal length will be large. Given a desired resolution, the projector could be moved to the corresponding position. Also, for the fabrication of one layer with large area but small features, the mask image could be segmented into multiple images and stitched for multiple curing with different projector positions.

3.2.2 Dependence of Vertical Resolution on Focal Length:

Experiments were conducted for further analysis of the vertical resolution by measuring cure depth ($C_d$). In the experiment, the laser projector produced a mask at $20.0$ mm, $30.0$ mm, $40.0$ mm, $50.0$ mm, $60.0$ mm and $70.0$ mm focal lengths, each having a set of exposure time of $200$ s, $300$ s, $400$ s, $500$ s and $600$ s. A commercial resin Perfactory Acryl R5 red from Envisiontec was
utilized for the following set of experiments [35]. Other resin parameters such as penetration depth $D_p$ and critical exposure $E_c$ can be obtained from the Beer-Lambert formula provided in equation below [39].

\[ C_d = D_p \times \ln\left(\frac{E_{\text{max}}}{E_c}\right) \] ........ (1)

Also, the values of $D_p$ and $E_c$ can be verified from the graph below. The graph shows the relation between the cure depth and exposure energy per unit area on the resin surface. The results indicate that cure depth is linearly proportional to the natural logarithm of exposure energy per unit area. Theoretically, the slope of the line is its penetration depth $D_p$ and $E_c$ is the energy when cure depth is 0, but this does not indicate the gel point of the resin [40]. It is observed from the graph that the value of $D_p$ is 0.266 mm whereas $E_c$ is 23.46 mJ/cm$^2$.

![Graphical relationship between exposure energy and cure depth](image)

Figure 11: Graphical relationship between exposure energy and cure depth

By further extending Beer Lambert equation, the relationship between the cure depth, $C_d$ and focal length, $f$ has been established using equation 1 as represented below:
\[ C_d = D_p \times \ln \left( \frac{E_{\text{max}}}{E_c} \right) \]

\[ C_d = D_p \times \ln \left( \frac{P_{\text{max}} \times t_c}{A \times E_c} \right) \] .................................. (2)

where, \( P_{\text{max}} \) = Laser Power, \( t_c \) = Exposure time, \( A \) = Build area.

Since the build area \( A \) is directly proportional to the focal length \( f \), the above equation can be represented as follows:

\[ C_d = D_p \times \ln \left( \frac{P_{\text{max}} \times t_c}{K \times f \times E_c} \right) \] .................................. (3)

where \( K = \frac{A}{f} \). Given a specific focal length and exposure time, all the variables in Equation (3) could be approximated as constants, leading to the following equation:

\[ C_d = K_{\text{constant}} - D_p \times \ln(f) \] ............ (4)

where, \( K_{\text{constant}} = D_p \times \ln \left( \frac{P_{\text{max}} \times t_c}{K \times E_c} \right) \)

The above equation can be validated with the experimental results plotted below that shows the relation between the cure depth and focal length. In the experiments, an overhanging layer was cured by projecting a mask image with an exposure time ranging from 200 sec to 600 sec (interval of 100 sec), and a focal length from 20.0 mm to 70.0 mm (interval of 10.0 mm). The thickness of the cured layer was measured and recorded as the cure depth associated to the exposure time and focal length. The graph below justifies the linear relationship between the cured depth and focal length, thereby verifying Equation (4).
Figure 12: Graphical relationship between focal length and cure depth
4. EXPERIMENTAL RESULTS AND DISCUSSION


To verify the efficacy of our approach, models with multiple resolutions, varied sizes were fabricated using the testbed shown in Section 2.2. These 3D STL models were initially sliced layer-by-layer into 2D images and projected through a portable laser projector. The unique feature of these experiments was tuning the focal length dynamically to achieve dynamic resolution during building process. The change in resolution was achieved in a single building setup that resulted in achieving high build speed. This characteristic provided flexibility to fabricate parts with changing feature sizes and cross section areas in a single building task.

4.1 Large Area Fabrication with Resolution R81:

The manufacturing capability of fabricating parts with large surface area was tested and verified by fabricating a spur gear. The CAD model and fabricated result is shown in Figure 13. After analyzing this model, it was found that the part can be fabricated with one resolution. A resolution of 81 micron/pixel was adopted which is good enough to produce all details of this gear model. The scalability of such a large area can only be achieved when the distance between the laser projector and Petri dish is large. Based on the resolution and focal length relationship the laser projector’s focal length was kept at 65 mm so as to obtain the desired resolution.
Figure 13: Spur gear test case: (a) Isometric view of STL model; (b) Isometric view of built part; (c) Top view
This fabricated model constituted of 50 layers in total, including 7 base layers with a layer thickness of 90 microns. Initial exposure time for the base layer was 600 seconds per layer whereas for the subsequent layer it was 70 seconds each. It is recommended to have large exposure time for the base layers as it requires more time for the resin to bond and stick to the platform surface as compared to the bonding between resins amongst themselves. The fabricated gear as shown in Figure 13(b) and 13(c) had a diameter of 35.0 mm with 4.5 mm depth.

After the part has been fabricated it was rinsed with isopropyl alcohol and placed in the ultrasonic cleaner to remove any uncured resin from the surface. The same cleaning procedure was adopted for all the test cases.

### 4.2 Small Area Fabrication with Resolution R30:

The system showed appropriate results for large area fabrication. The same experimental setup was adopted to test the limits of resolution and efficacy of small area fabrication. The CAD model as demonstrated in Figure 14(a) is a hollow ball with nine circular cuts on its circumference. Four symmetric bigger circular cuts along the center whereas above it includes four circular cuts of slightly smaller diameter. Lastly, the top portion is drilled to form the smallest circle. A single resolution of 30 micron/pixel was adopted for fabricating the whole part with desired accuracy while a shortest build time. Thus, the focal length was fixed at 13.5 mm to give a 30 micron/pixel resolution for building all layers.
Figure 14: Hollow ball test case: (a) Isometric view of STL model; (b) Microscopic image of the front view; (c) Microscopic image of the top view
The fabricated part, thus formed was 2.8 mm in diameter and 2.65 mm in height with bigger and smaller circular cuts of diameter 800 micron and 600 micron respectively. Also, the top circular portion had a diameter of 70 micron. The Figure 14(b) and 14(c) are microscopic images of the isometric and top view of the part respectively. The entire structure was comprised of 63 layers including 7 base layers. Each layer corresponds to a thickness of 43 micron. Due to the reduced focal length the exposure time for both base and subsequent layers were kept as low as possible, mainly 200 seconds and 30 seconds respectively which resulted in a faster fabrication process.

4.3 Multi-Scale Fabrication with Resolution R41, R61 and R81:

The system successfully fabricated parts with a single resolution. The fundamental property of laser projector for focus-free operation was put to use by dynamically adjusting the resolution with the following test cases, to verify the manufacturing capability of building multi scale features in a single building task. For this purpose, a gear set with concentric center was designed as shown in Figure 15(a). With our image processing algorithm, we identified that for the bottom gear, a pixel size of 81 micron is good enough to give the desired accuracy and build size. For the top gear, since its feature is much smaller, a smaller pixel size, 41 micron is desired to fabricate the features precisely. After setting up different resolutions for layers, we could assign the corresponding projector position. According to the parametric dependence developed in this research, the focal length was obtained as 65 mm and 25 mm for the bottom and top gear respectively.
Figure 15: Multi-scale gear test case: (a) Isometric view of STL model; (b) Isometric view of built part; (c) Top view; (d) Microscopic image of top gear

The fabricated part constituted 40 layers including 7 base layers with a layer thickness of 90 micron. The 7 base layers were cured for 600 seconds and the subsequent 13 layers were cured for 70 seconds whereas the last 20 layers (top gear) were cured for 35 seconds. The bottom gear is built with a diameter of 30.0 mm whereas the top gear is built with a diameter of 5.00 mm and has an overall depth of 3.6 mm. The microscopic image of top gear is shown in Figure 15(d) highlighting the part accuracy and surface smoothness.

An example showed in Figure 7 was also fabricated which include a test case that has multiple resolution in a single layer. As discussed in Section 3.1, each layer was fabricated by using R61 and R41. The cross section was segmented to two portions, the rectangular frame, and the four teeth. The projector first moves to 45.0 mm level to cure the rectangular frame with the macro image, which has a resolution of R61. Then it moves to 25.0 mm level to cure the teeth with the micro image, which has a resolution of R41. Thus, the entire layer was formed by stitching these two areas. Figure 16 shows the fabricated part and microscopic image of the small feature.
Figure 16: Frame test case: (a) STL model; (b) Front view of built part; (c) Microscopic image of the tooth
The fabricated part was comprised of 25 layers including 7 base layers with each layer having a thickness of 75 micron which ultimately corresponds to an overall part thickness of 1.9 mm. Since each layer constituted 2 different resolution and focal length, the curing time for both the steps were different. The outer rectangle had a curing time of 35 seconds, whereas the inner tooth had a curing time of 20 seconds. The part dimension of outer rectangle consist of 22.0 mm in length and 11.0 mm in width whereas the inner tooth has a diameter of 2.0 mm.

4.4 Continuous Resolution Control Fabrication with R41-R61:

The first two test cases in Section 4.1 and 4.2 demonstrates the capability of our approach on fabricating parts with a specific resolutions but different building area. Section 4.3 verifies the effectiveness and efficiency of our approach on fabricating a part with two different resolution settings in one build. Furthermore, in this section, another test case is conducted to demonstrate the systems capability in continuously changing the resolution for each layer owing to the continuous change in the cross-section area of the part. The CAD file shown below in Figure 17(a) consists of a triangular structure with a circular hole drilled through its center. Also, the two sides of the triangle are drafted by an angle of 55 degree. Since the layer-by-layer sectional area of the part reduced continuously, the projector’s focal length was also changed from 45.0 mm (corresponding resolution 61 micron/pixel, first layer) to 25.0 mm (corresponding resolution 41 micron/pixel, last layer) ultimately improving the resolution by 0.34 micron/pixel for each layer. The projector’s focal length was controlled by synchronizing its motion with the platform.
Figure 17: Titled edges triangular surface: (a) Isometric view of STL model; (b) Isometric view of built part; (c) Microscopic image of the fabricated layers
The model comprised of 60 layers in total with each layer thickness corresponding to 75 micron. The base layer of the model was fabricated with a curing time of 300 seconds whereas the subsequent layers were cured for 30 seconds each. The isometric view along with part dimension is shown in Figure 17(b). Also, a microscopic image of the top surface of triangle that has the highest resolution is shown in Figure 17(c). The side of the triangle is measured to be 18.0 mm whereas the circular hole has a diameter of 5.0 mm. The top tilted edge is 9 mm long while the part thickness are measured to be 4.5 mm.

4.5 Building Performance Statistics:

<table>
<thead>
<tr>
<th>Model</th>
<th>Gear</th>
<th>Frame</th>
<th>Triangle</th>
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<tbody>
<tr>
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<td>Constant area, multi-resolution in one layer</td>
<td>Changing area, changing resolution in one build</td>
</tr>
<tr>
<td>X-Y dimension (mm)</td>
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<td>22.0 x 11.0</td>
<td>18.0 x 16.0</td>
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<td>Depth (mm)</td>
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<td>1.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Layer thickness (microns)</td>
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<td>75</td>
</tr>
<tr>
<td>Build time (min)</td>
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<td>30</td>
</tr>
<tr>
<td>Build time using conventional methods (min)</td>
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<td>88</td>
</tr>
<tr>
<td>Resolution Settings(micron/pixel)</td>
<td>81 (layer 1-20) , 41 (layer 21-40)</td>
<td>61 (outer part), 41(inner part)</td>
<td>41~61</td>
</tr>
</tbody>
</table>

Table 1: Statistics of all test cases
Table 1 above shows the effectiveness of this approach on fabricating parts with different layer areas and feature sizes efficiently through changing resolutions dynamically and even continuously for each layer. In the table, the build time was also compared with the time needed by using the conventional stitching approaches that uses a single resolution.

4.6 Build Speed Analysis:

The above test cases demonstrated unique advantages of the dynamic resolution control approach on building large sized objects with small features without sacrificing the build speed. In conventional stitching approach, the scanning stage or the frame moves continuously like a video animation pixel by pixel to get a best quality part, the displacement of frame is one pixel column at each sampling time [24]. Figure 18, shows that the total number of frames required to generate a layer is the addition of frame width pixels and pattern width pixels, where frame width is the build size and pattern width is the exposure length of the pattern along the X axis.

![Figure 18: Schematic of stitching approach](image)

In addition, the total displacement or travel distance, is the product of total number of frames and a pixel pitch or pixel size, i.e., 56 µm [24]. Thus, in this stitching approach, each layer
is formed by stitching each pixel column. Furthermore, assuming the frame velocity of 610 µm/s*, and a 1:1 frame width of 150 pixels, along the X and Y axes [24]. It is found that to fabricate the required pattern shown in Table 1, the system requires a pattern width of 540 pixels, 400 pixels and 330 pixels along the X-direction for the gear, frame and triangle test cases respectively. In addition, in all the above cases, the pattern does not fit completely in the Y-direction, which further adds to the overall build time. The scanning path thereby increases by 4 times for the gear test case, and 2 times for the frame and triangle test case. Since, the scanning frame moves continuously, a simple time-distance-velocity (speed) relationship, as shown in Equation 3, is utilized to calculate the overall build time for the stitching approach.

\[ \text{Total number of frames} = \text{Frame width pixels} + \text{Pattern width pixels} \ldots (1) \]

\[ \text{Travel distance (µm)} = \text{Total number of frames} \times \text{Size of a pixel (µm)} \ldots (2) \]

\[ \text{Build Time (sec)} = \frac{\text{Travel Distance (µm)}}{\text{Projector Velocity (µm/sec)}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldot
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<td><strong>Top Gear Tooth Thickness (mm)</strong></td>
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<td>0.85</td>
</tr>
</tbody>
</table>

Table 2: Geometrical accuracy of multi scale gear test case

To further examine the quality of the printed part, surface roughness test was carried out on the same test case of multi-scale gear, which used two different resolutions for fabricating top and bottom gear. A Contour Elite 3D Optical Microscope by Bruker Corporation was used to find the surface roughness for this test case. Although, the part was built in a single building setup with the same material, it constituted multi-scale resolution. It is because of the use of multiple resolutions, two surface roughness experimental readings were obtained, one for the top gear and one for the bottom gear. From the experimental results, it is found that the average roughness ($R_a$) value of the bottom gear fabricated with resolution R81 was 2.049 µm. The surface roughness profile of the bottom gear is shown below in Figure 19.
On the other hand, the top gear, which was fabricated with a resolution R41, has an average roughness ($R_a$) value of 0.127 $\mu$m. Figure 20 shows the surface roughness profile along the length of the top gear. From both the $R_a$ values, it can be summarized that the surface roughness decreases with the increases of resolution.
5. TEXTBOOK-SIZE 3D PRINTING SETUP

After successfully fabricating parts with varied dimensional and feature sizes in a single building task, and analyzing the part geometry and surface roughness, an attempt has been made to optimize the design with an intention to develop a portable, compact and low cost 3D printing setup. This is possible owing to the compact size of laser projector. In addition, another unique feature that makes it stand apart is its ability to use a smart phone, e.g. an IPhone, as a source to transfer sliced images. The optimized design is presented in this chapter, and a prototype machine has been built.

5.1 Portable and Compact Hardware Setup:

The 3D CAD model of the setup is shown in Figure 21 and it is scaled in 1:1 ratio with the actual setup.

![Figure 21: CAD model of portable and compact setup: (a) Isometric view; (b) Front view](image)
The optimized design consists of 2 NEMA 17 stepper motors, each of which is coupled with a lead screw rod. The rod has an outer thread, which mates with a brass nut, having inner thread. The brass nut travels up and down along the rod, changing the rotary motion of stepper motor to linear motion. The lead screw rod and brass nut are coupled with stepper motor to form a motor assembly, also termed as Z-Stage 1 and Z-Stage 2 in Figure 22(a). These 2 motor assemblies are connected with their respective attachments namely, a projector attachment to hold the projector up-straight, and a platform attachment to secure the platform. These attachments are designed in such a way that it is screwed to the brass nut and inserted securely in the linear guides. Both the attachments were fabricated using a commercial 3D printer, UP! Mini (www. UP3D.com) that utilizes Fused Deposition Modeling (FDM) approach. The machine uses an Acrylonitrile-Butadiene-Styrene (ABS) material, which is strong and offers good load bearing capacity. The linear guides used in this setup is an aluminum column having T-slot profile from 80/20 Inc. The advantage of using T-slot extrusion is that any connection can be made along the axis, providing flexible mounting positions. In addition, all 80/20 aluminum extrusions come standard with a clear anodize, which helps prevent oxidation and corrosion [41].

Aligning the motor assembly is an important factor to help reduce vibration in the setup when the motor is running. The setup uses a bottom-up projection method, which helps in reducing the size of resin vat. In addition, the bottom-up projection method consumes less resin as compared to top-down projection method that requires large resin vat volume and thereby more weight. The dimension of this prototype setup is 7.8 x 7.0 inch along the plane that is the size of a textbook and weighs ~8 pounds. The Figure 22(b) shows the compactness of the prototype setup.
5.2 Software Setup and Controls:

The Pico laser projector is compatible with computers and smart phones. Thus, for this setup a unique characteristic was adopted: instead of using a computer to transfer mask images, an IPhone was used to transfer mask images.

The stepper motor assembly is operated using an Arduino micro-controller. A motor driving shield is used to protect the Arduino board, since the motor produces voltage spikes when switched on/off. In addition, the shield has a heat sink that dissipates the excess energy and prevents the micro-controller from getting over heated. The advantage of using Arduino is its open
source prototyping platform and also the boards are inexpensive ($20.00), compared to other micro-controllers. The Arduino software uses an extension of C++ library and have built-in libraries to drive stepper motors at different velocities. \textit{The total cost of the developed prototype is $150.00.}
6. CONCLUSION


A novel mask image projection based stereolithography (MIP-SL) system has been developed to achieve dynamic resolution control. Compared to conventional MIP-SL systems, that stitch multiple images with a single resolution to form a large layer, the developed approach is based on fabricating layers with changing resolution. The number of stitches can be therefore minimized. As a result, the build speed could be optimized and the part quality would be probably better.

A compact laser projector is used as a light source. It is movable along the build direction, resulting in changing focal length and hence changing projection area and resolution. To facilitate the mask image planning in dynamic resolution control approach, an image segmentation approach has been developed to separate micro features from a sliced image. Parametric dependence of resolution and build size on focal length have been calibrated and modeled. The system also validates the relationship between planar resolutions and exposure energy. In addition, the linear dependence of cure depth on focal length is validated, which is an extension of Beer Lambert equation.

A prototype setup has been developed to demonstrate the capability of the proposed dynamic resolution control approach. The efficiency and effectiveness of the approach has been verified with multiple test cases having various surface areas, feature sizes and structures. Test
cases include parts with large surface area and low resolution, small surface area and high resolution, multi-scale structures, and continuously changing area and resolution. The dimensional accuracy of fabricated parts are further analyzed by comparing the build part with the desired CAD model. In addition, the surface roughness tests are carried out to analyze the surface finish of parts fabricated with different resolution settings.

Furthermore, an attempt has been made to design and develop a portable, compact and low cost dynamic resolution control approach based MIP-SL setup, by using a smart phone (currently IPhone) to transfer mask images to the laser projector in our system.

This research has demonstrated a novel MIP-SL process and system design to fabricate parts with multiple resolution in a single building task. It is verified that the proposed MIP-SL process with dynamic resolution control approach is capable of addressing the challenge of building large parts with multi-scale features, and meanwhile saving the overall build time by using minimum number of stitches.
7. REFERENCES


[27] Benedict (2015), "LLNL's Large Area Projection Micro Stereolithography (LAPuSL0 3D printing device wins tech-transfer awards", available at:


[41]  “80/20 Inc. Aluminum t-slot profiles” [Online]. Available: [https://8020.net/university-tslot](https://8020.net/university-tslot)
APPENDIX

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VITA

Name: Chintan R. Dagli

Education: University of Illinois at Chicago: Masters’ of Science Mechanical Engineering, 2016
   University of Mumbai: Bachelors’ in Mechanical Engineering, 2013


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