ME315 : Student Learning Project

Department of Mechanical Engineering

3D Marking in Glass using Femtosecond Lasers

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Abstract

Exploration of laser ablation technology for creating internal engravings in transparent materials, specifically glass is a topic of interest. The project focuses on developing a method for marking intricate 3D structures within the glass without altering its external surface. By manipulating key laser parameters—such as energy, feed rate, and depth of focus — the research aims to achieve high-precision engravings at varying depths and shades.

The report covers theoretical backgrounds of laser interactions with glass, current advancements in laser micro-machining, and the development of software tools to automate G-code generation for laser movements. Experiments included converting 2D images into 3D engravings using image segmentation techniques and optimizing the laser's parameters to achieve detailed and controlled internal markings.

The findings emphasize the potential of laser ablation in revolutionizing industries requiring high-resolution internal engravings, while also identifying areas for further improvement, such as calibration and process optimization. Future work includes improving the software algorithms, fine-tuning laser parameters, and increasing engraving resolution for industrial applications.

1 Introduction

1.1 Background

Laser ablation is used to modify or remove material from a surface or its internal structure by directing a high-intensity laser beam. In recent years, its application has extended to engraving internal structures in transparent materials, such as glass, without disturbing the external surface. This method opens up possibilities for creating complex 3D patterns within glass, which has numerous industrial uses, including micro-machining, laser marking and also creation of artistic patterns within the specimens. Similar techniques are applicable across various other translucent materials, predominantly plastics as was explored in [1].

A similar study was conducted using nanosecond pulsed laser system with a wavelength of 355 nm on glass and a heat conduction model was also developed to estimate the maximum temperature in the glass, providing insights into the absorption efficiency of transparent materials by [2].

Femtosecond lasers, with ultrashort pulses, offer high precision and minimal thermal effects, making them ideal for intricate, crack-free engravings inside glass. In contrast, nanosecond lasers deposit more heat, leading to larger heat-affected zones (HAZ), faster processing, but rougher results with potential micro-cracks. Femtosecond lasers excel in high-quality 3D microstructures, while nanosecond lasers are better for economical, faster, and deeper industrial engravings. The choice depends on the balance between quality, speed, and cost requirements.

Hence, our decision to go for Femtosecond laser engraving.

1.2 Motivation

Traditional engraving methods on glass often alter or damage the external surface, limiting their precision and durability [3]. The need for high-resolution, internal engraving techniques without surface alteration has driven the exploration of laser ablation technology. This project aims to enhance laser ablation for such tasks, offering detailed 3D structures inside transparent materials. The potential for this technology to revolutionize industries like decorative glass art, data storage, and security marking adds significant motivation for further development.

Additionally, the capability of making materials with colour changing abilities is also possible with nanometer precision grating in ultra fine glass substrates like Chalcogenide glass [4].

Owing to all the above, we further develop already existing 2D imprinting techniques to create 3D microfabrications and understand the relationship between ablation colouring and laser power.

1.3 Scope of the Report

This report focuses on the application of direct laser ablation technology for engraving precise 2D and 3D structures inside transparent materials, specifically glass. It explores the control of laser parameters such as energy, feed rate, and focus to achieve optimal engraving quality. The report delves into experimental setups for marking internal structures in glass without damaging the surface and provides insights into how these parameters affect the geometry, shade, and dimensions of the marks.

Additionally, the report covers the development of software for generating G-code, which automates the engraving process and converts 2D images into 3D engravings inside glass. The results of this study are intended to improve laser marking techniques for industrial applications such as micromachining, data storage, and decorative glass art, while highlighting areas for further optimization in terms of precision and consistency.

1.4 Outline of the Report

This report is organised into the following sections:

1. Introduction: Provides background on laser ablation and its use in internal glass engraving, along with the motivation and potential industrial applications.

2. Literature Review: Summarizes advancements in laser ablation and micromachining, focusing on controlling laser parameters for glass engravings and key technologies in the field.

3. Research Objectives: Defines the goals of the study, including optimizing laser parameters and developing software for converting 2D images into 3D engravings.

4. Experiments: Describes the experimental setup used to test laser intensities, feed rates, and focus depths, and how results are measured in terms of shading and geometry.

5. Marking of 2D Images: Explains the conversion of 2D grayscale images into engravings by adjusting laser feed rates to create varying depths and intensities.

6. Marking of 3D Structures: Describes the slicing of 3D objects into layers for engraving, using G-code to create internal structures inside glass.

7. Conclusion and Future Work: Summarizes key findings and suggests future work to improve process optimization and engraving accuracy.

2 Literature Review

In this section, we review the relevant advancements in the field of laser ablation and internal glass engravings through modern methods. The review is divided into two key areas: methods and software.

2.1 Modern Glass Engravings through Lasers

Laser Ablation (Internal Engraving)

Laser ablation involves using a high-intensity laser to remove material from the glass surface or inside the glass without affecting the exterior. The focused laser beam modifies the material by creating micro-explosions or inducing nonlinear optical processes, which result in internal markings. This method is used for creating intricate, high-resolution patterns inside glass, commonly applied in decorative glass art, security markings, and data storage. It allows for precise, internal marking without damaging the surface, making it ideal for complex designs.

Ultrafast Laser Marking (Femtosecond Pulsed Lasers)

Femtosecond laser marking uses extremely short laser pulses (on the order of femtoseconds) to induce localized modifications in the glass. This method minimizes heat diffusion, allowing precise markings inside the glass without cracking or surface damage. It is used in high-precision applications like microelectronics, medical devices, and optical components, where minimal thermal damage is crucial. It offers high precision and minimal heat-affected zones, allowing for intricate designs without compromising the glass structure.

2.2 Software for Glass Marking through Lasers

LightBurn

A laser engraving and cutting software designed for creating and controlling design layouts. In the context of glass marking, LightBurn provides direct control over laser cutters and engravers, allowing users to import both vector and raster images, adjust crucial laser parameters, and send the designs to the laser machine for precise engraving on glass.

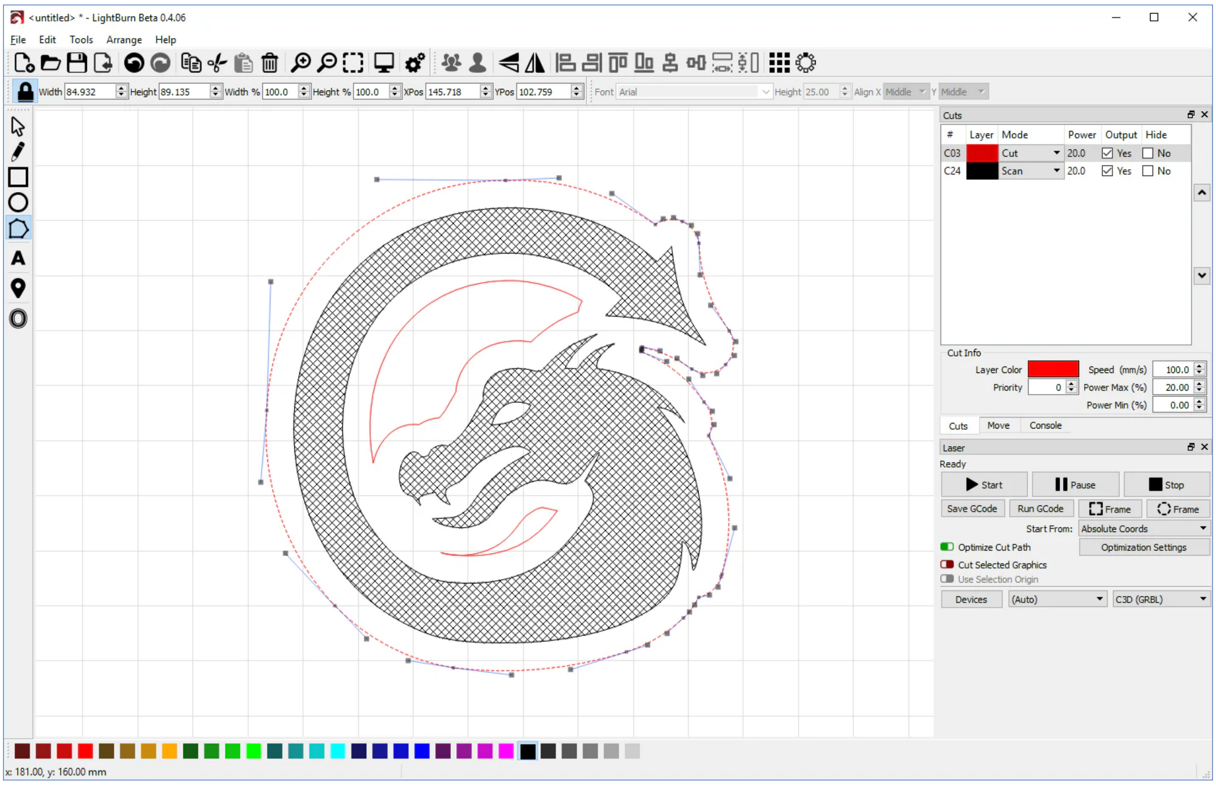

Figure 1: LightBurn interface for laser engraving

One of its standout features is the real-time control it offers over laser settings, including power, speed, and feed rate, making it highly adaptable for creating both 2D and 3D patterns with intricate details.

LaserGBRL

An open-source laser control software [7] designed for processing G-code. It is widely used for controlling laser engraving machines, making it highly applicable for glass marking. The software converts vector graphics and raster images into G-code, which is essential for controlling the laser's movement and parameters during the engraving process. One of its key features is its ability to efficiently generate G-code while allowing for adjustments to engraving depth and shading, making it a valuable tool for both 2D and 3D glass marking applications.

3 Research Objectives

3.1 Open Issues

In our laboratory, we successfully utilized laser ablation to print 2D structures inside glass. However, the primary challenge lies in refining this technique to achieve greater control over the process, particularly in understanding how variations in the depth of focus affect the height of ablation. Additionally, determining the precise power levels required for consistent and accurate ablation remains a critical issue.

The first objective is to print 2D images with shade variations, which involves converting images into segmented layers using image segmentation techniques. This process

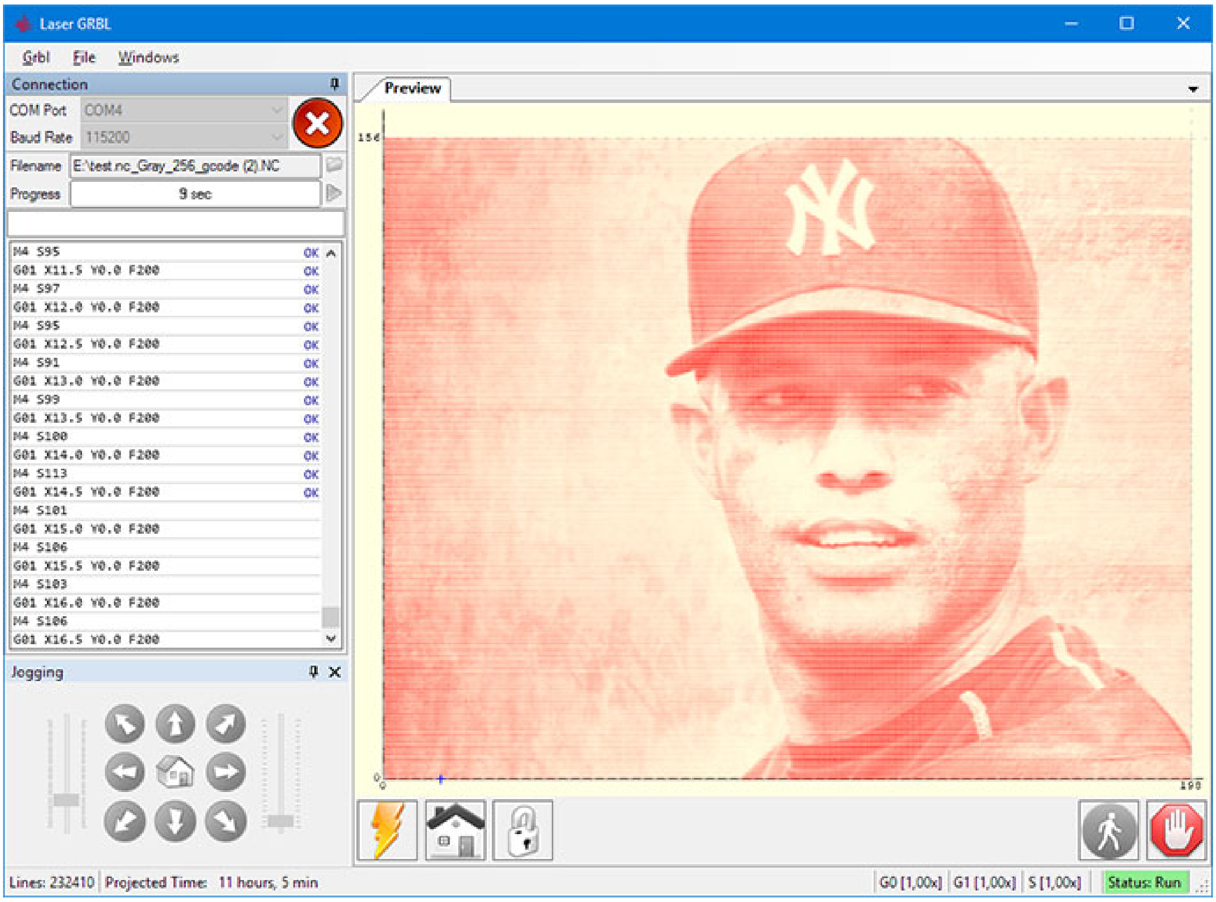

Figure 2: LaserGBRL interface for laser engraving

allows us to vary laser parameters to create distinct shades within the glass. For example, our goal is to print a 2D image of a face with different shades, simulating the grayscale variations by adjusting the laser's parameters via G-code.

The parameter chosen for variation is the scanning speed of the laser. This decision was made because continuously adjusting the laser's power in real-time is not feasible due to the inherent limitations of the laser control system, including its inability to maintain consistent energy output across rapid fluctuations. As such, controlling the scanning speed provides a more stable and reliable method for achieving the desired shading effect. Therefore, the initial step in this process is to successfully print an image with clear shade variations by manipulating the laser's scanning speed.

Once a satisfactory 2D print is achieved, the next step is to refine the technique to improve the quality and precision of the engraving. This includes mapping laser power to the Z-magnitude of the voxel being printed, allowing us to better understand how varying laser power affects depth and shape within the glass.

Following this, the development of a dedicated software tool becomes essential. This software should be capable of generating the necessary G-codes to control the laser for 3D ablation within glass. The software must also ensure that the laser parameters—such as energy, speed, and focus depth—are optimized to produce a 3D structure that is both visible and accurate, as studied in [9].

Lastly, an important aspect of this project involves developing software capable of converting 2D images into 3D structures. This process requires intensity extrapolation into the third dimension, where the variations in image intensity are translated into depth information. The final goal is to produce a 3D image that, when viewed from a specific angle, appears as a fully three-dimensional structure.

3.2 Aim and Objectives

The aim of this project is to refine laser ablation for printing 2D and 3D structures in transparent materials like glass. The goal is to understand how laser parameters—depth of focus, power, and scanning speed—affect engraving quality, particularly ablation height and shading.

The specific objectives are:

- **Understanding Laser Parameters:** To study how scanning speed, depth of focus, and power influence the engraving process to optimize settings for consistent 2D engravings.
- **Printing 2D Images with Shades:** To print a 2D image with varying shades using scanning speed to simulate grayscale. The first target is a face image with distinct shading.
- **Refining 2D Prints:** To further refine 2D engravings by mapping laser power to the Z-dimension of voxels for better depth control and precision.
- **Developing G-code Software:** To develop software that generates G-codes for 3D printing in glass, ensuring optimized laser parameters for clear 3D structures.
- **Converting 2D to 3D:** To create software that converts 2D images into 3D structures by extrapolating intensity variations into the Z-axis for a 3D appearance. Pre existing softwares exist which are learning - based as described in [10].

3.3 Methodology

1. **Theoretical Study:** Explored the interaction between laser parameters (power, focus, scanning speed) and their impact on ablation depth and shading.
2. **Experimental Variation:** Systematically varied laser parameters to observe their effect on engraving quality, aiming to optimize for shades and depths.
3. **Software Development:** Developed software to convert 2D images into 3D structures and generate G-codes for laser engraving, ensuring precise pattern reproduction.
4. **Code Details:** Subsequent sections detail Python-based G-code generation, including step-by-step instructions and images illustrating laser engraving results.

3.4 Work Plan

4 Experiments

4.1 Laser Set Up

The Pharos PH2 femtosecond laser from Light Conversion, Lithuania, was used in this project for precise laser ablation in glass. The key parameters of the laser are summarized

Phases	Task Description
Phase I	Project Formulation and Problem Statement Refinement
Phase II	Literature Review and Theoretical Formulation
Phase III	Image Segmentation and Shades Experiment in Lab
Phase IV	Conversion of 2D Shapes into 3D Structures and Software Debugging
Phase V	Final Set of Experiments and Printing of Structures
Phase VI	Report Making and Validation

Table 1: Project Work Plan

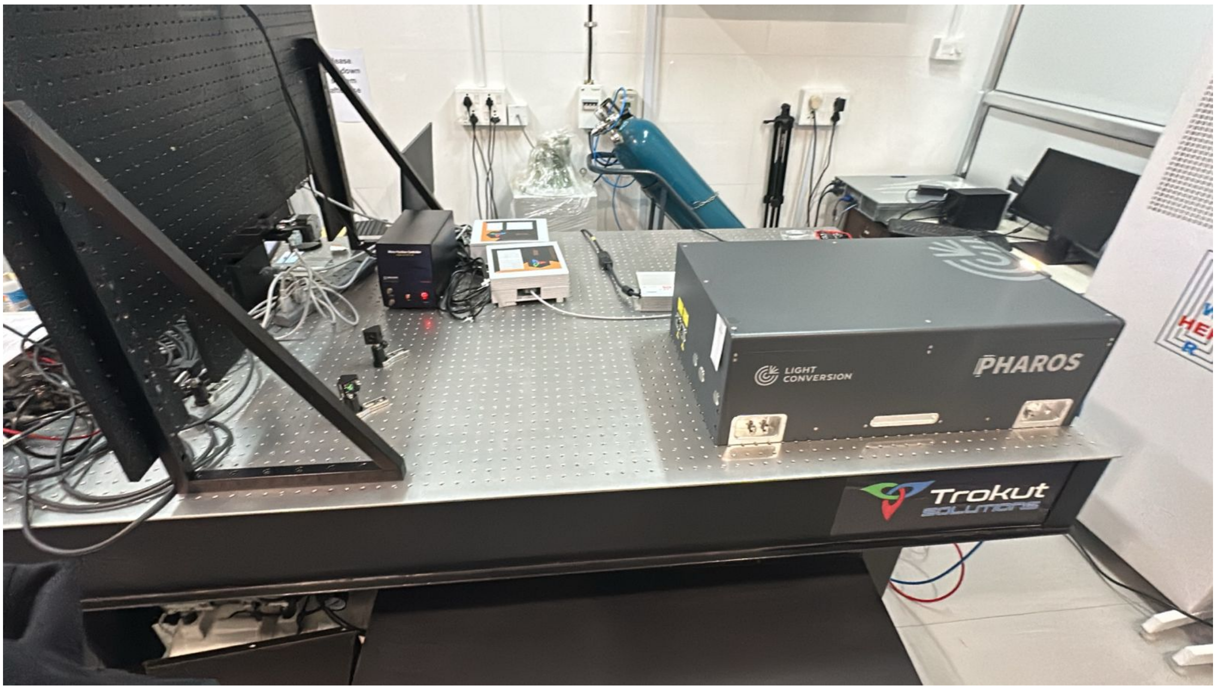

Figure 3: Pharos Laser setup in LAMP Lab, IIT Bombay

in Table 2.

4.2 Design of Experiments

The primary objective of this project is to vary the feed rate of the laser to achieve different shades inside glass, using image segmentation to classify various regions of intensity. Typically, varying shades or grayscale effects in laser engraving requires adjusting parameters such as laser power or feed rate. Since dynamically varying laser power during the engraving process is not feasible, we opted to adjust the feed rate, which is a more practical method. Slower feed rates allow more energy to deposit into the material, resulting in darker marks, while faster feed rates reduce energy exposure, creating lighter marks.

The following steps were taken to implement this approach:

1. **Image Acquisition:**

Parameter	Value
Wavelength	1030 nm
Average Power*	0.1 - 10 W
Pulse Energy	7.5 µJ at 200 kHz PRR, up to 50 µJ pulses
Pulse Repetition Rate (PRR)	200 kHz
Pulse Duration	295 fs
Beam Quality	TEM_{00}

Table 2: Laser setup Parameters

- A grayscale input image is used, where different shades represent varying levels of intensity that need to be engraved into the glass.

2. **Image Segmentation:**
   - The grayscale image is processed using image segmentation techniques, which involve dividing the image into regions based on the intensity or grayscale level of each pixel.
   - Thresholding algorithms are applied to classify the regions. For instance, pixels with brightness values from 0-50 represent the darkest regions, 50-150 for mid-tones, and 150-255 for the lightest areas.
3. **Mapping Shades to Feed Rates:**
   - After segmentation, each shade is mapped to a corresponding feed rate for the laser.
   - Darker regions (lower grayscale values) are assigned slower feed rates, which deposit more energy and create deeper or darker engravings.
   - Lighter regions (higher grayscale values) are mapped to faster feed rates, producing lighter engravings.
4. **Extrapolating Segmentation to G-codes:**
   - The segmented image data is converted into G-code commands. These commands control the laser's movement and feed rate for each region based on the corresponding shade.
   - For example, the G-code for a dark region may have a slower feed rate:

     G1 X10 Y20 F3000 (Slow feed rate for dark region)
   - A faster feed rate is assigned for lighter regions:

     G1 X30 Y40 F6000 (Faster feed rate for lighter region)
5. **Final Engraving:**
   - The laser follows the G-code instructions, moving at different speeds over various parts of the image. The result is a highly detailed engraving inside the glass that replicates the shades of the original image, with slower feed rates creating darker regions and faster feed rates creating lighter ones.

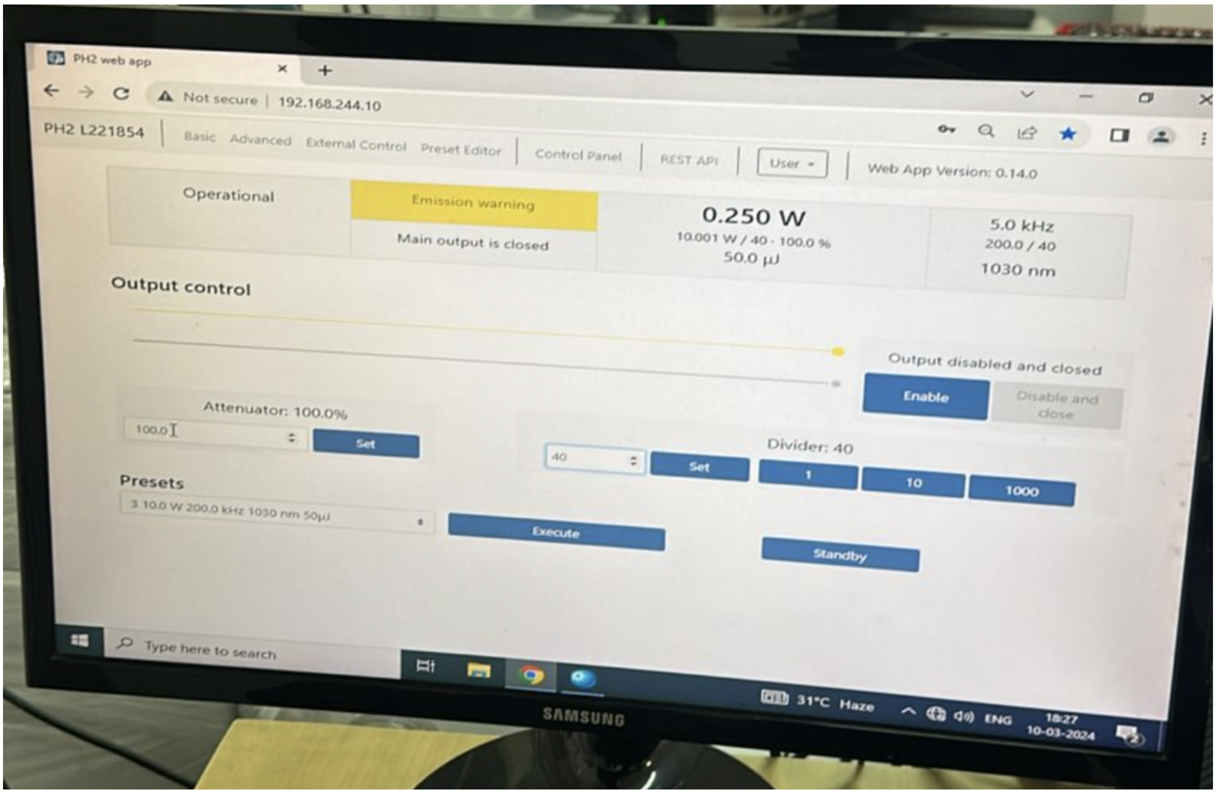

Figure 4: Laser Parameters

4.3 Results

Voxel Dimensions

The dimensions of the engraved voxels vary based on the laser parameters. By adjusting the energy and focus, different voxel sizes can be achieved inside the glass. The precise control of voxel dimensions is key to creating intricate internal structures. Figure 5 shows the relationship between shades and power.

Voxel Shading

The shade of each voxel is determined by the laser's feed rate for this report. Slower feed rates deposit more energy, resulting in darker voxels, while faster feed rates produce lighter shades. This allows the engraving to replicate grayscale images with high fidelity inside the transparent material.

Additionally, the material is also of utmost importance, as studied in [11], however, the aim is to try to develop a uniform and universal technique to mark all types of glasses, agnostic of quality.

5 Marking 2D Images

5.1 Procedure

The image chosen from the internet was first converted into grayscale, followed by image segmentation into various grayscale colors. This preprocessing step prepares the image for laser engraving.

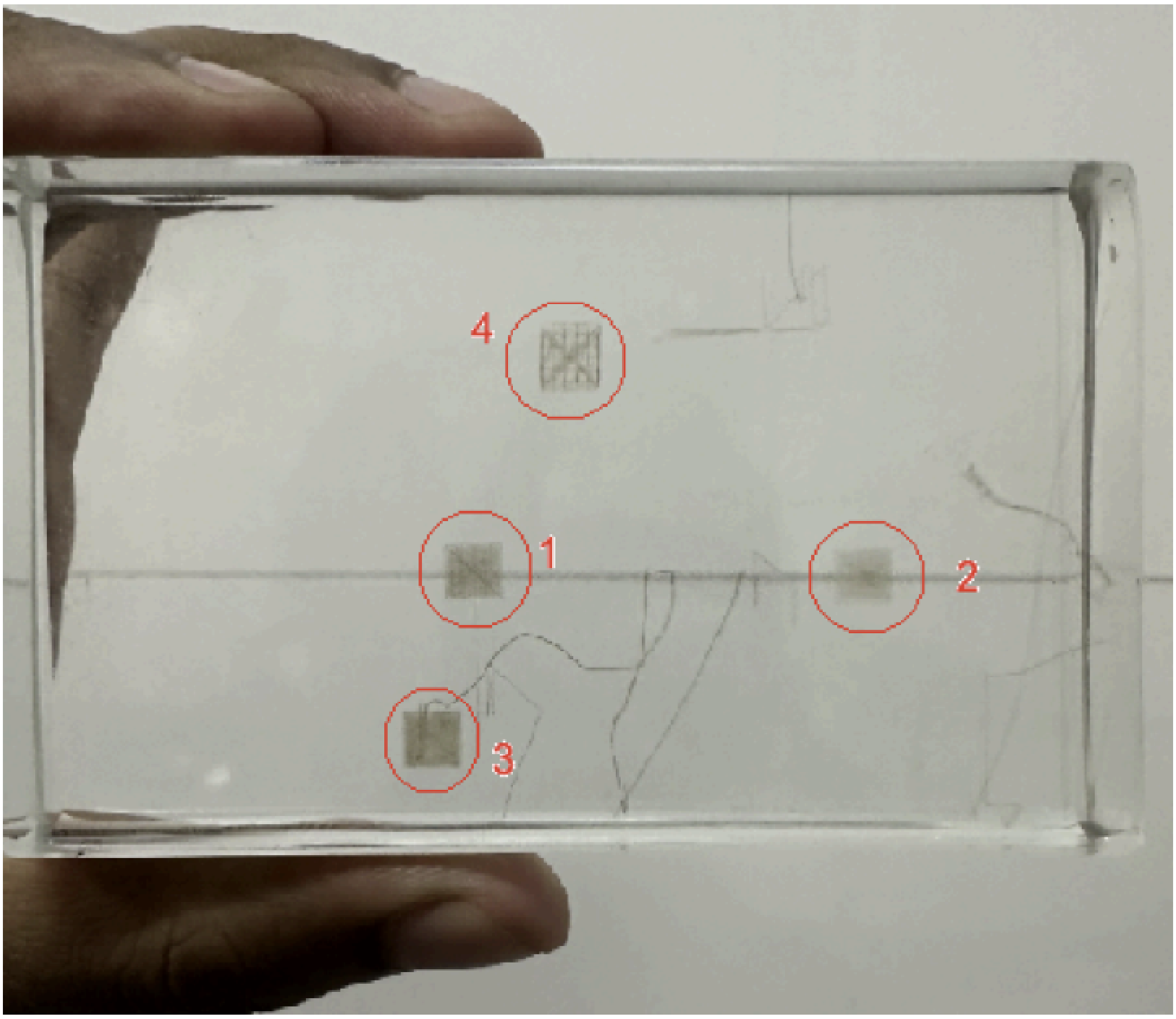

Figure 5: Power Ratings for 1 : 1 W, 2 : 0.8 W, 3 : 3 W, 4 : 3 W

5.2 Effect of Laser Parameters

After preprocessing, G-codes were generated to engrave the 2D shaded image. The results, however, were not satisfactory due to uncalibrated speeds and a laser power setting that ablated excessive material in the Z-axis

Hence, a carefully chosen combination of power and speed is selected to ensure that the ablated material becomes visible. For the above case, the feed rate chosen is 2.4 mm/s for one shade and 1.0 mm/s for another shade in the image with a power of 1.5 W.

5.3 Process Optimization

In order to achieve high-quality engravings with accurate shading, process optimization focused on refining the laser's path and speed to ensure efficient 2D printing while maintaining shade variation. The following steps were taken:

1. **Path Optimization:** The laser's path was optimized to minimize unnecessary movements and ensure smooth transitions, improving efficiency and reducing processing time without losing precision.

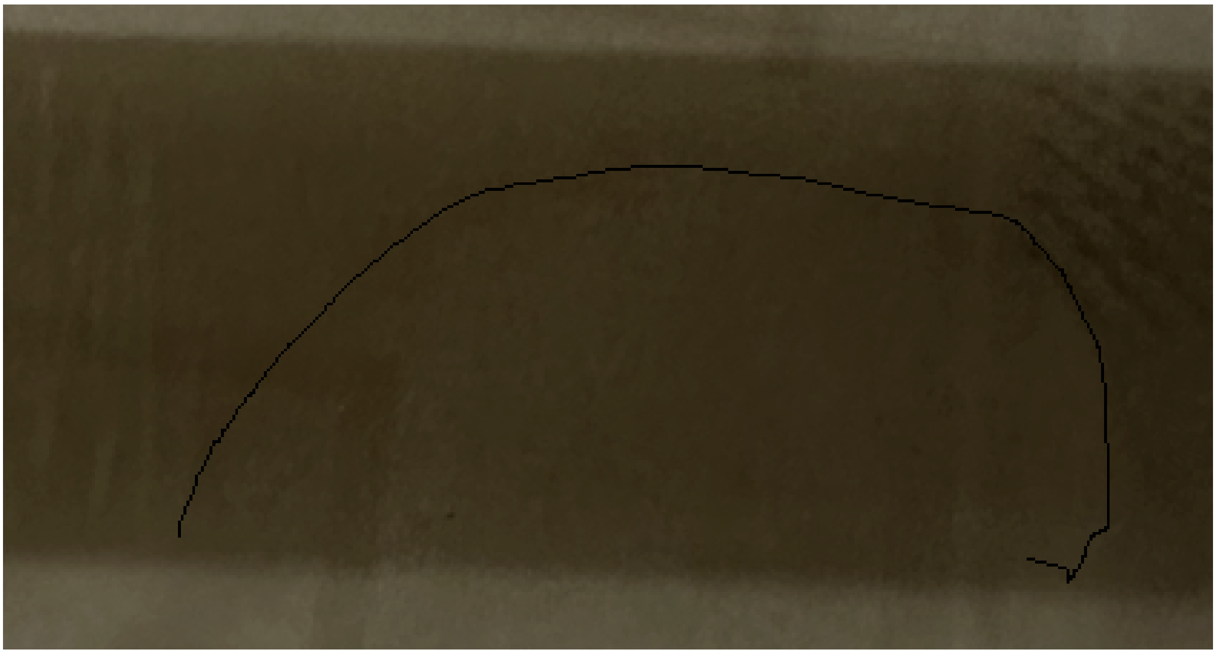

Figure 6: Voxel Shading at 2 different feed rates (from our lab)

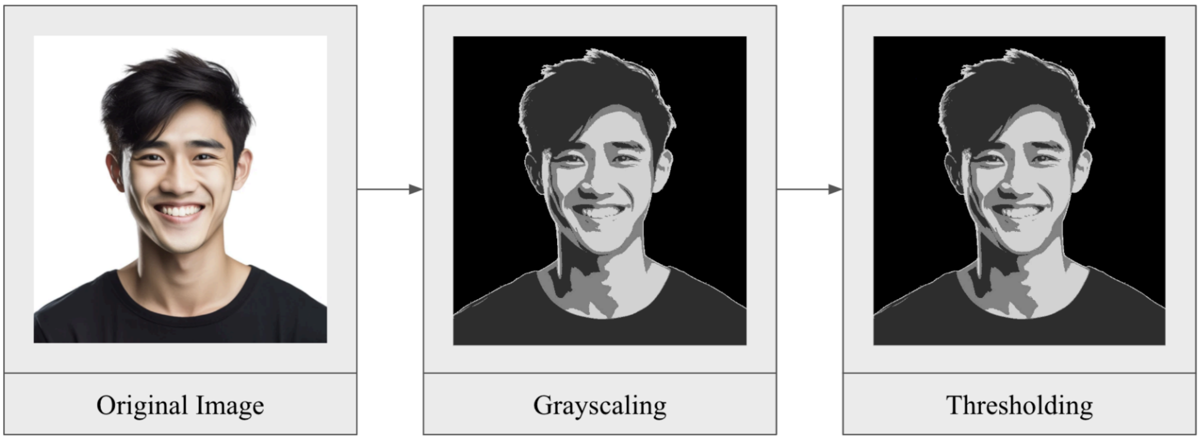

Figure 7: Image Segmentation Process

2. **Speed Optimization for Shade Variation:** Optimal speeds were chosen to produce distinct shades by adjusting the laser feed rates, ensuring shade variation without compromising engraving quality.

3. **Balancing Speed and Energy Deposition:** High speeds were balanced with energy deposition to achieve faster engraving while maintaining sufficient shade contrast.

The final optimized process allowed high-speed engraving with the necessary shade variations and minimal processing time.

5.4 G - Codes

Here is the pseudocode:

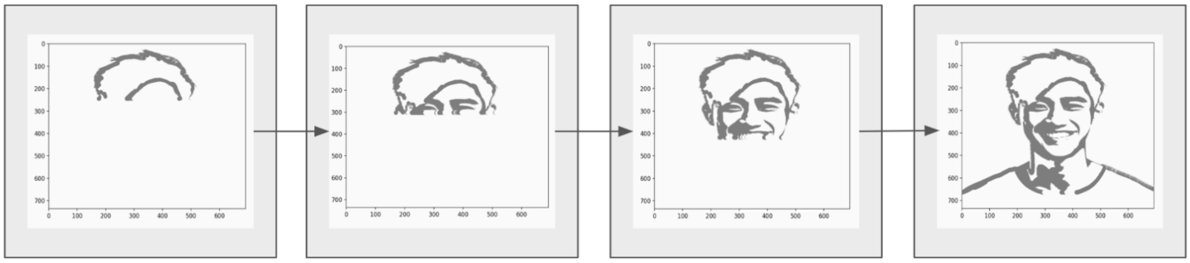

Figure 8: Printing Process

- **Input:** `image_path`, `max_size_cm`, `n_shades`, `feedrate_map`.
- **Output:** `gcode`: List of G-code commands.
- **Steps:**
  - **1. Load and preprocess the image:** Read and convert the image to grayscale.
  - **2. Resize the image:** Adjust to fit `max_size_cm` in pixels.
  - **3. Segment the image:** Divide into `n_shades`, mapping each pixel to a shade.
  - **4. Initialize G-code:** Set up units, positioning, and start laser at (X0, Y0).
  - **5. Generate G-code:** Traverse each row (zigzag pattern), convert pixel position to mm, map shade to feedrate, and generate G-code.
  - **6. Finalize G-code:** Add the command to end the program (M2).

6 Marking 3D Structures

6.1 Procedures

Figure 11 is a 3D plot showing a 3D object sliced into 2D layers at different Z-coordinates. The transparent blue slices are stacked in a step-like structure. The X and Y axes represent the object's horizontal dimensions, while the Z-axis shows its height. These slices illustrate the layer-by-layer breakdown for laser engraving into glass.

Figure 12 is a 3D point plot showing a grid of blue dots representing discrete points in the object's 3D space. The points, evenly spaced along the X, Y, and Z axes, are used for G-code generation in laser marking. The grid illustrates the object's structure, with dot density indicating engraving resolution and key points for marking.

6.2 Strategy of 3D Marking

This image shows a transparent glass block with several engraved square-shaped patterns inside which was manufactured inside the lab. The laser engraving marks are visible as slightly darkened squares, indicating regions where the laser has modified the glass structure. Engraving 1, 2 and 3 are pyramids and engraving 4 is a cube.

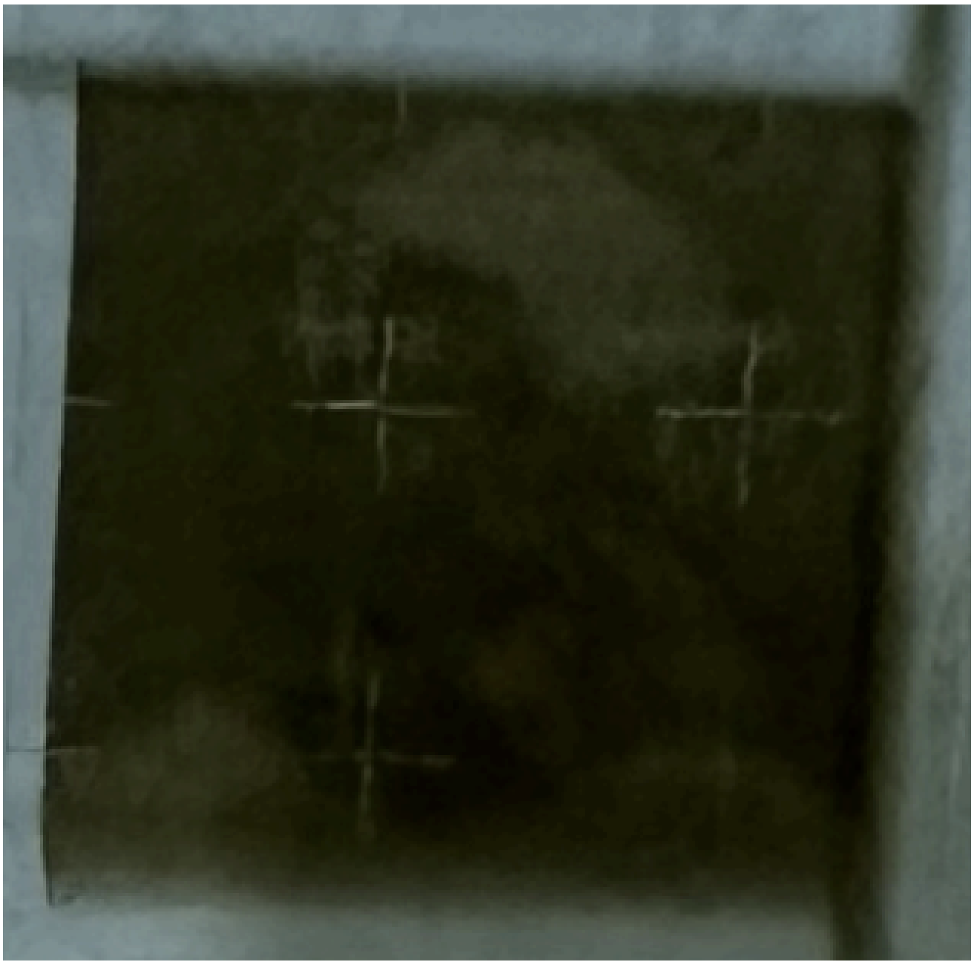

Figure 9: Results of 2D shade printing

6.3 G-Code for Generating a Reducing Pyramid

Inspired from [6], the following pseudocode generates G-code to create a reducing pyramid structure. The process starts at the base (5x5 grid) and moves upwards, reducing the size at each step.

- **Input:**
  - `move_speed`: Feed rate for movement (units per minute).
  - `max_size`: Maximum base size (5x5 grid).
  - `step_size`: Step size for grid reduction at each level.
  - `grid_spacing`: Spacing between grid lines.
- **Output:** `G-code file` for tracing a reducing pyramid grid.
- **Steps:**
  - Initialize G-code:
    - Set units to millimeters.
    - Set absolute positioning.
    - Set movement speed to `move_speed`.

Figure 10: Shade difference highlighted in the imprint

- For each `z` level (starting from `z = 0`):
  - Calculate the half size of the current grid (`half_size = max_size / 2`).
  - Trace grid lines in X and Y directions:
    - For each Y position in the range $[-half\_size, half\_size]$ with `grid_spacing`:
    - Move to the start of the X-axis line at `X=-half_size, Y=y, Z=z`.
    - Trace the X-axis line from `X=-half_size` to `X=half_size`.
    - For each X position in the range $[-half\_size, half\_size]$ with `grid_spacing`:
    - Move to the start of the Y-axis line at `X=x, Y=-half_size, Z=z`.
    - Trace the Y-axis line from `Y=-half_size` to `Y=half_size`.
  - Reduce the grid size by `step_size`.
  - Move to the next `z` level (`z += step_size`).
- Finalize G-code:
  - End the program with `M2`.

6.4 Results

The results from the 3D case were highly successful in terms of precision, shading control, structural integrity, and visual quality. The laser feed-rate and path optimization played

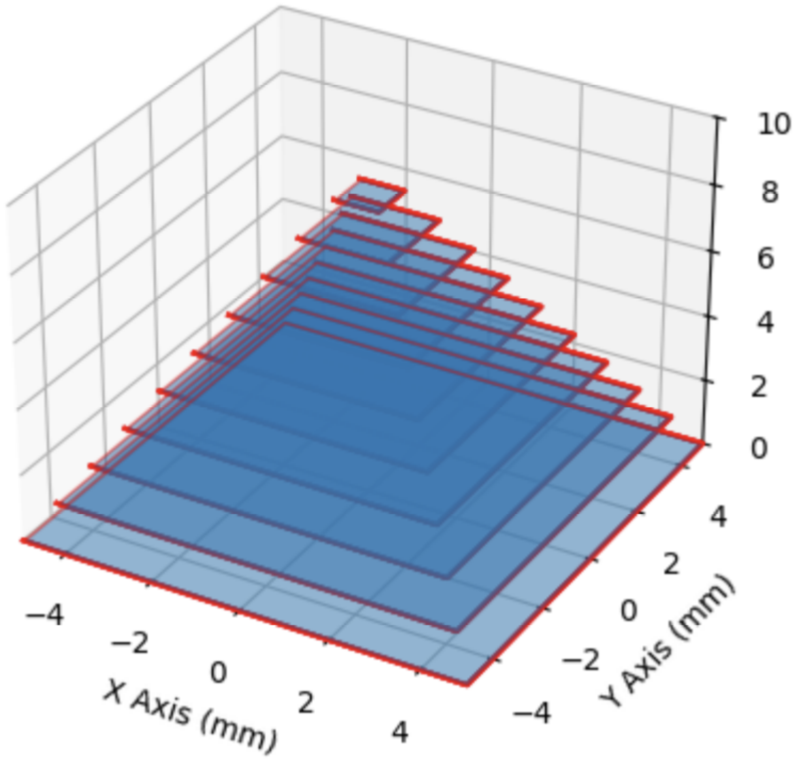

Figure 11: Making a 3D Objects

a critical role in achieving the desired 3D effects, with each layer of the reducing pyramid structure being accurately engraved into the glass.

7 Conclusions

From the experiments conducted with both 2D and 3D laser marking, several insights were gained regarding the optimization of laser engraving processes:

1. **2D Image Marking:** The grayscale image conversion and segmentation allowed for basic 2D engraving, but issues such as uncalibrated laser speeds and improper power settings led to suboptimal results. These parameters caused excessive material ablation in the Z-axis, highlighting the need for precise control over the laser's speed and power.

2. **3D Object Marking:** The slicing technique used for 3D engraving into multiple 2D layers demonstrated the ability to mark complex internal structures like grids and pyramids. The grid and pyramid patterns within the glass showed that laser ablation could accurately mark at different depths. However, the need for further fine-tuning of laser parameters and process strategies became evident to improve the clarity and precision of the engravings.

Overall, the results showed that while the basic process for both 2D and 3D marking is functional, improvements in laser calibration and power management are necessary to avoid over-ablation and achieve higher quality and resolution in engraving.

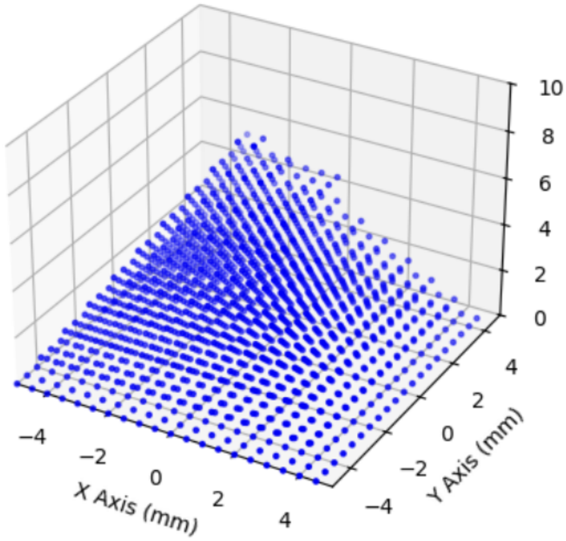

Figure 12: 3D Bit Map Creation

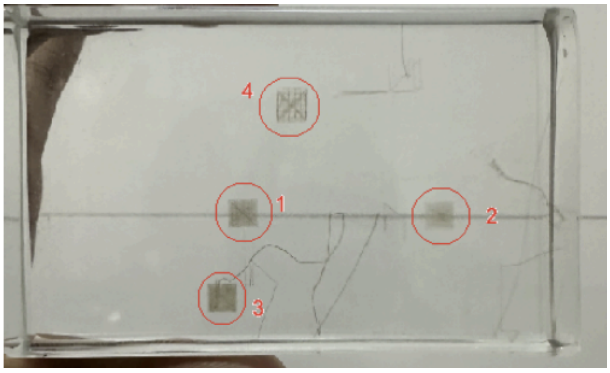

Figure 13: Printing Pyramids in a Glass Substrate

8 3D Image Engraving and Shade Mapping

This section explores the process of 3D image engraving and shade mapping, focusing on the relationship between laser parameters and engraving outcomes, as well as the development of custom software for generating G-code from image data.

8.1 Laser Parameter Optimization for Shade Variation

The engraving shade is influenced by laser power, the number of scans, and scanning speed. By adjusting these parameters, different depths and shades are achieved, enabling the creation of intricate 3D designs.

8.2 Custom Software for G-code Generation

To automate the engraving process, custom Python-based software was developed to convert image data into G-code instructions for laser engraving. The software processes multiple image layers, each representing a different depth level in the 3D structure. It

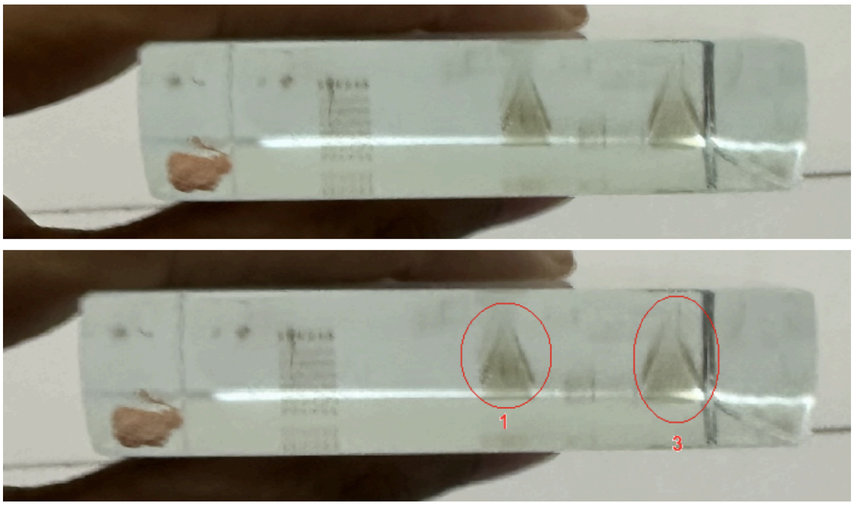

Figure 14: Right Cross Sectional View of 3D Prints

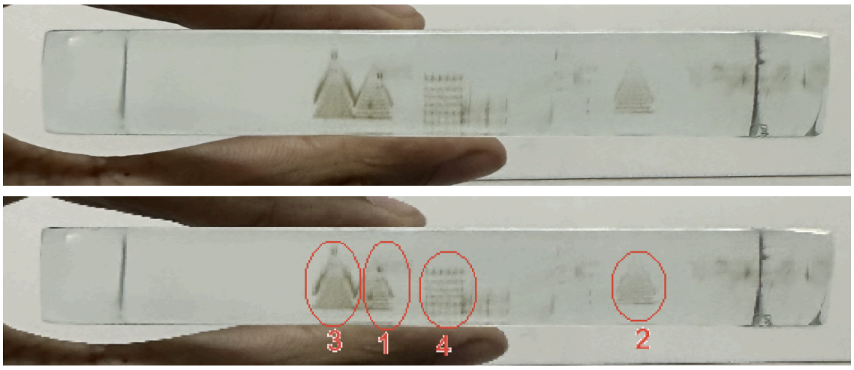

Figure 15: Left Cross Sectional View of 3D Prints

employs an iterative depth-first search (DFS) algorithm to generate tool paths for each layer, ensuring comprehensive coverage of the design.

The core components of the software include:

- **Image Processing**: Each image layer is loaded and converted into a binary matrix, distinguishing traversable paths from obstacles.
- **Path Planning**: Starting from the first traversable pixel, the DFS algorithm constructs a path that covers all accessible areas, effectively mapping the engraving trajectory.
- **G-code Generation**: The software translates the computed paths into G-code, specifying movements in the X, Y, and Z axes, along with feed rates and layer heights.

Figure 16 showcases a 3D structure engraved using the G-code produced by this software, demonstrating its capability to accurately translate image data into physical engravings.

This integration of parameter optimization and custom software development enhances the precision and efficiency of 3D laser engraving, facilitating the creation of complex designs with varying shades and depths.

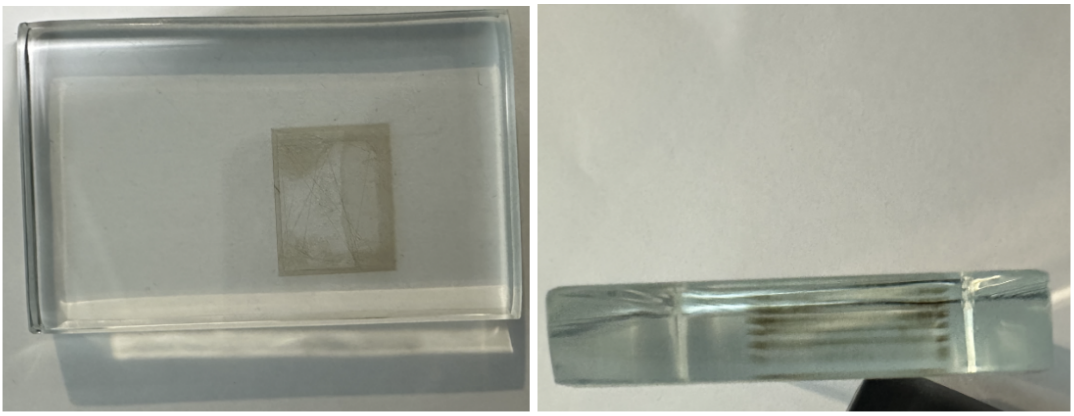

Figure 16: 3D structure engraved using custom-generated G-code

9 Future Work

The current algorithm in Figure 17 successfully converts 2D images into 3D images, with initial tests showing the feasibility of imprinting basic 3D structures. The next phase of this project will focus on refining and enhancing this process, particularly for creating fine 3D engravings, such as faces, inside glass. To achieve this, we plan to develop dedicated software capable of handling more intricate details. The future work will focus on the following key areas:

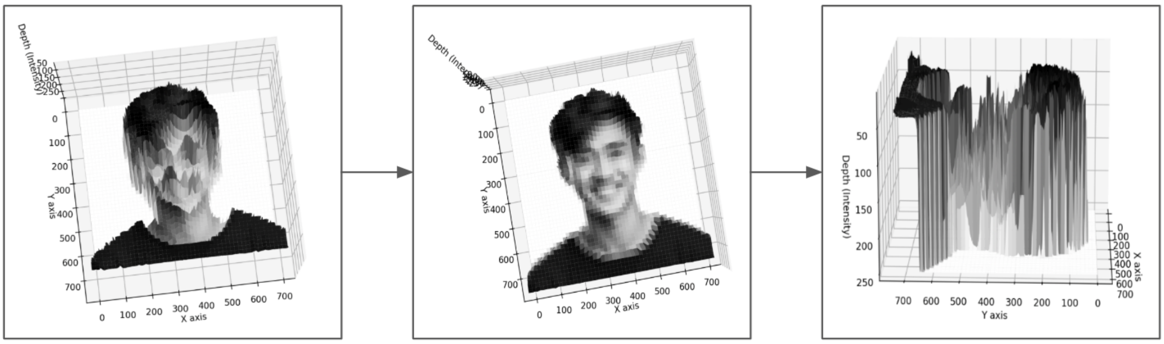

Figure 17: 3D Depth Extrapolation using intensity in 3rd Dimension

1. **Parameter Calibration:** Conduct experiments to fine-tune laser speed and power settings for different materials and depths. Develop an automated system for consistent calibration.

2. **Process Optimization:** Use advanced algorithms for G-code generation and image preprocessing to improve segmentation, shading, and depth control for complex 3D engravings.

3. **Material Studies:** Study the behavior of various materials under different laser parameters to reduce unwanted ablation and enhance engraving sharpness.

4. **Enhanced Resolution:** Increase grid resolution for finer, smoother engravings, particularly for high-precision applications.

5. **Software and Simulation Tools:** Develop software to simulate laser engraving, predict results, optimize paths, and reduce trial-and-error.

These strategies aim to improve engraving precision, efficiency, and applicability across various industrial uses, ensuring high-quality, detailed engravings.

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