Aalto-yliopisto
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**Master's Programme in Mechanical Engineering**

# Development of Methodology for Multi-Material VAT Photopolymerization Printing

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**Abstract**

This study aims to develop a methodology for multi-material vat photopolymerization printing and conceptualize a viable prototype with a reduced footprint. Vat photopolymerization is a well-established technology where detailed objects can be manufactured with photo-curable resin.

There have been previous attempts in multi-material vat photopolymerization. Their methodologies and learnings are well-studied and analyzed. The approaches to achieve fully automated multi-material printing are evaluated. In this study, a series of systematic experiments were carried out utilizing vat photopolymerization printing to understand the parameters and limitations of hardware and photopolymer resins. These experiments also investigated multi-material printing capabilities such as multi-material printing within multiple layers and within the same layer with static or dynamic layer thickness. These experiments provided valuable insights for optimizing printing methodologies and expanding the scope of multi-material printing capabilities. Concurrently, based on the above studies a prototype was developed aiming at key factors such as multi-material vat photopolymerization capability, full automation, commercial applicability, and compact form factor. Based on a commercially available vat photopolymerization printer, the new prototype was developed by integrating in-house developed hardware along with the control system.

The envisioned outcome of this research is a fully automated commercial multi-material VAT photopolymerization printer, poised to facilitate diverse applications in research and manufacturing of end-user products. This study represents a significant stride toward realizing the goal of advancing technological capabilities in the realm of multi-material printing.

**Keywords** Multi-material, Additive manufacturing, VAT photopolymerization, 3D printing, Resin printing, Photopolymer.

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# Acknowledgement

This study aimed at developing a novel product to push boundaries of technology. The idea for this project originated through a potential use case where manufacturing of a medical pill with multiple chemicals in one pill manufactured in a way where selective discharge of medicine can be achieved with multi- material printing. Hence this project was initiated with the aim of developing multi-material capable vat photopolymerization printer with compact form factor for commercial use.

I would like to express my deep gratitude to my supervisor Professor Jouni Partanen for the inspiration that sparked the concept for the project and his unwavering guidance and support throughout the project. I would like to extend my gratitude to Dr. Jan Akmal for the support and guidance throughout this study. Also, I am thankful to Mr. Roy Björkstrand for his support as thesis advisor along with the tasks performed within the laboratory and with the procurement of resources for the project. I would also like to extend my gratitude to staff at the design factory Miss. Jasmine Xie and Mr. Aaro Uitto who aided in manufacturing hardware and electronic components. Moreover, I would also extend my gratitude to Assistant Professor Mika Salmi and Additive Manufacturing Research group for the support given throughout the thesis project.

Finally, I would like to thank my family and friends who have supported me throughout this endeavour which enable to push the boundaries of technology.

Espoo, 29 December 2023
Wudith Woranga

# Abbreviations

| | |
|---|---|
| AM | Additive Manufacturing |
| BJT | Binder Jetting |
| CNC | Computer Numerical Control |
| CAD | Computer Aided Design |
| DED | Direct Energy Deposition |
| DLP | Digital light projection |
| HDMI | High-Definition Multimedia Interface |
| IPA | Iso Propyl Alcohol |
| LCD | Liquid crystal Display |
| LED | Light Emitting Diode |
| MJT | Material Jetting |
| MEX | Material Extrusion |
| MMSL | Multi-Material Stereo Lithography |
| MIPI | Mobile Industry Processor Interface |
| NC | Numerical Control |
| OS | Operating System |
| PBF | Powder Bed Fusion |
| P$\mu$SLA | Projection Micro Stereo Lithography |
| PLA | Polylactic Acid |
| SHL | Sheet Lamination |
| SLA | Stereolithography |
| UV | Ultraviolet |
| VPP | Vat Photopolymerization |

# 1 Introduction

Additive manufacturing (AM) technologies have revolutionized the world in diverse disciplines. It has revolutionized methodologies such as prototyping, end-user product manufacturing, rapid tooling (Akmal, et al., 2022) and has enabled new technologies and inventions to be born through various techniques. Out of these techniques some of them have evolved with multi material capability. Vat photopolymerization (VPP) technology has progressed in terms of theory of operation and has contributed significantly to technical spectrum in manufacturing objects which require high resolution as well as unique properties. There is a significant potential in multi-material VPP where multiple research groups have studied and developed concepts. The aim of this study is to determine the capabilities of multi-material VPP printing and to develop a feasible compact multi-material capable printing concept.

## 1.1 Background

Out of the diverse AM technologies photopolymer resin based VPP technology stands out as an AM technology which is capable of manufacturing components with a high-resolution. Usually, material extrusion (MEX) and VAT photopolymerization technologies stand out from the rest of AM technologies as significant amount of enterprises have commercialized above two technologies to a small physical footprint at a reasonable cost where they are mass produced to be used from households to large industrial environments. Out of these two, MEX has developed multi-material capability while maintaining a similar footprint as well as cost of the printer. Currently there is a lack of multi-material capable commercial VPP printers. Multi-material VPP printing involves manufacturing with the use of two or more photopolymer resins. When switching from one resin to another within the print, resin contamination should be overcome. Moreover, VPP relies on photo-curing, offering a unique set of advantages such as printing with variable layer height, etc. There are diverse range of applications that multi-material VPP would serve in the industry which demands a compact multi-material capable VPP printer at a reasonable price point.

## 1.2 Research Problem

Multi-material AM technologies have been present and have evolved along the way for a significant time. Yet there is a lack of prominent research and commercial applications on multi-material VPP technology due to a unique set of challenges. Several compelling industrial applications demand these challenges to be overcome yet at a reasonable cost as a product.

“How can a VAT photopolymerization technology developed to be capable of inter and intra layer multi-material manufacturing with static and dynamic layer height?”

## 1.3 Objective

The main objective of this study is to determine optimal printing parameters in multi-material VPP printing to explore the capabilities in inter layer and intra layer multi-material printing while maintaining static and dynamic layer heights. Moreover, the above gathered data along with previous attempts in multi-material VPP printing is systematically assessed to formulate a methodological framework. This framework is intended to serve as the basis for developing a compact multi-material VPP printer with an affordable price point.

## 1.4 Scope

This thesis seeks to explore and deepen the understanding of VPP technology, with a specific focus on its application in multi-material contexts. The research is structured around several key objectives. First, single-material VAT photopolymerization will be thoroughly investigated through a series of tests using conventional techniques. This endeavour aims to unravel the properties of single-material printing, delineate optimal operating conditions, and identify limitations inherent in the process. Subsequently, the investigation extends to the realm of multi-material VPP, utilizing conventional equipment to conduct tests with photo-polymer resins of multiple colours to demonstrate multiple materials. These tests will unravel the capabilities of inter layer as well as intra layer printing with static and dynamic layer heights.

In parallel, an extensive literature review will be conducted, delving into previous multi-material VPP projects. The analysis will scrutinize the merits and drawbacks of these endeavours and critically evaluate the methodologies employed. This critical examination will inform the selection of the most effective approach, laying the groundwork for the subsequent phases of the research. Building on this foundation, a suitable technology will be chosen from conventional multi-material techniques to initiate the prototype development. Lessons learned from the shortcomings of previous multi-material applications will be incorporated, ensuring the prototype's performance and efficiency are enhanced.

# 2 Literature Review

## 2.1 Background on 3D Printing Technologies

AM technologies offer diverse methods of operation, materials, and applications, each contributing to the versatility of this innovative field. According to ISO/ASTM 52900:2021 standard, it contains seven process categories which include material extrusion, vat photopolymerization, powder bed fusion, binder jetting, material jetting, direct energy deposition, and sheet lamination. **MEX** is characterized by the layer-by-layer extrusion of thermoplastic filaments, making it a cost-effective choice for prototyping and low-cost part production using materials like ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid). **VPP** employs a liquid photopolymer resin selectively cured by UV light or laser, excelling in high-detail prototypes and intricate jewelry designs (Gibson et al,. 2015). **Powder bed fusion (PBF)** often utilizes a laser pr electron beam to fuse various materials like polymers, metals, ceramics or composites, allowing for functional prototypes and end-use parts. The process supports wide range of materials from metals, ceramics, polymers etc (Gibson et al,. 2015). **Binder Jetting (BJT)** involves depositing a binding agent onto a powder bed, offering versatility in materials such as sand, metals, and ceramics, making it suitable for full-color prototypes and metal part production (Gibson et al,. 2015). **Material Jetting (MJT)** employs droplets of photopolymer material onto a build platform, offering high precision and multi-material capabilities for applications like high-precision prototypes and dental models (Salmi, et al 2021). **Direct Energy Deposition (DED)** is an advanced AM technique that involves the precise deposition of a material using a focused energy source, such as a laser. In DED, a material, typically in the form of powder or wire, is melted and deposited layer by layer to build up a three-dimensional object (Gibson et al,. 2015). **Sheet lamination (SHL)** builds objects through bonding and cutting sheets of materials such as paper, plastic, or metal, making it a cost-effective solution for prototyping and architectural models (Gibson et al,. 2015) . These additive manufacturing technologies cater to a broad range of industries, providing solutions for prototyping, end-use parts, and tooling across aerospace, healthcare, and consumer goods.

### 2.1.1 Technologies in VAT Photo-polymerization Printing

VPP itself consists of 3 major technologies as Stereolithography (SLA), Digital Light Projection (DLP), and Liquid Crystal Display (LCD). This is primarily based on the method of selective curing of the photopolymer resin.

As in Figure 1, SLA printing utilizes a concentrated laser which is reflected through a mirror to the transparent surface of the resin vat. The

light source is manipulated with the use of the mirror which it is used to reflect in such a way that light source traces the path of the object in a numerical control method. The vat comprises of a transparent bottom where it cures the photopolymer resin on the build platform. After completing a 2D layer of this pattern the build platform moves away from the vat surface for the next cycle.

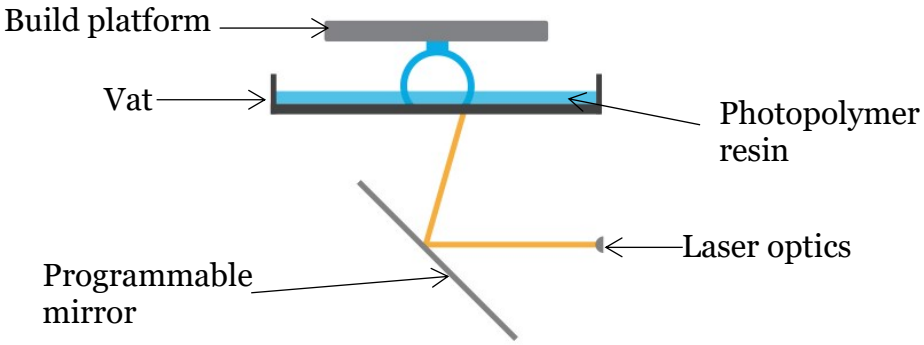


Figure 1: Schematic of SLA VPP printing (Academic accelerator, 2023)

As in Figure 2, DLP is a VPP method where the curing light source is a projected image of the desired 2D pattern on the vat surface. Hence the pattern illuminated by the light source is exposed to the resin at the bottom surface of the vat through the transparent surface. After the exposure time is spent, the projector gets switched off and the build plate moves away from the vat. This cycle is repeated throughout the build-duration.

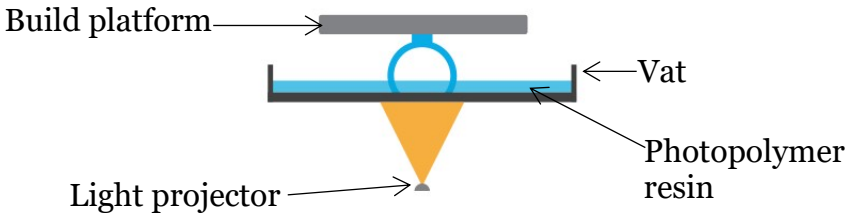


Figure 2: Schematic of DLP VPP (Academic accelerator, 2023)

VPP printing, utilizing LCD technology, operates through a vat of liquid photopolymer resin. As in Figure 3, An LCD screen positioned below the vat displays each sliced layer of a 3D model, with the screen selectively allowing UV light to pass through by the specific layer's pattern. This exposure causes the liquid resin to solidify, forming one layer of the object. The build platform then incrementally ascends, and the process repeats for each subsequent layer until the entire 3D object is created.

The final printed product is often subjected to additional UV curing for full hardening. This approach, combining the precision of LCD technology and the versatility of photopolymer resins, finds applications in diverse fields.

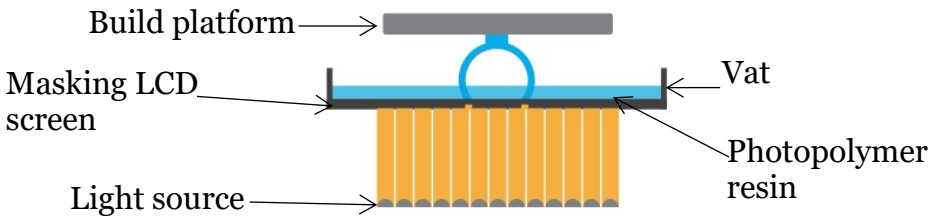


Figure 3: Schematic of LCD VPP (Academic accelerator, 2023)

## 2.2 Existing Muti-Material Capable Additive Manufacturing Technologies

Multi-material capable MJT technology is an advanced AM process that enables the simultaneous deposition of multiple materials. This technique allows for the creation of complex, multi-component structures with diverse material properties and colours in a single print run. Typically utilizing inkjet-like mechanisms, the technology precisely deposits different materials layer by layer, offering versatility in material combinations and enhancing the functionality and aesthetics of printed objects.

Multiple companies throughout the globe lead the way in multi-material jetting technology including Stratasys (Stratasys ,2023) employing PolyJet™ for intricate, multi-material prints; 3D Systems, offering printers capable of simultaneous jetting of various plastics and elastomers; and Mimaki, known for UV-curable inkjet technology in full-colour 3D printing. Palitra employs Augmented Polymer Deposition for industrial applications (Palitra, 2023), while XJet utilizes nano-particle Jetting for metal and ceramic printing with multi-material capabilities (Xjet3D, 2023 ).

Applications span diverse industries. Multi-material jetting finds prominence in prototyping for realistic product development. In the medical field, it aids in creating detailed anatomical models, implants etc. Consumer product manufacturing benefits from intricate designs, and customized manufacturing thrives with the ability to print unique, personalized items. Additionally, multi-material jetting is instrumental in producing art pieces, electronic prototypes, and various applications where combining materials enhances functionality and design.

Multi-material MEX technology advances traditional 3D printing by enabling the concurrent use of multiple materials in the MEX process. Unlike

standard MEX, which typically uses a single thermoplastic material, multi-material MEX printers have either multiple extruders (Lopes, et al,. 2018) or a single extruder (Bambu Lab Wiki, 2023) to deposit different materials simultaneously. This capability allows for the creation of 3D-printed objects with diverse properties and characteristics within a single print job.

## 2.3 Methodologies in Different Multi-material VPP Printing

As our goal is to build a compact commercially viable multi-material VPP printer, it is vital to study the previous attempts at multi-material VPP technology.

### 2.3.1 Manual Switching of Vats

When focusing the on manual switching of resin vats the time taken to switch the vats is significantly higher than that of the mechanized counterpart, yet the design of the apparatus would be less complex. Moreover, a dedicated user would be required to switch the vats.

Orientation of VAT relative to the build platform plays a key role in multilateral VAT photopolymerization as well. In Figure 4-(a), the build platform is placed in an orientation where the build surface faces downwards. This allows minimum contact of the build object with the photopolymer resin. In Figure 4-(b) the build platform is faced upwards where the whole platform needs to be submerged in the resin to cure the resin. When comparing the above techniques, it is evident that Figure 1-a contaminates less surface area of both build platform and build object compared to Figure 4-(b) when immersed in the vat. Before switching the vat, it is a must to clean the contaminated area before being immersed in the next vat. Hence all the approaches of multi-material VVP technologies have adapted bottom curing method (Figure 4-(a))

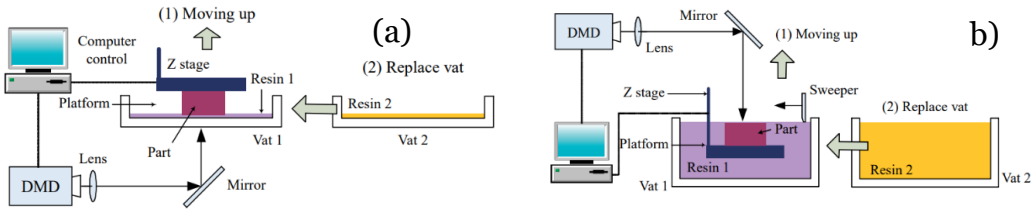


Figure 4: Multi-material VPP via manually switching resin vats (Zhou, et al,. 2019)

### 2.3.2 Mechanical Switching of Resins

The mechanical switching of resins of multi-material printing was first conceptualized by Wicker's (Wicker, et al,. 2004). This research was based on a rotating VAT carousel which enabled the moving of the VATs in a rotary path where the build platform was positioned stationary. This system of rotary switching of resin VAT was further developed by Choi's research group (Choi, et al,. 2011) where the automatic resin levelling system was introduced. They have utilized an automated syringe pump to control the resin level of each VAT which aids in lowering contamination of the build with each resin. They also had a build plate in the rotary axis to enable the manual cleaning of the build plate.

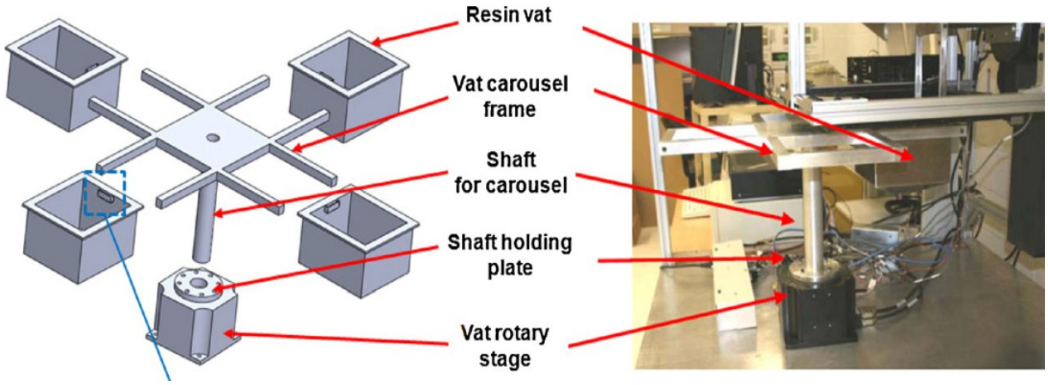


Figure 5: Mechanical switching of resins with rotary VAT carousal (Choi, et al,. 2011)

Mechanically dispensing resin puddles with an automated system was utilized by Kowasari's research group (Kowsari, et al,. 2018). As shown in Figure 6, an automated syringe system was used to dispense the puddles. This glass plate on the bottom is used to dispense the resins.

The glass plate on the bottom is used to dispense the resins. A jet stream of compressed air was used to clean the build glass surface of the resin. Henceforth resin was injected to the glass surface for the next cycle. This method was utilized for projection micro stereolithography (P$\mu$SLA) where small objects are manufactured with the technique. Hence it is more convenient to manipulate resin with syringe to deposit in the vat surface and to clean the resin with air between the cycles as the resin volume used in each layer is relatively small compared to conventional VPP methodologies.

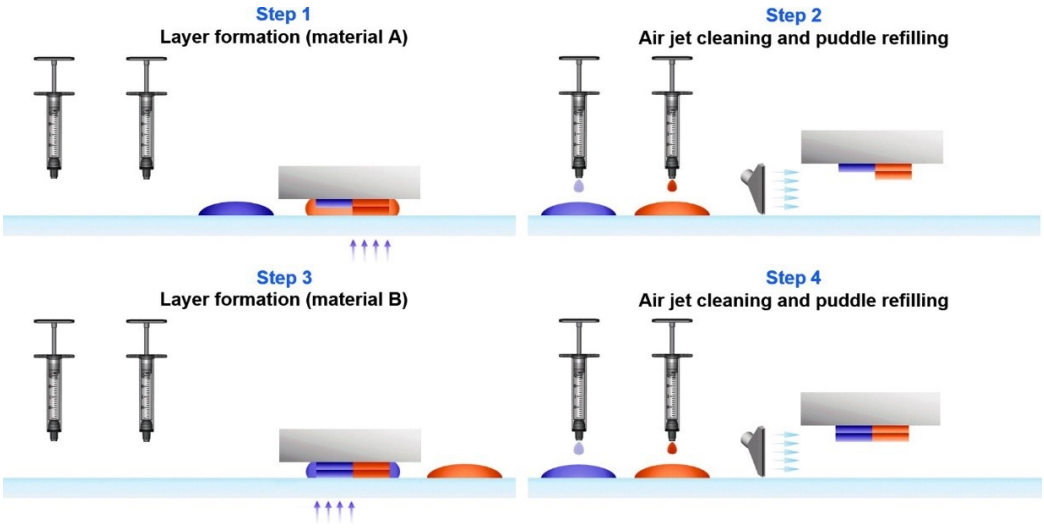


Figure 6: Mechanism of switching resin with dispensing puddle of resin (Kowsari, et al,. 2018).

### 2.3.3 Manual Cleaning

In prior literature of multi-material VPP printing, there is a notable absence of an automated solution for cleaning both the build object and the build platform, where manual cleaning techniques are followed. This would often require the built platform to be removed from the assembly where it could be cleaned in a separate chamber to be properly cleaned or an additional mechanism would be needed to move the build-platform away from the VATs.

In this project, manual switching of VAT was followed in the testing phase with the use of a commercial VAT photopolymerization printer. In this process, the build platform had to be removed to clean the contamination by the initial resin with disposable tissue soaked in IPA. After cleaning the build platform, the build platform was fixed to the printer to resume the print with the following resin. Manual cleaning would consume time elapsing from 5mins to 15mins depending on the contamination level.

This process inherits defects in the build process as when pausing the print mid-stage, the build platform rises to a higher level. This might induce stepper motor backlash as the backlash error induced due to motion from the set position to a far position and return to the original set position is also significant. When fixing the build-platform after the manual cleaning stage there is a possibility for occurrence of a deviation in the positioning of the build-platform compared to its original position before switching the vat as there are errors incurred in tightening fasteners manually.

### 2.3.4 Ultrasonic Cleaning

Ultrasonic cleaning is a widely used cleaning technique in the world in numerous fields including medical surgical instruments, jewelry, the automotive industry, etc. Ultrasonic cleaning implies the promise in cleaning objects that require extensive cleaning and objects that are fragile under loads that may occur under movement made due to conventional cleaning methods.

Typically, ultrasonic cleaning utilizes water or a water-based solution with a cleaning agent. Hence water-soluble resins would not require any special solvent and can be cleaned with conventional small scale ultrasonic cleaners as in Figure 7.


Figure 7: conventional low-cost ultrasonic jewellery cleaner.

Most of the photopolymer materials commercially available in the market are not water-soluble. Hence solvents such as IPA are required to clean the polymer resin from the cured surfaces and build platforms. The use of IPA in an ultrasonic clear has a major drawback as IPA bearing a flammable liquid could ignite if it reaches flash point under ultrasonic cleaning conditions (Microcare, 2023).

There is a potential danger in spark formation due to the ultrasonic transducer and due to the presence of flammable vapor above an IPA solution, its forbidden to use liquids such as IPA in conventional ultrasonic cleaning equipment. The company “Elmaultrasonic” (Elmaultrasonic, 2023) has introduced an active vacuum ultrasonic cleaning device as in Figure.8 This system utilizes a series of techniques to remove any oxygen of flammable solvent vapor from the chamber containing the solvent.

Yet Elmaultrasonic’s machines are not compact nor open to the outer atmosphere which requires maintaining a vacuum seal from the outer environment. Due to complex components within the equipment, the size of the object would not be optimal for the proposed compact VAT

photopolymerization printer as well as would induce more complexity to the operation.


Figure 8: Vacuum ultrasonic machine capable of cleaning with flammable cleaning solutions ( Elmaultrasonic, 2023)

NASA published an article (NASA, et al,. 1961) regarding the use of flammable cleaning solvents in ultrasonic cleaning applications. As per Figure 9, the part to be cleaned is placed inside an enclosed plastic bag where it is clamped from the top. The tank itself is filled with water and the ultrasonic transducer is exposed to water. Ultrasonic pulses reach the part to be cleaned through both cleaning solvent and water. This method is widely utilized among the communities as a cost-effective method to clean parts that require cleaning with a flammable solvent.

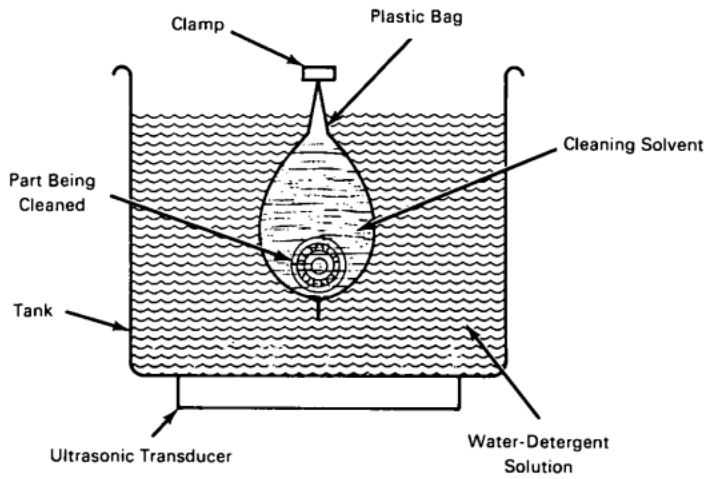


Figure 9: Ultrasonic cleaning with use of flammable solvent which is not exposed to the transducer (NASA, et al,. 1961)

### 2.3.5 Advantages and Shortcomings in Previous Setups for a Commercial Multi-Material Printer

Different approaches to multi-material VAT photopolymerization printing have adapted unique methodologies to address challenges faced in executing multi-material print. The most basic solution of manual switching of resins can be executed with use of commercially available vat photopolymerization printer with the requirement of modifying the operational sequence in slicing software. The challenges face in this approach is having to switch the resins manually while cleaning the system manually as well. This increases machine downtime and prone to mishaps and errors while switching the vats.

Wicker's and Choi's (Choi, et al,. 2011) approach to multi-material photopolymerization involving automating the switching of resins have minimized the need of human interaction. Yet rotary system does not necessarily enable the overall setup to be compact. Kowasari's (Kowsari, et al,. 2018) approach of dispensing the resin restricts the use case of multi-material printing to micro level (dimensional) objects.

Moreover, almost all the approaches do not provide a sound methodology to automate the cleaning of the build platform and the build object in between switching of vats where it is crucial that the resins do not contaminate each other when the build platform along with the object is switched in between.

# 3 Building the Prototype

## 3.1 Background and Working Principle.

It is a vital requirement to develop a multi-material capable VPP printer which could demonstrate the capabilities of Multi-material VPP printing. Having a low physical footprint would potentially enable novel research and industrial applications in diverse sectors.

As discussed in the literature review, out of 3 types of VPP printing technologies, one type of technology had to be ruled in to select the best one with the ability to modify easily with least effort. Also, the technology should facilitate modification which would enable multi-material capability as well.

Use of SLA printer would enable multi-VAT curing with the same laser, yet it requires manipulation of the laser optics with the use of a movable mirror and numerical control program. Hence it would be a challenge to program the curing laser for multiple VATs while the build plate is changing the VATs compared to LCD typed VPP printer.

Another important aspect of selecting a base printer for the prototype development would be the accessibility of the hardware to modify into a multi-material capable printer. It would be ideal to initiate with an existing printer where the functionality and nature of the hardware components associated with commercial VPP printers are studied to observe the design aspects of the printer while serving as a platform to develop a potential commercial multi-material capable VPP printer.

## 3.2 Commercial Printer and Functionality

The prototype was aimed to demonstrate Multi-material VPP printing of two photopolymer resins along with a cleaning function. Moreover, it was determined to develop at two stages where initially two vats that can accommodate two photopolymer resins are built along with the option to clean the object along the build cycle. Also, it is a vital factor that the result would be a compact solution to be able to have diverse industrial applications.

The company “Creality” (Creality, 2023) has introduced a wide range of LCD VPP printers which are relatively low cost and would enable modifications relatively easily. The model Halot One (Creality store, 2023) as in Figure 10, which costs around 150euros, was selected and it contains the following features.


Figure10: Creality Halot One VPP printer (Gsm arena, 2021)

The main build plate has a build area of 127 x 80 mm². The build plate is movable in one axis with the use of a stepper motor and a lead screw. This enables precise motion in the vertical direction. This allows an object with height of 160 mm to be printed. The VAT itself comprises of a transparent bottom where the UV curing occurs.

The Halot One printer utilizes a LCD type VPP where a Monochrome display manipulates the area of UV light exposed to the object. As in Figure 11, the UV Light Emmitting Diode(LED) located at the base of the printer floods the LCD screen with UV light. The LCD screen selectively exposes UV light on the photopolymer resin based on the image displayed on the LCD screen.

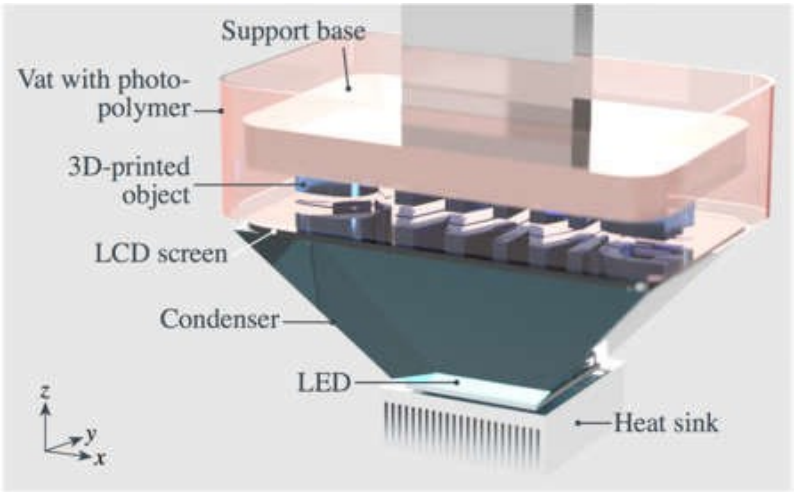


Figure 11 : Operational components of LCD VPP printing (Malas, et al,. 2019)

Here the UV light source intensity is maintained at a constant level and the light is switched on and off by the main controller. Simultaneously the LCD screen masks the resin hindering any light exposure on the resin.

The operational sequence of the VPP printer is as follows:

- Initially the build platform is topmost home position where it detects the home position with use of a limit switch.
- The build platform screws are loosened and moved down until it is against the bottom of the vat. The loosened screws are tightened so that the build platform surface is parallel to the curing surface/vat bottom. Hence calibration of the build platform at the bottom position is complete.
- The build plate moves up to the clearance level which is predefined in the printer setting (from 6 mm-10 mm).
- The build plate idles at clearance level for predefined time. This allows photopolymer resin to reset at the base of the vat. The idle time is set based on the viscosity of the resin.
- The build plate moves to the bottom position to initiate the base layer where the build plate is positioned at a height of one layer thickness above the vat bottom.
- The LCD screen is projected with the desired 2D image and UV light is projected by the controller. The UV light exposed time is set in the control program.
- After the exposure time is completed the UV light is switched off and the screen is darkened.
- The build plate moves to the clearance level and holds for a designated time for the resin to settle down in the bottom of the VAT.
- Afterwards the remaining cycles are repeated.

## 3.3 Proof of Concept

To demonstrate a multi-material printing capability, it is vital have an automated methodology for vat switching, apart from manual switching resins. It could be rotary, as in choi's implementation (Choi, et al,. 2011) or linear motion. In the demonstration of compact multi-material VPP 3D printing it would be favourable to have two photo-polymer resins along with a method to remove the contamination of resin when switching the VATs. Hence having only two resins would enable to utilize a simpler linear design which require fewer moving parts. A linear actuated build plate would enable switching of VATs as conventional VPP techniques already utilize motion in vertical axis to move the build platform. In this study vats themselves would not be moved as the build platform is switched between the vats. The accuracy of the linear actuation is well over the required limit where it was pre-calculated in the design stage of the hardware and is discussed in the following chapters.

The multiple vats requirement is fulfilled by the use of the same vat in the commercial printer which is divided into compartments. Hence this enables use of single LCD screen which overlaps both of the vats. Utilizing multiple screens and curing hardware for each vat would incur more complexity and cost to the final prototype. To visualize the operating principle of the multi-material printing a sample object can be designed as in Figure 12.

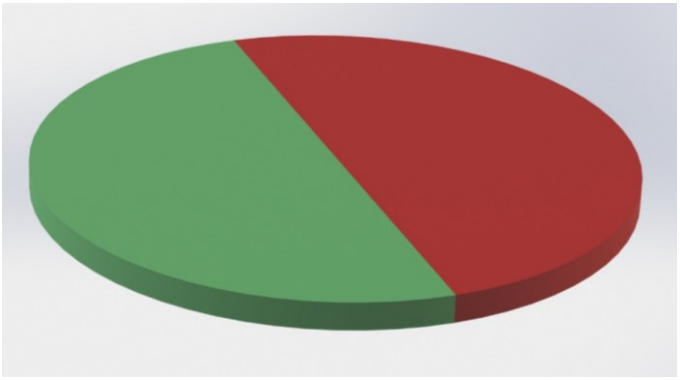

Figure 12: Sample object for visualizing the multi-material VAT photopolymer printing.

As this object is constructed with two materials as red and green, two separate resin material along with separate VATs would be required. The base layer of the object would be halves of the circle separately cured in two individual resin materials. The single vat is partitioned into two vats as vat 1 and vat 2. Figure 13 depicts the curing region of the single layer of both materials in each vat of the sample object.

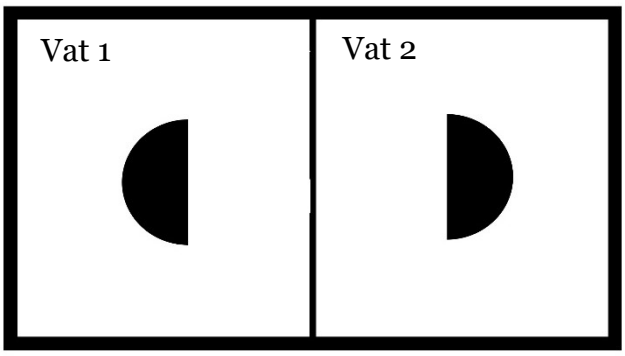


Figure 13: schematic of projection of image on two VATs

The separate segments of each layer must be processed where each layer segment should be projected to the display. Hence if the green segment is printed in Vat 1 the red segment would be printed in vat 2. The images

should be projected in the accurate position in the display so the corresponding segments in the layer. Since the images are manipulated in the same display, placement of the image within the given resolution is crucial.

Figure 11 illustrates the proposed multi-material VPP schematic in front view. The design consists of two vats (depicted in Figure 12), cleaning station, position of the build platform and the operation of UV light. The Figure 11 exhibit as a reference for Figure 14, multi-material VPP operational sequence.

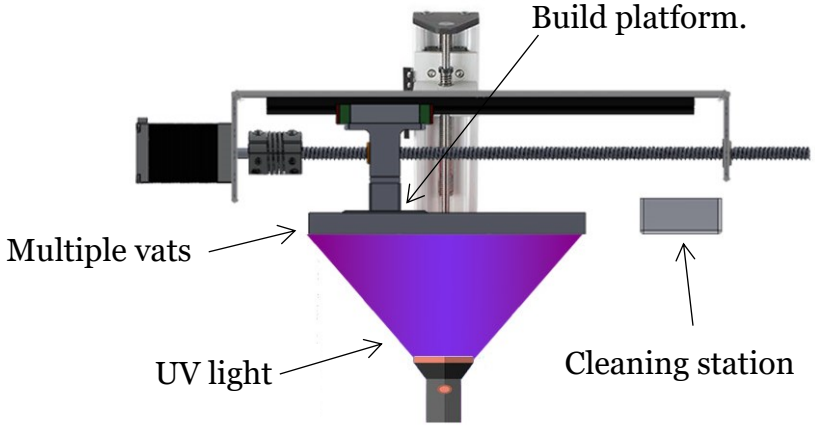


Figure 14: Schematic of the proposed multi-material VPP setup

This projection is executed in a sequence as in Figure 15. The position of the build plate over the vat and cleaning station, operation of UV light and the depicted image over in the LCD screen is to be highlighted. Here at step 1 the build platform is inserted into VAT 01 and the desired pattern to be exposed is projected in the display in the corresponding segment. The UV light is exposed on the display to cure the pattern. After the curing cycle is complete, the UV light is switched off, and the build platform is withdrawn from the VAT with the use of vertical axis actuation and switched to the cleaning position. At step 2, the cleaning station the build plate is carefully washed with a solution which is the solvent of the photo-polymer resin in both VAT 1 and VAT 2. In this, no UV exposure occurs as well as the display blocks any light reaching the VAT. At the final stage step 3, the build platform is placed in VAT 2 at desired height for the build, and image 2 is displayed at VAT 2. Simultaneously the UV light is switched on the photo-polymer resin at VAT 2 is selectively cured in the build platform. Upon completing the steps as above the initial layer is completed and the following layers are repeated in a similar procedure.

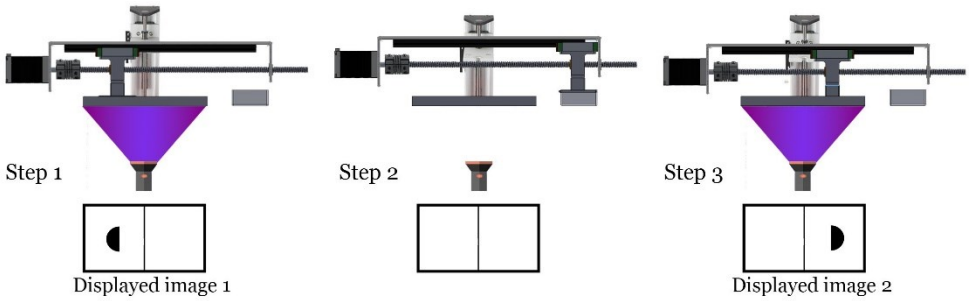


Figure 15: Steps in multi-material VAT photopolymerization

## 3.4 Prototype Build

To enable the build plate to switch from one VAT to another, an additional linear motion is required. Hence a setup with a stepper motor along with a lead screw thread bar would provide linear actuation with precise positioning in the horizontal direction. The stepper motor selected for horizontal linear actuation is model 39bygh405b; 12V bipolar stepper motor which it is lightweight compared to the conventional nema 24V stepper motors. The threaded bar selected for to convert rotational motion to linear motion was 6mm lead screw with a pitch of 1mm (from conventional 8mm with 2mm pitch) so it also contributes to lightweight and precise motion as error due to motor overshoot is reduced in half.

Linear error of the horizontal actuation occurs due to the error in motor step rotation. As per the data sheet of 12V stepper motor (Annex C), the step angle is 1.5° with an error of ±5%. The linear error can be calculated as follows,

$$Linear\ error = \frac{stepper\ step\ size\ \times error \times pitch\ of\ the\ lead\ screw}{360°}$$

$$Linear\ error = \frac{1.5° \times 0.05 \times 1\ mm}{360°}$$

$$Linear\ error = 2.084 \times 10^{-4}\ mm$$

$$= 0.2\ \mu m$$

Hence the linear error 0.2 µm is negligible compared to the 50 µm linear accuracy of the printer in XY directions.

The coupling between the lead screw and the stepper motor is flexible which aids to mitigate the vibrations induced by the misalignment of the centers of the lead screw and the output shaft of the motor. The lead screw is held with a 6mm inner diameter flanged bearing at the other end.

Since lead screw mechanism is a rotating linear guide. A small buckle in the lead screw might affect the geometry of the build platform which is attached to it. Stability of the build platform is crucial in VAT photopolymerization printing as the resolution is at a 10 µm level. A HGR-20 liner guide rail as shown in the Figure 16, was used in parallel with the lead screw to ensure smooth linear motion of the build platform along with the lead screw.

Figure 16: HGR 20 linear rail (Image courtesy: Maker store, 2023)

The bracket holding the above parts was manufactured using a 3 mm aluminum sheet as it is lightweight as well as easily machinable. The bracket was manufactured with the use of a waterjet cutter (Model; ProtoMax Omax) (Figure 17 right) and bent with a metal bending machine to fit the exact profile so that the centers for the stepper motor and flanged bearing align co-centric way. (Figure 17 left)

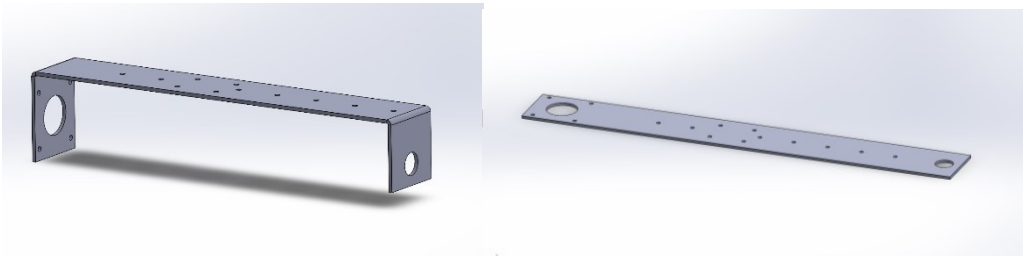

Figure 17: Design of machined sheet metal (right), machine bent part (left)

The flanged bearing is press fit to the bracket and lead screw was machined to fit the coupling. The linear rail was fastened to the aluminum bracket which also added additional rigidity to the bracket. Hence, all the elements were assembled (As in the Figure 18).

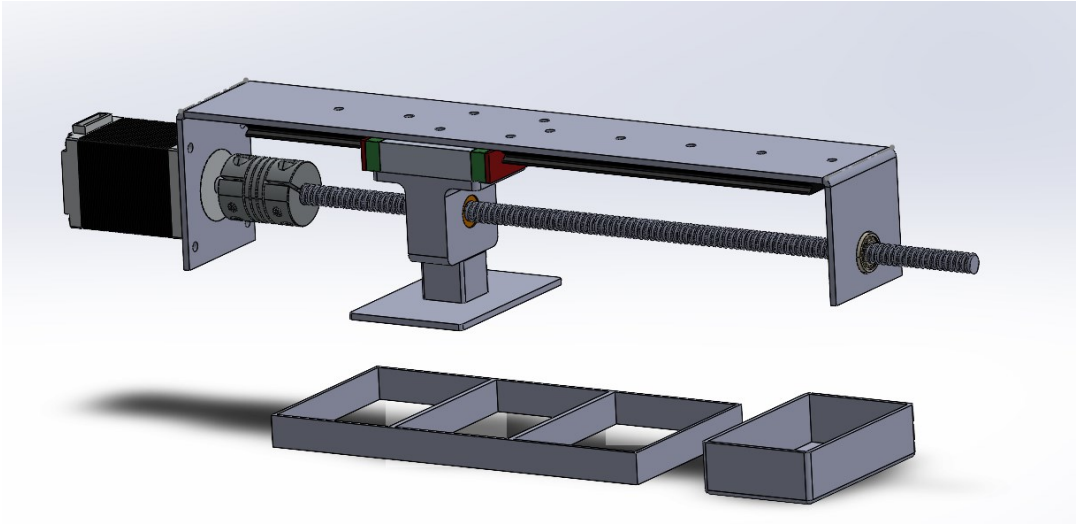

Figure 18: Designed assembly attachment to enable multi-material printing.

The whole assembly is fitted to the position where the build plate of previous printer was with the same fastening positions. This allows to align the new setup with the curing setup. The frame itself is aligned to the left as in Figure 19 so that the weight of the stepper motor balances with the rest of the frame allowing the center of gravity of the new attachment to be close to the mounting point. This also allows a separate area for protentional automated cleaning station outside the curing area.

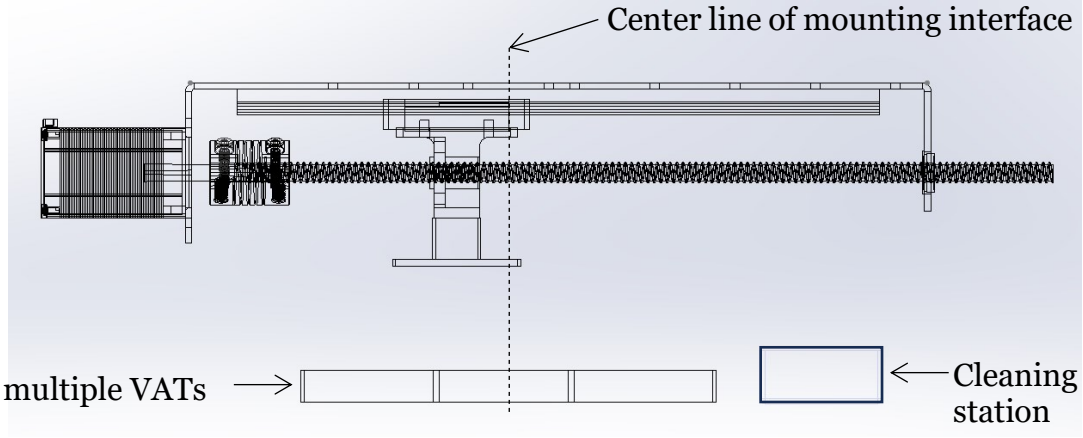


Figure 19: Front wireframe view of the CAD with VAT positions and cleaning station

Upon manufacturing the assembly, it is vital the build plate surface remains parallel to the curing surface (VAT bottom) while it translates along the horizontal axis to switch between VATs. It would be ideal if it's possible to calibrate the above assembly to ensure linearity along the horizontal axis. The bracket developed (Figure 20) to mount the linear rail, lead screw along with build plate was modified an additional support to facilitate a dial gauge as in figure 20. The adapter was manufactured using material extrusion 3D printing technology with PLA (Polylactic Acid) as material. Ultimater 2+ connect was used in manufacturing this component.

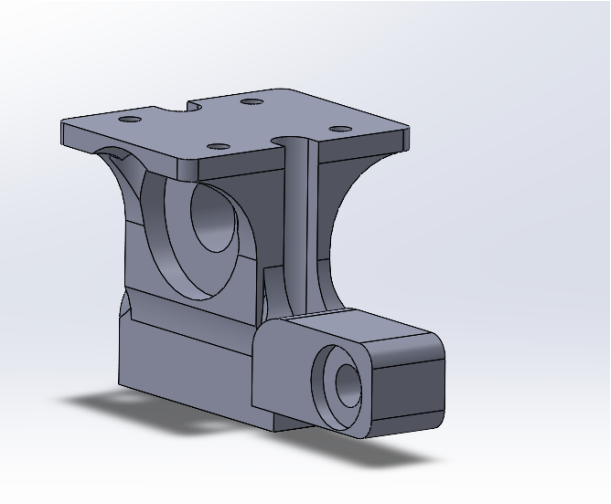

Figure 20: CAD of the build platform adapter mount which facilitates dial gauge.

The primary bore of build plate adapter has a 10mm diameter [Annex CAD Drawings of Build Platform Adapter] along with a flange for the lead screw nut. The lead screw nut (Figure 21-a) which is manufactured of brass material is press fitted to the build plate adapter and further secured with self-tapping screw into adapter. The nut and the lead screw were well lubricated with silicon-based grease to reduce friction and smooth operation of the linear actuation.

An analog dial gauge 0.01mm of resolution as in Figure 21-b was mounted in the 5.6mm bore in the protruding arm in the build platform adaptor as detailed in Appendix B. Afterwards, the horizontal actuation assembly was completed along with the dial gauge as in Figure 22. With use of the horizontal actuation stepper motor, the dial gauge pointer was dragged along the curing surface where the deviation of the level was observed and was calibrated with adjustment screws in the interface between the new developed bracket and the chassis of the existing printer.

a b

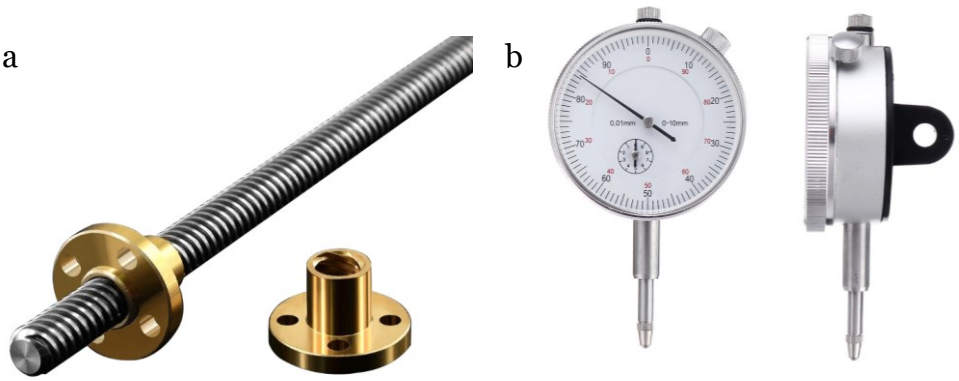

Figure 21: 6mm lead screw with brass nut (Image courtesy: Tevoup , 2023) Analog dial gauge Front view and side view (Image courtesy: IFC.com/blog, 2022)

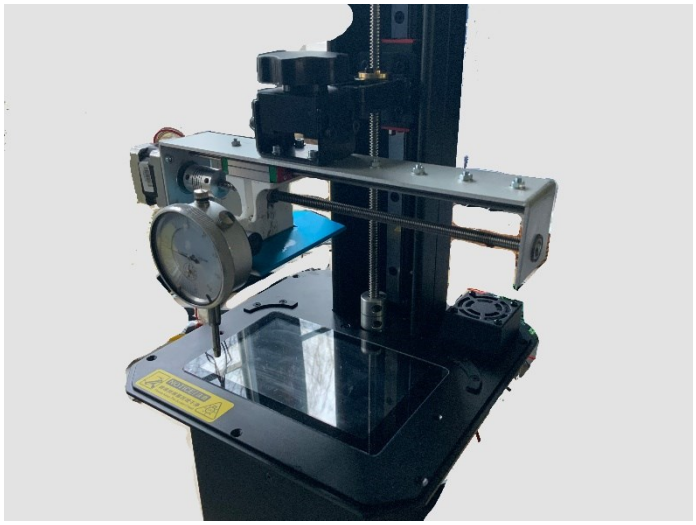

Figure 22: Printer setup with the dial gauge for calibration.

The build platform is manufactured using modification to the existing build platform of a commercial VPP printer. This is due to the ease of accessibility to build platforms of such printers and there is a significant cost and time saving in modifying an existing build platform rather than manufacturing from raw material. The critical factor is that the mounting interface of the build platform to the printer facilitates the build surface remains parallel to the curing surface. This is further achieved and validated with the dial gauge in the previous steps. After the calibration is complete, the dial gauge is removed. The build platform switching assembly is completed as in Figure 23 with the build platform of 60X87mm$^2$ surface area.

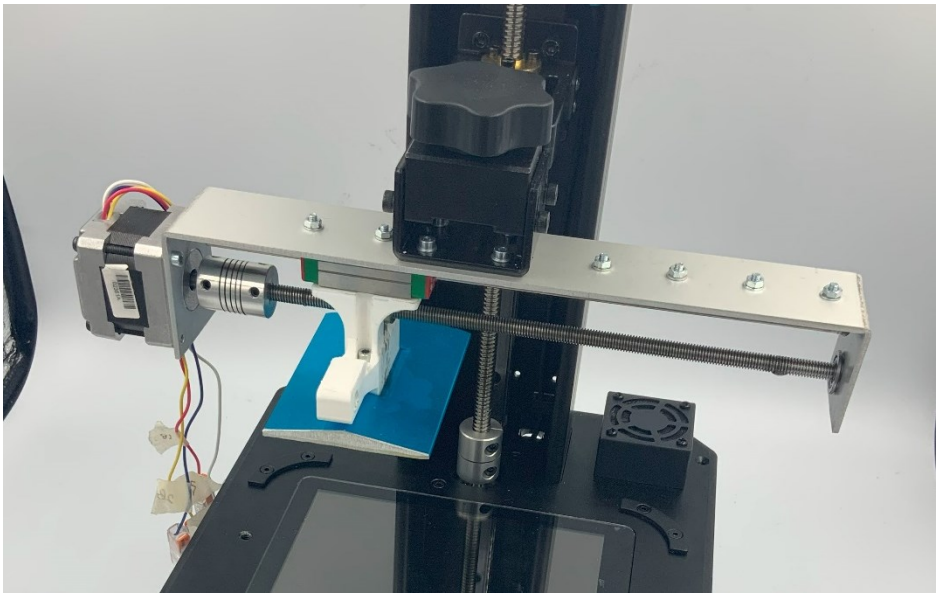

Figure 23: build platform switching assembly assembled to the main chassis of the printer.

### 3.4.1 Projection Setup

The original monochrome display which was used to project the image correlated to the specific layer had to be replaced due to the driver of the display being proprietary to the manufacturer. The Halot One commercial 3D printer was equipped with 2560 x 1620-pixel resolution monochrome display with FPC (Flexible Printed Circuit) interface as the Halot One utilizes a priority control board to control the actuators, sensors, display, and all the other power circuits. A new monochrome IPS (In-Plane Switching) LCD with a driver was selected with 2560 x 1620 resolution (as in Figure 24). The display contains an FPC connector. The display driver contains a High-Definition Multimedia Interface (HDMI) connector which enables it to connect with a companion PC or microcontroller along with a 5V power input. The driver, being a generic hardware component, contains a MIPI (Mobile Industry Processor Interface). A MIPI to FPC converter was used to connect the display to the driver as the driver utilizes a MIPI ribbon connector.

The new screen which was selected was 6.01inch in diagonal length to match the cutout grove in the Halot one chassis. Hence no modification was needed in the Halot one chassis to facilitate the new display. The desired image can be projected onto the display with the use of a PC or a capable micro-controller.

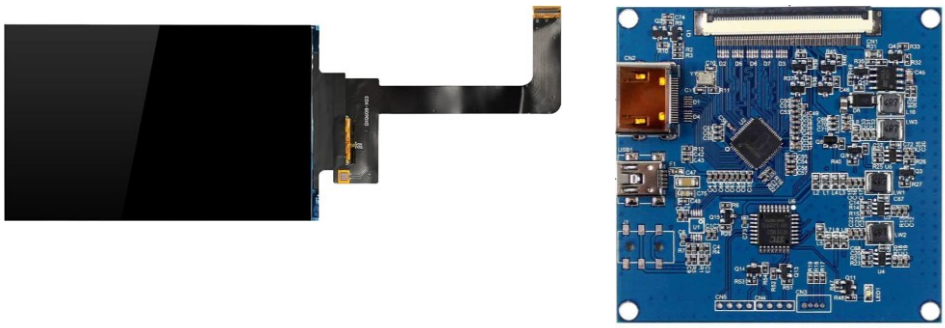

Figure 24: LCD monochrome display(left) and display driver (right)

### 3.4.2 VAT Modification

The vat itself had to be modified to accommodate 2 resins. Hence the vat of Halot one printer was modified so that there is a liquid-tight barrier dividing the vat to two equal sections as in Figure 25. The resin holding capacity is significantly lower in the new setup due to the separation barrier height is set at 5 mm. The original VAT has a capacity of 300 ml of resin.

Maintaining a lower resin level is beneficial so that it induces lower contamination of the build platform and the building object after a curing cycle as it is a requirement to clean the build platform and the build object in while switching the resins. Yet due to the lower resin input, builds which require larger resin volumes would require refilling of VATs in the mid build process.

Figure 25: Modified VAT to accommodate 2 resins.

## 3.5 Controller Setup

The commercial printer that was selected to build the Multi-material VAT photopolymerization printer is equipped with a single-board proprietary controller. Hence modifying and updating the control software as well as adding new hardware input and outputs was restricted. The requirement for a new controller was apparent.

Initially, the controller choice for the above application was Arduino Uno given the simplicity of working with actuators such as servo motors as well as sensor modules. Yet having a controller with a separate operating system (OS) and graphic manipulation capability without having to utilize additional graphic hardware is an added advantage.

Hence Raspberry Pi 4 was selected as it runs on Linux-based Raspbian OS which enables to development of the prototype without the need for an additional Computer. Raspberry Pi has 2 video output interfaces (HDMI) so that we can manipulate the image on the display and observe the development source code and status of the overall system at the same time.

The controller framework as in Figure 26 was set up to accommodate the requirements of the overall system and consideration of required voltage levels and power demand.

There are two TB6560 stepper motor drivers utilized in the system to control the stepper motors which are used in vertical and horizontal movements of the build plate. The stepper motor utilized in the vertical movement is 24V. Hence the maximum voltage input in the system is 24V.

A 130W step-down buck converter was used to power the stepper driver 12V as the stepper motor which powers the horizontal movement of the build plate operates in 12V of input power.

A LM2596 buck converter is used as a step-down 24V to 5V to power Raspberry Pi, the cooling fan for the Raspberry Pi, and as the logic level converter.

Raspberry Pi signal output is at 3.3V for pin high signal (1) and 0V for pin low signal. However external modules such as stepper motor controllers commonly utilize +5V as a high signal (1) and 0V as a Low signal (0). Two IIC I2C logic level converters were used to convert the logic level from 3.3V to 5V to control the stepper drivers with the use of Raspberry Pi.

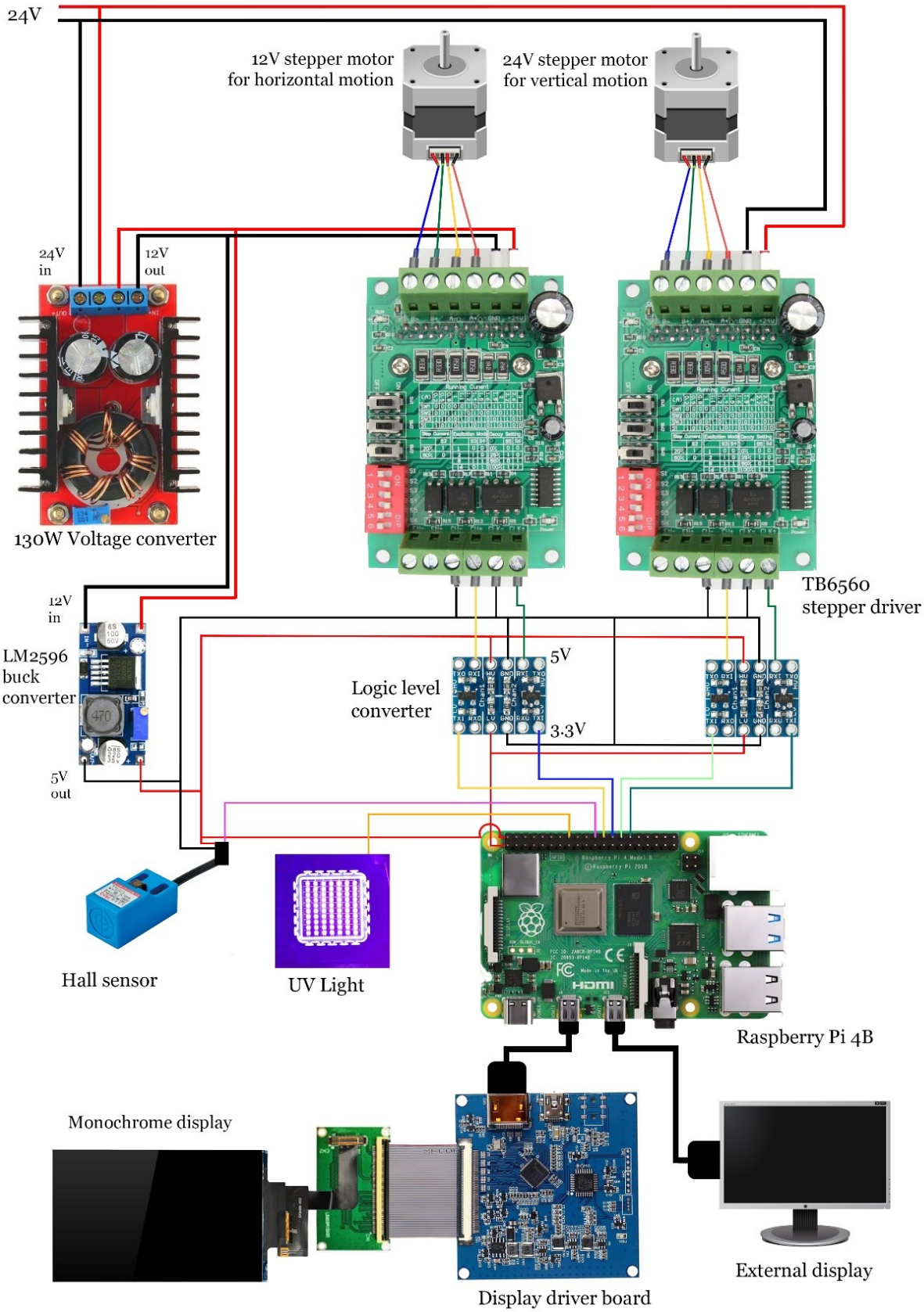


Figure 26: Schematic of the control setup

## 3.6 Proposed Motorized Cleaning Methodology

After observing the manual cleaning process, a potential mechanized cleaning process can be a mechanism to mimic the manual method. As of Figure 27, a brush which is formed in a belt-shape and driven with a motorized roller and an idler roller is placed in a bath of IPA or water. When the build platform is lowered to the cleaning station, the roller brush which was in contact with the solvent scrubs off the resin from the build platform and the build object. The photopolymer also gets dissolved upon contacting the solvent. After the bristles of the brush extract resin, it gets dipped in the solvent to clean the brush itself to be ready for the next cycle.

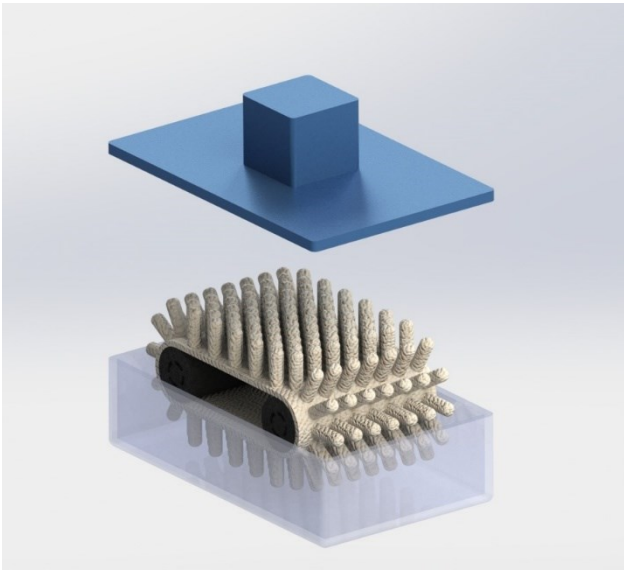

Figure 27: Spinning brush dipped in a cleaning bath to build the build platform between switching of vats.

Hence the resin extraction from the build platform to eliminate the contamination would be completed depending on the level of contamination and the nature of the object.

# 4 Testing for Multi-material Printing

The initial testing of the LCD VPP printing was aimed at understanding parameters such as exposure time, initial exposure, layer height, resin chemistry as well as the geometry of the model on the print quality. Subsequently multi-material printing capabilities of the VPP technology was aimed to test. For multi-material testing it would be ideal to utilize the fabricated prototype where it would be beneficial to test the prototype as well. Yet due to time constraints and limited resource availability, multi-material testing was done with use of conventional VPP printer.

A sample test model was designed as in Figure 28. The sample has a height of 10mm where it is segmented into 3 segments which have varying cross sectional area. The base is 20mm in diameter and the follow-up sections are 15mm and 10mm respectively. The base layer has a chamfer at 45°. In VPP printing the vat itself has a flexible bottom. This is to ensure the cured resin is bonded to the build plate rather than the vat where when curing is complete, and the build plate moves away from vat the build gets separated from the vat by deformation of the bottom of vat.

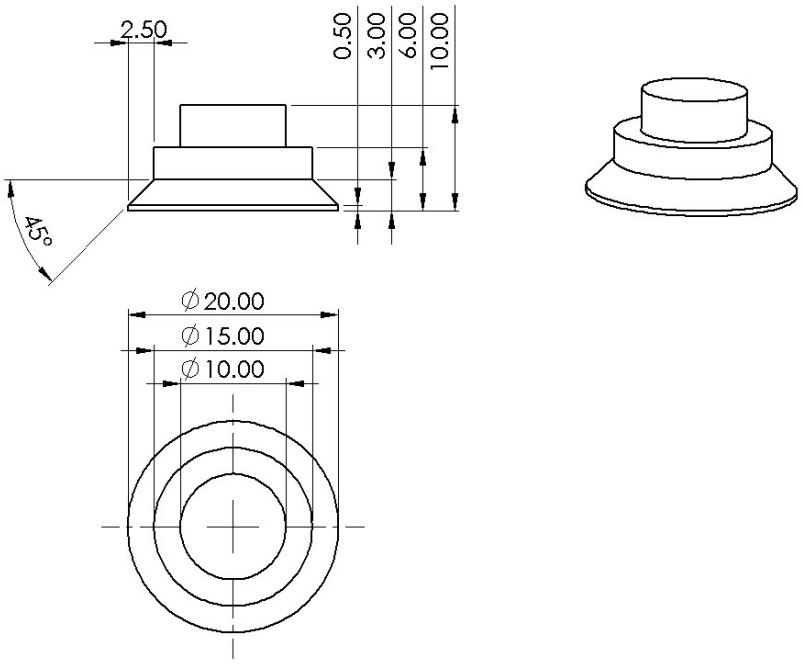


Figure 28: Schematic of test sample

The reduction of cross section from base layer in build direction additionally aids in eliminating premature failure of the sample build as the bond with lower cross sectional aera is lower than of layers with higher cross-sectional area. Hence it ensures 100% build success under nominal parameters of the resin and the printer. The details in the sample assist in identifying the effects of change of printing parameters while a sample print is executed.

A commercially available UV curable resin (curable under for 405 nm wavelength of UV light) was chosen as the material throughout the whole project where the material was colorless. A series of 4 pigments; Cayan, Magenta, Yellow, and Black were used to get the desired colors. (Figure 29)


Figure 29: Anycubic clear photopolymer resin (Anycubic Nordic, 2023) and Primacreator CMYK(Cyan, Magenta, Yellow, Black) pigment (Primacreator ,2023)

In this project to demonstrate the multi-material capability we are using the same colorless resin with different pigmentation so that different colours of materials do not require additional hardware to do the tests. Below Figure 30 represents how different colors of resin can be made with use of pigments with respect to weight of both clear/white resin and CMYK pigment. Using the commercially available printer, samples were printed to compare the follow-up prints. The initial test printing procedure was as follows.

CMYK Pigment Colour Formulas

| | COLOUR | RAPID CLEAR | RAPID WHITE | CYAN | MAGENTA | YELLOW | BLACK |
|---|---|---|---|---|---|---|---|
| 1 | Trans Pink | 100 gm | | | 0.072 gm (2 drops) | | |
| 2 | Opaque Pink | | 100 gm | | 0.0661 gm (2 drops) | | |
| 3 | Trans Blue | 100 gm | | 0.103gm (3 drops) | | | |
| 4 | Trans Green | 100 gm | | 0.065 gm (2 drops) | | 0.065gm (2 drops) | |
| 5 | Opaque Green | | 100 gm | 0.113gm (3 drops) | | 0.146 gm (4drops) | |
| 6 | Trans Grey | 100 gm | 1.016 gm | | | | 0.0313gm (1 drop |
| 7 | Trans Brown | 100gm | | | 0.036 gm (1 drop) | 0.034 gm (1 drop) | 0.032 gm (1 drop) |
| 8 | Trans Lime | 100 gm | | | | 0.166 gm (2 drops) | |
| 9 | Green PMS 360 | 100 gm | | 0.033 gm (1 drop) | | 0.138 gm (4 drops) | |
| 10 | Red (PMS220) | 100 gm | | | 0.82 gm | | |
| 11 | Trans Purple | 100 gm | | 0.036 gm (1 drop) | 0.115 gm (3drops) | | |

Figure 30: Datasheet for different colour resin setup with clear or white resin along with CMYK pigment (3D print services.co.nz, 2023)

## 4.1 Determining the Printing Parameters

The key parameters in the test campaign is layer height and exposure time which are both independent of each other. The UV light intensity is always maintained at a constant level. The layer height was set at 0.05mm which is the default setting recommended by the commercial printer manufacturer with initial exposure to 40sec to initiate a good bond with the build plate. The following exposures were set at 3 seconds. The sample height was 10mm where total build had 200 layers.

Henceforth the experiment was conducted in such a way that transparent photopolymer was initially tested following resins colored with CMYK pigments which resulted in blue, red, green, and yellow. Layer height varied from 0.1mm to 0.05 in steps of 0.01 and from 0.05 onwards 0.02 in steps of 0.005. For selected layer heights exposure time was reduced from 3 seconds whereas for given layer heights the minimum exposure time attainable was observed and the data are as follows.

## 4.2 Testing for Inter-Layer Multi-Material Printing.

Henceforth with the use of the same sample model, another set of experiments was done with resins with two different pigments. A sample print was initialized with a single resin, the print was paused at layer 90 of 200 which is in segment 2. In the paused stage the build plate rises to 150mm from the current build position. This allows removing and switching the VAT manually and cleaning the build plate to remove the previous resin material.

IPA was used where it was soaked in tissue paper to clean the build surface and the object thoroughly. These cleaning operations and the effects of cleaning methods are vital in determining a suitable method for the cleaning mechanism in the final prototype. Moreover, the switching of vats

incurs an additional complexity of the backlash of the stepper motor. When switching the vat, the build plate reaches around 100mm away from the build surface. Hence this would result in these tests, it was evident that the build plate contamination of the previous material depended heavily on the level of the resin in the previous vat. More contamination would require more effort in cleaning the built plate on both the bottom and top surfaces. Yet use of a lower level of resin would affect print quality resulting in multiple defects within the print. The print resulted in air pockets in each layer and often resulted in not reaching the desired layer height.

## 4.3 Testing for Intra-Layer Multi-Material Printing

The next round of testing is aimed at printing two materials in the same layer. With the use of only one printer two sets of programs were set up. Initially, the red color was printed with a layer height of 0.05mm and it was printed for 2 layers. A sample depiction of the layer configuration is shown in Figure 31.

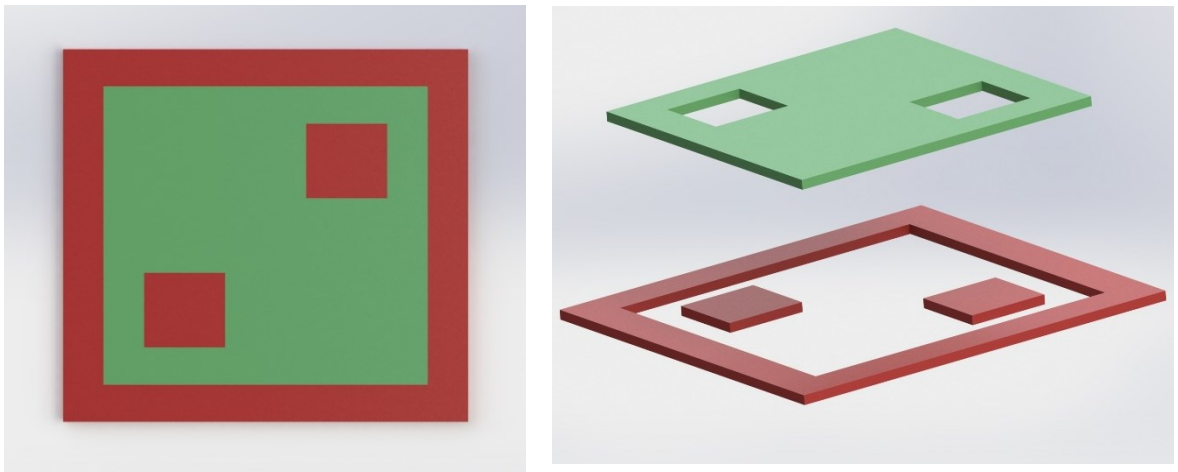

Figure 31: Top view of same layer printing (left) and Isometric exploded view of same layer printing (right)

The initial exposure was set at 60sec while the following layer was exposed for 10secs. The next layer was built at 0.1mm layer height with an initial exposure of 60 seconds.

The model was designed initially such that there is no overlap between the two religions and the result was observed. The final print was removed from the build plate and cured in UV light at an elevated temperature. Upon applying a lateral force on the sample, it failed.

Hence the model was improved to overlap between the two regions, cleaned and cured. The sample was again subjected to lateral load where it did not fail from the interface of the two materials.

## 4.4 Printing Multi-Material on Variable Layer Heights on Demand.

After concluding first 3 tests, a combination of all the above tests would reveal the true potential of multi-material VAT photopolymerization printing. For this a unique experiment is setup with specialized modification to the slicing software. Two resins are utilized in this test and manual switching is adapted as in section 4.2 and 4.3.

In section 4.1 we have determined the optimal exposure parameters for given layer heights. Hence in this experiment our aim is to vary the layer height within the build. Throughout this experiment, the exposure time would be set between 2.5s to 3s.

As in Figure 32-a, the print is initialized with a red photopolymer resin. The layer height for this print is 0.05mm. The follow-up layer is set at 0.1mm adjacent to the first layer with green photopolymer resin as in Figure 32-b while maintaining a small overlapping margin of 1mm is set to secure the bond between the two materials. This concludes the base layer, yet the surface does not maintain uniform layer height setting an offset of 0.05mm.

Next, the same resin material is utilized to print a with the layer height of 0.1mm on the surface of the red resin which was printed initially as in Figure 32-c. The overlap margin of 1mm is maintained with the green

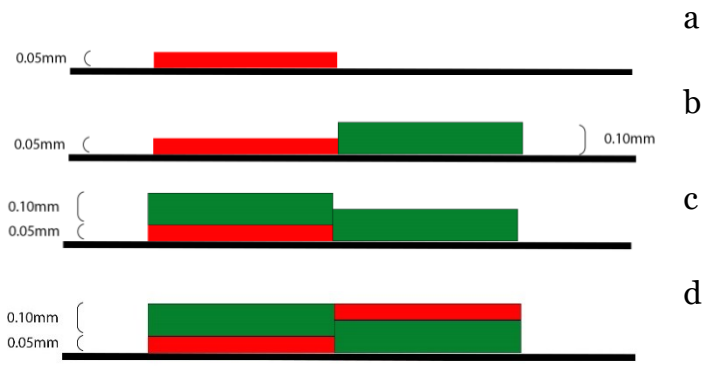


Figure 32: Steps of multi-material printing on variable heights

polymer. After this step the topmost layer does not maintain uniform layer height where there is 0.05mm offset between the two green polymer surfaces. As the final step, as in Figure 32-d, red photopolymer resin was used with a 0.05mm layer height with an overlap margin of 1mm. This resulted in levelling of the surface of the final print.

# 5 Results

## 5.1 Results of Testing the Printing Parameters.

The tests that were conducted to determine printing parameters were initially conducted on transparent resin and following those resins with pigments which resulted in colours blue, yellow, green, and red were tested (Figure 33). During these tests UV power was maintained at a constant level.

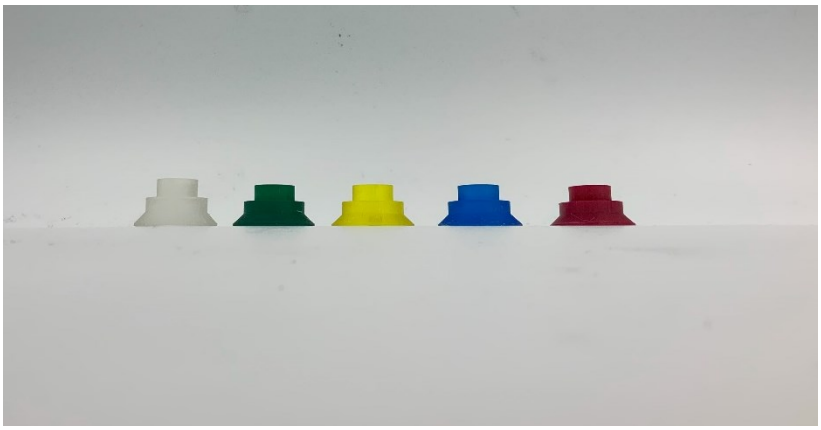

Figure 33: Test articles to determine printing parameters.

The results indicate no distinct variation by colour for the given resin. The minimum exposure time for a given layer height is depicted in the Table 01. Here the resolution of the printer used in the test sequence exposure time resolution of 0.1mm. The layer height resolution is 0.005mm. The maximum and minimum attainable layer height is 0.1mm and 0.035 respectively. Hence the minimum exposure rate fluctuates around a small period, 1.4sec – 1.8sec.

Table 1: Minimum exposure for given layer height.

| Maximum layer height(mm) | Minimum exposure (sec) |
|---|---|
| 0.1 | 1.8 |
| 0.08 | 1.8 |
| 0.06 | 1.6 |
| 0.05 | 1.5 |
| 0.045 | 1.5 |
| 0.04 | 1.4 |
| 0.035 | 1.4 |

## 5.2 Results of Inter-Layer Multi-Material Printing

Multi-layer multi-material printing experiment was to demonstrate switching of vats in a multi-layer print. The test sample utilized for the print was paused mid build process and the vat was switched for resin in a different pigment at 45% into the build process. As in Figure 34, the leftmost sample (blue) is a reference sample. A clear variation in sample height is observed when the build process is of two material and involves switching of VATs.

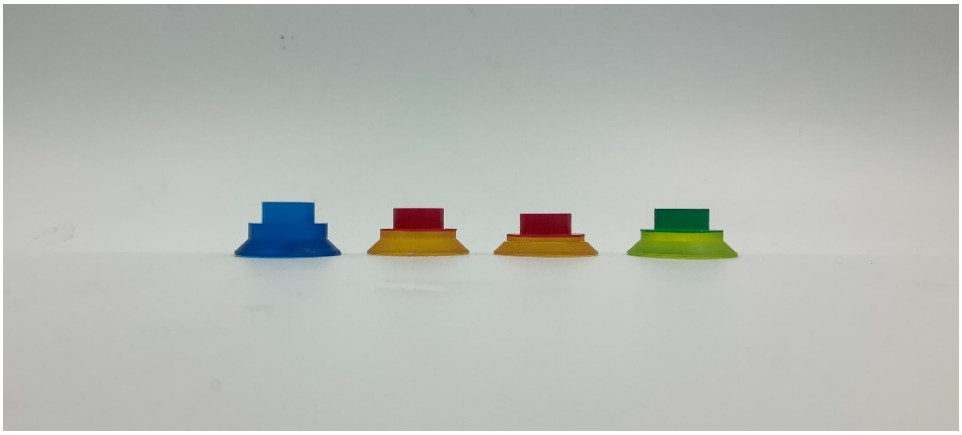

Figure 34: Test articles to determine effect of multi-material on different layers.

Compared to the reference sample (Figure 33, leftmost sample in blue colour), samples manufactured in two colours clearly vary in sample height. Out of all the dimensions in the sample the middle height step which in 15mm of diameter and height of 3mm is out of design dimensions. The total sample height with regard to layer height is given in Table 2. Upon measuring the dimensions. It was evident that the deviation of the sample height from reference sample height of 10mm directly corelated to the layer height. The deviation is at minimum when the layer height is minimum.

Table 2: Sample height resulted for given layer height.

| Layer height (mm) | switching layer | Sample height (mm) |
|---|---|---|
| 0.05 (reference) | - | 10 |
| 0.1 | 45 | 7.8 |
| 0.08 | 56 | 8.2 |
| 0.07 | 64 | 8.5 |
| 0.06 | 75 | 8.6 |
| 0.05 | 90 | 8.8 |
| 0.045 | 100 | 8.8 |
| 0.035 | 128 | 8.9 |

## 5.3 Results of Intra-Layer Multi-Material Printing

The experiment aimed at multi-material printing in same layer was to observe the possibility and define the methodology for optimal multi material printing. The methodology followed at section Testing for Intra-Layer Multi-Material Printing resulted in multi-material printing at the same layer with different properties.

Initially the set of tests which was conducted multi-material printing within the same layer without any overlap between the layers (Figure 35). Under shear loads the test sample failed.

Figure 35: Multi-material printing in the same layer

Upon observing the printed sample, it was modified to overlap the two materials and to change the exposure parameters. Here the two materials are overlapped by 1mm each other the initial exposure of the material is reduced by 40%. The overlapped test resulted (Figure 35) in strong bond between two material interface carried mechanical properties of a uniform material under loading conditions.

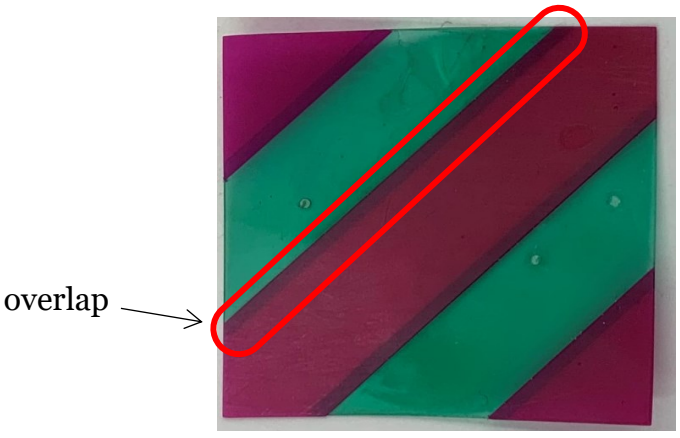


Figure 36: Multi-material printing in the same layer with overlapping of two materials.

Moreover, the test was repeated to try out the possibility of infusing foreign material, i.e. metal to the clear resin as in Figure 37. Iron powder was mixed with clear resin. This test sample revealed potential applications of multi-material vat photopolymerization printing. These Iron particles can be heated with inductive heating where unique properties of the materials can be enhanced.

Figure 37: Multi-material printing in same layer with metal powder infused resin.

# 6 Discussion

## 6.1 Process and Results

The primary objective of this investigation was to formulate a methodology for the implementation of multi-material vat photopolymerization printing, with the overarching aim of generating empirical data to facilitate the development of a commercially viable compact multi-material vat photopolymerization printer. Multi-material vat photopolymerization, an extensively researched domain, has garnered attention from various research entities exploring diverse applications.

Critical components within multi-material vat photopolymerization necessitate meticulous consideration. The construction process must seamlessly transition between different resins according to specific material layout requirements, while simultaneously averting cross-contamination between the distinct resins. Modifications are imperative for both the build sequence and program generation. Researchers have approached these elements with varying strategies, employing either automated or manual procedures for specific tasks. After a comprehensive examination of these research findings, optimal design parameters and configurations for a potential prototype were determined.

Manual operation was deemed unsuitable for commercial applications. Automated resin switching facilitated by movement of vats, posed challenges, given the liquid form of the resin within the vats, necessitating intricate hardware to facilitate movement without spillage. Consequently, relocating the build platform emerged as the preferred scenario, requiring an additional axis of motion. A prototype was initiated based on a conventional commercial vat photopolymerization printer, augmented with custom-fabricated hardware to enable vat switching. The vat itself underwent modification to accommodate two distinct resins, while a dedicated control system was devised and programmed to oversee the entire operational framework.

A critical facet of the design involved the automation of the cleaning process for both the build platform and the manufactured part during transitions between two photopolymer resins. Given the varied properties of different resins, the cleaning operation demanded specialized methodologies. Consequently, an exhaustive examination of cleaning options was undertaken.

The experimental sequence was meticulously planned to investigate parameters pertinent to VAT photopolymerization and assess the capabilities of multi-material vat photopolymerization. Utilizing a bespoke sample, limitations of multi-material photopolymerization printing were identified and evaluated. The experimentation encompassed multi-material printing across multiple layers, uniform layers, and variable layer heights on demand.

This project has unveiled pivotal insights and capabilities inherent in multi-material vat photopolymerization printing. The outcomes have laid the foundation for the development of a commercial multi-material vat photopolymerization printer characterized by a compact design footprint.

## 6.2 Challenges

A unique set of challenges were faced during the project when developing the prototype as well as in testing. The key challenge was deconstructing the existing commercial vat photopolymerization printer; Creality Halot One. The control board is comprised of an all-in-one hardware architecture where it runs proprietary firmware as well as hardware. It was a significant challenge to find a suitable mono-chrome LCD along with the driver for the multi-material application as well as to suit the existing printer frame.

When conducting the test campaign, multi-material printing required pausing the print mid-build process where the build platform raises to 160mm above the base position. After switching the vats, the build was resumed, and it was observed that there was an offset due to stepper motor backlash. Since most of the testing was carried out with the use of the commercial printer this error affected the results and in determining the parameters associated with multi-material printing. Moreover, when testing with a commercial printer that was designed for single-material printing, the slicing software does not support multi-material printing. Hence the flexibility to conduct a diverse range of multi-material tests was hindered.

# 7 Future Work

Multi-material vat photopolymerization is a promising technology with potential applications in diverse disciplines including research as well as manufacturing technologies. The goal of this study is to develop a compact commercial multi-material vat photopolymerization printer. The data gathered through the literature as well as experimentation aided in critical decision making in further developing prototype. The prototype should be further calibrated considering build platform and LCD projection. The motor backlash could be optimized through incorporating the error shoot to the build program.

Currently the program is run with manual command to display given images in the LCD. The images are preformed manually dissecting the object with consideration of layer height and the material type. Moving forward a dedicated software that can slice the object with regard to material type and variable layer height requirement should be developed. This would enhance the true potential of the multi-material vat photopolymerization printer.

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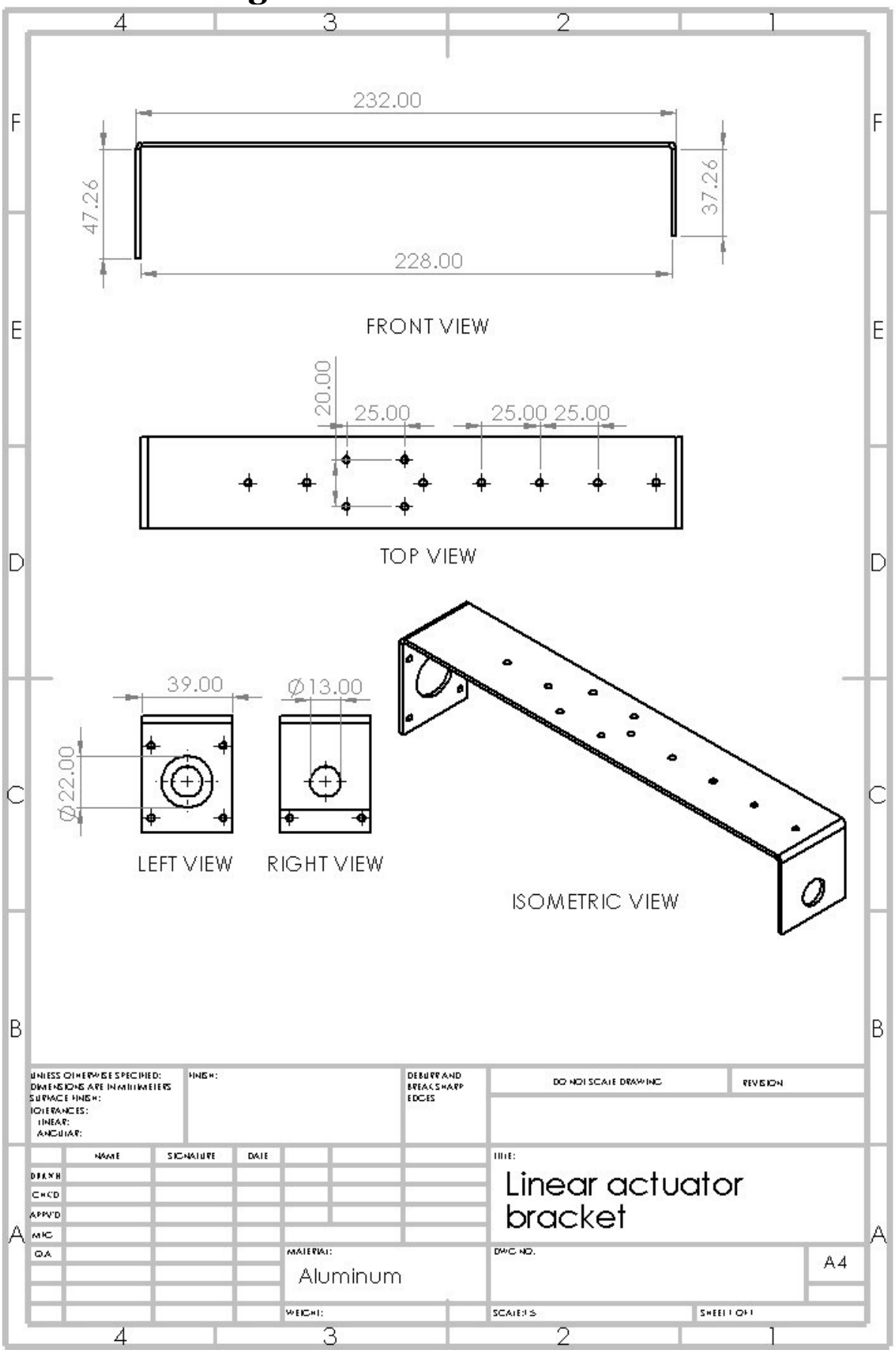
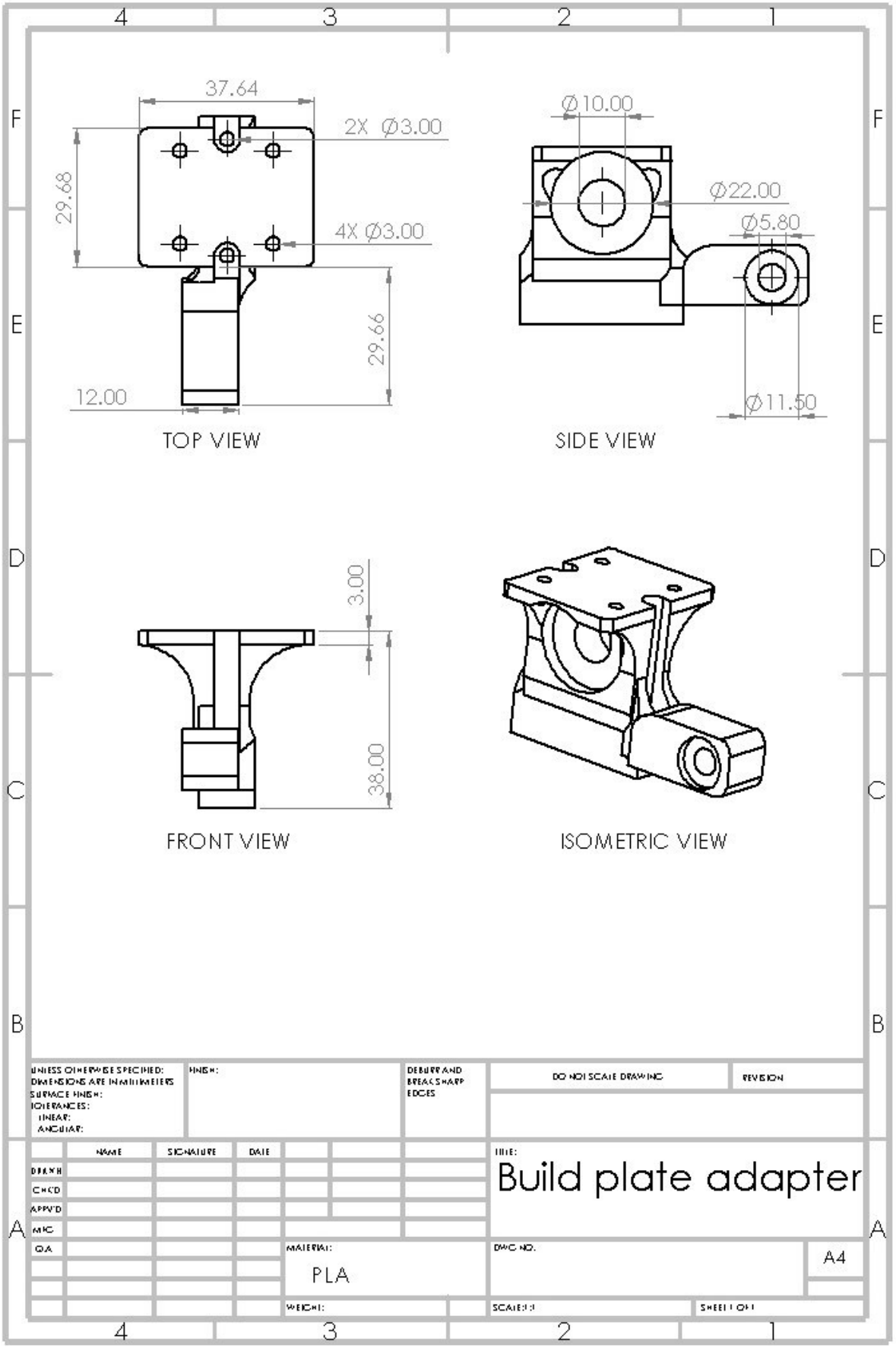
# Appendix

A. **CAD drawings of Build Platform Adapter.**
B. **CAD drawings of Linear Actuator Bracket.**
C. **Data sheet for 12V stepper motor - 39bygh405b**
D. **Script for the Control Logic.**

# A. CAD Drawings of Linear Actuator bracket

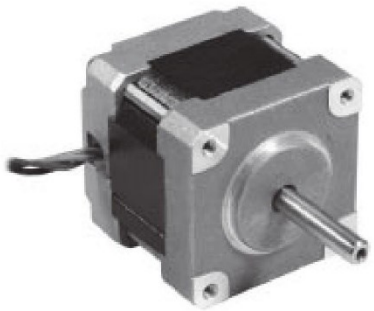


## B. CAD Drawings of Build Platform Adapter



# C. Data sheet for 12V stepper motor - 39bygh405b

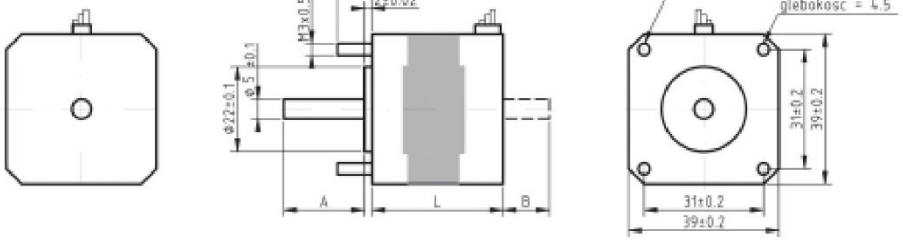
**2-PHASE STEPPER MOTOR**
**39BYGH SERIES**



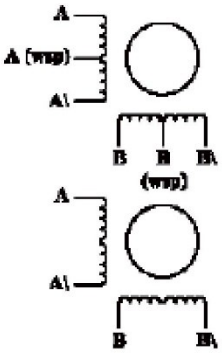
Small, standard 2-phase motors with high ratio torque to dimensions. Outline dimensions: 39*39mm, shaft 5mm. We recommend motors ...402 and ...405, which have high torque in relation to small dimensions and an attractive price. Leads of phase (unipolar or bipolar) are given by cables 30cm length.

Recommended drivers: **SMC 50, SMC 52, SMC 81**.

- **2-phase motor with step 1,8º ± 5%;**
- **Operating temperature 0 ~ +50ºC;**
- **Insulation resistance min. 100MΩ/ 500VDC;**
- **Insulation class B ;**
- **Weight 0,15kg;**
- **Axial play: 0,02mm.**




| MODEL | MOTOR TYPE | STEP (°) | VOLTAGE (V) | CURRENT (A) | RESISTANCE (Ω) | INDUCTANCE (mH) | TORQUE (Nm) | ROTOR INERTIA (gcm²) | WEIGHT (kg) |
|---|---|---|---|---|---|---|---|---|---|
| 39BYGH 001 | Unipolar | 1,8 | 5 | 1 | 5 | 4 | 0,18 | 13 | 0,15 |
| 39BYGH 402UD | Unipolar | 1,8 | 12 | 0,3 | 40 | 45 | 0,11 | 20 | 0,24 |
| 39BYGH 402U | Unipolar | 1,8 | 12 | 0,4 | 30 | 32 | 0,11 | 25 | 0,20 |
| 39BYGH 402B | Bipolar | 1,8 | 12 | 0,3 | 40 | 20 | 0,11 | 20 | 0,24 |
| 39BYGH 405B | Bipolar | 1,8 | 12 | 0,4 | 30 | 32 | 0,21 | 20 | 0,24 |
| 39BYGH 603 | Unipolar | 1,8 | 12 | 0,16 | 75 | 50 | 0,11 | 20 | 0,24 |
| 39BYGH 702U | Unipolar | 1,8 | 12 | 0,4 | 30 | 32 | 0,21 | 20 | 0,25 |
| 39BYGH 002 | Unipolar | 1,8 | 6,5 | 0,5 | 13 | 7,5 | 0,08 | 13 | 0,15 |




| MODEL | A | B | C | L | COLOUR CABLES | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | [mm] | | | | A | A (wsp) | A\ | B | B (wsp) | B\ |
| 39BYGH 001 | 21 | - | - | 34 | white | - | yellow | red | - | blue |
| 39BYGH 402UD | 14 | 12 | 9 | 34 | black | yellow | green | blue | white | red |
| 39BYGH 402U | 14 | - | 9 | 34 | black | yellow | green | red | white | blue |
| 39BYGH 402B | 22 | - | - | 34 | white | - | yellow | red | - | blue |
| 39BYGH 405B | 18 | - | - | 34 | white | - | yellow | red | - | blue |
| 39BYGH 603 | 18 | - | | 34 | black | yellow | green | blue | white | red |
| 39BYGH 702U | 22 | - | - | 45 | black | yellow | green | red | white | blue |
| 39BYGH 002 | 21,5 | - | - | 20 | black | yellow | yellow | red | white | blue |

## D. Script for the control logic

```
from time import sleep
import RPi.GPIO as gpio

#dir1 - yellow 16
#step1 - green 19
#dir2 -  blue 20
#step2 - brown 26
DIR1  = 16
STEP1 = 19

DIR2  = 20
STEP2 = 26

CW =0
CCW =1
vatPosition = 1
verticalPos = 80

gpio.setmode(gpio.BCM)
gpio.setup(DIR1, gpio.OUT)
gpio.setup(STEP1, gpio.OUT)
gpio.output(DIR1,CW)
gpio.setup(DIR2, gpio.OUT)
gpio.setup(STEP2, gpio.OUT)
gpio.output(DIR2,CW)



# Main body of code
```

```
def forward(IN_DIR,IN_STEP):
    for i in range(400):
        gpio.output(IN_DIR,CW)
        gpio.output(IN_STEP,gpio.HIGH)
        sleep(.001)
        gpio.output(IN_STEP,gpio.LOW)
        sleep(.001)

def backward(IN_DIR,IN_STEP):
    for x in range(400):
        gpio.output(IN_DIR,CCW)
        gpio.output(IN_STEP,gpio.HIGH)
        sleep(.001)
        gpio.output(IN_STEP,gpio.LOW)
        sleep(.001)

def vatPosition01():
    if vatPosition==1:
        print("one")
    elif vatPosition==2:
        for j in range(68):
            backward(DIR2,STEP2)
    elif vatPosition==3:
        for j in range(136):
            backward(DIR2,STEP2)
    return 1

def vatPosition02():
    if vatPosition==1:
        for j in range(68):
```

```
            forward(DIR2,STEP2)
    elif vatPosition==2:
        print("two")
    elif vatPosition==3:
        for j in range(68):
            backward(DIR2,STEP2)
    return 2

def vatPosition03():
    if vatPosition==1:
        for j in range(136):
            forward(DIR2,STEP2)
    elif vatPosition==2:
        for j in range(68):
            forward(DIR2,STEP2)
    elif vatPosition==3:
        print("three")
    return 3

def home():
    if verticalPos==100:
        print(home)
    else:
        for j in range(100-verticalPos):
            forward(DIR2,STEP2)
    return 100


def clearance():
    for j in range(10):
```

```
            forward(DIR1,STEP1)

    def verticalbuild(Y_POS):
        for j in range(Y_POS):
            backward(DIR1,STEP1)



    def base():
        print("base level")


    try:
        while True:
            verticalbuild(40)
            sleep(5)

    except KeyboardInterrupt: # If there is a KeyboardInterrupt exit the
program and cleanup
            print("Cleaning up!")
            gpio.cleanup()
```