DESIGNING AND DEVELOPING A DIGITAL LIGHT PROCESSING BASED STEREOLITHOGRAPHY 3D PRINTER

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ABSTRACT

DESIGNING AND DEVELOPING A DIGITAL LIGHT PROCESSING BASED STEREOLITHOGRAPHY 3D PRINTER

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The Digital Light Processing (DLP) 3D printer is a device using Computer-Aided Design (CAD) to produce a 3D model directly from the CAD model, by using the Additive Manufacturing (AM) technology. There are different ways of 3D printing technologies that vary in most aspects such as the material, the methods of forming the sample, the speed and accuracy and many other parameters. Choosing the right way of production depends on the required task so that the material and quality fits the level required. The DLP technology is recognized by its simple structure yet it provides a remarkable range of quality and flexibility. This research suggests a custom build that promises to provide a good production quality. Three types of experiments have been made with different CAD designs to ensure the ability of the designed 3D printer. These experiments have been successfully implemented in terms of surface quality, tiny details and accurate measurements. Furthermore two different tests were made to verify the desirable output results.

Keywords: 3D printer, DLP 3D printer, additive manufacturing, rapid prototyping, resin printer.

ÖZ

DİJİTAL IŞIK İŞLEME TABANLI STEREOLİTOGRAFİ 3B YAZICI TASARLAMA VE GELİŞTİRME

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Haziran 2020, 50 sayfa

Dijital Işık İşleme tabanlı 3B yazıcı, Eklemeli İmalat (AM) teknolojisini kullanarak doğrudan CAD modelinden bir 3B model üretmek için Bilgisayar Destekli Tasarım (CAD) kullanan bir cihazdır. 3B baskı teknolojilerinin materyal , numuneyi oluşturma yöntemleri, hız ve doğruluk gibi birçok farklı yöntemi bulunmaktadır. Doğru üretim şeklini seçmek, malzeme ve kalitenin gereken seviyeye ulaşması, seçilen teknolojiye bağlıdır. DLP teknolojisi basit yapısıyla tanınır, ancak dikkate değer bir kalite ve esneklik yelpazesi sunar. Tasarlanan 3B yazıcının yeteneğini ispatlamak için farklı CAD tasarımları ile üç tip deney yapılmıştır. Bu deneyler yüzey kalitesi, küçük detaylar ve doğru ölçümler açısından başarıyla uygulanmıştır. Ayrıca, istenen çıktı sonuçlarını doğrulamak için iki farklı test yapılmıştır.

Anahtar Kelimeler: 3B yazıcı, DLP 3B yazıcı, Eklemeli İmalat, hızlı prototipleme, reçine yazıcı.

To my role model who pushed me to achieve my goals since the day I was born,

my father Prof. Dr. Imad.

To the greatest heart ever, my mother Rajaa.

To the backstage heroes who supported me along the way, my brothers and sister.

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I would also like to thank everyone who was involved in this work, and also special thanks goes toward the staff of manufacturing lab and also for the simulation lab staff of Atılım University.

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LIST OF SYMBOLS/ABBREVIATIONS

DLP	Digital light Prosessing
SLA	Stereolithography apparatus
AM	Additive manufacturing
RP	Rapid prototyping
SLS	Selective laser sintering

CHAPTER 1

INTRODUCTION

1.1 Background of the study

DLP based SLA 3D printer is apart from additive manufacturing besides the other technology like FDM and SLS etc. in general 3D printing technology starts from 1981 by Dr. Hideo Kodama with the patent, he is the first one who applied the laser beam to cure the resin as what we know now as SLA in Japan. While in France, there was a team of three people Jean-Claude André, Olivier de Witte, and Alain le Méhauté. They were trying to get the patent to make the "rapid prototyping device" in 1984, but because of the funding problem, they were forced to leave the project. In 1986 Chuck Hull had established the term Stereolithography technology and making a patent in the same year, and he released his first commercial product in 1988 (1987 [1]) and it was called SLA-1 [2].

In 1988 Carl Deckard at the University of Texas has filed a patent for SLS technology, and he used laser instead of a UV light to solidify the powder polymers layer by later making the desired 3D object. After that, in 1989, Scott Crump from Stratasys company filed the patent for FDM technology. After the release of the SLA-1 by Hull in a few years, the first FDM was released in 1991 by Stratasys, and in 1992 DTM Inc. released its first SLS 3D printer.

Till 2012 there was nobody able to produce and affordable SLA 3D printer in the market, this changed after 2012 by B9Creator company, they started from Kickstarter to produce a similar technology to SLA called DLP; also a startup company called Formlabs used the Kickstarter, but they produce an SLA 3D printer called Form1.

In 2014 the most patents of 3D printing has been expired, and one of them was Chuck Hull's patent, and this means giving the individuals more space for innovation to process the SLA 3D printing [1], this thing allows some companies and individuals to work on different 3D printing technology including SLA and DLP. They tried to develop it and make it smaller and less costly, so it can be available in the standard market not just for industrial usage, as what can be noticed these days they become more available at some reasonable price.

1.2 Statement of the purpose

The standard SLA and DLP 3D printers still cost a lot (from 3000 to 10000 USD for the basic models) in comparison to other 3D printing methods [3]. A similar issue with the speed that the SLA provides is considered a much slower option in comparison to DLP and many other affordable printing technologies [4]. Although they provide a unique quality and a wide range of materials, they still provide a limited space of flexibility, as they are limited to their manufacturer's plans. Therefore this research suggests using open-source programming software alongside altering the components to maintain a lower price and a more extensive range of experiments and adjustments.

In this study, a custom DLP 3D printer will be made and will go through a series of tests examining the replaced equipment on different levels, such as speed, quality, and durability. The test will also expand to different forms of adjustments and measurements that expose the final sample's quality and accuracy. Therefore this thesis will focus on designing and developing a custom DLP based SLA 3D printer made from commercial components.

1.3 Objectives of the study

To study the technology of the DLP 3D printer and its application, to study the working procedure of each component of the DLP 3D printer, designing and developing DLP 3D printer by using commercial components, and using relatively cheap parts that they can produce high quality printed models in comparison to other printed parts that collected from famous ready-made printers.

1.4 Significance of the research

Since this printing technology is not so widely spread, therefore there is a lack of studies related to this technology or similar ones, and this study may help who have an interest in this 3D printing technology to work on it, and it is open to development.

Also, there are vivid details that have been discussed and proved during the experiments and validation of the printer. There is not much research doing this. Different custom designs have been tried on this printer, and practical tests have been done, such as the Repetition and positioning in the building platform, with all accurate measurements with one micro.

1.5 Thesis outline

This thesis consists of 5 chapters. Chapter 1 summarizes a brief history of 3D printing technology, additive manufacturing, explaining the Stereolithography technology, and how it works. Chapter 2 reviews the literature for relevant topics. Chapter 3 gives information about the components that have been used and the assembling. Chapter 4 has two parts, the first one talking about the experiments and producing the 3D samples, and the second one is talking about the test and validation of the 3D printer. Chapter 5 contains a conclusion and future work.

1.6 Additive Manufacturing

Additive manufacturing (AM) is a method for producing 3D objects from a 3D Computer-aided design (CAD). This method is using a technology called layer by layer process by using a liquid or solid state filament as a material for printing [5]. Unlike the well-known technology called subtractive manufacturing, as it has some limitations in producing some complexity parts by requiring different tools changing while the process that thing makes it a bit harder than the AM technology for producing 3D objects.

The key behind the AM is by adding materials on top of each other in layers form, the layer has a predefined parameter like thickness and time duration while making the layer by either curing, melting or softened [6], the one layer is consist of the whole cross-section for the part that is aiming to print.

1.6.1 The Steps of AM Process

Several steps are starting from the CAD design to the final model as following; making the CAD file, converting it to STL form, doing the slicing, convert it to the machine software, build the 3D model, then remove the 3D model, and post-process of the final 3D model [7] (see Figure 1).

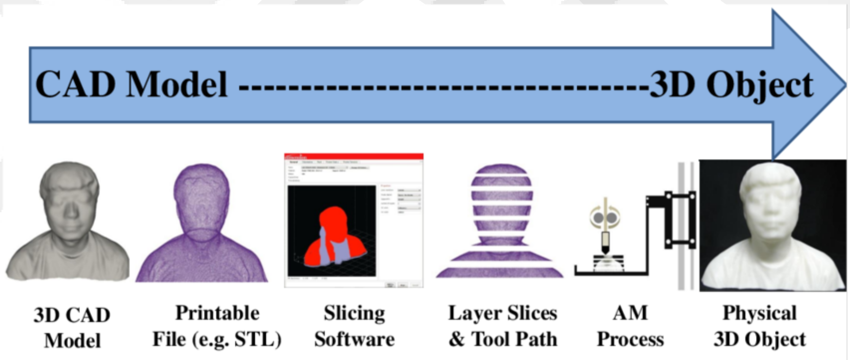

Figure 1 AM steps [8]

1.6.2 AM Methodologies

AM technology has a wide range of applications in the real-world for recent years. One of the critical applications for the previous several years is the ability to print the biomaterials and organs. Now in some researches, they were able to make some organs for the human body. Michael and his team were able to use the AM in the urological surgery by printing some parts for the education of trainees and patients, surgical planning, creation of urological equipment, and bioprinting. The improvement of the full application for AM, such as building houses, food biomedical, and engineering manufacturing, increase printer availability, and decrease costs [9].

The term of AM has a wide range of methods and materials that is used for this technology from the plastic to metals, each material has its method, for example, SLA, FDM is used for plastic, and selective laser sintering (SLS) used for metal powders, in Table 1, a comparison of different AM technologies have been made.

Table 1 Comparing between AM technologies [10]

S.No	Technologies	Materials used	Surface finish
1	Stereolithography	Photocurable resin	none
2	Selective laser sintering	Stainless steel, tool steel, plastics, ceramics	Rough surface finish
3	Selective laser melting	Steel(stainless steel 316L, hot work steel, tool steel, maraging steel), Titanium CP, titanium-based alloy(Ti-6Al-4V,Ti-6Al-7Nb),Inconel 718, Inconel 625,Aluminium based alloys	30-60 μm
4	Laminated object manufacturing	Any material in sheet form	none
5	Three dimensional printing	Specially designed stainless steel powder	none
6	Direct metal deposition	Titanium(Ti–6Al-4V), stainless steel((316, 304L, 309, 420),tool steel(H13, P20, P21, S7, D2), Nickel based alloys(Inconel 600, 625, 690, 719), Copper and its alloys, Satellite and Tungsten carbide	200-300 μinch

To understand this thesis subject some technologies needed to be discovered and be clear before going deep in this thesis subject, therefore one of the closest technologies that this thesis stands on is called SLA, an explanation for this technology will later be done on to understand the fundamentals of this thesis subject.

1.7 Stereolithography

Stereolithography (SLA or SL) 3D printer, It is also known as photo-solidification or optical printing [11], which is one of the standards and fully separated technologies in the term of AM. SLA uses a high power UV laser to harden the liquid resin that is included in a vat (tank) to create the desired 3D object from the computer-aided design (CAD), as its part from the AM method, therefore, it uses the layer by layer building method by using laser with photopolymerization method, as shown in Figure 2.

SLA is also apart from the 3D printing family with the other types like fused FDM and SLS; also, a similar technique always sticks with SLA called digital light processing (DLP) it uses a projector instead of laser with some technical differences [12].

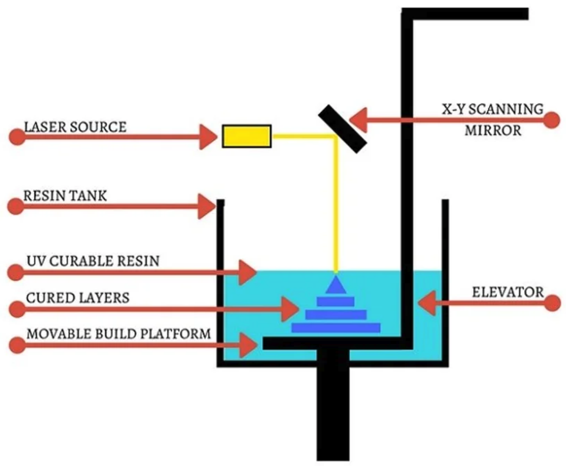

Figure 2 Stereolithography printer parts [12]

A simple comparison between the advantages and disadvantages of stereolithography technology is; it has been used in rapid prototypes (RP) printing because of the fast process, high surface resolution, and almost the same accuracy as the CAD model [11].

On the other hand, one of the disadvantages is the limitation of process materials such as resins because it is expensive and not widely separated; also, it does not work for some metals [10].

1.7.1 How does SLA work

It starts with making the building platform position in the liquid photopolymer resin tank with the distance of one layer down the liquid surface, and then, the UV laser starts to select the desired area for the first layer to cure and solidify the photopolymer resin. The laser beam is focused and moving using a set of mirrors, called Galvos, while the laser beam is stable during this procedure, after finishing the first layer, the building platform is moving down to let the space for the sweeper blade recoating the surface of the resin above the cured layer, then the same procedure is repeated till complete the 3D object. The last step is called post-processing; before this step, the part is still green, which means it does not fully cure. Therefore it needs to place it under a UV source to let it become harder [13].

1.8 Working mechanism

The main parts for this study are DLP video projector, resin vat, and Z-axis with a removable building platform, These parts are controlled via the same computer.

The working mechanism starts with the CAD design made by any 3D design program that can produce STL format like Solidworks. Then it is converted into slices where each slice is the cross-section image for the 3D model in JPEG form. These slices are used by the projector to exposure each image (slice) on the building platform sequentially, regarding the parameters that already specified in the slicing program like layer thickness, exposure time and Z-axis moving speed, the exposure time, and Z-axis speed must be synchronized to prevent printing failure.

CHAPTER 2

LITERATURE REVIEW

3D printing is part from AM technology, and this technology has a significant effect on most manufacturing and model design implementation since the first creation of 3D printers in the '80s of the last century [5]. In this part of the study, the studies related to 3D printers using DLP technology between 2009-2019 are examined.

Solid oral dosing using a modified 3D printer, including a DMD, is conducted by Kadry et al. The study emphasized using this specific technology, DMD (as shown in Figure 3) rather than binder deposition, bioprinters, FDM, and SLA. Each one of these methods has its weaknesses. According to them; binder deposition techniques suffer from poor resolution and mechanical strength, on the other hand, bioprinters require additional post-processing such as heating, drying for solidification process, FDM requires a high degree of heating for the filaments and to apply that much of heat it requires a particular type of thermostable materials. The stereolithography was modified by adding DMD in the path of the laser. This adding is essential to prevent the laser from scanning each row during printing and make a complete section area for the layer.

They make a simple comparison between the laser-based stereolithography and DLP printers. The result says that DLP 3D is faster and more efficient and can run in with different wavelengths. This efficiency makes the DLP compatible with custom resin.

This study focuses on the flexible ability of the printer parameters, such as UV intensity, exposure time, UV light source, wavelength, and amount of polymers. To do this, they used digital light processing (DLP Discovery 4100) from TI company, with Omnicure s2000 as a UV source and SolidWorks software to create the tablet CAD file. They have printed the tablet at room temperature with 7.5 mm x 5.4 mm x 4 mm, and the layer thickness was 200 µm.

Overall, this study suggests that the concentration of the photopolymer and the UV intensity or the exposure time is playing the primary role in printing tablets using the

DLP printers. When they used a 5% polymer, the result was too soft, and the shape of the solid oral dosage kept its shape. On the other hand, when they increase the polymer percentage to 10% with UV intensity of 6mW/cm2 at 25 s/ layer, there were no improvements from the previous experience while keeping the same polymer concentration with 12mW/cm2and 35 s/layer the printing fails and loses to save the tablet shape. As a result, they obtain the best solution when they used the concentration of 20%, UV intensity, and exposure time of 12mW/cm2 and 35 s/layer [14].

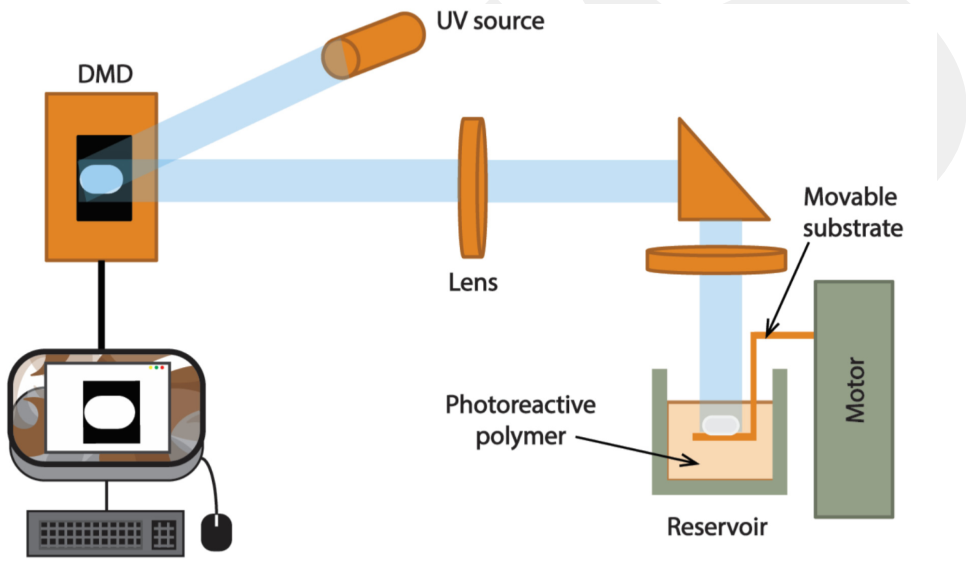

Figure 3 A diagram for the usage of DMD

In the study of Varghese et al. they had been studied 3D printing technologies for the ceramic industry. Their study aimed to reach different ceramic material properties such as; aesthetic value, biocompatibility, and Physico-chemical properties; therefore, it will be highly suitable for biomedical, biochemical, and diagnostic applications. They suggest using AM, as this technology can be used to fabricate complex geometrics from a CAD file directly and can be applied to a wide range of materials like polymers, metals, and ceramics. Therefore in this research, they used this technology to fabricate advanced ceramics(as shown in Figure 4), and during their research, they presented more than one technology like SLS, FDM, SLA, inkjet-based systems. However, each of these technologies has its weakness and strength, while SLA gave them a high resolution and surface quality results, but it is quite expensive. Therefore they were trying to make the same quality of SLA 3D printer with low cost by modifying the laser-based SLA with DLP projector instead of a laser. Also, there are two possible methods in 3D printers (SLA and DLP) these are top-bottom and bottom-up, they mention that top-down is better for SLA, while bottom-up is for DLP like what they did in this research, the resin that they used was alumina, 3-YSZ, and 8-YSZ. Photoactive resins by mixing 25-60 wt% ceramic with poly (ethylene glycol) diacrylate and a photoinitiator dissolved in ethanol to be a UV sensitive for a commercial DLP projector, furthermore they notice that the percentage of the ceramic should not exceed 60% because it will appear as a loose powder on the surface of a sintered object.

The main parts used in this study i) HDMI 3D-FULL HD 1080 DLP projector manufactured by Texas Instruments, ii) Autodesk inventor professional, USA, iii) creation workshop. The most important points and results of this study were the use of a commercial DLP projector and the bottom-up method [15].

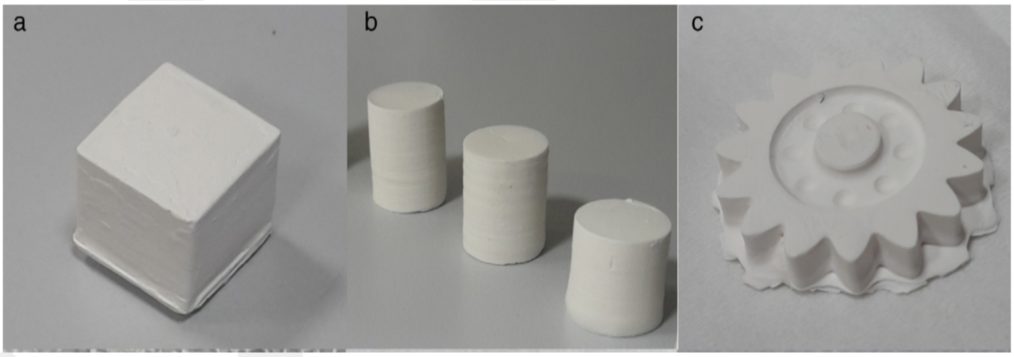

Figure 4 Green bodies of photo resin loaded with 55% 3-YSZ

Valentincic et al. produced two types of DLP stereolithography systems. They named them as free surface (denoted as top-down stereolithography) and constrained surface (denoted as bottom-up stereolithography) and gave every one of them some advantages and disadvantages. Also, this study emphasizes three main challenges and the solution for them. These are an uneven illumination of commercial DLP projectors, a direct illumination, and a selection of optimal 3D printing parameters.

Each one of these challenges makes the DLP based stereolithography 3D printer offers quicker and more accurate production compared to the FDM.

Furthermore, they also proved the effect of oxygen because; the oxygen-rich environment makes the constrained surface stereolithography better than the free surface-based systems. So, the elimination of the oxygen inhibition effect makes this method more advantageous, and the resin can be cured faster, so oxygen affects the size, shape, and properties of the part that has been fabricated using stereolithography (as shown in Figure 5). For this study, they used DLP projector Acer p1500 with 1920 x 1080 pixels and 3000 lumens, Deep Black resin, Creation Workshop for NC-code, Arduino Mega 2560, Gecko drive and stepper motor (in the free surface machine they need another stepper motor for wiper). They found the optimal printer parameter for Deep Black resin, where the exposure time 16.5s, and layer thickness was 0.06 mm, between two consecutive exposure 4s [16].

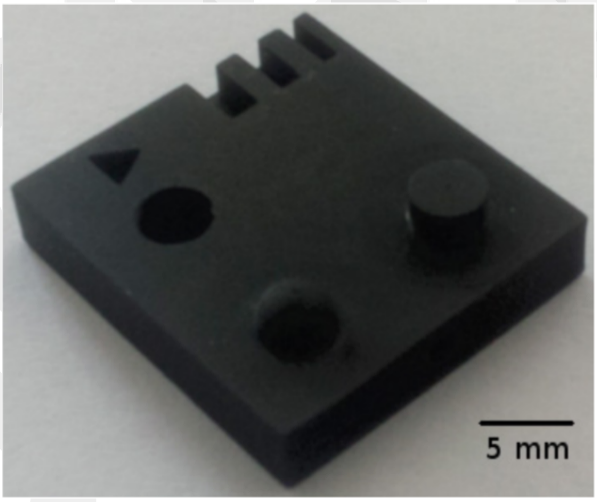

Figure 5 Test sample manufactured

In this study, the authors focused on the accuracy of 3D printing by comparing the result with the CAD model. Obtaining the volume error for the printed prototype by either shrinking or expansion called as curing effect, and finding the accuracy allowance during manufacturing by using microtechnology, they said this happens because of any 3D printing process should use one of these technologies, softened, melted, or light irradiation to polymerize. Furthermore, this study aims to establish allowance and adjustment in dimension during the printing process because of the shrinkage and positioning from photopolymer material. In this research, the authors used a digital model made in Solidworks containing holes. The size of the model was 30x30 mm with a 3 mm thickness, and the holes were 200 x 200 um with a depth of 500 um(as shown in Figure 6). The model was printed in Formlabs v2.0 with a clear resin, and they used Carl Zeiss optical microscope at 12.5x magnification for the measurement purpose. Using Excel tables to put the values for the printed object and the digital model and notice the difference between them will make the necessary adjustments on the CAD model to produce more accurate models [6].

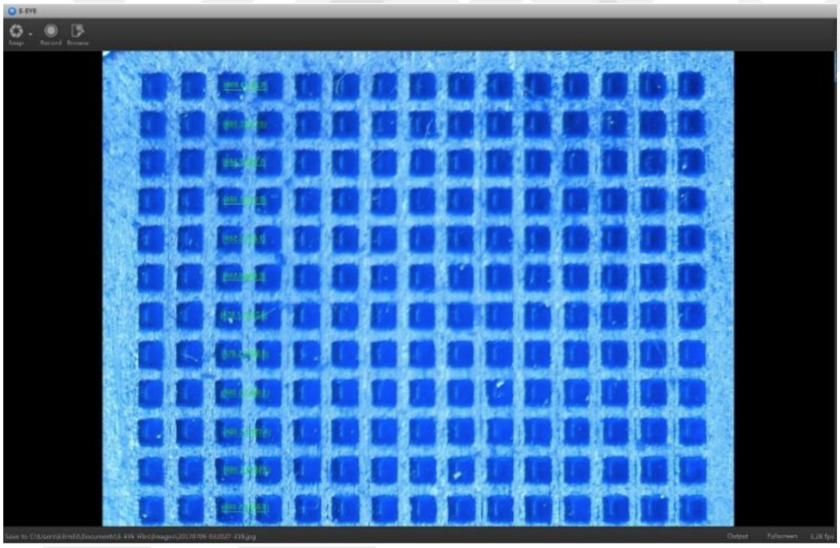

Figure 6 The 3D printed model

In this literature review, two approaches have been used to fabricate 3D models using the SLA process, and DLP based SLA ; i) Top-down, ii) bottom-up approach.

While reviewing these papers, some advantages and disadvantages have been analyzed during each review for each approach. Moreover, they used different materials from the standard resin to the modified one by mixing it with ceramic. Table 2 represents a summary of the reviewed studies.

Table 2 Literature revew abstact

Year	authors	Tile	objectives	Method	equipment	Future study
2019	Hossam Kadry, Soham Wadnap, Changxue Xu, Fakhrul Ahsan,	Digital light processing (DLP) 3D-printing technology and photoreactive polymers in fabrication of modified-release tablets	Fabrication of solid oral dosage forms by using DLP 3D printer	They use 4 methods, binder deposition techniques,bioprints, FDM, SLA	DLP Discovery4100 Omnicure s2000 SolidWork software	none
2017	Giftymol Varghese, Mónica Moral, Miguel Castro-García, Juan José López-López, Juan Ramón Marín-Rueda, Vicente Yagüe-Alcaraz, Lorena Hernández-Afonso, Juan Carlos Ruiz-Morales, Jesus Canales-Vázquez	Fabrication and characterisation of ceramics via low-cost DLP 3D printing	Fabricate advanced ceramics	SLA with DLP	Comercial DLP projector, autodesk inventor professional, creation workshop	sintering process may be achieved by modifying the debinding condition
2017	Joško Valentinčič, Matej Peroša, Marko Jerman, Izidor Sabotin, Andrej Lebar	Low Cost Printer for DLP Stereolithography	Three main challenges:uneven illumination,directin of illumination, optimal 3D printing parameters	DLP 3D printer based sla	DLP projector Acer p1500, Deep Black resin Creation Workshop for NC-code Arduino Mega, Gecko drive and stepper motor	none
2017	Emil Yankov, and Maria P. Nikolova	Comparison of the Accuracy of 3D Printed Prototypes Using the Stereolithography (SLA) Method with the Digital CAD Models	accuracy of the 3D printing by comparing the result with the CAD model	Comercial SLA printer	SLA printer Formlabs 2.0	none

Under the light of literature, the studies were using the same process called layer by layer approach and its kind of AM.

In this study, a desktop stereolithography based DLP 3D printer is developed by using a commercial video projector as a UV light source, the printer is established in a bottom-up approach. Details of the design and assembly are given in Chapter 3.

CHAPTER 3

COMPONENT AND ASSEMBLING

Going through different 3D printing technologies and builds, DLP 3D printing has been found as the most suitable form of printing to study and develop in this research, based on the possibility to use a different mechanism for image generation and the high flexibility that allow not specialized but tweaked components to be a part of the project.

The starting point was to search for a wide range of available building components and to choose them based on three main factors: Flexibility, Quality, and price.
The flexibility here refers to the ability of each component to perform different tasks in different working platforms. The quality of performance is always the fundamental concept that allows it to shift from an option to another while keeping the printing properties at it is the best quality for the purpose intended. The price factor was also an essential factor that this research is covering. To keep the budget as low as possible without compromising the quality was essential for this study. There was no point in experimenting with high-end equipment that mostly does not allow that wide range of customization and adjustments, allowing us to explore new depths within the 3D printing developing technology.

3.1 DLP 3D printer components

The components used in this DLP 3D printer are listed below with detailed specifications of each component.

3.1.1 DLP projector Dell 2400MP

The core element in this DLP 3D printer is the curing device that can convert the liquid resin to a solid form according to the CAD model. In this study a digital image projector has been used as a UV image producer that will reflect the due model slice as a light image to cure the resin precisely, mimicking the required layer underneath the previous one which will eventually form the required structure alongside the supporting elements that holds the fragile elements of the structure during the printing process.

This model was chosen depending on some feature that makes it one of the compatible devices for this work because it usually works as a video projector, not for 3D printers. Therefore, better results have been achieved by modifying the device, and these changes will be listed later on.

The specifications of this projectors are as the following:
It is a commercial DLP projector that came with DMD (XGA 1024x768) inside to produce 1024x768 resolution (Using a visible light range that contains a percentage of UV light, with 3000 Lumen, projector size is 10 cm x 27 cm x 21 cm (HxWxD), as shown in Figure 7 [17].

Figure 7 Dell 2400mp commercial projector

3.1.1.1 Enhancement for the commercial projector

Some parts need to be modified during the curing process of the resin to make the projector work efficiently. Each projector has UV filter in front of the lamp, as shown in Figure 8 to reduce the UV light from reflecting on the human eye in normal usage, while the UV light is what we want from the projector for curing purpose; therefore this filter need to be removed from the projector, the UV filter in this projector is made from rectangle glass with diameters about 1.5x1.5 cm [18, 19].

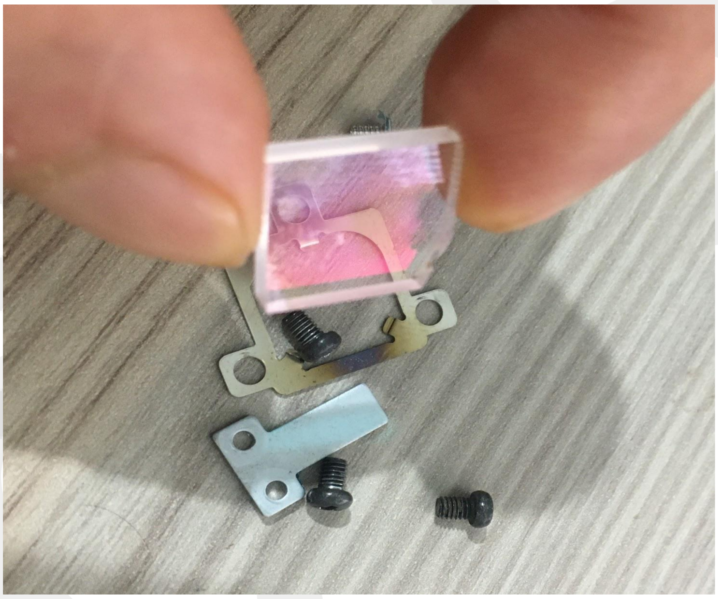

Figure 8 The UV filter

The second thing that has been improved is removing the color wheel (see Figure 9) that is placed in front of the lamp to prevent the color during projecting. The result of this improvement is that the final light came out from the projector is in black and white to prevent the disruption while curing and also reduce the UV filtering [18,19,20].

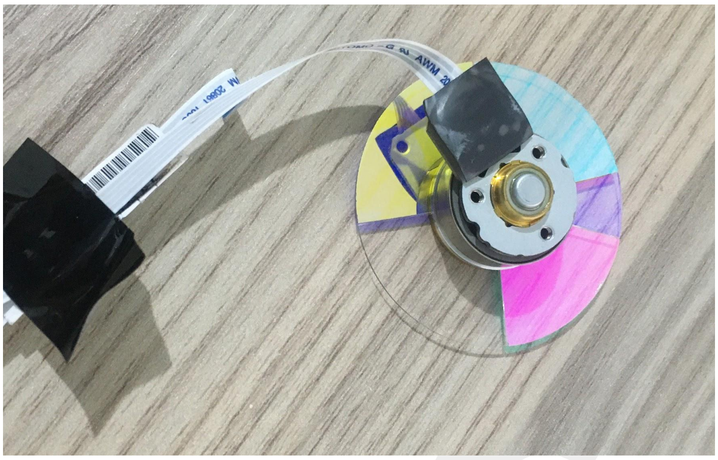

Figure 9 The color wheel

3.1.2 The lens

The same built-in lens has been used that came with the projector (dell 2400mp), but this lens was designed for long-distance projection the minimum distance is 1.2 m [17], and to make it fit our needs some changes were made to make it fully compatible with this 3D printer with a distance of 20 cm between the lens and the building platform.

Changing the targeted distance

The DLP projector designed to target a distant projection wall, to change this working principle and convert it into a close-up image projector, with changing the distance between the DMD and the lens (by removing some parts inside) to obtain the best focus and dimensions of the X and Y axis to the desired printing area on the printing platform (the elevator) from the bottom side of the aluminum plate, these changes will affect the printing in ways that increase the power of projector and in result to reduce the time consuming while printing [19], the lens is given in Figure 10 (f/2.4-2.7 lens).

Figure 10 The projector lens

3.1.3 The resin vat

The vat (resin tanks) was custom designed. It was made from a 4 mm transparent acrylic plastic cut with a laser machine to achieve the fine assembling details. It consists of two parts; the base is plane acrylic with a square canal of 2 mm depth in the outer size of cubic (see Figure 11 A), the second part is square 40 mm height with base and 8 round hols, the second part was designed to go inside the 2 mm canal depth in the base (see Figure 11 B) to make the FEP film more tension, with the eight screws to hold the two parts as shown in Figure 11 C.

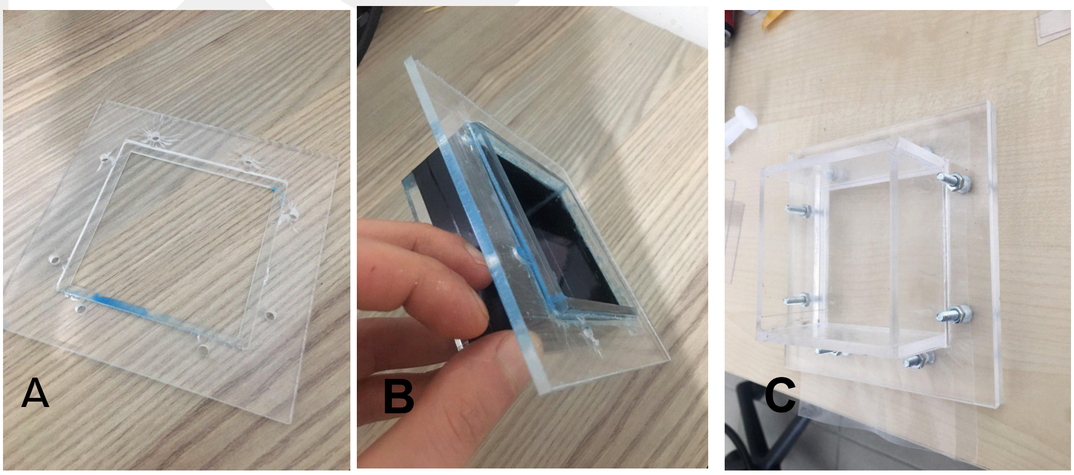

Figure 11 The resin vat

3.1.4 The Actuator for Z-axis linear movement

For this linear movement, an electric motor was needed. There are several types of electric motors the most popular types is: DC, stepper, and servo motors, each one of them has its weakness, strengths, and applications, for this work we need a motor that has very accurate movement, big torque, easy to control its speed, step size and direction of rotation, and reasonable price [21], therefore a stepper motor was chosen.

This stepper motor was responsible for the Z-axis's leaner movement, to move the building platform up and down during printing. This stepper motor (see Figure 12) model was chosen depending on these specifications as follows: Operating Voltage: 2.8V, Drowned Current on Each Phase: 1680mA @2.7V, Phase Resistor Value: 1.65 Ohm, Phase Inductor Value: 3.2 Mh, Step Angle: 1.8°, Step Number on Each Tour: 200, Holding Torque: 3.7 kg-cm, Sizes: 42.3x38x38mm (NEMA 17), Motor Shaft Thickness: 8mm, Cable Length: 16cm, Weight: 385g [22].

Figure 12 The stepper motor

3.1.5 Software and hardware component

3.1.5.1 Software

- **Workstation**

It is an open-source software it can work with differant resin 3D printer types SLA, DLP, LCD as a slicer, and a host controller, and it has been used in this study as a slicer and printer controller [23].

- **SolidWorks**

It is a computer-aided design (CAD) software from Dassault Systèmes, it can perform parametric design, and produce three kinds of files, and if any change happens in one file, it will apply for the other two files.
It was used in this study in two parts, the first one was by making the conceptual design for the whole printer, and the second one was making the custom design of the 3D models that will be tried in the experimental section [24].

3.1.5.2 Electronic component

In this study, two primary electronic devices have been used to control the stepper motor for the Z-axis movement and make it synchronized with the projection time for each layer.

- Arduino

"Arduino is an open-source electronics platform based on easy-to-use hardware and software" [25], and in this study, an Arduino UNO has been used.

- A4988 driver

It is a stepper motor driver with a built-in translator, it is designed for bipolar stepper motors in full, half, quarter, eighth, and sixteenth-step modes, output voltage up to 35 V with 2 A, therefore it can operate the NEMA 17 stepper motor easily [26].

The electronic circuit and the connection between each component have been shown in Figure 13.

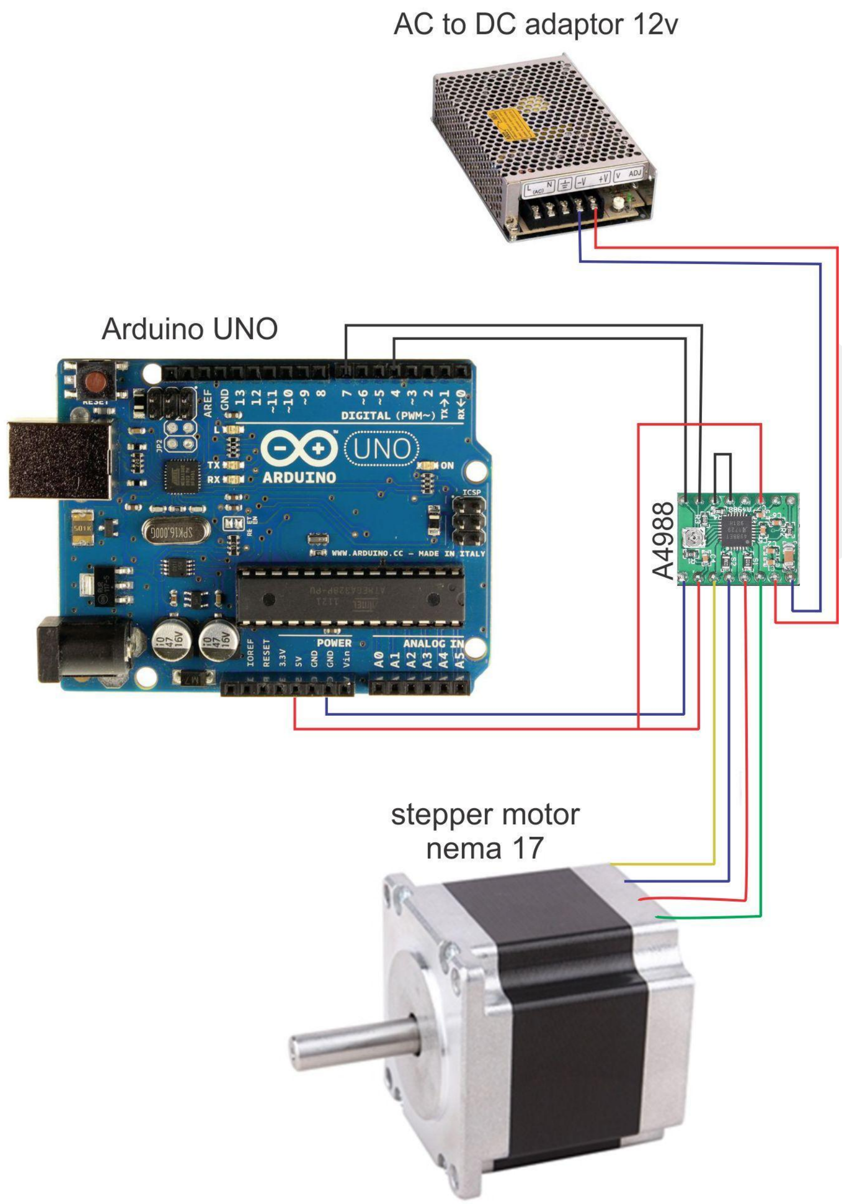

Figure 13 The circuit diagram

3.2 Staking the slices

Stacking the produced slices is the only moving process that this form of printing method uses. This method of printing based on an essential movement toward the Z-axis is required to perform this hierarchy structure. This movement needs to be precise and adjustable so that it will define the z stacking resolution and to make it compatible with the other building parameters to ensure a correct presentation of aspect ratio between all of the building dimensions.

It is performing a double action, the first one is to produce the gap that will be transformed into the next layer afterward, and the second action is to perform a precisely calculated movement that helps peels the newly cured layer from the (FEP film) with the minimum possible deformation to the cross-section area preparing it to receive the next layer.

3.3 Implementing and testing the Z-axis

One of the main elements in this printer is the step size of the Z-axis, because the layer resolution of the printed object is dependent on that step size, and the layer thickness has a significant effect on the mechanical properties of the printed object [27]. Therefore it should be adequately accurate to perform around 15 um. To achieve that a measurement should be taken to ensure that accuracy, by using 01mm Micrometer Round Dial Indicator Gauge approving has been done and it can perform good accuracy with 7% Instrument error in 400 um, and this Instrument error percentage will not affect the final object, the device used shown in Figure 14.

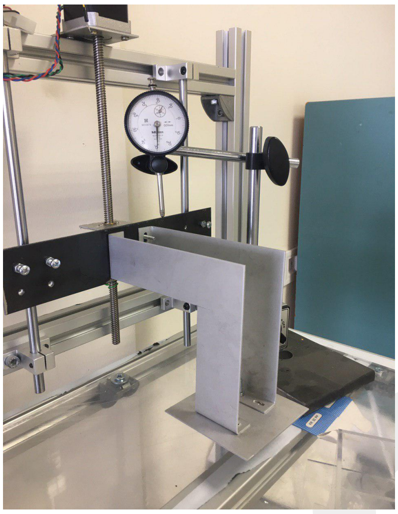

Figure 14 Micrometer Round Dial Indicator Gauge

3.4 What is resin and how it works

Resin is a liquid solution that consists of a composite mixture of different monomers and oligomers in a short-chain form; most of these chains are made of carbon atoms with few functional groups. It will still liquid unless a source of energy hits the resin surface by making long chains using these monomers and oligomers to give the hard plastic material for DLP, SLA, LCD printers.

Photopolymerization is the process that is responsible for hardening (curing) the resin. In this process, the out source of energy is needed, where the beam of light is the provider of energy for the molecules at the terminal ends of the monomers and oligomers to escape. This procedure makes imbalance in the monomers and oligomers; therefore their terminal ends are now free to react to each other, after that, they will start to make the long polymers chains, this whole procedure does not happen in a one-step process, these long-chain polymers continue to form during the procedure, and it may take part of a second.

One of the advantages of the resin-base 3D printing that the adhesive between the layers is much stronger than the FDM printers because during the printing process of the 3D model does not make the resin layer full cured, therefore it will make the layers bonded to each other in a way that makes it like one piece, and there will be no change between the three dimensions while using the resin-based 3D printers [28].

3.5 Final assembly

The DLP 3D printer assembly goes through several steps until it reaches the final shape. The first step was making the conceptual design by using SolidWorks 3D software for all components (the outline structure, stepper motor, projector, resin vat, and the elevator mechanism). The second step was to find every single component in the Turkish market according to the conceptual design. Some of them bought online, and others are from factories, the third step is the important one, starting to build the aluminum profile and attach each component on the structure inside the university lab, the fourth step was to connect each part with the controlling unit, the stepper motor connected to Arduino UNO across a motor driver. The projector is connected directly with Arduino to the computer to make the synchronization between all components.

3.6 Working principles

The process starting from making the desired 3D object (part) in CAD software like SolidWorks or any other software can produce STL format files, after that, transferring the designed object to another software in my study an open-source program Creation Workshop has been used, throw this program slicing process can be managed depending on the desired part resolution, even 0.001 mm can be achieved, by the help of the same software each layer can be projected to the building platform (as shown in Figure 15) which is in the lowest point of the resin vat to cure the first layer and it will be the first attached layer on the building platform after that Z-axis will move one step up to let the uncured resin collect under the first cured layer so the projector can cure the second layer and so on until the part is reaching the last layer that's mean the part is completed, then the building platform will move up to easily remove the part, and cleaning the part by apply isopropyl alcohol mixture and water.

In this setup, four parameters play the primary role in 3D printing: the Z-axis speed and lens focus, light intensity, and resin composition. An experimental study has been made to find the optimum parameters for the linear speed of the Z-axis and light intensity.

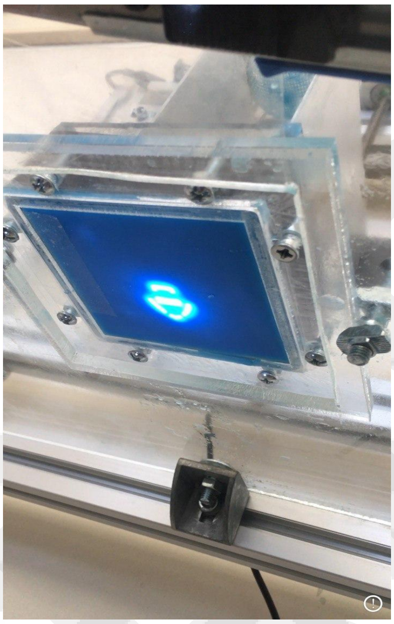

Figure 15 Light under resin vat (curing)

3.7 Finding the printing parameters

It was challenging to choose the correct parameter for the printer, a long experiment was needed to find the adequate parameters, and there was nothing to depend on to provide help in finding these parameters. Therefore it was a little hard to find the ideal parameters that are capable of printing any CAD design start from solid to hollow with complicated details designs. In the beginning, there was a massive number of different variables like type of the resin vat. Z-axis steps with the speed of linear movement, which program to be used to control, the internal setting of the projector (contrast, brightness, etc.), exposure time for each layer also it may change while changing the layer thickness, how much Z-axis move up after curing each layer, and the exposure time with the number of the first layers.

The experiment can't be done with this massive number of variables. Therefore one variable has been chosen every single experiment and tries to reach the best result with this one parameter and then jump to the other parameter by repeating this procedure several times to ensure that the best parameters have been made.

For the resin tank, in the first experiment, a vat from glass has been used. However, there was a problem in the glass vat because the resin after curing was sticking on the glass surface without sticking to the building platform. After this failure, a vat from transparent acrylic plastic is used, but the same result with glass has been got, the successful one was made from acrylic cubic with a base made from FEP (fluorinated ethylene propylene polymer) film.

For the Z-axis step, it can be diverse from 10 to 200 um; for the linear movement speed, the best result was found with the higher speed was better than slow speed for the moving the Z-axis up after each curing.
For the software after an extensive search, the best choice was found in was Creation Workshop because it is an open-source program and has all the features that were needed to control all features for the 3D printer.

There was a problem with over curing for the internal setting of the projector at the default projector setting, which means there were parts around the printed object that were also cured. This problem causes many problems; therefore, some settings inside the projector were changed, such as brightness, contrast, and color mode. Furthermore, better results were achieved without any curing problems.

For the exposure time, there were three types of change, in this first one: how many seconds for the bottom layers (these are some layers for the base from 2 to 6), they are essential because they cause the object to stick on the building platform. The second one is how much it required for one layer to be cured; while the third one is this time for each layer should be change depend on the layer thickness.

For Z-axis moving up after each layer, it depends on how big the cross-section area, big layer area needs more to get the building platform from the FEP film, and an average has been founded about 6 mm move up it can work for different area.

CHAPTER 4

THE EXPERIMENT AND VALIDATION

4.1 The experiment

4.1.1 The first experiment

Complete results have been obtained in the first set of experiments. Before that, there were several failed experiments before the resin vat, and the building platform has been changed. In this experiment, almost exceptional results are obtained, as given in Table 3. The 3D CAD model was chosen as given in Figure 16; it is a cubic with two supporting legs from the bottom.

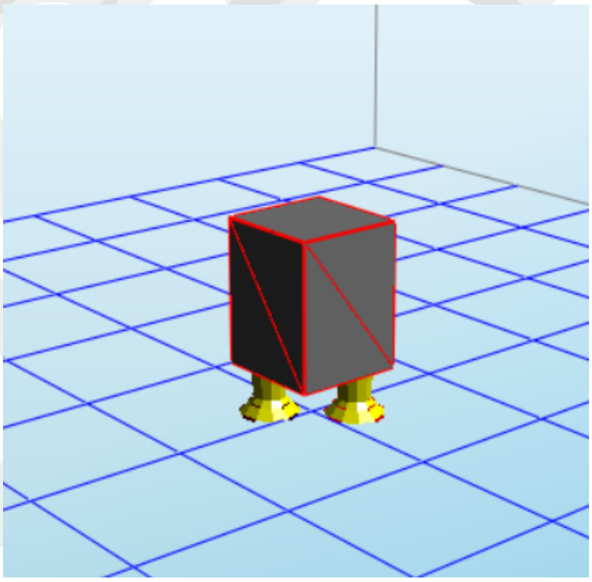

Figure 16 The CAD model for the first experiment.

Table 3 The first experiment

No	Z speed in mm/m (milimeter / meter)	Slice thickness In mm	Exposure time in ms (miliseconds)	Bottom exposure in ms	Bottom layers	Z lift distance mm	picture
1	80	0.100	1100	8000	3	4	Figure 17 A
2	80	0.100	1300	10000	3	4	Figure 17 B
3	80	0.050	900	10000	3	4	Figure 17 C
4	30	0.050	900	10000	3	5	Figure 17 D

Table 3.1 explanation: (No) the number of experiments. (Z speed) the speed of the Z-axis axes movement, up and back down. (Exposure time) the time for each normal layer to be cured. (Bottom exposure) the time for the few bottom layers for the base of the object. (Z lift distance) how much mm the building platform will move up after each cured layer.

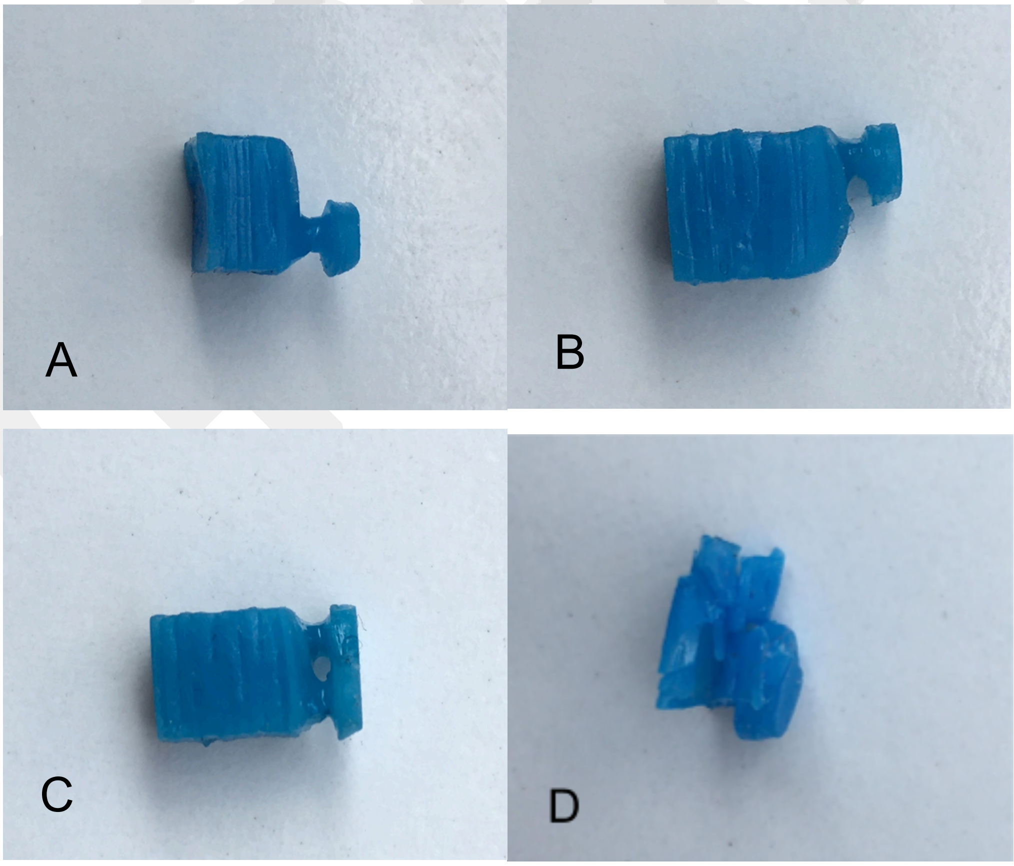

Figure 17 The first experiment samples

In the first try, the object did not complete because of the few exposure time, and one of the supporting legs was lost, in the second try, a completed object is printed by increasing the exposure time and bottom exposure time. In the third try, trying to decrease the layer thickness from 100 um to 50 um, a better result has been achieved compared to the second try with 900 ms. In the fourth try, trying to reach a better result by decreasing the Z-axis speed from 80 to 30 mm/m, but the worst result has been got, from this result, it was clear that the more speed that has been implemented on the z-axis movements the best result will obtain with some limits that will be discovered later on.

4.1.1.1 Calibrating the measurements

In the first set of the experiment a measurement calibration has been done for the X, Y-axis to ensure that the right measurements will be getting for the final printed object.

4.1.1.2 Changing the building platform

After the first part of the experiment, an abnormal movement has been noticed in the building platform because of the horizontal arm was tall from the lead screw of the stepper motor (as shown in Figure 18) that makes it bending down when the Z-axis is moving up because of the effect of the adhesion strength between the building platform and the FEP film. Therefore the building platform has been changed with a new one to perform better printing results.

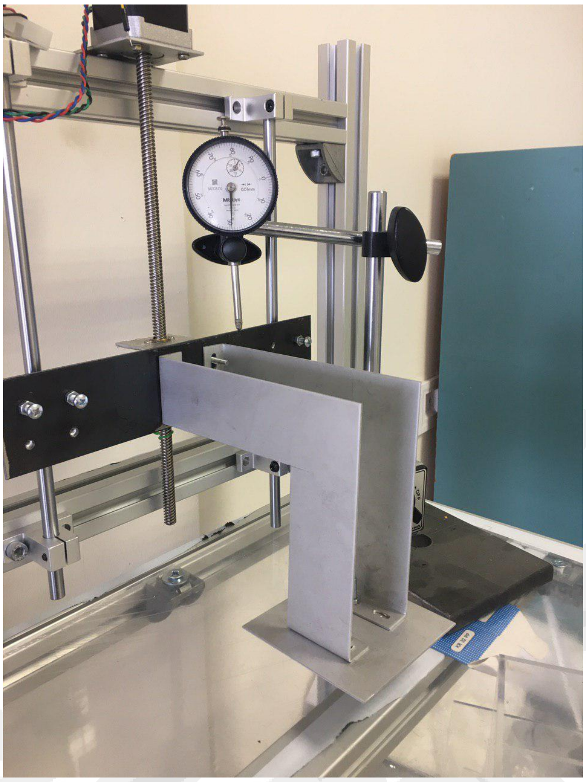

Figure 18 The old platform

4.1.1.3 Modifying the building platform

After the first experiment has been done, a new building platform has been made consisting of two parts made from PLA filament in an FDM 3D printer, the two parts connected by a screw to give the ability to remove the vertical part to remove the printed object easily or even seeing the result during printing (see Figure 19 and 20). The reason for using the FDM 3D printer to build this part was to gain the accuracy for the parts with the solid form that is desired instead of the old one, which was made from the aluminum sheet with 3 mm thickness. After installing this modified building platform a new set of experiments has been made to try the new equipment that has been applied to the printer (see Table 4).

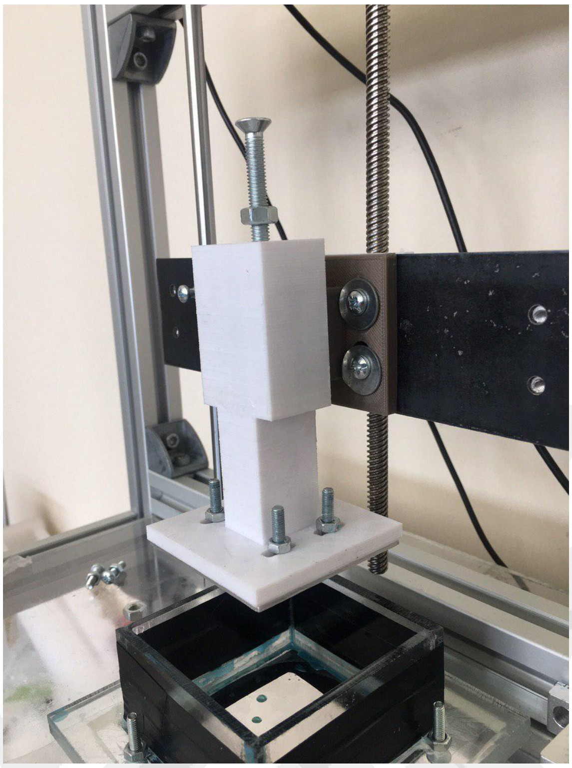

Figure 19 Modified building platform (front)

Figure 20 Modified building platform (back)

4.1.2 The second experiment

In this second experiment, a Benchy 3D model (see Figure 21) was tested with three parameters, relying on the first experience in some parameters. Each experiment is explained in the following sections.

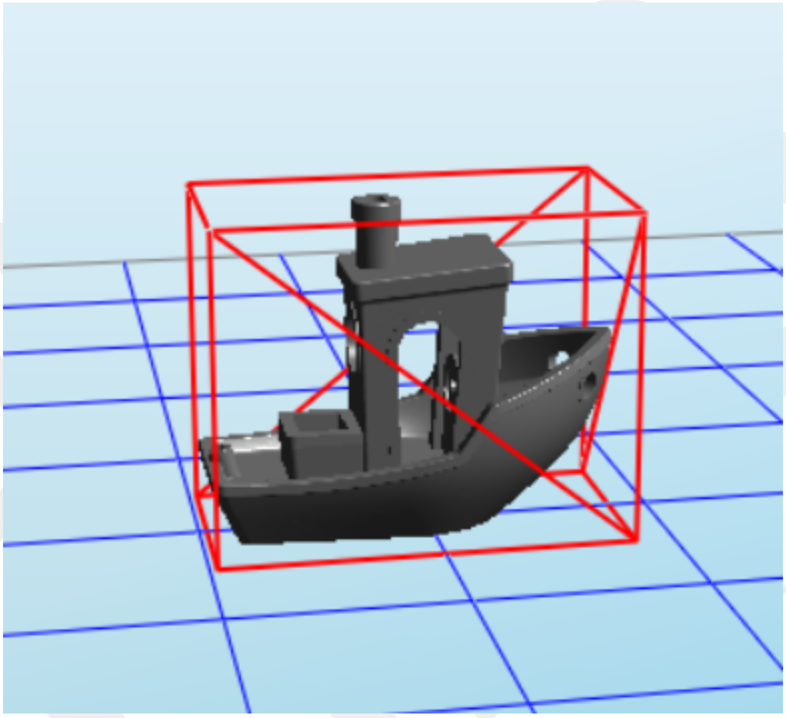

Figure 21 The Benchy CAD model

Table 4 The second experiment

No	Z speed in mm/m	Slice thickness In mm	Exposure time in ms	Bottom exposure in ms	Bottom layers	Z lift distance mm	picture
1	160	0.200	2500	10000	3	4	Figure 22 A
2	160	0.200	2600	10000	3	4	Figure 22 B
3	160	0.200	2800	10000	3	4	Figure 22 C

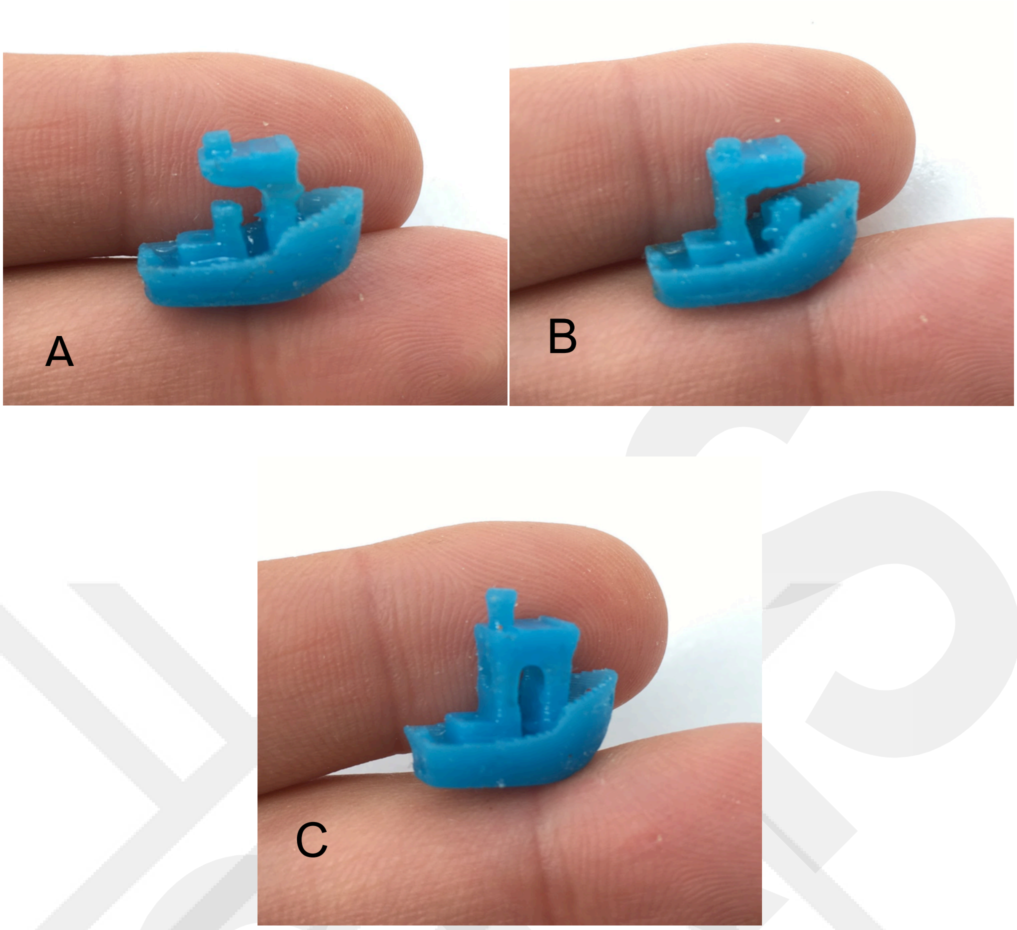

Figure 22 The second experiment (A, B, C)

The first try entirely printed, but it has some failure in the small details; however, the outline shape was clear with 2500 ms for exposure time. The second try and exposure time has been increased with 100 ms to see if it will go better or worse. It became 2600 ms for the standard layers, a better result has been obtained in comparesion to the first try but still has some missing parts, but there was an improvement. For the third try, by increasing the exposure time with 200 ms and it became 2800 ms, the delighted result has been got for the printed object without any missing parts or merging between small details like holes.

4.1.3 The third experiment

In this third experiment, a much detailed model needs to be printed to ensure the printer's ability to print any desired shape. Therefore a custom design has been made by using SolidWorks 2019(as shown in Figure 23), to make a hole cubic with 2 cm diameters with a wall thickness of 1.5 mm, with bricks of 0.5 mm thickness as a texture on the wall from outside.

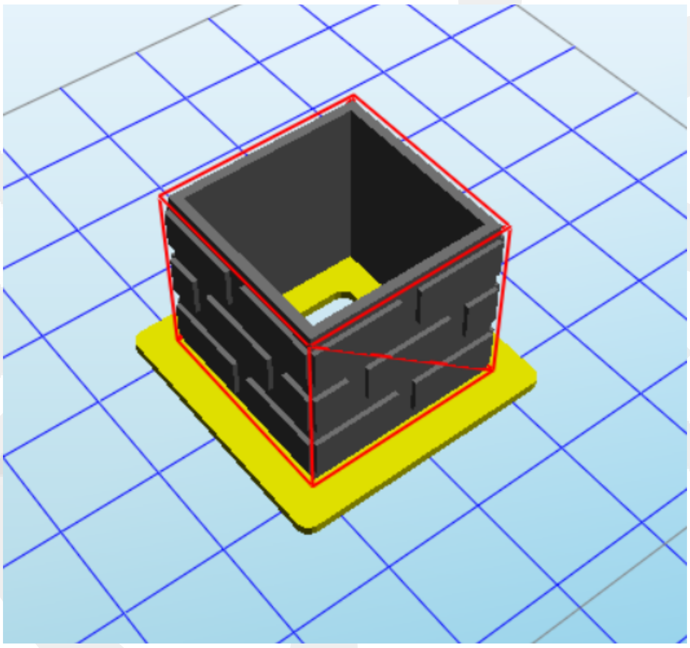

Figure 23 The cubic CAD model

Table 5 The third experiment

No	Z speed in mm/m	Slice thickness In mm	Exposure time in ms	Bottom exposure in ms	Bottom layers	Z lift distance mm	picture
1	160	0.200	3000	10000	3	5	Figure 24 A
2	160	0.200	3200	12000	3	5	Figure 24 B
3	160	0.200	3200	12000	4	5	Figure 24 C

In the first try, the object is fully completed with good quality, but there was a problem there was the missing part in the first 3 mm from the platform to the object body like a hole, almost the same problem that happened in the second experiment.

With the Benchy model, therefore the exposure time should be increased as happened in the previous experiment and it has been solved the problem, in the second try the normal layers exposure time and the bottom layer has been increased but also the same problem has been got, also missing part next to the building platform, in the third try a 1 mm solid base has been implemented in the bottom of the cubic with the same parameter with the previous try, a perfect 3D model has been obtained without any missing parts with a perfect surface finish.

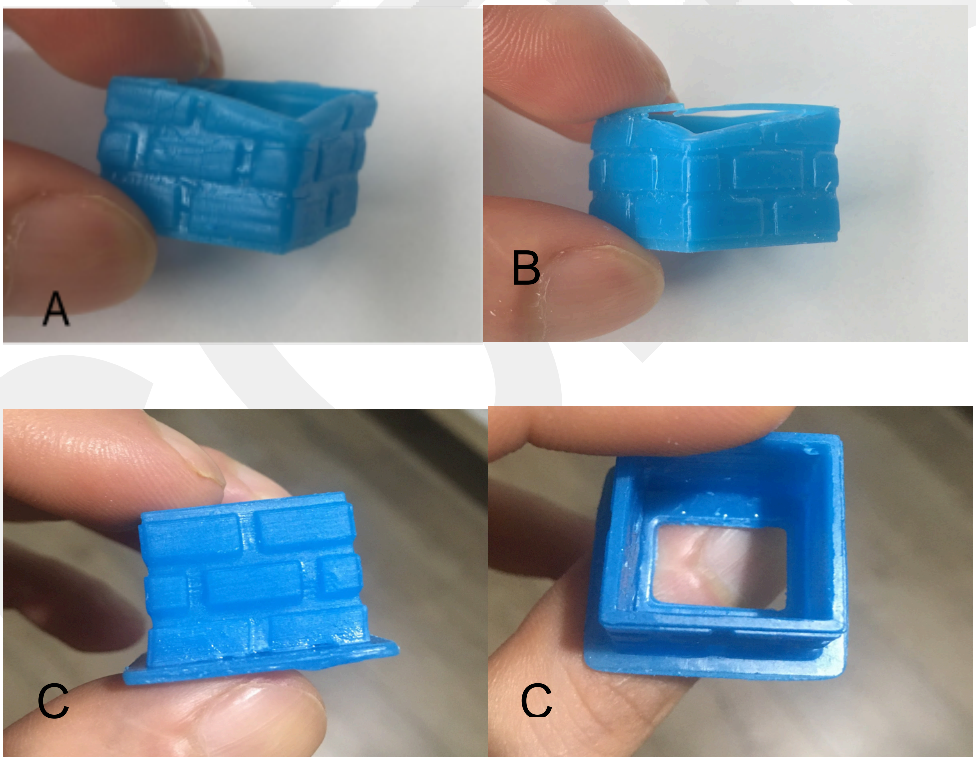

Figure 24 The third experiment (A, B, C)

After getting very good results in the third experiment with nice surface finish, while the CAD model design was a flat cubic with Bricks and it successfully printed, a more detailed CAD design was aiming to produce for further check about the printer abilities for different 3D models, this shape has been chosen as shown in Figure 25.

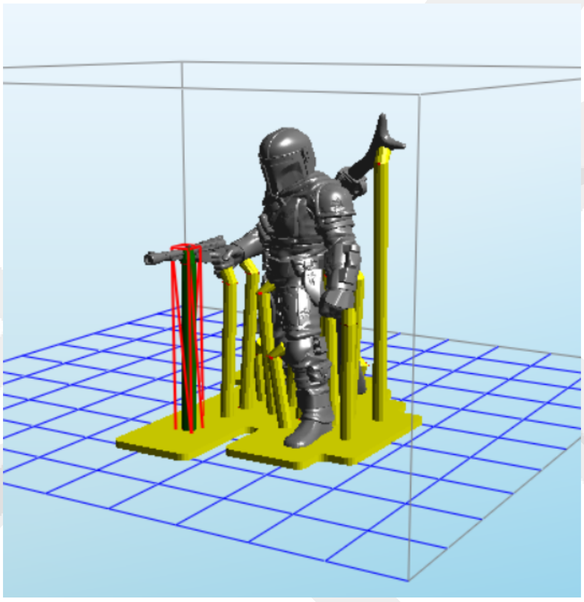

Figure 25 the CAD model

It was successfully printed out from the first try with the same parameter in the last try of the third experiment as previously explained, the printed model shown in Figure 26.

Figure 26 The printed model

4.2 Test and validation

To ensure the validation of the printer, for the printed samples, two tests were performed. The first one was about the Repetition while the second one was about positioning in the building platform.

4.2.1 The repetition test

In this test, ten samples were printed in almost the same weather condition and time, the weather was changing from 30 to 24 centigrade degrees, and the time was from 1:30 PM till 1 AM. The printed sample consists of a solid cylinder over a solid cubic (see Figure 27 and 28).

Where A is represent the height and B represent the width for the cubic, and C is representing the Diameter for the cylinder.

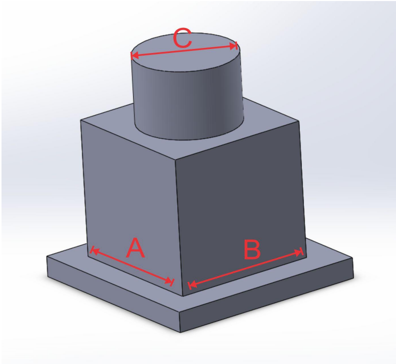

Figure 27 Test CAD model

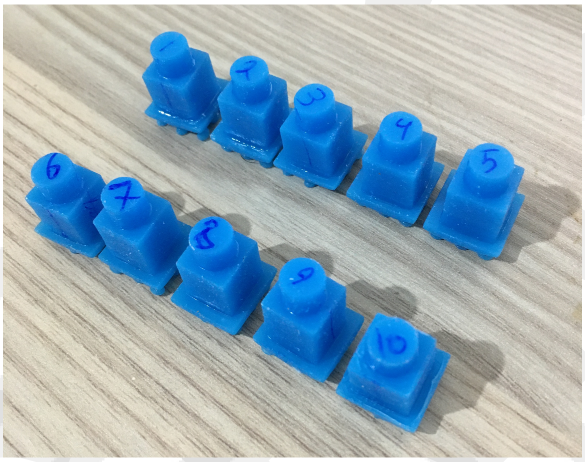

Figure 28 Ten samples

The test results are given in Table 6, and the location of the parameters shown in Figure 27. The test was made using a micrometer with the accuracy of one micro (see Figure 29). Data analysis is performed using SPSS (version 21; IBM Corporation, New York, USA) within a 95% confidence level. A, B, and C differences are analyzed using descriptive statistics (see Table 7).

Table 6 The result of the first test

No	A (mm)	B (mm)	C (mm)
1	10.004	9.988	7.000
2	10.004	9.988	6.995
3	10.001	9.987	6.998
4	10.005	9.988	6.997
5	10.006	9.990	7.002
6	10.008	9.992	7.000
7	10.000	9.983	6.992
8	10.000	9.982	6.994
9	10.001	9.983	6.995
10	10.001	9.982	6.988

As seen in Table 6; considering A, B, and C for 10 samples (N), a mean of M=10,0030 is calculated for A, a mean of M=9,9863 for B and M=6,9961 for C with standard deviations SD=.002789, .003561, .004202 respectively.

Table 7. Descriptive results for A, B, C

	N	Mean	Std. Deviation
A	10	10,00300	,002789
B	10	9,98630	,003561
C	10	6,99610	,004202
Valid N (listwise)	10		

Figure 29 The micrometer instrument

4.2.2 Positioning in the building platform test

In this test, five samples were printed and tested under the same circumstances with the first experiment. The same shape has been implemented under this test. The only difference was the position of every one of the five samples; they were distributed in a 6x6 matrix (see Figure 30 and Figure 31).

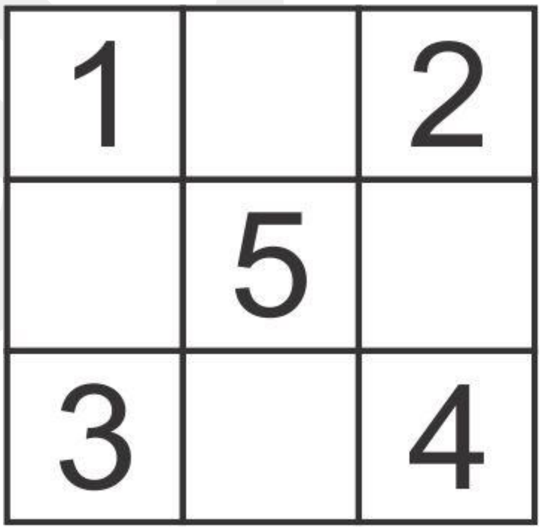

Figure 30 6x6 matrix of the samples

Figure 31 Separated samples in the building platform

The test results are given in Table 8, and the location of each sample is represented in Figure 30. The test was made by the use of a micrometer with the accuracy of one micro (as given in Figure 29).

Table 8 Result of the second test

Position	A (mm)	B (mm)	C (mm)
1	10.018	9.985	6.993
2	10.002	9.981	6.994
3	10.011	9.985	6.990
4	10.009	10.006	7.008
5	10.000	9.983	6.992

As seen in Table 9; considering A, B, and C for 5 samples (N), a mean of M=10,0080 is calculated for A, a mean of M=9,9880 for B and M=6,9954 for C with standard deviations SD=.007246, .010198, .007197 respectively.

Table 9. Descriptive statistics for different positions

	N	Mean	Std. Deviation
A	5	10,00800	,007246
B	5	9,98800	,010198
C	5	6,99540	,007197
Valid N (listwise)	5		

CHAPTER 5
DISCUSSIONS AND CONCLUSION

After doing the three experiments, the output results seem to be acceptable after which was mentioned in Chapter 3. One of the most effective parameter was the exposure time both for the normal layers and the base layers (normally they are first layers attached to the building platform from 3 to 5 layers), and the exposure time can be fixed for each printed layer thickness. For example, if the desired printed part in 50 micro it will be 900 ms and for 100 micro it will be 1450 ms and for 200 micro it will be 3200 ms and so on. The time increasing when the layer thickness is increasing (these numbers has been extracted throw many experiments). On the other hand, for the based layers, 12000 ms is needed to let the object fully attached to the building platform. The second parameter was the speed of the Z-axis. It is proved that, 160 mm/s is the ideal speed for it, also low speed does not give better results. The other important point was the lifting distance for Z- axis during printing to let the cured layer separate from the FEP film and letting the fresh resin to gathering again underneath the printing part.

This printer is based on the simplicity in usage, so any one can use it. However there are some recommendations that should be followed before using it. The place where this printer will work must have an air circulation mechanism because the curing mechanism can produce smell emission and it may be harmful for health. The person who use the printer should wear a mask for filtering the air and also should wear gloves during working with resin. Furthermore user should avoid looking directly to the light source for the eye safety.

In this thesis, a DLP 3D printer based on SLA technology has been successfully made, with an available component in the market with several self-made components, together they assemble this printer with the lowest costs. One of the aims of this research is to make this technology more spreaded in the future for the academic students and for the manufacturers to benefit from this technology along with the other AM technologies.

Different 3D models and self-made 3D designed models ensure the printing quality in different sizes and shapes and have been printed using this DLP printer with satisfactory surface quality and dimension measurements using the commercial 3d printing resin. The printing procedure was so easy from the beginning until the end of the 3D model that even the post-process mechanism was simple, and anyone can use it without any previous knowledge by just following some steps. However, it still has the problem that after the printing process is finished some cleaning process has to be made to ensure there is no resin remain in the resin vat or the building platform unlike the other AM technology like FDM it not require any cleaning process.

There is still more room for improvement of this DLP 3D printer; as shown in the previous chapters, the printed 3D models' surface is not very soft. It has some obstacles, and it appears in some shapes in some parts of the model.

The next step to get a good surface is to use a more specific projector for this purpose with UV light, not a regular light as it was used in this research.

The aim after this thesis is to implement this technology in the medical production to produce a biocompatible material that can be implemented in the human body such as dental implants, dental coverage, and fillings. These products can help the dentist to produce more accurate shapes with much lower time

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