Journal of the Technical University of Gabrovo

https://mc04.manuscriptcentral.com/jtug

DESIGN AND BUILD HIGH PRECISION SLA 3D PRINTER

Pavel Ikonomov*, Andrew Wyman, Sudarshan Rawale

Western Michigan University, Michigan, USA

ARTICLE INFO

Article history:
Received 1 June 2020
Accepted 8 June 2020

Keywords:
3D printing, Additive Manufacturing, SLA, DLP, micro-manufacturing

ABSTRACT

The goal of this research was to build a high precision 3D printer to be able to produce high-resolution biological structures. We designed, build from scratch, and tested 10 microns resolution SLA 3D printer to create high precision structures with complex 3D external and internal spaces. The laser moves on predefined paths on X and Y- axes to cure resin, layer by layer, and then moves up on the Z-axis for each subsequent layer until the part is produced. The 3D printing process utilizes a three-axis platform with motion resolution of +/-5 microns and curing laser with diameter 10 microns to enable curing of the resin and building of thin walls and cavities not possible with other 3D printer technology. Furthermore, this 3D printer increases the accuracy and finished surfaces of the printed structures. The printing is controlled by CNC system, providing simultaneous motion in all three axes using stepper motors and preloaded ball screws. We had built several FDM, SLA, and SLS 3D printers and CNC machines, which experience helped us to achieve a design with desired high resolution. The 3D printer serves as a foundation for future research to print high precision parts such as biocompatible bone structures.

1. INTRODUCTION

3D printing, also called Additive Manufacturing (AM) or rapid prototyping in the past, has been growing exponentially in recent years, worldwide it is expected to reach $15.8 billion in 2020, and $35.6 billion in 2024 [1]. Two of the most common 3D printing methods are Fused Deposition Modeling (FDM) and stereolithography (SLA).

In general, a 3D printing process is based on the 3D digital model created in Computer Aide Design (CAD) or other modeling software. The 3D model is sliced in so-called layers to allow the printing of each layer on a horizontal plane. Each layers' geometry is calculated from the cross-section of the sliced 3D model at the layer high. Depends on the type, 3D printers use different techniques to create a part layer by layer. FDM delivers molten plastic though hot extrusion nozzle (similar to hot glue gun) on a digitally control path. This method employs a plastic filament from a coil that steadily supplies material to an extrusion nozzle. [2]. The FDM technique deploys the extruded material onto a flat building platform in design pattern, to create the first layer. The plastic solidifies in the air after leaving the nozzle and bonds to the platform. Then the head with the nozzle moves up in the Z direction to the next layer, the material is delivered on the top of the previous layer, and the process is repeated multiple times to complete the part. [3]. SLA 3D printer uses ultraviolet (UV) light laser to cure the resin placed in a vat. We will explain later in detail about how SLA works. Selective Laser Sintering (SLS) uses a laser to sinter plastic or metal power dispersed on a bed platform.

Why we need a new high precision printer?

We have been using different types of printers for numerous research applications. We have ongoing research to design and 3D print bone substitutes. We were able to print human bone substitutes with exact shape and designed structures, based on models created from actual individual bones using medical Digital Imaging and Communications in Medicine (DICOM) images. In our research, biocompatible polymers were used for 3D printing and tested to build external bone structures.

Later, when we tried to print the internal parts of the bone, spongy (cancellous) bone structure, we were not able to find a 3D printer that can print them. According to our measurements of the spongy bone internal structure, the thickness of the walls can be as low as 15 microns. Therefore, one of the main issues we had was that due to the lower resolution of typical 3D printers, they couldn't print such a fine structure. Existing FDM, SLA, and other type 3D printers can print with a lower resolution up to 70-100 microns [4]. Due to the nature of the technology, we learned that FDM could not be designed and built for resolution less than 50 microns, which was more than three times bigger than the desired resolution of 15 microns. Even with top of the line 3D printer like Stratasys Objet Eden 260VS, Objet 260 Connex3 provides relatively high resolution on Z-axis (16 microns) but lower in X, Y directions (60-70 microns) [5]. We found one of the so-called ultra-high-resolution laser stereolithography 3D printer, Photonic Professional GT, can achieve up to 1-micron resolution. Unfortunately, the size they could print

* Corresponding author. E-mail: pavel.ikonomov@wmich.edu

was only about 10 mm (0.41 inches), which was not enough for making bone structure [6].

After investigating different design and technology methods, we concluded that we should design and build our own SLA type 3D printer that could meet our printing requirements with sub-15-micrometer resolution. Therefore, the goal of this research was to produce a high precision SLA 3D printer to be able to print super-fine structures.

2. OBJECTIVES TO BUILD HIGH-RESOLUTION 3D SLA PRINTER

On average, the cost of a 3D printer on the market can range from $300 for low quality, low-resolution printers to $500,000 for a very high-quality rapid prototyping industrial printer. With this project, the overall goal was to design, build and test a high precision SLA 3D printer with a level of precision exceeding the high-level 3D printers on the market but at a fraction of the cost [7]. The clear benefit of this has been gaining the ability to produce at least a 10-micron level of resolution of the laser beam spot and motion precision of 5 microns. Additionally, this project created a platform for researchers to take their concepts and then reproduce them in a relatively quick manner. This SLA printer differs from the abilities of the available 3D printer in that the high precision would allow the user to visually identify small issues with design ideas that a lesser level of accuracy would not let the user see details correctly. The applications are not limited only in the research area but open the possibilities with high-resolution 3D printing for medical applications and to industry.

2.1. Selecting the technology to meet the requirements for printing

The SLA type 3D printers have evolved over the years, and there are several different categories of 3D printers on the market. This research document is focused on building Stereolithography (SLA) printers and investigating some of the similar Digital Light Processing (DLP) printers.

Some of the attributes that determine what kind of 3D printer is best suited for an application are: file-to-file finished part speed, part cost, accuracy, print capacity, and color. We chose the SLA 3D printer for our application solely on our need for higher resolution and accuracy of the parts needed to be produced [8]. SLA and DLP printers use similar processes, where photopolymer liquid resins are cured to form a solid. The main difference between the two methods is that SLA uses a laser-based process, while DLP uses a projector [9, 10].

Figure 1 shows the main components of an SLA 3D printer. SLA printers create parts by using software to slice stereolithography (STL) 3D models into layers. The layers are traced using a laser mounted to a motion scanner system onto a platform, dipped inside the resin vat. The traced outline of the layer is cured by the UV laser and bonds to the platform, creating the initial layer. After the initial layer is cured, the stage is dropped one step equal to the thickness of the layer. This process is repeated multiple times until the part is created.

Figure 2 shows the main components of a DLP 3D printer [12]. DLP, like SLA printers, create parts by using software to slice STL part files into layers. An image is projected through the photopolymer vat of resin onto a stage to create a layer. The image projection, on the bottom side of the stage, cures the resin, creating the initial layer. Next, the stage is raised on a distance equal to the thickness of the layer; the image is projected again and cures the resign to create the next layer. The process of layers curing is repeated multiple times until the part is formed.

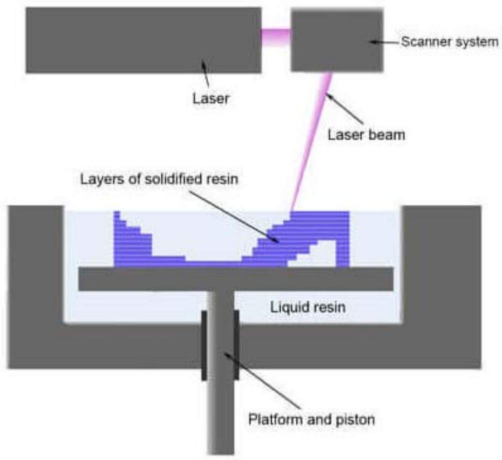

Fig. 1. SLA 3D Printing [11]

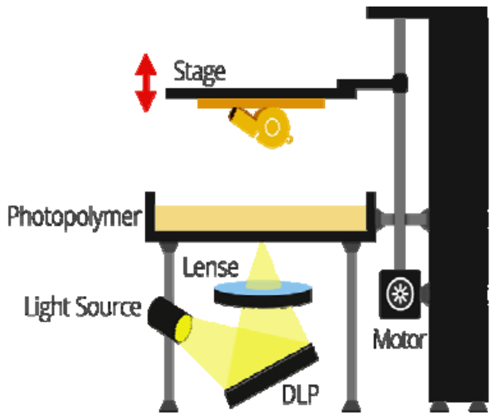

Fig. 2. DLP 3D printer [12]

2.2. Choosing the 3D printer technology

3D printing technology depends on the precise resolution in 3 dimensions; for each layer, it is 2D plane dimensions (X&Y), and for layer thickness is vertical Z dimension [13].

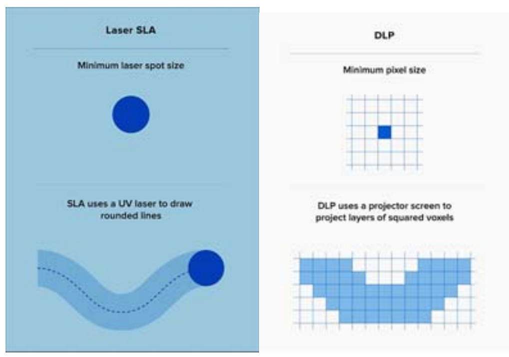

Fig. 3. SLA (left) and DLP (right) 3D print technology [12]

The resolution of the SLA printer depends on the minimal steps of movements of the laser on the XY plane and the laser spot size projected on the plane, see Figure 3. When the laser head home on the plane, it creates a smooth high-precision path. For example, Form 3 LFS 3D printer delivers 85-micron laser spot size and XY motion resolution 25 microns, which limits the physical size of the smallest wall thickness to 85 microns and in practice 100 microns with curing the surrounded resin [14].

The resolution of the DLP printer depends on the smallest pixel size that contingent on the projector resolution. For a full high definition projector (1920X1080), the resolution on the XY plane is between 35-100 microns. Even if 4K (3840 x 2160 pixels) projectors were used, like Phrosen Shuffle 4K, the resolution is still 31-47 microns, not enough for our needs. Another problem is that the DLP renders using pixels (XY) or voxel if you add Z dimension, it creates rectangular voxels, so the transition between them is jagged, no smooth, see Figure 3.This effect is easy to understand if we zoom a digital image up to pixel level and see the jagged edges. While in computer graphics, we can use anti-aliasing on image or 3D models to visually smooth the edges; this solution is not possible with the DLP printer as voxels are physical matters.

Therefore, we concentrated our study on SLA technology because it was possible to reduce the laser spot drastically. Then if high precision of X, Y, and Z movements were achieved, it was possible to reach 3D printing smaller than 15 microns. Finally, we selected the SLA method for the project because of its capabilities. In the following sections, we will explain the process of completing the SLA 3D printer. It begins with the design process, goes through the build process, and ends with testing the 3D printer [7].

3. METHODOLOGY

3.1. Design and selection of components for the 3D SLA printer

Initially, the project started by selecting a DLP as the light source to cure the liquid resin. As stated above, the DLP projector could not meet the required precision of 15 microns for the project, so the light source was changed to laser as the SLA 3D printer. Shown in Figure 4 is the SLA designs modeled and simulated in CAD software.

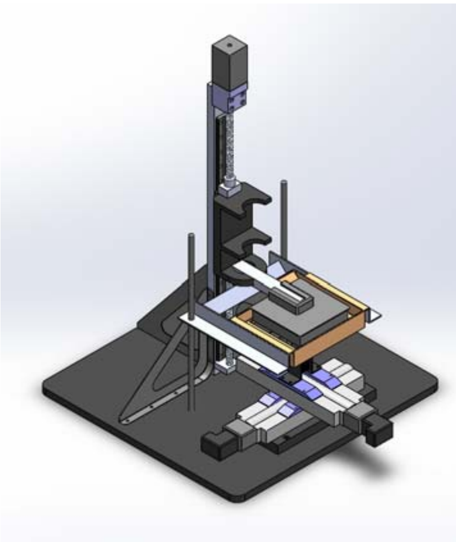

Fig. 4. Precision SLA 3D printer design

The final SLA design took attributes from existing SLA printers on the market. It has a build capacity of 150 x 150 x 320 mm. The heavy wear items on the printer were designed to be easily replaced and readily available. The main heavy wear items that we focused on was the laser, resin tank, and build platform. All of these are standard parts, relatively inexpensive, and can be repurchased online with little to no lead time.

There are many different parts to make the SLA 3D printer; the main parts are pointed out in Figure 5. Each part will be explained more in depth later in the paper. The major parts listed are: A - horizontal XY moving table, B - vertical Z axis moving stage, C – stepper motors on, X, Y, and Z axis, D-laser, H- adjustable platform, G-resin tank, F-Build Platform, E- resin.

We had built several FDM and SLS 3D printers and CNC machines that experience helped us to achieve a design with desired high resolution. To accelerate the process of building we desided to purache most of the components when possible.

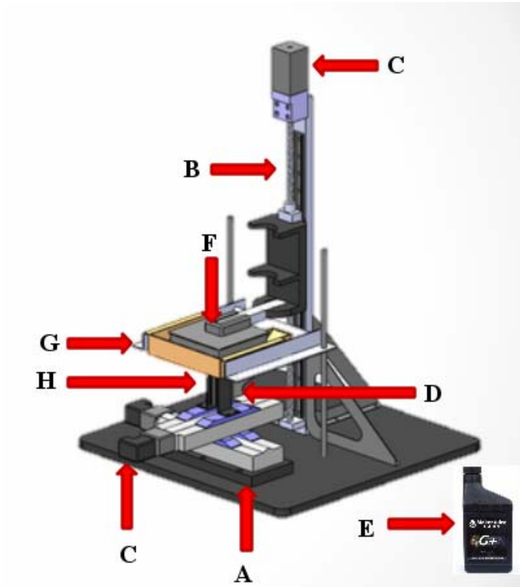

Fig. 5. LSA printer main components

The horizontal XY motion table, purchased online, was made by Parker industries, a very reputable company in the world. The Parker 404XR linear actuator XY stage is long 304mm with 150mm travel, see Figure 6. This linear actuator utilizes precision ground ball screws to achieve 1.3-microns precision. The SLA 3D printer uses the XY table to move the laser in a predefined path, essentially tracing each layer on the build platform. The table moves in X and Y directions by motors driven by the CNC controller.

Fig. 6. XY motion table

The table came with two hybrid servo motors, but we couldn't find the specific controllers for them. Then, we replace them with the high precision stepper motor on each axis. Coincidentally, the bolt pattern was the same, so we mounted stepper motor easily using a spring-loaded coupling. Although the stepper motors did not provide as high precision, as the original servo motors (1.3 microns), we found out the 5 microns of accuracy could be easily reached on +/-X and +/-Y directions. CNC control was used to move the stepper motor and ball screw, and we measure the resolution with a high-precision dial indicator. In the future, replacing them with higher resolution servo motors would increase the accuracy back to the original 1.3 microns.

The vertical Z-axis moving stage was repurposed from existing high precision optical scanning equipment. The technical issue we had was the precision aligning the stepper motor spindle to the ball screw spindle, see Figure 7. To solve this problem, we fabricated a custom bracket to bolt-on to align both the spindle and ball screw, utilizing an adjustable spring-loaded coupling allowing an easy assembly and maintenance. After we assembled the stage, we tested the precision of this axis. CNC control drives the stepper motor and ball screw to move the attached stage and we measured the resolution with a high-precison dial indicator. On the Z-axis, we were able to achieve 5 microns of precision of movements in both directions – up and down.

Fig. 7. Z-axis moving stage

The laser is attached to the XY table using a fabricated bracket and is easily swappable. This laser is a focusable high precision 405 nm purple 200 mW laser, with 9 DC-volt power and integrated cooling fan. It is essential to match the laser UV wavelength and the tower high to ensure the resin is cured correctly. Later, we also purchased more powerful lasers with 500 mW and 1,000 mW for testing the printing performance with different materials used for future research.

The laser had a beam spot larger than required by our design. To solve this problem, we used a precision aperture to ensures that the laser light beam is precisely 10 microns, see Figure 8. The aperture part is mounted to a fabricated bracket that is attached to the horizontal XY moving table. We believe that when building this SLA printer, we were the first in the industry to use a precision 10 microns aperture pinhole to ensure the resin is cured correctly.

The SLA printer uses UV curable liquid resin. For testing, a general-purpose fast curing resin from Maker Juice Labs called a G+ resin was uses. This resin cures at a light length of 405 nm, which perfectly matches our laser. The problem we found with this particular resin is that when it cures, it expands; therefore, even if we use a 10-micron laser beam, we cannot cure it with the same precision we were aiming. We found that high precision resins, available on the market, can only cure around 25 to 50 microns. Even the resin did not cure so well, for this research, we have reached our goal to build an SLA printer to have physics resolution capabilities of 10-micron. The next step is to find resin matching these requirements. Dr. Ikonomov has been working for several years, with the printing department at Western Michigan University, on a research project to create a special UV curable biocompatible resin that could print at 10 microns or less.

Fig. 8. 10 micron aperture

The resin tank holds the liquid resin during the printing process. The resin tank was purchased from Form labs [15]. It is made from shatter-resistant polycarbonate plastic to withstand impact. The tank is also tinted, so it blocks out other UV rays; this way, the part is not altered in the printing process. The included lid allows to store resin within the tank and has a squeegee to spread evenly. The resin tank is attached to the 3D printer body on a platform with adjustable screws.

The build platform is attached to the Z-axis. It slowly moves the part out of the resin tank as the resin is cured. The build platform was purchased from Form labs [16]. This building platform is made out of high strength aluminum to withstand multiple prints.

4. RESULTS AND DISCUSSIONS

4.1. Build process

We started the build process by calculating how much space is needed to fit the horizontal, vertical table, and the mounting system for the resin tank. At first, we attached the horizontal XY moving table to the vertical Z-axis stage; then, we built an adjustable platform for the resin tank to allow the user to regulate the distance and the power of the laser, see Figure 9. The screws allow adjusting the high of the resign tank position, while it is still rigidly fixed to both the base and support vertical stage column.

The SLA printer components, such as the stepper controllers, power, and electronics, were paced in a controller box and connected to the PC base CNC system and table motors. All the wires were arranged, isolated, and placed in plastic tubing to make the printer safe and look more professional. As one can see, the SLA printer in Figure 10 looks professional, easy to use, and aesthetically pleasing (PC and monitor are not shown here).

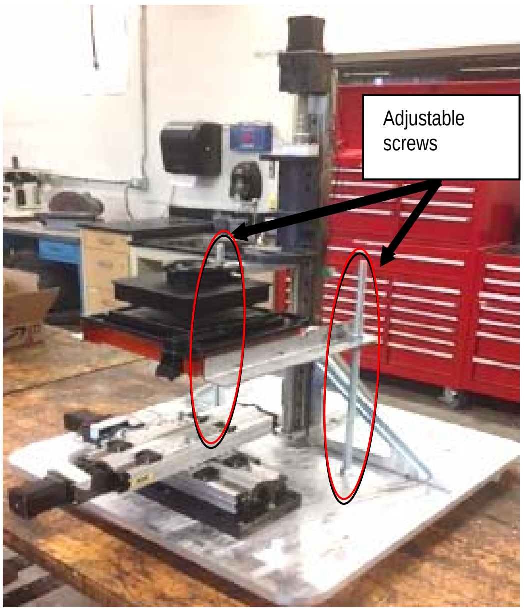

Fig. 9. SLA printer assembled

Fig. 10. Completed SLA printer

The primary source of communication between the XY table motors, Z-axis motor, and the laser were two controllers. With the primary controller being the CNC controller and the secondary controller being the driver controller. The CNC controller, using Mach 3 [17] software, connects directly to the operating computer. This controller produces high quality, consistent stepper pulse of around 4 MHz, which allows the motors to operate very efficiently with small steps capable of achieving the desired precision. The laser is switch on-off from the CNC controller.

We used Mach 3 CNC controlling software for all printing operations. We chose this software for three main reasons. First, the software was compatible with the controllers, and no changes are required to run the machine. Secondly, the software was already available, and we know how to use it. Finally, the software utilizes CNC programming using G-code/M-code that allows flexibility to adjust the 3D printing process. Although the Mach 3 CNC software was not natively designed to be used as a 3D printing software, it was relatively easy to be reconfigured for use, since the 3D printers work as CNC machine. One of the excellent features with the Mach 3 CNC software was the ability to preview prints. The software featured the ability to load in the CNC program and scrolled through line by line allowed us to catch errors in our code before we even initiated a print. Furthermore, it enabled flexibility to start, run, stop, adjust, and continue the 3D printing process, a feature no available with other 3D printers.

4.2. Testing procedures

During the testing, we found out that the laser adjustment is the most crucial piece of the SLA printer because it cures the resin to form the part. The original design was focusing the laser light using an aspheric condenser lens to focus the laser. With initial testing, it was proven more difficult than anticipated to focus the laser with lenses. The solution was to replace the lenses with a precision aperture that only allows a 10 micron in diameter laser beam pass through. The next testing was on the compatibility of the laser's ability to cure the resin done with a small sample of the liquid resin chosen. This test created a small cured part proving the laser and resin were curing correctly. Next, we measured each of the axis motion precision with a digital dial indicator mounted against each carriage using a predefined step in the software. We measure the actual deviations to be +/-3.5 microns, which was even better than the designed specification of +/-5microns.

The final goal of this project was to build a 3D printer precise enough to print at least 10 microns controlled resolution. The ability to print at 10 microns requires tight control of the printer's variables directly related to precision. These variables include the type of resin used, the drive system for the X, Y, and Z-axes, the optics system that will direct the laser into the resin bath to cure the resin, and the actual laser itself. The printer's design followed proven concepts from other 3D printers to accelerate the process and avoid problems. The expectations were that by analyzing various configurations, the best ideas from each 3D printer could be used in the final design. The refined design was then built and tested. The printer testing was done thoroughly by checking for fitment and layout issues. Adjustments in the designs were made, and iterations on the building of the new design were completed as needed. Once the printer was complete, we tested it to verify if the level of precision meets the requirements. The final stage for the project was to make a step-by-step operations manual for the printer since the printer is not a standard type.

5. CONCLUSIONS

In conclusion, we designed, built from scratch, and tested, a precise SLA 3D printer capable of printing at 10 microns resolution. We created one of a kind design that combines the precision laser, with the aperture to allow 10 microns beam, with a high precision CNC motion controller system, delivering +/-5 micron resolution. Our extensive research has not found any other commercial, industry, or personal SLA 3D printer that utilizes a 10 microns aperture setup to cure resin to a specific precision. The 3D printer was successfully completed to meet the goal of high precision 3D printing of biological structures. This high precision allow users to visually identify small issues with design ideas that a lesser level of accuracy would not let the user see details correctly. We believe this achievement is a big step in 3D prototyping to be used at Western Michigan University and elsewhere. In the near future, following the success of this research, we can push 3D printing out of the realm of prototyping into the realm of producing fully functional high precision components.

ACKNOWLEDGMENTS

Finally, we want to thank the Office of Vice President for Research at the Western Michigan University for awarding us with a $2,000 Undergraduate Research Excellence Award, which we used to buy componensts and materials.

REFERENCES

[1] TJ McCue, Significant 3D Printing Forecast Surges to $35.6 Billion, 20 May 2020 https://www.forbes.com/sites/tjmccue/2019/03/27/wohlers-report-2019-forecasts-35-6-billion-in-3d-printing-industry-growth-by-2024/#128e99c47d8a

[2] Fred Fischer, F, Thermoplastics: The Best Choice for 3D Printing., White Paper, Stratasys Inc., retrieved 15 May 2020, https://www.smg3d.co.uk/files/ssys-wp-thermoplastics-09-11_ashx.pdf

[3] Turning filament into industrial-strength parts, retrieved 15 May 2020, https://www.materialise.com/en/manufacturing/3d-printing-technology/fused-deposition-modeling

[4] Dikova T., Dzhendov D., Ivanov D., Bliznakova K., Dimensional accuracy and surface roughness of polymeric dental bridges produced by different 3D printing processes, Archives of Materials Science and Engineering, 2018 Dec;94(2):65-75.

[5] Objet260 Connex3, retrieved 15 May 2020, https://www.stratasys.com/3d-printers/objet260-connex3

[6] Photonic Professional GT, retrieved 15 May 2020, https://www.nanoscribe.com/en/solutions/photonic-professional-gt2

[7] Cole Miller, Eric Cook, Joe Caruso, Wilson Pines, Pavel Ikonomov, High Precision 3D Printer, Senior Design presentation, 11 April 2017, CEAS, Western Michigan University.

[8] 3D Printer Buyer's Guide: 2020 Edition, 3D Systems, retrieved 15 May 2020, https://www.3dsystems.com/3d-printer-buyers-guide

[9] Dikova T. (2020) Specifics in Production of Fixed Partial Dentures Using 3D Printed Cast Patterns. In: Mitrovic N., Milosevic M., Mladenovic G. (eds) Computational and Experimental Approaches in Materials Science and Engineering. CNNTech 2019. Lecture Notes in Networks and Systems, vol 90. pp. 92-102. Springer, Cham.

[10] Dikova T. Properties of additively manufactured dental materials. DSc thesis, Technical University of Gabrovo, Gabrovo, Bulgaria, 2019, 260 p.

[11] Stereolithography (SLA) Technology, retrieved 15 May 2020, https://3dinsider.com/3d-printer-types/

[12] 3D printing processes. (2016). 3D Printing Industry, retrieved 25 May 2020, https://3dprintingindustry.com/3d-printing-basics-free-beginners-guide#04-processes

[13] SLA vs. DLP: Guide to Resin 3D Printers, retrieved 25 May 2020, https://formlabs.com/blog/resin-3d-printer-comparison-sla-vs-dlp/

[14] Phrozen Shuffle 4K: Review the Specs, , retrieved 27 May 2020, https://all3dp.com/1/phrozen-shuffle-4k-review-3d-printer-specs/

[15] Form 2, retrieved 20 May 2019, https://formlabs.com/3d-printers/form-2/

[16] Formlabs Resin Library, retrieved 27 May 2020, https://formlabs.com/materials/

[17] Mach3, https://www.machsupport.com/software/mach3/