Comparative analysis of geometric deviations of a part with complex geometry 3D printed by FDM and SLA technologies

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Abstract— **This paper presents comparative analysis of geometric deviations of four parts with complex geometry made by two 3D printing technologies. CAD model of the part was made in SolidWorks. Three parts were 3D printed from PLA, PETG and SILK, using FDM technology. The fourth part was 3D printed using SLA technology. Every part was scanned with 3D scanner with turntable and specialized software. During comparative analyses, each generated 3D model was compared with CAD model in order to find deviations in dimensions. Comparative analysis results showed that the lowest geometric deviations in dimensions were for Propeller made of PETG, while the highest was for one made of PLA in positive section, and SILK in negative section. However, distribution of deviations of dimensions was different for each part, but mostly appears on five shaped parts with multi-directional curves with fillets.**

Keywords-CAD, 3D printing, FDM, SLA, 3D scanning, comparison, geometric deviation

I. INTRODUCTION

Nowadays, 3D printing technology as part of Additive Manufacturing, is present in many different applications, such as technical, medical, art, manufacturing, food, etc. [1] Furthermore, it is not possible to say with certainty if there is any field of everyday life where 3D printing is not present even in its small part. The main reason is that different technologies and materials of 3D printing offers almost endless possibilities in many areas. The simple procedure of 3D printing is well-known, and basically includes creating CAD model, CAD-STL conversion, generating G-code, and starting 3D printing process. That implies that by use of 3D printing technology, it is possible to produce parts of simple and complex geometry, in a wide range of dimensions, materials, usage, etc. [1, 2] However, although looks simple, there are many challenges that follow process if 3D printing, from idea to final product.

Based on the way how is material deposited in order to produce parts, there are several types of 3D printing technologies. The most common division of technologies on FDM (Fused Deposition Modeling), SLA (Stereolithography), SLS (Selective Laser Sintering), LOM (Laminated Object Manufacturing), and DLP (Digital Light Processing), etc. [2]. On the other side, each technology uses different materials, so that provides a wide variety of materials, such as polymers, ceramics, metals, composites, thermoplastics, paper and metal filled tapes, etc. According to that, technology and materials may have applications in various fields. For example, FDM technology usually has applications in prototyping, biomedical, toys, advanced composite parts, home use applications, food technology, buildings, construction, etc., while SLS and 3DP technologies have applications in the field of biomedical, electronics, aerospace, lightweight structures, heat exchangers. SLA technology has application in biomedical prototyping and investment casting, as well as is excellent for form testing and producing water-resistant material. LOM has application in paper manufacturing, foundry industries, electronics, biomedical, smart structures, and is ideal for nonfunctional prototypes [1, 2].

However, as any other technologies, every 3D printing technology has own advantages and disadvantages. For example, FDM technology is relatively cheap, simple and can be used with many materials and colors, but requires supports, has low resolution and poor quality of surface. On the other hand, SLA technology has fine resolution, but limited materials, and more expensive than the FDM technology. Beside choosing of appropriate technology based on its advantages and disadvantages, as well as usage, the great impact on quality of 3D printed part has printing parameters. Those parameters such as print speed, infill, layer thickness, etc. affect on mechanical characteristics of part (tensile strength, stress, Young's modulus), dimensional and geometric features and accuracy, quality of surface finish [3, 4, 5]. Because of that, many metrology techniques were used for examination of parts produced by 3D printing technology. Computed tomography was used for providing of information on the internal structures of objects for dimensional metrology, due to the large and anisotropic grains in Additive Manufacturing. The result of epitaxial growth of grains is peculiar surface finish, that is sensitive to liquid dye penetration testing, magnetic particle testing, eddy current testing, etc. [2]. Semi-to-fully automated inspection methods powered by Coordinate measuring machine (CMMs), is best suited for the manufacturing environment. CMM is used extensively in metrology where dimensions for straightness, flatness, squareness and parallelism can be easily measured with very high precision, that was usable for 3D printed parts [2, 6]. Considering that parts produced by 3D printing technology have higher porosity compared to the ones produced by use of conventional manufacturing methods with irregular or rough surfaces, penetrant testing was used to detect defects [2]. On the other side, for metrology in geometry and property variation, structure light testing methods were used, while ultrasonic testing was used to detect voids or weak deposition layers [2].

In this paper, comparative analysis of geometric deviations of a part with complex geometry was presented. CAD model of part Propeller was made in SolidWorks, and by the use of CAD-STL interface exported in STL file format. Four parts were 3D printed using FDM and SLA technology. Comparative analyses were performed using 3D scanner and specialized software, in order to compare deviations in dimensions of printed parts compared to the CAD model.

II. METHODOLOGY AND MATERIALS

Comparative analysis of geometric deviations of a part with complex geometry was done through four phases. First, CAD model of part Propeller was created using SolidWorks software. Then, the parts were made by use of two 3D printing technologies – FDM and SLA, and thus two 3D printers. Three 3D printed parts in FDM technologies were made by same printer but of three materials with different color: PLA – super blue, PETG – gray, SILK – purple. Different colors and materials were selected because of its common use in different applications, glossy effect, as well as different quality of surface. However, material colors were selected so it is possible to perform 3D scanning process without well-known problems as reflection, absorption, etc. One 3D printed part in SLA technology was made of resin, white color. In the next phase, every part was scanned with 3D scanner with turntable, and four 3D models were generated. Comparative analyses of geometric deviations of a part with complex geometry were done based on comparison of 3D model generated through 3D scanning process and CAD model created with SolidWorks software.

A. CAD model

The process of creating of CAD model was performed in SolidWorks software, through certain sketches and features. The CAD model of the part has a complex geometry with vertical cylinder in the center and five shaped parts with multi-directional curves with fillets. Through the process of creating of the CAD model, the STL file format was exported also by use of SolidWorks software. During CAD-STL conversion, resolution was set as Fine, with deviation tolerance 0.077 mm, and angle tolerance 10 deg.

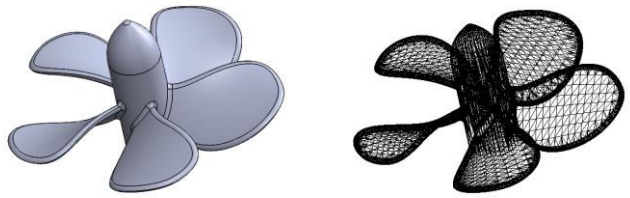

Figure 1. CAD model (left), CAD-STL conversion (right)

B. FDM technology

Fused Deposition Modeling (FDM) technology is based on the deposition of filament on certain surface. The filament can be prepared before and transport to extruder or can be prepared in the extruder. Deposition of material on a surface is performed layer by layer, where one layer is created usually by movement extruder and in the most cases, surface so-called bed. The most used material for FDM technology is thermoplastic that is melted in the extruder, and deposed on hot surface [2, 7].

During experimental work, part Propeller was produced using FDM technology on 3D printer Prusa MK3S+. This 3D printer has build volume od 250x210x210 mm, layer height 0.05-0.35 mm, and support wide range of thermoplastics, including PLA, PETG, ASA, ABS, PC (Polycarbonate), CPE, PVA/BVOH, PVB, HIPS, PP (Polypropylene), Flex, nGen, Nylon, Carbon filled, Woodfill and other filled materials [8]. In order to set print parameters and generate G-code, Prusa Slicer software was used (Fig. 2.). Three parts of Propeller were made, using materials PLA, PETG and SILK (Fig. 3). All parts were printed with 30% infill, with organic support everywhere to achieve as high quality of surface and accuracy as possible, with optimal orientation considering complex geometry of the part. Printing parameters were set up according to filament manufacturers' recommendations, especially temperatures of nozzle and bed [9]. In all three cases, layer thickness was 0.2 mm, and supports were removed by hand and using hand tool pliers, without additional post processing such as sanding or any physical or chemical treatment.

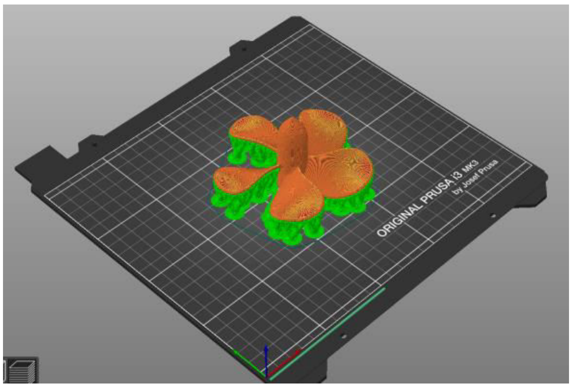

Figure 2. Generated G code with supprots in Prusa Slicer software

According to set print parameters, printing times, as well as used filament were different for all three materials (Table I). Considering that same model was used for 3D printing process, it was expected that used filament will be approximately same. However, according to different print parameters, printing times were different, but without big differences.

TABLE I. 3D PRINTING PARAMETERS FOR EACH MATERIAL

Material	Color	Printing time	Used filament [grams]	Used filament [meters]
PLA	Blue	7 hours 47 minutes	49	17
PETG	Gray	7 hours 42 minutes	49	17
SILK	Purple	7 hours 53 minutes	49	17

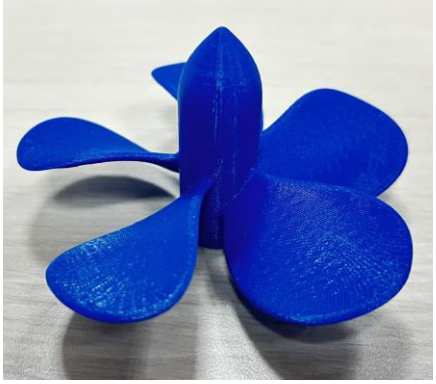

Figure 3. 3D printed part Propeller – FDM technology, material PLA

Figure 4. 3D printed part Propeller – FDM technology, material PETG

Figure 5. 3D printed part Propeller – FDM technology, material SILK

C. SLA technology

Stereolithography (SLA) technology uses liquid material so-called resin, which has the property of hardening under the influence of ultraviolet light certain wavelength. During 3D printing process with SLA technology, each layer in liquid state is exposed by ultraviolet light and those hardened. Depending on used resins, first layer exposure time as well as exposure time (known as normal exposure time) can be different [2].

During experimental work, part Propeller was produced using SLA technology on 3D printer Anycubic Mono X. This 3D printer has build volume 192x120x245mm, with layer resolution 0.01-0.15mm, XY resolution 0.050mmm, LCD resolution 3840x2400 (4K), Z Axis accuracy 0.01mm, and use 405nm UV Resin material [10]. Setting of print parameters and generating G code were performed using Photon Workshop software (Fig. 6.). Printing parameters were set up according to the resin manufacturers' recommendations, so layer thickness was 0.05 mm, first layer exposure time was set up on 50 seconds, while exposure time was set up on 10 seconds. Some resins' parameters are as follows: density 1.05-1.25g/cm3, viscosity 150-200cP, surface hardness 84HS, Tensile strength 36-45 MPa, etc. [11]. Supports were generated as Tree, in order to decrease contact surface of support and part, as well as to reduce of material consumption. However, according to the complex geometry of part, additional support was needed. Total print time was 9 hours and 12 minutes, with used 31 ml of resin. After finishing 3D printing, supports were removed using hand tool pliers. Then, the part was washed 2 minutes and cured 4 minutes, using Anycubic Wash and Cure Machine, without additional physical or chemical treatment (Fig. 7).

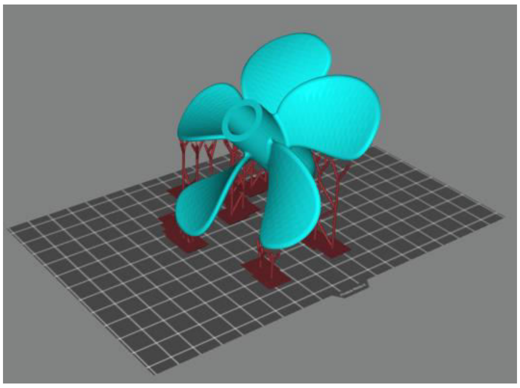

Figure 6. Generated G code with supprots in Photon Workshop software

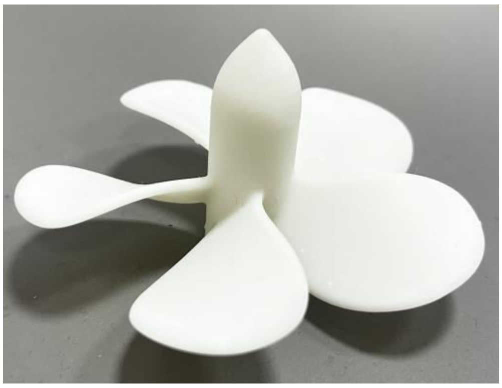

Figure 7. 3D printed part Propeller – SLA technology

D. 3D scanning

3D scanning process is technique based on lighting, illumination, and laser triangulation. Significant impact on measuring accuracy during the 3D scanning process have laser reflection of scanned objects' surface and detection of the laser stripe's peak. However, camera calibration and adjustment of scanning process parameters such as lens distortion, laser tilt, camera focus, the angle between the camera axis and the scanner's linear motion, and the lighting level are very important before starting of 3D scanning process [12, 13].

During experimental work, RangeVision Smart 3D scanner with turntable (Fig. 8.) was used for 3D scanning process of all four 3D printed parts. This scanner uses monochromatic light and structured light technology and coupled with ScanCenter NG software generate solid 3D model of scanned part. In 3D scanning process, it was needed to set parameters as lighting level on a scale of 1 to 5, number of scans, type of light source white, black and stripe, etc., as well as cameras had to be heated on 50°C.

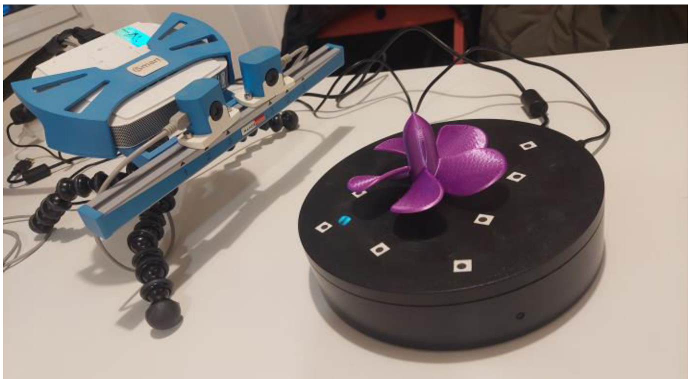

Figure 8. 3D scanning experimental setup

III. Results and Disccusion

In 3D scanning phase, every part was scanned with RangeVision Smart 3D scanner with turntable. ScanCenter NG software was used for generation of solid 3D model. In the phase of comparative analysis, each generated 3D model from 3D scanning process was compared with CAD model created with SolidWorks software, using ScanCenter NG software. Through comparison, deviations in dimensions were analyzed in positive and negative section, with determination of maximum deviation in both sections. Considering that high ambient temperature (over ~50°C) can affect on geometric deviations of parts 3D printed by FDM technology, 3D scanning process was performed in constant ambient temperature of 20°C.

A. Propeller – FDM technology, material PLA

The 3D printed part Propeller made of PLA material was scanned with maximum illumination level 5, because the color of PLA material was super blue with gloss surface of material. Other illumination sources in the surrounding area did not exist, e.g., ambient light. The type of light source used in this case is white. In order to obtain the best possible results, the model was scanned from two positions, with 12 scans in each. The number of elements scanned during the first scan was 2038535, while the number of elements obtained during the second scan was 1849747. The total number of elements was 3888282. When generating the model, the selected type of model resolution is 4, where the generated model was obtained with 558168 number of elements. Comparison of CAD model and generated model (material PLA) is shown in Fig. 9.

Comparative analysis showed that maximum geometric deviations of part Propeller 3D printed of PLA material were +0.75 mm in positive section, marked with orange color on Fig. 9. The maximum geometric deviations of same part were -0.5 mm in negative section, marked with blue color n Fig. 9.

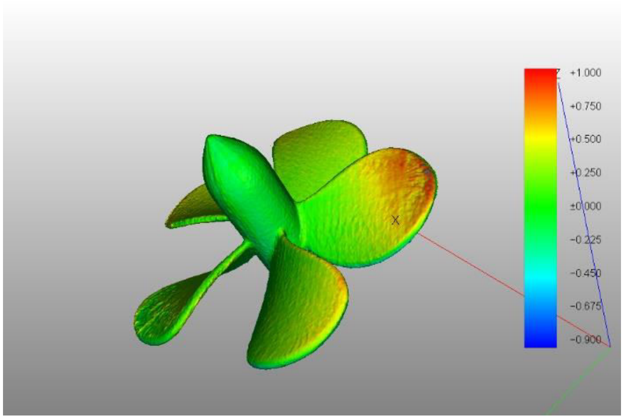

Figure 9. Comparison of CAD model and generated model (material PLA)

B. Propeller – FDM technology, material PETG

The 3D printed part Propeller made of PETG material was scanned with maximum illumination level 4. That illumination level was selected because the color of PETG material was gray with no gloss surface of the material. During 3D scanning process, the used type of light source was white, and other illumination sources in the surrounding area did not exist. The part was scanned in two positions, with 12 scans in each. Number of elements from the first scan was 2171722, while from the second scan was 3040433. The total number of elements was 5212155. During the process of model generation, the selected model resolution was 4, and generated model was obtained with 284924 number of elements.

Comparison of CAD model and generated model (material PETG) is shown in Fig. 10.

Comparative analysis showed that maximum geometric deviations of part Propeller 3D printed of PETG material were +0.25 mm in positive section, marked with orange color on Fig. 10. The maximum geometric deviations of same part were -0.25 mm in negative section, marked with blue color in Fig. 10.

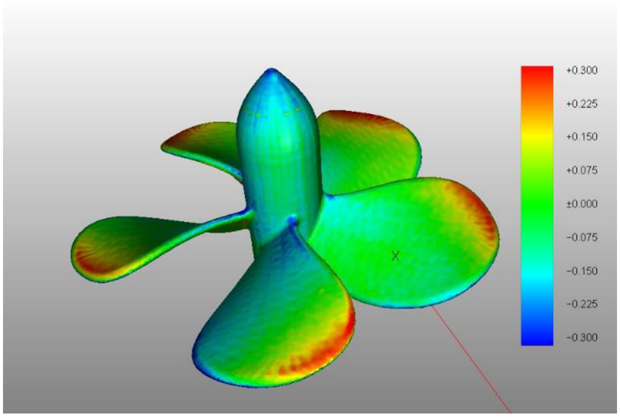

Figure 10. Comparison of CAD model and generated model (material PETG)

C. Propeller – FDM technology, material SILK

The 3D printed part Propeller made of SILK material was scanned with maximum illumination level 2, without other illumination sources in the environment. The color of SILK material was purple, with high gloss surface of the material and silk texture. During 3D scanning process, the used type of light source was black. Due to the glossy surface, certain points were not scanned, where the rays were scattered, and in this case, a darker level of light was required, as well as the lowest possible level of illumination of the projector. The part was scanned in three positions, with 12 scans in each. The number of elements from the first scan was 1890758, the second scan was 822896, while from the third scan was 1200271. The total number of elements was 3913925. During the process of model generation, the selected model resolution was 2, and generated model was obtained with 142818 number of elements. Comparison of CAD model and generated model (material SILK) is shown in Fig. 11.

Comparative analysis showed that maximum geometric deviations of part Propeller 3D printed of SILK material were +0.7 mm in positive section, marked with red color on Fig. 11. The maximum geometric deviations of same part were -0.6 mm in negative section, marked with blue color in Fig. 11.

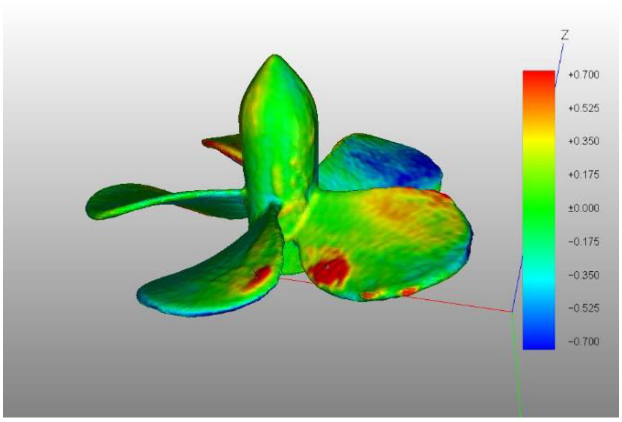

Figure 11. Comparison of CAD model and generated model (material SILK)

D. Propeller – SLA technology

The 3D printed part Propeller made with SLA technology. Because of white color whose reflects light, the part was scanned with maximum illumination level 5, without other illumination sources in the environment. During 3D scanning process, the used type of light source was white. The part was scanned in two positions, with 12 scans in each. The number of elements from the first scan was 2890727, and the second scan was 2810849. The total number of elements was 5701576. During the process of model generation, the selected model resolution was 4, and generated model was obtained with 562256 number of elements. Comparison of CAD model and generated model (SLA technology) is shown in Fig. 12.

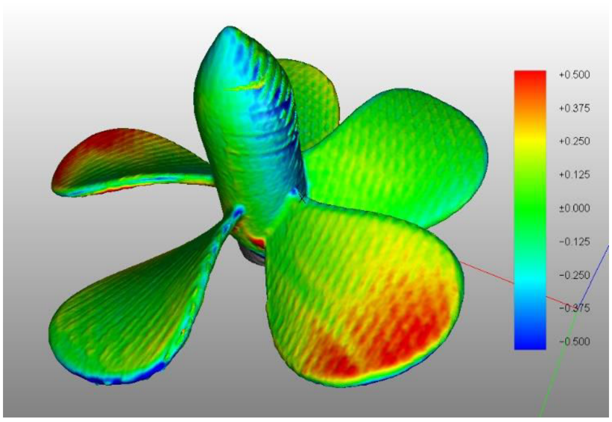

Figure 12. Comparison of CAD model and generated model (SLA technology)

Comparative analysis showed that maximum geometric deviations of part Propeller 3D printed with SLA technology were +0.4 mm in positive section, marked with orange color on Fig. 12. The maximum geometric deviations of same part were -0.4 mm in negative section, marked with blue color in Fig. 12.

During the 3D scanning process, for Propellers made of PLA, PETG and with SLA technology (in further WHITE) the same type of light and scanning positions was used. For Propeller made of SILK, black type of light was used with one more scanning position, because high gloss surface of the material and silk texture. Illumination level was same during scanning PLA and WHITE Propellers, while the model resolution was different only for SILK. The highest total number of elements during model generation was for WHITE, while the lowest was for SILK, so significant affect on number of elements have surface of material, color, and material.

Based on comparative analysis results, the lowest geometric deviations in dimensions were for Propeller made of PETG, while the highest was for Propellers made of PLA in positive section, and SILK in negative section. However, distribution of deviations of dimensions was different for each part, but mostly appears on five shaped parts with multi-directional curves with fillets. That was expected because of the complex geometry of the part, disadvantages of FDM and SLA technology and used materials, as well as occurrence of increased scattering of light during 3D scanning of high gloss surfaces. In Table II, 3D scanning parameters and comparative analyses results is shown for all four Propellers.

TABLE II. 3D SCANNING PARAMETERS AND COMPARATIVE ANALYSES RESULTS

Material/Technology	PLA	PETG	SILK	SLA technology
Illumination level	5	4	2	5
Light source	white	white	black	white
No. of scanning positions	2	2	3	2
No. of scans	12	12	12	12
Total number of elements during scan	3888282	5212155	3913925	5701576
Model resolution	4	4	2	4
Total number of elements during model generation	558168	284924	142818	562256
Maximum geometric deviations – positive section [mm]	+0.75	+0.25	+0.7	+0.4
Maximum geometric deviations – negative section [mm]	-0.5	-0.25	-0.6	-0.4

IV. CONCLUSION

Rapid product development requires use materials and technologies that can obtain production of prototype or even final product in the shortest time. However, increasing of human and industrial needs resulted to fast development of new technologies that can meet the challenges. Additive technologies represent production technology that very quickly finds a place in everyday life. However, as any other technology, additive technology, e.g., 3D printing technologies have advantages and disadvantages.

This paper presents comparative analysis of geometric deviations of four parts with complex geometry, e.g., Propeller made by two 3D printing technologies. Based on created CAD model, three parts were made by using FDM technology (PLA, PETG and SILK material), while one was made by using SLA technology. In order to make comparison in dimension deviations between 3D printed parts and CAD model, all parts were scanned using 3D scanner and specialized software.

Results showed that the lowest geometric deviations in dimensions were for Propeller made of PETG material, while the highest was for Propellers made of PLA in positive section, and SILK in negative section. Distribution of deviations was different for each part, however, mostly appears on five shaped parts with multi-directional curves with fillets. Considering that those shaped parts have complex geometry, it was expected that errors would occur already during the CAD-STL conversion. In addition, both 3D printing technologies have own disadvantages. On the other side, used 3D printers were not for industry use, but hobby, and has certain resolution and accuracy. Used materials have own affect as occurrence of increased scattering of light during 3D scanning of high gloss surfaces. Considering all, it can be concluded that the combination of 3D printing and 3D scanning can contribute significantly improving the product development process, quality control, as well as the process of production final products.

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