Design of Machines and Structures, Vol. 14, No. 1 (2024), pp. 61–74.
https://doi.org/10.32972/dms.2024.006

RESEARCHING THE GEOMETRIC LIMITS OF 3D LASER SCANNING

FERENC SARKA[1] – ANDRÁS MALIK[2]

[1]*University of Miskolc, Institute of Machine and Product Design*
H-3515, Miskolc-Egyetemváros
[2]*Schaeffler Automotive GmbH & Co. KG, Bühl, Germany*
[1]*ferenc.sarka@uni-miskolc.hu,* [2]*malikandras@gmail.com*
[1]*https://orcid.org/0000-0003-3136-4248*

Abstract: The paper presents the geometrical properties of those surfaces that can be digitized by 3D laser scanners. First the circumstances of the experiment are described. The device (Roland LPX-1200) and applied software (Dr. Pizza) are also introduced, such as the brief historical development of 3D digitization. Based on the data found in the literature, all those problems are collected, that can emerge during 3D laser scanning. In order to find the limits of the scanner, a test specimen was designed with a variety of geometric elements (planes in different positions, curved surfaces (concave, convex), roundings and chamfers in different sizes and positions, holes of different depths and diameter). During the design of the test specimen, those properties that were developed for additive technologies were used. The test specimen was produced by milling technology (Roland MDX 650), and then scanning with different settings were performed on it. The experiment was carried out until the largest real surface was digitized. Based on the test, it was summarized which geometries can be fully or partially scanned. Finally, a recommendation to achieve the best possible result was formulated.

Keywords: *3D scanning, laser scanning, scannable geometry, test piece for 3D scanning.*

1. INTRODUCTION

3D scanning, or digitization, occupies an increasingly large part of today's engineering practice. With the spread of various 3D technologies (3D printing, CAxx technologies), digitalization technologies have also developed. The market for 3D scanners is huge, ranging from hobby-level devices to special-purpose devices worth tens of thousands (EUR). Their field of use is very broad, whether it is for civil or military applications. It can be used in almost every part of the natural science field, be it mechanical engineering, archeology, architecture, art, or even medical (MRI, ultrasound). In the present paper, the use for mechanical engineering purposes of 3D

scanning is introduced, during which those geometric limits that are still suitable for digitization were looked for.
Research on the topic was started on the basis of an assignment from an industrial partner. It became necessary to replace and reproduce a plastic injection moulded part. During the scanning of the part, we observed geometric surfaces that the laser scanner could not digitize (Figure 1). Based on the experience gained, we realized that it would be worth to examine the problematic geometries in a controlled manner.

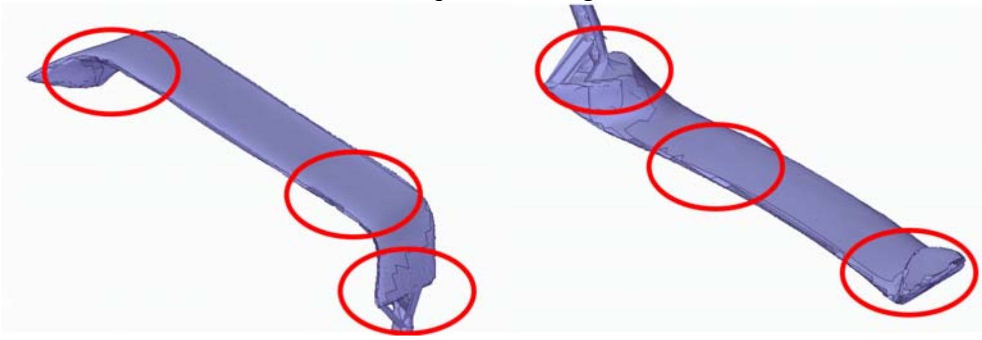


Figure 1. *Image of the part the research started with (Solid Edge 2020)*

Figure 1 shows that the model created by the scanner is incorrect in several places, non-existent surfaces were included, and existing surface parts were not digitized. Most of the problems were at the junction of the surfaces and at the edges.

2. The history of the 3D scanner – in brief

The production/reconstruction of bodies in sculpture appeared already in ancient times and artists used different techniques to create a sculpture based on a model or the original body (Sargentis, et al., 2022). In practice, the techniques of the time were the forerunners of scanning and printing. The first optical recording of geometry dates from 1859 (Sobieszek, 1980). François Willème patented a process he called photosculpture. During the procedure, he took 24 pictures of the object, every 15 degrees along a circle (Figure 2).
Based on the 24 images, he recorded the contour of the body, then displayed the profile using a pantograph milling machine. By placing the 24 profiles in the correct position, you get a (fairly rough) optical copy of the original body. Of course, a real sculptor was also needed to complete the final result. Willème was originally a sculptor, so the ability was available. The technological development of scanning was given a big boost by the development of computer technology and its ever-lower price. The first scanners appeared in the early 1960s, these systems used light,

cameras and projectors. The shape of the surface was recalculated from the distortion of the image (structured light) projected onto the body. Scanners operating on this principle are still available today, called optical scanners (Edl, Mizerák, & Trojan, 2018), (Sarka & Szente, 2011), (Kristály & Ficzere, 2021b). The use of laser light (discovered by Hughes in 1960) for recording the geometry of bodies only appeared in the 1990s. Even this date represents 30 years of development and experience up to the present day. The scanner used in the presented research was manufactured in the 2010s. The scanner used is a non-contact, surface digitizing device, which determines the points of the surface using a laser beam. The control software creates a point cloud from the measured data, from which it generates a surface. It determines the points based on the reflection of the emitted laser beam into the sensor. The device measures the time between the start and arrival of the emitted laser beam, determines the distance of the given point based on the speed of the beam (spot-beam triangulation). The process is easy to understand based on Figure 3.

Figure 2. *The photosculpture (Edl, Mizerák, & Trojan, 2018)*

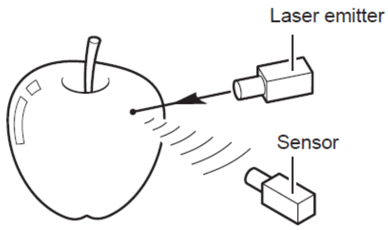


Figure 3. *Operating principle of the laser scanner*

LPX-1200 User's Manual, Roland DG Corporation

3. Presentation of the device used

For scanning, LPX-1200 type laser scanner from Roland DG was used, which was purchased at the Institute in 2011. The scanner is shown in Figure 4. The scanner can operate in two modes, rotary and planar. In the case of rotary scanning, the specimen table rotates while the source of the laser beam moves vertically. In the case of planar, both the beam source and the specimen table move, but only at an angle of +- 20° relative to a specific vertical plane. The smallest value of the resolution is 0.1 mm. The device can scan components with a size of Ø130 mm x 203.2 mm (5 inch x 8 inch).

Figure 4. *Image of the applied device*

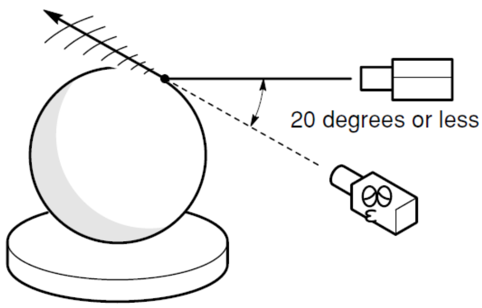


Figure 5. *The laser beam arriving at a low angle is not reflected, but "travels further"*

LPX-1200 User's Manual, Roland DG Corporation

Instructions of the device draw attention to some problems at the very beginning, that may occur during body scanning.

- The body-surface where the laser beam hits the body cannot be scanned at a low angle. Enter this angle as 20°. Figure 5 shows why is this problem almost unavoidable. Each body come to an end somehow, so we are bound to encounter problems at the top and bottom of the parts.
- Relatively smooth surfaces can be scanned well, while fabrics or bodies with very rough surfaces cannot be scanned.
- There are objects that cannot be scanned due to their material, such as transparent or translucent materials. In these cases, the laser beam passes through them without being reflected.
- The colour of the objects also affects the result of the digitization. The colours black and dark blue absorb the light of the laser beam, so that no light is reflected from the surface of the objects to the sensor.
- A similar problem was experienced with shiny and reflective surfaces, regardless of the colour of the object. In case of objects like this, the laser beam is scattered and does not return to the sensor.
- There were also suggestions for how to place the objects on the specimen table, the most important of which is to place the objects in the centre of the table if possible.
- If an object with a hole (with a bore) has to be scanned, the object should be placed in such a position that the laser beam has the opportunity to pass through the hole (bore).

Even if the listed conditions are met, there is no guarantee that the result will be good. This was exactly experienced during the task described in the Introduction. That is why additional problematic geometries were looking for. With the help of a specimen developed for the test grouping and organizing of the revealed geometries were in the focus of the further research.

4. Search for test part

Before the test part was designed, a literature survey was carried out to see if anyone else had a similar problem. Several test bodies with hair-raising shapes were found. After reading the description of these models, most of them are used for testing 3D printers. Some of them are shown in Figure 6**Hiba! A hivatkozási forrás nem található.**.

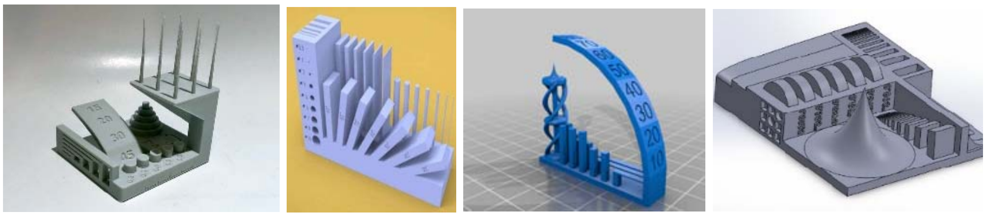


Figure 6. *Various test bodies*

https://www.printables.com/
https://3dmatic.com.au/download/3d-printing-test/
https://creazilla.com/nodes/7836086-3d-printer-tolerance-test-3d-model

Based on the research, and on the authors own thoughts the following functions were determined:

- Curved surface parts: convex surfaces (different sizes) and concave surfaces (in different sizes).
- Flat surface parts: placed at different angles to the base plane, or undercut, recurved surfaces.
- Holes, depressions with different diameters, or/and with different depth.

The properties of the scanners are determined by several metrics, so the test specimen also must have such properties that the limits of these metrics can be stretched. During the research, we found several metrics that can be affect the quality of scanning.

- Resolution: x, y, z, coordinates, in case of planar scanning, and degree and z coordinate in case of rotary scanning.
- Depth of Field (DOF): in the case of optical scanners, the distance at which a sharp structured image can still be projected onto the body.
- Accuracy: the difference between the scanned and the real body.

Since the revealed test parts support the examination of the quality of 3D printing, the test specimen was started to be designed. When designing it, the main focus was on all the suspected problematic geometries could be inserted into the same part.
Based on previous scanning experiments, problematic geometries should be understood as chamfers, roundings, edges, smaller or larger depressions, and planes located in a certain direction compared to the scanner's base plane.
For chamfers and roundings, a variable amount of edge-modifications were created, so that the size that the scanner can still digitize could be found. The edge modification is between two flat surfaces, which are 90 degrees in relation to each other in the first approach (in a later experiment, the extent to which the angle closed

between the edges affects the scanning result will also be examined). To make the holes scannable, holes of variable diameter and depth must be created.

5. THE DESIGNED SPECIMEN

In addition to taking into account the above aspects, the technology of its production must also be taken into account when designing the planned test specimen. In the case of forming by cutting, on the bordering surfaces a draft was applied. In this case that part of the machining tool where there is no cutting edge does not rub against the workpiece. Figure 7 shows the CAD model of the specimen and the different geometries marked from A to J.

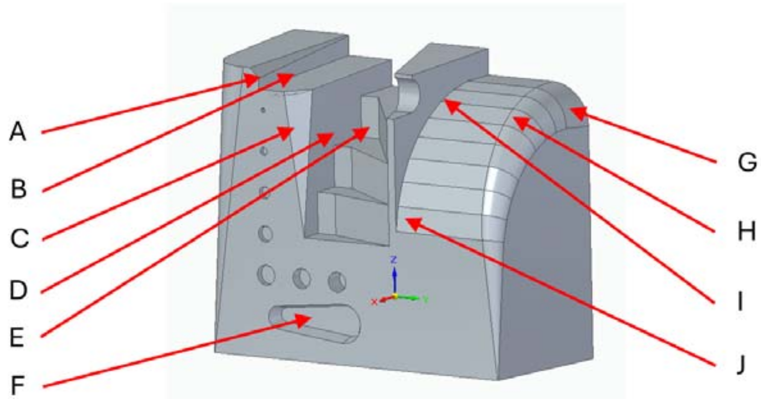


Figure 7. *The designed specimen and the various surface parts*

Geometries:
A: Rounding with variable radius.
B: Chamfer with variable size in the direction of scanning.
C: Holes of different diameters and depths.
D: Chamfer of variable size perpendicular to the scanning direction.
E: Flat surface parallel to the scanning direction.
F: Conical surfaces of different sizes.
G: Rounding with a variable radius, between surfaces with different angles.
H: Planes subtending different angles with the scanning direction (every 10 degrees).
I: Concave, curved surface with variable width.
J: Planes subtending different angles with the scanning direction.

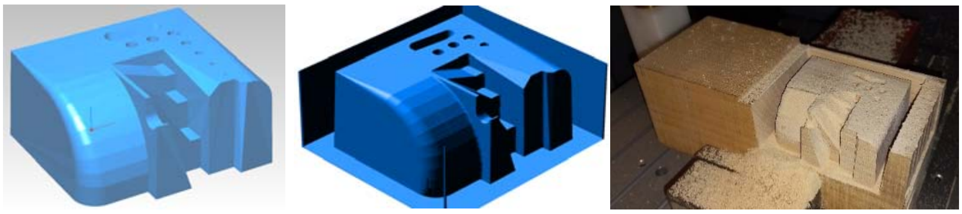


Figure 8. *The model is in the software of the milling machine, in the simulation program, and then during production (from left to right)*

It would be obvious to use 3D printers to produce the test piece, but in order to the specimen to be as precise, as a standard or a tool, it was produced by traditional cutting technology. Cutting is done with a Roland MDX-650 prototype milling machine. Before cutting, a simulation was carried out (Figure 8) to determine which tool size is capable to perform the cutting operation. The simulation was performed with the software included with the Roland machine (Modella Player and Virtual Modella). The vast majority of the formed surfaces can be created with a straight-edged tool with a diameter of 3 mm (Figure 8). Small holes were produced later by drilling. The test specimen was made of steamed beech material. The test specimen (Figure 9) was cut out of the raw material and performing some minor grinding operations.

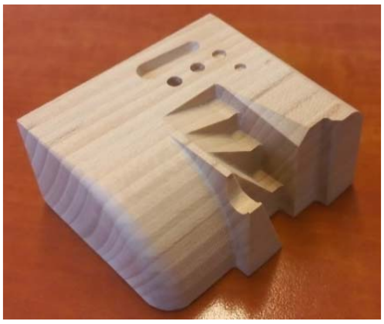


Figure 9. *The finished test specimen*

6. STRUCTURE AND PRESENTATION OF THE STUDY

Possible operation modes of the scanner were used as a basis for the structure of the test series. When introducing the scanner, it was already mentioned that the scanner can operate in two modes (rotary, planar). In the case of plane scanning, it is possible to enter several planes (maximum of six). In both operating modes, it is possible to change the resolution. Based on these, the following list was compiled:

- Rotary scanning at 180 degrees, with a resolution of 1 mm.
- Rotary scanning at 180 degrees, with a resolution of 0.5 mm.
- Planar scanning, 1 plane, with two resolutions. The plane is parallel to the front surface of the workpiece.
- Planar scanning, 2 planes, 30 degrees relative to each other (one rotated to 15 degrees, the other to -15 degrees.
- Planar scanning, 3 planes, 40 degrees relative to each other (one rotated to 40 degrees, the other to -40 degrees, the third stayed in 0 degree position.

The specimen was placed in the centre of the specimen table. Fixing plastic provided by Roland was used to fix the specimen in its position. Figure 10 – Figure 15 show the results of the scanning.

Rotary scanning

In the first approach, the rotary scanning option was chosen. The specimen was placed in the centre of the table as recommended. The scan was made with two different resolutions (circumferential pitch: 0.9 and 0.4 degree, height direction pitch 1 mm and 0.5 mm) (Figure 10).

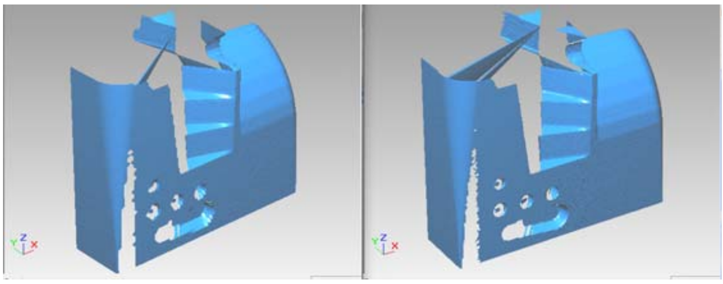


Figure 10. *The result of the rotary scan in two resolutions*

There is no change in the size of the digitized surface, but the surface detail has improved. Based on this, it can be stated that the resolution has no effect on the size of the scanned surface, only its quality. In the next step, the body was placed closer to the source of the laser beam, as close as the table could allow. The resolution remained the same as in the previous case. The result can be seen in Figure 11. The image on the left is the result when the specimen was placed in the centre of the specimen table, the image on the right is the result when the specimen was placed on the edge of the specimen table. With this, all the possibilities inherent in the rotary scanning option were exploited. The result is not satisfying.

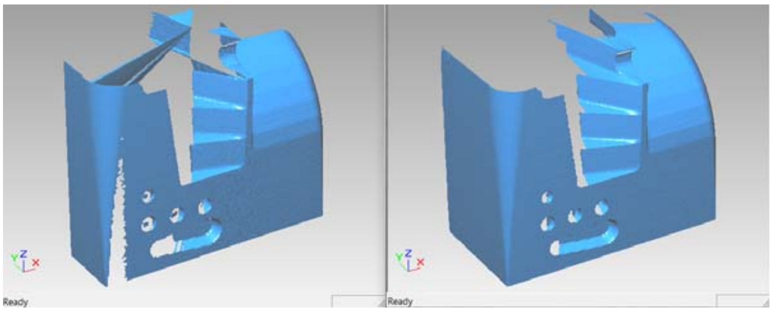
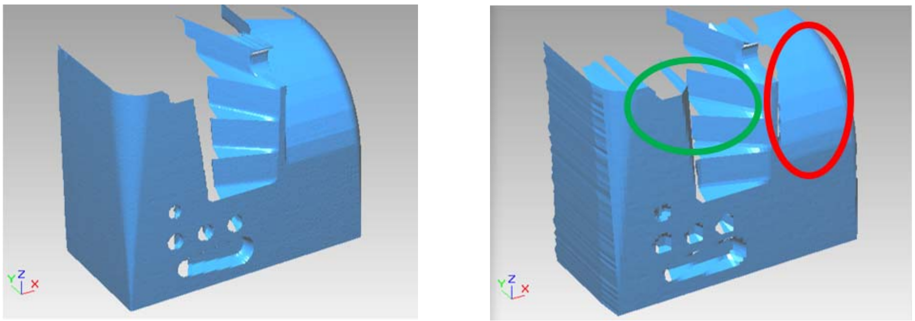


Figure 11. *Image of the test specimen placed in the centre and the test specimen placed on the edge*

Planar scanning

After that, the planar scanning option was switched. The first test option was one plain scan. The resolution is 1 mm. A comparison of the results can be seen in Figure 12.



rotary planar

Figure 12. *The result of planar scanning compared to rotary scanning*

The specimen remained in a position close to the radiation source. More of certain parts of the surface managed to be digitized (green), but some parts were lost (red). The direction is promising, but the surface of the specimen is still not known.

Continuing the work, the number of scanning planes were increased. First, 2 planes were activated. There was a 30° difference between the planes (+15° – -15°). The surface got much better, but the quality is still not good enough (Figure 13).

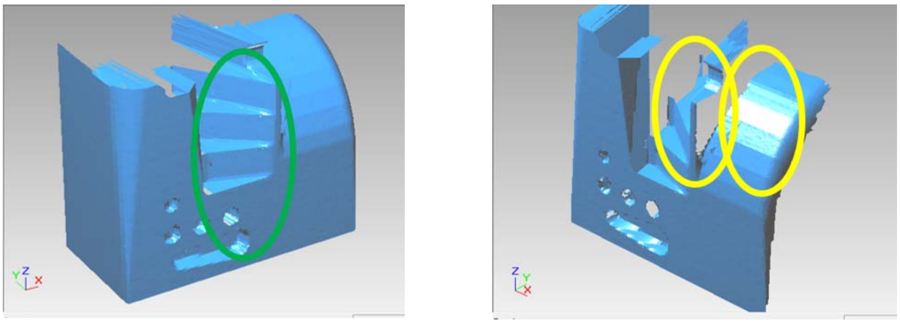


Figure 13. *The result when using two scanning planes*

Based on the above mentioned, scanning those planes that are parallel to the direction of the source of the laser beam is difficult. The further the specimen is from the source, the more uncertain the result is. Next another plane was introduced, so scanning takes place from three directions. The goal is to explore the limits of the machine. If the scanned surface that cannot be created better with the machine is found, then it can be determined which geometries mean a problem for the laser scanner. The three planes were located at -40°, 0°, +40°. Figure 14 shows the results.

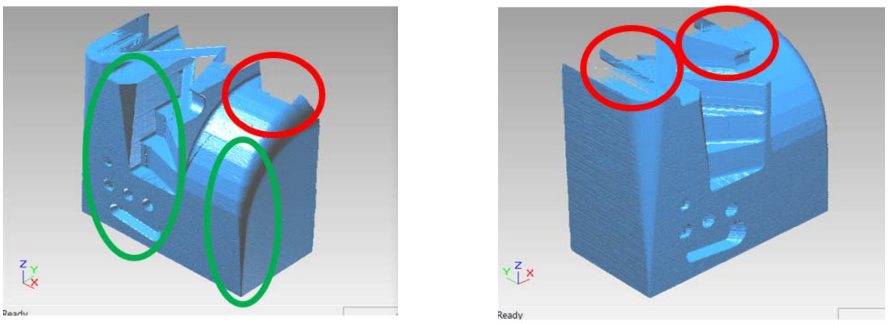


Figure 14. *The result of scanning in three planes, viewed from two directions*

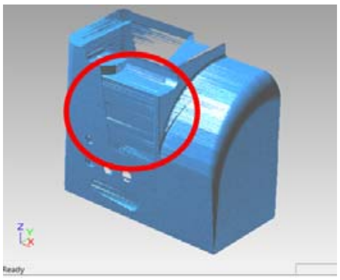


Figure 15. *The result when 3 planes are used, the planes are 90° apart*

In the left image of Figure 14, the significant increase of the scanned surface is clearly visible. This is because of the use of the new scanning plane. However, there are still parts of the surface that are not visible for the scanner (marked with red in Figure 14, and there are also surface elements that are not existing on the real specimen. These can be removed from the model with meticulous work, but that way the primary purpose of scanning would be lost. From the test, it can be deduced that surfaces parallel to the direction of scanning laser beam and at an angle smaller than 10° cannot be scanned. This is a favourable result as the factory description gave 20° for this value. During the test, the angle between the scanning planes was further increased to 90 degrees, the result can be seen in Figure 15. A lot of unreal surfaces have already appeared here, this model can no longer be used even with manual modifications. The last test was already well beyond the limit that would still result an acceptable model.

7. Application of surface coating

After the scanning experiments, the change in the surface structure of the test specimen and its effect on the scanning result were examined. For this we used a primer (Mr. Hobby, MrFinishing Surfacer 1500, white) as it can be seen in Figure 16. The paint was applied to the surface of the specimen with an airbrush gun, approximately 60 µm thick, applied in 3 layers. This operation is not allowed in all cases. On the one hand, the real dimensions of the part are modified, on the other hand, it is not possible to apply paint to a shaped surface at a constant thickness, so the change in size will not be uniform. Removing the paint is not easy, it is often impossible without damaging the original part.

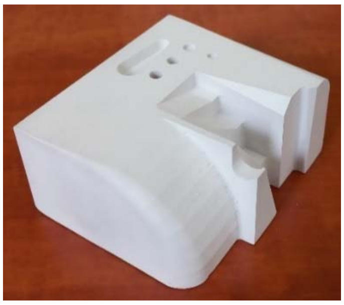


Figure 16. *The painted specimen*

The use of white matte paint slightly improved the result (Figure 17), but there are still many surfaces that are incorrect, have not been digitized, or simply do not exist. In the case of a component with a shiny, glossy surface, matting is essential, but no significant improvement can be achieved on the original matt surface of steamed beech.

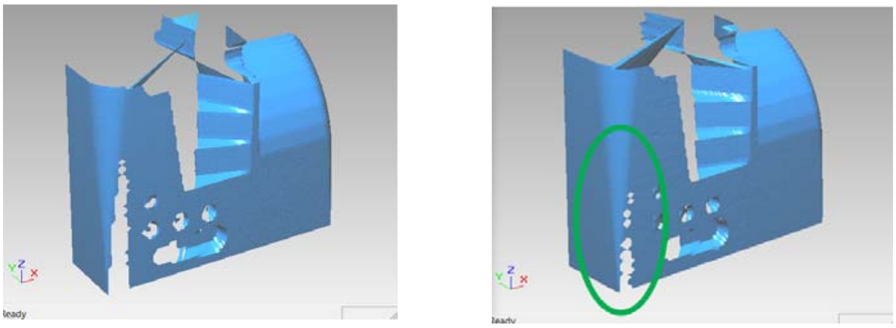


Figure 17. *Comparison of the scanned results of painted and unpainted parts*

8. Summary of results

The size of the surfaces recognized by the laser scanner depends on the relative position of the radiation source and the object. In the study, the body placed closer to the source gave better results, both in case of rounding and chamfering.

The data found in the literature, according to which the laser beam must form an angle greater than 20 degrees with the scanned surface, can be changed to the fact that it must form an angle greater than 10 degrees. Surfaces parallel to the direction of the laser beam cannot be scanned at all. If the depth of the holes is greater than 1 mm, it cannot be scanned.

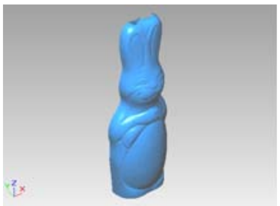


Figure 18. *Model of a hollow chocolate figure*

Based on the series of experiments, it can be concluded that the geometries that are common in technical practice, usually built from basic bodies (cylinders, columns, planes, etc.) can be digitized less satisfying with the help of a laser scanner. On the other hand, sculptural, relief-like bodies with not too large depressions and a matte white surface can be easily scanned. Figure 18. shows a gypsum model of a hollow chocolate figure. The scanning is almost perfect, except for the upper peak, where the laser beam hit the body at an angle of less than 10 degrees.

REFERENCES

Edl, M., Mizerák, M., & Trojan, J. (2018). 3D laser scanners: history and applications. *Acta Simulatio, 4*(4), 1-5. doi:https://doi.org/10.22306/asim.v4i4.54

Kristály, Á., & Ficzere, P. (2021a). Utilization of 3D Printing in Replacement of Basic Plastic Workpieces. *International Journal of Engineering and Management Sciences, 6*(2), 274-282. doi:https://doi.org/10.21791/IJEMS.2021.2.24.

Kristály, Á., & Ficzere, P. (2021b). Study on the Photo-Based 3d Scanning Process. *Hungarian Journal of Industry and Chemistry, 49*(2), 15-18. doi:https://doi.org/10.22306/asim.v4i4.54

Sargentis, G.-F., Frangedaki, E., Chiotinis, M., Koutsoyiannis, D., Camarinopoulos, S., Camarinopoulos, A., & Lagaros, N. (2022). 3D Scanning/Printing: A Technological Stride in Sculpture. *Technologies, 10*(1), 9. doi:https://doi.org/10.3390/technologies10010009

Sarka, F., & Szente, J. (2011). *Interaktivitás a tervezésben és a prototípusgyártásban.* Budapest: Nemzeti Tankönyvkiadó.

Sobieszek, R. (1980). Sculpture as the Sum of its Profiles: François Willème and Photosculpture in France. *The Art Bulletin, 62*, 617-630.