MM Science Journal | www.mmscience.eu
ISSN 1803-1269 (Print) | ISSN 1805-0476 (On-line)
**Special Issue | CUTTING TOOLS 2024**
**1st International Conference on Cutting Tools**
November 20-24, 2024, Trnava, Slovakia
DOI: 10.17973/MMSJ.2025_03_2025013

**CUTTINGTOOLS2024-00003**

# A COMPARATIVE ANALYSIS OF THE DIGITIZATION OF GEOMETRIC OBJECTS FABRICATED VIA ADDITIVE FDM TECHNOLOGY WITHIN THE FRAMEWORK OF REVERSE GEOMETRIC MODELLING APPLICATIONS

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**Abstract**
Additive manufacturing is already a commonly used manufacturing method encountered in industry. With the increasing demands for precision manufacturing, the need for reverse engineering also needs to be addressed. The aim of this study is to compare the results of digitizing primitive geometric objects using a coordinate measuring machine (CMM) and industrial computed tomography (CT) in terms of reverse geometric modeling. The principles of reverse geometric modelling are applied to samples produced by additive Fused Deposition Modelling (FDM) in order to create a geometrically accurate 3D CAD model from the acquired data. In the experiment, curves obtained from primitive geometric objects such as a cylinder were compared. 5 curves were obtained from each object. These curves were fitted to a nominal curve and the resulting curve dimension was compared with respect to the data acquisition method used. The results of the study showed comparable accuracy of the two data acquisition methods. The investigated diameters were in tolerance of 40 +- 0.15 mm and thus correlated with the STN EN 2768 - 1 standard for nontoleranced surfaces. The individual data can be used to speed up the creation of 3D CAD models improving the accuracy and quality of these models.
**Keywords:**
Reverse geometric modelling, digitization, computed tomography, reverse engineering, coordinate measuring machine, additive manufacturing

## 1 INTRODUCTION

Currently, additive manufacturing technologies are becoming increasingly popular in a variety of industries due to their ability to quickly and efficiently create complex geometric objects. These technologies enable the production of parts with high precision, for which they have also gained a place in industries such as healthcare, aerospace or automotive.

Reverse geometric modelling is a process in which physical objects are digitised, and their accurate digital models are then created. This process is essential for a variety of applications, including quality control, historical artefact reconstruction, and the development of new products. When reverse engineering is applied to the component manufacturing process, a key step is the reconstruction of the 3D polygonal model. For this reason, the process of manufacturing parts using reverse engineering has been enriched with a phase that involves reconstructing a planar or volumetric 3D model from a polygonal 3D model or polygonal mesh. This step is known as reverse geometric modelling.

However, with the increasing presence of additive technologies, we are also increasingly seeing more of these manufactured parts entering the reverse engineering process, which brings up several questions. FDM technology is a commonly used technology because of the affordability and versatility of the materials, and the surface of the parts it produces is well known. The surface consists of a rugged surface that contains visible traces of additive manufacturing in the form of layers. For reverse geometric modelling, this can pose the question of how much such a complex surface can affect the accuracy of reconstruction and the creation of a new 3D CAD (computer aided design) model through reverse geometric modelling. The process of reverse geometric modelling can be influenced by a large number of factors that enter into the whole process.

Reverse engineering is a common means of obtaining 3D models of existing parts. In Van's study, the reconstruction of a fishing boat propeller using reverse engineering is discussed [Van 2024]. The reverse engineering technique was used by Verim in their work to reconstruct a 3D model and produce a prototype of an agricultural component [Verim 2023]. A new approach to reverse geometric modelling was also pursued by the author Buonamici in his study. The author presented a new method for reconstructing 3D CAD models based on presegmented mesh data [Buonamici 2018]. Several studies discuss data collection methods for the use of reverse engineering. Faizin's research investigated the accuracy of AI-based photogrammetry and the Agisoft Metashape software. The author concludes that the accuracy results were comparable [Faizin 2024]. In his case study, Helle discusses the challenges of 3D scanning technology for use in reverse engineering [Helle, 2001]. In another study by author Liu, industrial CT and touch CMM methods are compared to validate the capabilities of the two methods. Liu discovered that by using industrial CT, similar accuracy to the contact CMM method can be achieved for both rough and smooth surfaces. The author notes that for use with parts manufactured by additive methods, when the surface is rough, the probe tip can hardly penetrate through the rugged surface to the bottom [Liu 2024]. The author Kruth in his study analysed industrial CT for dimensional metrology. He describes the use of CT in the context of measuring dimensions that would be difficult to access with a CMM. The author states that in the case of complex internal structures produced mainly by additive technologies, industrial CT is the only applicable technology to obtain good quality data [Kruth 2011]. A comparison between industrial CT and CMM measurements was also investigated by the author VIllarraga-Goméz. In his study, he compared the two methods for the measurement of internal geometries and easily deformable structures. The results of the study yielded data on the magnitude of the deviation between the mentioned technologies in the majority of less than 5 µm [Villarraga-Goméz 2018]. The accuracy of 3D CAD models was discussed by author Wakjira, who in his study discussed the topic of dimensional accuracy of a medical model, where he looked at the combination of reverse engineering technology along with additive manufacturing. Therefore, the aim of the study was to obtain a 3D model using three different optical scanners to verify the accuracy of reverse engineering technology [Wakjira 2024]. Author Turek discussed the analysis of CAD modelling accuracy using reverse engineering techniques. The study focused on the geometric reconstruction process to create 3D CAD models for specific parts that are measured using different methods. CAD modelling methodologies have been developed for specific parts to enable the creation of copies of individual parts within the tolerance limits of their manufacture [Turek 2024]. Manmadhachary's study focused on improving the accuracy of STL (Standard Tessellation Language) file format for medical applications, where an STL file format consists of a list of a facet data. In his work, he developed an algorithm for creating more accurate and smoother STL that will help for the production of accurate medical models [Manmadhachary 2016]. The impact of reverse geometric modelling was studied by Dubnicka, who investigated the effect of point reduction on the dimensions and position of geometric elements such as cylinder, sphere or cone for parts produced by FDM and SLA (Stereolithography) technologies. Industrial CT was used in the research [Dubnicka 2024]. Similar research was done by Milde who investigated the effect of point reduction and remodelling techniques on the model obtained by 3D optical scanning [Milde 2024].

## 2 MATERIALS AND METHODS

The aim of this study is to compare the possibilities of digitizing parts produced by additive FDM technology in the context of surface reconstruction of these components. We focus on the analysis of the impact of digitization on dimensional deviations, since FDM additive manufacturing produces a rugged surface. The overall aim is to determine if data can be obtained to achieve the tolerance requirements of STN EN 2768-1. The study investigates the impact of digitisation as an input to the reverse engineering process, and future research plans to analyse other factors that influence this process.

A simple geometric object, specifically a cylinder, was chosen and designed for the experiment. The reason for choosing a simple cylinder shape was to observe basic characteristics such as the diameter of the cylinder, because by observing the basic characteristics we can see the effect of digitization and then apply this to observe more complex and intricate shapes. The cylindrical shape has a diameter of 40 mm and a height of 60 mm. For the study, the parts were produced using additive FDM technology. The Stratasys F370 professional 3D printer was used. The printing material was Stratasys ABS M30, which is the original material produced by Stratasys. Within the production parameters lower and upper limits for layer height and fill density were set in GrabCAD Print software. All other additive manufacturing parameters remained unchanged and constant. Specific values of manufacturing parameters are shown in Table 1.

A total of 4 cylinders were produced with different combinations of parameters. Table 1 also describes the + and - indexes for the lower and upper limits. These indexes indicate by which manufacturing parameters the cylinder was produced. Below in the paper, the individual cylinders are also labelled according to these indexes, where the first index means the layer height and the second index means the infill density. The individual cylinders were subjected to measurements on a CMM as well as on a CT. The first method was the contact method of data collection, as one of the most accurate methods for data collection [Confalone 2023, Pham 2008]. For the purpose of measurement, the cylinders were placed on a plate to which it was attached with screws to ensure the fixed position of the components during the measurement and also to ensure the positioning and navigation of the CMM. Fig. 1 shows the alignment of the cylinders during measurement with the CMM.

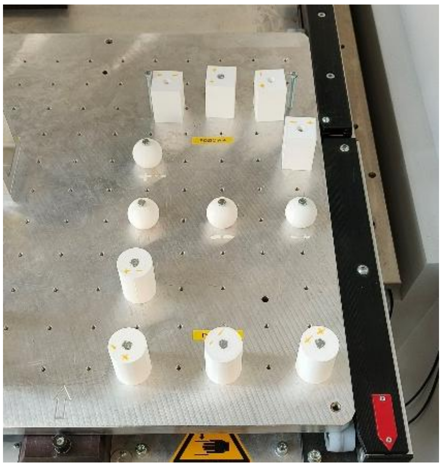


*Fig. 1 Component layout for CMM measurement*

*Table 1 Production parameters of components*

| Process parameter | Lower Limit (index -) | Upper Limit (index +) |
|---|---|---|
| Layer height | 0.18 mm | 0.33 mm |
| Infill Density | 25 % | 75 % |

The measurements on the Zeiss CenterMax CMM consisted of obtaining parametric curves representing the surface of the individual cylinders. The contact sensor probe used had a diameter of d = 3 mm. These curves were obtained at five predetermined locations (Figure 2). Each parametric curve measurement was determined in the Calypso software. The parametric curves were obtained using a circular path strategy whose parameters were set to a velocity of 8 mm/s and a step size of 0.1 mm. A total of 20 parametric curves were obtained. The location of each segment position is shown in Figure 2.

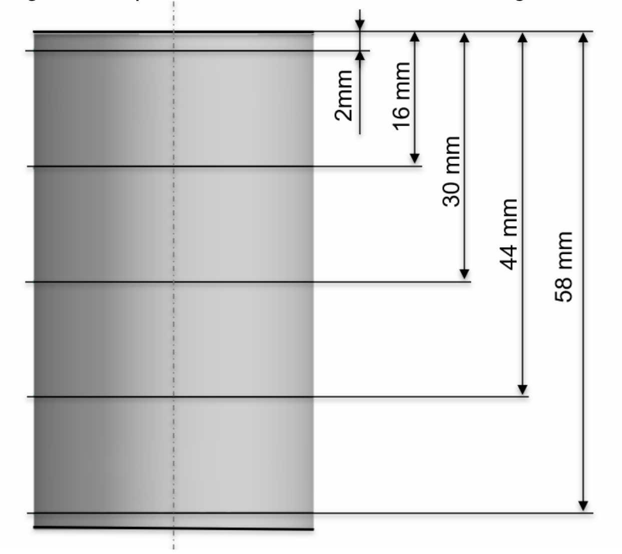



*Fig. 2 Position of the sections*

The second data collection method used in the experiment was industrial CT, which is often associated with additive manufacturing due to the ability to sense even internal structures without damaging the material [Kruth 2011]. The measurements were performed using a Zeiss Metrotom 1500 industrial CT scanner in order to obtain scans of the cylinders that were measured in the previous step using a CMM. The scanning parameters were as follows:

- Current: 500 μA
- Voltage: 160 kV
- Integration time: 1000 ms
- Detector resolution: 2048 x 2048 px
- Gain: 8,0 x
- Measurement distance: 450 mm
- Voxel size: 59,79 μm

Before the data from the industrial CT scanner were evaluated, the data had to be exported to a STL. The acquired cylinder scans were imported into the Zeiss Inspect software, where the point cloud was polygonised using the High Quality profile in the INSPECT X-Ray extension. The reason for polygonization with a particular setup was based on better model manipulation. The details of this step are described in the RESULTS section. The resulting STL was used to evaluate the data in the Zeiss Inspect software. We focused on obtaining information about the cylinder diameters in specific regions when acquiring the data (Fig. 2). To measure the diameter, we inserted a circle (auto-circle function, the gaussian best fit method used) in the obtained perimeter curve and then it was compared with a nominal circle of size d = 40 mm. In this way, circles were generated for each perimeter curve. Example of the parametric curve can be seen in Fig. 3

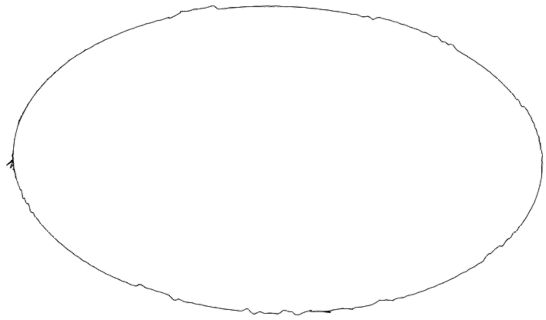


*Fig. 3 Example of parametric curve obtained from CMM*

The process was different when obtaining data from the polygonal 3D model, as we were obtaining data from the solid model. The first step was to align (best fit alignment) the scans together with the reference cylinder model, then it was necessary to create sections through each cylinder at specific distances (Fig. 2) and then fit a circle to the obtained contours (same method as for parametric curves), similar to the previous case for the perimeter curves. A depiction of the cylinder scan with the circles formed can be seen in Fig. 4.

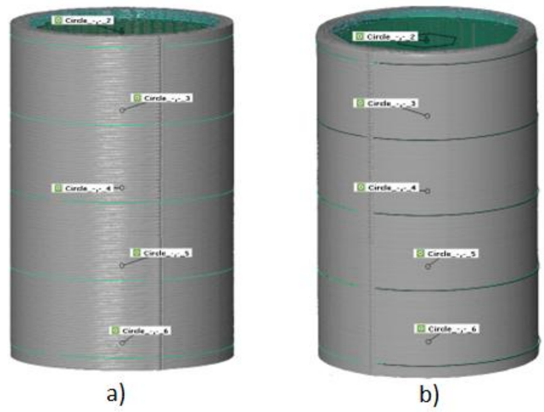



*Fig. 4 Measurement of cylinder diameter on polygonal 3D model*

*a) for layer thickness 0.33,*

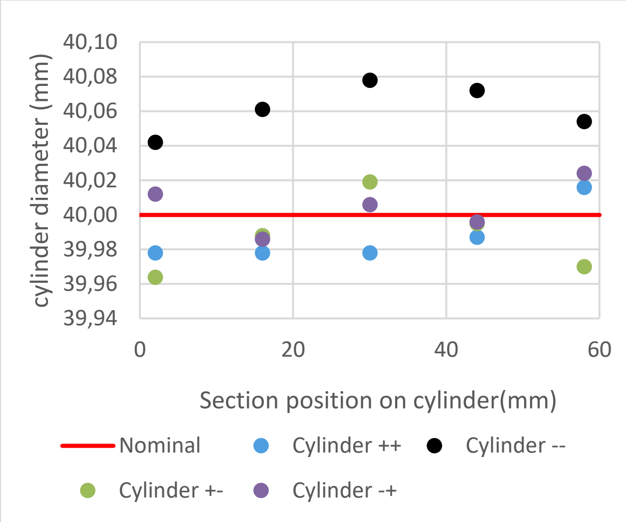
*b) for layer thickness 0.18*

*Table 2 Circle diameters result from CMM measurement*

| section position | cylinder ++ (mm) | cylinder -- (mm) | cylinder +- (mm) | cylinder -+ (mm) |
|---|---|---|---|---|
| 2 mm | 39.978 | 40.042 | 39.964 | 40.012 |
| 16 mm | 39.978 | 40.061 | 39.988 | 39.986 |
| 30 mm | 39.978 | 40.078 | 40.019 | 40.006 |
| 44 mm | 39.987 | 40.072 | 39.995 | 39.996 |
| 58 mm | 40.016 | 40.054 | 39.970 | 40.024 |

## 3 RESULTS

Selected data were collected and evaluated. In the first step, the data from the CMM were evaluated from the perimeter curves. individual curves were created circles on which the diameter was measured. The measured values are published in Table 2. For the diameters of the circles that copied the values of the parametric curves from Table 2, Graph 1 was created which displayed the data graphically.




*Graph 1 Data obtained on the CMM*

The individual values of the measured cylinder diameters can be observed visually on the graph. The measured cylinders are separated by individual colours. The red line indicates the nominal value of the cylinder compared to the measured values from the CMM. From the graph the diameter values of the individual circles oscillate around the nominal value d = 40 mm. For the cylinder with manufacturing parameters - - it was measured that the values of all diameters are above the nominal value, while for the cylinder with manufacturing parameters ++ this fact is opposite in four out of five measured diameters. As a result, it can be concluded that the largest deviation detected was at the level of 78 µm. As far as the difference in values between the smallest measured value and the largest value is concerned, it is at 114 µm.

Due to the fact that ˝raw data˝ were not used for the experiment, for the reasons described in the MATERIALS AND METHODS chapter, but the ˝High Quality˝ polygonization setting was used, it is necessary to state the impact caused by this decision, and therefore in first place to focus on the number of points of which the individual files are consisted.

The details of the number of points from which the polygonal model was formed for each type of polygonization is shown in Table 3. Another modification of the polygonal models was to remove unnecessary parts that increased the file size. These were the center of the cylinders, which were not necessary for the experiment since only the measurement of the cylinder area was performed. The table 3 shows that we were able to reduce the overall ensemble size to 4 % - 12 % of the original size. Fig. 5 shows the model without modification, as well as the model that had the unnecessary part removed, due to which we were able to reduce the file size.

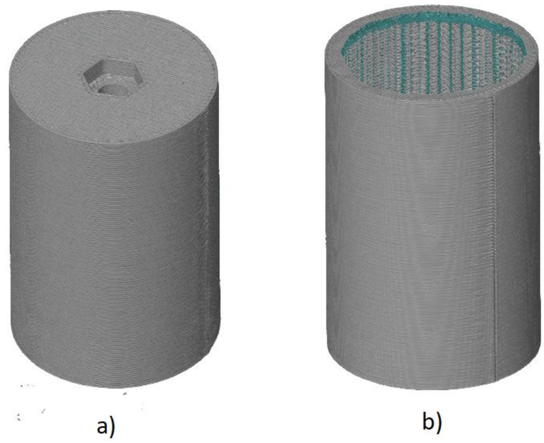
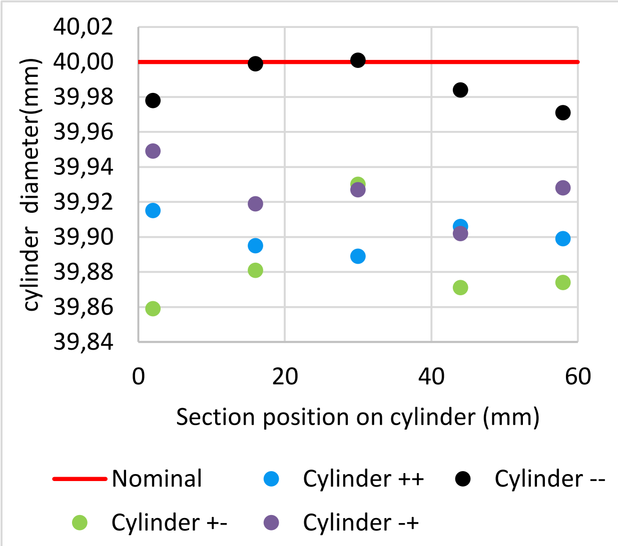



*Fig. 5 Model of the cylinder for inspection a) before point reduction, b) after point reduction*

Compared with the data obtained on the CMM, the cylinder measurement data obtained by the data acquisition method, CT, at the High Quality polygonization setting are shown in Table 4.




*Graph 2 Data obtained on the CT – polygonal 3D model (polygonization High Quality)*

Table 4 shows the cylinder diameter measurement values obtained by the CT data acquisition method with the High Quality polygonization setting. In the comparison of graph 2 with graph 1, the difference in the distribution of the

*Table 3 Cylinder values by type of polygonization*

| Type of cylinder | Number of points ˝Raw data˝ (-) / File size (MB) | Number of points ˝High Quality˝ (-) / File size (MB) | Number of points ˝High Quality˝ after editing (-) / File size (MB) |
|---|---|---|---|
| + + | 88 174 923 / 8.721 | 71 961 120 / 7.096 | 7 925 432 / 0.762 |
| + - | 63 332 533 / 6.201 | 52 207 353 / 5.107 | 9 378 313 / 0.902 |
| - + | 77 039 647 / 7.662 | 62 894 976 / 6.271 | 4 223 639 / 0.402 |
| - - | 58 244 091 / 5.709 | 44 330 668 / 4.446 | 2 383 316 / 0.229 |

*Table 4 Circle diameters result from CT measurement*

| Section position | cylinder ++ (mm) | cylinder -- (mm) | cylinder +- (mm) | cylinder -+ (mm) |
|---|---|---|---|---|
| 2 mm | 39.899 | 39.971 | 39.874 | 39.928 |
| 16 mm | 39.906 | 39.984 | 39.871 | 39.902 |
| 30 mm | 39.889 | 40.001 | 39.93 | 39.927 |
| 44 mm | 39.895 | 39.999 | 39.881 | 39.919 |
| 58 mm | 39.915 | 39.978 | 39.859 | 39.949 |

individual values can be seen, in graph 2 the values of the cylinder diameters are lower than the nominal value. The maximum measured deviation for this method was at 141 µm, which is almost identical to the deviation between the minimum and maximum measured value (142 µm).

The reason for the difference between the different data acquisition methods can of course be attributed to the accuracy of the different methods, where we have to factor into the accuracy the possible influence of the accuracy in the type of polygonization (as it was not Raw Data), but we also have to take into account the rugged surface of the part, where the CMM machine's sensor is not able to reach all the measured locations of the surface. Other errors that affected the cylinder diameter measurement were also errors in the manufacturing of the cylinder itself. During production, the part may have been reduced in size compared to the CAD model. In FDM additive manufacturing, we encounter a seam that represents the beginning or end of a layer. To detect deviations from the CAD model of the part, 3D scans of the cylinders were created obtained using the CT method, colour deviation maps showing deviations from the nominal model throughout the surface of the cylindrical surface. These colour deviation maps are shown in Fig. 6.

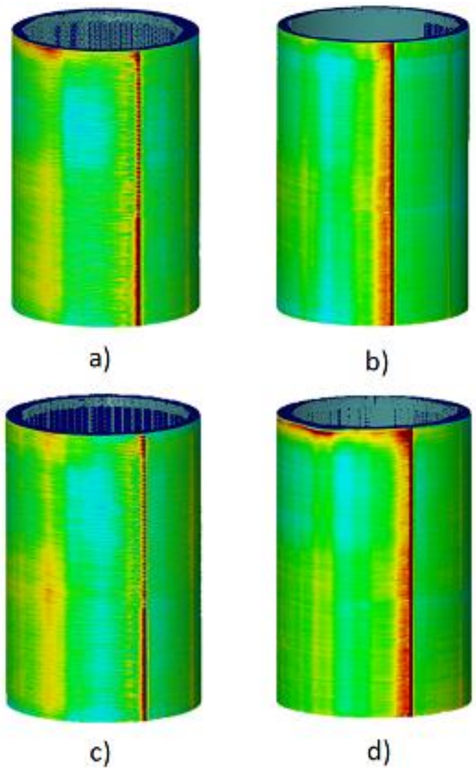



*Fig. 6 Surface comparison actual mesh cylinder to fitting cylinder: a) parameter ++, b) parameter --, c) parameter +-, d) parameter -+, colour scale is set to +-0,15 mm*

The coloured deviation maps show the deviations of the current model with the nominal model. According to Fig. 6, it can be said that the cylindrical surface of the individual cylinders is within the tolerance of STN EN 22768-1 which is defined according to the very fine accuracy class (f) at ±0.15 mm. The only area that deviates from this tolerance is the seam, which arises due to the technology where a single layer is formed and ends at a certain point on the parametric of the cylindrical surface.

## 4 CONCLUSION

In this paper, the types of digitization of simple cylinders produced by additive manufacturing FDM are compared. This comparison was made in the context of use in the reverse engineering process, specifically reverse geometric modelling.

The aim of the study was to investigate the effects of digitization types on the dimensions of a simple component produced using FDM additive manufacturing technology.

2 types of digitization were compared. The first one was a contact method CMM, the second method used was a non-contact method industrial CT. From the results we obtained it can be stated that both methods were comparable and the difference between the technologies was at the level of 0.08 mm. It is difficult to predict which dimension was correct as there were a large number of factors that could have influenced the size of the part being measured. However, the almost constant difference between the CT and CMM values can also be explained by the aforementioned data collection method. While in the touch method a 3 mm diameter touch probe is used for a structured surface, it is difficult to reach all parts of the surface. Industrial tomography works with the size of the voxel, which affects the detail of the collected data, therefore it is possible to get into all locations of the cylindrical surface under investigation. From this point of view, it is possible to explain the larger value of the cylinder diameter in CMM as opposed to CT.

For inverse geometric modelling, the dimensional accuracy of the investigated data is important. According to STN EN 22768-1, the accuracy class - high precision has a dimensional tolerance for a size of 40 mm ± 0.15 mm. Within this range all the elements under investigation (parametric curve, section) are within this range. Because of this phenomenon, the colour deviation maps shown in Fig. 6 were also generated. This information is crucial for surface reconstruction, as it demonstrates that utilizing any parametric curve or section through a cylindrical surface followed by the cylinder's reconstruction enables the attainment of a form compliant with the tolerance stipulated in STN EN 22768-1.

Future research will investigate other influences that enter the reverse engineering process. These are the effects of point reduction, the effects of reverse engineering techniques. Likewise, individual impacts will be investigated on other simple objects (cube, sphere) with the understanding that a complex component may subsequently be used. Individual data can be used to speed up the creation of 3D CAD models improving the accuracy and quality of these models and simplifying the reverse engineering process.

## 5 ACKNOWLEDGMENTS

This work was supported by the call for doctoral students and young researchers of Slovak University of Technology in Bratislava to start a research career (Grant ESG 23-06-14-A).

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