

A Methodology for Evaluating Dimensional Accuracy in Reverse Engineering Workflows

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Received: 4 May 2026/Accepted: 20 July 2026/Published online: 30 September 2026

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Abstract

Reverse engineering is widely used for the digital reconstruction of physical objects; however, the dimensional accuracy of the resulting models depends on a sequence of interconnected processes, including manufacturing, 3D scanning, data processing, and model reconstruction. Most existing studies evaluate individual devices or technologies separately, while the cumulative influence of the entire workflow is rarely addressed in a systematic manner. This paper proposes a structured methodology for evaluating the dimensional accuracy of reverse engineering systems as integrated processes. The proposed framework defines a repeatable workflow consisting of reference artifact design, additive manufacturing, object digitisation, mesh processing, CAD reconstruction, and dimensional evaluation. The methodology provides a general framework that can be applied to different reverse engineering technologies and measurement systems. Its objective is to support consistent accuracy evaluation, improve the comparability of results across studies, and contribute to the development of standardised procedures for assessing reverse engineering workflows.

Keywords:

3D scanning, accuracy evaluation, measurement, mesh processing, engineering

1. INTRODUCTION

Reverse engineering based on 3D scanning has become a widely used approach in product development, quality control, and digital reconstruction of physical objects. Modern structured-light and laser scanners allow rapid acquisition of complex geometries, which can subsequently be transformed into editable CAD models. Despite the technological maturity of individual devices, the overall accuracy of reverse engineering (RE) processes remains difficult to evaluate in a consistent and repeatable way [1–4].

Most manufacturers specify the accuracy of their scanners using proprietary procedures or reference standards focused solely on the scanning device. International standards such as VDI/VDE 2634 define procedures for testing optical 3D measuring systems, but these standards address only the performance of the scanner itself under controlled laboratory conditions [5]. They do not consider the complete reverse engineering workflow, which typically includes multiple stages: data acquisition, mesh processing, conversion into CAD geometry, and often subsequent reproduction using additive manufacturing [6]. As a result, the declared scanner accuracy does not necessarily reflect the dimensional fidelity of the final reconstructed model.

Several researchers have pointed out that the accuracy of 3D scanning is strongly influenced not only by hardware

parameters but also by external and procedural factors. Kersten et al. demonstrated that operator experience, calibration quality, object positioning, and lighting conditions significantly affect the resulting measurement accuracy [1, 7–9]. These influences introduce variability that is not captured by standard device specifications.

Similarly, Campanelli et al. emphasised that surface properties, scanning strategy, and data processing steps can cause deviations between the real object and its digital representation. Their work highlights that the error is cumulative and propagates throughout the workflow rather than being isolated to the scanning stage alone [6].

Medřický et al. further analysed the influence of environmental conditions and post-processing software on the final mesh quality. Their findings indicate that smoothing, simplification, and filtering algorithms can significantly alter the geometry of the scanned object, often improving the visual quality at the expense of dimensional accuracy [5]. This introduces an important challenge for reverse engineering applications where dimensional fidelity is critical.

As previously mentioned, reverse engineering often includes more stages, where each of these stages introduces its own type of error, and their combination determines the overall dimensional accuracy of the process [10–13]. However, there is currently no standardised approach

describing how such a system should be tested, what type of test object should be used, how measurements should be performed, or how the results should be statistically evaluated [1].

For evaluation purposes, some authors have used simple geometric artifacts (spheres, cubes, cylinders) to test scanner accuracy. While suitable for device calibration, such objects are insufficient for assessing reverse engineering workflows, where complex geometrical features and transitions between simple and detailed surfaces play a crucial role [14–16]. Therefore, the design of a dedicated test artifact containing a combination of simple and fine geometrical elements becomes essential for meaningful evaluation.

Moreover, a traditional dimensional comparison between the original and reconstructed model is often limited to a small number of linear measurements [17]. This approach does not fully describe the geometric fidelity of the surface [18, 19]. The use of statistical indicators, such as the root mean square error obtained from best-fit alignment in inspection software (e.g., GOM Inspect), provides a more comprehensive description of surface trueness and overall geometric accuracy [14].

From the analysis of existing research, it becomes evident that while many studies address partial aspects of reverse engineering accuracy, there is no unified, repeatable, and standardised methodology for evaluating the accuracy of reverse engineering systems as a whole [12].

This gap motivates the need for a methodological framework that:

- defines a suitable test artifact;
- specifies measurement procedures for both physical and digital models;
- standardises the evaluation process;
- allows repeatable comparison of different reverse engineering setups.

The following sections therefore propose a standardised methodology for accurately assessing reverse engineering systems and experimentally verifying their applicability using a complete CAD–print–scan–reconstruct cycle.

2. MATERIALS AND METHODS

When reverse engineering is carried out using 3D scanning, the overall process includes successive stages of physical object digitisation, processing of the acquired data in the form of a polygonal mesh, possible mesh modifications, conversion into a CAD model, and subsequent reproduction or further utilisation of the digital geometry. Each of these stages introduces its own type of geometric error into the process, and the resulting inaccuracy is the mathematical sum of the errors associated with individual steps, while also being strongly influenced by their mutual interactions and parameter settings within the entire workflow.

For this reason, the objective of this work is not only to determine the final error at the end of the process, which

expresses the degree of inaccuracy of the overall reproduction, but also to perform a detailed analysis of the individual stages of the reverse engineering cycle, identify dominant sources of error, and investigate possibilities for their minimisation through appropriate scanner software settings and data post-processing strategies.

In order to ensure accuracy is evaluated objectively, this work adopts an experimental approach in which a reference CAD model created by the author is available at the beginning of the process.

The use of a CAD model as the starting point of the methodology is deliberate and necessary to objectively evaluate the accuracy of the individual process stages. By creating a custom CAD model, it is possible to clearly define the reference geometry and subsequently analyse the accuracy of the manufacturing device, which in the context of reverse engineering represents a common production system, such as a 3D printer.

The first step of the methodology is to design a test specimen in the CAD environment. This specimen serves as a reference object, and its geometry facilitates accuracy evaluation in different directions and across various types of geometric features. The CAD model represents an ideal, theoretical geometry free of manufacturing errors and serves as the basis for subsequent comparisons.

The CAD model is then physically created using 3D printing. At this stage, the first source of geometric deviation is introduced, as additive manufacturing is subject to technological limitations such as axis positioning accuracy, layer resolution, material shrinkage, and part orientation on the build platform, which introduces a level of manufacturing error to the physical model relative to the original CAD model.

In order to quantify this error, the physical model is subjected to direct dimensional measurements of selected characteristic dimensions. In this work, fourteen dimensions are selected, representing different types of geometric features of the specimen. Measuring these dimensions makes it possible to determine the average manufacturing deviations and provides information about the accuracy of the manufacturing device itself.

The next step in the methodology is to digitise the physical model using a 3D scanner. Scanning is performed under various scanner software settings, which may generally include acquisition modes, point density, smoothing, or noise suppression. The result of the scanning process is a polygonal mesh that represents a digital approximation of the physical surface of the specimen.

It should be emphasised that a mesh model is inherently a discrete representation of the surface, composed of numerous small facets and affected by irregularities caused by noise, interpolation, and data processing algorithms. Consequently, further mesh modifications such as smoothing, simplification, or hole filling can significantly influence the resulting geometry of the model.

At this stage, the methodology considers two possible paths for further data processing. Following the 3D scanning process and the generation of the STL model, two possible workflows can be considered. The first workflow

involves the direct use of the STL file for manufacturing a new specimen without any further geometric modifications. This path represents a situation in which the objective of reverse engineering is the rapid reproduction of an object without the need for further modifications. In such a case, however, the resulting specimen carries all the irregularities and errors inherent in the polygonal representation.

The second option is to convert the polygonal mesh into a CAD model, that is, into a solid file. This step not only enables further modification of the specimen but also leads to a 'regularisation' of the geometry, as the CAD model consists of a smaller number of ideal surfaces. The resulting surfaces are smoother and geometrically more regular; however, this regularisation may suppress local geometric details and thus lead to deviations from the original physical model.

A key step in evaluating the accuracy of the reverse engineering system is comparing the digital data with the reference CAD model. This comparison is performed in inspection software using an alignment function, which compares the scanned model with the reference geometry.

Since the scanned object is already a physical model affected by manufacturing error, the resulting deviation after alignment simultaneously includes the 3D printing process error and the scanning process error, which makes it necessary to separate these errors within the methodology. In this work, this separation is achieved via direct physical measurement of the dimensions of the manufactured reference model, which provides information about the manufacturing error. By subsequently comparing the CAD model with the scanned data, the combined error caused by printing and scanning can be determined. After subtracting the manufacturing error, the error of the scanning process itself can be approximated.

The proposed methodology thus makes it possible to systematically evaluate the accuracy of individual steps of the reverse engineering process as well as the accuracy of the entire system as an integrated workflow, and it establishes a framework within which different software settings, data processing strategies, and manufacturing approaches can be compared, while ensuring that the results are mutually comparable and repeatable.

The experimental research consists of multiple steps, which are discussed in detail separately in the following sections. At the outset, it was necessary to approach the experimental problem in a highly comprehensive manner in order to design a component with an optimal shape and dimensions that would satisfactorily fulfil its intended purpose. This means that the component has to consist of various shapes and dimensions that will effectively demonstrate the accuracy of reverse engineering systems.

After the component had been designed and modelled in the CATIA V5 software environment, six identical specimens were manufactured using a Prusa 3D printer based on FDM (Fused Deposition Modelling) technology. All specimens were produced using the same printing pa-

rameters to ensure the repeatability of the manufacturing process. Once printed, all specimens were scanned using a 3D scanner based on structured-light technology. Subsequently, all six scans were saved in STL-format data files and processed and converted through several intermediate steps into PART-format models using the SolidWorks software.

For comparison purposes, both the original scan in STL format and the final reconstructed PART model were again printed in six copies each. Finally, all selected dimensions were measured on the initial printed parts, the scanned models, and all twelve final printed specimens. Each of these steps involves many operations and parameter settings, which are described in detail, as they directly influence the final results.

A significant portion of the experiment was carried out within various software environments, including component modelling, scanning, scan editing, data conversion, and subsequent dimensional measurement. Throughout the entire experiment, the functionalities of all used software tools were examined, and results obtained under different parameter settings were compared with the aim of optimising the overall process to achieve the highest possible accuracy while considering time efficiency and experimental complexity.

During the preliminary phase of the study, the geometry of the test component was iteratively refined in order to achieve a suitable balance between geometric complexity and reliable data acquisition. The final design was selected to ensure stable and repeatable scanning conditions while still containing a sufficient variety of geometrical features for accuracy evaluation.

The ExScan Pro software provides a wide range of scanning parameters, the influence of which on the scanning results was investigated experimentally by scanning the printed component under various parameter combinations. The resulting scans were subsequently compared in the GOM Inspect software. This comparative analysis played a key role in identifying and selecting the optimal scanning parameter settings for the purposes of this experiment. A concise schematic representation of the experimental process is shown in Figure 1.

This concise diagram defines the experiment and describes its steps. These steps are discussed in greater depth in the following tree diagram of the experimental plan, which also expands on them with additional, previously unmentioned steps. Within the 3D-scanning process diagram, the progressive development of the software parameter settings is illustrated in Figure 2, including:

- pre-scanning settings (non-HDR / HDR) – option to perform scanning in HDR quality;
- post-scanning settings (HIGH detail / LOW detail) – preservation of details during the conversion of the point cloud into a mesh;
- mesh processing (non-SMOOTH / SMOOTH) – option to apply surface smoothing to the scan;
- mesh processing (non-SIMPLIFIED / SIMPLIFIED) – option to reduce the number of polygons.

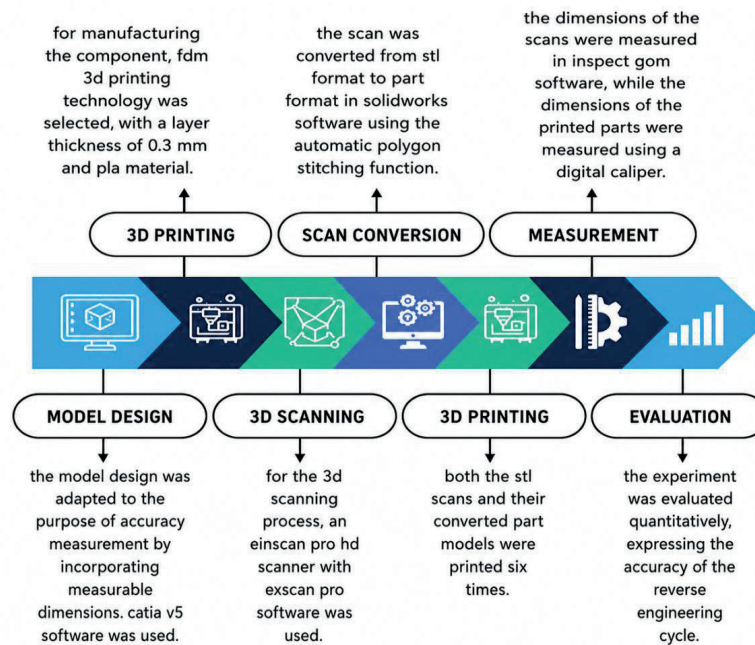


Fig. 1. Concise schematic representation of the experimental process

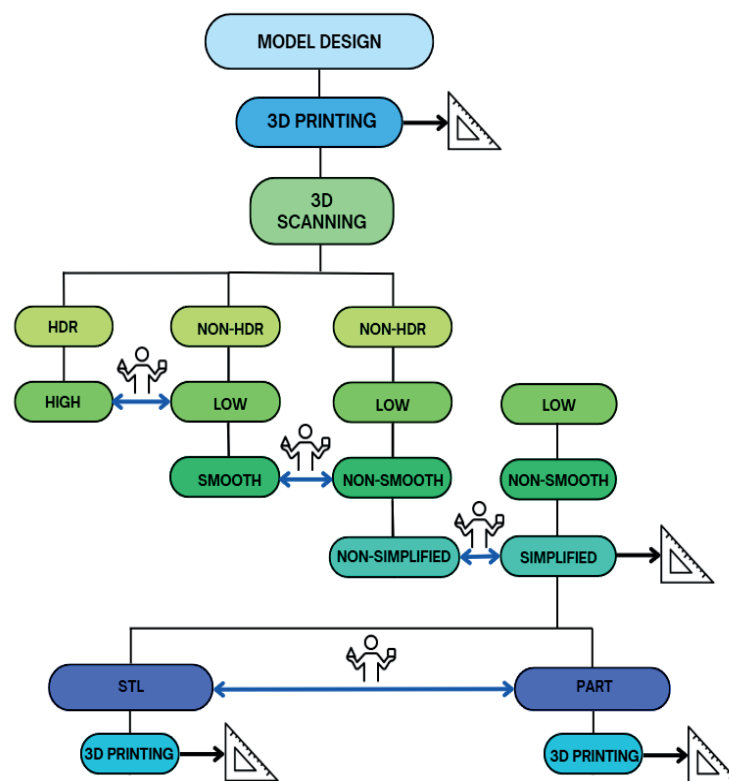


Fig. 2. Tree diagram of the experimental plan

By progressively comparing the scans, as indicated by the bidirectional blue arrow, decisions were made regarding which parameter settings would be used for the experiment. The comparisons were carried out in the Inspect GOM software using the deviation colour map function, which was used to visualise the extent to which individual scanning and post-processing settings influenced the dimensional accuracy and surface trueness of the resulting scan. The final column

was selected as the optimal configuration, namely scanning without HDR, mesh generation with the lowest quality setting (LOW), no surface smoothing (NON-SMOOTH), and, in order to reduce the file size, mesh simplification to 4% of the original polygon count. All scans were then printed in their original STL format as well as in their converted PART format versions. All components (printed parts and scans) whose dimensions were measured are marked with a ruler symbol.

2.1. Design of the test artifact

The first and most critical step of the experiment is the design of a suitable test artifact, developed by the author specifically for the purposes of this study, as the ability to demonstrate and evaluate the accuracy of reverse engineering systems directly depends on the properties of the selected model. The geometry of the artifact must satisfy conflicting requirements: it should not be excessively complex in order to avoid complications during additive manufacturing and, in particular, during 3D scanning, while also being sufficiently diverse to demonstrate the capability of the 3D printer to fabricate smaller and more intricate features, and the ability of the structured-light 3D scanner to capture such features with adequate detail.

The CATIA V5 CAD software was used to design the test artifact. The model was conceptually divided into two parts, which are evaluated separately. The main part consists of a cuboid with dimensions of 80 mm × 40 mm × 10 mm, as shown in blue in Figure 3, while the second part comprises six smaller geometrical features located on the top surface of the main body, as shown in yellow in Figure 3. This division reflects the fact that both the 3D printer and the 3D scanner exhibit significantly different accuracy depending on the size and shape of the manufactured or scanned object.

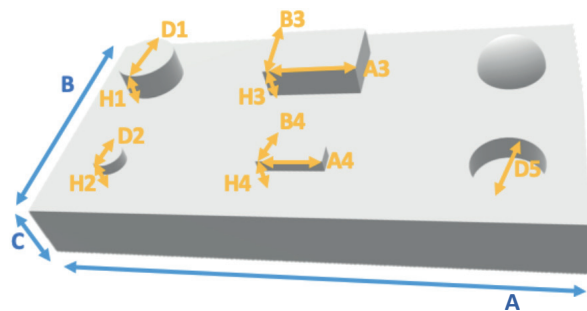


Fig. 3. Designed test artifact

For this reason, the accuracy of the two parts is assessed independently. The first evaluation focuses on the accuracy of the 3D printing and 3D scanning of a simple prismatic geometry with flat surfaces and sharp edges. The second evaluation investigates the accuracy and capability of the 3D printing and 3D scanning processes when applied to small features of different geometrical characteristics, including prismatic, circular, and spherical shapes. This approach makes it possible to directly compare the performance of the reverse engineering system when dealing with simple reference geometry and when capturing and reproducing fine and geometrically diverse features. Figure 3 shows all measured dimensions divided into two categories, as previously mentioned.

Table 1
Dimensions of the designed artifact

Designation	A	B	C	D1	H1	D2	H2	H3	A3	B3	H4	A4	B4	D5
Reference value (mm)	80	40	10	10	5	5	2	5	15	10	2	10	3	10

The numbering of the dimensions corresponds to the individual geometrical features of the test artifact rather than to consecutive dimension identifiers. Therefore, some indices are intentionally omitted.

Table 1 shows all dimensions of the designed artifact.

2.2. Manufacturing of the test artifact

The second step of the experimental methodology is to additively manufacture the designed test artifact using an Original Prusa i3 MK3 3D printer based on the FDM technology. Prior to initiating the 3D printing process, the CAD model created in CATIA must be exported correctly into the STL file format. Incorrect export settings can lead to improper slicing of the model, which subsequently results in inaccurate layer generation and printing errors. After converting the CAD model into an STL file, the file is imported into the PrusaSlicer software, which is freely available and commonly used in combination with 3D printers manufactured by Prusa Research. The printing parameters are defined within the slicing software prior to manufacturing. The test artifact was printed six times from PLA filament using a layer height of 0.3 mm and a nozzle diameter of 0.4 mm. An infill density of 15% was selected, resulting in an approximate printing time of 45 minutes per specimen.

2.3. 3D scanning of the test artifact

The scanning process represents a complex and highly flexible part of the reverse engineering workflow. It can be broadly divided into two interconnected domains: external conditions and software-based processing. External factors, such as lighting conditions, surface properties of the scanned object, scanning angles, and object positioning, can be influenced to a certain extent and were adjusted in this work in order to achieve the most stable and repeatable scanning conditions possible. Prior to scanning, a thin layer of white matte scanning spray was applied to the surface of each specimen in order to reduce reflections and improve the quality and consistency of the data acquisition. However, an equally important part of the scanning process takes place within the scanner software environment, where the operator plays a crucial role and continuously influences the resulting quality and accuracy of the acquired data.

The scanning was performed using an EinScan Pro HD structured-light 3D scanner (SHINING 3D) operated through the ExScan Pro software. In the Fixed Scan mode used in this study, the scanner provides a single-shot accuracy of 0.04 mm, a point resolution of 0.24 mm, a scanning area ranging from 209 mm × 160 mm to 310 mm × 240 mm, and a scanning speed of less than 0.5 s per scan, according to the manufacturer's specifications. The software provides a wide range of functions and adjustable parameters. Depending

on the operator's knowledge and experience, these settings may lead either to highly accurate results or to significant inaccuracies. For this reason, particular attention was paid to the selection and combination of software parameters. Fixed scanning mode was selected for data acquisition, in which the scanner remains stationary while the object is scanned from multiple viewpoints. Although real scanning environments are rarely ideal, the scanning conditions were adapted to minimise disturbances and ensure consistent data acquisition. These external adjustments were made to support the software-based scanning process and are not the primary focus of this methodology. Within the scanning software, several key parameters significantly influenced the resulting data. One of the main parameters was the number of scanning positions, which determines how many individual scans are captured during one scanning cycle. In this work, eight scanning positions were selected, meaning that the object was scanned at evenly distributed angular intervals.

During the scanning process, the individual scans are progressively aligned and merged, resulting in a gradually forming digital representation of the scanned object. After completing a single scanning cycle, the resulting data consisted of an incomplete point cloud, which could not yet be used for further reverse engineering steps. To obtain complete geometric information, additional scanning cycles were performed with the object repositioned, allowing data acquisition from previously inaccessible surfaces. The software subsequently aligned and merged the individual scans based on the detected geometric features, resulting in a dense point cloud representing the scanned artifact. Camera brightness was another important software parameter, whose intensity directly affected the scanner's ability to capture surface geometry. Proper adjustment of this parameter required operator experience, as it had to be adapted to the prevailing external lighting conditions. Inappropriate brightness settings led to missing data or distorted geometry, particularly in areas with limited visibility or an unfavourable surface orientation.

The resulting point cloud represents the primary digital output of the scanning process and serves as the main input for subsequent reverse engineering steps. The density of the point cloud depends on the selected scanning resolution, with a higher resolution resulting in hundreds of thousands to millions of points. While a higher point density provides more detailed geometric information, it also increases the data complexity and computational demands in later processing stages.

Post-processing represents the next critical step and is performed within the same scanning software environment. During this phase, the point cloud is inspected and manually corrected where necessary. In particular, sparse or irregular point distributions occurring at sharp edges or transitions between surfaces were identified and removed, as they were considered scanning artifacts with unknown origin Figure 4. If left uncorrected, such irregularities could lead to significant geometric errors in the reconstructed surface.

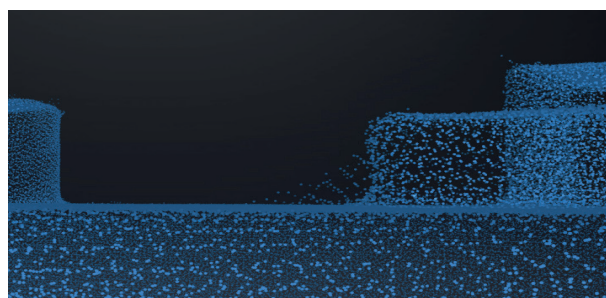


Fig. 4. Sparse or irregular point distributions

After the point cloud was adjusted to a satisfactory state, a polygonal mesh was generated by connecting the points into a large number of triangular facets, resulting in a watertight mesh. The duration of this process and the size of the resulting file depend on the selected resolution level. The initial mesh typically includes all captured data points, except for very sparse regions that are automatically discarded by the software. However, such meshes are often unnecessarily large, making them difficult to handle in subsequent software tools.

Influence and selection of ExScan Pro software settings on dimensional accuracy

The influence of selected scanning and post-processing parameters was systematically evaluated to achieve an optimal balance between dimensional accuracy and data efficiency. The analysis focused on three key aspects: HDR scanning mode, mesh resolution, and post-processing functions, including smoothing and mesh simplification.

The evaluation was performed using comparative deviation analysis in the GOM Inspect inspection software, as shown in Figure 5, where different parameter combinations were applied to the same scanned object and the resulting geometries were compared. The methodology was based on isolating the effect of individual parameters while keeping all other conditions unchanged.

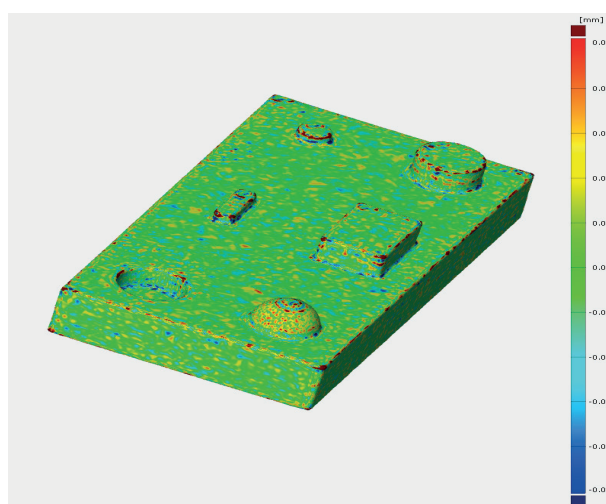


Fig. 5. Deviation map of comparison of non-simplified and simplified scanned models

First, the influence of the HDR mode and mesh resolution was assessed by comparing extreme configurations (HDR

with high resolution versus non-HDR with low resolution). The results showed only minor local deviations, primarily in geometrically complex areas, while no significant differences were observed on planar surfaces. Since the increase in data size and computational complexity was not accompanied by a measurable improvement in dimensional accuracy, the HDR mode combined with high resolution was not considered efficient for further use.

Subsequently, the effect of surface smoothing was evaluated. Although smoothing improved the visual continuity of the mesh, deviation analysis confirmed that it had a negligible influence on the dimensional accuracy. Therefore, this operation was not included in the final workflow, as it increased the processing time without providing measurable benefits.

Finally, the influence of mesh simplification was analysed. The results demonstrated that reducing the number of polygons significantly improved data manageability while preserving dimensional accuracy. No systematic geometric distortion was observed after simplification.

Based on these findings, the optimal configuration for subsequent processing was defined as non-HDR scanning with a low mesh resolution and applied mesh simplification, while smoothing was omitted. This configuration ensures sufficient dimensional accuracy, together with efficient data handling and processing.

2.4. Conversion of the scanned mesh into a CAD model

The direct output of the 3D scanning process is a polygonal mesh in STL format, which represents the object's surface as a collection of interconnected triangular facets. While this representation is suitable for visualisation and certain manufacturing applications, it does not allow the direct parametric modification or advanced geometric analysis typically required in reverse engineering workflows. For this reason, it is often necessary to convert the mesh into a CAD model.

In this work, the conversion was performed using the 'Scan to 3D' functionality available in SolidWorks. This tool transforms polygonal mesh data into a surface-based CAD representation by automatically fitting analytical and freeform surfaces to the scanned geometry. Mesh simplification was applied prior to conversion to reduce the data complexity and ensure stable processing within the CAD environment.

A deviation analysis was performed to evaluate the influence of this conversion step on the dimensional accuracy by comparing the original mesh with the resulting CAD model. The deviation map revealed that most of the surface remained within a narrow tolerance range, indicating a high level of geometric fidelity between the mesh and the reconstructed CAD model. Localised deviations were observed primarily in regions with high curvature and sharp geometric transitions, where surface approximation is inherently more challenging.

Figure 6 presents a zoomed-in deviation map comparing the mesh with the converted CAD model, confirming that the mesh-to-CAD conversion preserves the overall geometry with only minor localised deviations reaching a value 0.32 mm, which may further complicate remanufacturing the model.

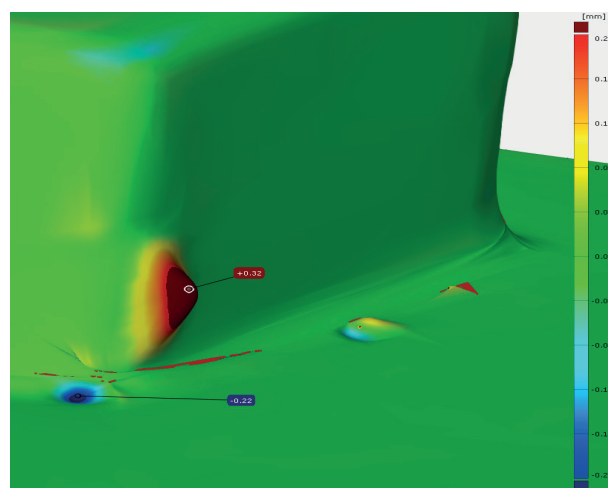


Fig. 6. Deviation map comparing the mesh and the converted CAD model

2.5. Manufacturing and evaluation of the reconstructed model

Following the mesh-to-CAD conversion, both the original scanned mesh and the reconstructed CAD model were physically reproduced using the same additive manufacturing process. This step made it possible to directly compare their manufacturability, surface quality, and dimensional fidelity.

Both digital representations were prepared under identical conditions and subsequently fabricated in order to evaluate how different data representations influence the final physical output. This comparison is essential, as reverse engineering workflows can use either direct mesh-based reproduction or CAD-based reconstruction depending on the application.

The comparison confirmed that both printed models exhibit surface irregularities. In the mesh-based model, these originate from inherent imperfections in the scanned data, which are directly preserved in the polygonal representation. In contrast, the reconstructed CAD model shows additional surface deviations caused by geometric approximation introduced during the conversion process.

It was also observed that even after reconstruction, the resulting geometry does not fully eliminate surface imperfections, and new local deviations may appear as a consequence of surface fitting. This indicates that the conversion step itself represents a potential source of geometric inaccuracy.

2.6. Dimensional measurement and accuracy evaluation

Dimensional measurements of the initial printed specimens were performed using a digital calliper. Each characteristic dimension was measured six times, and the arithmetic mean of the six measurements was used for the subsequent evaluation. The obtained values were then compared with the reference CAD model created in CATIA V5. This comparison was used to quantify the manufacturing errors introduced by the additive manufacturing process. Subsequently, each scanned model was manually measured in the GOM Inspect inspection software, where the same fourteen characteristic dimensions were evaluated directly on the digital geometry.

The measured digital dimensions were then compared with the corresponding dimensions obtained from the physical printed specimens. This comparison enabled the quantification of the dimensional accuracy of the 3D scanning process independently of the manufacturing error.

Digital comparison of the mesh and the reconstructed CAD model using deviation maps in the GOM Inspect software provides information about the errors introduced during the mesh-to-CAD conversion process in SolidWorks. Furthermore, the inaccuracy introduced in the final stage of the process can be quantified by physically measuring the printed reconstructed parts and printed scan-based models using a digital calliper and comparing these measurements with their digital counterparts.

Dimensional measurement of the scanned model

Dimensional measurements were performed directly on the scanned mesh using the GOM Inspect inspection software to evaluate the dimensional accuracy of the 3D scanning process. This software provides advanced tools for measuring geometric features and comparing digital models with reference geometry.

The scanned mesh was first imported into the software environment, where reference geometric elements were created at the locations corresponding to the selected characteristic dimensions. Planar features were generated using the Gaussian best-fit method, which calculates the optimal plane based on the spatial distribution of mesh points while minimising the influence of local irregularities. This approach reliably extracts dimensional information from non-ideal scanned surfaces.

For cylindrical features, reference cylinders were generated using the same best-fit principle. The diameters of these features were then calculated directly from the fitted geometric elements. Figure 7 shows the creation of reference geometric features used for the dimensional measurement of the scanned model. For cylindrical features, reference cylinders were generated using the same best-fit principle, and their diameters were calculated directly from the fitted geometric elements.

The original mesh visualisation was temporarily hidden to ensure accurate and unobstructed measurements, allowing direct inspection of the fitted reference geometry, which is represented in Figure 8.

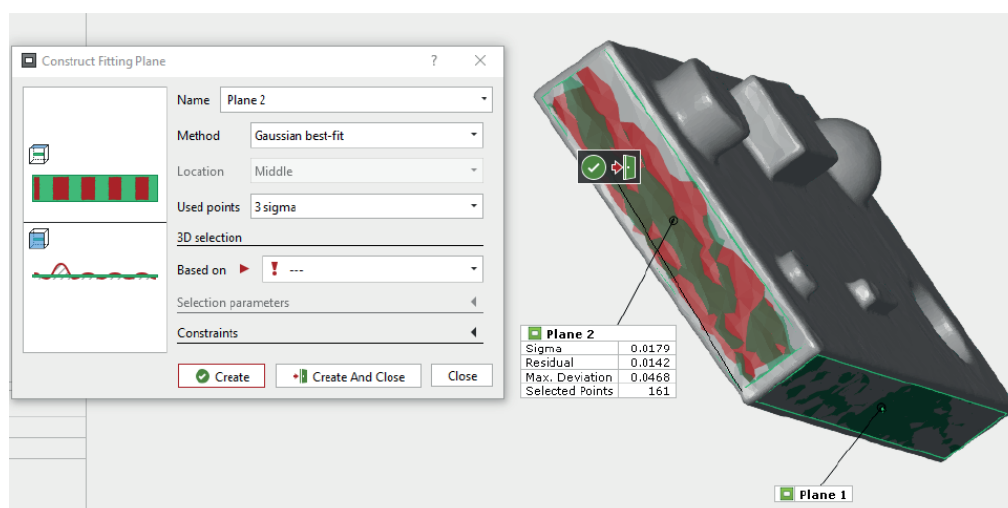


Fig. 7. Plane creation with 'Gaussian best fit' function

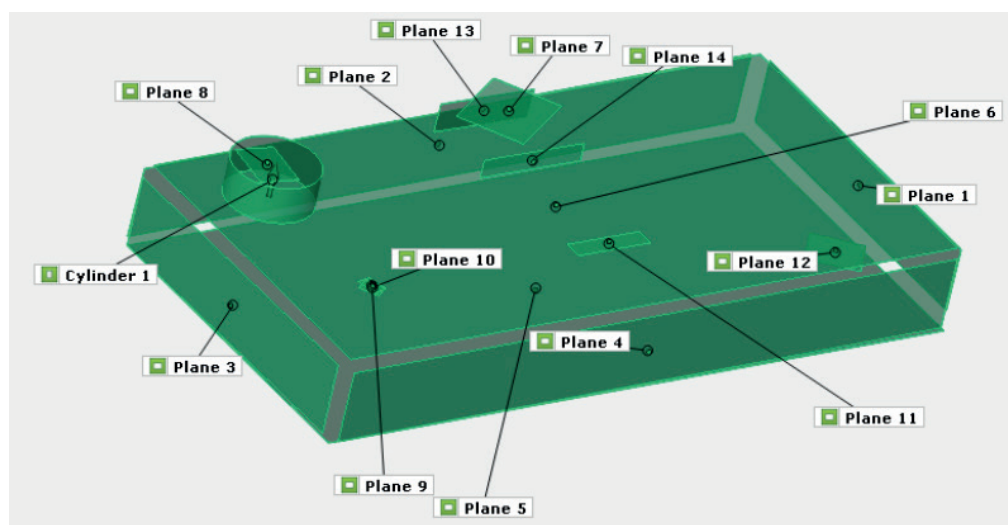


Fig. 8. All created surfaces on the hidden mesh model

Dimensional measurements were performed using the Construct → Distance → Point and Plane function in the GOM Inspect software. This function measures the perpendicular distance between two opposing surfaces. The first point was defined on one surface of the model, and the corresponding point on the opposite surface was automatically projected along a direction normal to the reference plane, ensuring that the measured distance represented the true perpendicular dimension.

For each evaluated dimension, six independent distance measurements were performed at approximately uniformly distributed locations across the measured surfaces, and the resulting values were recorded (see Fig. 9).

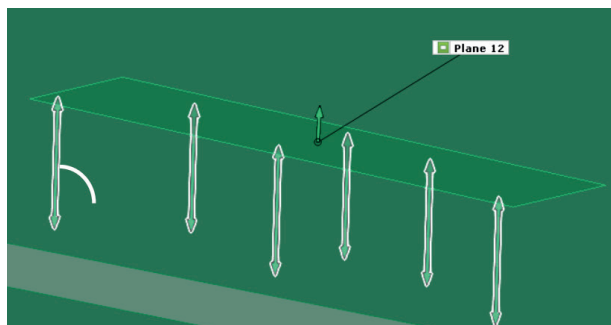


Fig. 9. Measurement method of the scanned model dimensions

3. RESULTS

The evaluation of the experimental results was performed by analysing individual stages of the reverse engineering cycle separately in order to quantify their respective contributions to the overall dimensional inaccuracy. The analysis followed the complete workflow, starting with additive manufacturing of the reference model, continuing through 3D scanning and mesh processing, and concluding with the fabrication of the reconstructed model.

The dimensional accuracy at each stage was determined by comparing the measured characteristic dimensions between consecutive steps of the process. Specifically, the accuracy of the additive manufacturing was evaluated by comparing the dimensions of the printed reference specimen with the original CAD model. The accuracy of the 3D scanning process was determined by comparing the dimensions measured on the scanned model with those obtained from the physical printed specimen. Finally, the accuracy of the reconstructed model reproduction was evaluated by comparing the dimensions of the final printed models with their corresponding digital representations.

Figure 10 illustrates the evaluation scheme used to quantify the dimensional accuracy at each stage of the reverse engineering workflow. The individual differences between the reference dimensions, printed dimensions, scanned dimensions, and reconstructed model dimensions represent the isolated inaccuracies introduced by the additive manufacturing, 3D scanning, and subsequent reconstruction and reproduction steps.

In addition to dimensional deviations, surface quality was evaluated using statistical analysis of the measured values. The standard deviation of repeated measurements

was used as an indicator of surface consistency and local geometric stability. All selected characteristic dimensions were included in the analysis to ensure a comprehensive evaluation of the entire specimen geometry.

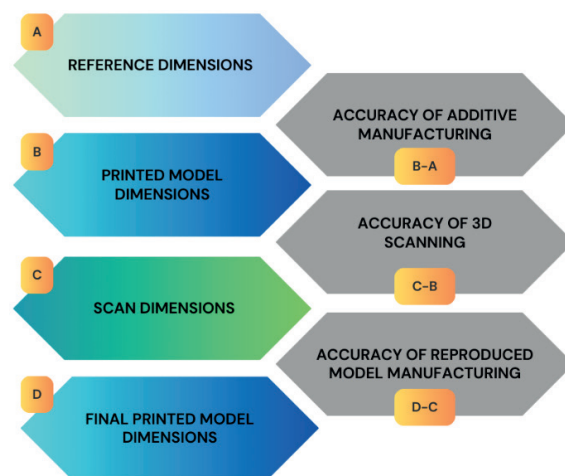


Fig. 10. Evaluation scheme for quantifying dimensional accuracy

3.1. Dimensional accuracy of the reverse engineering cycle

In this section, all measurements previously performed individually for each stage of the reverse engineering workflow are summarised in the following tables and graphical representation. Since the focus of this study is on the proposed evaluation methodology rather than on the specific accuracy values of individual reverse engineering systems, the presented results serve primarily to demonstrate the applicability and structure of the methodology rather than to provide a detailed performance assessment of particular devices or technologies.

Table 2 summarises the average deviations associated with the individual stages of the reverse engineering workflow, representing the isolated accuracy of additive manufacturing, 3D scanning, mesh-based reproduction, and CAD-based reconstruction. These values were obtained by averaging the deviations of the measured characteristic dimensions presented in the previous sections.

Table 2

Isolated dimensional deviations of all the reverse engineering steps

Process type	a	b
3D printing	0.04	-0.05
3D scanning	-0.16	-0.11
3D printing of scan	0.00	0.05
3D printing of part	-0.06	-0.09

Table 3 further presents the dimensional deviations of individual models relative to the original reference CAD geometry. Unlike the isolated deviations of individual processes, these values represent cumulative deviations, as each stage builds on the previous one and propagates its associated inaccuracies.

Table 3

Dimensional deviations of individual models relative to the original reference CAD geometry

Process type	a	b
3D printing	0.04	-0.05
3D scanning	0.12	-0.11
3D printing of scan	-0.12	-0.06
3D printing of part	-0.18	-0.09

Figure 11 graphically illustrates the progression of dimensional deviations relative to the reference geometry throughout the reverse engineering cycle. It can be observed that dimensional deviations increase after the scanning stage and remain present in the final reproduced models, confirming the cumulative nature of dimensional errors introduced during the workflow.

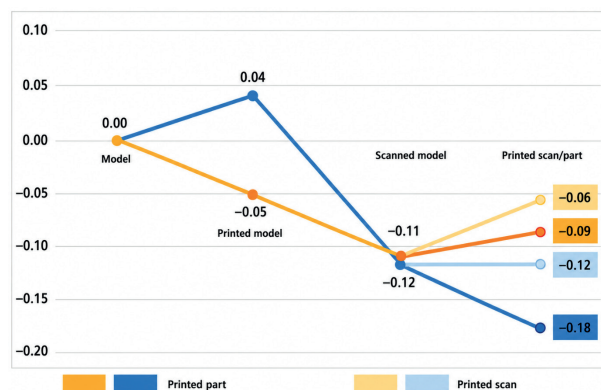


Fig. 11. Progression of dimensional deviations relative to the reference geometry throughout the reverse engineering cycle

The final dimensional deviations depend on whether the reproduced model was manufactured directly from the scanned mesh or from the reconstructed CAD model. With reproduction using the reconstructed CAD model (mesh-to-CAD conversion), the deviations reached approximately -0.18 mm for dimension group 'a' and -0.09 mm for dimension group 'b'. In contrast, when the scanned mesh was reproduced directly without conversion to a CAD model, the deviations were lower, reaching approximately -0.12 mm for dimension group 'a' and -0.06 mm for dimension group 'b'. These results indicate that the mesh-to-CAD conversion step introduces additional geometric deviations, which contribute to the overall dimensional inaccuracy of the reverse engineering cycle.

3.2. Surface quality evaluation of printed models

In addition to the dimensional accuracy evaluated in the previous sections, it is necessary to consider the variability of individual measured values, which reflects the surface irregularities of the printed models. This characteristic can be quantified using the standard deviation of all measured dimensional values for the printed reference models, the printed scan-based models, and the printed reconstructed CAD models. Six repeated measurements were performed

for each characteristic dimension, and the arithmetic mean was used for the dimensional evaluation. The standard deviation was calculated from these repeated measurements to quantify the variability of the measured values and to assess the local surface consistency of the printed specimens.

The standard deviations of the printed reference models, printed scan-based models, and printed reconstructed CAD models are graphically illustrated in the following Figure 12.

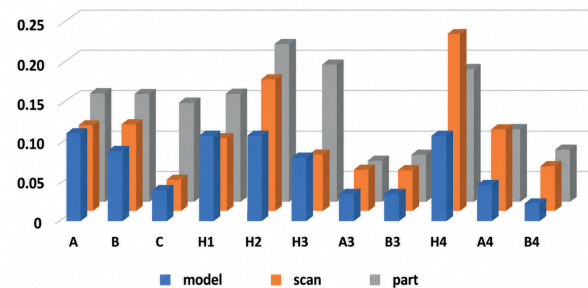


Fig. 12. Standard deviation comparison for three types of manufactured parts

The graphical comparison of the standard deviation values for all three printed models clearly demonstrates a gradual increase in the average standard deviation from the reference model print to the reconstructed CAD model print. This trend is consistent with the irregular surface characteristics of the STL-based scanned model, which are directly transferred to the scan-based print. These surface irregularities also influence the reconstructed CAD print; however, the higher standard deviation observed for the reconstructed model is attributed to additional surface distortions introduced during the conversion process in SolidWorks.

4. DISCUSSION

The authors of this study presented a systematic experimental evaluation of dimensional accuracy within a complete reverse engineering workflow, encompassing CAD design, additive manufacturing, 3D scanning, mesh processing, CAD reconstruction, and final reproduction. The proposed methodology enabled the separate assessment of individual process stages as well as analysis of their cumulative influence on the final dimensional fidelity of the reproduced object.

The results demonstrate that dimensional deviations progressively accumulate throughout the reverse engineering cycle. Each stage of the workflow (manufacturing, scanning, data processing, and reconstruction) introduces its own contribution to the overall inaccuracy. Direct reproduction of scanned mesh data results in lower cumulative deviation compared to reproduction via mesh-to-CAD conversion, indicating that automatic surface reconstruction introduces additional geometric approximation effects.

Surface quality evaluation further confirmed that the geometric consistency decreases with each additional

processing step. The increased variability observed in the reconstructed models highlights the influence of both scanning irregularities and the surface-fitting procedures applied during CAD conversion.

The presented evaluation framework provides a structured and repeatable approach for assessing reverse engineering systems as integrated processes rather than isolated devices. The findings emphasise the importance of considering cumulative error propagation when reverse engineering workflows are applied in dimensionally sensitive applications.

Future research may focus on optimising surface reconstruction strategies and further refining data processing parameters in order to minimise geometric deviations within the complete reverse engineering cycle.

ACKNOWLEDGEMENT

This research was funded by the Scientific Grant Agency of the Ministry of Education, Research, Development and Youth of the Slovak Republic and the Slovak Academy of Sciences (VEGA) grants number: 1/0267/25, 1/0263/26 and APVV-24-0240.

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