sciendo

Management Systems in Production Engineering

2025, Volume 33, Issue 4, pp. 539-545

Date of submission of the article to the Editor: 04/2025
Date of acceptance of the article by the Editor: 10/2025

DOI 10.2478/mspe-2025-0055

THE USE OF REVERSE ENGINEERING FOR THE DEVELOPMENT OF A MODEL USING COMPUTER-AIDED DESIGN

Roksana Poloczek
Silesian University of Technology

Abstract:
The aim of this article was to investigate the potential of reverse engineering for developing digital 3D models based on real, worn mechanical components, particularly in cases where original manufacturer documentation is unavailable. The main research question concerned the effectiveness and accuracy of reproducing the geometry of a physical object using various 3D scanning technologies and CAD design tools. The subject of the study was a hydraulic cylinder ball – a worn, deformed component that could no longer be sourced on the market. Two types of 3D scanners were used in the study: a handheld device and a stationary system. Measurement data obtained from each scanner was processed in the VXelements software and then used to create precise models in the SolidWorks environment. Conventional measurements were also conducted and served as a reference point. Comparative analysis showed a high degree of consistency between the methods, with dimensional differences not exceeding 0.4 mm and 2°. The results confirm that reverse engineering, supported by 3D scanning and CAD design, is an effective solution for the individual reconstruction of technical components. The significance of the findings directly relates to industrial practice – particularly in the context of rapid prototyping, spare part reproduction, and maintenance support. The developed methodology can support the digitization and automation of engineering processes, particularly in the context of documentation management and preparation of manufacturing data. In this study, the geometry of a worn component was reproduced without attempting to reconstruct its original shape. The resulting CAD model reflects the current state of wear.

Key words: CAD, reverse engineering, 3D models, 3D scanning, production systems

INTRODUCTION

In modern engineering and industrial manufacturing, digital 3D models are gaining increasing importance as a foundation for design, analysis, and quality control. These models, created in CAD environments, are used not only in numerical simulations (FEM), but also in CNC machining, 3D printing, and BIM (Building Information Modeling) visualization. However, in many cases – particularly when technical documentation is missing or components are worn – there is a need to reconstruct the physical shapes through reverse engineering. This process, which involves digitizing the geometry of a physical object and developing its digital counterpart, has become a key tool in the reconstruction of technical components and assemblies. The research problem addressed in this article focuses on the effectiveness and accuracy of reverse engineering processes, particularly 3D scanning and CAD modeling, in recreating the complex geometry of a worn mechanical part. The primary objective of this study was to develop a methodology for reproducing the geometry of a worn component using 3D scanning and CAD modeling, as well as to compare the accuracy of geometry reconstruction achieved through different methods. The research hypothesis assumed that the application of reverse engineering based on 3D scanning and modern design software enables the creation of a precise and functional model that can be directly utilized in subsequent design and manufacturing processes. The article presents a comparative analysis of various measurement methods, an assessment of their applicability, and potential uses of the resulting models in engineering practice.

LITERATURE REVIEW

Contemporary engineering and manufacturing industries are undergoing a dynamic digital transformation, in which three-dimensional models created in CAD environments form the foundation for finite element method (FEM) strength analyses, CNC control, and additive technologies such as 3D printing [1, 2, 14, 17]. These models also play a crucial role in quality inspection systems and digital design documentation [3, 6, 7]. Challenges arise in cases where physical objects – especially worn components or those lacking technical documentation – must be reproduced. In such cases, obtaining accurate CAD models requires the application of reverse engineering (RE) techniques, which enable the conversion of 3D scanning data (point clouds) [8] into digital representations of objects [4, 5]. This process includes scanning, data processing, and modeling in environments such as SolidWorks, and its effectiveness depends on both the technology used and the operator's expertise [6].

The applications of reverse engineering are diverse, spanning from the automotive and aerospace sectors to medical [9, 10, 11, 12]. RE plays a particularly important role in quality control, where digital models allow for comparing actual dimensions with reference documentation or designing replacement parts [13]. Studies have shown that Binder Jetting can be effectively used in the additive manufacturing of complex components, including those reconstructed using RE methods [15, 16]. Moreover, digital reconstruction enables the analysis of deformation and wear – especially in the context of maintenance, diagnostics, and repair planning.

In the construction sector, 3D models created in CAD software form the basis of BIM technologies, enabling precise management of object-related information and geometric parameters [10]. Reverse engineering also supports the assessment of the technical condition of historical buildings by enabling their digital documentation and analysis for revitalization purposes [11]. The use of RE and 3D scanning facilitates accurate evaluation of deformations and wear in structural elements, which reduces the risk of erroneous design decisions in the case of heritage structures [12].

The research problem addressed in this article focuses on analyzing the potential and effectiveness of reverse engineering techniques – particularly 3D scanning – in the comprehensive development of accurate CAD models. The following sections present a detailed analysis of the individual stages of the reverse engineering process, starting from the acquisition of raw geometric data using advanced 3D scanning methods, through the processing and optimization of point clouds, to the final development of accurate CAD models ready for further engineering applications.

In light of the latest research on additive technologies – such as binder jetting and digital light processing (DLP) using composite materials – as well as modern quality control systems based on FMEA analysis and continuous improvement strategies in the automotive industry, this study aims to demonstrate how reverse engineering can be effectively applied for the digital reconstruction of real-world components. The integration of these approaches enables high dimensional accuracy, faithful reproduction of functionality, and potential for further optimization, making this method a valuable solution in response to contemporary engineering challenges [18, 19].

RESEARCH METHODOLOGY

The study was conducted to develop a 3D model of a worn mechanical component using reverse engineering and computer-aided design (CAD) tools. The entire process of digitization and modeling was evaluated based on the case of a worn hydraulic cylinder ball. The general research assumptions included the analysis of the possibility of reproducing the geometry of a complex element using modern measurement and design techniques. The goal was to compare different methods of acquiring geometric data, their processing, and the development of a digital model suitable for use in further stages of design and manufacturing.

The research sample consisted of a single worn component – a hydraulic cylinder ball. This part exhibited visible signs of wear, such as surface abrasion, material loss, and deformation. Its selection was deliberate and justified by the necessity of reconstructing a part that could not be sourced on the market.

The methods used included both conventional measurement techniques (e.g., caliper, depth gauge, and protractor) and advanced reverse engineering tools, including 3D scanning and digital data processing. Measurements were performed in parallel using manual methods and two types of 3D scanners – a handheld device (ACADEMIA) and a stationary scanner (SMARTTECH3D ON 5-5 MP). The data obtained in the form of point clouds was further processed using VXelements software to clean, align, and optimize the scanned data, enabling precise mesh generation and surface reconstruction as a preparation step for CAD modeling. Subsequently, the processed mesh was imported into SolidWorks software, where the final parametric 3D model was created using surface and solid modeling techniques. This model served as the basis for dimensional analysis, comparison with nominal geometry, and preparation for potential remanufacturing.

3D scanning using a handheld scanner

The digitization process of the component's geometry began with 3D scanning using the ACADEMIA handheld scanner, which operates based on white LED light technology. The scanner offered a measurement accuracy of up to 0.25 mm. After connecting the device to a computer, calibration was performed using a dedicated reference board. This process involved guiding the scanner appropriately in relation to the calibration plate and verifying its position through color indicators displayed in the VXelements software. To ensure full registration of the hydraulic cylinder ball's geometry, three separate scans were carried out in different orientations: vertically with support on the cylindrical section, vertically with support on the spherical section, and horizontally (Fig. 1). Each scan captured a different portion of the surface, allowing the data to be later merged into a complete point cloud.

Fig. 1 Scanning position – horizontal

Scan data processing

The acquired point clouds were subjected to further processing in the VXelements software. Initially, unnecessary background elements and artifacts (e.g., fragments of the rotary table) were removed from each scan. Then, the scans were merged using the “best fit” function (Fig. 2), which allowed the three independent scans to be combined into a single coherent model. After merging, geometric discontinuities were eliminated and missing surfaces were filled using the “fill holes” function (Fig. 3).

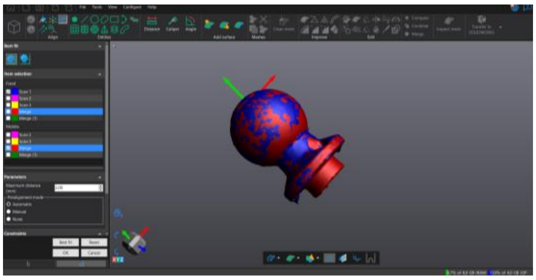

Fig. 2 Automatic scan alignment using the “best fit” function

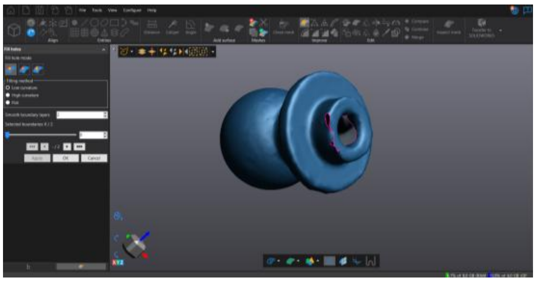

Fig. 3 Filling missing surfaces in the model

The next step involved positioning the object within the Cartesian coordinate system so that the base plane of the model aligned with the XY plane. The model was then subjected to dimensional analysis. Reference planes and auxiliary lines were created in the software, enabling the determination of diameters, radii, lengths, and angles characteristic of individual sections of the element. Measurements were performed using tools such as “Sphere” (Fig. 4), “Angle” (Fig. 5), “Circle” (Fig. 6), and “Caliper” (Fig. 7).

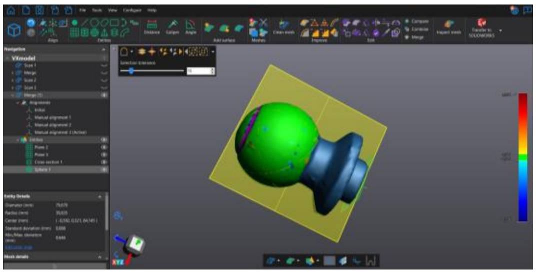

Fig. 4 Measurement of the spherical part radius

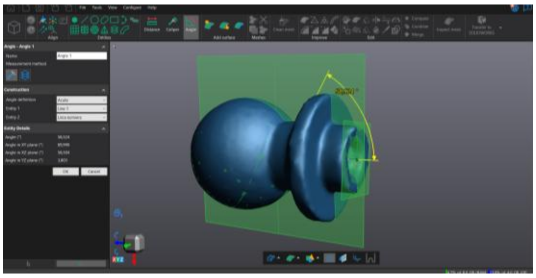

Fig. 5 Measurement of the taper angle of the conical surface

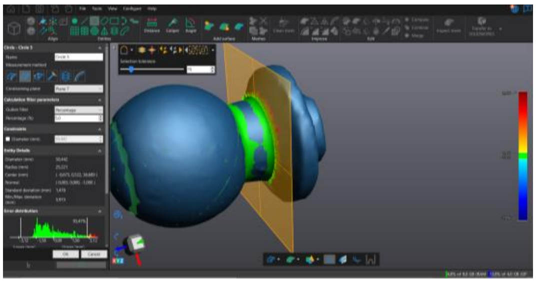

Fig. 6 Measurement of cylindrical element diameters

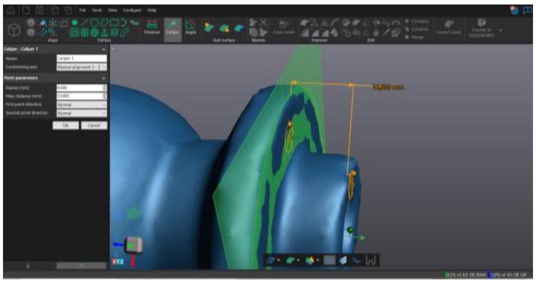

Fig. 7 Measurement of the flange length of the model

CAD Modeling in SolidWorks

After completing operations in the VXelements software, the generated mesh model was imported into the SolidWorks environment for further development. Although two different scanning processes were performed – using both a handheld and a stationary 3D scanner – the comparative evaluation of the data quality led to the selection of the most accurate and complete scan for further processing. As a result, a single CAD model was developed based on the selected scan, and only one complete set of design documentation was prepared.

Initially, the point cloud was converted into a triangular mesh and subsequently transformed into a structure suitable for solid modeling. This enabled the creation of a fully parametric model that accurately reflects the current shape of the worn component, reconstructed from the 3D scanning data.

The modeling process began with recreating an axial cross-section profile on the XZ plane, capturing the key geometric features of the actuator ball. A revolve operation around the Z-axis was then applied to generate a solid body, which served as the foundation for further design work. In subsequent steps, functional features of the part were introduced – lubrication holes, a fitting socket, and threads were modeled based on measurement data and reverse engineering reconstruction. These features were created using standard SolidWorks tools, such as cutouts, drilling, chamfering, and both internal and external threading.
Additionally, smooth geometric transitions between cylindrical and spherical surfaces were incorporated to ensure both technical accuracy and aesthetic integrity of the model. The result was a complete 3D model (Fig. 8) accurately representing the original shape of the component.

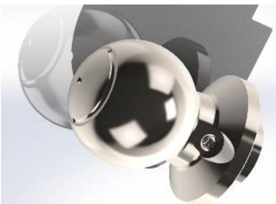

Fig. 8 3D model of the hydraulic cylinder ball

Based on this model, a technical drawing was also developed, including orthographic views, cross-sections, and dimensioning, enabling the fabrication of the part using either conventional or additive manufacturing technologies. The entire process not only allowed for the precise reconstruction of the worn component but also facilitated the preparation of comprehensive design documentation ready for production implementation.

3D scanning using the SMARTTECH3D stationary scanner
In the next stage of the study, the examined component was scanned using a stationary 3D scanner – SMARTTECH3D ON 5-5 MP – operating with white LED light technology. The data obtained from the SMARTTECH3D scanner were also processed using the VXelements software. The device is equipped with a 5-megapixel sensor and offers a very high measurement accuracy of approximately 0.022 mm, making it suitable for applications that require precise detail reproduction.
The sample was placed on an automated rotary table, allowing full access to the object's surface without the need for manual repositioning (Fig. 9).

Fig. 9 Preparation of the object on the rotary table

During the scanning process, sequential images were captured and automatically merged into a unified point cloud. The measurement data were saved in .STP format, enabling direct import into SolidWorks.
The resulting digital model was subjected to the same analysis as the data acquired from the handheld scanner. The same geometric criteria, functional features, and CAD model structure were applied, allowing a direct comparison of the accuracy and quality of reproduction achieved with both devices.

Vrification of measurements using conventional methods and result analysis
Four measurement methods were analyzed: conventional measurement, data analysis using VXelements software, modeling in the SolidWorks environment, and measurements using the stationary 3D scanner SMARTTECH3D ON 5-5 MP.
For comparative purposes, the examined component was measured using conventional tools: a digital caliper (accuracy of 0.01 mm), a depth gauge (accuracy of 0.05 mm), an analog protractor, and a thread gauge. These tools enabled the determination of fundamental geometric parameters, such as lengths, diameters, hole depths, and taper angles of conical surfaces. The same geometric features were measured in the digital models to ensure consistency across methods. Each dimension was measured multiple times and averaged.
The manual measurements served as a reference point for assessing the accuracy of the models obtained through 3D scanning and digital modeling. The range and location of all analyzed dimensions are presented in Fig. 10.

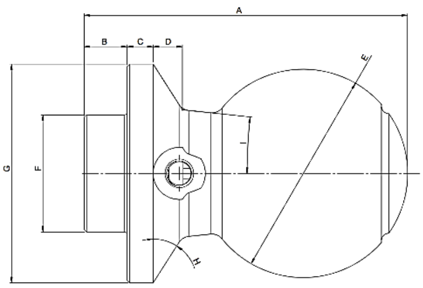

Fig. 10 Dimensions and annotations

In the final stage, the developed 3D model was verified by comparing its geometric dimensions with measurements obtained through conventional methods (caliper, protractor, depth gauge) as well as with data derived from point cloud analysis. Selected critical features of the component – such as diameters, angles, socket depths, and the positioning of holes – were measured and evaluated.
This comparison enabled the assessment of dimensional consistency between the CAD model and the physical part, as well as the accuracy of the reconstructed geometry depending on the data acquisition method. The analysis showed that the model generated based on 3D scanning exhibited high dimensional agreement with manually acquired values, with deviations falling within acceptable measurement tolerances. The results

confirmed the suitability of reverse engineering and digital reconstruction techniques for accurately reproducing the geometry of worn technical components.

RESEARCH RESULTS

As a result of the conducted research, a complete digital reconstruction of the worn hydraulic actuator ball was achieved using reverse engineering methods and computer-aided design (CAD) tools. A comparison of measurement results obtained using four methods – conventional measurement, point cloud analysis in VXelements, modeling in the SolidWorks environment, and measurements based on data from the SMARTTECH3D stationary scanner – is presented in Table 1.

Table 1
Summary of dimensions

Dimension	A [mm]	B [mm]	C [mm]	D [mm]	E [mm]	F [mm]	G [mm]	H [°]	I [°]
Manual measurement	123,80	16,90	10,50	10,50	79,60	44,80	83,90	30,00	4,00
VXelements	123,82	16,90	10,50	10,40	79,67	44,80	83,98	31,50	3,65
SolidWorks	124,00	16,50	10,00	11,20	80,00	45,00	84,00	32,50	6,00
SMARTTECH3D	123,73	16,50	10,00	10,00	79,50	44,50	84,00	31,00	4,00

The analysis revealed that the differences between the individual measurement methods did not exceed 0.4 mm for linear dimensions and 2° for angular measurements. The largest deviations were observed in the total length and the radius of the spherical surfaces, which may be attributed to operational wear of the original component. The digital models showed high consistency with the reference measurements, confirming the effectiveness of reverse engineering methods in reproducing the geometry of complex and worn elements.

In conclusion, the study confirms the high applicability of 3D scanning in the reconstruction of worn components, as well as the effectiveness of CAD tools in developing models for subsequent design and manufacturing stages.

DISCUSSION

The results of the conducted research confirm the effectiveness of using reverse engineering – particularly 3D scanning technologies and CAD software – as a method for accurately reproducing the geometry of worn or unavailable structural components. The digital reconstruction of a hydraulic cylinder ball, performed using both the handheld ACADEMIA scanner and the stationary SMARTTECH3D ON 5-5 MP device, resulted in highly detailed models that were subsequently used in the SolidWorks environment to develop a fully functional 3D model.

The data analysis showed that dimensional discrepancies between the different scanning and modeling technologies did not exceed 0.4 mm for linear measurements and 2° for angular values. These minor deviations demonstrate the high precision of both handheld and stationary scanning methods and are consistent with findings from recent publications focused on accurate geometric reconstruction of mechanical components and quality control in production processes.

A key aspect of the study was the comparison between two types of scanners – handheld and stationary – which differed not only in design and resolution, but also in operational context. The stationary scanner, used under laboratory conditions, produced higher-accuracy data with reduced noise; however, its use is associated with greater hardware requirements and limited mobility. In contrast, the handheld scanner, despite its lower resolution, proved to be more flexible in terms of positioning and access to hard-to-reach surfaces, making it a valuable tool in industrial or field conditions. This distinction aligns with other studies that highlight the complementary nature of different scanning technologies depending on operational and environmental requirements.

Another important aspect was the processing of measurement data in the VXelements software, which involved various steps such as cleaning, merging, and interpolating missing data. Although largely automated, this process required operator intervention and engineering expertise, reinforcing the significance of user experience in the effectiveness of the reverse engineering process.

The CAD model developed in SolidWorks allowed not only for the accurate reconstruction of the component's shape but also the addition of functional features, such as lubrication channels, threads, and undercuts. As a result, the obtained model can be directly used in manufacturing processes – including CNC machining and additive manufacturing technologies.

The final CAD model confirms the usefulness of 3D scanning as a basis for designing replacement parts. It was developed based on processed scan data obtained using 3D scanning methods (both handheld and stationary), from which the most complete and dimensionally accurate point cloud was selected. This point cloud was converted into a mesh in VXelements software, cleaned, aligned, and then imported into SolidWorks, where a fully parametric 3D model was created using surface and solid modeling techniques.

The modeling process was guided by the geometry extracted from the scan but also adjusted where appropriate to restore original nominal features affected by wear or deformation. Key functional dimensions were verified and supplemented with information from manual measurements and engineering interpretation to ensure the model's usability for future manufacturing.

It is also worth noting the issue of wear and deformation of the analyzed component. The hydraulic cylinder ball exhibited material loss and visible shape distortion, which influenced the accuracy of certain measurements. At the same time, this fact emphasizes the importance of reverse engineering in cases where technical documentation is unavailable and access to the original, unworn component is not possible.

CONCLUSIONS

The conducted research clearly confirms that reverse engineering – when supported by modern 3D scanning technologies and CAD modeling environments—is an effective and reliable method for the digital reconstruction of worn or undocumented mechanical components. The methodology developed in this study allowed for the precise reproduction of a hydraulic cylinder ball using both handheld and stationary 3D scanning systems, with subsequent processing and modeling in professional software tools.

By employing two different types of scanners – ACADEMIA (handheld) and SMARTTECH3D ON 5-5 MP (stationary) – the study enabled a comparative evaluation of data quality and scanning performance under varied conditions. The stationary scanner, operating in a controlled laboratory setting, offered higher resolution and accuracy, while the handheld scanner provided greater flexibility and accessibility in scanning complex geometries. Both devices successfully captured sufficient geometric data for developing a complete 3D model.

The acquired point clouds, processed in the VXelements software, enabled the generation of clean and accurate mesh models. These were used as a foundation for further development in the SolidWorks environment, where a fully parametric CAD model was created. This model included all functional features of the component – such as holes, sockets, threads, and surface transitions – and was adjusted where necessary to account for material loss and deformation. Manual measurements were used to verify and supplement the reconstructed geometry, ensuring dimensional reliability.

A comparative analysis of four measurement methods – manual tools, VXelements, SolidWorks modeling, and SMARTTECH3D scanning – revealed high consistency, with maximum deviations not exceeding 0.4 mm for linear dimensions and 2° for angular values. The largest discrepancies were observed in the most deformed or worn areas of the component, confirming the importance of engineering interpretation and surface assessment in reverse engineering workflows.

The final CAD model not only reflects the current worn state of the component but also serves as a basis for potential redesign and manufacturing – whether through CNC machining or additive manufacturing technologies. The integrated use of scanning, processing, and modeling proved to be highly effective for documentation, diagnostics, and production planning.

In conclusion, reverse engineering – understood as a synergistic process involving 3D scanning, digital data processing, and CAD modeling – offers a flexible, precise, and scalable approach to the reconstruction of complex mechanical components. It addresses critical challenges in situations where original documentation is missing, and it enables the development of accurate replacement parts ready for modern manufacturing applications.

REFERENCES

[1] Pawłowicz, J.A., Knyziak, P., Krentowski, J.R., Mackiewicz, M., Skotnicka-Siepsiak, A. & Serrat, C. (2024). Reverse engineering as a non-invasive examining method of the water tower brick structure condition. *Engineering Failure Analysis*, 161, 108280. https://doi.org/10.1016/j.engfailanal.2024.108280

[2] Regassa Hunde, B., Debebe Woldeyohannes, A. (2022). Future prospects of computer-aided design (CAD) – A review from the perspective of artificial intelligence (AI), extended reality, and 3D printing', *Results in Engineering*, 14, 100478. https://doi.org/10.1016/j.rineng.2022.100478

[3] Bacciaglia, A., Ceruti, A., Liverani, A. (2020). Photogrammetry and additive manufacturing based methodology for decentralized spare part production in automotive industry, *Advances in Intelligent Systems and Computing*. https://doi.org/10.1007/978-3-030-39512-4_121

[4] Bernaczek, J., Budzik, G., Dziubek, T., Przeszłowski, Ł., Wójciak, K. (2023). Dimensional-shape verification of a selected part of machines manufactured by additive techniques, Advances in *Science and Technology Research Journal*, 17(1). https://doi.org/10.12913/22998624/157289

[5] Jović, G., Ćirić, D., Pešić, F., Ivanović, M., Mijajlović, M. (2023). Deviation of the 3D solid model from the printed model', in: 2023 *22nd International Symposium INFOTEH-JAHORINA* (INFOTEH 2023). https://doi.org/10.1109/INFOTEH57020.2023.10094160

[6] Klimecka-Tatar, D. and Krynke, M. (2025). Reverse engineering tools – 3D scanning – as support for precise quality control in automated special processes', *Procedia Computer Science*, 253, pp. 1933–1942. https://doi.org/10.1016/j.procs.2025.01.255

[7] Montalti, A., Ferretti, P., Santi, G.M. (2024). A cost-effective approach for quality control in PLA-based material extrusion 3D printing using 3D scanning, *Journal of Industrial Information Integration*, 41, 100660. https://doi.org/10.1016/j.jii.2024.100660

[8] Helle, R.H., Lemu, H.G. (2021). A case study on use of 3D scanning for reverse engineering and quality control, Materials Today: Proceedings, 45, pp. 5255–5262. https://doi.org/10.1016/j.matpr.2021.01.828

[9] Wakjira, Y., Kurukkal, N.S., & Lemu, H.G. (2024). Reverse engineering in medical application: Literature review, proof of concept and future perspectives. *Scientific*

Reports, 14, Article 23621. https://doi.org/10.1038/s41598-024-74176-z

[10] Subeshan, B., Abdulaziz, A., Khan, Z., & Uddin, M.N. (2022). Reverse engineering of aerospace components utilizing additive manufacturing technology. In TMS 2022 151st Annual Meeting & Exhibition Supplemental Proceedings (pp. 238–246). Springer. https://doi.org/10.1007/978-3-030-92381-5_21

[11] Dalpadulo, E., Petruccioli, A., Gherardini, F., & Leali, F. (2022). A review of automotive spare-part reconstruction based on additive manufacturing. *Journal of Manufacturing and Materials Processing*, 6(6), 133 https://doi.org/10.3390/jmmp6060133

[12] Fabian, M., Huňady, R., & Kupec, F. (2022). Reverse engineering and rapid prototyping in the process of developing prototypes of automotive parts. *Manufacturing Technology*, 22(2). https://doi.org/10.21062/mft.2022.084

[13] Helle, R.H., & Lemu, H.G. (2021). A case study on use of 3D scanning for reverse engineering and quality control. Materials Today: Proceedings, 45(6), pp. 5255-5262. https://doi.org/10.1016/j.matpr.2021.01.828

[14] Zhao, K., Su, Z., Ye, Z., Cao, W., Pang, J., Wang, X., Wang, Z., Xu, X. and Zhu, J. (2023). Review of the types, formation mechanisms, effects, and elimination methods of binder jetting 3D-printing defects. *Journal of Materials Research and Technology*, 27, pp. 5449-5469. https://doi.org/10.1016/j.jmrt.2023.11.045

[15] Deng, H., Huang, Y., Wu, S., & Yang, Y. (2022). Binder Jetting Additive Manufacturing: Three-Dimensional Simulation of Micro-Meter Droplet Impact and Penetration into Powder Bed. Journal of Manufacturing Processes, 74, pp. 365-373. https://doi.org/10.1016/j.jmapro.2021.12.019

[16] Wheat, E., Simch, A., et al. (2023). A Review on Metal Binder Jetting 3D Printing: Process, Materials, and Methods [ICMPC 2023]. *E3S Web of Conferences*, 430, 01146. https://doi.org/10.1051/e3sconf/202343001146

[17] Wajdi, F., Tontowi, A.E. (2024). 3D printed stent from graphene-polyethylene glycol diacrylate using digital light processing technique, *Management Systems in Production Engineering*, 32(4), pp. 555-562. https://doi.org/10.2478/mspe-2024-0053

[18] Zeiser, A., van Stein, B., & Bäck, T. (2022). Deep learning based pipeline for anomaly detection and quality enhancement in industrial binder jetting processes. https://doi.org/10.48550/arXiv.2209.10178

[19] Saimon, A.I., Yangue, E., Yue, X., Kong, Z.J., & Liu, C. (2024). Advancing additive manufacturing through deep learning: A comprehensive review of current progress and future challenges. arXiv. https://doi.org/10.48550/arXiv.2403.00669

Roksana Poloczek
ORCID ID: 0000-0002-4842-7949
Silesian University of Technology
Faculty of Materials Engineering
ul. Krasińskiego 8, 40-019 Katowice, Poland
e-mail: roksana.poloczek@polsl.pl