Original Article

Reverse Engineering and Dimensional Deviation Analysis of an Automotive Thermostat Housing using Structured Light 3D Scanning

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Abstract - Reverse Engineering (RE) is widely used in the industry when the original design data is unavailable to fabricate existing parts. This work presents the RE and dimensional deviation analysis of the cast thermostat housing of a Tata Zest car using the aid of the Structured Light (SL) 3D scanning. This is to come up with a digital model of the housing and analyze its geometric conformity with the CAD reference data through systematic deviation analysis. A high-resolution SL optical scanner was employed in the process of training the complicated outer shape and present inner features at a sub-millimetric accuracy. The data, in the form of point clouds, were subsequently processed in Geomagic Control X using best-fit alignment and Iterative Closest Point (ICP) registration options to match the scan with the CAD model. The dimensional deviations were quantified using statistical values and graphical tools such as 3D colour maps and 2D sectional comparisons. They determined that around 74.5 percent of the points of the scanned surface fall within a band of ±2.5 mm in the tolerance, and the overall Root Mean Square (RMS) error between the scan and CAD geometry is 0.4085 mm, a good overall fit. The increased outliers were largely confined to the fillets and the interior cavities, whereby the reflective surfaces and scanner inspectability placed a restriction upon the quality of the data. The results emphasize the accuracy of SL scanning when it comes to obtaining detailed geometries and validate its possibility of application in component inspection, design validation, and the development of digital twins in the car industry. This work substantiates the use of 3D scanning-based RE as a powerful metrology tool in precision manufacturing, quality assurance, and the management of the lifecycle of complex engine parts.

Keywords - Reverse Engineering, 3D Scanning, Thermostat housing, Dimensional accuracy, CAD deviation, Geomagic Control X.

1. Introduction

Reverse Engineering (RE) has become an integral part of numerous engineering processes and offers a viable path to rediscover the geometric, material, and functional data directly on physical components and transform them into useful computer-based representations [1]. It is specifically relevant in cases where the original drawings or the CAD files are lost or incomplete. Such cases are very common when it comes to the modernization of old machinery and in the aftermarket automotive industry. With the growth of digital manufacturing processes, the precision of re-creation of complex part geometries is becoming more and more important to the preservation of dimensional control, aiding quality assurance, and facilitating seamless integration with modern CAD / CAM space [2, 3]. In the automotive industry,

RE is the basis of redesigning, testing, and validation of vehicle parts, including manifolds, housings, brackets, and cooling system parts [4]. Particularly sensitive in that respect are thermostat housings, which control the flow of coolant between the radiator and engine block, and geometrical errors can be the cause of leakage, worse heat transfer, and engine performance and fuel consumption [5]. Strict dimensional checking of these housings is thus necessary to ensure proper working and compliance with manufacturing tolerances.

Conventional dimensional inspection tools, such as Coordinate Measuring Machines (CMMs), are very precise but limited to their non-contact mode of operation, comparatively slow measurements, and access to internal or recessed features [6]. These disadvantages inspired the

creation of non-contact optical metrology methods, such as laser triangulation metrology and SL 3D scanning, that can capture dense high-resolution data on complex freeform surfaces in significantly less time [7, 8]. A series of light patterns is demonstrated over the part surface in SL systems, and the distortions of the patterns that are perceived by one or more cameras are used to recover a 3D point cloud with an assurance of sub-millimetre resolution [9].

The recent advancements in optical scanning allow the acquisition of millions of points of measurements per second, with a stronger ability to overcome noise and other surface reflectivity-based problems [10]. These systems can be used to perform high-precision deviation studies of nominal CAD models, producing intuitive colour maps and detailed statistical summaries when combined with dedicated inspection software, e.g., Geomagic Control X, PolyWorks, or the CATIA Digitised Shape Editor [11]. The adoption of robust registration algorithms like Iterative Closest Point (ICP) and best-fit alignment has further improved alignment accuracy, positioning optical scanning as a strong alternative or a replacement to conventional inspection methods in the automotive and aerospace sectors [12, 13].

Several research works have demonstrated the benefits of 3D scanning in automotive component analysis. Ruiz et al. [14] compared SL and laser scanners for part inspection, finding that SL provided superior resolution for curved geometries with lower reflectivity artifacts. Similarly, Komara et al. [15] evaluated scanning-based RE workflows for industrial castings, reporting RMS deviations below 0.5 mm for large freeform components.

Lagudi et al. proposed a metric-based methodology to evaluate dimensional accuracy and point-cloud quality of structured-light scanners specifically for automotive inspection, demonstrating that carefully designed artifacts and statistical indicators are essential to qualify SLS systems for production-grade dimensional control [16].

Kamali et al. reviewed advances in 3D digital model generation for industrial digital twins and showed how SL and laser scans are increasingly fused with CAD/BIM to support geometry-rich twins, while also flagging gaps in AI-assisted feature extraction and uncertainty treatment for design-critical assets [17]. Jiang et al. introduced HSPC-Net, a hierarchical deep-learning framework that completes sparse or occluded point clouds of machine parts, illustrating how learning-based completion can repair scan data before downstream CAD or FEA and thus improve digital model fidelity for complex geometries [18].

However, challenges remain in maintaining geometric fidelity, especially when dealing with reflective or occluded surfaces. Surface curvature, scanner positioning, and environmental lighting conditions can all introduce measurement uncertainty [10]. It is therefore required to optimise the scanning and the data alignment workflow to have a high-fidelity reconstruction. In this respect, ISO 10360-8 can provide information about the assessment of the scanner accuracy and traceability to ensure that the international metrology standards are observed.

Although the process of RE parts of a legacy or damaged component has been extensively documented, much of the research ends with CAD rebuilding and offers little tolerance-dependent test of whether the resultant geometry is precise enough to be remanufactured and functionally replaceable. In components like thermostat housings, small variations in sealing, bolt, and mating interfaces can have a direct influence on fit and service performance, demanding a metrology-guided RE strategy.

In this regard, the novelty of the present work lies in dealing with the issues of rebuilding a worn-out thermostat housing and objectively determining dimensional fidelity by assessing a systematically aligned and deviated dimensional fidelity at functionally sensitive zones, thus allowing an engineering judgment of replication appropriateness.

An investigation on the RE of a thermostat housing of a Tata Zest car with the help of SL 3D scan, digital alignment, and deviation analysis is carried out. The general workflow involves experimental scanning, processing of point clouds, and comparison with a reference CAD model to assess geometric conformity.

The analysis will combine modern optical scanning with the CAD-based measurement instruments to accelerate dimensional checks, minimize the errors that depend on the operator, and retrieve useful geometric information to check the design and guarantee the quality of production. In this respect, the targeted goals of the work are:

- To scan a thermostat housing with a high-resolution SL scanner and get a 3D representation of its geometry in detail.
- To match the scanned data with the reference CAD model by best-fit and ICP-based alignment processes.
- To measure and represent dimensional deviations with global 3D colour mappings and 2D sectional appraisals.
- To determine dimensional conformity and investigate the effectiveness of SL-based scanning for reverse engineering an automotive component.

The current research is an addition to the area of digital metrology because it demonstrates that SL scanning has the potential to produce rapid, precise, and repeatable RE results, thus making it possible to move to full digitized manufacturing processes. Figure 1 presents the flowchart of the work.
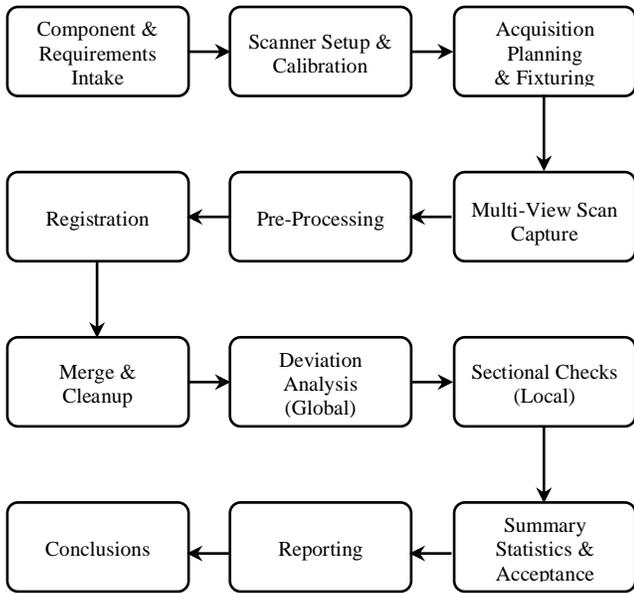
Fig. 1 Flowchart of the work

2. Materials and Methods

2.1. Component

The part under consideration is a thermostat casing that controls the amount of coolant passing between the radiator and the engine block in the four-cylinder internal combustion engine of the Tata Zest four-wheeler. Though small in size, the housing is of a complex geometry that comprises a number of inlet and outlet ports, internal flow passages, mounting flanges, as well as sealing grooves, which require stringent dimensional control in order to provide accurate assembly and dependable thermal performance. The component is presented in Figure 2. The material of the component is an aluminium alloy cast with surface machining at critical interfaces. The nominal dimensions of the housing are approximately 120 mm × 90 mm × 85 mm. The internal features include a cylindrical thermostat seat, flow passages, and a connection flange for the coolant pipe. The geometry presents several challenges for scanning, such as curved surfaces, varying reflectivity, and deep recesses.

Fig. 2 Thermostat housing undertaken for RE and DD analysis in different views

2.2. Scanning Setup and Equipment

An SL 3D scanner from 3D Systems, Inc. was used for data acquisition. The system projects a series of white and blue light fringe patterns onto the surface, while high-resolution stereo cameras capture the deformed images. Using phase-shift and triangulation algorithms, a dense point cloud representing the part surface is generated. The specifications of the scanner are presented in Table 1.

Table 1. Technical specifications of the SL 3D scanner

Parameter	Specification
Scanner Type	Structured Light (Blue LED Projection)
Accuracy	±0.02 mm
Resolution	0.01 mm
Measurement Range	200 × 200 × 150 mm
Field of View	200 mm
Output Format	STL, OBJ, PLY
Software Used	Geomagic Control X (2025 Edition)

Before scanning, the component was cleaned with isopropyl alcohol to remove dust and oil residues. A thin matte spray coating was applied to reduce glare and surface reflectivity. The housing was mounted on a motorized rotary platform to facilitate complete 360° coverage. Scans were performed from multiple orientations to ensure full data capture, particularly around internal cavities and port intersections. The scanning process is depicted in Figure 3.

Fig. 3 SL scanner, rotary table, and the mounted component

Environmental parameters were maintained at 22 ± 1 °C temperature and 50 ± 5% relative humidity to minimize thermal and optical distortion. Each scan produced approximately 2.5-3 million data points, with a total of 12 scans merged to form the complete digital model.

2.3. Data Processing and Alignment

The raw point clouds acquired from multiple scanning positions were imported into Geomagic Control X for preprocessing. Outlier points and background noise were filtered using a radius-based cleanup algorithm. The individual scan clusters were aligned using a two-stage process. Firstly, the initial alignment was performed manually

by defining three reference planes corresponding to the parts' primary, secondary, and tertiary datums (mounting base, vertical flange, and coolant outlet face). Then, it was refined to be the best-fit alignment using the ICP algorithm, which minimizes the RMS deviation between corresponding surface points of the scanned and reference CAD models. The representations of the initial and best fit alignment are presented in Figures 4(a) and 4(b), respectively. Figure 4(a) represents the initial alignment where multi-view scans are brought into a common pose using a datum-guided pre-alignment: three orthogonal reference planes are established on the mounting base, vertical flange, and outlet face to define primary-secondary-tertiary constraints. This step suppresses gross rigid-body offsets and ensures that subsequent optimization proceeds from a physically meaningful initialization, particularly around the high-curvature bosses and fillet transitions that are prone to mis-registration when starting from arbitrary poses. Figure 4(b) depicts the refined best-fit solution obtained via an Iterative Closest Point (ICP) routine that minimizes point-to-surface distances between the merged STL and the nominal CAD. The refinement uses robust correspondence filtering (distance and normal-angle gates) and feature-aware weighting on planar, cylindrical, and flange regions so that locally noisy or partially occluded patches do not dominate the objective. The result is a stable, globally consistent registration that preserves feature geometry and sets the foundation for traceable 3D/2D deviation mapping reported in the next subsection.
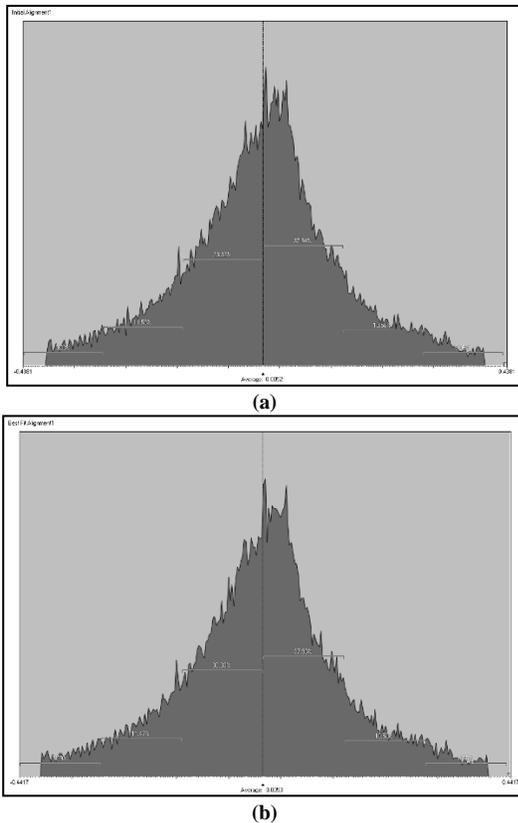

(a)

(b)
Fig. 4 Alignment, (a) Initial, and (b) Best-fit.

2.4. Deviation Analysis

After the alignment step, the merged STL model was smoothed to eliminate the residual artefacts without losing the underlying geometry. Geomagic Control X computed pointwise deviations and gave both numerical and graphic results, such as: (i) minimum, maximum, and mean deviations, (ii) Root Mean Square (RMS) deviation, (iii) standard deviation, and (iv) the distribution of tolerances, as the percentage of points within or outside the given limits. The tolerance levels were determined as ±0.3 mm (critical areas such as mounting holes, sealing flanges) and ±2.5 mm (non-critical areas such as outer walls and curved areas). The final deviation data were used for quantitative comparison and visual inspection. Figure 5 summarizes the end-to-end RE pipeline adopted in this work. The workflow is designed to be reproducible and standardized, coupling metrological discipline with efficient data handling so that downstream results are directly comparable across runs and parts.
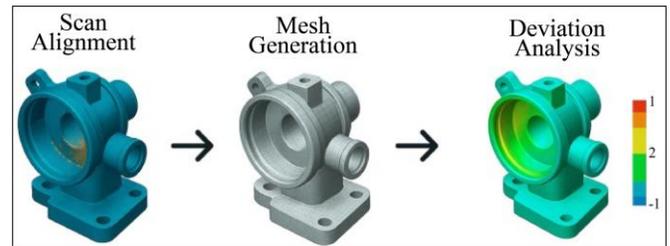

Fig. 5 Workflow of RE process using SL 3D scanning and Geomagic Control X

2.5. Calibration of the SL System

Prior to acquisition, the SL system underwent a daily calibration using a certified length artifact (100-150 mm span). The observed mean length error was ≤ 0.02 mm, which was acceptable. A verification scan of a sphere-plate confirmed a residual form error ≤ 0.03 mm. Data collection proceeded only after these confirmations.

3. Results and Discussion

The deviation analysis of the reverse-engineered thermostat housing was performed using the aligned 3D scan data and the reference CAD model in Geomagic Control X. Quantitative and visual assessments were used to evaluate the dimensional fidelity of the reconstructed geometry. The assessed results include 3D colour deviation maps, sectional deviation plots and related statistical summaries. The combination of both of these results not only proves the accuracy of the measurements of the SL scanning method, but also gives valuable information about the geometric characteristics and production errors of the thermostat casing.

3.1. The 3D Surface Comparison

A detailed 3D comparison between the scanned model and the reference CAD geometry was carried out to assess pointwise deviations. The spatial distribution of these deviations is illustrated in the colour-coded map in Figure 6.

Regions shown in green correspond to surfaces that lie within the specified tolerance band, whereas blue and red areas indicate negative and positive deviations, respectively.

Table 2 lists the deviation values for both the initial and best-fit alignments, giving a direct indication of how effectively the ICP procedure reduced residual pose errors.

Table 3 takes this further by summarising the deviation statistics for the full 3D comparison and for the two critical 2D sections, along with the percentage of points lying within the tolerance band. Together, these tables provide a concise overview of how closely the RE housing matches the nominal CAD model under different evaluation modes.
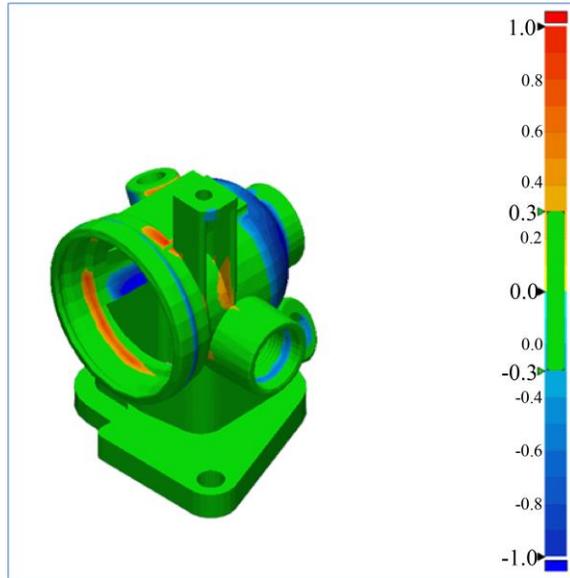

Fig. 6 The 3D colour deviation map showing tolerance zones (green: within tolerance, blue: undersized, red: oversized regions)

Table 2. Summary of alignment deviations

Parameter	Minimum (mm)	Maximum (mm)	Average (mm)	RMS (mm)	Std. Dev. (mm)
Initial alignment	-0.3947	0.3945	-0.0052	0.1444	0.1443
Best-Fit alignment	-0.3989	0.3987	-0.0053	0.1455	0.1454

Table 3. Summary of the overall deviations

Parameter	Minimum (mm)	Maximum (mm)	Average (mm)	RMS (mm)	Std. Dev. (mm)	In-Tolerance (%)
3D Comparison	-2.5224	2.5226	-0.0005	0.4085	0.4085	74.54
2D Section 1	-1.2118	1.2665	-0.0795	0.4347	0.4273	66.34
2D Section 2	-2.1933	2.1988	-0.0689	0.4240	0.4184	81.42

The alignment with the best fit had an RMS deviation of 0.1455 mm, which implies the high quality of the scanner and the efficiency of the ICP algorithm in minimizing alignment errors.

The general RMS difference between the scanned and CAD models of 0.4085 mm is within the normal tolerances of industrial cast aluminium parts, typically ranging between ±0.5 mm and ±1.0 mm.

Around 74.5% of the surface points lay within the specified tolerance band of ±2.5 mm, confirming that the reverse-engineered model represents the physical geometry of the housing with good fidelity.

The largest deviations were mainly found near fillet junctions, bolt bosses, and internal flow passages, which are regions prone to optical shadowing and limited line-of-sight, leading to a slight underestimation of material in the scan data. In contrast, locally oversized regions (positive deviations) appeared at some surface intersections, likely reflecting the influence of interpolation and mesh smoothing applied during post-processing.
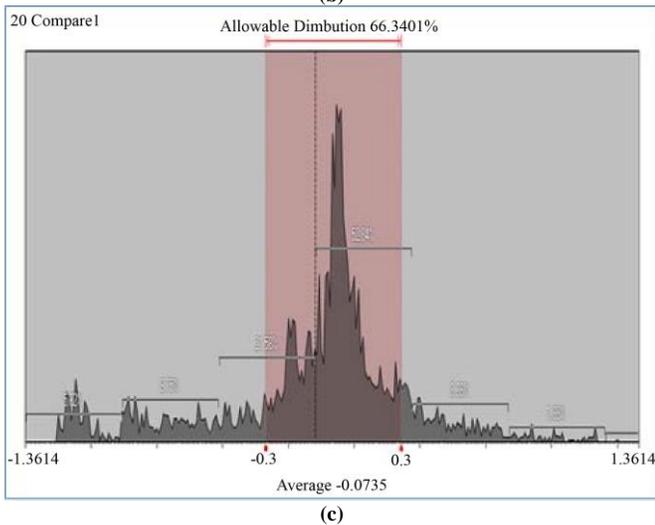
3.2. Sectional Deviation Analysis

To further examine geometric conformity, 2D sectional analyses were performed along selected reference planes. Two sections were taken perpendicular to the principal axes of the housing, and a representative section is illustrated in Figure 7.
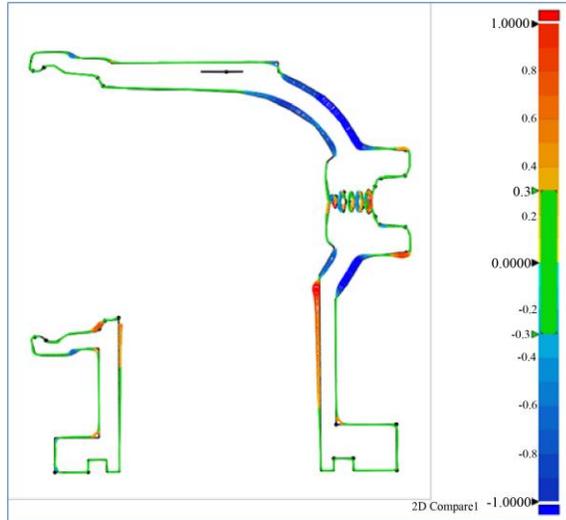
(a)
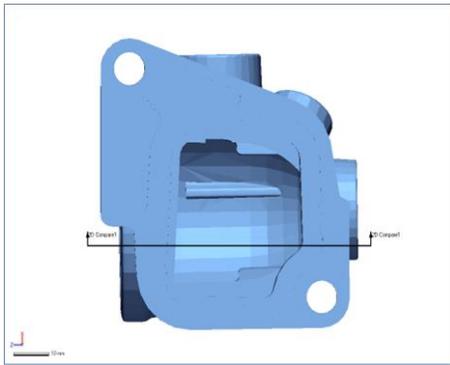
(b)

(c)

Fig. 7 Sectional deviation analysis, (a) 2D sectional deviation map, (b) Cross-sectional contour overlay, and (c) Deviation profile.

The sectional deviation profiles showed that between 66.3% and 81.4% of the measured points lay within the specified tolerance band. Cross-sections taken through the flange and outlet regions showed slight asymmetry related to local casting shrinkage and potentially local distortion that

occurred as a result of some of the post-machining processes. Deviations across the nominally planar surfaces in the flange and outlet regions were confined to about ±0.4 mm overall, which is consistent with conventional tolerances for machined aluminium parts.

Larger deviations, as much as ±2.5 mm, were mostly seen in the concave cavities and geometric transitions, which was to be expected based on trends observed during similar optical scanning studies. In general, the 2D sectional analysis supports the accuracy of the reconstructed geometry and the theoretical accuracy of SL scanning for capturing not only the global form but also finer local detail. The overall results further validate the scanner for non-contact inspection of automotive components with complex geometries.

3.3. Industrial Implications

SL 3D scanning, together with ICP-based alignment functionality in Geomagic Control X software, arises from this study as a coping strategy for metrology purposes for both RE and quality in automotive applications. The method enables the capture of millions of points in seconds and presents full-field deviation maps, drastically reducing inspection time compared with contact CMMs. More importantly, it is capable of measuring complex freeform and partially occluded regions that are impossible to probe mechanically. This is an important consideration for cast and machined housings and related engine hardware. The digital model developed in this study also provides immediate usefulness across the product lifecycle by incorporating efficiencies into updating designs, better informed decisions on tolerancing, and tighter feedback loops between manufacturing and CAE workflows. Possible operational applications of SL 3D scanning in the areas of automotive development and production include:

- Mold and tooling design: The accurate digital model can be used to modify or recreate dies and tooling, helping to improve batch-to-batch geometric consistency.
- Design verification: Physical prototypes can be checked directly against the nominal CAD during design reviews, and this helps in speeding up decisions and cutting down rework.
- Failure analysis: Repeated scans of in-service components make it possible to pinpoint local wear, distortion, or deformation, supporting root-cause investigations and targeted corrective measures.
- Digital twin creation: The RE model offers a high-fidelity geometric foundation for subsequent CFD and FEA. It establishes a geometrically reliable basis for downstream CFD and FEA, allowing for connections between geometric deviations and flow, thermal, or structural responses, which can lead to improved prioritization of tolerances.

The method shown in the present work is in accordance with Industry 4.0 objectives, since it improves the digital traceability of assets, allows a predictive maintenance route

via periodic re-scanning, and integrates well with the existing CAE tools. In practical terms, it helps to close the gap between the physical part and its digital representation on the shop floor: full-field colour maps and associated statistics become part of routine quality assurance, while the same datasets can be reused to inform simulation-based design and process planning. Taken together, these capabilities shorten the time needed to interpret inspection results, ease dependence on CMM-only inspection routes, and offer a scalable approach that can be extended to families of cast components in automotive production.

4. Conclusion

The present study developed an end-to-end RE and dimensional deviation workflow for an automotive thermostat housing using structured light 3D scanning and ICP-based alignment in Geomagic Control X. The procedure spans from multi-view data acquisition, datum-based registration, best-fit alignment, and 3D/2D deviation mapping, enabling rapid, non-contact inspection and generation of digital twins suitable for cast and machined components. The main conclusions drawn from this work are as follows:

- The scan-to-CAD comparison showed RMS deviation of approximately 0.4085 mm, which is acceptable for typical thermostat housing tolerance requirements.
- ICP-based best-fit alignment resulted in a residual error of about 0.145 mm, and this indicates a stable and reliable conformity between the different scan views.
- Around 74.5% of the surface points lay within the ±2.5 mm tolerance band, with out-of-tolerance regions occurring in localized zones rather than across the entire component.
- Planar and easily accessible surfaces generally met tighter tolerance limits of about ±0.4 mm, whereas larger deviations were concentrated around fillets, bolt bosses,

and occluded cavities, where optical shadowing and high curvature complicate accurate measurement.
- Compared with contact metrology, the workflow reduced inspection time and expanded surface coverage, with colour-map statistics improving interpretability for engineering decisions.

The work operationalizes a practical, repeatable SL-based inspection route that shortens time-to-insight for complex cast parts, delivers a usable digital twin for fit/assembly and CAE, and provides a transparent, section-wise conformity rubric that can be adopted on shop floors. By connecting deviation statistics to feature classes (planar faces, fillets, bosses), it helps prioritize tolerance control where it matters, supports tooling validation and change-impact analysis, and offers a template that SMEs can replicate without bespoke software development.

Future work will fuse structured light with photogrammetry or line-laser to curb occlusions and glare; deploy AI-assisted meshing with automatic GD&T out-of-tolerance flags to accelerate reporting; propagate measurement uncertainty through alignment and deviation maps to publish confidence bounds; and couple the digital twin with CFD/FEA so that tolerance limits are set by their impact on flow and stiffness, ultimately progressing toward robotized, in-line quality checks using template-based alignments on the shop floor.

Acknowledgements

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