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Review

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Reverse Engineering and Shape Acquisition Technologies: A Comprehensive Review

André F. V. Pedroso [1,2,*], Ricardo Marques [1], Biao Zhao [3], Ning Qian [3], Yonglong Liu [3], Nian Wan [3] and Wenfeng Ding [3]

[1] CIDEM, School of Engineering of the Technical University of Porto, Rua Dr. António Bernardino de Almeida, 4249-015 Porto, Portugal
[2] Department of Mechanical Engineering, Faculty of Engineering, University of Porto, Rua Dr Roberto Frias, 400, 4200-465 Porto, Portugal
[3] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
* Correspondence: afvpe@isep.ipp.pt; Tel.: +351-228340500

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Abstract: Reverse Engineering (RE) provides a route from an existing physical component to a digital model that can support inspection, redesign, reproduction and remanufacture. The reliability of this route depends strongly on the method used to acquire the component geometry, yet the available technologies differ markedly in measurement principle, achievable accuracy, acquisition rate, cost, surface sensitivity and geometric accessibility. This review examines shape-acquisition technologies for component-oriented RE and follows the workflow from geometric capture through point-cloud processing and mesh generation to CAD reconstruction. The literature considered includes photogrammetry, tactile coordinate measuring machines (CMMs), computed tomography (CT), structured-light scanning and laser triangulation, together with developments in automated processing and scan-to-CAD reconstruction. The review considers acquisition and reconstruction as a single engineering workflow, comparing the principal acquisition routes against common practical criteria and relating their performance to the subsequent requirements of CAD reconstruction, including recent automated and AI-assisted approaches. Its principal conceptual contribution is to clarify how acquisition decisions propagate through data quality, reconstruction effort, metrological validation and final model usability, providing a task- and traceability-oriented basis for reverse-engineering workflow selection. The comparative evidence shows that method selection is application-dependent rather than hierarchical. Tactile CMMs provide high metrological confidence but are comparatively slow for dense freeform acquisition. Photogrammetry offers low-cost and scalable capture, although its performance deteriorates on texture-poor and optically difficult surfaces. CT uniquely provides volumetric access to internal geometry but entails substantial equipment, reconstruction and uncertainty-management requirements. Structured-light and laser-triangulation systems provide faster external-surface acquisition, with different sensitivities to surface optical properties and referencing conditions. The review therefore identifies acquisition-method selection and the subsequent conversion of measured data into engineering-ready CAD geometry as the two principal determinants of RE efficiency and reliability.

Keywords: 3D digitisation; photogrammetry; coordinate measuring machines; structured-light scanning; computer-aided design

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1. Introduction

Reverse engineering (RE) has become an increasingly important activity within contemporary engineering practice, particularly in contexts in which an existing physical component must be understood, reproduced, modified, inspected, or digitally reconstructed without access to its original design intent, nominal geometry, or manufacturing documentation [1–4]. Its relevance now extends across a wide range of sectors, including manufacturing, medicine, product development, maintenance engineering, and rapid prototyping, where the recovery of geometric and functional information from legacy, damaged, customised, or undocumented parts has become strategically valuable [5–8].

Whereas traditional or forward engineering proceeds from design specification to physical implementation, reverse engineering inverts this logic by deriving design, geometrical, and, in some cases, manufacturing information from an existing artefact (Figure 1).

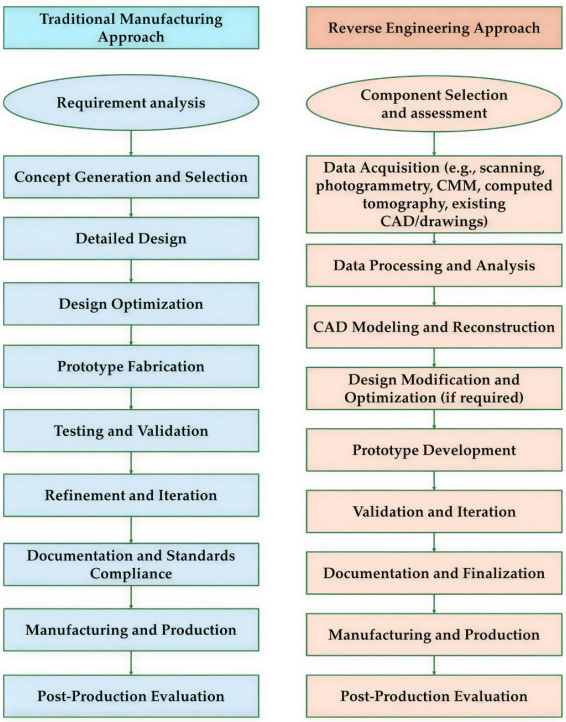


Figure 1. Traditional vs. RE manufacturing processes [9].

Raja [6] defines forward engineering as the physical implementation of a system through logical design, whereas reverse engineering seeks to infer that implementation from the manufactured component itself, frequently in the absence of prior process knowledge. In the context of digital product reconstruction, reverse engineering may also be understood as the derivation of a computer-aided design (CAD) model from three-dimensional point data acquired by scanning a component. In a related formulation cited by Raja [6], Yau [10] describes reverse engineering as the "process of retrieving new geometry from a manufactured part by digitising and modifying an existing CAD model". In this sense, reverse engineering is not merely a copying operation, but a technically demanding process of interpretation, abstraction, and reconstruction through which a physical object is transformed into a digital representation capable of supporting redesign, remanufacture, validation, dimensional verification, or performance improvement [6,10,11].

The growing industrial importance of reverse engineering is closely associated with advances in shape-acquisition technologies and their integration with CAD, digital metrology, and data-processing workflows [12,13]. The study by Buonamici et al. [14] introduces a template-based reverse-engineering framework that reconstructs fully parametric CAD models from mesh data while preserving feature history, design intent, and exact geometric constraints. Its principal challenges concern dependence on prior user knowledge, segmentation and template-definition effort, computational cost, and reduced robustness when dealing with dense meshes and high-dimensional parameter spaces.

Figure 2 is a schematic representation of the template-based fitting strategy proposed for reverse engineering, in which a parametric CAD template endowed with predefined topology and geometric constraints is fitted to

reference mesh data to obtain a dimensionally accurate CAD reconstruction, followed by validation through comparative testing against state-of-the-art reconstruction tools.

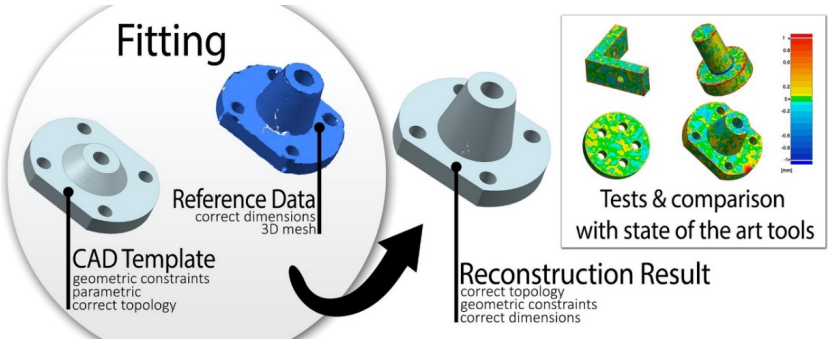


Figure 2. Template-based fitting strategy for reverse engineering, in which a parametric CAD template is fitted to reference mesh data to recover the required topology, geometric constraints, and dimensions [14].

Earlier forms of reverse engineering depended heavily upon manual measurement and interpretative reconstruction, which limited both speed and fidelity, particularly in the case of complex surfaces and freeform geometries. Contemporary reverse-engineering systems, by contrast, increasingly combine high-density geometric capture with computational processing, thereby enabling the conversion of physical parts into point clouds, polygonal meshes, and ultimately CAD models suitable for engineering use [12,13]. This capability is especially significant in applications involving obsolete or discontinued components, product modification, dimensional inspection, part-to-CAD comparison, and the reproduction or optimisation of objects for which no authoritative digital model exists [7,11]. Reverse engineering therefore occupies an important position at the interface between physical artefacts and digital engineering environments.

At a process level, reverse engineering may be understood as a sequence of interdependent stages, each introducing its own technical constraints and opportunities. The workflow generally begins with three-dimensional scanning or digitisation of the object of interest, followed by point-cloud generation and processing, surface or mesh reconstruction, and, where required, CAD modelling [9,15]. Among these stages, shape acquisition is particularly decisive, because the quality, completeness, and metrological reliability of the captured data condition all subsequent reconstruction steps. The purpose of shape acquisition is to obtain sufficiently accurate and sufficiently dense information about the surface of the object to support downstream modelling and analysis. The resulting data are typically organised as a point cloud, in which each point is associated with spatial coordinates and can subsequently be processed into a polygonal mesh or other surface representation [16,17].

Point clouds are especially valuable within reverse-engineering workflows because they permit comparatively flexible manipulation, including segmentation, editing, alignment, and merging, and therefore function as an effective intermediate representation between physical geometry and digital reconstruction [18]. Nevertheless, the raw point cloud is rarely a finished result. Owing to the limitations of shape-acquisition methods, additional processing is commonly required to reduce noise, remove irrelevant or spurious features, repair missing regions, and merge multiple datasets into a coherent whole, particularly where more than one acquisition setup is required to capture the entire geometry [6,19–21]. Once this stage has been completed, the point cloud is reconstructed as a mesh, typically by connecting neighbouring points into a polygonal surface representation [22,23]. The final conversion of that mesh into a CAD model remains one of the most demanding stages of the workflow, since it is often time-consuming, heavily dependent on expert intervention, and especially difficult in the case of freeform geometries [12]. This challenge has motivated a growing body of research on the automation of CAD reconstruction from scan-derived data [19–21].

A central difficulty in reverse engineering is that no single shape-acquisition method is universally optimal. The selection of an appropriate technology depends upon the geometry, size, material properties, optical characteristics, accessibility, and required accuracy of the object under study, as well as upon practical considerations such as acquisition speed, cost, portability, environmental sensitivity, and the intended use of the reconstructed model [24–26]. For this reason, the evaluation of acquisition methods is not simply a matter of comparing measurement principles in isolation; rather, it requires consideration of how each technology performs within the broader reverse-engineering workflow. Different acquisition routes generate different forms of data, demand different levels of preprocessing, and exhibit distinct strengths and limitations when confronted with challenging surfaces, internal features, thin structures, reflective materials, or freeform geometries. Reverse

engineering must therefore be approached as a systems problem in which metrology, computation, reconstruction, and application-specific requirements are tightly interrelated.

Within this context, shape-acquisition methods may be broadly classified into passive and active systems. Passive methods derive information from the environment without projecting or transmitting a controlled energy signal onto the object, whereas active methods rely on the interaction between emitted energy and the object's surface or internal structure [27]. Among passive approaches, image-based three-dimensional modelling, particularly photogrammetry and multi-view stereo techniques, has received considerable attention because of its relatively low cost, accessibility, and ease of deployment. By combining multiple overlapping images and reconstructing camera positions through feature matching, such methods can generate point clouds suitable for digital reconstruction [28], as depicted in Figure 3.

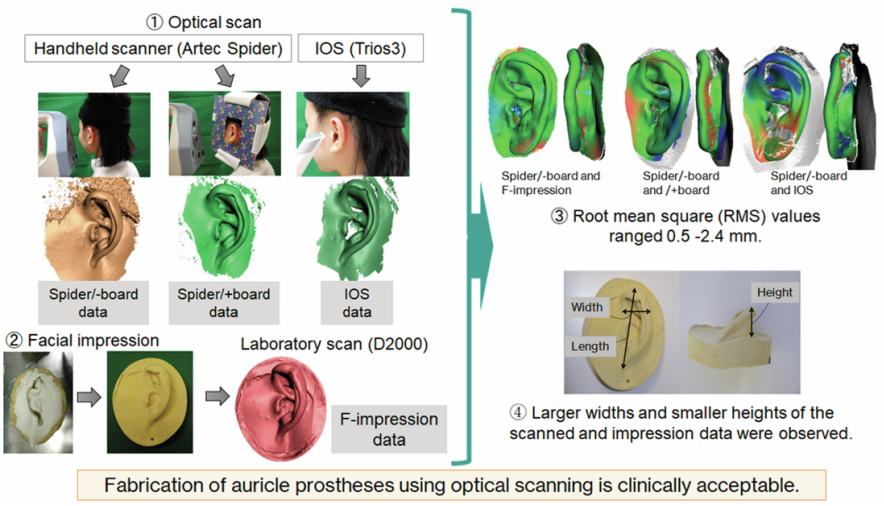


Figure 3. Workflow and comparative evaluation of optical scanning strategies for auricular prosthesis fabrication [29].

Figure 3 compares direct surface digitisation of the ear using two clinical optical systems—a handheld structured-light scanner (Artec Spider) and an intraoral scanner (TRIOS3)—with an indirect workflow based on conventional impression taking followed by laboratory digitisation of the resulting impression. The resulting datasets are compared through superimposition analysis, showing root mean square (RMS) deviations in the range of 0.5–2.4 mm between the alternative acquisition routes. Dimensional comparison further indicates a tendency towards greater width and reduced height in the scanned and impression-derived models. Overall, the figure illustrates the technical feasibility of optical scanning for auricular prosthesis manufacture and supports its clinical acceptability as a non-invasive acquisition approach.

The principal attractions of passive systems lie in affordability and flexibility, especially where extremely high geometric precision is not the dominant requirement. However, their effectiveness is strongly constrained by the presence of suitable surface texture, adequate image quality, and favourable optical behaviour; homogeneous surfaces, thin structures, and non-Lambertian materials such as transparent or highly reflective objects frequently lead to incomplete or unreliable reconstructions [30].

Active methods comprise both contact and non-contact systems. Contact techniques, most notably tactile coordinate measuring machines (CMMs), retain particular importance because of their exceptional accuracy and established role in dimensional metrology [31]. Through direct interaction between a probe and the component surface, tactile CMMs can generate highly reliable measurements with micrometric tolerances, making them especially valuable for inspection-oriented tasks [32]. Their advantages, however, are accompanied by notable practical limitations in the context of reverse engineering: they are slower than optical systems, often require controlled environments, may be unsuitable for compliant or delicate surfaces, and become less efficient as geometric complexity increases [33]. Consequently, although tactile methods remain indispensable where measurement precision is paramount, they are frequently more appropriate for dimensional inspection and validation than for the rapid digitisation of complex three-dimensional geometry.

Non-contact active methods offer broader versatility for many reverse-engineering applications. Computed tomography (CT) is of particular significance because it permits the non-destructive capture of both internal and external geometry, thereby overcoming the line-of-sight limitations that affect many surface-based techniques, making CT especially valuable for parts with concealed features or complex internal architecture, although cost, size constraints, material penetrability, and metrological uncertainty may restrict its wider industrial use [34].

Structured-light systems and laser scanners, by contrast, are surface-oriented optical methods that reconstruct geometry by analysing the deformation or reflection of projected light through triangulation principles [35]. These technologies are widely valued for their speed, portability, and ability to generate dense point clouds. Structured-light systems are often especially attractive because of their rapid acquisition and, in some configurations, their ability to self-position without adhesive targets; however, they may struggle with highly reflective, transparent, or very dark surfaces [36]. Laser triangulation systems may offer advantages on reflective materials and can be integrated into automated measurement platforms, although handheld implementations commonly depend upon positioning targets for dynamic referencing [37].

Taken together, these comparative characteristics illustrate the central premise of the present review: the effectiveness of reverse engineering is strongly conditioned by the choice of shape-acquisition method. Method selection must therefore be informed not only by the measurement principle itself, but also by the geometry and material properties of the object, the required metrological performance, the downstream reconstruction strategy, and the intended engineering application. It is in this context that the following sections examine the principal shape-acquisition methods used in reverse engineering and assess their functional principles, advantages, limitations, and suitability for component production and related industrial applications.

The principal scientific contribution of this review is the interpretation of reverse engineering as an integrated engineering chain rather than as a set of independent acquisition and reconstruction operations. The analysis connects physical-component characteristics and acquisition strategy with the quality and structure of the resulting data, the requirements imposed on point-cloud processing and mesh reconstruction, the feasibility of CAD generation, the confidence achievable through metrological validation, and the suitability of the final model for its intended engineering use. This perspective shows that acquisition performance cannot be evaluated independently of downstream reconstruction, because data density, completeness, accessibility, surface sensitivity and uncertainty directly influence processing effort, modelling strategy and validation requirements.

On this basis, the review provides a task- and traceability-oriented framework for comparing reverse-engineering routes. Rather than identifying a universally superior acquisition technology, it evaluates how effectively each method supports the complete progression from physical component to engineering-ready digital model. This integrated interpretation provides the conceptual basis for the subsequent comparative assessment of acquisition methods, their downstream reconstruction consequences, industrial applicability, automation potential, hybrid metrology, uncertainty propagation and metrological traceability.

The remainder of the paper is organised as follows. Section 2 describes the review methodology, including the search strategy, study-selection procedure and QA. Section 3 examines the principal shape-acquisition technologies considered in the review—photogrammetry, tactile coordinate measurement, computed tomography, structured-light scanning and laser scanning—and discusses the associated processing and reconstruction stages. Section 4 compares these approaches in terms of metrological performance, acquisition efficiency, cost, geometric and surface constraints, and industrial applicability, and also examines recent developments in automated and AI-assisted reconstruction. Section 5 summarises the principal conclusions, while Section 6 identifies research priorities for improving scan-to-CAD automation, metrological traceability and industrial integration. Limitations arising from inconsistent terminology, heterogeneous experimental protocols and uneven reporting practices are addressed in Section 4 (Discussion).

2. Method of Research

The review followed the PRISMA 2020 framework [38–40]. Bibliographic records were collected in February 2026, with Crossref used as the principal retrieval source and Dimensions.ai as a complementary database. Crossref was selected because its publisher-deposited metadata provide broad multidisciplinary coverage across the engineering and associated scientific domains relevant to this review, including manufacturing, metrology, computer vision, medical imaging, CAD, and three-dimensional digitization. Its cross-publisher coverage was particularly appropriate for a review in which the relevant literature is distributed across several research fields rather than concentrated within a single disciplinary index. Dimensions.ai was used to supplement retrieval and to support metadata verification where records were incomplete or inconsistently indexed. Scopus, Web of Science, and IEEE Xplore were also considered during development and verification of the search strategy. Cross-checking against these databases showed substantial overlap with the Crossref-derived corpus for the subject matter examined here, and no additional body of relevant literature was identified that materially altered the final study set. They were therefore not used as independent primary retrieval sources, avoiding unnecessary duplication while retaining broad coverage of the literature relevant to component-oriented reverse engineering. Records obtained from the selected sources were subsequently consolidated using a customised MATLAB® routine [41],

which harmonised bibliographic metadata and supported duplicate identification before screening. More information can be found within Appendix A.

2.1. Search Strategy and Information Sources

CrossRef was used as the primary bibliographic source because the scope of the review crosses several research domains, including manufacturing engineering, dimensional metrology, computer vision, three-dimensional digitisation, medical imaging, and CAD reconstruction. Its broad multidisciplinary coverage and structured bibliographic metadata also supported implementation of the search protocol and subsequent automated record consolidation. Dimensions.ai was used as a complementary source to broaden retrieval and to cross-check bibliographic information. Scopus and Web of Science were considered during development of the search strategy because of their established role as curated citation databases; however, they were not used as primary retrieval sources in the final search. Consequently, the search should not be interpreted as exhaustive of all records indexed exclusively in those databases, and this limitation is considered in Section 4.

The first group concerned reverse engineering and digital reconstruction, including terms such as “reverse engineering”, “component digitisation”, “3D reconstruction”, “surface reconstruction”, “point cloud”, “mesh generation”, and “CAD reconstruction”. The second group addressed shape-acquisition technologies, incorporating terms such as “photogrammetry”, “multi-view stereo”, “coordinate measuring machine”, “tactile CMM”, “computed tomography”, “structured light scanning”, “laser scanning”, and “laser triangulation”. The third group focused on performance and application criteria, including “accuracy”, “precision”, “resolution”, “dimensional inspection”, “surface digitisation”, “automation”, “non-contact measurement”, “contact measurement”, “portable scanning”, and “metrology”.

The Boolean search logic followed the general structure:

“Reverse Engineering” AND (“3D Reconstruction” OR “Surface Reconstruction” OR “Point Cloud” OR “CAD Reconstruction”)

AND

(“Photogrammetry” OR “Multi-View Stereo” OR “Coordinate Measuring Machine” OR “Tactile CMM” OR “Computed Tomography” OR “Structured Light Scanning” OR “Laser Scanning” OR “Laser Triangulation”)

AND

(“Accuracy” OR “Precision” OR “Resolution” OR “Dimensional Inspection” OR “Surface Digitisation” OR “Automation” OR “Metrology” OR “Portable Scanning”).

The search expression was constructed and verified sequentially to assess the effect of each conceptual block on retrieval breadth. An initial search using the mandatory term “Reverse Engineering” returned 222,158 records. Adding the digital-reconstruction block reduced the result set to 22,653 records. Incorporation of the shape-acquisition block further reduced the dataset to 12,477 records, while addition of the performance and application criteria yielded 12,164 records. These intermediate values represent successive refinements of the same search strategy rather than independent literature datasets. Subsequent application of the predefined publication, subject-area, document-type, temporal, and eligibility criteria produced the final corpus of 194 studies considered in the review.

Search queries were applied to the title, abstract, and keyword fields of the selected databases. To ensure the scientific relevance, comparability, and technical consistency of the collected literature, the following eligibility criteria were adopted:

- Publication period: 2010–2025
- Document type: peer-reviewed journal research articles, peer-reviewed review articles, and selected full-length peer-reviewed conference or proceedings papers providing sufficient methodological and technical detail for evaluation. Conference abstracts, extended abstracts lacking adequate methodological detail, grey literature and non-peer-reviewed sources were excluded.
- Language: English

These criteria were introduced to ensure that the review captured both the foundational and contemporary developments in reverse engineering for component production, particularly in relation to shape acquisition, data processing, reconstruction workflows, and the comparative performance of contact and non-contact digitisation systems, while excluding publications falling outside the scope of reverse-engineering methodologies and their industrial application.

2.2. Study Selection and Screening

Study selection followed the PRISMA 2020 procedure described above. The initial CrossRef search was supplemented with records from Dimensions.ai and covered both foundational and recent work on RE and shape-

acquisition technologies. Because the databases contain overlapping publisher records, early-access entries and duplicated metadata, the initial retrieval contained substantial redundancy.

To address these redundancies, an automated consolidation procedure was implemented using a bespoke MATLAB® script, supplemented by manual verification. This procedure harmonised bibliographic metadata across the different sources and enabled the systematic removal of duplicate records. The resulting dataset was then subjected to preliminary screening.

Screening and eligibility decisions were subsequently undertaken in accordance with predefined inclusion and exclusion criteria established prior to database interrogation, with the objective of minimising subjective bias and ensuring methodological consistency. Titles, abstracts, and keywords were examined in order to assess their relevance to reverse engineering for component production, with particular emphasis on shape-acquisition methods, point-cloud generation and processing, surface reconstruction, CAD modelling, dimensional inspection, metrological performance, and the comparative capabilities of contact and non-contact digitisation systems. Particular attention was given to studies addressing accuracy, precision, resolution, portability, automation, material and surface-related scanning limitations, and the suitability of different acquisition technologies for complex or freeform geometries.

Publications lacking methodological clarity, those unrelated to reverse-engineering workflows, or studies that did not address component digitisation, reconstruction, geometric acquisition, metrological evaluation, or application-specific limitations were excluded at this stage. A considerable proportion of the discarded literature concerned either general three-dimensional imaging developments with no direct reverse-engineering dimension, or broader manufacturing and computer-vision studies without substantive connection to reconstruction workflows, inspection, or component reproduction.

Full texts surviving the preliminary screening were then examined against the eligibility criteria. Studies were retained when they provided sufficient information on the acquisition or reconstruction method, experimental or computational procedure, performance assessment and relevance to component-oriented RE. Where several publications addressed closely related methods, priority was given to studies offering stronger technical detail, validation or comparative evidence. The resulting corpus formed the evidence base for the subsequent analysis of shape acquisition, surface reconstruction and CAD-oriented digitisation.

The search initially identified 222,158 records. Before screening, 199,505 records were removed, comprising 149,820 duplicate records, 47,439 records excluded through automated ineligibility filtering, and 2246 records removed for other reasons. The remaining 22,653 records underwent title and abstract screening, during which 10,176 were excluded. A total of 12,477 reports were subsequently sought for retrieval; 313 could not be retrieved, leaving 12,164 reports for full-text eligibility assessment. At this stage, 10,911 reports were excluded on the basis of scope, acquisition-method relevance, reconstruction content, document type, or other predefined eligibility criteria. The remaining 1253 publications proceeded to QA, of which 1059 did not meet the QA requirements, resulting in a final review corpus of 194 studies.

During the review process, a recurrent challenge concerned the absence of fully standardised terminology within the reverse-engineering literature. Identical or closely related processes are frequently described using different nomenclature, particularly in the case of scanning technologies, reconstruction workflows, and metrological descriptors. For example, image-based modelling may also be described as photogrammetry, structure-from-motion, or multi-view stereo, whilst optical digitisation systems may be reported variously as structured-light scanners, fringe-projection systems, optical scanners, or non-contact coordinate measuring systems. Comparable inconsistencies also arise in relation to reconstruction terminology, where expressions such as point cloud, polygon mesh, triangulated surface, digital model, and CAD reconstruction are not always used with strict definitional consistency. These variations required careful cross-verification of acquisition principles, processing workflows, and reported performance characteristics during the classification and interpretation of the retrieved studies. Minor orthographic differences between American and British English further introduced bibliographic inconsistencies in indexed metadata.

The formulation of precise research questions constitutes a fundamental element of any systematic literature review, as it defines the analytical scope and conceptual direction of the investigation. To ensure internal coherence and close alignment with the objectives of the present study, the Population–Intervention–Comparison–Outcome–Context framework was adapted as follows:

- Population: Experimental, computational, and review studies concerned with reverse engineering, component digitisation, and three-dimensional geometric reconstruction, particularly those addressing manufactured parts and their digital reproduction.

- Intervention: Shape-acquisition and reconstruction strategies applied to reverse engineering, including photogrammetry, tactile coordinate measuring machines, computed tomography, structured-light scanning, laser scanning, point-cloud processing, mesh generation, and CAD reconstruction workflows.
- Comparison: Comparative analyses between different acquisition methods and reconstruction strategies, as well as between contact and non-contact systems, particularly with respect to accuracy, precision, acquisition speed, automation potential, portability, and suitability for complex geometries and different material or surface conditions.
- Outcomes: Improvements in geometric capture, dimensional fidelity, reconstruction quality, workflow efficiency, and application suitability, together with the identification of persistent technical limitations, accuracy constraints, and unresolved research challenges in reverse engineering for component production.
- Context: Peer-reviewed academic publications addressing reverse engineering and shape-acquisition technologies in manufacturing and related application domains.

Based on this framework, a structured and hierarchically organised set of research questions was established to guide the systematic extraction, critical evaluation, and synthesis of the knowledge contained within the selected literature. These research questions are presented in Table 1.

Table 1. Research questions structured according to the PICOC framework.

ID	Research Question
RQ1	What are the principal technical challenges affecting the accuracy, completeness, and practical reliability of reverse-engineering workflows for component production across different shape-acquisition routes?
RQ1.1	How do acquisition-related limitations—such as incomplete surface capture, noise, occlusion, missing regions, optical artefacts, contact-induced constraints, and reconstruction inaccuracies—manifest in reverse-engineered components, and how do they affect geometric fidelity and downstream usability?
RQ1.2	Which material characteristics, surface conditions, geometric features, and environmental variables, including reflectivity, transparency, texture deficiency, freeform complexity, object accessibility, lighting conditions, and setup stability, exert the greatest influence on data quality, dimensional accuracy, and reconstruction performance in reverse engineering?
RQ2	How do shape-acquisition, processing, and reconstruction strategies determine the final quality and usability of reverse-engineered components?
RQ2.1	To what extent do point-cloud processing, mesh reconstruction, surface fitting, and CAD-modelling procedures improve data quality, geometric continuity, dimensional verification, and confidence in the reconstructed model?
RQ2.2	What are the principal trade-offs associated with reverse-engineering workflows, particularly in relation to accuracy, acquisition time, processing complexity, automation potential, operator expertise, and industrial implementation?
RQ3	How do acquisition parameters, equipment configurations, and technology selection influence the robustness, repeatability, and metrological performance of reverse engineering?
RQ3.1	Which operational variables—such as scanner positioning, measurement path, image overlap, calibration quality, probe strategy, light wavelength, resolution, and acquisition setup—most strongly affect repeatability, geometric accuracy, surface capture, and reconstruction quality?
RQ3.2	How do different shape-acquisition technologies and system architectures influence the applicability, effectiveness, and limitations of reverse-engineering strategies used to digitise and reconstruct components?
RQ4	What recent developments in digital reconstruction technologies, modelling approaches, and automated processing tools contribute to improved reverse-engineering performance and workflow optimisation?
RQ4.1	How can computational modelling, automated point-cloud registration, intelligent surface fitting, ML-assisted reconstruction, and CAD-oriented data-processing tools support improved accuracy, efficiency, and reconstruction reliability in reverse engineering?
RQ4.2	What technical, methodological, and industrial limitations currently hinder the broader implementation of automated reconstruction, intelligent processing, and digitally assisted reverse-engineering workflows in industrial environments?
RQ5	What are the emerging research trends and future opportunities in reverse engineering for component production?
RQ5.1	Which advanced concepts—such as automated feature recognition, ML-assisted CAD reconstruction, hybrid metrology, intelligent point-cloud processing, and integrated digital workflows—show the greatest potential for improving the industrial viability and technical performance of reverse engineering?
RQ5.2	What key knowledge gaps remain regarding the integration of shape acquisition, metrological validation, surface reconstruction, CAD generation, and data-driven automation in the development of next-generation reverse-engineering systems?

The present review considered peer-reviewed publications spanning both foundational and contemporary contributions to reverse engineering, with particular emphasis placed on studies addressing shape acquisition, point-cloud generation and processing, surface reconstruction, CAD modelling, and metrological evaluation. This temporal scope was selected to capture the technological development of reverse-engineering workflows, particularly with respect to photogrammetry, tactile coordinate measuring machines, computed tomography, structured-light scanning, laser scanning, and associated digital reconstruction procedures. Particular attention was devoted to studies examining dimensional accuracy, geometric fidelity, reconstruction completeness, surface-related acquisition limitations, portability, automation potential, and the suitability of different digitisation methods for complex and freeform geometries.

The literature search procedure, as illustrated in Figure 4, was implemented using structured Boolean queries designed to identify studies situated at the intersection of reverse-engineering applications, shape-acquisition

technologies, and reconstruction or metrological evaluation methodologies. The search strategy therefore incorporated combinations of keywords related to reverse engineering and digital reconstruction, including *"reverse engineering", "3D reconstruction", "surface reconstruction", "point cloud", "mesh generation",* and *"CAD reconstruction",* together with terms associated with shape-acquisition technologies, such as *"photogrammetry", "multi-view stereo", "coordinate measuring machine", "tactile CMM", "computed tomography", "structured light scanning",* and *"laser scanning".* A third group of terms addressed performance, validation, and application-related considerations, including *"accuracy", "precision", "resolution", "dimensional inspection", "metrology", "surface digitisation", "non-contact measurement", "contact measurement", "automation",* and *"portable scanning".*

This structured search strategy enabled the targeted retrieval of scientific contributions directly concerned with reverse engineering for component production, particularly studies addressing shape acquisition, geometric reconstruction, metrological evaluation, and workflow optimisation. It was designed to capture literature relevant to the acquisition and processing of geometric data, the generation and refinement of point clouds and meshes, CAD-oriented reconstruction, and the comparative assessment of contact and non-contact digitisation methods. In this way, the search protocol supported a technically rigorous evaluation of the principal challenges, methodological trade-offs, and emerging opportunities associated with achieving accurate, reliable, and industrially viable reverse-engineering workflows.

Figure 5 shows a clear increase in the number of retrieved publications between 2010 and 2025. Growth becomes more pronounced from the middle of the 2010s, with publication activity remaining high after 2020. The increase coincides with broader adoption of optical digitisation, tactile and volumetric metrology, point-cloud processing and CAD reconstruction in engineering workflows. It also reflects the expansion of RE beyond component reproduction towards dimensional verification, redesign and digital recovery, where the quality of the acquired geometry directly affects subsequent engineering use.

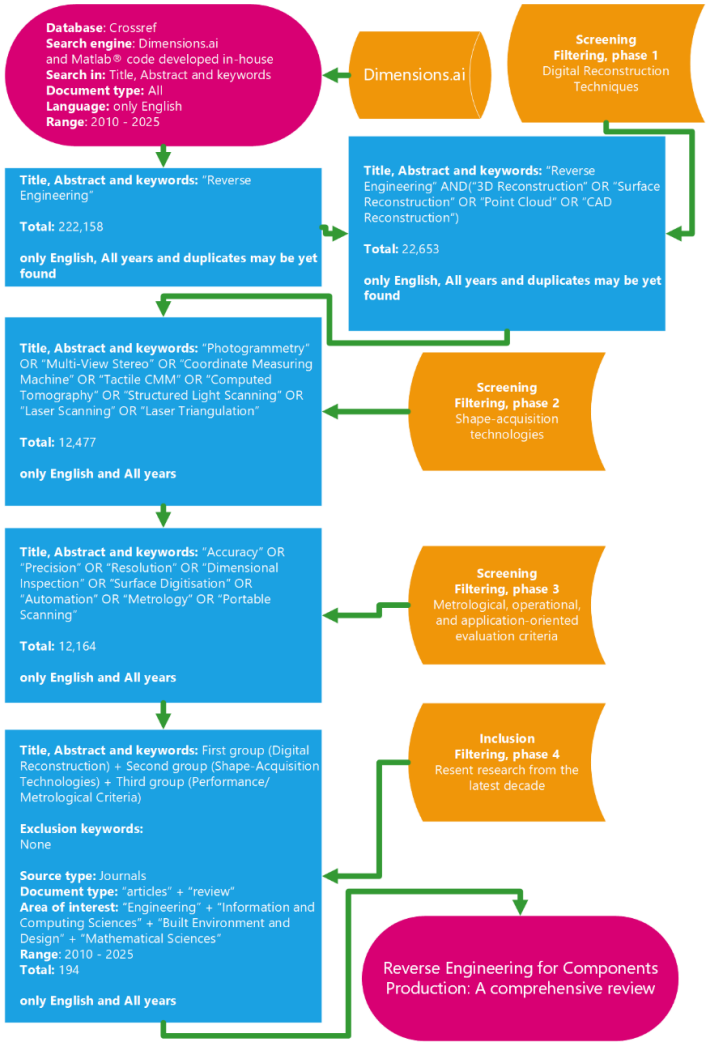


Figure 4. Sequential construction and refinement of the literature-search strategy used to identify studies on reverse engineering and shape-acquisition technologies.



Figure 5. Annual distribution of CrossRef-indexed publications on reverse engineering and shape-acquisition technologies between 2010 and 2025.

2.3. Study Selection and Quality Assessment (QA)

Following full-text screening, 1253 publications proceeded to a four-domain QA (Figure 6). The assessment considered research design and conceptual coherence, definition of the reverse-engineering and acquisition workflow, methodological and analytical rigour, and technological and industrial relevance. Each domain contributed 25% of the overall assessment, with individual criteria scored as Yes = 1, Partly = 0.5, or No = 0. The QA was intended to distinguish studies providing sufficiently documented and technically interpretable evidence from contributions in which acquisition conditions, reconstruction procedures, validation, or industrial relevance were inadequately reported.

The four evaluation domains were defined as follows:

- Research Design and Conceptual Coherence (25%)—assessing the clarity of the study aims, the suitability of the research methodology, and the extent to which the investigation is supported by a coherent scientific and technical rationale.
- Definition of Reverse-Engineering Workflow and Acquisition Framework (25%)—examining whether the reverse-engineering process, the object or component under analysis, the acquisition system, the scanning conditions, and the relevant reconstruction parameters are described with sufficient precision, including details necessary for reproducibility, such as calibration procedures, lighting conditions, probe configuration, scanning strategy, resolution, positioning method, or data-processing criteria.
- Methodological Rigour and Analytical Transparency (25%)—evaluating the robustness of the experimental, computational, or analytical procedures, the adequacy of validation methods, and the consistency with which data interpretation is conducted and reported.
- Technological and Industrial Relevance (25%)—determining the degree to which the findings contribute to the practical understanding of reverse engineering, particularly in relation to dimensional accuracy, geometric fidelity, acquisition efficiency, reconstruction quality, automation potential, metrological reliability, and suitability for industrial application.

An overall QA score of 60% was adopted as the minimum threshold for final inclusion. Studies scoring below 50% were excluded directly, whereas those scoring between 50% and <60% were reassessed in full to verify the consistency of the initial scoring before the final exclusion decision. The reassessment focused on whether the acquisition conditions, equipment configuration, processing and reconstruction procedures, validation strategy, and reported performance were described with sufficient detail to support technical interpretation. Studies were excluded when these elements remained insufficiently documented after reassessment. The QA was performed by a single reviewer using the predefined scoring framework. Borderline cases were subsequently re-examined in full by the same reviewer to improve consistency in the application of the criteria. This repeat assessment therefore provided an additional within-reviewer consistency check rather than an independent duplicate assessment. Because no second reviewer independently evaluated the QA scores, inter-rater agreement could not be established

for this stage of the review. The reduction in the study set at the QA stage reflects the application of the predefined methodological criteria rather than exclusion on the basis of topic alone. Studies receiving lower QA scores typically provided insufficient information in one or more critical areas, including definition of the acquisition configuration, calibration or measurement conditions, description of the processing and reconstruction workflow, validation of the reconstructed geometry, or evidence required to assess the technical relevance of the reported results. Consequently, a publication could address a relevant reverse-engineering application while still being excluded when its methodological reporting was insufficient to support reliable comparison or interpretation.

Particular attention was given to studies within the borderline score range of 50–60%. These publications were reassessed from the full text to determine whether apparent deficiencies identified during the initial QA reflected genuinely missing methodological information or information that was reported elsewhere in the article. A borderline study was retained only when the complete publication provided sufficient evidence to interpret the acquisition or reconstruction procedure, the reported performance and the corresponding validation. The resulting QA-score distribution is shown in Figure 6, together with the predefined inclusion threshold. In total, 1059 publications were excluded at the QA stage, leaving 194 studies in the final review corpus.

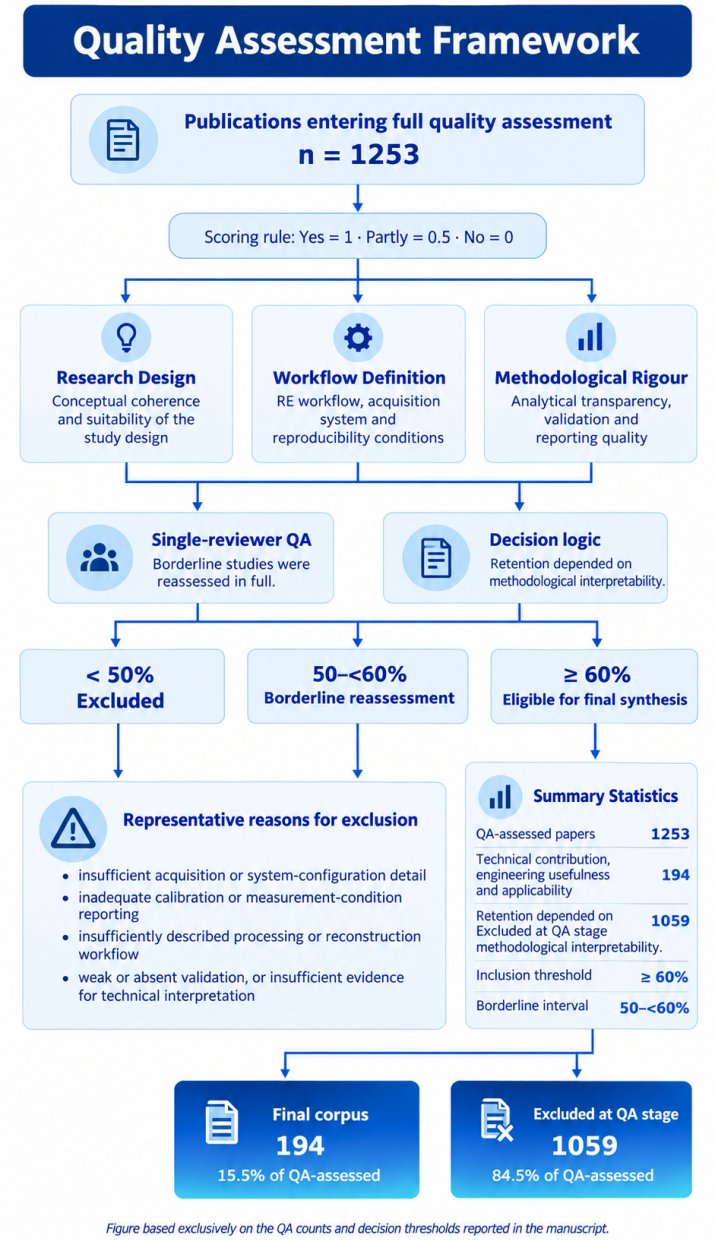


Figure 6. Distribution of quality-assessment scores for the 1253 publications subjected to full QA. The dashed vertical line indicates the 60% inclusion threshold. Studies scoring below 50% were excluded, while studies scoring between 50% and 60% were subjected to full-text reassessment before the final inclusion decision. A total of 194 studies were retained for the final synthesis.

As illustrated in Figure 7, the geographical distribution of authorship and institutional affiliation within the reviewed literature indicates a marked concentration of research activity in countries with established strengths in advanced manufacturing, metrology, optical measurement, and digital engineering. United States of America emerges as the most prominent contributor, followed by the United Kingdom, China, and Germany, with India and Italy also occupying significant positions within the scholarly output on reverse engineering, three-dimensional digitisation, and geometric reconstruction. This distribution reflects the industrial and scientific relevance of reverse engineering in sectors such as aerospace, automotive engineering, biomedical technologies, tooling, heritage preservation, and other high-value applications requiring demanding combinations of dimensional fidelity, reconstruction accuracy, and technical reliability.

The distribution also shows that RE research is not concentrated in a single geographical region. Contributions from North America, Europe and Asia are all represented among the most frequently occurring affiliations, which is consistent with the use of shape-acquisition technologies across manufacturing, biomedical engineering, heritage documentation and other application domains. The geographical spread should nevertheless be interpreted as a characteristic of the retrieved corpus rather than as a direct measure of national research capability.

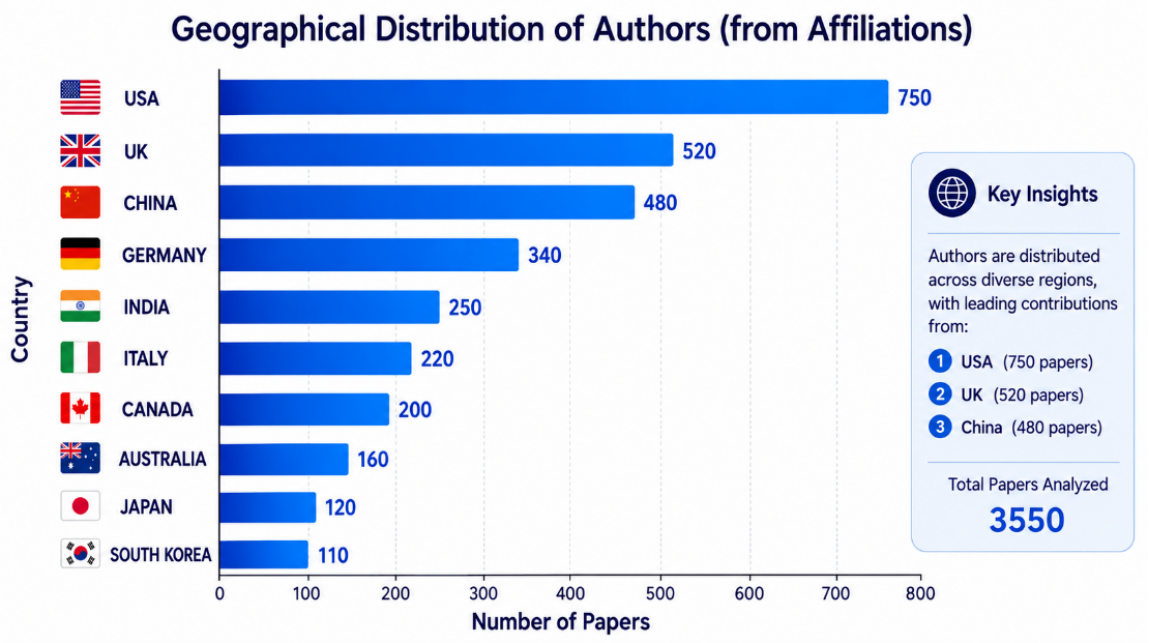


Figure 7. Geographical distribution of authors' institutional affiliations across the publications included in the review of reverse engineering and shape-acquisition technologies.

2.4. Descriptive Analysis and Taxonomic Synthesis

The included literature can be organised into two broad technical domains. The first concerns acquisition of geometric data from physical components and therefore covers contact and non-contact digitisation methods. The second addresses the conversion and verification of those data through point-cloud processing, mesh generation, surface fitting, CAD reconstruction and metrological validation. This division was used to organise the subsequent synthesis because it separates the measurement problem from the reconstruction problem while preserving their dependence within the overall RE workflow.

1. Shape acquisition and geometric digitisation: This domain encompasses investigations concerned with the acquisition of geometric information from physical components through contact and non-contact systems. Particular attention is given to the influence of acquisition conditions on data completeness, resolution, dimensional accuracy, surface capture, and measurement stability. Studies within this category examine the effects of variables such as calibration, scanner position, image overlap, lighting conditions, probe configuration, surface reflectivity, transparency, texture, and geometric complexity on point-cloud generation and the fidelity of the captured geometry. Research in this area is directed towards improving acquisition reliability, repeatability, and efficiency, whilst minimising noise, occlusion, and incomplete surface coverage.
2. Reconstruction, validation, and CAD-oriented modelling: The second domain concerns the processing and interpretation of acquired data in order to obtain usable digital models for inspection, reproduction, redesign, or further engineering analysis. This body of work includes studies focused on point-cloud processing, mesh

generation, surface fitting, CAD reconstruction, and metrological verification, together with investigations into their influence on geometric continuity, dimensional conformity, reconstruction quality, and downstream usability. These approaches are intended to overcome the limitations of raw acquisition data and to support the reliable industrial deployment of reverse-engineering workflows in demanding applications.

This classification highlights the inherently multidisciplinary character of current research in reverse engineering, in which manufacturing engineering, metrology, optical measurement, computer vision, geometry processing, and digital modelling intersect in order to address the complex geometrical, material, and procedural challenges associated with component digitisation and reconstruction. Across the reviewed literature, four principal thematic directions may be distinguished.

1. Acquisition limitations and reconstruction quality: A substantial proportion of the literature is devoted to the identification, characterisation, and mitigation of common limitations affecting reverse-engineering workflows, including noise, occlusion, missing regions, surface reflectivity, transparency, texture deficiency, thin features, and reconstruction inaccuracies. These studies seek to clarify the relationships between acquisition conditions, data quality, and final model fidelity, to improve geometric reliability and reduce reconstruction error.
2. Optimisation of acquisition parameters and repeatability: Another major line of investigation concerns the optimisation of operational variables in order to improve scanning quality, dimensional accuracy, and workflow stability. Particular emphasis is placed on the selection of acquisition conditions capable of controlling resolution, data density, calibration quality, measurement path, and environmental influence. In this context, increasing attention is also devoted to the repeatability and reproducibility of reverse-engineering procedures across different systems, object classes, materials, and operating conditions.
3. Validation, metrological assessment, and industrial applicability: Recent studies increasingly examine the capability of different validation and verification procedures to assess dimensional conformity, geometric fidelity, and practical usability. This includes analyses of tactile coordinate measurement, computed tomography, structured-light scanning, laser scanning, and photogrammetric techniques, as well as investigations into their metrological performance, technical constraints, and suitability for industrial implementation.
4. Automation, intelligent processing, and digital reconstruction: A further area of development involves the use of computational modelling, automated registration, ML-assisted reconstruction, intelligent surface fitting, and CAD-oriented processing tools to improve workflow efficiency and reconstruction robustness. These studies address feature recognition, point-cloud alignment, mesh refinement, automated surface generation, and data-driven support for digital reconstruction, thereby contributing to more reliable, scalable, and intelligent reverse-engineering systems.

Across the reviewed studies, several recurrent technical gains are reported, including:

- improved dimensional accuracy and geometric fidelity;
- enhanced completeness and quality of surface digitisation;
- improved processing and interpretation of point-cloud data;
- greater confidence in dimensional verification and model usability;
- improved understanding of the relationship between acquisition conditions and reconstruction quality;
- greater workflow efficiency and broader industrial applicability through integrated acquisition and reconstruction strategies.

Notwithstanding these advances, the literature also identifies several persistent challenges that continue to limit broader industrial implementation. These include the difficulty of achieving consistently high reconstruction accuracy across different materials and surface conditions, the complexity of correlating acquisition parameters with final model quality, the limited automation of CAD reconstruction for complex freeform geometries, the cost and technical constraints associated with high-accuracy digitisation systems, and the challenge of integrating acquisition, validation, and reconstruction procedures into coherent and economically viable reverse-engineering workflows. Additional constraints arise from the variability of reported acquisition settings, processing routines, validation criteria, and performance metrics across different technologies and application domains.

The three-stage screening procedure adopted in the present review, in accordance with the PRISMA 2020 framework, commenced with an initial appraisal of titles, abstracts, and keywords in order to identify publications relevant to reverse engineering, shape acquisition, reconstruction, and metrological validation. This preliminary screening was followed by detailed full-text assessment designed to verify conformity with the predefined inclusion criteria, with particular emphasis placed on methodological rigour, technical depth, and relevance to the objectives of the review.

The final analytical corpus comprised peer-reviewed journal research articles, peer-reviewed review articles, and selected full-length peer-reviewed conference or proceedings papers that satisfied the predefined eligibility and QA requirements. Publications written in languages other than English, conference abstracts or extended abstracts lacking adequate methodological detail, grey literature, non-peer-reviewed sources, and studies without sufficiently transparent analytical procedures were excluded. The resulting dataset therefore constitutes a carefully curated and scientifically robust body of literature, providing the evidential foundation for the analytical and interpretative framework developed in the present study.

3. Literature Review on Shape Acquisition Methods

Shape acquisition, also referred to as part digitisation, defines the means by which geometric information is captured from a physical object for subsequent three-dimensional reconstruction [42]. The acquired data are commonly represented as a point cloud, in which each point is defined by spatial coordinates (x, y, z) and stored in a digital dataset [43]. Following preprocessing and registration, these data may be converted into a polygonal mesh, commonly represented in STL format, which can subsequently provide the geometric basis for CAD reconstruction [23].

Selection of an appropriate acquisition method depends not only on the measurement hardware and associated processing software, but also on the geometry, material properties, surface condition, accessibility, and surrounding acquisition environment [44–46]. These factors directly affect the feasibility, completeness, and metrological reliability of the resulting scan. Figure 8 presents a classification of geometric data-acquisition techniques relevant to reverse-engineering applications, distinguishing between contact and non-contact measurement principles. Contact-based techniques encompass discrete point acquisition using touch-trigger probes and continuous measurement using scanning probes. Non-contact techniques are further classified into reflective and transmissive approaches, with reflective methods comprising optical and non-optical technologies. Optical acquisition methods are subdivided into passive techniques, including shape-from-shading, stereo vision and motion-based reconstruction, and active techniques, such as triangulation, structured-light projection and time-of-flight measurement. The classification also includes volumetric imaging techniques, notably CT and magnetic resonance imaging (MRI). Although destructive and semi-destructive acquisition techniques are available beyond the scope of the illustrated classification, the following review focuses principally on non-destructive measurement technologies because of their relevance to component digitisation, dimensional inspection, geometric reconstruction and preservation of the original physical component for subsequent engineering applications.

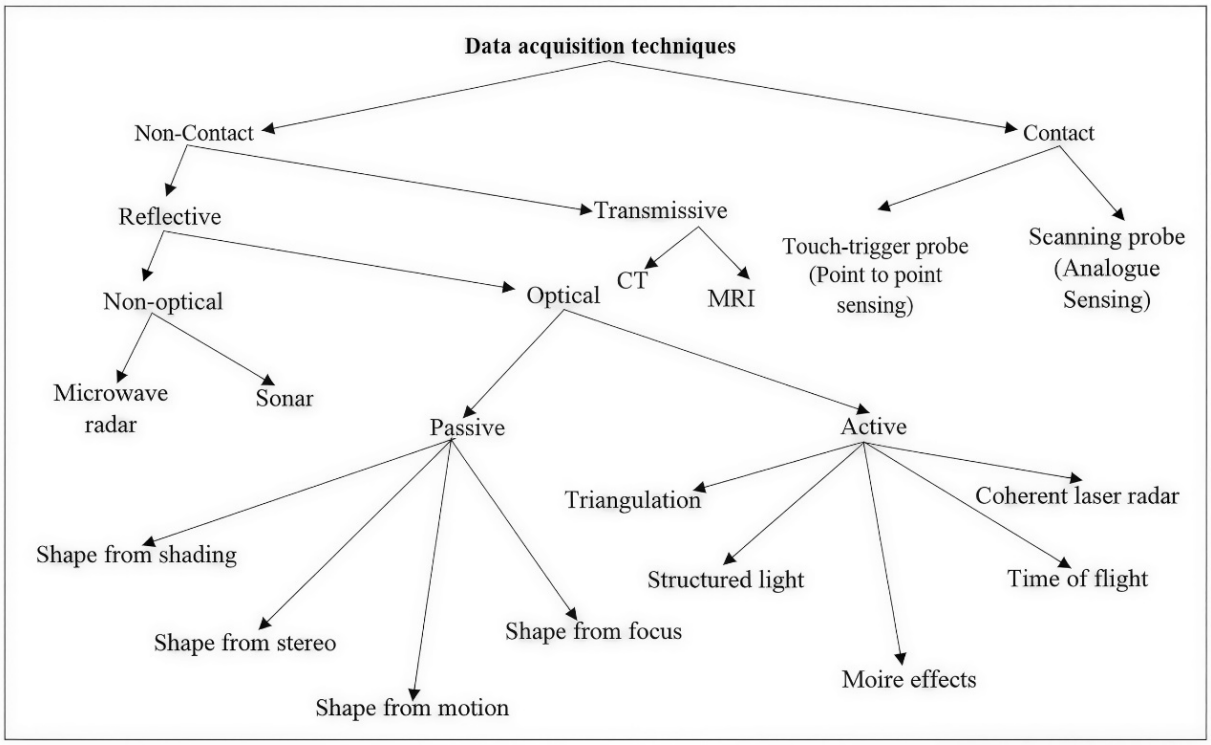


Figure 8. Classification of geometric data-acquisition methods used in reverse-engineering applications, based on the measurement principles and technological categories [47].

3.1. Contact

Contact shape-acquisition methods obtain dimensional information through physical interaction between a measuring instrument and the surface of the component [48,49]. Conventional callipers and related manual instruments represent the simplest form of contact acquisition and remain applicable to components containing readily accessible prismatic or regular features. Their usefulness decreases rapidly as geometric complexity increases, since discrete manual measurements provide insufficient spatial information for the efficient reconstruction of intricate or freeform surfaces [23]. Automated tactile coordinate metrology was developed in part to overcome these limitations.

3.1.1. Tactile CMM

Page et al. [23] identify the coordinate measuring machine (CMM) as one of the earliest technologies to automate coordinate acquisition for reverse-engineering applications. Tactile CMMs determine surface geometry through physical interaction between a calibrated probe and the component [50]. Vozár et al. [51] describe the measurement process in terms of Cartesian coordinates, whereby displacement along the X, Y, and Z axes is recorded to establish the spatial position of individual surface points. Repeated measurements therefore produce a set of three-dimensional coordinates from which the geometry of the measured surface can be reconstructed.

Two principal tactile acquisition strategies are generally distinguished: point-to-point measurement and continuous, or analogue, scanning [5,47]. In point-to-point measurement, the probe contacts the surface, records an individual coordinate, retracts, and is repositioned before the subsequent measurement. In analogue scanning, the probe remains in contact with the surface while continuously acquiring coordinates along the prescribed measurement path [52]. Continuous scanning therefore produces a considerably denser dataset and generally offers higher acquisition efficiency than discrete probing [53], although Bastas [54] notes that this approach may require more extensive calibration.

Tactile CMMs may be equipped with touch-trigger or scanning probes [55]. Touch-trigger probes are primarily employed for discrete point-to-point measurements [56], whereas scanning probes can acquire both discrete and continuous measurement data. Bastas [54] provides a detailed comparison of the performance and operating characteristics of these probing configurations.

CMMs are divided into two categories, fixed CMMs and portable CMMs.

- Fixed CMMs are available in several structural configurations. Bridge-type CMMs are among the most widely used, whereas gantry configurations provide larger measurement volumes and greater structural capacity for large components. Horizontal-arm CMMs offer improved access to features that may be difficult to reach using conventional bridge systems, although this flexibility is generally accompanied by lower measurement accuracy [5,51,57].
- Portable CMMs, particularly articulated measuring arms, provide substantially greater mobility and accessibility than fixed installations. Their performance, however, is more susceptible to environmental influences such as vibration, dust, humidity, and temperature variation. Tactile CMMs nevertheless remain among the most accurate coordinate-measurement systems used for dimensional inspection, with measurement capability extending into the micrometre range under appropriate operating conditions [58].

Measurement uncertainty in tactile CMMs can arise from probe-related effects, vibration, environmental conditions, fixturing and machine calibration. Probe-tip and pre-travel errors may be mitigated through compensation algorithms [59–63], while vibration effects can be reduced through appropriate damping and environmental control. Gapinski et al. [64] compare the accuracy of several shape-acquisition methods, including tactile CMMs. Achieving the high-dimensional capability associated with tactile measurement generally requires controlled temperature, low vibration, limited contamination and stable fixturing, which increases installation and operating costs [65]. Physical probe contact also imposes limitations when components are delicate, compliant or susceptible to deformation; the stylus, commonly fitted with a ruby ball [66], may either damage or be damaged by the measured surface [67]. Acquisition is also comparatively slow, particularly when dense geometric sampling is required [68], and the component must remain securely fixed throughout the measurement process [69,70]. For these reasons, tactile CMMs are generally more suitable for traceable dimensional inspection and validation than for rapid full-field digitisation of complex three-dimensional geometry.

Representative tactile-CMM studies are compared in Table 2, with emphasis on measurement constraints and their contribution to reverse-engineering workflows.

Table 2. Representative studies using tactile CMMs in reverse-engineering applications.

Ref	Challenges	Highlights
[71]	Computational burden; repeated inspection cycles; dependence on stable coordinate referencing; prolonged iterative acquisition and model updating.	Curvature-guided adaptive sampling; closed-loop verification; micron-level reconstruction accuracy; integration of measurement, modelling and freeform-surface evaluation.
[72]	Its principal limitations concern measurement speed, operational efficiency, and practical competitiveness against faster non-contact systems when inspecting geometrically complex free-form blade surfaces.	The tactile CMM offers a robust reference framework for turbine-blade digitisation, providing dependable geometric acquisition and supporting controlled comparison between contact and optical measurement strategies.
[73]	Its principal challenge lies in the dependence of the entire reverse-engineering workflow on repeated high-precision probing, demanding extensive measurement effort and strict dimensional consistency.	The tactile CMM provides ultra-precise dimensional acquisition, enabling reliable GD&T-based characterisation of magnetron geometry and supporting highly accurate resonant-frequency analysis and optimisation.
[74]	Its principal limitations arise from arm-positioning error, calibration sensitivity, and error accumulation across rotated axes, which constrain accuracy and complicate complete acquisition of deeply occluded features.	The articulated-arm CMM provides flexible multi-directional positioning, enabling expedient access to complex geometries and supporting integrated laser-line digitisation with approximately 0.2 mm system-level measurement accuracy.
[75]	Its principal limitation, in the context of this article, is reduced practicality for dense freeform digitisation, where richer datasets and greater efficiency are obtained from optical acquisition routes.	The tactile CMM represents the benchmark contact-measurement approach, offering high repeatability and dependable coordinate acquisition for geometries requiring rigorous dimensional reconstruction within reverse-engineering workflows.
[76]	Its principal limitation is that geometric acquisition alone cannot fully reconstruct the additional design information needed to trace original gear-strength requirements and design intent.	Tactile CMM measurement underpins accurate recovery of fundamental gear geometry, furnishing the dimensional basis for reverse-engineering key design parameters and subsequent strength evaluation.
[77]	Its principal limitation is that accurate geometry capture alone cannot recover the full strength-defining specification of worn, non-standard gears without supplementary material, loading, and service-history data.	Tactile CMM measurement is presented as the most rigorous metrological route for reconstructing spur-gear geometry, particularly where flank-profile fidelity and parameter extraction are critical.
[78]	Their principal limitations are slow acquisition, dependence on physical contact, and reduced practicality for complex anatomical geometries requiring dense, patient-specific, and non-invasive data capture.	The review recognises tactile CMMs as a structured and established contact-metrology option within reverse engineering, offering dependable dimensional capture under controlled measurement conditions.
[9]	The method remains constrained by comparatively low scanning speed, limited effectiveness on complex freeform forms, and weaker compatibility with scalable, hybrid, scan-driven digital workflows.	The review positions tactile CMMs as the most reliable contact-based metrology route for high-precision reconstruction, especially where strict dimensional control governs downstream manufacturing decisions.
[79]	Its principal limitations are slow point acquisition, dependence on sampling strategy, sensitivity to sparse-data reconstruction errors, and the need for numerically robust downstream modelling workflows.	The tactile CMM provides highly reliable three-dimensional coordinate acquisition for sculptured surfaces, furnishing structured measurement data that support robust reconstruction, diagnostic preprocessing, and CAD/CAM integration.
[80]	Their principal challenge, as implied by the review, is limited scalability within scan-to-simulation workflows, where dense geometries, large assets, and rapid industrial turnaround favour faster non-contact acquisition.	Tactile CMMs function as the traceable metrological benchmark, anchoring task-specific uncertainty evaluation and providing the reference fidelity against which scan-derived geometries are judged.

Caption: CAD—Computer-Aided Design, CAM—Computer-Aided Machining.

3.1.2. Manual Measurement

Manual measurement represents the most traditional contact-based route within reverse-engineering workflows and remains relevant where the object under study exhibits simple geometry, accessible features, and modest accuracy requirements. In its most common form, it relies on conventional metrological instruments such as callipers, micrometres, depth gauges, and similar devices to acquire discrete dimensional information from an existing component. Its principal strengths lie in its low cost, broad accessibility, minimal technological complexity, and practical suitability for preliminary inspection or basic dimensional verification. Nevertheless, manual measurement is inherently limited by its pointwise nature, strong dependence on operator skill, and restricted ability to capture complex freeform surfaces, hidden features, or dense three-dimensional geometric

detail. For this reason, although it retains utility in workshop-level applications and initial assessment tasks, manual measurement is generally insufficient as a stand-alone solution for advanced reverse engineering, particularly when the objective is to reconstruct geometrically intricate components, generate complete digital models, or support downstream CAD, simulation, and manufacturing workflows.

Table 3 brings together studies in which manual dimensional measurement is used either as a primary reconstruction method or as a reference for scan-based approaches.

Table 3. Representative studies involving manual measurement in reverse-engineering applications.

Ref	Challenges	Highlights
[81]	From a manual-measurement perspective, the paper implicitly highlights the inadequacy of conventional hand measurement for complex freeform plastic geometries requiring dense surface capture and faithful reproduction.	The paper effectively bypasses manual measurement by adopting high-density optical scanning, thereby enabling accurate capture of complex geometry and supporting a shortened reverse-engineering workflow.
[82]	The study highlights manual measurement as labour-intensive, time-consuming, and poorly scalable, particularly when extracting representative values and constructing BIM models from dense railway scan data.	Manual parameter measurement from point-cloud-derived scan data enabled the construction of a maintenance-oriented BIM model and demonstrated the feasibility of representative-parameter-based track assessment.
[83]	Its principal limitation is that discrete manual readings cannot adequately characterise global crankshaft misalignment after fracture, particularly for geometrically complex components requiring spatially resolved inspection.	Manual micrometre measurement provided a reliable baseline for validating journal wear, supporting interpretation of scanner-derived data and anchoring the reverse-engineering inspection in workshop practice.
[77]	The method remains constrained by instrument error, sensitivity to wear-induced distortion, and the fundamental inability of conventional measurements alone to reproduce gear geometry unambiguously.	Manual measurement is highlighted for its accessibility, low cost, and practical suitability for preliminary geometric reconstruction of non-standard gears using workshop-available instruments and conventional procedures.
[84]	The work implies that manual measurement lacks the spatial completeness, speed, and robustness required for full-field mesoscale reconstruction, particularly where motion, translucency, or high reflectance are present.	The study effectively supersedes manual measurement by delivering high-resolution, non-contact panoramic 3D acquisition, well suited to mesoscale objects requiring dense geometric reconstruction and full-surface coverage.
[85]	The paper implies that manual measurement is comparatively slower, less comprehensive, and less effective for holistic spatial verification, especially when rapid three-dimensional comparison with design data is required.	Conventional manual surveying provides the foundational positional information needed for initial setting-out control and remains embedded in routine construction verification practice.
[9]	The method remains constrained by limited precision, incomplete capture of intricate geometry, dependence on operator skill, and poor scalability for digitally integrated remanufacturing pipelines.	The review presents manual measurement as a viable entry-level reverse-engineering route for simple components, particularly where affordability, immediacy, and workshop practicality outweigh precision demands.
[79]	The method remains constrained by labour-intensive sampling, limited efficiency on complex geometries, and the need for repeated human intervention before a machining-ready digital model is obtained.	Manual coordinate-based acquisition provides structured, high-integrity surface data that can support rigorous downstream reconstruction, diagnostic signal analysis, and machining-oriented geometric evaluation of sculptured surfaces.
[86]	The study highlights its limited suitability for complex geometries, owing to lower efficiency, higher susceptibility to human error, and reduced capability for detailed deviation analysis.	Manual measurement remains useful for basic dimensional checks and preliminary verification, particularly where simple geometric features can be assessed without advanced digital metrology.
[80]	The review effectively positions it as inadequate for scan-to-CAD and scan-to-simulation workflows, owing to poor data density, limited traceability, and weak support for task-specific uncertainty control.	Manual measurement retains limited value for preliminary dimensional checking and simple feature verification, particularly where rapid, low-complexity inspection is sufficient before digital reconstruction.

3.2. Non-Contact

Non-contact shape-acquisition methods determine geometry without requiring physical interaction between the measuring device and the component. Within the scope of this review, these methods are considered in terms of passive and active acquisition principles, with active approaches further encompassing reflective optical and transmissive techniques.

Vukašinović and Duhovnik [42] distinguish passive from active acquisition according to the source of information used for reconstruction. Passive methods infer geometry from information already present in the observed scene, whereas active methods introduce a controlled energy source and determine geometry from the interaction between the emitted and received signals.

3.2.1. Passive

Photogrammetry

Photogrammetric reconstruction is constrained primarily by feature visibility, image quality and achievable metric accuracy. Geng and Bidanda [87], drawing on the work reviewed by Tippetts et al. [88], highlight the trade-off between acquisition and processing effort and reconstruction accuracy in stereo-based methods. One of the

principal advantages of image-based three-dimensional modelling is its comparatively low entry cost: a modern camera or smartphone combined with suitable photogrammetric software may provide sufficient input for applications in which high-end metrological accuracy is not essential [89,90]. Photogrammetry is therefore attractive for preliminary reconstruction, heritage documentation, educational applications and geometrically tolerant reproduction. In some applications, the resulting mesh may also be transferred directly to an AM workflow without requiring complete parametric CAD reconstruction [91].

The photogrammetric studies summarised in Table 4 illustrate the trade-off between low-cost deployment, geometric coverage and metric reliability.

Table 4. Representative studies using photogrammetry in reverse-engineering applications.

Ref	Challenges	Highlights
[92]	The study demonstrates that photogrammetry can successfully support introductory reverse-engineering training, combining low cost, operational flexibility, and sufficiently realistic reconstructions for educational CAD and prototyping tasks.	Photogrammetry is highlighted as an accessible, economical and pedagogically effective entry point to reverse engineering, enabling satisfactory three-dimensional reconstructions with minimal equipment and broad educational applicability.
[93]	Performance remains constrained by reduced metric reliability relative to TLS, workflow fragmentation, and the absence of a clear universal methodology for integrating disjoint photogrammetric data sources into BIM.	Digital photogrammetry is highlighted for rapid acquisition, high-quality colour information, and strong visual representation, making it especially valuable for heritage documentation and BIM enrichment.
[94]	Its principal limitations concern longer processing times, dependence on image-acquisition quality and surface texture, and lower geometric fidelity than benchmark structured-light scanning.	Performance remains constrained by computationally intensive post-processing, sensitivity to photographic conditions, and reduced absolute accuracy relative to structured-light and professional laser-based acquisition.
[9]	The method remains constrained by precision trade-offs, environmental sensitivity, and error propagation, particularly where demanding tolerances or metrologically robust reconstruction are required.	The review presents photogrammetry as a democratised reconstruction route, capable of generating dense point clouds and enabling parametric modelling without dependence on industrial-grade scanners.
[95]	Performance remained constrained by statistically inferior trueness relative to conventional impressions and by angulation-dependent reductions in scan accuracy across the tested systems.	Photogrammetry enabled cost-effective and comparatively accurate brake-pad reconstruction, supporting rapid CAD regeneration, dimensional verification, and subsequent structural optimisation within a railway engineering context.
[96]	The study shows that photogrammetry can achieve clinically relevant full-arch implant accuracy while offering a fully digital alternative for recording multi-unit abutment positions.	Photogrammetry enabled full-arch implant capture without image stitching, producing clinically acceptable trueness overall and demonstrating practical potential for digital implant impression workflows.
[97]	Performance remained constrained by dimensional inconsistency, reconstruction noise, and loss of absolute scale, making photogrammetry less dependable than structured light for rigorous geometric evaluation.	Photogrammetry delivered visually rich, highly textured reconstructions and demonstrated clear utility for documentation and digital visualisation within an industrial digital-twin workflow.
[98]	Performance remained constrained by moderate metric accuracy, dependence on image quality and scale definition, and the requirement for additional mesh cleaning and geometric refinement.	The study demonstrates that photogrammetry can support rapid, resource-efficient reconstruction of industrial components, supplying usable geometric input for CAD redevelopment and physical adaptation tasks.
[80]	Its principal challenges lie in view-planning sensitivity, multi-station registration drift, environmental instability, and scale-dependent uncertainty, which can limit decision-grade fidelity for downstream tolerancing and simulation.	Photogrammetry is highlighted for scalable, efficient global geometry capture of large metal assets, particularly when integrated within hybrid workflows supporting retrofit, fit-up, and simulation-oriented reconstruction.
[99]	Its principal limitations concern expression-dependent variability, registration sensitivity during multimodal fusion, and reduced repeatability for parameters influenced by posterior tooth visibility and smile intensity.	The study demonstrates that stereophotogrammetric photogrammetry can capture subtle three-dimensional perioral adaptations with clinically meaningful precision, supporting more rigorous orthognathic smile evaluation.

Stereo Vision/SfM/MVS

Image-based 3D modelling derives from Computer Vision; it reconstructs a 3D model of an object by analysing the data provided from images [46]. According to Furukawa and Hernández [22], Multi-view Stereo (MVS) is the general term given to a group of techniques that use stereo correspondence as their main cue and use more than two images. Most of the photogrammetry software of today relies on Multi-view Stereo methods to automate the process in the 3D reconstruction of images [57]. The process can be briefly described through these steps:

- Data collection
- Data processing using photogrammetry software
- Surface generation from the point cloud.

Data collection consists of capturing multiple overlapping images. It is important to minimise blur and keep a proper framing of the object of analysis [89]; diffuse lighting is also important to prevent shadows from distorting the software's processing of the images [91].

The images captured are then processed by the photogrammetry software. Shape-from-motion (SfM) algorithms can reconstruct the camera pose by identifying matching features in the provided images; Westoby et al. [90] describe that these features are tracked from image to image, allowing the algorithm to estimate the camera positions and object coordinates.

The MVS algorithms, through triangulation of the common points in the overlapping images, are able to build a point cloud. Other popular techniques, such as depth map reconstructions, however, as stated by Furukawa and Hernández [22], depth maps suffice for various interesting applications such as scene analysis and visualisation; their main problem is how to merge them into a global 3D model. Furthermore, also mentions multiple sources regarding the many different techniques that merge multiple depth maps [88,100–104].

After the point cloud is complete, and the required manual adjustment of said data through the software, a surface mesh is generated from which a CAD model can be modelled upon. Certain surfaces and shapes pose significant limitations for this method; Furukawa and Hernández [22] classify three types: a lack of texture, thin structures and non-Lambertian surfaces. Lack of texture describes homogeneous surfaces and low roughness; this impedes photogrammetry algorithms from detecting and triangulating common points of reference. Furukawa and Hernández [22] conclude from a benchmark [105] that MVS algorithms are able to capture weak and intricate image textures from shading or shadowing effects, but it relies on a very high-quality set of images. Thin structures can be as wide as only a few pixels, and photogrammetry algorithms require substantially more pixels in width to pixel match. Controlled camera motion and a larger set of photographs can simplify the feature matching [106]. Non-Lambertian surfaces describe surfaces with non-diffuse effects. Transparent and specular reflective ("mirror like") surfaces are some of the examples, the reason MVS algorithms struggle with these surfaces is that they rely on Lambertian (diffuse) reflectance, as they provide the photometric consistency to match identical features.

Table 5 summarises studies employing stereo vision, structure-from-motion and multi-view stereo in reverse-engineering and geometric-reconstruction workflows.

Table 5. Representative studies using stereo vision, SfM, and MVS in reverse-engineering applications.

Ref	Challenges	Highlights
[107]	Its principal limitations concern lower geometric accuracy than conventional dense scanning, sensitivity to tracking noise and occlusion, and reliance on user-guided curve abstraction rather than full-field capture.	The active stereo system enables fast, low-cost, interactive three-dimensional acquisition, supporting real-time curve-based modelling with immediate visual feedback and efficient integration into reverse-engineering workflows.
[108]	Performance remained constrained by image-processing sensitivity, limited measurement fidelity for detailed surface reconstruction, and the need to complement stereo vision with a more precise scanner.	Stereo vision enabled rapid, sufficiently accurate defect-boundary localisation and automated alignment, substantially simplifying region targeting before high-precision scanning and repair-path generation.
[109]	Its principal limitations concern marker visibility, stereo occlusions, probe-orientation sensitivity, and accuracy degradation when board inclination reduces robust correspondence detection between the two cameras.	The study demonstrates that passive stereo vision can effectively support reverse engineering by tracking a tactile probe and integrating pointwise and full-field data.
[110]	Performance remained constrained by limited native sensitivity to subtle surface features, residual scan noise, and dependence on accurate cross-view registration during multi-position acquisition.	The active stereo-vision system provides accurate 3D point geometry and, when coupled with re-projected photometric information, supports finer surface-detail recovery without additional hardware complexity.
[111]	Performance remained constrained by point-cloud registration error, calibration uncertainty, edge noise, and the susceptibility of multi-view fusion to alignment imperfections and geometric redundancy.	The MVS approach enabled complete and comparatively accurate 360° reconstruction of fine workpieces, combining convenient system architecture, rapid acquisition, and effective multi-view point-cloud integration.
[112]	Performance remained constrained by lens-to-lens distortion inconsistency, calibration sensitivity, and the risk of substantial localisation error when stereo pairs exhibit mismatched optical behaviour.	The paper demonstrates that careful intrinsic calibration can markedly improve stereovision precision, particularly by stabilising disparity-based localisation in long-range multi-camera tracking applications.
[9]	The method remains constrained by image-quality dependence, unstable calibration, environmental sensitivity, and persistent reconstruction inaccuracies when high-precision mechanical fidelity is required.	Stereo vision, SfM, and MVS are highlighted for enabling comparatively low-cost, image-based three-dimensional reconstruction, supporting accessible digitisation workflows for mechanical parts and legacy components.
[113]	Performance remained constrained by passive-stereo weakness on low-feature surfaces, thresholding sensitivity, dependence on stable calibration, and visibility restrictions imposed by dual-camera line-of-sight.	The stereovision strategy enabled markerless 3D digitisation without scanner repositioning, offering a compact solution for confined spaces and surfaces inaccessible to conventional scanning workflows.
[114]	Performance remained constrained by domain-shift sensitivity, insufficient native spatial detail in ViT representations, and the enduring difficulty of correspondence estimation near boundaries and occlusions.	The stereo-vision framework improves disparity estimation in occluded and boundary regions by integrating frozen DINOv2 semantics with multi-scale attention fusion and geometry-guided refinement.

Caption: DINO—Distillation with No Labels; ViT—Vision Transformer.

3.2.2. Active

Active non-contact shape-acquisition methods comprise a major class of reverse-engineering technologies in which geometric information is obtained through the controlled emission of energy towards the object and the subsequent analysis of the returned or modified signal. Unlike passive approaches, which depend primarily on ambient visual information, active systems generate their own measurement conditions and therefore offer greater robustness in applications where surface texture is poor, illumination is variable, or geometric precision is a dominant requirement. Their performance, however, depends strongly on the interaction between the emitted energy and the material, optical, and geometric characteristics of the target. In reverse engineering, active methods are particularly valuable because they can provide dense and metrically reliable data with comparatively limited dependence on natural scene features. This category includes both surface-oriented optical systems and transmissive techniques, each suited to different measurement tasks, accuracy levels, and component complexities within the broader scan-to-model workflow.

Optical Surface Methods

Optical surface methods constitute the most widely adopted subgroup of active non-contact techniques in reverse engineering, owing to their combination of acquisition speed, portability, automation potential, and capacity to generate dense geometric datasets. These methods reconstruct surface geometry by projecting or emitting light onto the object and interpreting its deformation, reflection, or phase behaviour through calibrated optical principles. Their suitability is especially evident in industrial applications requiring rapid digitisation of external geometry for inspection, redesign, replication, or CAD reconstruction. Nevertheless, their performance is not uniform across all components, since highly reflective, transparent, dark, or geometrically intricate surfaces may compromise measurement quality. For this reason, optical surface methods must be assessed not only in terms of nominal accuracy, but also with respect to their practical behaviour under real acquisition conditions. Within this group, structured light, laser triangulation, and related interferometric approaches represent the principal technological routes.

Vukašinović and Duhovnik [42] state that optical surface methods emit a weaker source of energy (compared to transmissive methods) and measure the changes in the object surface's reflection. The review paper will focus on Laser and Structured Light scanners, which both use light waves as the energy source.

Structured Light

Structured light is a scanning method that relies on projecting structured patterns on a surface and triangulation for 3D reconstruction [115]. Zhang [116] points out the similarities with a stereo vision system, with the difference being the replacement of one camera with a projector. The projected patterns help this method avoid correspondence problems of passive stereo vision [19].

A Structured light scanner consists of two cameras and a projector; the projector projects a pattern on the object's surface, the pattern is distorted by the features of the object's surface, and the cameras capture the reflection of the distorted patterns from different perspectives [117–119]. The correspondence is established by analysing the distortion of captured structured images with known features (the patterns) projected by the projector. Furthermore, the reconstruction of the coordinates of the points is done through similar methods used in stereo vision techniques [120–123].

Structured light scanners are extremely versatile, being popular in several industries (entertainment, medical, manufacturing, etc.) due to their costs, variety in layouts (portable handheld scanners being a highlight) and fast data acquisition, being able to capture millions of points (for the point cloud 3D reconstruction) in seconds [120–123]. They can also be distinguished by the wavelength used: blue light and white light. In Huang et al. [124] study both of these technologies are reviewed, stating that white light scanners provide the possibility of measurements in different light conditions and a faster calibration process; however, they are less accurate than blue light scanners since blue light has a shorter wavelength. It is also important to note that white light scanners are significantly less expensive than blue light scanners.

RE with portable handheld structured light scanners is usually compared with handheld laser scanners. A major advantage of handheld structured light scanners compared with handheld laser scanners is the ability to capture colour and, most importantly, the non-reliance on positioning targets. Positioning targets are stickers placed on the surface of the object as a reference for the handheld scanner's self-positioning (dynamic referencing) [125]; these stickers can damage the surface of the object. Handheld structured light scanners have the capability to self-position through the textures and features of the object itself; this can be an issue on flat surfaces with a lack of texture. Transparent, very dark and highly reflective surfaces are also challenging to scan [126–129].

In short, RE with structured light scanners have several use cases; blue light scanners provide accurate, fast scans and portability without size limitations on the object of analysis, and can also be automated [130], making

them an ideal option for industrial applications while being significantly cheaper than a Tactile CMM [131]. White light scanners provide a more portable option in the form of handheld scanners and can self-position without the use of positioning targets, cutting down the time required. However, structured light scanners struggle with reflective surfaces, whereas laser scanners do not.

Table 6 compares representative structured-light studies, focusing on acquisition rate, reconstruction fidelity and sensitivity to surface and measurement conditions.

Table 6. Representative studies using structured-light scanning in reverse-engineering applications.

Ref	Challenges	Highlights
[132]	Its principal limitations concern dependence on suitable initialisation, inability to accommodate topology changes, and the need for complete multi-view coverage and reliable structured-light decoding.	Structured light is advanced beyond point-cloud generation, enabling direct mesh reconstruction from image intensities with improved sharp-edge recovery, strong noise robustness, and simultaneous multi-view optimisation.
[133]	Performance remained constrained by the difficulty of capturing global dependencies in conventional CNN-based profilometry and by the deployment cost of high-resolution structured-light models.	The study improves structured-light profilometry by delivering a lighter network architecture that preserves reconstruction accuracy while enhancing global feature perception through hybrid convolution–transformer decoding.
[75]	Its principal limitations arose from manual multi-view merging, incomplete capture of sharp edges, and surface wear effects, which increased negative deviations and local reconstruction uncertainty.	Laser triangulation enabled high-resolution capture of engineering components, supporting accurate CAD reconstruction of largely prismatic and mixed-form geometries with deviations broadly consistent with manufacturing tolerances.
[84]	Performance remains constrained by edge artefacts, shallow depth of field, trade-offs between resolution and speed, and the need for robust compensation under scattering and high-reflectance conditions.	The study advances structured-light metrology by enabling handheld panoramic mesoscopic 3D measurement with robust multi-view registration, improved fringe quality, and high-fidelity reconstruction in challenging scenarios.
[93]	The main limitation, regarding structured light, is the absence of any direct treatment of fringe projection, calibration strategy, or structured-light-specific reconstruction uncertainty.	The paper highlights the value of dense optical capture for generating high-fidelity geometric records that can subsequently support semantically enriched BIM and heritage-oriented digital workflows.
[134]	Its principal limitations concern sensitivity to preprocessing quality, residual susceptibility to noise, and the dependence of overall structured-light precision on reliable stripe segmentation.	The study strengthens structured-light measurement by improving stripe-centre extraction under severe reflections and surface undulations, delivering markedly better robustness, accuracy, and computational efficiency.
[135]	The principal limitation, with respect to structured light, is that acquisition-specific issues such as projection artefacts, reflectivity, calibration, and reconstruction uncertainty are not analysed directly.	The study highlights faster and more reliable primitive classification from scanner-derived mesh data, reducing modelling effort and supporting more efficient reconstruction of engineering-relevant CAD features.
[136]	Performance remains constrained by cumulative alignment error, marker-based registration demands, decimation-versus-accuracy compromises, and the need to tune triangulation geometry to object size and reflectivity.	The study demonstrates that structured-light active stereovision can function as a stand-alone reverse-engineering digitiser, combining rapid acquisition, portability, dense point clouds, and industrially useful accuracy.
[9]	Its principal limitations arise from reflective surfaces, complex freeform regions, and downstream mesh-processing sensitivity, which can impair fidelity, dimensional consistency, and robust automation.	The review positions structured-light scanning as a fast, precise, and industrially practical technology for capturing dense surface data suitable for remanufacturing and redesign.
[137]	Its principal limitations concern sensitivity to reflectivity, viewing angle, and environmental variability, together with calibration dependence and trade-offs between reconstruction quality and computational cost.	Structured light is highlighted for rapid, high-resolution, non-contact inspection, with the proposed methodology enabling repeatable evaluation of dimensional accuracy and point-cloud quality under industrial conditions.
[138]	Performance remained constrained by noise in extrinsic parameter estimation, calibration complexity, and the susceptibility of reconstruction accuracy to stripe-centre localisation errors.	The study demonstrates that structured light can achieve highly stable and accurate 3D measurement when supported by improved scanning-direction calibration and robust stripe extraction.
[139]	Performance remained constrained by the non-trivial interdependence of multiple optical degrees of freedom and by the computational difficulty of controlling structured light in complex media.	The article demonstrates that machine intelligence substantially extends structured-light capability, enabling data-driven generation, decoding, correction, and application of complex optical fields across scales and domains.
[80]	Its principal limitations arise from surface reflectivity, local texture, calibration sensitivity, occlusions, and coating-induced bias, all of which can compromise metrological traceability and downstream model credibility.	Structured-light scanning is highlighted for rapid, high-density acquisition of external metal geometries, supporting near-line digitisation, robust reconstruction workflows, and decision-grade scan-to-simulation pipelines.
[140]	Performance remained constrained by specular-surface incompatibility, calibration complexity, phase and fringe distortions, environmental sensitivity, and unresolved errors during multi-modal data fusion.	The review highlights structured light, particularly fringe projection profilometry, as a high-speed, full-field and adaptable solution for diffuse-region reconstruction within composite-surface metrology frameworks.

Laser Triangulation

Laser scanning or Laser Triangulation can be classified into two methods, time-of-flight and triangulation; this review paper will focus on triangulation methods since time-of-flight scanners are more suitable for terrestrial scanning (civil engineering, geology, archaeology, etc. [141–145]) as they can cover a very large volume of measurement at the cost of accuracy.

Triangulation scanners consist of a laser source and a pair of CCD (charge-coupled device) cameras [142]; the process consists of hitting the object's surface with a laser pattern, which can be a line or a grid, and the cameras capture the reflections of the reference pattern to determine the geometry of the surface through the distortions of the pattern [67,146,147].

There are two wavelengths used in these systems, red and blue lasers; blue lasers are more accurate due to a shorter wavelength but come at a higher cost. Triangulation scanners can be fitted in CMMs (optical CMMs) [130,148,149] and thus automated [13], and like structured light scanners, are also available in several layouts, including the highly portable and popular handheld format. Handheld laser scanners tend to be more accurate than the structured light counterparts and can also scan reflective surfaces; however, they require retroreflective stickers (positioning targets) to be able to self-position during scanning. Dynamic referencing is what allows the handheld scanner to move freely around the object, since the reference is based on the object itself rather than an outside fixed one; handheld scanners require to "see" at least three positioning targets. It is also important to mention that these stickers may or may not be placed on the object's surface; it depends on its size and the use of fixtures (which can be used to apply positioning targets).

Laser-triangulation applications reported in the reviewed literature are summarised in Table 7, including handheld, fixed and integrated metrology configurations.

Table 7. Representative studies using laser triangulation in reverse-engineering applications.

Ref	Challenges	Highlights
[150]	Performance remained constrained by heavy point-cloud datasets, laborious registration and modelling workflows, and the limited suitability of automated conversion for irregular traditional components.	Structured laser scanning is highlighted for precise acquisition of existing cultural-heritage geometry, supporting archive-grade point-cloud capture and subsequent BIM-based information management.
[151]	Its principal limitations concern alignment sensitivity, fixed-focus-induced reconstruction error, edge artefacts, shading effects, and lateral-resolution degradation towards the scan-field boundaries.	The paper demonstrates that laser triangulation can be substantially accelerated via fast optical scanning, achieving comparable profile measurements with far greater throughput.
[152]	Its principal challenges concern calibration dependence, sensor-to-sensor variability, speckle-induced uncertainty, optical limitations, and the need to restrict the effective measuring range to lower-error regions.	The paper demonstrates that laser triangulation sensors can be meaningfully assessed for length metrology through systematic calibration, statistical analysis, and predictive modelling from datasheet parameters.
[153]	Performance remained constrained by laser–surface interaction effects, software limitations, noise, missing surfaces, and the need for substantial post-processing to recover usable meshes.	The study demonstrates that low-cost laser triangulation can produce practically useful 3D meshes for small objects, especially when supported by open-source post-processing and surface reconstruction.
[154]	Performance remained constrained by transparent and glossy surfaces, refraction and specular reflection effects, partial line detection, and pronounced variability introduced by material colour and roughness.	The paper demonstrates that laser triangulation reliability can be significantly improved through material-specific optimisation of sensor orientation based on incidence-angle–intensity characteristics.
[155]	Its principal challenges concern coupled error sources, including speckle, surface roughness, inclination, calibration, machine geometric errors, environmental effects, and accuracy-sensitive path planning.	The review highlights laser triangulation as a particularly effective on-machine metrology solution, combining non-contact operation, micrometric accuracy, and large measuring range for complex surfaces.
[75]	Its principal limitations arose from manual multi-view merging, incomplete capture of sharp edges, and surface wear effects, which increased negative deviations and local reconstruction uncertainty.	Laser triangulation enabled high-resolution capture of engineering components, supporting accurate CAD reconstruction of largely prismatic and mixed-form geometries with deviations broadly consistent with manufacturing tolerances.
[9]	Its principal limitations arise from reflectivity-induced noise, incomplete capture of fine features, and error propagation during reconstruction, which can compromise dimensional fidelity and downstream manufacturability.	Laser triangulation is highlighted for rapid, high-density, non-contact surface acquisition, enabling efficient reconstruction, redesign, and remanufacturing of complex mechanical components within digital workflows.
[156]	Performance remained constrained by calibration demands, temperature and vibration sensitivity, feature occlusion, registration uncertainty, and scanner-dependent trade-offs between working volume and resolution.	The review highlights laser triangulation scanning as a powerful non-contact, full-field tool for capturing accurate surface geometry, geometric imperfections, and high-fidelity numerical-model input.
[157]	Performance remained constrained by material-dependent optical behaviour, deteriorating profile accuracy beyond about ±17° pitch, and limited transferability across different triangulation sensor geometries.	The study advances laser triangulation practice by systematically optimising sensor positioning and settings, thereby improving point-cloud completeness and profile accuracy across diverse industrial materials.
[158]	Performance remained constrained by geometric sensitivity to partial lead fractures, orientation-dependent detection gaps, alignment tolerance, and the limitations inherent to single-plane two-dimensional profiling.	The paper shows that laser triangulation offers a robust, economically viable means of high-throughput geometric inspection, combining near-zero false rejection with strong sustainability benefits.
[80]	Its principal challenges arise from surface-condition sensitivity, calibration dependence, coating-related bias, occlusion effects, and uncertainty introduced by filtering and registration within downstream reconstruction pipelines.	Laser triangulation is highlighted for fast, dense external-surface acquisition, practical shop-floor deployment, and strong suitability for traceable reconstruction workflows supporting simulation-oriented manufacturing decisions.
[159]	Performance remains constrained by inaccessible internal geometries, unavoidable scanning inaccuracies, mesh-cleaning requirements, scanner–software dependency, and the absence of rigorous dimensional or mechanical verification.	The study demonstrates that handheld laser triangulation can provide sufficiently accurate digital geometry for reconstructing undocumented, damaged polymer parts within an integrated reverse-engineering workflow.

Interferometry

Interferometry constitutes a high-precision active optical approach within non-contact shape acquisition, distinguished by its capacity to resolve extremely small variations in surface height, form, displacement, or optical path length through the controlled superposition of coherent light waves. In reverse-engineering contexts, their principal value lies not in general-purpose full-object digitisation, but in the metrological reconstruction of fine geometric detail, particularly where micrometric or sub-micrometric resolution is required. This makes interferometric techniques especially relevant for precision-engineered components, optical elements, micro-scale features, and surfaces whose topography must be characterised with exceptional sensitivity. Nevertheless, their applicability is constrained by practical limitations, including sensitivity to vibration, environmental instability, restricted measurement range, and difficulties associated with discontinuous, highly rough, or optically complex surfaces. For these reasons, interferometry is best understood as a specialised optical surface method, complementing rather than replacing more versatile acquisition routes such as structured light or laser triangulation.

Table 8 collates interferometric approaches relevant to high-resolution surface measurement and geometric reconstruction.

Table 8. Representative studies using interferometric techniques in reverse-engineering applications.

Ref	Challenges	Highlights
[160]	Performance remained constrained by sensor-dependent crosstalk, wavelength-specific phase-shift errors, noise amplification in phase subtraction, and trade-offs between cost, spatial resolution, and measurable depth.	The review highlights multi-colour interferometry as a fast, versatile route to ambiguity-resolved optical metrology, enabling simultaneous multi-wavelength acquisition for discontinuous, rough, and dynamic specimens.
[161]	Its principal challenges concern sensitivity to environmental disturbance, system noise, scanning-interval selection, and algorithm-dependent trade-offs between reconstruction accuracy, robustness, and computational efficiency.	The paper demonstrates that interferometric surface reconstruction benefits markedly from Hilbert-transform and FFT-based envelope detection, which outperform centroid estimation in accuracy and noise immunity.
[162]	Its principal challenges concern the ill-posed nature of interferometric inverse problems, sensitivity to non-ideal acquisition conditions, and the difficulty of ensuring robust, generalisable learning-based solutions.	The review positions interferometry as a foundational optical-metrology modality and shows that deep learning is increasingly enhancing fringe denoising, phase retrieval, unwrapping, and error compensation.
[163]	Performance remained constrained by tunable-focus-lens astigmatism, temperature-dependent focal drift, digitisation and contour-extraction error, and the assumption of optically uniform, parallel-sided transparent specimens.	The study advances interferometric metrology by introducing an actively tunable Twyman–Green configuration that enables bulk-motion-free thickness and refractive-index characterisation of transparent samples.
[78]	The main challenge, regarding interferometry, is the absence of any substantive discussion of interferometric principles, medical implementations, performance metrics, or application-specific advantages.	From an interferometry perspective, the article is useful chiefly for classifying interferometry as a recognised active non-contact scanning principle within broader medical reverse-engineering workflows.
[164]	Performance remained constrained by speckle-dominated noise, calibration demands for dual-wavelength synthesis, potential instability of recorded intensities, and finite allowable sample tilt and height.	The study advances interferometric profilometry by enabling compact, single-shot dual-wavelength measurement of large, rough, dynamic surfaces through polarisation-resolved acquisition and simplified processing.
[124]	Its principal challenges concern periodic nonlinear errors, phase-demodulation complexity, environmental sensitivity, and persistent trade-offs between measurement range, absolute capability, structural complexity, and stability.	The review highlights interferometry as the metrological benchmark for ultra-precise length measurement, offering exceptional resolution, traceability, and expanding capability through optical frequency comb integration.
[165]	Its principal challenges concern line-of-sight restriction, multiple-target interference within range bins, incomplete 3D displacement retrieval, material-dependent reflection behaviour, and limited routine adoption in practice.	The review establishes ground-based interferometric radar as a high-resolution, rapid, non-contact technique for bridge monitoring, particularly effective for displacement measurement and dynamic feature extraction.

Transmissive—Computed Tomography Scanning (CT Scan)

Transmissive methods emit a powerful energy and analyse the gradients of energy that penetrates the object of analysis [42]. The review paper will focus on Computed Tomography scanners.

CT Scanning is a technique that is able to scan internal geometries of an object non-destructively, which was first applied and widely used in Medicine [166,167] and later adapted for industrial practices [168,169] (for example, casting inspection in foundries [170,171]).

A comparison between a medical and industrial CT scanner was done by du Plessis et al. [172], where it can be concluded that industrial CT scanners have a slower scan time (prolonged radiation exposure), higher energy output (material's density and dimensions may impose restrictions), higher cost and higher accuracy.

Vozár et al. [51] stated that X-ray tomography is a class of radiological examination techniques where X-ray tube motion is a common feature, in which these references are cited [167,173–175]

The scanning system of a CT Scanner consists of an X-ray lamp and an array of detectors. The object is placed between these two devices; the X-rays pass through it and are weakened by absorption; the rays that pass through the object are collected by the detectors; the radiation measured by the detectors is converted to an electrical signal and then sent to the CT Scanner's computer; the output represents a tomographic image. During the scanning, there's a combination of two movements, rotational and linear; these can be done by the scanning system or the table where the object is placed, depending on the type of CT scanner. For example, in a medical CT, the scanning system is located in a ring which does the rotational movement, and the table does the linear movement through the ring [57,167,176].

There are two types of CT Scanners: fan beam (FBCT) and cone beam (CBCT, the most recent layout). Scarfe and Farman [177] presented a thorough explanation of CBCT Scanners, describing the lower radiation exposure, which is ideal in medical applications and hence why its usage in maxillofacial radiology [178,179].

Reverse engineering applications in Medicine are used with CT scanning [180,181]. Le et al. [182] list several end-use applications in Table 2, showcasing examples within those applications; some examples are implants for bone reconstruction, medical training models and hip or knee implants. Furthermore, Kumar et al. [183] presented a medical reverse engineering process of a human joint with 3D printing (Fused Deposition Modelling) manufacturing, which can be valuable for biomedical studies of a patient.

RE applications with CT scanners are more significant in medical applications than industrial ones due to the high costs of industrial CTs (compared with other alternatives) and their size imposing restrictions on the dimensions of the object of analysis. However, a medical-grade CT scanner can be used for RE even if said application isn't medical, at the cost of accuracy [172]. Further studies regarding the accuracy of CT Scanning were made by Hiller and Hornberger [184].

To summarise, RE with CT Scanning can be used to scan internal and complex geometries [60]; it isn't compromised by surface optical properties (for example, transparency); it can gather enough data for 3D reconstruction with just one setup (where other methods require rotating or moving the part to scan inaccessible geometries) and identify the object's material [185]. However, the cost of CT Scanners can be very expensive (especially industrial CT Scanners [172]), the dimensions of the objects they can scan are limited by the size of the CT scanner, and it is unsuitable for objects that are not penetrable by X-rays due to their density or thickness [84]. Furthermore, Hiller and Hornberger [184] concluded that necessary significant effects that limit measurement accuracy and repeatability for individual cases are unknown, which leads to unreliable reference measurement data.

Table 9 summarises CT-based studies covering external and internal geometric reconstruction, segmentation, dimensional assessment and application-specific limitations.

Table 9. Representative studies using computed tomography in reverse-engineering applications.

Ref	Challenges	Highlights
[186]	Progress remains constrained by disparate partial solutions, limited experimental validation in some studies, unresolved feedback-driven orientation optimisation, and the difficulty of generalising across applications.	The paper advances CT scanning by framing automation as a complete architectural problem, linking robotic handling, trajectory optimisation, reconstruction, and defect-analysis stages.
[187]	CT use remains constrained by radiation burden, limited justification for routine orthodontic cases, dependence on advanced software and expertise, and integration demands within complex digital workflows.	The article highlights CBCT as the foundational CT-based reverse-engineering tool in digital dentistry, enabling accurate three-dimensional craniofacial reconstruction, segmentation, diagnosis, and treatment planning.
[188]	Performance remains constrained by undersampling-induced artefacts, system-scale deployment demands, reconstruction dependence on learned priors, and the trade-off between imaging quality, speed, and hardware count.	The study advances industrial CT by proposing a stationary, conveyor-integrated real-time architecture that combines sparse-view reconstruction with deep-learning enhancement for rapid non-destructive inspection.

Table 9. *Cont.*

Ref	Challenges	Highlights
[75]	Accuracy remained constrained by anisotropic voxel structure, threshold-based segmentation decisions, mesh regularisation demands, and the time-intensive generation of numerous NURBS surface patches.	CT scanning enabled non-contact acquisition of anatomically complex internal and external geometry, providing volumetric medical data suitable for segmentation, STL generation, and subsequent CAD reconstruction.
[78]	CT-based workflows remain constrained by radiation-related concerns, reconstruction uncertainty, data-processing demands, and the difficulty of translating image-derived geometry into clinically reliable solid models.	The paper shows that CT scanning underpins medically oriented reverse engineering by supplying anatomically faithful volumetric datasets suitable for personalised reconstruction and custom device development.
[189]	Its principal challenges concern ambiguous material mapping, limited public datasets, domain-specific acquisition constraints, imbalance between clinical and industrial evidence, and persistent reliance on expert knowledge	The review highlights CT's growing transition from physics-based material decomposition towards deep learning, clarifying how data-driven methods can improve material-sensitive imaging accuracy and robustness.
[190]	Its principal challenges concern medical-CT resolution limits, metallic artefacts, incomplete rendering of armatures, material-segmentation ambiguities, and the need for substantial expert-led post-processing	The paper shows that CT-based volumetric analysis can extend cultural-heritage documentation beyond surface capture by enabling material-specific 3D reconstructions of internal figurine structures.
[191]	Regarding CT, the main challenge is analytical superficiality, since acquisition parameters, segmentation limitations, reconstruction uncertainties, and modality-specific trade-offs are not examined in depth.	The article acknowledges CT scanning as an enabling medical 3D digitisation technology, particularly for generating anatomical models that support precise preoperative planning.
[9]	The method remains constrained by reconstruction complexity, feature-extraction uncertainty, and sensitivity to material combinations, which can compromise geometric fidelity and downstream modelling reliability.	The review presents CT as a uniquely valuable modality for capturing inaccessible internal architecture, thereby supporting simulation-ready reconstruction of mechanically complex, legacy, and high-value components.
[192]	Its principal challenges concern field-of-view limitations, dry-state rather than in-situ analysis, parameter-sensitive pore segmentation, and the difficulty of fully capturing anisotropic porous-network behaviour	The study shows that micro-CT, combined with SNOW-based pore partitioning, enables high-resolution, pore-specific characterisation of cellulose networks beyond conventional bulk porosity metrics.
[193]	Performance remains constrained by tissue-composition effects within trabecular bone, simplifying assumptions in material decomposition, limited sample scope, and the still restricted clinical availability of PCT.	The study shows that photon-counting and dual-energy CT, using virtual monochromatic imaging, improve BV/TV assessment by reducing sensitivity to marrow-composition variability and calibration-phantom dependence.
[80]	The method remains constrained by reconstruction artefacts, segmentation sensitivity, and the difficulty of establishing traceable surface determination for simulation-ready, mechanically credible geometries.	XCT is highlighted for non-destructive capture of both internal and external geometry, enabling decision-grade digital models for hidden channels, complex AM parts, and repair-critical components.

Caption: BV/TV—Bone Volume/Total Volume: CBCT—Cone-Beam Computed Tomography; NURBS—Non-Uniform Rational B-Splines, PCT—Photon-Counting Computed Tomography; XCT—X-Ray Computed Tomography

4. Discussion

The Discussion is organised around reverse engineering as an end-to-end engineering chain that connects the physical component to its final digital and engineering use. Conceptually, this chain can be represented as: physical component and engineering requirements → acquisition strategy → primary geometric data → registration and processing → mesh or surface representation → CAD abstraction → metrological validation → engineering use. The stages are strongly interdependent: component geometry, material and surface condition constrain acquisition; acquisition determines the density, completeness, spatial organisation and uncertainty of the measured data; these characteristics affect registration, cleaning, meshing and surface fitting; and the resulting geometry determines the feasibility and reliability of CAD reconstruction and subsequent dimensional verification. Final model usability therefore depends on the propagation and control of information and uncertainty across the complete chain rather than on the nominal performance of the acquisition system alone.

This sequence is not identical for every acquisition principle. Optical systems commonly generate dense point clouds before meshing, tactile measurements may provide sparse or structured coordinate data that can be used directly for feature reconstruction or validation, and CT initially produces volumetric data requiring segmentation and surface extraction. The workflow should therefore be interpreted as a functional engineering framework rather

than as a rigid sequence of mandatory data representations. The following subsections examine the principal decisions and dependencies along this chain.

4.1. Physical-Component Requirements and Acquisition Strategy

The reverse-engineering chain begins with the physical component and the engineering objective for which its geometry is being recovered. Geometry, scale, material, surface optical behaviour, accessibility, presence of internal features and required tolerance determine which acquisition principles are technically feasible, while acquisition rate, portability, cost and intended downstream use determine their practical suitability. Acquisition-method selection should therefore be regarded as the first decision stage of the end-to-end workflow rather than as an isolated comparison of scanner specifications. Table 10 compares the principal acquisition routes against these criteria.

Metrological terminology. The comparative assessment requires a clear distinction between several measurement concepts that are sometimes used interchangeably in the reverse-engineering literature. In this review, measurement accuracy describes the degree of agreement between a measurement result and the corresponding reference quantity. Measurement precision concerns the closeness of agreement among repeated measurement results obtained under specified conditions and therefore primarily reflects measurement dispersion rather than agreement with a reference value. Repeatability represents precision under repeatability conditions, in which the relevant measurement procedure, system, operator, location and other operating conditions are maintained over a short time interval.

Resolution describes the smallest change or spatial detail that a measurement system can discriminate, although its practical expression depends on the acquisition principle. For example, surface-point spacing, image resolution, voxel size and interferometric spatial resolution describe different properties and should not be treated as directly equivalent measures of dimensional accuracy. Measurement uncertainty, by contrast, characterises the dispersion associated with the quantity value attributed to the measurand and expresses the level of confidence that can be assigned to the measurement result under the specified measurement conditions.

These characteristics are related but not interchangeable. High resolution does not necessarily imply high accuracy; a system may provide highly precise and repeatable measurements while retaining systematic deviation from the reference geometry; and good repeatability alone does not establish low measurement uncertainty or metrological traceability. Accordingly, the terms are used separately throughout the following comparison, and performance claims reported in the reviewed literature are interpreted according to the metrological quantity actually evaluated wherever the available methodological information permits this distinction.

The comparison demonstrates that methods offering the highest metrological confidence are not necessarily those providing the greatest acquisition efficiency. Tactile CMMs remain particularly effective when traceable dimensional verification and repeatability are the primary requirements. Their relatively low data-acquisition rate and dependence on physical accessibility, however, restrict their suitability for the rapid digitisation of complex freeform components. Manual measurement presents similar geometric limitations and is more appropriately regarded as a low-cost solution for simple dimensions than as a comprehensive digitisation route.

Photogrammetry occupies the opposite end of the economic spectrum. Its limited equipment requirements, portability, and scalability make it attractive for large objects and applications in which moderate geometric accuracy is acceptable. Nevertheless, its performance depends strongly on image acquisition quality and the presence of identifiable surface features. Consequently, the apparent efficiency of image capture may be offset by extensive preprocessing, image matching, point-cloud cleaning, and correction of incomplete regions. It is therefore particularly effective where cost and measurement flexibility are prioritised over traceable micrometre-level accuracy.

Structured-light and laser-triangulation systems provide a more balanced compromise between acquisition speed, point density, accuracy, and industrial flexibility. Both can digitise freeform external surfaces considerably more efficiently than tactile probing. Structured-light systems are especially advantageous for the rapid capture of dense surface data, whereas laser-based systems offer flexible handheld, robotic, and CMM-mounted configurations. However, neither method eliminates the influence of optical surface behaviour, occlusion, calibration, and scan registration. Surface preparation, multiple viewpoints, and positioning targets may therefore remain necessary, increasing the effective inspection time and potentially modifying sensitive surfaces.

Industrial CT provides the most distinctive capability because it permits the volumetric reconstruction of internal and external geometry without sectioning the component. This characteristic makes it particularly valuable for components containing concealed channels, cavities, lattice structures, or inaccessible features. Its wider use is nevertheless constrained by equipment cost, acquisition and reconstruction time, part-size restrictions, X-ray

attenuation, and measurement uncertainty. CT is consequently most defensible for high-value components or applications in which internal geometry cannot be reconstructed reliably through surface-based methods.

The comparative evidence therefore confirms that no individual acquisition technique is universally preferable. Industrial method selection should instead be formulated as a multi-criteria decision problem. Optical techniques are generally favoured when rapid and dense external-surface acquisition is required; tactile CMMs remain appropriate for high-confidence dimensional verification; photogrammetry offers an economical and portable solution for larger objects and less demanding accuracy requirements; and CT is most valuable where internal geometry is decisive. Hybrid workflows are increasingly relevant because they allow the dense coverage of optical acquisition to be combined with tactile traceability or volumetric information. Their industrial benefit, however, depends on effective calibration, registration, interoperability, and uncertainty management.

To consolidate these observations within a common decision framework, Table 10 compares the principal shape-acquisition routes in terms of metrological accuracy, spatial or geometric resolution, acquisition speed, relative cost, portability, sensitivity to surface conditions, capability for internal-feature acquisition, post-processing complexity, and representative industrial suitability. These criteria were selected because they reflect both measurement performance and the practical constraints that govern technology selection in component-oriented reverse engineering.

Table 10. Comparative assessment of the principal shape-acquisition techniques used in reverse engineering.

Technique	Acquisition Efficiency	Relative Cost	Principal Strengths	Principal Limitations	Representative Industrial Applicability
Manual dimensional measurement	Low	Low	Simple implementation; minimal equipment requirements; suitable for basic prismatic dimensions and preliminary inspection	Highly operator-dependent; limited point density; unsuitable for freeform surfaces, complex geometries, and comprehensive digital reconstruction	Simple components, maintenance activities, preliminary dimensional verification, and low-volume reproduction
Tactile coordinate measuring machine (CMM)	Low to medium	High	High dimensional accuracy and repeatability; established metrological traceability; effective for precise inspection of accessible geometric features	Point-by-point or line-based acquisition can be time-consuming; requires fixturing and, frequently, a controlled environment; contact forces may affect compliant or delicate components; limited access to concealed geometry	Precision inspection, calibration, dimensional validation, tooling, aerospace, automotive, and high-value manufactured components
Photogrammetry/ SfM–MVS	Medium to high	Low	Low entry cost; high portability; scalable measurement volume; colour and texture capture; suitable for large objects and field deployment	Accuracy depends strongly on image quality, calibration, overlap, texture, and lighting; limited performance on reflective, transparent, homogeneous, or very dark surfaces; substantial computational processing may be required	Preliminary reconstruction, heritage documentation, large components, low-cost digitisation, customised products, and applications with moderate accuracy requirements
Structured-light scanning	High	Medium	Rapid acquisition of dense point clouds; comparatively high surface resolution; portable and automated configurations available; efficient for freeform external geometry	Line-of-sight restriction; sensitivity to ambient illumination and optically challenging surfaces; reflective, transparent, or dark components may require surface preparation; limited capability for internal geometry	Industrial component digitisation, dimensional inspection, product development, tooling, biomedical modelling, and quality control
Laser triangulation scanning	High	Medium to high	Dense and comparatively accurate surface acquisition; suitable for localised geometric detail; compatible with handheld, robotic, and CMM-mounted systems; strong automation potential	Restricted to visible surfaces; sensitive to scanning angle, stand-off distance, occlusion, and some reflective conditions; handheld systems may require positioning targets; multiple scans and registration are commonly necessary	Automotive and aerospace inspection, tooling, mould and die reconstruction, robotic scanning, dimensional verification, and production-line metrology
Industrial CT	Low to medium	Very high	Non-destructive acquisition of both external and internal geometry; reduced line-of-sight constraints; volumetric inspection within a single acquisition framework; simultaneous assessment of concealed features and internal discontinuities	High capital and operating cost; acquisition and reconstruction may be time-intensive; measurement volume, material density, and section thickness impose restrictions; accuracy is affected by voxel size, beam hardening, scattering, and calibration.	Internal inspection of complex components, castings, additive-manufactured parts, assemblies, biomedical devices, and high-value components with concealed features

Table 10. *Cont.*

Technique	Acquisition Efficiency	Relative Cost	Principal Strengths	Principal Limitations	Representative Industrial Applicability
Hybrid or multi-sensor acquisition	Medium	High to very high	Combines complementary capabilities; enables optical systems to provide dense surface data while tactile or volumetric methods supply traceable or internal measurements; may improve completeness and validation confidence.	Increased equipment, registration, interoperability, and data-fusion complexity; higher capital cost; requires robust calibration and reference-system alignment.	High-value components, complex assemblies, aerospace structures, precision tooling, and applications requiring both comprehensive coverage and metrological verification

Disclaimer: The ratings are qualitative and represent general tendencies across the reviewed literature rather than fixed performance classes. Direct numerical comparison of accuracy and resolution across technologies is not always appropriate because these quantities are defined and reported differently according to measurement principle—for example, probe sampling in tactile CMMs, point spacing in optical scanning, voxel size in CT, and lateral or axial resolution in interferometric systems. Actual performance depends on equipment configuration, measurement volume, calibration, acquisition parameters, component geometry and material, environmental conditions, and the validation procedure adopted.

A further distinction is required between nominal scanner capability and effective workflow performance. Scanner specifications such as stated accuracy, resolution, point-acquisition rate or nominal scanning speed characterise the measurement system under defined operating conditions, but they do not by themselves describe the performance achievable during reconstruction of a complex engineering component. Effective workflow performance also depends on the operations required to obtain, process and validate a usable geometric model.

These additional operations can include calibration and reference verification, component fixturing, surface preparation, positioning-target placement, selection of measurement viewpoints or paths, scanner repositioning, repeated acquisition of occluded regions, multi-view registration, removal of artefacts and outliers, data cleaning, mesh or surface reconstruction, dimensional validation and manual interpretation. The influence of these stages can be substantial. A system offering a high nominal acquisition rate may provide limited overall time savings if extensive preparation and registration are required, while high nominal spatial resolution does not guarantee equivalent reconstruction fidelity where surface behaviour, occlusion, calibration or processing modifies the acquired geometry.

For this reason, the comparisons presented in this review distinguish, where the available evidence permits, between characteristics of the acquisition device and performance of the complete reverse-engineering workflow. Manufacturer-reported or system-level specifications should be interpreted as capability indicators rather than as direct measures of achievable industrial performance. Workflow evaluation should instead consider the effective time, dimensional confidence, geometric completeness, processing effort and operator intervention required to obtain a validated model suitable for its intended engineering use.

Within this workflow-level interpretation, acquisition time alone is also an incomplete measure of industrial productivity. A more representative indicator is the effective reverse-engineering time, defined here as the elapsed time required to progress from preparation of the physical component to a reconstructed and validated digital model suitable for its intended engineering use. This interval includes activities that may occur before and after the nominal scanning operation and that can substantially alter the practical efficiency of an acquisition strategy.

For a predominantly sequential workflow, the principal contributions can be represented conceptually as in the Equation (1)

$$T_{RE,eff} = T_{prep} + T_{setup} + T_{acq} + T_{reg} + T_{proc} + T_{recon} + T_{CAD} + T_{val}, \quad (1)$$

where T_{prep} denotes component preparation, including cleaning or surface treatment; T_{setup} includes fixturing, calibration, target placement and reference definition; T_{acq} represents geometric acquisition, including repeated views or sensor repositioning where required; T_{reg} represents registration and coordinate-system alignment; T_{proc} includes filtering, cleaning and other data-processing operations; T_{recon} represents mesh or surface reconstruction; T_{CAD} represents CAD abstraction or parametric modelling where required; and T_{val} represents the validation necessary to establish fitness for the intended engineering use.

This expression should be interpreted as a reporting framework rather than as a universal additive model, since individual stages may overlap, be automated, be repeated iteratively or occur in parallel. Future studies should therefore report both the total elapsed time from component preparation to validated output and, where practicable, the duration of the principal workflow stages. Active operator time may also be reported separately

from computational or unattended processing time, since the two quantities have different implications for industrial labour demand and throughput.

A similar workflow-level distinction is required for economic assessment. Equipment purchase price or nominal capital cost does not represent the complete economic burden associated with producing a validated reverse-engineered model. An acquisition system with relatively low initial cost may require extensive operator intervention, surface preparation, repeated measurements or downstream processing, whereas a system with greater capital investment may reduce some of these requirements for a particular application. Economic performance should therefore be assessed across the complete reverse-engineering workflow rather than from acquisition-hardware cost alone.

For a defined reverse-engineering task, the effective reverse-engineering cost can be represented conceptually as written in Equation (2)

$$C_{RE,eff} = C_{hw} + C_{sw} + C_{cal} + C_{fix} + C_{cons} + C_{lab} + C_{comp} + C_{val} + C_{maint} + C_{re} \quad (2)$$

where C_{hw} represents the proportion of hardware or capital cost attributable to the task; C_{sw} represents software licensing or usage cost; C_{cal} includes calibration and reference-system requirements; C_{fix} represents fixtures, positioning aids or other dedicated setup resources; C_{cons} includes consumables and surface-preparation materials; C_{lab} represents operator and specialist labour; C_{comp} represents computational processing resources; C_{val} represents metrological validation; C_{maint} represents the relevant maintenance burden; and C_{re} represents costs associated with repeated acquisition, processing or reconstruction when the initial workflow does not provide an acceptable result.

The formulation is intended as an economic reporting framework rather than as a universal costing model. The magnitude and allocation of individual contributions depend on equipment utilisation, organisational accounting practices, component complexity, automation level and the required engineering output. Future comparative studies would nevertheless benefit from reporting these principal cost contributions separately, or at least from distinguishing capital investment from the variable and labour-related costs required to obtain a validated model.

The comparison in Table 10 also shows that technology selection changes according to the dominant engineering requirement. Where dimensional traceability is decisive, tactile CMMs remain preferable despite their lower acquisition efficiency. Where dense external geometry must be acquired rapidly, structured-light and laser-triangulation systems offer a stronger balance between speed, resolution and industrial flexibility. Photogrammetry is advantageous when portability, measurement volume and cost dominate the decision, whereas CT becomes technically justified when concealed or internal geometry is essential. Interferometric techniques occupy a more specialised role where very high local surface resolution is required. Hybrid approaches become attractive when no single measurement principle can satisfy the complete combination of coverage, accuracy and accessibility.

4.1.1. Reverse-Engineering Technology Selection Framework

The comparative evidence examined in this review can be translated into a structured engineering framework for selecting a reverse-engineering acquisition strategy. The proposed framework does not seek to identify a universally superior technology. Instead, it progressively eliminates technically unsuitable routes and compares the remaining alternatives according to the requirements imposed by the component, the desired digital representation, the required metrological confidence and the intended engineering application. Technology selection is therefore treated as a constrained, multi-criteria decision process extending beyond scanner performance alone.

Stage 1—Engineering objective and required output.

The selection process begins by defining the engineering objective and the required digital output. A workflow intended primarily for visualisation, documentation or geometrically tolerant reproduction does not impose the same requirements as one intended for dimensional inspection, tolerance-sensitive redesign, finite-element analysis, tooling manufacture or production of a replacement component. The required output also determines whether a polygonal mesh is sufficient or whether an editable and dimensionally validated CAD representation is required. Metrological requirements, including acceptable uncertainty and the need for traceability, should therefore be established before acquisition technology is selected..

Stage 2—Physical and geometric characteristics.

Component dimensions and measurement volume should be evaluated together with geometric complexity, freeform content, feature scale, accessibility and the presence of concealed or internal geometry, because the suitability and attainable performance of an acquisition principle may change substantially with component scale.

Small or localised features may favour acquisition routes capable of higher spatial resolution or tighter dimensional control, whereas increasing component dimensions place greater emphasis on measurement volume, portability and acquisition coverage. Geometric accessibility should also be treated as a continuum rather than as a simple distinction between external and internal geometry. Externally accessible surfaces, undercuts, narrow recesses, deep cavities, thin-wall features, internal channels and fully enclosed volumes impose progressively different requirements in terms of line-of-sight access, sensor orientation, probe accessibility, spatial resolution and volumetric imaging capability. Where internal geometry is essential, surface-based optical and tactile systems alone are insufficient and volumetric methods such as CT, or a hybrid strategy incorporating CT, become necessary. Where geometry is externally accessible, tactile, photogrammetric and optical surface-acquisition routes remain potential alternatives, with their suitability depending on the required sampling density and dimensional confidence. Component scale should therefore be considered jointly with the required dimensional tolerance rather than as an independent selection variable.

Stage 3—Material and surface compatibility.

Material characteristics and surface optical behaviour determine whether the remaining acquisition principles are physically and optically compatible with the component. Surface optical behaviour should be treated as a cross-cutting technology-selection variable because the same surface condition can influence several non-contact acquisition principles through different physical mechanisms. Relevant conditions include high reflectivity or specularity, transparency or translucency, very low reflectance associated with dark surfaces, insufficient natural texture or homogeneous appearance, and spatially heterogeneous or mixed surface finishes.

Photogrammetric acquisition depends strongly on identifiable image features, suitable texture and stable image formation, making low-texture, transparent, highly reflective and very dark surfaces particularly challenging. Structured-light systems generate their own projected texture but still require the projected pattern to be observed reliably and may therefore be affected by specular reflection, transparency and weak optical return. Laser triangulation can provide greater robustness than structured light for some reflective industrial surfaces, although its performance remains dependent on material optical behaviour, incidence angle, surface roughness and sensor configuration. Interferometric methods offer very high local sensitivity but can likewise be constrained by optically complex, rough or discontinuous surfaces.

Tactile coordinate measurement and CT provide useful contrasts because their measurement principles are not governed directly by visible-surface optical behaviour. Tactile measurement instead depends on physical accessibility, contact suitability and probe–surface interaction, while CT performance is governed principally by material attenuation, section thickness, measurement volume and volumetric reconstruction conditions. Surface optical behaviour can therefore become a decisive criterion for selecting between measurement principles rather than merely a secondary limitation of an otherwise selected scanner.

Surface preparation may mitigate some optical limitations through matting coatings or other treatments, but such interventions introduce a metrological trade-off. In addition to increasing effective reverse-engineering time and cost, an applied layer may modify the geometry presented to the sensor and introduce systematic or spatially varying dimensional effects. Surface treatment should therefore be considered part of the measurement process and, for tolerance-sensitive applications, its influence should be characterised or incorporated into the uncertainty assessment. Technologies whose measurement principle remains fundamentally incompatible with the untreated component surface should alternatively be excluded, or another acquisition or hybrid route considered.

Stage 4—Metrological and operational requirements.

Required tolerance, repeatability and traceability must be considered together with acquisition rate, measurement volume, portability, environmental constraints, available equipment and cost. Tactile CMMs remain particularly appropriate where dimensional confidence dominates the decision, whereas structured-light and laser-triangulation systems are advantageous where dense external geometry and acquisition speed are priorities. Photogrammetry becomes attractive when portability, measurement scale and low equipment cost dominate and moderate dimensional requirements are acceptable, while CT is justified where access to concealed geometry outweighs its greater cost and processing burden. These relationships are synthesised in Table 10.

Stage 5—Downstream reconstruction compatibility.

Technology selection should consider not only whether a system can acquire the component, but also whether the resulting data are suitable for the required processing and modelling route. Sparse but traceable coordinate measurements can constrain critical dimensions and analytical features but may be inadequate for complete freeform reconstruction. Dense optical data facilitate mesh generation but may introduce registration, occlusion and artefact-correction requirements. CT provides volumetric completeness but introduces segmentation- and threshold-dependent reconstruction. The expected point-cloud or volumetric processing effort, mesh-generation

requirements, CAD abstraction and preservation of design-relevant information should therefore form part of the acquisition decision rather than being considered only after scanning.

Stage 6—Validation strategy and final engineering use.

The reconstructed model should be verified according to the task for which it was generated. Visual similarity may be sufficient for documentation-oriented applications, whereas inspection, manufacturing, simulation and tolerance modification require greater dimensional confidence and, where appropriate, traceable reference measurements. The selected workflow is considered technically appropriate only when the acquisition and reconstruction chain can provide the information and uncertainty level required by the final application.

When no individual acquisition route satisfies the combined requirements for accessibility, geometric completeness, data density and metrological confidence, the framework directs the user towards a hybrid or multi-sensor strategy. Dense optical acquisition may, for example, be combined with tactile measurements of critical features, while CT may supplement surface scanning where concealed geometry is present. Hybrid acquisition should not, however, be adopted solely to maximise data quantity, since the benefits must justify the additional calibration, registration, coordinate-system alignment and uncertainty-management requirements.

The resulting selection process is summarised in Figure 9. Rather than assigning universal numerical scores or fixed weights to the decision criteria, the framework distinguishes between mandatory constraints, which determine technical feasibility, and optimisation criteria, which differentiate among the feasible alternatives. This distinction is necessary because the relative importance of accuracy, acquisition time, cost, portability and processing effort varies with the engineering application. The framework therefore provides a repeatable decision logic while retaining the flexibility required for different reverse-engineering contexts.

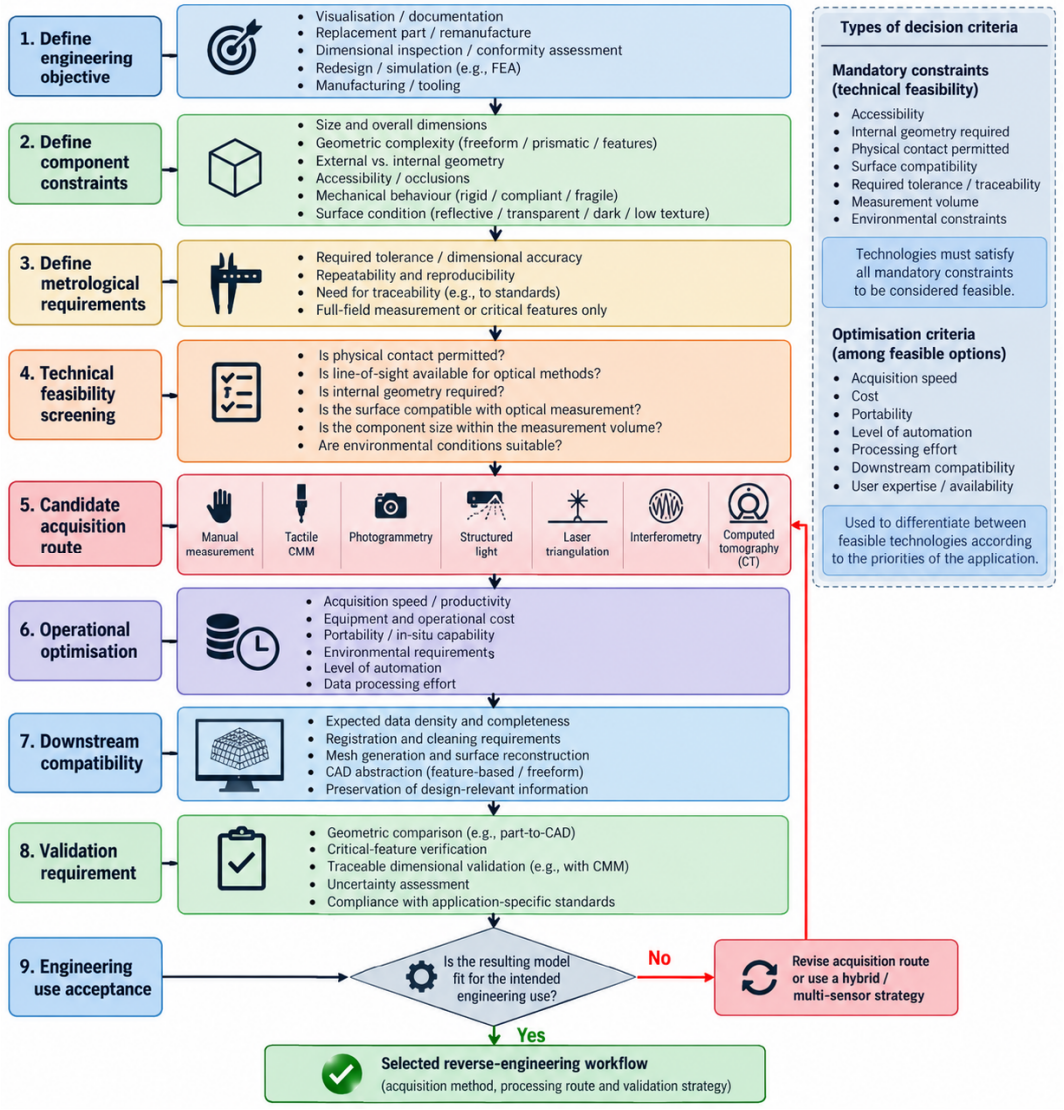


Figure 9. Reverse-Engineering Technology Selection Framework linking component characteristics, acquisition constraints, downstream reconstruction requirements, metrological validation and final engineering use.

As identified in Stage 2, component scale and required dimensional tolerance form an important pair of interacting criteria for acquisition-method selection. Their relationship is important because increasing measurement volume generally changes the attainable spatial sampling, uncertainty and practical implementation of a measurement system, while the dimensional requirements of the final engineering model determine the level of metrological control that must be preserved throughout acquisition and reconstruction. Component size and required tolerance should therefore be considered jointly rather than as independent selection variables.

Figure 10 presents a qualitative map of the principal operating tendencies identified across the reviewed technologies. Photogrammetry provides the greatest scalability and is particularly attractive for large components or structures where portability and geometric coverage are more important than highly demanding dimensional tolerances. Tactile CMMs are concentrated towards applications requiring greater dimensional confidence and traceability, although measurement volume, accessibility and acquisition speed can limit their suitability for complete dense reconstruction. Structured-light and laser-triangulation systems occupy broad and partly overlapping intermediate domains, providing dense external-surface acquisition over component scales ranging from localised features to comparatively large industrial parts depending on system architecture. Industrial CT is more strongly constrained by available measurement volume, component material and X-ray penetration, but adds access to internal geometry that cannot be represented by the two-dimensional scale–tolerance relationship alone.

The domains shown in Figure 10 are intentionally overlapping and should not be interpreted as fixed metrological limits. The achievable performance of each technology depends on the specific instrument, calibration, measurement volume, component geometry and surface condition, acquisition strategy, environmental conditions and validation procedure. The map is therefore intended to support preliminary technology screening, after which the system-specific capability must be verified against the dimensional and functional requirements of the application.

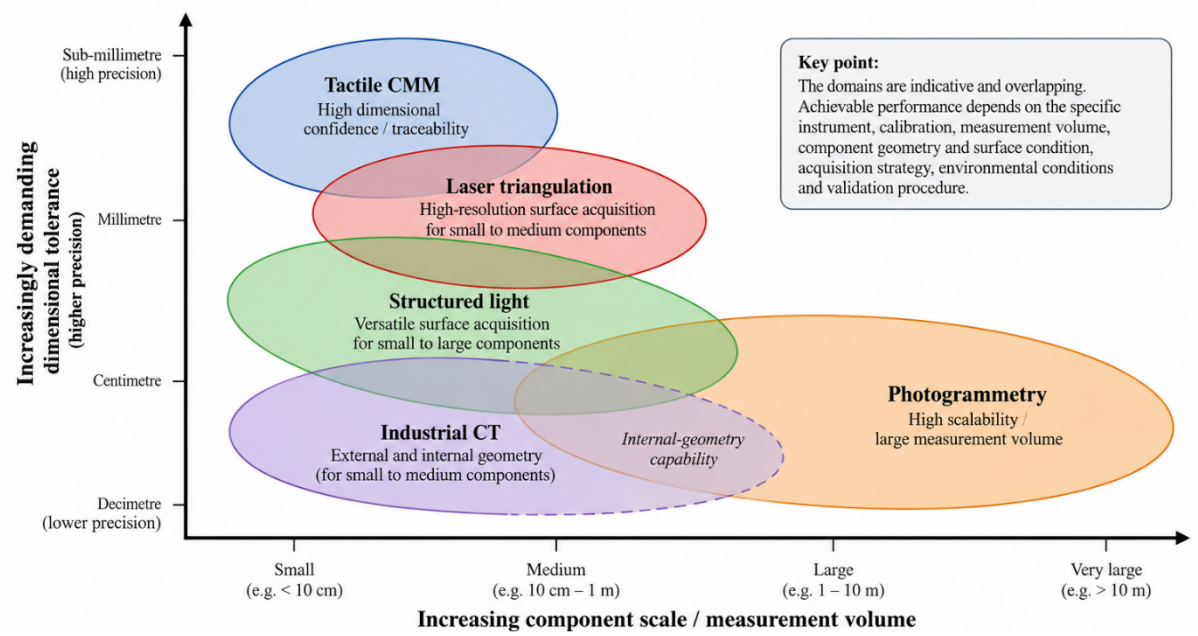


Figure 10. Qualitative component-scale versus required-tolerance map for principal reverse-engineering acquisition technologies. Overlapping domains represent general operating tendencies rather than fixed performance limits; achievable capability depends on system configuration, calibration, measurement volume, component characteristics, acquisition conditions and validation procedure. CT additionally provides internal-geometry acquisition, which is not represented by the two-dimensional map.

Geometric accessibility constitutes a second interacting dimension of acquisition-method selection. Unlike component scale, accessibility concerns whether the measurement principle can physically or optically reach the geometry that must be reconstructed. Externally accessible surfaces can generally be addressed by tactile, photogrammetric and optical surface-acquisition methods, whereas increasing occlusion, undercut depth and cavity aspect ratio progressively restrict direct line-of-sight and probe access. Fully internal channels and enclosed volumes represent a more fundamental accessibility boundary because their geometry cannot normally be recovered completely using conventional external-surface acquisition alone.

Figure 11 relates this progression in geometric accessibility to the required level of metrological confidence. Tactile CMMs occupy a strong position for accessible and tolerance-critical features but become increasingly dependent on probe geometry and access as recesses and undercuts become more severe. Structured-light and laser-triangulation systems provide dense external-surface information and can accommodate moderate geometric complexity through multi-view acquisition, but their effectiveness decreases when direct optical access is restricted. Photogrammetry remains particularly suitable for accessible geometry where broad coverage and moderate dimensional requirements dominate. Industrial CT extends acquisition into deep, concealed and fully enclosed geometry, although the attainable metrological performance remains dependent on measurement volume, material attenuation, voxel size, surface determination and calibration. Hybrid strategies become particularly relevant where demanding metrological requirements coincide with difficult accessibility, because different measurement principles can provide complementary external, internal and reference information.

Thin or closely spaced features require additional interpretation within this framework. Their acquisition difficulty is not governed solely by whether they are externally accessible, since reconstruction also depends on the capability to resolve neighbouring surfaces, edges and local thickness without excessive smoothing or segmentation error. Thin-feature performance should therefore be considered as a cross-cutting geometric constraint superimposed on the accessibility–metrology relationship.

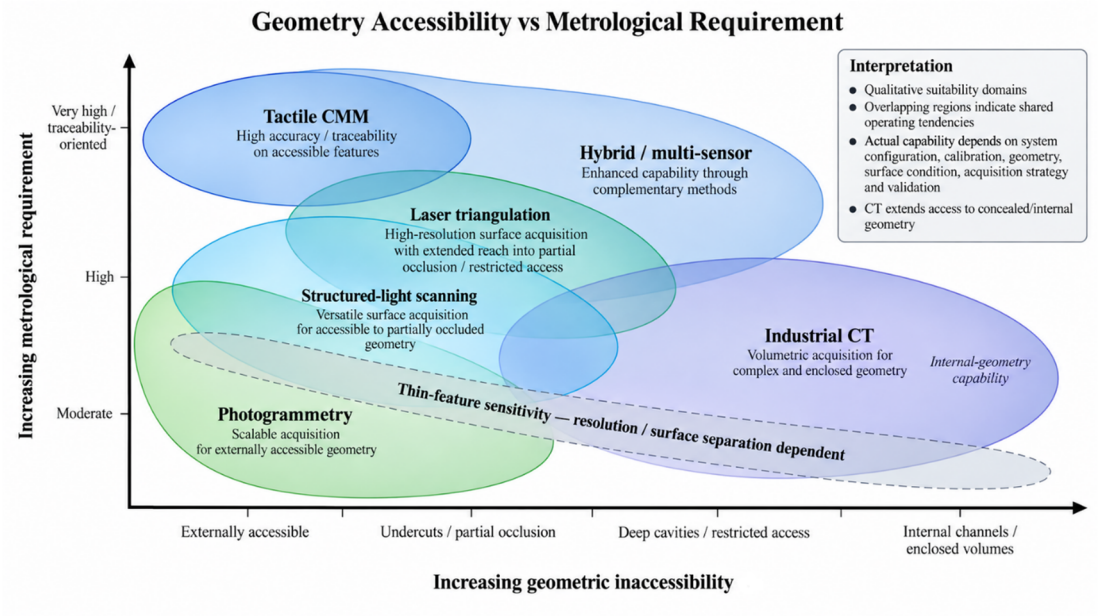


Figure 11. Qualitative geometry-accessibility versus metrological-requirement map for principal reverse-engineering acquisition technologies. The horizontal axis represents increasing difficulty of geometric access from externally visible surfaces to internal channels and enclosed volumes, while the vertical axis represents increasing metrological requirements. Technology domains are intentionally overlapping and indicate general suitability rather than fixed capability limits. Thin-feature acquisition represents a cross-cutting constraint influenced by spatial resolution, acquisition geometry and surface determination.

Figure 11 highlights that geometric accessibility can become a primary feasibility constraint independently of nominal scanner accuracy. As access becomes progressively restricted, the applicability of line-of-sight and contact-based methods decreases because of occlusion, probe interference, limited sensor orientation and incomplete surface coverage. Industrial CT therefore occupies a distinct role for internal channels and enclosed volumes, whereas tactile CMMs, structured-light systems and laser-triangulation methods remain strongest where the required geometry can be physically or optically accessed. Hybrid and multi-sensor strategies become particularly relevant where difficult accessibility coincides with demanding metrological requirements, since complementary measurement principles can combine dense external acquisition, traceable critical-feature measurement and volumetric information.

The map should nevertheless be interpreted as a qualitative decision aid rather than as a fixed hierarchy of acquisition technologies. Individual system capability depends on probe or sensor configuration, measurement volume, feature dimensions, material and surface characteristics, calibration and the adopted validation procedure. Geometry accessibility should therefore be evaluated together with component scale, required tolerance and downstream reconstruction requirements when selecting an acquisition strategy.

Following the feasibility screening and technology-selection logic established in the Reverse-Engineering Technology Selection Framework, Table 11 provides a multi-criteria decision matrix for comparing the technically feasible acquisition routes. The matrix evaluates the principal technologies according to dimensional accuracy, geometric-data density, acquisition speed, internal-feature accessibility, external-surface coverage, surface sensitivity, portability, measurement volume, preprocessing requirements, CAD-conversion effort, metrological traceability, capital cost, operator expertise, automation potential, and industrial maturity. These criteria encompass measurement performance, geometric accessibility, operational requirements, downstream reconstruction burden, and industrial implementation. Because the underlying measurement principles differ fundamentally, the ratings represent qualitative tendencies identified across the reviewed literature rather than universal performance classes.

Ratings represent qualitative tendencies identified across the reviewed literature rather than fixed performance classes. For capability-related criteria, higher ratings indicate greater capability. For criteria marked §, higher ratings indicate greater sensitivity, effort, cost or expertise requirement and should therefore not be interpreted as inherently favourable. Acquisition-speed ratings refer to practical acquisition efficiency at workflow level and not solely to nominal sensor capture rate; setup, calibration, surface preparation, repositioning and repeated acquisitions may substantially affect effective acquisition time.

Capital-investment ratings refer principally to the relative equipment and system infrastructure required for each acquisition route and should not be interpreted as total workflow cost. Effective economic performance also depends on software, calibration, fixtures, consumables, surface preparation, operator labour, computational processing, validation, maintenance and repeated acquisition or processing.

Dimensional accuracy, precision/repeatability and geometric-data density or resolution are treated as distinct characteristics; a high rating in one category should not be interpreted as implying equivalent performance in the others.

The matrix should be interpreted in conjunction with the selection framework rather than as a universal ranking of the available technologies. Mandatory feasibility constraints should first be used to exclude unsuitable acquisition routes, after which the remaining alternatives can be compared according to the optimisation criteria most relevant to the intended application. This distinction is important because factors such as internal-feature accessibility, permissible physical contact and required traceability may determine technical feasibility, whereas acquisition speed, cost, portability and processing effort primarily differentiate among otherwise feasible alternatives.

The generic concept of surface sensitivity used in Table 11 can be resolved further by considering the interaction between surface optical behaviour and measurement principle. Figure 12 provides a qualitative surface–technology compatibility framework for this purpose. The framework does not rank technologies according to overall performance; instead, it indicates whether a given surface condition is generally favourable, conditional or challenging for the physical measurement principle involved. Tactile CMM and CT are shown separately from visible-light surface techniques because visible-surface optical behaviour is not their primary limitation, although each remains subject to its own contact-, material- or attenuation-related constraints.

Table 11. Multi-criteria decision matrix for shape-acquisition technologies used in reverse engineering.

Decision Criterion	MM	CMM	PG	SL	LT	INT	CT	HYB
Dimensional accuracy	L–M	VH	L–M	H	H	VH *	M–H	VH †
Geometric-data density	VL	L–M	H	VH	H	VH *	VH ‡	VH
Acquisition speed	L	L–M	M–H	H	H	M	L–M	M
Internal-feature accessibility	VL	L	VL	VL	VL	VL	VH	H †
External-surface coverage	L	M	H	H	H	L	H	VH
Surface sensitivity §	L	L–M	VH	VH	M–H	H	L	L–M †
Portability	VH	L–M	VH	H	H	L–M	VL	L–M
Measurement volume	L–M	M	VH	M–H	H	L	L–M	Var.
Preprocessing requirements §	L	L–M	H	M	M–H	M	H	VH
CAD-conversion effort §	M–H	M	H	H	H	H *	H	VH
Metrological traceability	L–M	VH	L–M	M–H	M–H	VH *	M–H	H–VH †
Capital investment §	VL	H	VL	M	M–H	H	VH	H–VH
Operator expertise §	M	H	M	M	M	H	VH	VH
Automation potential	VL	H	H	VH	VH	M–H	H	VH
Industrial maturity	VH	VH	H	H	VH	H *	H	M–H

Caption: MM—Manual Measurement; CMM—Tactile Coordinate Measuring Machine; PG—Photogrammetry/SfM–MVS; SL—Structured Light; LT—Laser Triangulation; INT—Interferometry; CT—Industrial Computed Tomography; HYB—Hybrid/Multi-sensor; VL—Very Low; L—Low; M—Medium; H—High; VH—Very High; Var.—Variable. * Interferometric performance refers primarily to local surface or microgeometry measurement rather than complete-component reconstruction. † Hybrid-system capability depends on the constituent technologies and on effective calibration, coordinate-system alignment and uncertainty management. ‡ For CT, geometric-data density refers to volumetric voxel sampling rather than conventional surface-point density.

Figure 12 shows that surface condition can alter the feasible technology set before conventional optimisation criteria such as acquisition speed, portability or cost are considered. A surface that is favourable for one optical principle may require preparation, parameter adaptation or an alternative sensing route for another. Surface preparation should therefore be regarded as part of the acquisition strategy rather than as a neutral preprocessing step, particularly when the added coating or reference features may modify the measured geometry or increase workflow time and uncertainty. Where the surface behaviour remains incompatible with the required optical measurement principle, tactile, tomographic or hybrid acquisition may provide a more robust route, provided that their respective accessibility, attenuation and metrological constraints are acceptable.

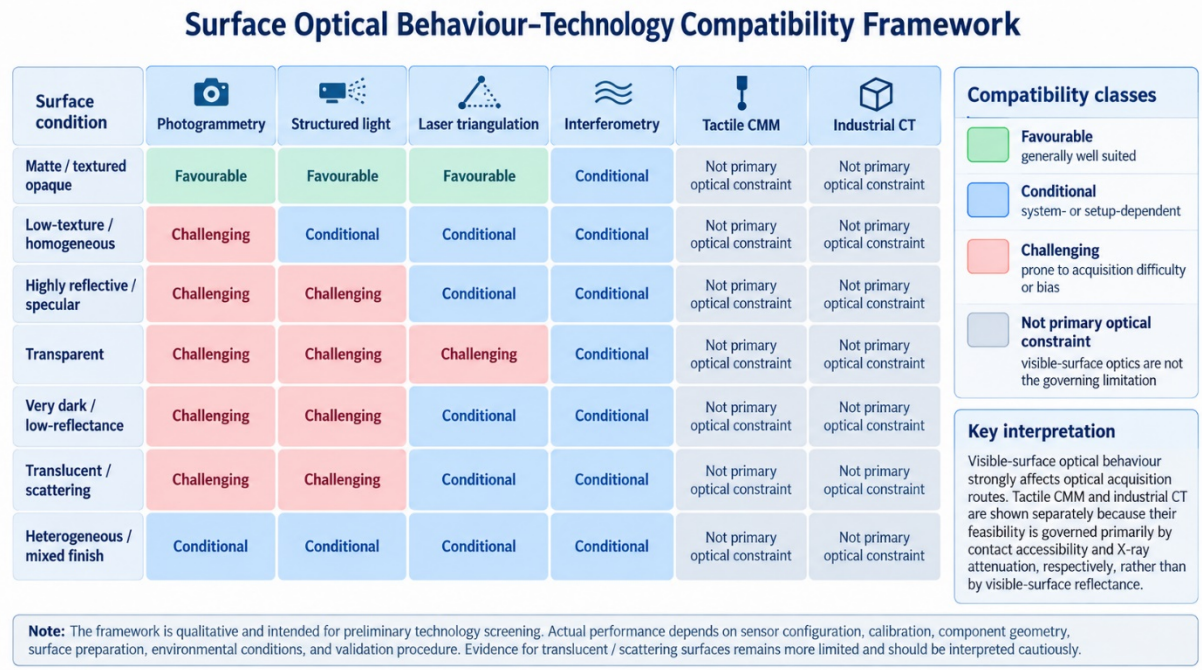


Figure 12. Qualitative surface optical behaviour–technology compatibility framework for principal reverse-engineering acquisition methods. The framework indicates general compatibility tendencies for matte/textured, low-texture, reflective, transparent, dark, translucent/scattering and heterogeneous surface conditions. Ratings are intended for preliminary technology screening and should not be interpreted as fixed performance limits, since actual capability depends on system configuration, calibration, acquisition geometry, surface preparation, environmental conditions and validation procedure. For tactile CMM and industrial CT, visible-surface optical behaviour is not the primary governing constraint; their applicability is instead controlled mainly by contact accessibility and X-ray attenuation, respectively.

Surface preparation introduces an additional trade-off within this compatibility framework. Matting sprays, temporary coatings and other surface treatments can improve optical acquisition by reducing specular reflection, increasing diffuse return or improving the visibility of projected or image-based features. From a metrological perspective, however, the preparation should not be regarded as a neutral operation because the acquisition system may subsequently measure the prepared surface rather than the original component surface.

A deposited coating can introduce a systematic offset from the underlying geometry, while non-uniform application can produce spatially varying surface displacement. Local accumulation may also affect edges, small-radius transitions, narrow grooves, fine features or other regions in which the coating thickness is not negligible relative to the required tolerance or feature dimensions. The resulting influence is therefore dependent not only on the coating itself but also on the application procedure, component geometry and dimensional requirements of the reconstruction task.

The decision to apply surface preparation should consequently balance the improvement in optical data quality against the additional geometric modification and uncertainty introduced by the treatment. For documentation or geometrically tolerant reconstruction, this contribution may be of limited practical consequence, whereas tolerance-sensitive inspection, dimensional verification or engineering reconstruction may require the preparation-induced effect to be characterised independently, included in the uncertainty budget, or avoided through selection of an alternative acquisition principle. Where surface treatment is necessary, the preparation material, application procedure and relevant metrological implications should be documented explicitly.

4.1.2. Hybrid and Multi-Sensor Metrology Strategies

Hybrid metrology extends reverse-engineering technology selection beyond the choice of a single acquisition principle by deliberately combining measurement systems that provide complementary forms of engineering information. The defining principle is therefore not the number of sensors employed, but the extent to which each measurement technology contributes information that cannot be obtained with sufficient reliability, accessibility, resolution or metrological confidence from the other systems in the workflow. This concept may be described as information complementarity. Dense optical acquisition can provide extensive freeform surface geometry but may lack the traceable dimensional confidence required for critical features; tactile measurement can provide highly reliable coordinates, datums and functional dimensions but is inefficient for dense surface reconstruction; CT can provide inaccessible internal geometry that line-of-sight systems cannot observe; and local precision techniques can supply microgeometric information beyond the effective resolution of a global acquisition system. A hybrid strategy is therefore most strongly justified when these information contributions are non-redundant and jointly necessary for the intended engineering output.

A useful distinction can be made between hybrid workflows based on the role performed by the secondary measurement principle. In verification-oriented hybrid metrology, one system provides the principal geometric dataset while another independently verifies critical dimensions or features. In reference-constrained hybrid metrology, traceable tactile measurements define datums, axes, mating interfaces or other geometric constraints used to position or reconstruct dense scan data. In complementary-geometry workflows, different technologies acquire physically different regions or scales of the component, such as external surface geometry and concealed internal features. Fully integrated multi-sensor workflows extend this principle by combining complementary sensing systems within a common measurement platform or coordinate framework.

Dense optical acquisition combined with tactile metrology represents one of the most relevant hybrid strategies for component-oriented reverse engineering. Structured-light or laser-triangulation systems can rapidly acquire freeform external geometry, while tactile CMM measurements can provide higher-confidence information for datums, bores, mating surfaces and tolerance-critical dimensions. The tactile data may be used either as independent verification of the reconstructed model or as constraints during alignment and CAD reconstruction. This combination is particularly valuable where dense geometric coverage and dimensional traceability are simultaneously required.

In reference-constrained hybrid metrology, tactile measurements can establish functional datums, axes, mating interfaces and other tolerance-critical features, while dense optical acquisition provides the surrounding freeform geometry. The resulting reconstruction can then be evaluated within a functionally meaningful coordinate system rather than solely through global best-fit alignment.

Another class combines external optical acquisition with CT-based volumetric reconstruction. Optical techniques can provide rapid and detailed external-surface data, whereas CT supplies information about internal channels, cavities, concealed interfaces or other features inaccessible to line-of-sight measurement. The resulting workflow can provide greater geometric completeness than either system alone, but requires reliable cross-modal registration, coordinate-system alignment and management of the different uncertainty characteristics associated with surface and volumetric acquisition.

Hybrid metrology can also address differences in measurement scale. A global optical or photogrammetric model may be supplemented by high-resolution local measurements, including interferometric or other precision surface measurements, when microgeometry or surface topography is relevant to the engineering task. In such cases, the local dataset enriches selected regions of the global reconstruction rather than replacing the principal acquisition route.

The benefit of hybridisation must therefore be assessed against its additional integration burden. Combining sensors introduces calibration, coordinate-transformation, registration and data-fusion requirements and may create correlated or sensor-specific uncertainty contributions that are absent from single-system workflows. Hybrid acquisition is consequently most justified when the additional measurement principle resolves a clearly identified limitation in geometric coverage, accessibility, traceability or resolution and when the resulting improvement is relevant to the intended engineering use.

The principal hybrid strategies considered within this framework are summarised in Table 12. The classification is based on the functional and informational contribution made by the complementary measurement principles rather than on a fixed pairing of instruments, because the same sensor combination may fulfil different roles depending on whether the missing information concerns geometric coverage, datum definition, dimensional traceability, internal accessibility, local resolution or independent verification.

Table 12. Taxonomy of hybrid and multi-sensor metrology strategies for reverse-engineering workflows.

Hybrid Strategy	Representative Combination	Primary Contribution	Complementary Contribution	Principal Benefit	Main Integration Challenge
Dense acquisition + tactile verification	Structured light or laser scanning + tactile CMM	Dense external/freeform geometry	Verification of critical dimensions and features	Combines geometric coverage with metrological confidence	Common referencing, uncertainty consistency and verification planning
Optical acquisition + tactile datum definition	Laser or structured-light scanning + tactile probing	Full-field surface acquisition	Definition of datums, axes, bores, mating interfaces or reference features	Constrains dense scan geometry to functional references	Coordinate-system alignment and transformation uncertainty
External + internal geometry fusion	Optical surface acquisition + industrial CT	Rapid/high-detail external geometry	Internal and concealed geometry	More complete component reconstruction	Cross-modal registration, voxel/surface correspondence and differing uncertainty characteristics
Global + local multi-scale metrology	Optical/photogrammetric acquisition + interferometric or precision local measurement	Global component geometry	Local microgeometry or surface-topography information	Preserves global coverage while enriching functionally critical regions	Scale reconciliation, local-to-global registration and data representation
Integrated multi-sensor acquisition	CMM-mounted laser scanner + tactile probe or equivalent multi-sensor platform	Dense automated scanning	Traceable feature measurement within a related measurement environment	Reduced sensor repositioning and stronger coordinate integration	Sensor-to-sensor calibration and combined uncertainty evaluation

These categories are not mutually exclusive. A demanding industrial workflow may combine several hybrid functions, for example using optical scanning for global geometry, tactile probing for datum definition and critical-feature verification, and CT for concealed regions. The appropriate configuration should therefore be determined by the information required from the final model and by the limitations remaining after the primary acquisition route has been selected.

Hybrid workflows should also distinguish between data fusion and metrological verification. When measurements from different sensors are merged into a single geometric representation, cross-sensor calibration and uncertainty propagation become part of the reconstruction problem. When the complementary system is used only to verify selected dimensions or features, the datasets may remain separate while still providing metrological confidence in the final model. This distinction is particularly relevant when assessing traceability and uncertainty across the complete reverse-engineering chain.

Information complementarity does not exclude deliberate measurement overlap. Overlapping regions or common reference features may be necessary for registration, sensor-to-sensor calibration and independent cross-validation. Such overlap serves an integration or verification function, whereas complementarity concerns the additional engineering information uniquely contributed by each measurement principle. A robust hybrid workflow therefore requires both sufficient common information to relate the datasets and sufficient non-redundant information to justify the use of multiple sensing technologies.

4.2. From Acquired Data to CAD Reconstruction

The consequences of acquisition-method selection extend beyond the measurement stage because each technology produces data with different density, spatial organisation, completeness and uncertainty characteristics. These differences determine the amount and type of processing required before the measured geometry can be converted into an engineering-ready model. Point-cloud density alone is therefore an insufficient indicator of reconstruction quality. A densely sampled dataset containing registration error, optical artefacts or systematic surface deviations may require more corrective processing than a sparser but metrologically controlled dataset. Conversely, highly accurate discrete measurements may provide insufficient geometric information for reliable reconstruction of complex freeform surfaces. The acquisition and reconstruction stages should therefore be considered as a coupled process rather than as independent operations.

An important distinction must therefore be made between measurement accuracy and engineering reconstruction accuracy. Measurement accuracy refers to the degree to which the coordinates, surface points or volumetric data generated by the acquisition system represent the physical component under the specified calibration, environmental and operating conditions. Engineering reconstruction accuracy, by contrast, refers to the dimensional and geometric fidelity of the model obtained after the acquired data have been transformed into a mesh, reconstructed surface or CAD representation suitable for engineering use. The two quantities are related, but they are not equivalent.

A highly accurate acquisition system can still lead to a less accurate reconstructed model if additional deviations are introduced during downstream processing. Registration may introduce alignment error between multiple datasets; filtering and smoothing may suppress genuine local geometry; decimation may reduce feature resolution; hole filling may create inferred rather than measured surfaces; meshing may alter local curvature or edge definition; segmentation and threshold selection may shift reconstructed boundaries; surface fitting may approximate measured geometry; and feature recognition or CAD abstraction may replace measured freeform geometry with idealised analytical or parametric features. Each transformation therefore has the potential to alter the geometry inherited from the preceding stage.

For this reason, the dimensional performance of a reverse-engineering workflow should not be inferred solely from the nominal accuracy of the acquisition device. Final-model validation should instead assess the reconstructed geometry after processing and CAD generation, particularly where the model is intended for tolerance-sensitive redesign, dimensional inspection, simulation or manufacturing. Where metrological traceability is required, uncertainty should be considered across the complete acquisition-to-reconstruction chain rather than being reported only for the initial measurement stage.

Manual measurement and tactile CMM acquisition produce comparatively sparse geometric datasets, although their metrological characteristics differ substantially. Manual measurements are generally limited to discrete dimensions and accessible geometric features and consequently provide little direct support for automated mesh generation or freeform-surface reconstruction. CAD modelling from such data normally requires the geometry to be interpreted and rebuilt using assumed primitives, dimensional relationships and engineering judgement. Tactile CMMs provide considerably greater dimensional confidence and can generate structured coordinate datasets suitable for fitting analytical features and verifying reconstructed CAD geometry. Their limited sampling density, however, means that complex freeform surfaces may require extensive interpolation or deliberately planned scanning paths. Tactile data are therefore particularly valuable for dimensional verification and for constraining critical CAD features, but less efficient as the sole input for dense surface reconstruction.

Photogrammetric reconstruction produces substantially denser geometric information, but the resulting point clouds may contain non-uniform point density, noise, missing regions and local errors associated with image overlap, calibration, scale definition, texture availability and surface optical behaviour. These characteristics directly influence registration and mesh generation: incomplete or weakly reconstructed regions require cleaning, filtering, hole repair or additional image acquisition before a continuous surface can be obtained. Mesh generation may therefore be computationally straightforward once a satisfactory point cloud exists, while producing a dimensionally reliable CAD model remains more demanding. For visualisation, heritage documentation or geometrically tolerant reproduction, a cleaned polygonal model may already be usable; for tolerance-sensitive redesign or dimensional verification, additional registration to reference geometry and independent metrological validation are generally required.

Structured-light and laser-triangulation systems generally provide dense surface datasets with more controlled scale and local geometry than passive image-based methods, which facilitates mesh generation and freeform-surface fitting. Their downstream performance nevertheless remains dependent on the completeness of line-of-sight coverage and on the treatment of reflective, transparent, dark or occluded regions. Multiple scans are frequently required to capture a complete component, making registration quality a direct contributor to the uncertainty of the reconstructed mesh. Residual misalignment, local noise and surface-preparation effects may subsequently propagate into fitted surfaces and CAD dimensions. These technologies are therefore well suited to external-surface reconstruction and part-to-CAD comparison, but dimensional verification still requires appropriate calibration, reference-system control and validation of critical features. Laser and structured-light acquisition can reduce the manual effort required to create a geometrically complete mesh, but they do not by themselves recover feature hierarchy, design constraints or manufacturing intent.

Computed tomography generates a fundamentally different reconstruction problem because the primary dataset is volumetric rather than surface-based. External and concealed features can be recovered from the same acquisition, but their conversion into usable surface geometry depends on volumetric reconstruction, segmentation and threshold selection before polygonal surfaces or CAD-compatible representations can be generated. Errors introduced during these stages can modify wall thickness, edge position and the apparent dimensions of internal features, meaning that voxel resolution and segmentation strategy directly affect subsequent dimensional verification. CT can therefore provide uniquely complete geometric information for components containing internal channels, cavities or inaccessible features, but the resulting CAD reconstruction may involve greater computational effort and requires careful uncertainty assessment when the model is intended for tolerance-sensitive engineering use.

Interferometric techniques occupy a more specialised position in this chain. Their very high local surface resolution makes them valuable for microgeometry and surface-topography characterisation, but the limited measurement range and field of view generally prevent them from serving as a complete component-reconstruction

route. Their data are consequently more useful for supplementing a global geometric model with local surface information than for generating complete CAD geometry independently. Hybrid and multi-sensor strategies extend this principle by combining datasets with complementary characteristics. Dense optical or photogrammetric geometry may, for example, be constrained by tactile measurements at critical dimensions or supplemented by CT where concealed features are present. Such combinations can improve final model completeness and verification confidence, but they transfer part of the technical burden to cross-sensor registration, coordinate-system alignment, uncertainty propagation and data fusion.

These relationships have an important implication for final model usability. A reconstruction intended primarily for visualisation or geometric reproduction may tolerate local smoothing, interpolation and mesh repair that would be unacceptable in a model intended for dimensional inspection, finite-element analysis, tolerance modification or manufacturing. Engineering usability therefore depends not only on geometric similarity to the original component, but also on whether the acquisition and reconstruction chain preserves the dimensional information, feature relationships and uncertainty required by the downstream task. Table 13 summarises how the principal acquisition routes influence the successive stages from raw geometric data to CAD reconstruction and final model use.

Table 13. Propagation of acquisition characteristics and reconstruction-related uncertainty through downstream reverse-engineering stages.

Acquisition Method	Acquired-Data Characteristics	Point-Cloud/Mesh Implications	Surface and CAD Reconstruction	Dimensional Verification	Final Model Usability
Manual measurement	Sparse discrete dimensions; operator-dependent	No intrinsic dense point cloud; insufficient for direct freeform meshing	Geometry generally rebuilt from dimensions and assumed primitives; high dependence on engineering interpretation	Suitable for basic feature checks; limited full-field verification	Simple components, preliminary reconstruction and workshop-level reproduction
Tactile CMM	Sparse-to-moderate, structured and metrologically controlled coordinate data	Reliable coordinates but limited surface density; freeform reconstruction requires planned sampling/interpolation	Strong for analytical features and constraint definition; inefficient for dense freeform CAD reconstruction	Very high suitability for critical dimensions and traceable verification	Precision reconstruction, inspection, validation and tolerance-sensitive engineering
Photogrammetry/ SfM–MVS	Dense but frequently non-uniform point clouds; sensitive to image geometry, texture and scale	Filtering, registration, hole repair and noise removal may be substantial	Mesh generation readily achievable after cleaning; engineering CAD reconstruction requires further abstraction and validation	Low–medium unless independently referenced and validated	Visualisation, large-scale reconstruction, heritage, preliminary redesign and moderate-tolerance reproduction
Structured-light scanning	Dense, metrically scaled surface point clouds	Generally favourable for meshing; incomplete views and optical artefacts require registration and local repair	Effective for freeform surface fitting; design intent and parametric features still require reconstruction	Medium–high with appropriate calibration and reference control	Rapid industrial digitisation, part-to-CAD comparison, tooling and external-geometry reconstruction
Laser triangulation	Dense local surface data with high geometric detail	Multiple scans commonly require accurate registration; occlusion and scanning-angle effects may propagate to the mesh	Well suited to detailed external surfaces and local feature reconstruction; CAD abstraction remains necessary	Medium–high depending on system architecture and calibration	Industrial inspection, robotic scanning, mould/die reconstruction and production metrology
Interferometric methods	Very high-resolution local surface/topography data	Highly detailed local datasets but restricted field of view and measurement range	More suitable for local surface enrichment than complete component CAD reconstruction	Very high for appropriate local surface measurements	Microgeometry, precision-surface verification and complementary metrology
Industrial CT	Volumetric voxel data containing external and internal geometry	Requires volumetric reconstruction, segmentation and surface extraction before meshing	Enables reconstruction of inaccessible internal and external features; segmentation strongly affects derived CAD geometry	Medium–high, but dependent on voxel size, thresholding and uncertainty control	Components with concealed geometry, complex assemblies, internal channels and volumetric inspection
Hybrid/multi-sensor	Complementary datasets from different measurement principles	Requires cross-sensor registration, alignment and data fusion	Can combine dense geometry with traceable critical features or internal information	Potentially very high when reference systems and uncertainty are controlled	High-value and complex components requiring completeness together with metrological confidence

4.2.1. Uncertainty Propagation across the Reverse-Engineering Chain

Uncertainty within a reverse-engineering workflow should be treated as a property of the complete measurement and reconstruction chain rather than as a characteristic of the acquisition device alone. The geometry available at each processing stage is inherited from the preceding stage and may subsequently be modified by algorithmic processing, parameter selection, geometric approximation or interpretation. The uncertainty associated with the final CAD model therefore reflects both the uncertainty of the original measurements and the additional uncertainty introduced during their transformation into an engineering representation.

At the acquisition stage, uncertainty originates from the measurement principle and its operating conditions. Relevant contributors include sensor calibration, spatial resolution, probe behaviour, image geometry, surface optical properties, environmental conditions, positioning, voxel size and other technology-specific factors. These contributions define the metrological quality of the primary coordinate, image-derived or volumetric dataset but do not, by themselves, define the accuracy of the final reconstructed model.

Registration introduces a second uncertainty contribution whenever multiple views, scans or sensor datasets must be expressed within a common coordinate system. Imperfect feature correspondence, target localisation, best-fit alignment, coordinate transformation and cross-sensor referencing may generate local or global misalignment. Because subsequent processing is performed on the registered dataset, these deviations can propagate directly into mesh geometry, surface position and reconstructed feature dimensions.

Preprocessing can introduce further geometric modification. Noise filtering, smoothing, outlier removal, resampling, decimation, point-cloud completion and hole filling are often necessary to obtain a usable dataset, but these operations may also suppress genuine local features, modify edge locations or replace missing information with algorithmically inferred geometry. This distinction is especially important for AI-assisted completion, because a geometrically plausible output may reflect learned shape priors rather than direct evidence from the measured component. The uncertainty associated with preprocessing is therefore not limited to random noise reduction; it also includes the possibility of systematic geometric alteration and model-dependent inference introduced by the selected processing strategy and its parameters.

Mesh generation and surface reconstruction represent further transformation stages. Triangulation can introduce discretisation effects related to point spacing, element size and mesh topology, while smoothing and mesh repair may modify curvature, sharp edges and small features. Subsequent surface fitting introduces approximation error because analytical, spline or NURBS surfaces are fitted to finite and potentially imperfect geometric data. The resulting surface can therefore be mathematically smooth and internally consistent while differing locally from the measured component.

Feature recognition and CAD abstraction introduce a distinct form of uncertainty because the objective changes from reproducing measured geometry to interpreting it as engineering geometry. Recognition of planes, cylinders, holes, fillets, freeform regions or manufacturing features requires classification and geometric fitting, while parametric CAD reconstruction may impose idealised dimensions, constraints, topology and feature relationships. These operations can improve editability and recover design intent, but they may also increase the deviation between the measured component and the reconstructed engineering model if the selected feature interpretation is incomplete or incorrect.

The final CAD-reconstruction uncertainty consequently reflects the combined influence of the preceding stages. Conceptually, the relationship may be expressed as it is in Equation (3).

$$U_{CAD} = F(U_{acq}, U_{reg}, U_{pre}, U_{mesh}, U_{surf}, U_{feat}, U_{CAD-abs}), \tag{3}$$

where U_{acq} represents acquisition uncertainty; U_{reg}, registration and coordinate-transformation uncertainty; U_{pre}, preprocessing-induced geometric uncertainty; U_{mesh}, meshing uncertainty; U_{surf}, surface-reconstruction or fitting uncertainty; U_{feat}, feature-recognition uncertainty; and $U_{\mathrm{CAD\text{-}abs}}$, uncertainty associated with CAD abstraction and parametric reconstruction. The function F is intentionally not defined as a simple algebraic summation because the individual contributions may be correlated, non-linear, spatially dependent and strongly influenced by the selected reconstruction method.

This framework implies that uncertainty should be assessed at appropriate validation checkpoints rather than only once at the acquisition stage. These checkpoints may include verification of the raw or registered dataset, comparison of the reconstructed mesh with the measured data, assessment of surface-fitting residuals, verification of critical reconstructed features and final comparison of the CAD model against traceable reference measurements where required. The level of validation should be determined by the intended engineering use: a model intended for visualisation may tolerate substantially greater geometric modification than one intended for dimensional inspection, tolerance-sensitive redesign, simulation or manufacture.

To clarify the origin and propagation of these contributions, Table 14 summarises the principal uncertainty sources associated with each stage of the reverse-engineering chain, their potential influence on reconstructed geometry, and the corresponding validation opportunities.

Table 14. Uncertainty-propagation framework across the reverse-engineering workflow.

Workflow Stage	Principal Uncertainty Sources	Potential Geometric Consequence	Recommended Validation
Acquisition	Calibration, sensor/probe behaviour, resolution, environment, surface optical interaction, surface preparation/coating, positioning	Coordinate or voxel uncertainty; missing or biased geometry; preparation-induced surface displacement	Calibration verification; reference artefact; repeated acquisition; assessment of preparation-induced dimensional change where relevant
Registration	Correspondence error, target localisation, transformation, best-fit alignment	Global/local misalignment; accumulated registration drift	Registration residuals; independent reference features
Preprocessing	Filtering, smoothing, decimation, outlier removal, deterministic or AI-assisted completion, hole filling and inferred geometry	Feature suppression; edge displacement; reconstructed geometry unsupported by direct measurement	Before/after deviation analysis; measured-versus-inferred region identification; independent validation of critical inferred features
Meshing	Triangulation, element size, topology, interpolation	Curvature/edge modification; discretisation error	Point-cloud-to-mesh deviation
Surface reconstruction	Surface fitting, spline/NURBS approximation, smoothing	Local fitting residuals; deviation from measured geometry	Residual/error maps; section comparisons
Feature recognition	Classification, primitive fitting, topology inference	Incorrect feature type, size, orientation or relationship	Feature-wise comparison with measured data
CAD abstraction	Parametric idealisation, constraints, design-intent recovery	Difference between as-measured and idealised geometry	CAD-to-data comparison; critical-dimension verification
Final engineering model	Accumulated and interacting upstream contributions	Reduced dimensional reliability or fitness for intended use	Independent metrological validation according to application

Note: Geometry generated during preprocessing, meshing, surface reconstruction, feature recognition or CAD abstraction should retain its provenance where practicable, distinguishing direct measurement support from interpolation, deterministic constraint-based reconstruction and data-driven inference.

4.2.2. Levels of CAD Reconstruction and Engineering Readiness

The expression engineering-ready model requires clarification because reverse-engineering workflows can produce digital representations with substantially different geometric structure, editability and engineering information content. A polygonal mesh, a fitted surface model and a feature-based parametric CAD model may all reproduce the visible geometry of a component, but they do not provide equivalent capabilities for dimensional modification, tolerance definition, simulation, manufacturing or recovery of design intent. Engineering readiness should therefore be interpreted relative to the intended downstream task rather than as a single universal model class.

At the most basic level, a polygonal representation describes the measured surface through discrete facets. Such models may be sufficient for visualisation, documentation, direct geometric comparison or geometrically tolerant reproduction, including some additive-manufacturing workflows. Their engineering editability is nevertheless limited because they do not inherently describe analytical features, design constraints, dimensional relationships or manufacturing intent.

A higher level of reconstruction is obtained when the measured geometry is represented through fitted analytical or freeform surfaces, including spline- or NURBS-based descriptions. These representations provide smoother and more compact geometric definitions than polygonal meshes and may support high-quality freeform reconstruction, but surface continuity and geometric fidelity alone do not necessarily provide the feature hierarchy or parametric relationships required for conventional engineering modification.

More structured reconstruction can be achieved through boundary-representation or solid CAD geometry, in which faces, edges and vertices define a topologically consistent solid model. When analytical features and dimensional relationships are subsequently organised into a feature-based parametric structure, the reconstructed model becomes more suitable for redesign, dimensional modification, simulation and manufacturing because individual features and constraints can be edited rather than only the resulting external surface.

For tolerance-sensitive engineering applications, geometric reconstruction alone may still be insufficient. The reconstructed model may also need to preserve or re-establish datums, critical dimensions, geometric relationships and tolerance requirements, with these elements verified against traceable measurements. At a still higher level of semantic reconstruction, the objective extends beyond reproducing the as-measured geometry towards recovering functional relationships, manufacturing features and design intent. Such recovery is particularly demanding because the measured component contains the geometric consequences of manufacturing, wear and service history rather than an explicit record of the original designer's intentions.

Accordingly, this review uses the term engineering-ready to describe a model whose representation, dimensional confidence, editability and information content are sufficient for its declared downstream application. The threshold is therefore application-dependent. A validated polygonal model may be engineering-ready for direct replication or documentation, whereas redesign, tolerance modification, finite-element analysis or manufacturing planning may require surface or solid reconstruction, parametric feature definition and independent dimensional validation. Engineering readiness should consequently be reported together with the intended use of the reconstructed model rather than inferred solely from geometric resemblance to the measured component.

4.2.3. Digital Reconstruction Maturity Levels

The different digital representations generated during reverse engineering can be organised according to their increasing suitability for downstream engineering use. To make this progression explicit, this review introduces a Digital Reconstruction Maturity Level (DRML) framework. The framework classifies reconstruction outputs according to the degree of geometric organisation, editability, semantic information, parametric structure, validation and metrological traceability incorporated into the model.

DRML 0 corresponds to the raw acquired dataset. For optical and image-based methods, this is commonly an unprocessed point cloud or preliminary three-dimensional reconstruction; for CT, it may correspond to volumetric data; and for tactile systems it may consist of discrete measured coordinates. At this level, the data retain the closest relationship with acquisition but may contain noise, incomplete regions, misalignment, artefacts or redundant information and are not yet suitable for direct engineering interpretation.

DRML 1 represents processed and spatially consolidated measurement data. The acquired datasets have been cleaned, filtered, registered, aligned or otherwise organised into a common reference system. Although geometric consistency is improved, the representation remains predominantly measurement-oriented and does not yet constitute a complete surface or engineering model.

DRML 2 corresponds to a coherent polygonal representation, typically a repaired and sufficiently closed mesh. At this stage, the measured geometry has been converted into a continuous surface suitable for visualisation, geometric comparison and, in some cases, direct manufacturing or replication. Engineering editability remains limited, however, because the mesh generally contains no explicit feature hierarchy, dimensional constraints or design semantics.

DRML 3 represents fitted geometric surfaces. Analytical, spline or NURBS surfaces are reconstructed from the measured or meshed geometry, providing smoother and more compact geometric descriptions. Such models are more suitable for freeform-surface manipulation and downstream geometric operations, but may still lack a complete solid topology, editable feature history or parametric relationships.

DRML 4 corresponds to editable CAD geometry, such as a consistent surface or solid model that can be modified using conventional CAD operations. The model is no longer merely a geometric representation of the scan but can participate directly in redesign, simulation, tooling or manufacturing workflows. Nevertheless, its geometry may still be largely history-free or lack an explicit reconstruction of the original feature logic.

DRML 5 represents a feature-based parametric CAD model. At this level, geometric primitives, manufacturing features, dimensions, constraints, symmetry conditions and topological relationships are represented explicitly within an editable parametric structure. The model supports systematic redesign, optimisation and configurable manufacture, while nominal geometry and partial design intent may be inferred where these interpretations are supported by the available geometric and engineering evidence..

DRML 6 represents a validated engineering model. The reconstructed model has been dimensionally validated for its intended engineering use and incorporates the level of metrological traceability required by the application. Where sufficient evidence is available, it may also include justified nominal features, tolerances, functional or mating relationships, manufacturing-relevant constraints and recovered design intent. DRML 6 therefore represents the highest level of reconstruction maturity considered in this framework, but does not imply that design intent can always be recovered uniquely from geometry alone. For advanced or safety-critical applications,

this maturity level may additionally include persistent provenance information linking reconstructed regions or CAD features to their acquisition source, reconstruction history, uncertainty information and validation status.

The maturity sequence should not be interpreted as a mandatory linear workflow. Some applications may terminate appropriately at DRML 2, for example where a validated mesh is sufficient for documentation or direct reproduction, whereas tolerance-sensitive redesign or manufacturing may require DRML 5 or DRML 6. Similarly, tactile, CT and hybrid workflows may bypass or modify some intermediate representations. The DRML framework therefore describes increasing engineering maturity rather than a fixed software-processing sequence. The defining characteristics, engineering capabilities and typical limitations of each maturity level are summarised in Table 15.

Table 15. Digital Reconstruction Maturity Levels for reverse-engineering workflows.

DRML	Digital Representation	Principal Characteristics	Engineering Capability	Typical Limitations
0	Raw acquired data	Unprocessed point cloud, discrete coordinates or volumetric data	Preserves primary measurement information	Noise, artefacts, incompleteness, misalignment
1	Processed/registered data	Cleaned, filtered, aligned and consolidated dataset	Geometric inspection and preparation for reconstruction	No continuous engineering surface; limited semantics
2	Polygonal mesh	Continuous, repaired/closed polygonal geometry	Visualisation, comparison, documentation, direct reproduction	Limited editability; no feature hierarchy or design intent
3	Fitted geometric surfaces	Analytical, spline or NURBS surface representation	Freeform reconstruction and surface modification	Limited parametric and feature information
4	Editable CAD model	Editable surface/solid or B-rep geometry	Redesign, simulation and manufacturing integration	May lack feature history and design semantics
5	Feature-based parametric CAD	Explicit features, dimensions, constraints, symmetry and topology; nominal geometry and partial design intent may be inferred where supported	Systematic redesign, optimisation and configurable manufacture	Design intent may remain incomplete or non-unique
6	Validated engineering model	Dimensionally validated model with application-appropriate traceability; may include justified tolerances, functional relationships and recovered design intent	Tolerance-sensitive manufacture, inspection, simulation and lifecycle engineering	Highest reconstruction and validation effort; some design intent may remain unrecoverable

4.2.4. Geometric Fidelity and Design-Intent Recovery

A further distinction is required between geometric fidelity and design-intent recovery. Geometric fidelity describes how closely a reconstructed representation reproduces the geometry of the physical component in its measured condition. Design-intent recovery addresses a different question: whether the reconstructed model captures the nominal features, dimensional relationships, constraints and functional logic that the component was originally intended to embody. A reconstruction may therefore exhibit very high geometric fidelity while still providing little information about the nominal engineering definition of the part.

A physical component can represent several distinct geometric states that should not be conflated during reverse engineering. The as-designed geometry corresponds to the nominal geometry defined by the original engineering specification; the as-manufactured geometry contains the dimensional and geometric deviations introduced by the production process; and the as-measured or as-served geometry additionally reflects any wear, permanent deformation, damage, repair-induced modification or other change accumulated during service. Shape acquisition observes the latter physical state rather than the original nominal definition. Consequently, high-fidelity reproduction of the measured surface does not necessarily constitute recovery of the geometry that was originally designed.

The appropriate reconstruction target therefore depends on the intended engineering use. For dimensional inspection, wear assessment, damage evaluation, failure analysis or condition documentation, preservation of the measured deviations may be essential because those deviations are themselves the information of interest. For replacement-part manufacture, remanufacture, redesign or functional restoration, however, direct reproduction of the measured geometry may reproduce component imperfections rather than recover the intended nominal geometry. In such cases, the reconstruction process must distinguish between features that represent design intent and deviations resulting from manufacturing or service history.

Design intent and nominal geometry should therefore be treated as inferred layers of engineering information rather than as directly measured quantities. Their recovery may be supported by geometric regularities such as symmetry, repeated features and nominal feature relationships; by mating or neighbouring components; and by available functional, tolerance, manufacturing or service information. Such inference should not be used indiscriminately to regularise measured geometry, because an apparent deviation may represent either an imperfection or a functionally significant feature. Where the available evidence is insufficient, the reconstructed model should distinguish clearly between measured as-served geometry and inferred nominal geometry rather than presenting the latter as uniquely determined by the acquired data.

The distinction is already evident in the reviewed literature. The template-based approach discussed in [14] seeks to preserve feature history, geometric constraints and design intent rather than reproducing mesh geometry alone. Similarly, the reviewed gear-reconstruction studies show that accurate measurement of gear geometry does not by itself recover all of the design information required to reconstruct the original strength-related specification or functional intent [77,78]. These examples demonstrate that acquisition accuracy and geometric similarity provide necessary information for engineering reconstruction but may not be sufficient for recovering the nominal component definition.

Design intent should therefore be treated as an inferred layer of engineering information rather than as a directly measured quantity. Its recovery may be supported by geometric regularities such as symmetry and repeated features, by mating or neighbouring components, and by available functional or manufacturing information. Where such evidence is insufficient, the reconstructed model should distinguish clearly between measured geometry and inferred nominal geometry rather than presenting the latter as uniquely determined by the acquired data.

4.2.5. Component-State Framework for Reverse Engineering

The distinction between measured geometry and intended geometry can be formalised through four component states: As-Designed, As-Manufactured, As-Used and As-Reconstructed. These states describe different representations of the same component and clarify why reverse-engineering workflows may pursue substantially different reconstruction objectives.

The As-Designed state represents the nominal engineering definition of the component, including its intended geometry, dimensional relationships, tolerances, feature organisation and, where available, functional or manufacturing constraints. The As-Manufactured state represents the physical geometry produced by the manufacturing process and therefore contains permissible and impermissible deviations from the nominal definition arising from manufacturing capability, process variation, material behaviour and assembly conditions.

The As-Used state represents the component after manufacture and subsequent service. In addition to manufacturing deviations, it may contain wear, permanent deformation, damage, corrosion, repair-induced modifications or other service-related changes. This is commonly the physical state directly observed by reverse-engineering acquisition systems, particularly when legacy, damaged or service-exposed components are digitised.

The As-Reconstructed state is the digital representation generated from the available geometric measurements and engineering evidence. Unlike the preceding states, it is not determined exclusively by the physical condition of the component, because its required content depends on the intended engineering application. An As-Reconstructed model may deliberately preserve the As-Used geometry, estimate the As-Manufactured condition, infer the nominal As-Designed geometry, or combine measured and inferred information when functional restoration is required.

The relationship can therefore be represented conceptually as

$$\text{As-Designed} \rightarrow \text{As-Manufactured} \rightarrow \text{As-Used} \rightarrow \text{acquisition and interpretation} \rightarrow \text{As-Reconstructed}$$

where the first three states describe the evolution of the physical component, while the As-Reconstructed state represents an application-dependent digital interpretation of the available evidence. Reverse engineering should consequently define the target state before acquisition and reconstruction decisions are made.

For inspection and conformity assessment, the principal objective may be to compare the As-Manufactured or As-Used state against the As-Designed definition while retaining measured deviations. Failure analysis and condition assessment similarly require preservation of wear, deformation or damage because these deviations constitute the information of interest. By contrast, legacy-part recovery, replacement-part manufacture and remanufacturing may require reconstruction towards a nominal or functionally restored state rather than direct reproduction of the worn component. Redesign uses the recovered geometry and functional relationships as an engineering baseline for subsequent modification, while maintenance and condition-oriented digital-twin updating may require the As-Reconstructed model to reproduce the evolving As-Used condition as faithfully as the application demands.

In this lifecycle-oriented interpretation, reverse engineering is not restricted to the creation of a single digital representation at one point in time. Repeated acquisition of the same component at defined service intervals can generate a sequence of As-Reconstructed states that document the geometric evolution of the physical asset. Comparison of these successive states can support dimensional monitoring, localisation and quantification of wear, permanent deformation or material loss, assessment of repair effectiveness, and identification of geometry requiring restoration or replacement. Reverse engineering can therefore contribute to digital-twin updating by supplying periodically refreshed geometric information describing the evolving physical condition of the component.

Such longitudinal comparison requires greater metrological control than isolated digitisation. Apparent differences between successive reconstructions may originate not only from physical change, but also from variations in calibration, fixturing, datum definition, acquisition coverage, registration, surface condition or reconstruction parameters. Lifecycle-oriented workflows should therefore maintain a consistent reference system and, where practicable, comparable acquisition and processing conditions across measurement epochs. Changes interpreted as wear or deformation should exceed the uncertainty associated with the repeated acquisition and reconstruction process or otherwise be verified independently.

When these conditions are satisfied, repeated reverse-engineering measurements can provide geometric evidence for condition-based engineering decisions. Rather than remanufacturing or repairing a component solely according to predetermined intervals, the current reconstructed condition can be compared with nominal geometry, previous service states or functional limits to support repair planning, remaining-geometry assessment and condition-based remanufacturing. The resulting digital representation becomes a dynamically updated record of component condition rather than a static reconstruction generated only at the beginning of the reverse-engineering process.

The framework should not be interpreted as implying that the original As-Designed state can always be recovered uniquely from an As-Used component. Information may have been lost through manufacturing variation, wear, damage or missing design documentation, and several nominal geometries may be compatible with the same measured evidence. Where this occurs, inferred nominal geometry should be identified explicitly as an engineering interpretation rather than as directly recovered design information.

The practical significance of these four states depends on the purpose of the reverse-engineering activity. Table 16 summarises the information represented by each state and relates it to the principal engineering objectives for which reverse engineering may be applied. The distinction is particularly important because the required As-Reconstructed model does not necessarily correspond directly to the geometry of the measured component: depending on the application, the reconstruction may preserve the current physical condition, support comparison with a nominal definition, or infer a functionally restored or redesigned geometry from the available evidence.

Table 16. Component-state framework linking physical-component evolution with reverse-engineering objectives and reconstruction targets.

State	Represents	Principal Information	Typical Reverse-Engineering Relevance
As-Designed	Nominal engineering definition of the component	Intended geometry, dimensions, feature relationships, constraints, tolerances and functional requirements	Nominal reference for conformity assessment, design recovery, redesign and functional interpretation
As-Manufactured	Physical component immediately after production	Nominal geometry together with manufacturing-induced dimensional and geometric deviations	Production inspection, quality assessment, conformity verification and manufacturing-process evaluation
As-Used	Component in its current or service-exposed condition	As-manufactured geometry modified by wear, deformation, damage, corrosion, repairs or other service-induced changes	Maintenance, condition assessment, failure analysis, wear/deformation monitoring, repeated lifecycle acquisition and digital-twin updating
As-Reconstructed	Application-specific digital representation generated through reverse engineering	Measured geometry combined, where justified, with interpolated, constraint-reconstructed or inferred nominal, functional and design information; geometric provenance should remain identifiable	Inspection, legacy-part recovery, remanufacturing, replacement-part production, redesign, simulation, repair planning, condition-based remanufacturing, digital-twin updating and engineering documentation.

The As-Reconstructed state is therefore not a fixed representation of the As-Used component, but an application-dependent reconstruction target. For inspection, failure analysis and condition monitoring, preservation of measured deviations may be essential because wear, damage or deformation constitute the information of interest. For legacy-part recovery, replacement-part manufacture or remanufacturing, the reconstruction may instead seek to suppress service-induced deviations and infer a nominal or functionally restored

geometry. Redesign may use either state as a starting point, depending on whether the objective is to preserve existing interfaces, recover nominal functionality or modify the component for a new requirement. Similarly, digital-twin updating may require the reconstructed model to remain closely aligned with the evolving As-Used condition rather than with the original nominal definition. The framework should not be interpreted as implying that the original As-Designed state can always be recovered uniquely from an As-Used component. Information may have been lost through manufacturing variation, wear, damage or missing design documentation, and several nominal geometries may be compatible with the same measured evidence. Where this occurs, inferred nominal geometry should be identified explicitly as an engineering interpretation rather than as directly recovered design information.

In addition to identifying the component state represented by the As-Reconstructed model, the provenance of its geometry should also be preserved. A reconstructed model may contain regions supported by substantially different forms of evidence even when they are represented as a single continuous surface or solid. Four principal provenance classes can be distinguished: directly measured geometry, interpolated geometry, constraint-reconstructed geometry and AI-inferred geometry.

Directly measured geometry is supported explicitly by acquired coordinates, surface points, images transformed through a calibrated reconstruction process, tactile measurements or volumetric data. Interpolated geometry is generated between or across available measurements using geometric continuity, meshing, surface fitting or local gap-repair procedures and therefore remains related to nearby measured data but is not itself directly observed. Constraint-reconstructed geometry is generated using explicit deterministic relationships such as analytical primitives, symmetry, repeated features, datum relationships, dimensional constraints or other engineering rules. AI-inferred geometry is generated or completed through learned relationships derived from training data or model priors and may therefore represent a statistically or geometrically plausible solution without being uniquely supported by the physical measurements.

These provenance classes should remain distinguishable throughout reconstruction, CAD abstraction and validation rather than being lost when the datasets are merged into a continuous engineering model. Region- or feature-level provenance metadata would allow downstream users to determine whether a surface or feature originates directly from measurement, interpolation, explicit engineering constraints or data-driven inference. Such information is particularly important for tolerance-critical features, mating interfaces, datums, thin walls and inaccessible geometry, where the engineering consequences of an incorrect reconstruction may be substantially greater than those of local visual inconsistency.

Geometric provenance should therefore be regarded as complementary to the component-state framework rather than as an additional component state. The As-Reconstructed model defines what physical or engineering condition the digital representation is intended to describe, whereas geometric provenance identifies how the information defining each region of that model was obtained. Preserving both forms of information would improve transparency, uncertainty assessment and metrological validation in future intelligent reverse-engineering systems.

Geometric provenance can be extended into a broader data-provenance concept for engineering reverse engineering. In addition to identifying how a geometric region was generated, a provenance-aware digital model could retain information describing the acquisition source from which the geometry originated, the principal processing operations applied to it, the reconstruction method used to create the corresponding surface or CAD feature, the uncertainty information associated with that representation and its subsequent validation status. Provenance would therefore provide an auditable connection between the final engineering model and the measurement and computational history from which it was derived.

At feature level, such information could indicate, for example, which scanner, tactile measurement or volumetric dataset contributed to a reconstructed feature; whether the underlying data were filtered, registered, interpolated or completed; whether the final geometry was obtained through direct fitting, deterministic geometric constraints or AI-assisted inference; what uncertainty or confidence information is available; and whether the feature has been independently verified against a reference measurement. Preserving these attributes would become increasingly important as reverse-engineering workflows combine multiple sensors and reconstruction methods within the same CAD representation.

Data provenance should nevertheless be distinguished from metrological traceability. Provenance describes the origin and transformation history of information, but does not by itself establish traceability to a recognised reference through a documented calibration chain with associated measurement uncertainty. It can, however, provide the information infrastructure required to determine which parts of a reconstructed model have direct measurement support, which processing operations have modified them and what validation evidence is available. For high-value, tolerance-sensitive or safety-critical applications, this distinction could enable different levels of confidence and acceptance criteria to be assigned to individual features rather than to the CAD model only as a whole. Future intelligent reverse-engineering systems should therefore seek not only to generate editable

geometry, but also to preserve machine-readable provenance throughout the scan-to-CAD chain. Feature-level provenance could support subsequent revalidation, model revision, auditability and lifecycle use by preventing measurement evidence, reconstruction assumptions and validation history from being lost when heterogeneous datasets are consolidated into a final engineering model.

4.3. Metrological Validation and Engineering Use

The final stages of the reverse-engineering chain concern validation of the reconstructed geometry and determination of whether the resulting model is suitable for its intended engineering use. Geometric resemblance alone is insufficient when a model is intended for dimensional inspection, redesign, simulation, tooling, repair or manufacturing. The reconstructed geometry must retain the dimensional information, critical feature relationships and uncertainty level required by the application, and validation should therefore be selected according to the intended use of the model. Tactile reference measurements, part-to-CAD comparison, volumetric verification or hybrid metrology may be required depending on the acquisition route and tolerance requirements. The industrial value of reverse engineering is consequently most clearly understood when acquisition, reconstruction and validation are related to the engineering task that the final model is expected to support.

- **Legacy and obsolete-part reproduction** represents one of the most direct applications of reverse engineering, particularly where drawings, nominal CAD geometry or manufacturing documentation are unavailable [7,11]. For components dominated by simple prismatic features, manual measurement can remain economically justified, whereas worn or non-standard gears illustrate the need for more rigorous acquisition when functional geometry must be recovered [77,78]. Dense structured-light or laser-based scanning becomes preferable for complex external forms because it reduces the number of manually interpreted dimensions and provides richer geometric information for surface reconstruction. Where inaccessible internal passages or concealed features are relevant, CT offers an additional capability unavailable to surface-based techniques. In practice, reconstruction of a serviceable replacement component may therefore combine dense surface acquisition with tactile verification of critical dimensions before CAD remodelling and remanufacture.
- **Dimensional inspection and conformity assessment** impose a different priority. In these applications, the objective is not necessarily to recover every visible surface but to establish whether critical dimensions and geometric features conform to specified requirements. Tactile CMMs retain a strong role because of their repeatability and metrological traceability, particularly for precision-manufactured components. The turbine-blade application examined in [73], for example, demonstrates the importance of acquisition accuracy when freeform geometry must be evaluated rather than merely visualised. Optical scanners can provide much faster full-field deviation information, making structured-light and laser-triangulation systems attractive for production inspection, while tactile measurements can be retained as reference measurements for critical features. The industrial integration of automated CMMs in automotive production further illustrates the importance of combining measurement accuracy with production-line compatibility [70].
- **Cultural-heritage applications** place greater emphasis on non-contact acquisition, geometric coverage and visual information than on conventional manufacturing tolerances. Photogrammetry is particularly attractive because large or immovable artefacts can be captured with relatively limited equipment while preserving colour and texture information; the reviewed literature includes its use for heritage documentation and BIM enrichment [93]. Laser-based acquisition provides a complementary route where more explicit geometric measurement is required, including integrated three-dimensional replication and heritage-archive workflows [145,150]. CT can extend this concept beyond visible surfaces by revealing internal structures or material regions that cannot be recovered through external digitisation alone, as demonstrated for heritage objects in [190]. In this domain, therefore, the reconstructed output may range from a visual digital archive to a geometrically accurate replica or information-rich heritage model.
- **Biomedical reverse engineering** requires acquisition routes that minimise physical interaction while reproducing patient-specific or anatomically complex geometry. Optical scanning is particularly useful for accessible external anatomy because it provides dense surface information without contact; Figure 3, for example, illustrates structured-light acquisition for auricular prosthesis workflows. Photogrammetric approaches have also been applied to full-arch implant recording [96]. CT and CBCT become substantially more important where the reconstruction must incorporate internal anatomical structures, with the reviewed studies reporting applications in craniofacial reconstruction, segmentation, treatment planning and patient-specific device development [76,79,187]. The choice between optical and tomographic acquisition is therefore closely linked to whether the required engineering model concerns external morphology alone or both external and internal anatomy. The manuscript already demonstrates this distinction across the biomedical literature.

- **Tooling, aerospace and automotive applications** combine demanding geometry with stronger requirements for dimensional verification, repeatability and manufacturing integration. Turbine-blade reconstruction provides a representative aerospace-type case in which tactile and non-contact acquisition must be evaluated against complex freeform geometry and accuracy requirements [73]. Laser triangulation and structured-light scanning are particularly suitable for moulds, dies, tooling and large freeform components because they provide dense external geometry considerably faster than conventional probing, while robotic and CMM-mounted configurations facilitate automation. Tactile verification remains valuable for datums, mating interfaces, bores and other tolerance-critical features. This combination explains the growing interest in hybrid acquisition workflows for high-value components where neither dense optical acquisition nor sparse traceable measurement alone provides sufficient information.
- **AM workflows** illustrate how reverse engineering can extend beyond replication into redesign and manufacturing optimisation. Scan-derived geometry may be reconstructed directly as a polygonal model for geometrically tolerant reproduction or converted into an editable CAD model when design modification, simulation or optimisation is required. Patgar et al. [194] provide a recent automotive example in which the geometry of a clutch fork was recovered through reverse engineering, subsequently subjected to structural analysis and design optimisation, and finally linked to AM. This workflow demonstrates that the industrial value of RE lies not only in reproducing an existing component but also in using recovered geometry as the starting point for a redesigned manufacturing solution. CT is additionally relevant to AM parts where internal channels, lattice structures or concealed defects must be reconstructed or inspected, whereas optical methods remain more efficient when the requirement is limited to external geometry.

These examples show that industrial suitability cannot be assigned solely according to sector. Within the same industry, different stages of the component lifecycle may require different acquisition principles. A tactile CMM may be preferred for final dimensional verification, structured light or laser triangulation for rapid surface recovery, CT for concealed geometry, and photogrammetry for large-scale or low-cost capture. Industrial RE is therefore most effectively implemented as a task-specific workflow in which the acquisition technology is selected according to the geometry to be recovered, the required uncertainty level, the downstream digital model and the intended manufacturing, inspection or documentation task. A further lifecycle application arises when reverse engineering is repeated rather than performed as a one-time reconstruction. Successive validated acquisitions can provide time-resolved geometric information for a digital twin, allowing the evolution of wear, deformation, damage or repair-induced changes to be evaluated against previous states and functional limits. In this context, the value of shape acquisition lies not only in reproducing geometry, but also in detecting statistically and metrologically meaningful geometric change across the component lifecycle. The same lifecycle perspective also establishes a connection between reverse engineering and circular manufacturing. Legacy- and replacement-part recovery, repair, remanufacturing and functional restoration use geometric information from existing components to retain, recover or reproduce engineering value that might otherwise be lost when original design data are unavailable. The reviewed literature specifically identifies reverse engineering as an enabling route for digitally integrated remanufacturing and sustainable metal-manufacturing workflows [15,81], while the component-state analysis developed here shows how reconstruction can support decisions between preserving the As-Used condition, restoring nominal functionality and producing a replacement component.

The sustainability benefit should nevertheless be interpreted at workflow and lifecycle level rather than attributed to digitisation alone. Reverse engineering contributes to circular-manufacturing strategies when the recovered information enables continued use, targeted repair, remanufacturing, refurbishment or justified replacement, thereby supporting retention of existing component and material value. Repeated condition assessment can further strengthen this role by identifying whether deterioration requires intervention or whether continued service remains geometrically acceptable. In this sense, reverse engineering can support component-life extension and condition-based recovery strategies, although the resulting environmental benefit remains dependent on the acquisition, processing, repair and manufacturing resources required by the specific application.

This text is supported by use cases already represented in your review rather than introducing unrelated applications. The manuscript already contains, for example, worn-gear reconstruction [77,78], turbine-blade digitisation [73], heritage applications [93,145,150], medical reconstruction [76,79], and the automotive/additive-manufacturing case [194].

4.3.1. Application-Driven Technology-Selection Framework

The application evidence discussed above can be translated into an application-driven technology-selection framework in which the engineering task, rather than the acquisition technology, provides the starting point for

workflow definition. Different application domains impose markedly different priorities regarding geometric coverage, dimensional accuracy, permissible physical contact, internal-feature accessibility, acquisition speed, portability, visual information, metrological traceability and required digital-model maturity. Technology selection should therefore begin by identifying the dominant application requirements before evaluating the acquisition and reconstruction routes capable of satisfying them.

Table 17 summarises these relationships for the principal application domains represented in the reviewed literature. The indicated acquisition routes should be interpreted as application-dependent tendencies rather than fixed prescriptions. Within any one sector, component geometry, material, surface condition, accessibility and tolerance can shift the appropriate strategy towards a different or hybrid measurement route. The reconstruction column is included because selection of the acquisition technology cannot be separated from the form and validation level required of the final digital model.

Table 17. Application-driven technology-selection framework for reverse-engineering workflows.

Application Domain	Dominant Engineering Requirements	Acquisition Emphasis	Reconstruction and Validation Emphasis
Legacy- and spare-part recovery/remanufacturing	Recovery of functional geometry; absent or incomplete CAD documentation; distinction between wear and nominal geometry; economic viability	Manual measurement for simple regular features; structured light or laser triangulation for complex external geometry; CT where concealed geometry is required; tactile measurement for critical dimensions	Editable or feature-based CAD where manufacture or redesign is required; explicit distinction between As-Used and inferred nominal geometry; validation of mating and tolerance-critical features
Cultural heritage and documentation	Non-contact acquisition; portability; large measurement volume; preservation of colour, texture and visible detail; minimal intervention	Photogrammetry for large-scale and texture-rich documentation; laser-based acquisition where stronger geometric definition is required; CT where internal structure is relevant	Mesh, surface, BIM or archive-oriented representation according to purpose; emphasis on geometric completeness and visual/documentary fidelity rather than conventional manufacturing tolerances
Biomedical and patient-specific reconstruction	Minimal physical interaction; complex anatomy; patient-specific geometry; external and/or internal morphology	Structured-light or other optical acquisition for accessible external anatomy; photogrammetry in suitable image-based applications; CT/CBCT where internal anatomical information is required	Segmentation and anatomically faithful surface reconstruction; patient-specific digital models; validation level determined by the intended clinical or device-related use
Tooling, mould and die reconstruction	Dense freeform geometry; surface detail; dimensional fidelity; wear assessment; manufacturing integration	Structured-light or laser-triangulation scanning for dense external geometry; tactile CMM for datums, bores, mating interfaces and tolerance-critical features; hybrid acquisition where both coverage and traceability are required	Surface or editable CAD reconstruction; preservation/recovery of functional features; datum- and feature-based dimensional validation
Aerospace and other high-value precision components	Complex freeform surfaces; tight dimensional requirements; internal or concealed features; traceability; high consequence of reconstruction error	Dense optical acquisition for external geometry; tactile CMM for critical features and datums; CT for internal geometry; hybrid metrology where completeness and metrological confidence must coexist	Engineering-ready or validated CAD; explicit uncertainty control; GD&T- and feature-oriented validation; high importance of geometric provenance
Automotive and production metrology	Acquisition throughput; repeatability; automation; production-line compatibility; dimensional conformity	Structured light and laser triangulation for rapid full-field acquisition; automated CMM for traceable feature verification; CT where internal inspection is required	Automated registration and part-to-CAD comparison; targeted verification of critical dimensions and datums; strong emphasis on repeatable workflow integration
Additive manufacturing, redesign and optimisation	Complex geometry; possible internal channels or lattice structures; design modification; simulation/manufacturing integration	Optical methods for external geometry; CT where internal geometry must be reconstructed or inspected	Mesh representation may suffice for direct geometrically tolerant reproduction; editable CAD required for redesign or optimisation; simulation- and manufacture-oriented validation
Lifecycle maintenance, repair and condition-based remanufacturing	Repeatability over time; wear/damage detection; common datum definition; geometric change assessment; component-life extension	Repeated acquisition using a technology compatible with the geometry and required uncertainty; hybrid verification where critical changes require higher confidence	Longitudinal comparison of successive states; preservation of provenance; uncertainty-aware change detection; support for repair, continued-service or remanufacturing decisions

The framework illustrates that application domain is useful as an initial decision layer, but should not replace component-specific technology selection. Aerospace and automotive applications, for example, may require rapid optical acquisition for extensive external geometry, tactile verification for datums and tolerance-critical features, or CT when internal structures must be recovered. Similarly, biomedical reconstruction may shift from optical surface acquisition to tomographic imaging according to whether the required model concerns external morphology or internal anatomy. Application-driven selection should therefore identify the dominant requirements first, after which the component-, surface-, accessibility- and tolerance-based screening criteria established in Section 4.1.1 can be applied to determine the final acquisition strategy.

The required digital output provides a second selection layer. Heritage documentation may terminate at an accurate mesh or information-rich digital archive, whereas tooling, aerospace, automotive or remanufacturing applications may require editable CAD, explicit functional features and traceable dimensional validation. Acquisition and reconstruction strategy should consequently be selected jointly according to both the application requirements and the maturity required of the final engineering representation.

4.3.2. Functional Datums, Critical Features and GD&T-Based Validation

Metrological validation of a reverse-engineered model should distinguish between global geometric agreement and conformity of functionally significant features. Full-field comparisons, colour deviation maps and scalar indicators such as mean or root mean square deviation can provide useful information on overall geometric similarity, but they do not necessarily determine whether the reconstructed component is suitable for its intended engineering function. A relatively small global deviation may coexist with unacceptable local errors in a datum surface, bore, axis, mating interface or other tolerance-critical feature.

RMS deviation should consequently be interpreted as a global summary statistic rather than as a complete measure of reconstruction quality. Because the squared deviations are aggregated over the evaluated surface, the resulting value contains no direct information about the spatial location or functional significance of the individual errors. Two reconstructed models can therefore exhibit comparable RMS deviations while having markedly different deviation distributions: one may contain relatively small and spatially distributed errors, whereas another may contain localised deviations concentrated in a tolerance-critical feature or functional interface. Their global RMS values may be similar even though their engineering consequences are substantially different. RMS assessment should therefore be complemented by spatially resolved and feature-oriented measures. Depending on the intended application, these may include signed deviation maps, maximum or percentile-based local deviations, dimensional errors of individual features, and verification of form, orientation, position and runout relative to functional datums. The appropriate combination of metrics should be determined by the engineering function of the reconstructed component and by the tolerances governing its acceptance.

Engineering validation should therefore consider the functional reference structure of the component. Datums establish the reference frame within which the location and orientation of other features are interpreted, and their reconstruction can be more important than minimising unconstrained global surface error. Where a component contains functional planes, axes, bores, locating surfaces or mating interfaces, these features should be identified explicitly and evaluated relative to the appropriate datum system rather than only through a best-fit comparison of the complete measured surface.

The same principle applies to geometric dimensioning and tolerancing. Depending on the function of the component, acceptance may depend on the form of individual features, their orientation relative to reference datums, their position within an assembly, or their rotational behaviour rather than on surface similarity alone. Form, orientation, position and runout requirements therefore represent a different level of engineering verification from global point-to-surface deviation. Their relevance is particularly high where the reconstructed model is intended for replacement-part manufacture, assembly, precision inspection, tooling or tolerance-sensitive redesign.

This distinction also affects acquisition-strategy selection. Dense optical systems are advantageous for assessing extensive freeform geometry and generating full-field deviation information, whereas tactile coordinate measurement remains especially valuable for establishing or verifying datums, analytical features and critical dimensions with greater metrological confidence. Hybrid workflows can therefore combine global geometric coverage with targeted validation of functional features, provided that the different datasets are related through a controlled reference system and their respective uncertainties are considered.

Accordingly, validation of an engineering-ready reconstruction should be hierarchical rather than based on a single global error metric. Overall surface fidelity may first be characterised using full-field deviation maps and statistical measures such as RMS, but these results should subsequently be supplemented by local analysis of critical regions and feature-specific verification relative to the functional datum system. Where dimensional or

geometric tolerances govern component acceptance, compliance with those requirements should take precedence over the magnitude of a global surface-deviation statistic. The required level of verification should ultimately be determined by the intended engineering use of the reconstructed model.

4.4. Automation and AI across the Reverse-Engineering Workflow

Automation and AI increasingly act as cross-cutting enablers within the end-to-end reverse-engineering workflow, although their most mature applications currently occur in the processing and reconstruction stages that follow geometric acquisition. Recent studies use learning-based methods for point-cloud denoising, segmentation, registration and completion, as well as for extracting geometric information before surface fitting or CAD reconstruction. The immediate objective is practical: to reduce the manual cleaning, alignment and interpretation required before scan data can be used for engineering modelling. Registration is a representative example, because algorithms can establish correspondences between overlapping datasets and reduce manual alignment effort, although their performance remains sensitive to point density, missing regions and scanner-specific artefacts.

A task-specific distinction is nevertheless required between problems that benefit from learning-based inference and those for which deterministic geometric procedures remain more appropriate. Machine Learning (ML) is most valuable where the input data are irregular, incomplete, noisy or heterogeneous and where the required operation involves classification, semantic interpretation or inference from complex spatial patterns. Segmentation, denoising, point-cloud completion, feature recognition and topology inference fall naturally within this category because their solution often requires identifying patterns or relationships that are difficult to express through a fixed set of geometric rules. Learning-based methods can also assist surface reconstruction by providing initial segmentation, feature classification or locally inferred geometric information before subsequent fitting.

Deterministic algorithms retain important advantages when the geometric problem is explicitly defined and the resulting operation must remain transparent and metrically controllable. Registration to known datums or reference features, analytical primitive fitting, geometrically constrained surface fitting, dimensional constraint enforcement and final metrological verification can generally be expressed through explicit coordinate transformations, optimisation criteria or geometric relationships. In such cases, deterministic procedures offer interpretable residuals and parameters, do not depend on representative training datasets and are more readily incorporated into traceable validation chains. Their principal limitation arises when the geometry, topology or feature class cannot be specified reliably in advance.

The strongest role for AI within engineering reverse engineering is therefore likely to be complementary rather than substitutive. A learning-based stage may identify regions, recognise candidate features, infer topology or propose missing geometry, after which deterministic geometric algorithms can refine the dimensional representation, impose analytical or parametric constraints and verify the resulting model against measured data. This separation between data-driven interpretation and deterministic geometric enforcement is particularly important for tolerance-sensitive applications, because a geometrically plausible learned output is not necessarily a metrically valid engineering reconstruction.

This distinction becomes particularly important when AI-assisted methods generate geometry in regions that were not directly observed by the acquisition system. Point-cloud completion, surface inpainting, learned shape completion and related reconstruction methods may produce geometrically coherent surfaces across occluded, missing or sparsely sampled regions, but such outputs should be interpreted as inferred geometry rather than as direct measurements of the physical component. Geometric plausibility therefore does not establish metrological validity.

The provenance of reconstructed geometry should consequently be retained throughout the digital workflow. In accordance with the geometric-provenance framework introduced in Section 4.2.5, future intelligent workflows should distinguish directly measured, interpolated, constraint-reconstructed and AI-inferred regions rather than representing all reconstructed geometry as evidentially equivalent Regions derived directly from measured data should be distinguishable from regions generated, extrapolated or regularised computationally, particularly when the model is intended for dimensional inspection, manufacturing, simulation or tolerance-sensitive redesign. Where AI inference affects datums, mating interfaces, thin walls, bores or other functionally critical features, the reconstructed geometry should be verified independently where feasible rather than accepted solely on the basis of visual continuity or global surface similarity. Reconstruction maturity should not be confused with geometric provenance. A model may reach a high DRML while containing a combination of directly measured, interpolated, constraint-reconstructed and inferred geometry. Higher reconstruction maturity therefore does not, by itself, imply that every region of the model has equivalent metrological evidential support; provenance should be retained and considered independently during validation.

Validation of AI-assisted reconstruction should also reflect the fact that uncertainty is spatially non-uniform. Confidence in directly measured regions may be governed principally by acquisition and processing uncertainty, whereas inferred regions introduce an additional model-dependent contribution associated with the training data, learned prior, inference architecture and degree of missing information. AI-assisted workflows should therefore report which portions of the final model are measured and which are inferred, together with the validation evidence supporting the latter. Where dimensional traceability is required, inferred geometry should not be treated as equivalent to traceably measured geometry unless independently verified.

Feature recognition becomes more demanding when the required output is an editable engineering model rather than a polygonal representation. Current approaches seek to identify geometric primitives, manufacturing features and topological relationships in scan-derived data and to transfer this information into parametric or feature-based CAD representations. Such abstraction is important for redesign and manufacturing because dimensional relationships, constraints and feature connectivity must remain editable; geometric resemblance alone is insufficient. ML classification and topology inference can therefore support the interpretation of unstructured scan data, while geometric fitting and rule- or constraint-based reconstruction provide the explicit engineering structure required for editable CAD generation.

For AI-assisted completion in particular, validation should distinguish agreement with measured geometry from plausibility in unmeasured regions, since the latter cannot establish dimensional correctness without an independent reference. Training data are often restricted to particular component families or acquisition conditions, and performance can deteriorate when geometry, surface condition, point density or sensor characteristics differ from the training set. Metrological traceability is another unresolved issue: many learning-based pipelines report geometric reconstruction performance without propagating acquisition and processing uncertainty to the final CAD model. Automated systems can therefore reduce preprocessing effort and assist feature interpretation, but expert intervention remains necessary when geometry is ambiguous, tolerances are critical or the reconstructed model must recover functional design intent. Accordingly, performance assessment of AI-assisted reconstruction should include not only geometric error, but also generalisation across component and sensor conditions, explainability of the inferred geometry, uncertainty behaviour, reproducibility and compatibility with metrological traceability.

From an industrial standpoint, automation should therefore be evaluated within the task-specific acquisition and reconstruction framework discussed in Sections 4.1–4.3. Its principal value lies in reducing the manual effort required to convert heterogeneous scan data into engineering-ready models without compromising the dimensional and functional information required by the intended application. Finally, the review highlights several limitations in the literature itself that affect interpretation. Terminological inconsistency remains widespread, particularly across photogrammetry, stereo vision, optical scanning, reconstruction, and CAD-generation studies. Reporting quality is also heterogeneous, with many studies lacking sufficiently detailed descriptions of scanner configuration, calibration, acquisition setup, environmental conditions, or reconstruction parameters. This makes direct comparison difficult and weakens the generalisability of performance claims. The use of Crossref as the principal bibliographic source also entails a dependence on publisher-deposited metadata, whose completeness varies across records; complementary searches and metadata verification were therefore used to reduce the likelihood of relevant studies being overlooked. A further methodological limitation concerns the QA procedure, which was conducted by a single reviewer. Although predefined scoring criteria were applied and borderline studies were subjected to a second full-text assessment, that reassessment was performed by the same reviewer and therefore cannot establish inter-rater agreement. The procedure may consequently remain susceptible to reviewer-dependent judgement, particularly for studies close to the inclusion threshold. The predefined framework and reassessment procedure were intended to improve consistency, but they should not be interpreted as substitutes for independent duplicate assessment. Future systematic reviews in this area would benefit from QA performed independently by at least two reviewers, together with formal assessment and reporting of inter-rater agreement. Moreover, many investigations are method-specific and do not assess how acquisition choices affect the complete downstream workflow. These limitations suggest that future progress in reverse-engineering research will depend not only on better technologies, but also on more standardised reporting, more rigorous benchmark comparisons, and a stronger focus on end-to-end workflow performance rather than isolated scanning capability.

The principal unresolved issue is therefore not geometric capture in isolation, but the conversion of measured data into models that are sufficiently accurate, editable and traceable for their intended engineering use. Acquisition hardware has advanced considerably, particularly for dense external-surface measurement, whereas CAD abstraction, uncertainty propagation and automated recovery of design intent remain less mature. The performance of an RE workflow should consequently be assessed across the complete scan-to-model chain rather than from scanner specifications alone.

4.5. Minimum Reporting Standard for Experimental Reverse-Engineering Studies

The reviewed literature reveals substantial variability in the information reported for experimental reverse-engineering workflows. Incomplete descriptions of acquisition-system configuration, calibration, measurement conditions, processing parameters and validation procedures make it difficult to reproduce experiments or determine whether differences between reported results arise from the sensing technology itself, the measurement setup, the processing strategy or the validation method. A minimum reporting framework would therefore improve both reproducibility and comparability across reverse-engineering studies.

Table 18 proposes a Minimum Reporting Standard for Experimental Reverse-Engineering Studies based on the recurrent methodological and reporting deficiencies identified during the literature synthesis. The framework follows the complete acquisition-to-validation chain and is intended to specify the minimum information required to interpret an experimental result adequately. Not every item is applicable to every acquisition principle; for example, stand-off distance and positioning targets are principally relevant to optical systems, whereas probe configuration and probing strategy are more relevant to tactile measurement. Where a parameter is not applicable, this should be stated explicitly rather than omitted without explanation.

Table 18. Proposed minimum reporting standard for experimental reverse-engineering studies.

Reporting Category	Minimum Information to Report
Component/measurand	Component type, material, relevant dimensions or measurement volume, surface condition, principal geometric characteristics and features of engineering interest
Acquisition system	Manufacturer and model of scanner, sensor, CMM, CT system or other measurement instrument; relevant hardware and acquisition configuration
Calibration and metrological status	Calibration status and procedure, calibration or reference artefact where relevant, date or interval where applicable, and traceability information if claimed
Measurement geometry	Measurement volume or field of view, stand-off/working distance where applicable, sensor orientation, probe configuration or measurement path, and relevant acquisition geometry
Resolution and sampling	Reported spatial resolution, point spacing, image resolution, voxel size, sampling interval or equivalent quantity, with the specific meaning of the reported parameter clearly identified
Environmental conditions	Temperature and, where relevant, humidity, vibration, ambient illumination and other environmental conditions capable of affecting measurement performance
Surface preparation	Cleaning, coating, matting spray or other preparation; material/product used; application procedure and number of applications where relevant; indication of whether preparation modifies the measured surface; coating thickness or other characterisation of the induced geometric effect where known.
Target/referencing strategy	Positioning targets, reference markers, coded targets, datum features, external reference systems or alternative localisation strategy
Acquisition coverage	Number of images, views, scans, probe paths or CT acquisitions; overlap where relevant; repositioning strategy and repeated acquisition of incomplete regions
Registration and alignment	Registration algorithm, initial alignment method, datum- or best-fit strategy, software used, relevant parameters and registration-error criterion where reported
Filtering and preprocessing	Noise removal, outlier rejection, smoothing, decimation, hole filling or other preprocessing operations, including relevant parameter settings
Mesh/surface reconstruction	Meshing algorithm, software, mesh-resolution or reconstruction settings, repair operations, segmentation procedure for volumetric data, and surface-fitting method where applicable
CAD reconstruction	Reconstruction strategy, including direct mesh use, fitted surfaces, B-rep, parametric or feature-based modelling; software and principal modelling assumptions
Data and geometric provenance	Origin of measured and reconstructed geometry; association between relevant datasets and reconstructed regions or features; identification of interpolated, constraint-reconstructed or AI-inferred geometry where applicable; principal processing history; reconstruction method; and preservation of provenance metadata within the final model where supported.
Reference and validation method	Reference measurement system or nominal geometry, comparison/alignment method, global and local validation metrics, functional-feature or GD&T verification where applicable
Uncertainty and repeatability	Measurement uncertainty or uncertainty-related information, number of repetitions, repeatability or reproducibility assessment, and treatment of uncertainty through subsequent processing where available
Computational and workflow performance	Acquisition, registration, processing, reconstruction and validation time where available; computational hardware/software; total effective reverse-engineering time and active operator involvement where feasible

The framework is intended to distinguish adequately documented experimental workflows from results reported primarily through final accuracy or reconstruction metrics. In particular, reporting a scanner specification or final RMS deviation without documenting the acquisition conditions, processing operations and validation reference provides insufficient information to determine the origin of the reported performance. The reporting standard should therefore be applied across the complete workflow, from the physical component and acquisition configuration to the reconstructed and validated digital model.

The proposed framework should not be interpreted as a formal international reporting standard. Rather, it represents a structured recommendation derived from the methodological variability observed across the reviewed studies. Adoption of a common minimum reporting structure would facilitate replication, more rigorous

comparison between acquisition technologies and reconstruction algorithms, and future development of benchmark datasets and standardised evaluation procedures.

4.6. Benchmark Geometry Framework for Comparative Reverse-Engineering Studies

Standardised reporting alone cannot ensure meaningful comparison when different acquisition technologies are evaluated using components with substantially different geometry, accessibility, material and surface characteristics. Comparative reverse-engineering research would therefore benefit from a common benchmark component or, more realistically, a modular family of benchmark geometries designed to expose the principal strengths and limitations of different acquisition and reconstruction principles.

A benchmark intended for technology-neutral comparison should contain geometric features that challenge different stages of the reverse-engineering workflow rather than favouring a particular measurement principle. Planar and cylindrical regions can provide controlled analytical features for dimensional and datum-based assessment, while freeform surfaces test dense geometric acquisition and subsequent surface fitting. Sharp edges and small-radius transitions challenge spatial sampling, filtering and meshing because excessive smoothing may modify local geometry. Thin walls provide sensitivity to spatial resolution, surface determination and reconstruction stability, whereas deep cavities, narrow recesses and restricted-access features test line-of-sight limitations and the effect of sensor orientation. Concealed internal cavities or channels are required if volumetric methods such as CT are to be evaluated against surface-based acquisition strategies.

Surface behaviour should also form part of the benchmark design. The same nominal geometry could be produced or equipped with interchangeable regions exhibiting matte, reflective, dark and other optically challenging finishes. This would permit the geometric influence of acquisition technology to be separated, as far as practicable, from surface-dependent optical effects. Material and finish should nevertheless be reported explicitly because changing the surface condition may also affect measurement uncertainty and, in some cases, the physical geometry being evaluated.

For metrological comparison, the benchmark should include a clearly defined datum reference system and traceable reference values for its principal dimensions and functional features. This would allow evaluation to extend beyond global best-fit surface deviation to feature-specific errors in size, form, orientation and position. A common reference definition would also permit local errors at sharp edges, mating features, deep cavities and other critical regions to be distinguished from the overall surface statistics discussed in Section 4.3.

Because no single artefact is likely to represent all relevant scales, materials and acquisition principles adequately, a benchmark family is preferable to a single universally prescribed geometry. A core external-geometry artefact could be supplemented by accessibility, internal-geometry and surface-condition variants. The principal feature classes and their intended evaluation roles are summarised in Table 19.

Table 19. Proposed benchmark-geometry family for comparative reverse-engineering studies.

Benchmark Feature/Module	Principal Purpose	Relevant Evaluation
Planar datum surfaces	Establish controlled reference geometry and coordinate-system definition	Flatness, orientation, registration stability, datum reconstruction
Cylinders and bores	Assess analytical-feature recovery and dimensional reconstruction	Diameter, cylindricity, axis location/orientation, CAD feature fitting
Freeform surfaces	Challenge dense surface acquisition and reconstruction	Surface completeness, local/global deviation, mesh and surface-fitting fidelity
Sharp edges and small-radius transitions	Assess edge preservation and processing-induced smoothing	Edge localisation, radius recovery, local deviation
Thin-wall features	Test limited feature thickness and opposing-surface reconstruction	Wall thickness, completeness, local uncertainty
Deep cavities/narrow recesses	Assess accessibility and line-of-sight limitations	Coverage, missing-data regions, required repositioning, reconstruction completeness
Restricted-access or occluded features	Challenge sensor orientation and multi-view acquisition	Number of views/scans, registration burden, inaccessible area
Internal cavities/channels	Assess volumetric and hybrid acquisition capability	Internal dimensional accuracy, segmentation effects, wall thickness, completeness
Reflective/optically challenging surface regions	Evaluate sensitivity to surface optical behaviour	Data loss, artefacts, surface preparation requirement, local deviation
Repeated or symmetric features	Evaluate consistency and feature-recognition capability	Repeatability, feature-to-feature dimensional consistency, design-intent reconstruction
Functional datum and mating features	Support engineering-oriented validation	Position, orientation, fit-related dimensions and GD&T-based assessment

A benchmark study should evaluate more than the final surface deviation. At minimum, comparative assessment should consider geometric completeness, feature-specific dimensional error, local and global deviation distributions,

repeatability where repeated acquisitions are performed, uncertainty or traceability information, registration and reconstruction burden, effective reverse-engineering time, and the level of CAD reconstruction achieved. The reporting framework proposed in Section 4.5 should accompany the benchmark so that apparent differences between technologies can be related to acquisition conditions, processing decisions and validation procedures rather than to the scanner alone.

The benchmark family proposed here is conceptual and would require subsequent dimensional design, manufacture, reference characterisation and interlaboratory validation before it could function as a formal standardised artefact. Its immediate purpose is to define the feature classes and evaluation principles required for more reproducible and informative comparisons between reverse-engineering technologies.

4.7. Research-Question Synthesis

The research questions established in Section 2 were used to structure the extraction and interpretation of evidence concerning acquisition limitations, reconstruction quality, metrological performance, automation and future development of reverse-engineering workflows. The preceding Discussion has examined these issues through the complete component–acquisition–reconstruction–validation–application chain. To close the methodological loop, Table 20 relates each research question to the principal evidence emerging from the reviewed literature, the current synthesis supported by that evidence, the principal unresolved issue and the resulting research direction.

The term current synthesis is used here to describe the interpretation supported by the reviewed corpus rather than to imply universal agreement across all reverse-engineering applications. This distinction is necessary because acquisition technologies, experimental protocols, component classes and validation procedures remain heterogeneous, and several questions therefore support robust qualitative tendencies without yet permitting universally transferable quantitative conclusions.

Table 20. Synthesis of the research questions, principal evidence, current interpretation, unresolved issues and recommended research directions.

RQ	Principal Evidence from the Review	Current Synthesis	Principal Unresolved Issue	Recommended Research Direction
RQ1	Comparative evidence across contact, optical and tomographic acquisition; technology-selection, accessibility, surface-compatibility and uncertainty frameworks	RE reliability is governed by the complete acquisition–reconstruction chain rather than scanner performance alone. Geometry, accessibility, surface/material behaviour and required tolerance jointly constrain feasible workflows.	Lack of directly comparable evidence across technologies, components and validation procedures.	Common benchmark geometries, minimum reporting requirements and end-to-end uncertainty assessment.
RQ1.1	Recurrent evidence of occlusion, incomplete coverage, noise, optical artefacts, sparse sampling, registration error and reconstruction-induced modification	Acquisition limitations propagate downstream and may affect mesh completeness, feature recovery, CAD fidelity and final engineering usability. Missing data cannot be treated as equivalent to directly measured geometry.	Quantitative propagation of local acquisition defects into final CAD and functional features remains poorly characterised.	Feature-specific error propagation studies; measured-versus-inferred provenance; validation of critical reconstructed regions.
RQ1.2	Surface-behaviour, accessibility and scale/tolerance analyses; evidence concerning reflectivity, transparency, low texture, dark surfaces, internal geometry and acquisition conditions	Surface optical behaviour, geometric accessibility, feature scale and acquisition environment can change the technically feasible technology set before speed or cost are considered.	Limited cross-technology quantitative evidence for challenging surfaces and interacting component/environmental conditions.	Controlled interlaboratory studies incorporating representative surface states, accessibility constraints and surface-preparation effects.
RQ2	Downstream-analysis framework linking acquired-data characteristics to processing, meshing, surface fitting, CAD abstraction and validation	Final model quality depends on how acquisition characteristics interact with subsequent processing and reconstruction. High-quality acquisition alone does not guarantee an engineering-ready model.	Few studies quantify complete acquisition-to-CAD performance using common metrics.	End-to-end workflow evaluation combining geometric fidelity, reconstruction maturity, uncertainty, effective time and validation.
RQ2.1	Evidence on filtering, registration, meshing, fitting, feature recognition and CAD reconstruction; DRML and uncertainty-propagation frameworks	Processing can improve completeness and usability but can also suppress, smooth, interpolate or infer geometry. Increasing model maturity does not automatically increase metrological validity.	Limited reporting of processing-induced modification, algorithm sensitivity and provenance of reconstructed geometry.	Before/after geometric assessment, parameter-sensitivity studies, provenance-aware reconstruction and independent validation of critical features.
RQ2.2	Technology-selection matrix; effective RE time and cost frameworks; application-specific comparisons	Accuracy, coverage, speed, cost, portability, expertise, processing effort and traceability involve application-dependent trade-offs; no single acquisition route is universally optimal.	Workflow-level economic and productivity data remain inconsistent and difficult to compare.	Report acquisition-to-validation time and cost components separately and assess trade-offs using application-specific multi-criteria frameworks.

Table 20. *Cont.*

RQ	Principal Evidence from the Review	Current Synthesis	Principal Unresolved Issue	Recommended Research Direction
RQ3	Evidence concerning calibration, system architecture, acquisition strategy, referencing and technology selection	Operational configuration and measurement strategy can be as important as nominal hardware specification for repeatability and metrological performance.	Repeatability and reproducibility are rarely assessed under comparable conditions across systems and laboratories.	Traceably characterised artefacts, repeated measurements, reproducibility studies and explicit uncertainty budgets.
RQ3.1	Studies reporting effects of calibration, scanner position, overlap, stand-off, probe strategy, measurement path, illumination, wavelength and resolution	Acquisition performance is sensitive to interacting operational variables, and manufacturer specifications cannot be interpreted as complete workflow capability.	Relative importance and interaction of operational variables remain strongly system- and component-dependent.	Designed parameter-sensitivity and factorial studies with complete configuration reporting and repeated acquisition.
RQ3.2	Comparative analysis of manual measurement, tactile CMM, photogrammetry, structured light, laser triangulation, CT and hybrid systems	Tactile CMM provides strong dimensional traceability; optical systems provide dense and rapid external capture; CT provides volumetric access; hybrid strategies can combine complementary capabilities.	Capability boundaries are not fixed, and cross-modal calibration, registration and uncertainty management remain difficult.	Application-driven selection, hybrid-metrology validation and interlaboratory technology comparison using common benchmarks.
RQ4	Evidence on automated registration, segmentation, denoising, feature recognition, surface reconstruction, CAD generation and AI-assisted processing	Automation can reduce manual processing and assist interpretation, but general-purpose, reliable and metrologically traceable scan-to-CAD automation has not yet been demonstrated.	Robustness across component families, sensors and acquisition conditions remains limited.	Develop modular automation with explicit validation, uncertainty propagation, provenance and human oversight for critical decisions.
RQ4.1	AI and deterministic-method analysis covering segmentation, completion, feature recognition, topology inference, geometric fitting and constraint enforcement	ML provides advantages for semantic, noisy, incomplete or heterogeneous data, whereas deterministic geometry remains important for explainability, explicit constraints and metrological verification.	AI-generated geometric plausibility is not equivalent to dimensional validity, particularly in unmeasured regions.	Hybrid AI–deterministic pipelines; measured/inferred region labelling; spatial confidence assessment and independent verification of AI-inferred geometry.
RQ4.2	Evidence concerning training-domain dependence, expert intervention, data heterogeneity, interoperability and traceability limitations	Industrial automation remains constrained by limited generalisation, inconsistent data structures, incomplete uncertainty treatment and dependence on expert interpretation.	Lack of transferable datasets, interoperable representations and accepted validation procedures for intelligent RE.	Shared benchmark datasets, interoperable scan-to-CAD representations, feature-level provenance and validation protocols for automated reconstruction.
RQ5	Trends towards hybrid metrology, intelligent processing, lifecycle updating, provenance-aware models, standardised benchmarking and application-specific workflows	RE is evolving from one-time geometric digitisation towards integrated engineering workflows supporting reconstruction, validation, lifecycle monitoring and downstream manufacturing decisions.	Industrial maturity remains uneven and evidence is fragmented across technologies and application domains.	Validate integrated RE workflows under representative industrial and lifecycle conditions rather than evaluating isolated processing stages.
RQ5.1	Hybrid metrology, ML-assisted reconstruction, automated feature recognition, digital-twin updating and integrated digital workflows	The most promising developments are complementary rather than universally substitutive: hybrid sensing, task-specific AI and integrated acquisition-to-validation workflows address limitations that single technologies cannot resolve alone.	Comparative maturity and industrial benefit of advanced concepts remain insufficiently quantified.	Task-specific comparative studies and industrial demonstrators assessing accuracy, uncertainty, time, cost, robustness and final model usability.
RQ5.2	Knowledge gaps identified throughout the Discussion and Future Directions: uncertainty propagation, benchmarks, difficult surfaces, internal geometry, AI, provenance, interoperability and lifecycle updating	The principal remaining gap is not acquisition capability alone but the preservation of reliable engineering information from physical measurement through processing, CAD reconstruction and final use.	Absence of common end-to-end frameworks that combine metrology, reconstruction maturity, provenance, validation and lifecycle requirements.	Develop traceable acquisition-to-CAD frameworks integrating uncertainty, provenance, benchmarks, interoperable data structures and lifecycle-oriented validation.

The synthesis shows that the research questions converge on a common finding: reverse-engineering performance cannot be characterised adequately by acquisition accuracy in isolation. The reviewed evidence increasingly supports an end-to-end interpretation in which component characteristics constrain acquisition, acquired-data quality influences reconstruction, processing decisions introduce additional uncertainty and interpretation, and

final acceptability depends on application-specific validation. At the same time, the table identifies recurring gaps in cross-study comparability, uncertainty propagation, automated CAD reconstruction, provenance and industrial validation. These unresolved issues provide the direct basis for the research priorities presented in Section 6.

5. Conclusions

The complete evidence base supports a central proposition: reverse-engineering quality is fundamentally an end-to-end workflow property rather than an acquisition-system property. Scanner accuracy constrains the quality of the primary measured data, but cannot by itself guarantee the dimensional or functional quality of the final engineering representation. Between the physical component and the reconstructed CAD model, acquisition, registration, preprocessing, meshing, surface fitting, feature recognition, CAD abstraction and validation can each introduce uncertainty, modify geometric information or incorporate assumptions not contained explicitly in the original measurements. Engineering reconstruction quality should therefore be assessed across the complete component–acquisition–reconstruction–validation–application chain rather than inferred from the nominal performance of the acquisition device alone.

Five higher-level propositions emerge from the reviewed evidence:

First, uncertainty and geometric modification accumulate through successive transformations of the measured information. Registration can introduce coordinate-transformation and alignment error; preprocessing can suppress genuine features or infer missing geometry; meshing and surface fitting can alter edges, curvature and local dimensions; and feature recognition or CAD abstraction can impose idealised geometry, topology and engineering constraints. The final CAD model therefore contains the combined influence of acquisition uncertainty and subsequent transformation-dependent contributions, which may be correlated, spatially dependent and application-specific. Validation should consequently be performed at relevant intermediate stages and on the final engineering representation rather than being restricted to verification of scanner performance.

Second, future high-performance reverse-engineering systems are likely to become increasingly hybrid rather than technology-specific. The reviewed trade-offs among tactile, optical, image-based and tomographic acquisition show that the information required for demanding engineering reconstruction is rarely optimised by a single measurement principle. Dense optical acquisition can provide rapid and extensive external-surface geometry, tactile metrology can supply higher-confidence datums, analytical features and tolerance-critical dimensions, image-based methods can contribute scalable and visually rich geometric information, and computed tomography can recover internal or concealed features inaccessible to line-of-sight systems. Their limitations are therefore frequently complementary rather than simply competitive.

The value of hybridisation lies in information complementarity rather than in sensor multiplicity itself. A complementary measurement principle is justified when it resolves a clearly identified limitation in geometric coverage, accessibility, dimensional confidence, spatial resolution or independent validation. Hybrid workflows can consequently combine sensing and verification functions rather than requiring all datasets to be merged into a single geometric representation. Their increased capability nevertheless introduces additional requirements for sensor-to-sensor calibration, common referencing, registration, coordinate transformation, data fusion and uncertainty propagation. Future high-performance RE systems should therefore be designed around the engineering information required from the final model rather than around allegiance to a single acquisition technology.

Third, geometric similarity should not be equated with engineering validity. A reconstructed surface may reproduce the measured component closely while still failing to recover nominal geometry, functional relationships, tolerance-critical features or design intent. Engineering use therefore requires explicit distinction between measured, interpolated, constraint-reconstructed and inferred geometry, together with application-appropriate uncertainty assessment, provenance and validation. This requirement becomes especially important where reconstructed models are intended for manufacture, inspection, simulation, repair or other tolerance-sensitive applications.

Fourth, the principal technical bottleneck is increasingly shifting from geometric capture towards interpretation and engineering reconstruction. Acquisition hardware can now provide dense surface or volumetric data for a wide range of component classes, whereas reliable conversion of heterogeneous measurements into editable, feature-based and validated CAD remains strongly dependent on processing choices and expert interpretation. Automation and AI can assist segmentation, registration, feature recognition, completion and topology inference, but their most credible engineering role is complementary to deterministic geometric methods and metrological verification rather than substitutive.

Fifth, reverse engineering is evolving from a one-time digitisation activity towards a lifecycle-oriented engineering capability. Repeated acquisition can support condition monitoring, wear assessment, repair planning, digital-model updating and condition-based remanufacturing, while legacy-part recovery, refurbishment and

component restoration connect reverse engineering with broader circular-manufacturing strategies. Realising this role requires preservation of geometric and data provenance, consistent validation between measurement states and digital representations that retain sufficient engineering information for subsequent decisions.

These propositions point towards a broader transition from conventional Reverse Engineering towards Intelligent and Traceable Reverse Engineering. In such a framework, acquisition would no longer be treated as a fixed preliminary operation followed by largely independent reconstruction stages. Instead, component characteristics, preliminary measurements and reconstruction confidence could inform adaptive acquisition planning and the selective deployment of complementary tactile, optical, image-based or tomographic sensing. Acquired information would then pass through automated registration and uncertainty-aware processing while retaining its relationship with the original measurement evidence. Feature recognition, geometric reasoning and AI-assisted reconstruction could support interpretation and CAD generation, but inferred information would remain distinguishable from directly measured geometry and subject to application-appropriate metrological validation.

The defining characteristic of such a system would therefore be the joint development of intelligence and traceability. Increasing automation should not obscure how a reconstructed feature was obtained, modified or validated. Instead, geometric and data provenance should remain associated with the engineering representation, identifying acquisition source, processing history, reconstruction method, uncertainty information and validation status. This would permit automated or AI-assisted decisions to remain auditable and would enable different levels of confidence to be assigned to measured, interpolated, constraint-reconstructed and AI-inferred regions of the same model.

At industrial level, Intelligent and Traceable Reverse Engineering would connect the validated reconstructed model directly with CAD/CAM, simulation, inspection, repair, remanufacturing and manufacturing systems, while repeated acquisition could update digital-twin representations as the physical component evolves throughout service. Reverse engineering would consequently move beyond the generation of a static digital replica towards a closed, evidence-preserving engineering process in which physical measurement, computational interpretation, validation and downstream lifecycle decisions remain connected. This transition represents the principal long-term opportunity identified by the review for increasing the reliability, autonomy and engineering value of next-generation reverse-engineering systems.

6. Future Directions

Future research should concentrate on the weak links between geometric acquisition and engineering-ready model generation. Scanner capability has progressed more rapidly than automated interpretation of the resulting data, particularly for freeform or hybrid geometry, incomplete scans and components for which functional design intent must be recovered. Priority should therefore be given to scan-to-CAD automation, uncertainty propagation, multimodal data fusion, interoperable software workflows and validation procedures that preserve metrological traceability from acquisition to the final digital model.

The principal future directions emerging from this review may be summarised as follows:

- Greater emphasis should be placed on end-to-end workflow optimisation, in which acquisition, registration, reconstruction, validation, and CAD generation are treated as an integrated system rather than as loosely connected sequential stages.
- Future work should validate and refine common reporting protocols and benchmark geometries, including the frameworks proposed in Sections 4.5 and 4.6. Interlaboratory evaluation using traceably characterised artefacts containing analytical, freeform, accessibility-limited, optically challenging and internal features would improve comparison across acquisition systems, reconstruction algorithms and validation strategies.
- Future research should prioritise automated CAD reconstruction from point clouds and meshes, particularly for freeform and hybrid geometries, where current workflows remain heavily dependent on expert interpretation and manual intervention.
- Future studies should compare learning-based and deterministic reconstruction methods on a task-specific basis rather than assuming a general advantage of AI. Machine learning is particularly promising for segmentation, feature recognition, topology inference and interpretation of noisy, incomplete or heterogeneous data, whereas deterministic geometric methods remain essential where explainability, constraint enforcement, data efficiency and metrological traceability are dominant requirements. Hybrid pipelines combining data-driven interpretation with deterministic geometric reconstruction and validation should therefore receive particular attention.
- Hybrid and multi-sensor metrology frameworks should be developed further as a principal route towards high-performance reverse-engineering systems. Future work should determine how tactile, optical, image-based and tomographic measurements can be combined according to information complementarity, balancing

geometric completeness, acquisition efficiency, dimensional traceability and validation requirements while explicitly addressing cross-sensor calibration, registration, data fusion and uncertainty propagation.

- There is a clear need for more robust methods and comparative benchmarks for challenging surfaces, including reflective, transparent, translucent, dark, low-texture and optically heterogeneous materials. Future studies should characterise not only whether acquisition succeeds, but also the resulting dimensional bias, data completeness, preparation requirements and uncertainty for different measurement principles.
- Future studies should address the reconstruction of internal and inaccessible geometries more systematically, particularly through improved computed tomography workflows and multimodal fusion strategies capable of integrating internal and external geometric data.
- Future work should validate and refine common benchmarking procedures and minimum reporting protocols, including the framework proposed in Section 4.5, to improve comparability across acquisition systems, reconstruction algorithms and validation methods.
- Greater attention should be devoted to uncertainty quantification and metrological traceability throughout the reverse-engineering workflow, not only at the acquisition stage but also during point-cloud processing, mesh generation, and CAD reconstruction.
- Future research should develop repeatable and uncertainty-aware acquisition-to-model workflows capable of updating digital representations throughout the component lifecycle. Repeated acquisition should enable meaningful comparison between successive geometric states for dimensional monitoring, wear and deformation assessment, repair planning and condition-based remanufacturing. Particular attention should be given to common datum definition, longitudinal registration, uncertainty of change detection and preservation of provenance between measurement epochs so that genuine physical evolution can be distinguished from measurement or reconstruction variability.
- Improved interoperability between acquisition systems, reconstruction software, CAD platforms, simulation environments, and manufacturing tools will be essential for enabling more seamless and scalable industrial deployment.
- Future research should further examine reverse engineering as an enabling technology for circular manufacturing and component-life extension, particularly through legacy- and spare-part recovery, repair, remanufacturing, tooling refurbishment and condition-based restoration. Beyond demonstrating geometric reconstruction capability, future studies should quantify whether these workflows reduce unnecessary component replacement, preserve existing material and manufacturing value, and provide measurable lifecycle benefits relative to alternative replacement routes.
- Future reverse-engineering systems should preserve feature- or region-level data provenance across the scan-to-CAD workflow, linking reconstructed geometry to its acquisition source, processing history, reconstruction method, uncertainty information and validation status. Such provenance will be particularly important for hybrid, AI-assisted, high-value and safety-critical applications in which geometry with different levels of evidential support may coexist within the same engineering model.

These research directions should ultimately be considered as interacting elements of a common next-generation architecture rather than as independent developments. Progress towards Intelligent and Traceable Reverse Engineering will require adaptive and multimodal acquisition, automated but uncertainty-aware reconstruction, explicit preservation of measurement and reconstruction provenance, functionally meaningful CAD interpretation and metrological validation to operate within an interoperable digital thread. Linking this thread to manufacturing, inspection and digital-twin environments would allow reconstructed geometry to remain connected to both its physical evidence and its subsequent engineering use throughout the component lifecycle.

Author Contributions

Conceptualisation: W.D. and B.Z.; methodology: N.Q. and Y.L.; validation: W.D. and N.W.; formal analysis: A.F.V.P.; investigation: R.M.; data curation: W.D.; writing—original draft preparation: R.M. and A.F.V.P.; writing—review and editing: A.F.V.P.; visualisation: N.Q.; supervision: Y.L. All authors have read and agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

No new data was created.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Grammarly Premium v6.8.263 to verify and improve the British (UK English) language employed. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Appendix A

PRISMA 2020 Flow Diagram for New Systematic Reviews, which included Searches of Databases and Registers

This section presents the PRISMA 2020 flow diagram used to document the identification, screening, eligibility assessment, and final inclusion of studies considered in the present systematic review. The diagram provides a transparent representation of the literature-selection pathway and supports methodological traceability, consistency, and reproducibility in accordance with the PRISMA 2020 framework.

The systematic search was designed to identify literature published between 2010 and 2025 on reverse engineering, component digitisation, shape-acquisition technologies, point-cloud processing, surface reconstruction, CAD reconstruction and metrological performance. Search terms covering reverse-engineering concepts, acquisition methods and performance criteria were combined through Boolean operators and applied to the title, abstract and keyword fields of the selected databases. The resulting identification, screening and inclusion sequence is reported in Figure A1.

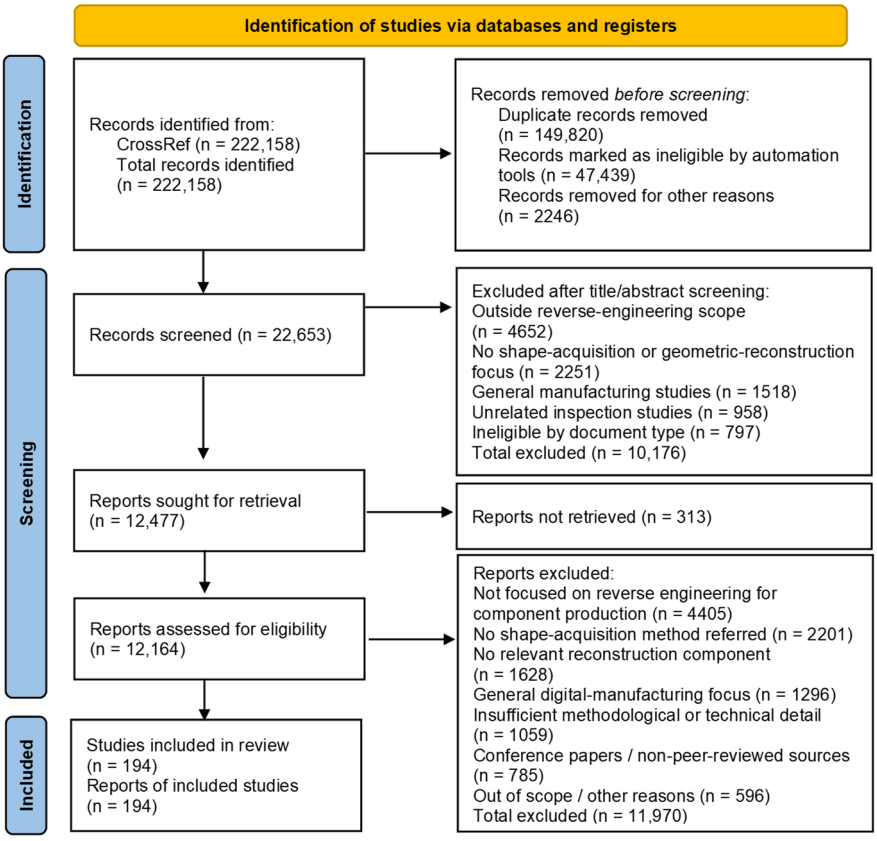


Figure A1. PRISMA 2020 flow diagram for the identification, screening, eligibility assessment, Quality Assessment, and final inclusion of studies on reverse engineering and shape-acquisition technologies.

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