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Systematic Selection and Industrial Evaluation of 3D Measurement Methods for Positional Tolerance Compensation in Final Assembly Lines

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Abstract

This paper presents a weighted-sum evaluation of non-invasive 3D measurement methods for positional tolerance compensation in aircraft cabin final assembly. The motivation is to replace invasive and time-intensive point-based measurements that slow takt time and impede automation while tight positional tolerances must be met. Normalized criteria (spatial resolution, trueness, precision, environmental robustness, throughput, operating envelope, and lifecycle cost) are scored using a shared processing pipeline to ensure fair comparison. The Airbus crown module serves as the use case, prioritizing reliable detection of 12–24 mm bores at 1.0–1.5 m working distance under realistic interior conditions and takt constraints. Structured light, LiDAR, and stereo vision are assessed under ISO 5725 accuracy concepts, with structured light cameras attaining the highest overall utility (0.85) over LiDAR (0.76) and stereo vision (0.74) due to finer spatial resolution and strong trueness and precision at meter scale. Sensitivity analysis confirms ranking stability across broad weight variations.

Keywords: "Tolerances; 3D Measurement; Assembly Assistance Systems; Utility Analysis; Productdesign;"

1. Introduction

To meet growing market demand, the aviation industry aims to reduce manufacturing times [1]. This includes increases in assembly efficiency; particularly in cabin installation, as a highly customizable part of the aircraft. Automation of these assembly processes requires extensive interface standardization, including guarantees on position and orientation tolerances of the as-built status. To achieve this, an interface layer shall be introduced, to decouple the tolerances of the fuselage and its attachment points from the guarantees made in the interior interfaces specifications. [2]. This in turn requires accurate knowledge about the information quality of the as-built positions of attachment points in the fuselage [3].

The currently implemented measurement process is mostly manual with long measurement cycles, in contrast to efficiency and automation objectives [4]. To overcome these deficits, a multi-stage approach was developed within the "Beating tolerances on-line" framework [5], requiring non-invasive data acquisition as the basis for tolerance compensation. Despite available contactless 3D metrology, there is a lack of a standardized, comparative performance evaluation at airframe scale that assesses technologies on accuracy, uncertainty budgets, and registration robustness under realistic aircraft assembly conditions [6].

This work aims to develop a systematic evaluation methodology for non-invasive 3D measurement methods and demonstrate their applicability using the industrial Crown Module example.

2. State of the art

First the use-case and the currently implemented process are briefly introduced. Followed by the introduction of potential

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candidates of non-invasive, alternative measurement technologies. Further selection of a solution will be performed later, applying the methodology to be introduced in section 3.

2.1. Use-Case and Process

The crown module in aircraft cabins is an assembly located in the upper interior of the fuselage, often referred to as the crown area. It is mounted to the primary fuselage structure, typically to frames and stringers, and serves as the attachment system for overhead storage compartments (OHSC) and other cabin monuments such as lavatories or crew rest modules. The idea is to enable modular installation and removal, allowing easier assembly and reconfiguration of the cabin without modifications to the main fuselage structure. Tolerance compensation is a crucial function of this interface layer, to ensure reliable installation of prefabricated cabin monuments despite geometric deviations in the fuselage and interior components. Accumulated manufacturing tolerances often result in misalignments on the order of several millimeters, which must be addressed during installation. Compensation elements, such as adjustable connectors and shims, allow to meet the necessary, narrow tolerance guarantees, despite these high tolerances of fuselage mounting points. In practice, effective tolerance compensation relies on a stable datum system of the primary structure, typically via the seat rails, and on precise capture of any as-built geometry of relevant fastening and interface points of the fuselage [4,7,8]. This ensures alignment-correct joining of large-scale secondary structures under tight tolerance, stiffness, and accessibility constraints [9].

Currently, target-based laser tracker systems are the predominantly used measurement device. They perform contactless tracking of retroreflective targets in a large measurement volume with high accuracy and, via datum linkage, refer directly to the cabin reference system [10,11]. Although the tracking itself is contactless, this measurement procedure is tactile, as targets have to be applied and held stationary at each measuring location. As such, the process is invasive and highly time-intensive, due to sightlines, confined access, and sequential operation, although it meets precision and traceability requirements. Assistance methods and systems do exist, but they are still invasive and unsuitable for the aircraft cabin environment [12].

This combination of high accuracy and process invasiveness marks the status quo of as-built acquisition in the cabin and motivates interest in contactless alternatives that can combine measurement volume, precision, and robust datum linkage in complex interior environments [12].

2.2. Non-Invasive Alternatives: 3D Capture Devices

The focus is on LiDAR (Light Detection and Ranging), structured light, and stereo vision because they are the leading state-of-the-art non-invasive 3D sensing methods, widely used in industry, and our initial comparison therefore centers on these well-established active and passive approaches.

LiDAR captures geometry using pulsed or frequency-modulated Time-of-Flight (ToF) methods and assembles the individual scans into 3D point clouds. With high-end Terrestrial Laser Scanning (TLS), range and noise errors in the near field of 1 to 10 m are typically below one millimeter and can even reach the sub-millimeter level under ideal laboratory conditions. However, achieving sub-millimeter accuracy strongly depends on surface properties, incidence angles, environmental factors, and the chosen scanning and registration strategy. Compared with passive imaging, LiDAR is generally robust to ambient illumination and many surface materials, though ambient light and material state can still affect it. Primary applications include industrial metrology, aerospace quality control, and structural monitoring and surveying. [13]

The structured-light measurement method uses cameras to record the distortion of a projected, calibrated stripe or grid pattern on a surface, and uses triangulation to yield a dense 3D model of the surface geometry. Under standardized test conditions, structured light systems typically achieve 0.2–0.5 mm accuracy at 1 m working distance, while at 10 m, depending on measurement field, surface, and illumination, accuracy degrades to about 1–5 mm [14,15]. Single-frame fringe projection demonstrates sub-mm in the near field and volumetric scaling (mm/m) over larger ranges [16]. Primary applications include industrial quality inspection and metrology, reverse engineering of mechanical parts, and in-process monitoring of additive manufacturing.

Stereo vision triangulates depth from two (or more) synchronized cameras; active systems may additionally project texture, while passive systems rely on natural image features. In active stereo, any projected pattern serves only to enrich texture for correspondence and is typically not geometrically calibrated and does not encode depth. Triangulation relies solely on the calibrated camera geometry, that is, the baseline and intrinsics. Active stereo in industrial setups typically achieves sub-millimeter to few-millimeter accuracy at 1–2 m (e.g., about 0.1 mm at 1 m; about 0.2 mm at 2 m with a large baseline) and at 5–10 m is commonly about 1–4% of distance (up to about 6% depending on baseline, optics, and method). Applications include robotic guidance and automation (e.g., bin-picking and part localization), autonomous vehicle perception and obstacle detection, and large-scale scene reconstruction for mapping and inspection. [17]

3. Methodology

To integrate both quantitative and qualitative dimensions into a unified evaluative process, utility analysis, is used as one of the most widely recognized approaches in the field of multi criteria decision analysis (MCDA). Utility analysis corresponds to the Weighted Sum Model (WSM), in which each alternative is evaluated across multiple criteria, weights are assigned to reflect relative importance, individual criterion scores are normalized, and an aggregate utility score is computed through summation [18].

The procedure of Utility Analysis follows a series of four steps, which ensure transparency, reproducibility, and traceability in the decision process.

The first step is to define the evaluation criteria that represent the relevant objectives of the design or selection problem. In technology selection, these typically include:

- Technical performance (e.g., precision, acquisition time, reproducibility),
- Operational robustness (e.g., sensitivity to lighting or surface conditions, industrial applicability),
- Economic aspects (e.g., acquisition and lifecycle costs).

The criteria are derived from stakeholder requirements, design specifications and project objectives. The completeness of the criteria is essential to ensure that all relevant design criteria are covered [19].

Not all criteria have the same importance. In the second step, each criterion is assigned a relative weight to reflect its priority in the decision. Weights are typically expressed as percentages summing to 100 % or as normalized values summing to 1. Methods for weighting include direct assignment, ranking methods, or pairwise comparisons (as in the Analytic Hierarchy Process) [20]. In a design management context, this step captures trade-offs between technical excellence and cost or feasibility, making stakeholder input essential [21].

In the third step each alternative is then evaluated against every criterion. To allow aggregation across different units, the scores are normalized.

For each alternative, the total utility score is calculated as the weighted sum of the normalized criterion scores:

$$U_j = \sum_{\{i=1\}} w_{\{i\}} \cdot s_{\{ij\}} \quad (1)$$

Where:
U_j = total utility of alternative j,
$w_{\{i\}}$ = weight of criterion i,
$s_{\{ij\}}$ = normalized score of alternative j for criterion i.

This aggregation step produces a single utility value for each alternative, representing its overall suitability under the chosen criteria and weights [19].

4. Application

The general criteria have been defined, fix the normalization ranges between 0–1 with respect to the Crown Module data-capture use case, and assign their weights accordingly. Generic definitions follow ISO 5725 [22] and state-of-the-art industrial 3D metrology and aerospace assembly requirements; normalization and weighting follow standard MCDA practice. Within the Beating-tolerances-on-line framework seen in Figure 1, non-invasive 3D acquisition is the first brick of the digital chain for pre-adjustment and precise installation, so small-feature detection is prioritized. For a better understanding, Figure 2 shows schematically, where the crown module is located, and where the connection points in form of 12-24mm holes are. It is assumed that data from all measurement systems are processed using an identical algorithmic pipeline (preprocessing, reconstruction, and feature extraction) to ensure a fair comparison.

Spatial resolution (inverse 0–1) denotes the minimum resolvable feature size required to detect edges and small holes on low-texture technical surfaces. It is critical for pre-alignment and the reliable detection of 12–24 mm holes and edges in the crown area, directly constraining downstream tolerance compensation. Anchors are normalized to the use case: a score of 1 requires reliable detection of 12 mm holes at 1.0–1.5 m stand-off with edge localization ≤0.2 mm, whereas a score of 0 indicates that even 24 mm holes are not reliably detected under the same conditions or that edge localization is ≥1.5 mm.

Trueness (inverse 0–1), per ISO 5725, is the systematic error against an accepted reference at nominal stand-off, measured as mean absolute bias (mm). Because bias propagates directly into misalignment risk in tolerance compensation, it must be negligible at the working distance. A score of 1 is assigned at bias ≤0.5 mm over a crown section at 1–3 m relative to the seat-rail datum, and 0 at ≥3.0 mm.

Environmental robustness (0–1) captures stability under cabin-typical lighting and surface properties (low-texture, dark/glossy coatings), measured as pass rate across scenarios or relative quality drop (%). Robustness ensures repeatable feature capture without aids in coated industrial interiors and avoids systematic interior failure modes. A value of 1 is assigned at a ≥95% pass rate across the scenario matrix without aids, and 0 at ≤50% or in the case of systematic failure.

Precision (inverse 0–1), per ISO 5725, covers random variation under repeatability and reproducibility, aggregating σRepeat and σReprod (mm) into a single score. Dispersion bounds decision confidence for pre-adjustment and is independent of trueness. A value of 1 is assigned at σRepeat ≤ 0.2 mm and σReprod ≤ 0.5 mm under industrial conditions (operator/shift/poses), and 0 at σRepeat ≥ 1.5 mm and σReprod ≤ 3.0 mm.

Throughput (min–max 0–1) measures end-to-end time from acquisition to usable 3D output (seconds per cycle/area) and determines feasibility in takt-bound assembly. Normalization is performed across tested alternatives on an identical standard task—a defined crown bay with 12–24 mm holes—so that 1 is the fastest acquisition-to-decision time and 0 the slowest.

The operating envelope (inverse 0–1) combines covered area/volume per acquisition with admissible stand-off and is expressed as the number of poses required for a defined crown geometry. It captures the practicability of fuselage coverage at 1–3 m with occlusions and access limits. A value of 1 is assigned when a standard crown bay at 1–3 m stand-off is covered in ≤3 poses (including occlusions), and 0 when ≥12 poses are required or the stand-off window cannot be maintained.

Total cost (TCO; min–max 0–1) is treated as lifecycle cost—including CAPEX, OPEX, service, and training—reported as NPV or annualized cost. At comparable TRL and compliance, 1 denotes the lowest lifecycle cost and 0 the highest, ensuring economic viability is reflected alongside technical performance.

Tracking and datum registration is defined as stable self-localization and linkage to a plant datum without targets, with a metric that aggregates RMS pose/drift and RMS datum registration (inverse mapping). As it is expected to be provided

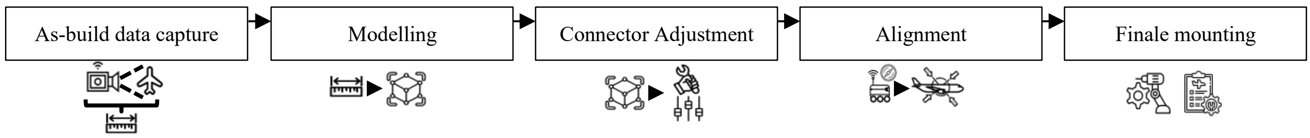

Figure 1: Beating Tolerances on-line Framework [5]

by scanner tracking and to be equal across candidates within the framework, it is included for completeness but unweighted in this comparison.

Weights are derived via swing/pairwise logic: Spatial resolution (0.25) is ranked first because reliable detection of small bores and edges on low texture interior surfaces is a hard prerequisite for usable as built data; the swing from poor to sub millimeter resolution directly determines whether attachment features are detected at all in the intended working range. Trueness (0.22) is second, since systematic error propagates into wrong connector pre adjustments; per ISO 5725, trueness (bias) must be controlled at nominal stand off to make tolerance compensation decisions valid. Environmental robustness (0.16) is third because variable lighting and challenging surface finishes in fuselage interiors strongly affect the completeness and quality of small feature capture across shifts and sites. Precision (0.13) follows, aggregating repeatability and reproducibility per ISO 5725, to secure process stability across setups and operators once bias is acceptable. Throughput (0.12) ranks next to respect takt times for in line use, but only after correctness enablers—resolution, trueness, robustness—are secured in the "Beating tolerances on line" flow. Operating envelope (0.07) is weighted for coverage and feasible range in the crown area, but can be mitigated by additional poses, making it secondary to correctness and takt drivers. Total cost (0.05) is lowest because selection is dominated by technical feasibility and correctness in a safety critical assembly context. Trueness and precision are treated separately per ISO 5725.

The resulting weighted and normalized scores feed directly into the utility analysis in Section 5. The weight set emphasizes small-feature detection for pre-alignment, while separately bounding systematic error and random dispersion per ISO 5725; robustness, throughput, operating envelope, and TCO capture the conditions necessary for reliable and economical deployment in aerospace assembly.

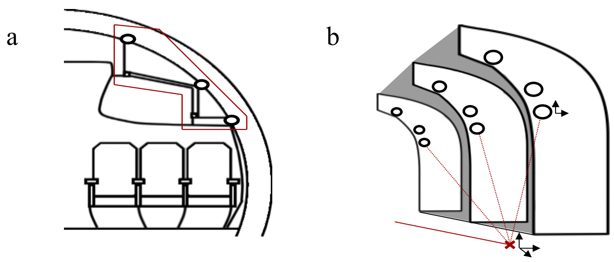

Figure 2: (a) position of the crown module, (b) position of the attachment points on the frames

5. Results

After scoring each method by criterion and aggregating with a weighted-sum MCDA, the overall results are: Structured Light 0.85 of 1.00, LiDAR 0.76, and Stereo Vision 0.74.

This reflects linear additive aggregation of criterion scores with normalized weights in a compensatory MCDA framework, yielding a ranking consistent with the stated weights and performances seen below. The scores are qualitative and grounded in the current state of the art, derived from a literature synthesis.

5.1. Spatial Resolution

Structured Light scores 0.9 because at 1–2 m it achieves 0.2–0.5 mm resolution and, despite degradation to about 1–3 mm at 1–3 m, its dense sampling supports reliable 12–24 mm hole detection with precise edge localization; VDI-conform evaluations report sub-0.1 mm edge error in optimized setups. [23]. Stereo Vision scores 0.75 because accuracy degrades roughly with distance (often scaling to 1–4% of range) and depends strongly on baseline and texture, which makes 12 mm features borderline at several meters [17]. LiDAR scores 0.65 because point density is lower than structured light, leading to coarser edge localization on 12 mm features even when range accuracy is at mm-level [13].

5.2. Trueness

Structured Light scores 0.85 because systematic errors are mainly calibration-induced and can be reduced below 0.5 mm with precise camera–projector calibration, supported by stable triangulation geometry and low RMS on industrial fields [16]. LiDAR scores 0.8 because time-of-flight reduces model bias, but boresight misalignment and stray light commonly introduce mm-level systematic error [13]. Stereo Vision scores 0.7 because residual biases from calibration, rectification, and disparity algorithms yield percent-of-distance reconstruction errors that translate to several millimeters at 1–3 m [17].

5.3. Environmental robustness

LiDAR scores 0.85 because active time of flight is less sensitive to ambient illumination and remains functional in various environmental surroundings as stated in section 2. Structured Light scores 0.80 because adaptive exposures and filtering improve performance, but ambient light and specular surfaces still limit robustness. Stereo Vision scores 0.65 because performance is strongly affected by ambient light and surface texture, with only partial mitigation from active stereo and filtering. [13,16,17]

5.4. Precision

Structured Light scores 0.85 because calibrated triangulation yields sub millimeter precision with low repeatability error in industrial setups, supported by stable camera–projector geometry and well established calibration procedures [14]. LiDAR scores 0.75 because repeatability is in the millimeter range but varies with environment and platform, and mobile systems inherit additional drift from IMU/GNSS integration [24]. Stereo Vision scores 0.75 because precision degrades in real scenes due to texture and lighting dependence and algorithmic sensitivity, reducing reproducibility outside controlled conditions [25].

5.5. Throughput

Structured Light scores 0.90 because industrial implementations achieve sub second acquisition and multi Hz end to end cycles, and high speed variants and single shot designs enable real time 3D extraction at production resolutions. Stereo Vision scores 0.85 but real time performance hinges on onboard acceleration and scene texture, so compute and lighting dependencies can inflate cycle time in challenging scenes. LiDAR scores 0.80 because scan based coverage and pose requirements often extend acquisition to decision time despite high scan rates. [26]

5.6. Operating envelope

LiDAR scores 0.85 because industrial sensors offer broad working ranges and multi plane scanning, enabling practical coverage from tens to hundreds of meters [13]. Structured Light scores 0.80 but practical working distances are shorter and coverage often requires multiple poses [15]. Stereo Vision scores 0.70 because usable range and field of view depend strongly on baseline/focal tradeoffs, forcing compromises across near and far tasks [25].

5.7. Total cost

Stereo Vision scores 0.85 because commodity cameras and onboard processing reduce hardware and integration costs relative to projector or laser-based systems. Structured Light scores 0.75 because specialized projectors/cameras and calibration add upfront cost compared with stereo. LiDAR scores 0.65 because specialized lasers, detectors, and scanning assemblies keep total cost higher, even as prices continue to fall. [13,16,17]

5.8. Sensitivity check

A sensitivity analysis was conducted for the MCDA weighting and reported upfront as part of the evaluation.

The results confirm an exceptionally robust dominance of Structured Light for the crown-module application: even extreme single-criterion weight shifts from −95% to +400%, with renormalization, do not overturn its lead, indicating well-calibrated weighting.

The method varied each criterion weight in 5–10% steps while holding the total weight at 1.0, tracking rank stability and any thresholds at which Structured Light would lose leadership; none were reached.

Victory margins of 0.092 (10.8%) over LiDAR and 0.122 (14.3%) over Stereo exceed typical MCDA sensitivity bands of about 5–10%, reinforcing robustness.

Dominance is primarily driven by Spatial Resolution (advantage +0.25 vs LiDAR, +0.15 vs Stereo) at the highest weight (0.25), with Trueness, Precision, and Throughput adding consistent +0.05 to +0.15 gains. Weaker flanks in Environmental Robustness (−0.05 vs LiDAR) and Total Cost (−0.10 vs Stereo), and a small deficit in Operating Envelope (−0.05 vs LiDAR), are muted by their lower weights (0.16, 0.05, 0.07). o critical threshold emerges even under weight perturbations beyond typical ±20–25% local sensitivity checks recommended in methodological handbooks [27], supporting practical confidence that the decision remains stable across realistic weighting differences.

6. Discussion

Laser trackers remain the reference for accuracy and traceable datum linkage and most probably show higher robustness. This study did not aim to surpass trackers on precision or compare other methods to it. It addressed a different design objective: selecting a non-invasive 3D method that reduces process invasiveness and cycle time in the cabin while maintaining accuracy sufficient for positional tolerance compensation. Within this objective, a comparison between structured light, LiDAR, and stereo vision as alternatives to target-based tracking has been performed. Tracking between individual acquisitions and global registration were not included. These must be treated as a system-level problem. The precision of the complete solution has to be measured end-to-end with a full uncertainty budget. Robustness under cabin conditions and usability, including operator workload and handling, must also be evaluated.

The utility-analysis method produced a clear decision.

Table 1: Overview of the scoring framework used to compare SL, LiDAR, and SV systems across weighted criteria

Criterion	Definition	Metric	Weight	SL	LiDAR	SV
Spatial resolution	Minimum resolvable feature size at nominal stand-off	Minimum feature size in mm; inverse 0–1 scaling	0.25	0.9	0.65	0.75
Trueness	Systematic error relative to a reference at nominal working distance	Bias in mm; inverse monotonic 0–1 scaling	0.22	0.85	0.8	0.7
Environmental robustness	Performance stability across lighting and surface conditions	Pass rate across scenarios or relative quality drop (%); 0–1 scaling	0.16	0.8	0.85	0.65
Precision	Random variation under repeatability and reproducibility conditions	Standard deviations in mm under both conditions; scaled/aggregated to 0–1	0.13	0.85	0.75	0.75
Throughput	End to end time to usable 3D output	Seconds per cycle/area; inverse 0–1 scaling	0.12	0.9	0.8	0.85
Operating envelope	Covered area/volume per acquisition including admissible working distance	Required poses per defined area/geometry; inverse 0–1 scaling	0.07	0.8	0.85	0.7
Total cost	Lifecycle cost	NPV or annualized cost; inverse 0–1 scaling	0.05	0.37	0.65	0.85
Tracking	Stability of self-localization and registration to plant datum without targets	RMS pose/drift + RMS datum registration aggregated; inverse 0–1 scaling	/	/	/	/

The sensitivity analysis showed stable rankings, which supports the chosen criteria and anchors and indicates no tuning toward a desired outcome. In this study, the evaluation framework is based on literature and use-case requirements, with industrial implementation as future work.

The criteria were chosen for transferability to similar assembly processes. Normalization (and, if needed, weights) must be adapted to each use case, such as stand-off, feature sizes, takt time, and access. Future work will integrate tracking and datum registration and assess the complete system in representative stations.

7. Summary and Outlook

Using a systematic selection method, a reproducible utility analysis (MCDA/weighted sum) was applied to score and weight the criteria, yielding a transparent basis for comparing invasive and non-invasive measurement approaches.

Technological progress supports a shift from invasive tracking to non-contact optical metrology and 3D scanning, helping to bridge the gap between high precision and non-invasiveness in industrial data-capture.

For industrial implementation, integration into existing workflows within a digital process chain without invasive steps is planned, coupled with real time scanning and data processing to support tolerance compensation and ongoing process optimization via contactless measurement.

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