



# Dimensional Engineering Approaches to Structural Assembly Precision in Electric Vertical Takeoff and Landing Aircraft

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## Abstract

*Electric vertical takeoff and landing aircraft compress weight limits, dense system integration, certification pressure, and low tolerance for geometric drift into a single structural problem. The article develops an eVTOL-specific dimensional-engineering framework for structural assembly precision. The framework extends an applied methodology previously developed by the author for vehicle-level variation reduction through 3DCS tolerance simulation, ADAMS/Car response modeling, mode FRONTIER-based design of experiments, sensitivity screening, cost-aware tolerance optimization, and six-sigma robustness targets. This methodology is transferred from suspension hardpoint and stiffness-compliance variation to eVTOL airframe assembly, where structural interfaces, datum continuity, robotic joining accuracy, certification evidence, and measured-geometry feedback form a single control chain. The article uses recent research on eVTOL requirement validation, airworthiness constraints, composite wing-box manufacturing, robotic drilling and inspection, deviation propagation, and digital-twin-based tolerance control to verify and position the proposed framework. The author's contribution comprises an interface-ranking logic, a data-continuity and process-capability model, a closed-loop tolerance-reallocation sequence, and monitoring metrics for early industrial deployment in eVTOL structural programs.*

**Keywords:** eVTOL, Dimensional Engineering, Assembly Precision, Aerostructures, Tolerance Allocation, Robotic Drilling, Digital Twin, Composite Wing Box, Geometry Assurance, Datum Control.

## INTRODUCTION

Electric vertical takeoff and landing aircraft place structural precision under unusual pressure. This pressure comes from the convergence of several constraints. eVTOL architectures combine battery, flight-control, and electric-motor systems in a tightly coupled configuration, which raises the burden on requirement traceability and interface validation. At the same time, airworthiness pathways for electrical propulsion and battery systems concentrate certification evidence on the same structural and installation interfaces that must remain geometrically stable throughout build and inspection. The manufacturing side adds a further constraint: lightweight composite structures offer little geometric slack, while co-curing and pre-assembled skeleton routes shift precision risk toward selected junctions, separation planes, and benchmark-transfer points. Recent aerospace assembly studies place such interfaces in the sub-millimeter regime, with illustrative closure references around 0.5 mm for gap and 0.2 mm for step difference, leaving limited room for

late correction once deviation begins to propagate through drilling, joining, and measurement transfer [5; 7–9]. Their airframes carry batteries, propulsion units, control hardware, thermal management elements, and service interfaces, all within lightweight layouts with little geometric slack. Under such conditions, assembly precision enters the design problem long before final inspection. Gap growth, hole drift, or locator inconsistency affect aerodynamic continuity, load transfer, sealing quality, system installation, and evidence preparation for certification.

The study aims to define a dimensional-engineering framework for structural assembly precision in eVTOL production. Three research objectives guide the analysis. The first is to identify why eVTOL development pushes dimensional control toward earlier design stages. The second is to determine which manufacturing and assembly approaches keep interface geometry stable in composite and aerostructural builds. The third is to formulate an implementable control logic that connects metrology, digital models, and tolerance decisions during production.

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The author's contribution lies in extending a previously applied dimensional-variation methodology to the structural assembly environment of eVTOL aircraft. Earlier work on vehicle-to-vehicle performance variation treated manufactured part deviations, hardpoint location tolerances, stiffness compliance, and response sensitivity as controllable design inputs. The present article transfers that logic to eVTOL airframes by redefining the controlled object: instead of ride-and-handling response spread, the framework targets certification-sensitive structural interfaces, datum transfer, hole and fastener accuracy, composite joining conditions, and measured geometry feedback. The literature corpus is used as a validation and positioning layer for this framework, while the proposed engineering sequence comes from applied dimensional-engineering practice.

The hypothesis states that stable structural precision in eVTOL programs depends on a continuous dimensional chain that starts with requirement decomposition, passes through datum and interface control, and closes with measurement-driven tolerance adjustment.

### MATERIALS AND METHODS

The source corpus contains ten publications issued between 2022 and 2025. One group addresses requirement validation and the certification-sensitive development of eVTOLs [5; 7; 8]. A second group addresses robotic drilling, automated assembly, inspection architecture, and precision improvement in aerospace structures [1; 4; 6]. A third group addresses digital twins, deviation propagation, non-nominal fabrication, and data-driven tolerance allocation [2; 3; 9; 10–12]. The selection logic excluded older classical tolerance papers and retained recent sources whose arguments can be transferred to structural assembly precision in eVTOL airframes.

The methodological basis combines three inputs. The first input is the selected source corpus on eVTOL requirements, composite manufacturing, robotic assembly, inspection architecture, deviation propagation, and digital tolerance control. The second input is the author's applied robust-analysis methodology, previously used to connect part-level dimensional deviations and stiffness compliance with system-level performance variation through tolerance stack simulation, multibody response modeling, DOE, sensitivity ranking, and six-sigma tolerance optimization. The third input is industrial dimensional-engineering practice: standards-based datum definition, tolerance stack-up logic, release-gate verification, metrology planning, corrective-action loops, and cross-functional review by design, manufacturing, quality, and metrology engineers. These inputs were converted into an eVTOL framework through methodological transfer: hardpoint-response sensitivity was translated into interface-criticality ranking, tolerance optimization into tolerance reallocation, and vehicle-level robustness targets into structural assembly precision metrics.

### RESULTS

The proposed framework's structure follows the engineering sequence used in applied dimensional control: define the performance-sensitive geometry, rank the contributors, simulate variation, isolate dominant variables, adjust tolerance bands, and verify the result against measurable targets. For eVTOL structural assembly, the same sequence is reformulated around airframe interfaces. Performance-sensitive geometry becomes certification-sensitive interface geometry; hardpoint sensitivity becomes joint, locator, datum, hole-pattern, gap, and flush sensitivity; response variation becomes assembly precision drift; tolerance optimization becomes selective tolerance reallocation across stations and suppliers.

Recent eVTOL literature moves dimensional control into the earliest stages of development. Requirement-validation research treats traceability matrices, validation plans, and formal verification routes as part of the development backbone [8]. Airworthiness-oriented work reaches a compatible conclusion from the safety side, since battery systems, electrical propulsion, and lightweight structures form a coupled configuration whose interfaces cannot drift freely without affecting qualification logic [5]. Within such a development environment, dimensional engineering starts with interface ranking. Engineers need to decide which joints, mounting zones, access edges, and drilled patterns fall within the aircraft's protected geometric envelope, because later process compensation cannot recover from a weak requirement architecture.

Composite structural manufacturing sharpens that point. The wing-box study on eVTOL cementing and co-curing describes a route in which the skeleton is pre-assembled, the skin and end-rib structures are laid on the tool, and the process separation plane is defined before final bonding and co-curing [7]. That sequence controls which geometric characteristics are fixed at each stage and which remain open to adjustment, as evidenced by deviation studies on aircraft rear fuselage frames. The assembly error does not occur once. It accumulates across stations through interactions among part variation, positioning deviation, and contact conditions [10]. For eVTOL structures, the implication is direct. Precision cannot be distributed uniformly across the airframe. It must be concentrated at the interfaces, where its drift propagates into later joins and installation references.

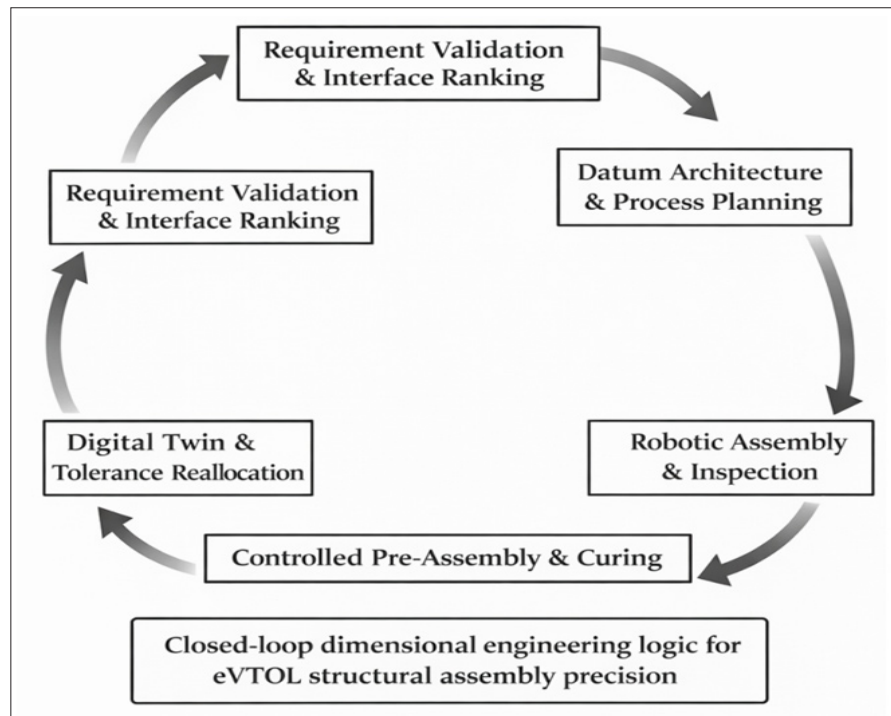
Robotic aerostructure assembly literature shifts the same logic from process planning to execution. A robotic system for thin-walled aerostructure assembly reaches high positioning accuracy through measurement-assisted compensation, hand-eye configuration control, minimized offset, and on-machine calibration [6]. The composite fuselage-panel study extends the argument to a full assembly and inspection cell. In that architecture, part referencing, tool orthogonality, countersink control, fastening verification, and workspace

monitoring are organized within a single distributed software and hardware environment [4]. Recent aircraft-component work adds a tolerance-optimization layer by combining multi-source error coupling, sensitivity screening, Monte Carlo simulation, and multi-objective optimization before the final tolerance update [1]. The common pattern is clear. Precision improves when metrology, execution, and error ranking operate within a single loop, where drilling accuracy forms only one element of control.

Researchers working on digital twins describe that loop in a more formal way. A broad perspective on mechanical and aerospace engineering argues that a digital twin gains value when it is designed for a purpose [2]. In fabricated aerospace assemblies, non-nominal welding simulation combined with 3D scanning shows how actual part geometry can be transferred into the virtual model and used to predict the geometrical outcome of joining operations [3]. Data-driven tolerance allocation research extends this logic into a closed control framework in which virtual and actual data

are coupled through point-cloud registration and free-form deformation, and tolerance decisions are updated online [9]. For eVTOL assembly, digital support needs to feed decisions on locator strategy, assembly sequence, and allowable interface drift, alongside visualization and traceability.

The framework consolidates four engineering functions into a single closed-loop sequence. The first function is the interface-criticality ranking, in which requirement and certification data define protected geometric characteristics. The second function is the datum architecture, where composite layup, curing, drilling, joining, and inspection references are maintained continuously across build stations. The third function is adaptive execution, in which robotic assembly and in-cell metrology convert nominal geometry into corrected build actions. The fourth function is feedback-driven tolerance reallocation, where measured geometry updates station priorities, supplier tolerance budgets, and next-build control plans. Figure 1 presents this defined sequence for eVTOL structural assembly.



**Figure 1.** Closed-loop dimensional engineering logic for eVTOL structural assembly precision [4; 7–9].

The reviewed studies favor selective control of dominant contributors over broad tightening inherited from older tolerance practice. Blanket tightening of all tolerances increases the burden on tooling and manufacturing, yet recent assembly research keeps returning to selective control of dominant contributors [1; 9; 10]. At the same time, eVTOL studies show that protected contributors are not chosen solely for manufacturing convenience. They are chosen by how geometry interacts with certification-sensitive systems and lightweight structural layouts [5; 8]. Dimensional engineering for eVTOL, therefore, takes the form of a ranked-control discipline. It screens interfaces, links them to process capability, and updates their tolerance logic with measured evidence from real builds.

## DISCUSSION

The proposed implementation model should be read as an applied engineering framework; its stages correspond to the decision points that dimensional engineering teams use when moving from requirements to tooling release and from first builds to production correction. Requirement decomposition defines the protected interfaces. Datum architecture converts those interfaces into reference logic. Process-capability matching tests whether the chosen manufacturing route can preserve

the protected geometry. Adaptive execution links measured deviation with local correction. Feedback-driven reallocation prevents repeated tightening of low-impact tolerances and directs control effort toward contributors with proven influence on assembly precision. Table 1 condenses that sequence into a decision structure for eVTOL structural programs.

**Table 1.** The author's eVTOL extension of the applied dimensional-engineering methodology for structural assembly precision

| Stage                        | Main engineering question                                                                       | Main action                                                                                 | Expected output                         |
|------------------------------|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|-----------------------------------------|
| Requirement decomposition    | Which interfaces affect fit, load path, sealing, system installation, or certification evidence | Rank structural and installation interfaces, and define protected geometric characteristics | Interface control matrix                |
| Datum architecture           | Which references remain stable across layup, curing, drilling, joining, and inspection          | Freeze the datum chain, locator logic, and benchmark-transfer rules                         | Datum continuity plan                   |
| Process-capability matching  | Which manufacturing route preserves each protected interface                                    | Align tolerance demand with co-curing, bonding, drilling, fastening, and inspection access  | Precision-oriented process plan         |
| Adaptive execution           | Which deviations need correction during build                                                   | Use in-cell metrology, calibration updates, local compensation, and controlled rework rules | Measured and corrected the build record |
| Feedback-driven reallocation | Which tolerances deserve tightening, redistribution, or release                                 | Compare predicted and measured deviation, update tolerance budgets, and station priorities  | Revised tolerance set for next builds   |

The model extends previous robust-analysis logic in three ways. First, it moves the controlled object from suspension hardpoints and stiffness-compliance variables to eVTOL structural interfaces. Second, it replaces response-based vehicle dynamics targets with geometric targets tied to fit, load path, sealing, propulsion-system installation, service access, and certification evidence. Third, it shifts tolerance optimization from a component-level cost problem to a cross-functional production control problem, where design engineering, manufacturing engineering, metrology, quality, and supplier teams share one ranked set of protected characteristics. Precision improves when engineering teams control the contributors that drive variation.

A second issue concerns plant-level monitoring. Dimensional control works best when process owners receive inspection data in time for corrective action. Table 2 presents a compact set of metrics for monitoring structural assembly precision across eVTOL builds.

**Table 2.** Monitoring metrics and illustrative quantitative references for structural assembly precision in eVTOL production [11; 12]

| Metric                              | What it tracks                                             | Illustrative quantitative reference                                                                                                                                                                                                                                   | Likely source of drift                                              | Typical response                                         |
|-------------------------------------|------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------|----------------------------------------------------------|
| Interface gap and flush             | External and internal closure quality at critical joins    | Gap around 0.5 mm and step/flush around 0.2 mm at protected interfaces                                                                                                                                                                                                | Datum transfer loss, local clamping distortion, part-state mismatch | Recheck the reference chain and local contact conditions |
| Hole position deviation             | Accuracy of drilled and reworked hole locations            | Robotic aerostructure assembly studies report a maximal positioning error of 0.08 mm; strict referenced assembly processes operate in regimes below 0.05 mm                                                                                                           | Calibration drift, tool offset error, and referencing error         | Update calibration and drilling offsets                  |
| Locator and benchmark stability     | Stability of physical references across repeated builds    | In strict-tolerance assembly, referencing becomes mandatory when tolerances fall below 0.05 mm                                                                                                                                                                        | Wear, maintenance drift, inconsistent setup                         | Requalify locators and restore benchmark surfaces        |
| Countersink and fastener conformity | Joint-quality consistency after machining and installation | Reported checks include hole-diameter tolerance of $\pm 0.038$ mm, hole-diameter measurement repeatability of $\pm 0.015$ mm, countersink-diameter repeatability of 0.071 mm, countersink-angle tolerance of $\pm 1^\circ$ , and normality tolerance of $\pm 2^\circ$ | Tool wear, orthogonality loss, process-parameter drift              | Correct tool condition and parameter set                 |

|                                 |                                                                                 |                                                                                                                                                                                                        |                                                                  |                                                          |
|---------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|----------------------------------------------------------|
| Prediction-to-measurement gap   | Reliability of the digital model against the physical build                     | Digital-twin-based aerospace assembly control is framed around sub-millimeter agreement; a mismatch approaching a 0.5 mm gap or 0.2 mm step at protected joints warrants review                        | Over-simplified twin, stale measurement pipeline, missing inputs | Narrow model scope and refresh data link                 |
| Rework concentration by station | Spatial clustering of dimensional problems and process capability deterioration | One recent tolerance-optimization study improved position pass rate from 67.4% to 100.0% and CPK from 0.31 to 2.19, while coaxiality pass rate improved from 93.5% to 100.0% and CPK from 0.62 to 1.06 | Upstream process instability                                     | Shift corrective effort to the dominant upstream station |

These metrics operationalize the contribution at the plant level. Each metric links a visible assembly symptom with a likely engineering cause and a corrective route. Hole drift with stable locator repeatability points toward calibration or tool-path error. Systematic gap growth across modules indicates benchmark-transfer loss, clamping distortion, or partial-state capture. Rework concentrated at one station redirects the investigation toward upstream process instability. This diagnostic structure extends the earlier sensitivity-ranking logic: it converts them into evidence for correcting data, adjusting processes, and reallocating tolerances in the next build cycle.

The same logic supports a specific implementation stance. Dimensional engineering should be managed as a program architecture function. Design teams define the protected interfaces. Manufacturing engineers translate those interfaces into datum logic and process choice. Metrology engineers decide which measurements feed immediate correction and which measurements feed the next tolerance release. Production managers then monitor where the deviation starts and where it becomes visible.

## CONCLUSION

Structural assembly precision in eVTOL aircraft begins with interface definition. The article contributes an eVTOL-specific dimensional-engineering framework that extends the methodology for variation reduction and robust tolerance optimization. Earlier methodology connected part-level dimensional deviations, hardpoint sensitivity, stiffness compliance, DOE, 3DCS tolerance simulation, ADAMS/Car modeling, modeFRONTIER optimization, and six-sigma targets. The present framework transfers that applied logic to eVTOL structural assembly, where the main controlled variables are certification-sensitive interfaces, datum continuity, composite joining conditions, robotic drilling accuracy, fastening conformity, and measured-geometry feedback.

The proposed framework consists of five linked engineering functions: interface-criticality ranking, datum architecture, process-capability matching, adaptive execution, and feedback-driven tolerance reallocation. This structure

clarifies how dimensional engineering contributes before tooling release, during build execution, and after inspection. The framework provides design, manufacturing, metrology, quality, and production teams with a shared control sequence to protect geometric characteristics that affect fit, load path, sealing, system installation, service access, and certification evidence.

The article's contribution lies in the practical transfer of proven, robust analytical logic into the emerging eVTOL production environment. The proposed model reduces dependence on broad tolerance tightening and redirects engineering attention toward ranked contributors, measurable drift sources, and closed-loop correction across repeated builds.

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