Motor Valley University of Emilia-Romagna

"Enzo Ferrari" Engineering Department

University of Modena and Reggio Emilia

IndyCar
2028 Bodywork
Golden Scanning Fixtures

Master's Degree in Racing Car Design

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Abstract

This thesis documents the development of golden fixtures to support dimensional validation of the 2028 IndyCar bodywork package during an internship at Dallara LLC. In this work, a golden fixture is defined as an inspection fixture intended to reproduce, as closely as practical, the real vehicle mounting points and local interface conditions of a body panel so that scan-to-CAD inspection is performed under representative boundary conditions. The need for such fixtures arose because the current quality-control approach is not uniform across the bodywork family: some parts are scanned only on request, many panels are checked primarily by visual or local dimensional inspection, and large semi-flexible parts can be difficult to evaluate repeatably when supported free-state or on temporary setups.

The main contribution of the thesis is therefore methodological as much as geometric. A repeatable fixture-development workflow was defined that begins with identifying the ready-to-sell part number and its surrounding assembly context, then establishes the datum reference frame (DRF) logic linking the part, fixture, and machining setup, selects the most suitable fixture architecture and scan orientation, and screens the concept by a preliminary statistical stack-up review before release. Two complementary architectures emerged from this process: an aluminum structural frame carrying machined polymer interface elements for larger or more irregular panels, and a monolithic machined RAMPF WB 1256 fixture for smaller or more compact components.

The resulting methodology provides gains relative to the previous inspection approach even where full physical validation remained outside the thesis timeframe. It creates a controlled and repeatable way to scan panels that were previously difficult or unreliable to inspect, reduces operator dependence and setup variability, supports physical go/no-go checks of selected gaps, flushness, and edge conditions, and introduces a reusable industrial workflow for part numbering, BOM definition, manufacture, refurbishment, and future validation. In that sense, the thesis demonstrates not only the feasibility of individual fixture designs, but also the feasibility of a standardized inspection-tooling methodology for regulated motorsport composite bodywork.

1 Introduction

1.1 Background

Motorsport has always been an engineering arms race conducted inside a rulebook. Even when technical regulations are highly prescriptive, competitors continue to search for performance in the grey area between what is explicitly prohibited and what can be practically detected. For that reason, regulation is never enforced only by written rules; it is also enforced by the technical means available to measure compliance.

What has changed in recent years is not the intent to exploit geometric loopholes, but the capability to detect them. High-resolution laser scanning and scan-to-CAD comparison have made it increasingly difficult to hide subtle changes in curvature, edge condition, rebate height, local thickness build-up, or surface blending that might previously have escaped visual checks or simple go/no-go gauges. In that context, the quality of the inspection setup becomes almost as important as the quality of the scanner itself.

The innovation behind the golden fixture project lies precisely in that inspection setup. A golden fixture is not simply a support used to hold a panel still during scanning. It is a physical translation of the vehicle's assembly logic into a metrology tool: it reproduces the mounting points, local interfaces, and datum structure that define how the panel exists on the car, and therefore defines the boundary conditions under which the panel is judged. The technical contribution of the project was to convert that idea into a repeatable fixture-development methodology that could be applied across a full bodywork family rather than treated as an ad hoc or temporary solution for a single part.

For the 2028 IndyCar bodywork, this was particularly important because the inspected components are large, thin carbon-fiber panels whose measured shape can change meaningfully with support condition, fastener strategy, and local contact geometry. The project therefore introduced a more rigorous inspection philosophy in which fixture design, scanner choice, datum logic, and refurbishment strategy were considered together. In practical terms, the fixtures were intended not only to improve repeatability of scan-to-CAD verification, but also to create traceable evidence capable of separating true manufacturing variation from fixture-induced error or suspected post-delivery modification.

1.2 Problem Statement and Goals

As IndyCar expands its use of modern metrology for bodywork compliance, Dallara requires an inspection approach that is repeatable, defensible, and compatible with large semi-flexible composite panels. The current quality-control process is governed by part-specific QC plans, but it is not uniform across the bodywork family: some parts are scanned, some are checked by dedicated physical or dimensional methods, and several large or flexible panels are difficult to evaluate repeatably when no dedicated locating fixture exists. In those cases, scan results or fit judgments can become overly sensitive to support condition, accessibility, and operator choices rather than to true part geometry.

A further design challenge was that a single fixture architecture was not suitable for every panel. Large or highly irregular components demanded lightweight structural frames carrying machined locating features, whereas smaller or more compact panels could be supported more effectively by monolithic machined blocks. One of the key outcomes of the project was therefore the development of a dual design strategy that linked part size, interface complexity, accessibility, and inspection intent to the most appropriate fixture architecture.

To meet this need, the project centered on developing golden fixtures for each major aerodynamic panel. These fixtures were intended to mimic, as closely as practical, the vehicle's mounting points and surrounding interface geometry so that inspection would occur under representative constraint conditions. The project goals were to:

- Establish a repeatable fixture design methodology that could be scaled across the 2028 bodywork family instead of treating each panel as an isolated tooling problem;
- Ensure semi-flexible bodywork and underwing components conformed to a defined, reasonable surface profile tolerance relative to nominal CAD geometry;
- Enable reliable inspection of both discrete features (fastener hole locations) and global conditions (outer profile and boundary geometry); and
- Support identification of whether measured deviations originated from manufacturing variation (for example process drift, trimming differences, or cure distortion) or from post-delivery modification by teams.

1.3 Requirements

The golden fixtures were required to function as long-term inspection references for the 2028 IndyCar bodywork program. Because the fixtures establish the boundary conditions under which scan-to-CAD comparisons are performed, the requirements emphasized repeatability, structural stability, and maintainability in addition to cost and manufacturability.

Key requirements for each fixture were defined as follows:

- **Repeatability (long-term):** The fixture must reliably and accurately reproduce the intended part mounting interfaces over years of use, enabling consistent inspection results across time, operators, and measurement sessions.

- **High stiffness:** The fixture structure must be sufficiently stiff such that deflection under part weight, handling, and constraint loads does not measurably influence the scanned geometry.

- **Thermal stability:** Fixture dimensions must remain stable across typical shop-floor temperature variation. Material selection and structural layout must minimize inspection error due to thermal expansion and gradients.

- **Alignment and validation features:** Each fixture must include a minimum of three alignment/registration features to support repeatable part alignment and periodic validation that the fixture remains within tolerance.

- **Repairable / refurbishable:** The fixture must allow replacement or repair of locating elements and wear items to restore alignment without requiring full fixture replacement.

- **Dimensional target tolerance:** Inspection intent was a target of ±0.3 mm relative to CAD, treated as a program requirement and potentially aggressive depending on part flexibility and measurement strategy.
- **One fixture per part:** Each selected bodywork component must have its own bespoke golden fixture.
- **Use of true mounting holes:** Fixtures must use all mounting hole locations normally required to mount the component to the car.
- **Cost and simplicity:** Fixtures must be as inexpensive and straightforward to manufacture and assemble as practical while meeting performance requirements.

These requirements established the engineering criteria used throughout concept selection, CAD development, tolerance stack-up evaluation, and final fixture definition.

1.4 Limitations

This thesis focuses on the engineering design and digital definition of bespoke golden fixtures intended to support scan-to-CAD inspection of selected 2028 IndyCar bodywork and underwing components. The work addresses fixture architecture, locating strategy, alignment feature definition, material selection, and design decisions intended to produce repeatable inspection boundary conditions representative of the vehicle interfaces.

The following limitations define what is not fully covered within this work:

- **Scanner-specific procedure development:** The fixtures are designed to support laser scanning, but detailed scan procedures, parameter tuning, and best-practice workflows for the specific scanning systems used are addressed separately and are not the primary focus of this section.
- **Formal metrology uncertainty studies:** Full measurement system analysis (e.g., Gage repeatability and reproducibility for scan-to-CAD), comprehensive uncertainty budgets, and certification-level validation are outside the primary scope unless explicitly noted.
- **Tolerance derivation:** The target tolerance (e.g., ±0.3 mm relative to CAD) is treated as a program requirement and is not fully derived from aerodynamic sensitivity, assembly stack-up, or composite process capability within this thesis.
- **Physical validation depth and long-term drift:** Comprehensive physical correlation testing for every fixture, long-term wear characterization, and multi-year stability studies are not fully captured. Likewise, no dedicated CAE-based stiffness study was completed within the thesis scope; stiffness was addressed primarily through architecture choice, section sizing, and support layout rather than through a formal simulation campaign.
- **Perfect replication of vehicle conditions:** While the individual golden fixtures mimic true mounting holes and interfaces, they cannot reproduce all real-world assembly effects (e.g., chassis compliance, joint stack-up across multiple panels, torque variation, and operational loads). The fixtures represent a controlled inspection boundary condition rather than a full vehicle assembly simulation.

- **Attribution of deviations:** The fixtures enable consistent comparisons and support evidence-based separation of as-built variation from suspected post-delivery changes; however, definitive attribution may also require additional traceability controls and supporting records beyond the fixture itself.
- **Completion of the full panel set:** Although the program identified a list of major bodywork and underwing components for golden fixture development, not all fixtures for every listed component were completed within the thesis timeframe due to internship and project schedule constraints. Even so, the thesis documents both the completed and partially completed fixture designs, as well as the methods used so the remaining yet to be started fixtures can be developed using the same process.

These limitations were accepted to keep the effort focused on delivering release-ready fixture designs consistent with program timelines and internship scope.

2 Literature Overview

Published guidance in dimensional metrology emphasizes that credible inspection depends not only on instrument capability, but also on datum definition, part setup, traceability, and inspection planning. In other words, the measurement system includes the way the part is constrained and referenced during inspection, not only the scanner or probe itself. That perspective is directly relevant to the present work because the golden fixture was developed to control the support condition and datum structure seen by the scanner rather than to act as a passive holding device [1-3].

2.1 Metrology Systems to be Used

The golden fixtures were only valuable if the associated inspection workflow was repeatable and practical for day-to-day quality control (QC) use. Two portable metrology systems were considered for use with the fixtures to support scan-to-CAD validation of the 2028 IndyCar bodywork: the FARO Quantum S FaroArm (and ScanArm configuration) and the Creaform MetraSCAN BLACK+|Elite (with the C-Track and HandyPROBE). In practice, the size of the bodywork component and its golden fixture influenced scanner selection primarily for convenience and workflow efficiency rather than because either system was fundamentally incapable of performing the measurement. The FaroArm was generally the more convenient option where rapid setup and direct access to specific features were important, whereas the MetraSCAN workflow required more setup effort, including calibration and C-Track placement, but offered faster full-field surface acquisition once running. The technical data of both systems are summarized in Appendix 9.1 [4-6].

2.1.1 FARO Quantum S FaroArm (portable articulated-arm CMM / ScanArm)

The Quantum S FaroArm was considered the most appropriate tool for fast, flexible measurement tasks while the component was constrained on its golden fixture. Within the intended inspection workflow it was especially relevant for:

- **Mounting-hole and interface feature inspection** (e.g., fastener hole locations and patterns) using probing.
- **Fixture validation** (periodic verification that fixture alignment features and datums will remain in tolerance).
- **Quick checks and troubleshooting**, where minimal setup time will be critical.
- **Supplemental surface digitization** when configured as a ScanArm (laser line probe), as needed.

For many panels, especially where the fixture envelope was smaller or access to key features was straightforward, the FaroArm was expected to be selected more often because it allowed a faster transition from setup to measurement with fewer dependencies. This made it the preferred option for frequent checks, feature-driven inspection of hole patterns and datums, and periodic fixture verification [4].

2.1.2 Creaform MetraSCAN BLACK+™|Elite (optical CMM scanner with C-Track and HandyPROBE)

The MetraSCAN BLACK+|Elite system was intended primarily for full-field surface inspection of complex composite geometry when the component was mounted on its golden fixture. Within the workflow it was used to:

- Generate **dense surface data** for scan-to-CAD deviation maps and surface profile evaluation.
- Verify **outer profile and boundary geometry** over large, free-form bodywork surfaces.
- Support repeatability in jig/fixture setups using Elite-specific **Setup Assistance tools**.

Although the MetraSCAN system provided efficient full-surface capture once running, it typically took longer to set up than the FaroArm. Correct calibration and appropriate C-Track placement were important so that the HandyPROBE and scanner remained robustly tracked throughout the inspection session. Because of this, the MetraSCAN system was more attractive when the component and fixture assembly were large enough that the additional setup time was justified by the benefit of rapid full-field surface acquisition [5,6].

2.1.3 Practical selection logic to be applied

Scanner choice therefore followed a workflow-efficiency rule derived from the characteristics of the two systems and from the inspection objectives of the project:

- **Smaller components / smaller golden fixtures:** the FaroArm was expected to be used more frequently due to faster setup-to-measurement and straightforward access for feature checks.
- **Larger components / larger golden fixtures:** the MetraSCAN BLACK+|Elite was expected to be used more frequently when full-surface coverage was required, even though calibration and C-Track placement increased setup time.

This logic allowed the golden fixtures to support production-oriented inspection efficiently while still generating the required outputs: surface profile verification, fastener-location checks, and periodic fixture validation.

2.2 Material Selection for the Golden Fixtures

Material selection for the golden fixtures was driven by the project requirements of repeatability, stiffness, thermal stability, repairability, and cost-effective manufacturability, while also reflecting practical constraints typical of production-support tooling. Because the fixtures were intended to serve as long-term inspection references and to be handled repeatedly in a shop-floor environment, cost and availability were major factors across the selected materials: aluminum, Delrin, and polyurethane tooling board. The final material strategy intentionally separated the fixture into two functional groups: a stiff and transportable structural base, and non-marring machinable contact elements used to replicate vehicle interfaces [7-9].

2.2.1 Aluminum for structural members and fixture bases

Aluminum was selected for primary structural members and the majority of fixture base architectures due to a combination of stiffness-to-weight, availability, and practical fabrication considerations.

- **Weight and handling:** The fixtures were expected to be transported from storage to the quality control room when needed. Aluminum provided adequate stiffness at relatively low mass, improving ergonomics and reducing handling risk compared with heavier steel structures. This directly supported long-term repeatability, since fixtures that are easier to handle are less likely to be dropped, overloaded, or mishandled.
- **Availability in rectangular tube form:** A key driver was the widespread availability of aluminum rectangular tubing, which aligned with the preferred fixture architecture. Most fixture bases were therefore conceived around rectangular tube, which provides efficient bending stiffness, a clean modular layout, and straightforward integration of mounting plates, gussets, and adjustable elements. Using a readily available stock geometry also supported rapid iteration and repairability.
- **Cost-effectiveness relative to alternatives:** Aluminum provided a practical balance between structural performance and cost. Alternative material and geometry strategies (e.g., welded steel frames, large machined plates, cast structures, or complex fabricated trusses) could increase mass, fabrication time, and cost. Aluminum rectangular tube construction allowed fixtures to meet stiffness and repeatability needs while remaining economical and straightforward to manufacture.

Overall, aluminum supported the requirements of high stiffness, good thermal behavior in typical shop conditions, repairability, and cost and simplicity, while also addressing the real operational constraint that fixtures will be moved and staged for use.

2.2.2 Delrin and RAMPF WB 1256 for contact and locating features

Delrin and tooling board (RAMPF WB 1256) were selected for fixture features that contact or locate the carbon-fiber bodywork because they are machinable, non-marring, and well-suited for creating complex interfaces without the time and cost penalties of machining metal. These polymer-based materials were used for the same general purpose: they form the mounting and support surfaces that interface with the B-side (non-aerodynamic side) of the composite panels and, where required, replicate surface-to-surface interface conditions between the scanned panel and surrounding bodywork.

This approach ties directly to the golden fixture definition: because the fixtures are intended to mimic true vehicle mounting points and interface conditions, the contact surfaces must be manufacturable at sufficient fidelity to represent real assembly boundaries while minimizing the risk of scratching or imprinting finished composite surfaces.

2.2.2.1 RAMPF WB 1256 (tooling board)

RAMPF WB 1256 tooling board was preferred when large, complex contact geometries had to be machined to replicate interface conditions.

- Cost and weight advantages: RAMPF tooling board is lighter than metallic alternatives and can be machined efficiently into large support surfaces. Those advantages become decisive when the design requires broad interface regions to be copied in order to mimic how a panel nests relative to surrounding bodywork. Lower cost directly supported the requirement to keep fixtures as economical and practical as possible, while lower weight improved handling and transport [7].

- High machinability for complex surfaces: Tooling board allows efficient machining of large contoured surfaces that would be more expensive and time-consuming in metal. This supported repeatability, reduced the risk of local panel deformation by distributing support over larger areas, and made it easier for the fixture to represent assembled-car boundary conditions.

For these reasons, RAMPF WB 1256 was selected wherever the fixture needed substantial sculpted surfaces to reproduce the surface-to-surface interfaces relevant to scan repeatability and scan-to-CAD alignment.

2.2.2.2 Delrin (acetal)

Delrin was selected when higher toughness and durability were required, particularly for localized locating features and contact points that would see repeated assembly and disassembly.

- Toughness and wear resistance: Delrin is well suited to repeated contact, localized loading, and occasional mishandling. Those characteristics support long-term repeatability and the requirement that fixtures remain repairable and refurbishable, since Delrin contact elements can be treated as replaceable wear items [8,9].

- Practical limits due to cost and stock geometry: Delrin use was limited by material cost and by the shapes in which it is readily available. In practice, suppliers commonly offer Delrin as rod or sheet rather than as large solid blocks. This restricts how efficiently large three-dimensional contoured interface surfaces can be produced from Delrin and makes it less economical when extensive volumetric machining is required [8,14,15].

As a result, Delrin was used strategically where its toughness added value, while RAMPF WB 1256 covered larger machined interface regions where cost, weight, and manufacturability were dominant.

2.2.3 How the requirements drove the final material strategy

The selected material combination was a direct response to the requirements defined for the golden fixtures:

- **Repeatability (long-term):** Aluminum structures provide stable geometry and durable frameworks; Delrin and tooling board allow precise, repeatable interface features that can be re-machined or replaced if needed.

- **High stiffness:** Aluminum rectangular tube bases deliver stiffness efficiently, reducing risk that fixture compliance will influence scan results.

- **Thermal stability:** Material selection and the separation of “structure” (aluminum) from “contact features” (polymers) reduce sensitivity to environmental variation and simplify future compensation/validation strategies.

- **Alignment and validation features:** Polymer contact and datum elements support precisely machined reference features, while the aluminum structure provides a stable backbone to hold those references in a controlled relationship.
- **Repairable/refurbishable:** Replaceable Delrin and tooling board elements enable refurbishment of wear surfaces and restoration of alignment without replacing the entire fixture.
- **Cost and simplicity:** Aluminum tube construction minimizes fabrication complexity; tooling board reduces machining time/cost for large contoured regions; Delrin is reserved for high-value features where durability justifies its cost.

In summary, aluminum provided the stiff and transportable structural foundation for the golden fixtures, while Delrin and RAMPF WB 1256 provided non-marring machinable interface surfaces that enabled accurate replication of mounting and adjacency conditions. This combination satisfied the functional requirements of the fixtures while remaining practical for production-support tooling in terms of cost, availability, and long-term maintainability.

3 Design Methodology

The design methodology for the golden fixtures ultimately matured into a repeatable engineering workflow rather than a collection of one-off fixture concepts. Its purpose was to translate the way a body panel truly exists on the car into a controlled inspection condition: the correct mounting interfaces, the relevant neighboring surfaces, the intended datum structure, and a scan orientation that allows practical access without introducing unnecessary deformation.

Just as importantly, the methodology had to remain compatible with how Dallara quality-controls parts in practice. The fixture was not being designed for an abstract idealized panel; it was being designed for the ready-to-sell part number that Quality Control would actually inspect, with all of the assembly-stage, handling, and traceability implications that follow from that production reality.

3.1 Methodology baseline and current quality control workflow

The starting point for the methodology was the current inspection baseline. Dallara uses QC plans that specify which characteristics of a given part number must be verified. Depending on the component, this may involve scanning, dedicated jig checks, or more conventional dimensional and visual checks such as hole sizes, hole spacing, laminate condition, thickness, and hardware condition. In other words, the existing process is not a single linear sequence; it is a part-specific inspection plan shaped by safety, fit, and performance requirements.

That baseline also revealed the main weakness that motivated the thesis. For several major body panels, especially large or semi-flexible components, scanning was either not routinely performed or was only carried out when specifically requested. Where scans were attempted without a dedicated fixture, the setup could depend on temporary supports, partial mounting, or free-state handling. That made repeatability sensitive to operator choices, part stiffness, local accessibility, vibrations, and other environmental influences.

The methodology therefore begins by identifying not only the target panel, but also the specific inspection problem the fixture is expected to solve: whether the current process lacks repeatable scanning altogether, whether local interfaces cannot be checked reliably, or whether the panel is currently inspected only by indirect dimensional checks. This initial problem framing is what determines the appropriate datum strategy, fixture architecture, and inspection outputs.

3.2 Step-by-step fixture-development workflow

Once the inspection need is defined, the fixture is developed through the step-by-step workflow summarized in the flowchart below (*Figure 1*). The sequence is deliberately written as a reusable method so that future fixtures can follow the same logic even when the component geometry changes.

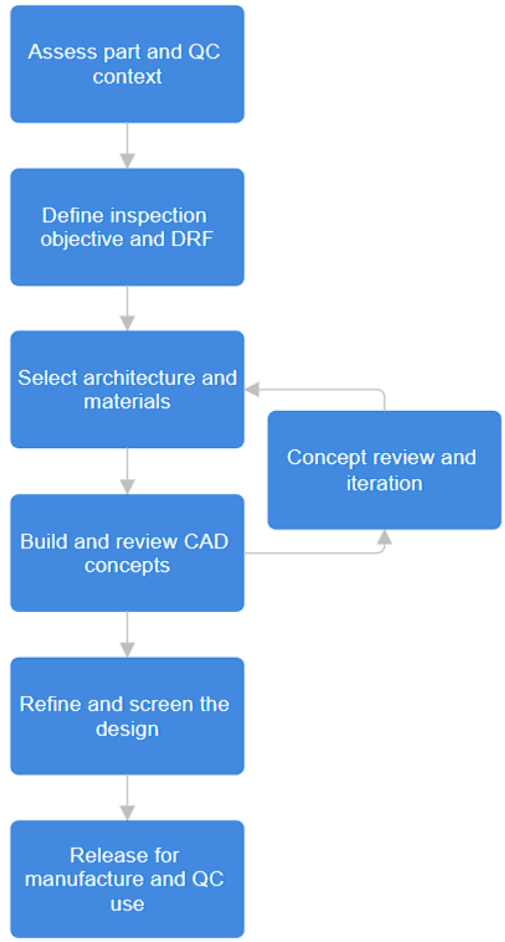

Figure 1:Flowchart summarizing the proposed reusable methodology for golden-fixture development

Phase 1 - Assess the production and assembly context. The full bodywork assembly that contains the target panel is reviewed first so that all relevant neighboring panels, supporting structures, and real vehicle interfaces are understood. At this stage the fixture designer identifies how the part mounts to the car, whether it mounts through floating or non-floating threaded elements, which surfaces govern local gap and flushness, how the part is removed in service, and which manufacturing stage corresponds to the ready-to-sell part number that Quality Control will inspect.

Phase 2 - Define the inspection objective, scan approach, and datum logic. The target response characteristic must be declared before any meaningful fixture geometry is created. Depending on the part, that response may be a critical mounting-hole position, a surface offset relative to datum features, or a local gap/flush condition at an interface. The part DRF is inherited from the vehicle coordinate system, the fixture DRF is defined so that it reproduces that same logic, and the intended scan orientation is chosen so that the relevant surfaces remain accessible without making the setup impractical.

Phase 3 - Select the fixture architecture and material strategy. At this point the part envelope, interface complexity, handling constraints, and inspection objective are used to choose between the two dominant architectures established in the thesis: a monolithic RAMPF WB 1256 fixture for smaller or more compact parts, or an aluminum frame carrying machined polymer interface elements for larger or more irregular panels. The same phase also determines whether Delrin or RAMPF should be used at each functional interface.

Phase 4 - Build and review CAD concepts. After the fixture part number is created in the company data system, the target panel and any extracted neighboring surfaces are imported into the controlling CAD file. Mounting-hole centers, support planes, interface offsets, and datum features are then created and used to generate one or more fixture concepts. These concepts are reviewed iteratively with the project advisor and coworkers until one direction is selected for further development.

Phase 5 - Refine the selected concept and screen its dimensional credibility. The chosen design is completed by adding pads, locating features, removable blocks, access clearances, standardized datum features, and the machining strategy required to generate the critical geometry in a controlled reference state. Before release, a preliminary stack-up review is performed so that the fixture is not allowed to consume an excessive share of the overall inspection tolerance budget.

Phase 6 - Prepare the fixture for manufacture, assembly, and future reuse. Once the CAD definition is mature, the BOM tree and staged part-number structure are created so that the raw material, welded/pre-machined/machined states, and final assembly can be traced. This stage is essential because the golden fixture is intended to become a durable industrial inspection tool rather than a temporary one-off prototype.

3.3 Datum reference frame logic for part, fixture, and machine

The datum-reference logic used in the thesis follows the coordinate system of the car itself. Across the bodywork program, positive Z is upward, positive X points rearward, and positive Y points to the driver's right. In the CAD environment, the YZ plane is located at the front of the monocoque, the ZX plane bisects the car longitudinally, and the XY plane corresponds to the bottom of the monocoque. The part DRF is therefore not an arbitrary best-fit frame; it is the vehicle assembly frame within which the nominal mounting points and surrounding surfaces were originally defined.

The fixture DRF is intentionally made consistent with that same vehicle-based logic. This is what allows extracted mounting surfaces and neighboring interfaces to be imported directly from CAD and placed into the fixture in a physically meaningful way. The fixture does not create a new geometric truth for the part; it reproduces, in controlled form, the datum relationships that already define the part on the car.

The machine DRF, by contrast, exists only to manufacture the fixture correctly. On the Belotti, the machining frame is tied to the table center and table surface. That machine frame is used to generate the fixture datums and functional surfaces, but it is not the inspection frame reported to Quality Control. In practical terms, the relationship is sequential: the machine DRF creates the fixture DRF, and the fixture DRF is used to reproduce the part DRF during inspection. This ordering is also what allows the stack-up chain to be defined rigorously, because the designer can identify which contributors belong to machining, which belong to the fixture itself, and which belong to part seating during use.

3.4 Architecture selection and methodological evolution

As the project progressed, the methodology evolved from a simple mounting-point replication philosophy into a broader interface-replication strategy. Early concepts focused mainly on recreating the nominal fastening locations with local Delrin pucks. That approach was fast and often useful, but it proved insufficient whenever the inspection problem depended on how the panel blended into neighboring surfaces or how a local rebate and gap were established in the assembled vehicle.

The mature methodology therefore retained panel-specific fixtures, but it designed them with enough local assembly fidelity that they could support more than one inspection mode. A finished fixture could hold the part in a repeatable scan condition, support direct verification of selected mounting features, and in some cases also function as a go/no-go reference for local gap, flushness, or edge-thickness checks. This is why the thesis did not simply choose between full-assembly and panel-specific thinking; instead, it used panel-specific fixtures that still preserved the most important adjacent-interface information.

From that evolution, a stable architecture-selection rule emerged. Large, long-span, or highly irregular parts generally favored an aluminum structural frame with machined polymer blocks because that approach kept weight manageable while still reproducing the required interfaces. Smaller, more compact, or more self-contained parts generally favored a monolithic RAMPF WB 1256 fixture because a single machined parent block reduced internal assembly interfaces and improved dimensional coherence. This dual-architecture logic became one of the main methodological outcomes of the project.

Something to note is that due to confidentiality agreements governing proprietary IndyCar bodywork geometry, the body panels themselves are not shown in this particular report; therefore, the design evolution is presented through the fixture structures, reference features, and interface logic without disclosing the underlying panel surfaces.

3.5 Common Parts/Features Across All Fixtures

Although each golden fixture was developed for a specific body panel, a common set of recurring features was intentionally standardized across the fixture family. This shared design language reduced development time, simplified manufacturing and refurbishment, and, most importantly, ensured that repeated assembly and inspection tasks would be carried out in a consistent manner regardless of the component being checked. The common elements described below therefore represent more than simple carry-over details; they form the foundation of how the fixtures locate the parts, how they are validated, and how they can be maintained as long-term inspection tools.

3.5.1 Threaded Inserts, Floating Nut plates, and Tridair Interfaces

Figure 2: Floating Tridair (left) and floating nut plate (right)

A recurring design requirement across the fixture set was the need to reproduce the real fastening condition of the vehicle as closely as practical. For inspection tooling of this type, a mounting hole cannot be treated as a simple drilled feature in a support block, because the type of threaded interface, the amount of permitted float, and the local support condition all influence how the part finally seats on the fixture. Some panels mount directly to the monocoque, while others mount to adjacent bodywork through captive threaded elements called Tridairs or nut plates (*Figure 1*). The reason behind the use of either has to do with how often that body panel or set of body panels will be put on and off. Tridairs offer a more durable thread engagement compared to the nut plates. In each case, the fixture had to replicate not only the nominal position of the interface, but also its functional behaviour during assembly.

Figure 3: Floating keensert (left) and non-floating keensert (right)

Where the vehicle uses a rigid threaded interface, the fixture uses a corresponding metallic insert so that the fastening condition remains durable and representative under repeated installation cycles. Where the real assembly uses floating nut plates or floating Tridair receptacles, the fixture preserves a controlled amount of radial compliance rather than replacing the joint with a fully rigid thread. This prevents the fixture from over-constraining the composite panel and forcing it into a non-representative position during mounting. In practice, non-floating locations were implemented with fixed metallic threaded inserts, or non-floating Keenserts as shown in *Figure 2*. Floating locations were reproduced either with commercially available self-aligning threaded insert solutions (floating keensert shown in *Figure 2*) or with a custom-designed carrier (*Figure 3*), depending on whether the interface was intended to mimic a floating nut plate or a floating Tridair. The custom Tridair bucket insert allowed the required float while remaining robust enough for long-term shop-floor use, and an example of the assembly is shown in *Figure 4*. This distinction was essential to ensuring that the fixture behaved like a controlled replica of the vehicle interface rather than like an artificially rigid assembly jig.

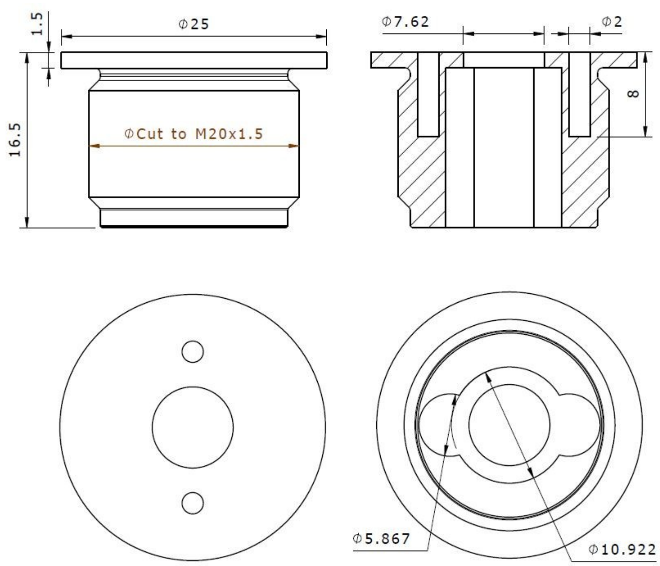

Figure 4: Tridair insert

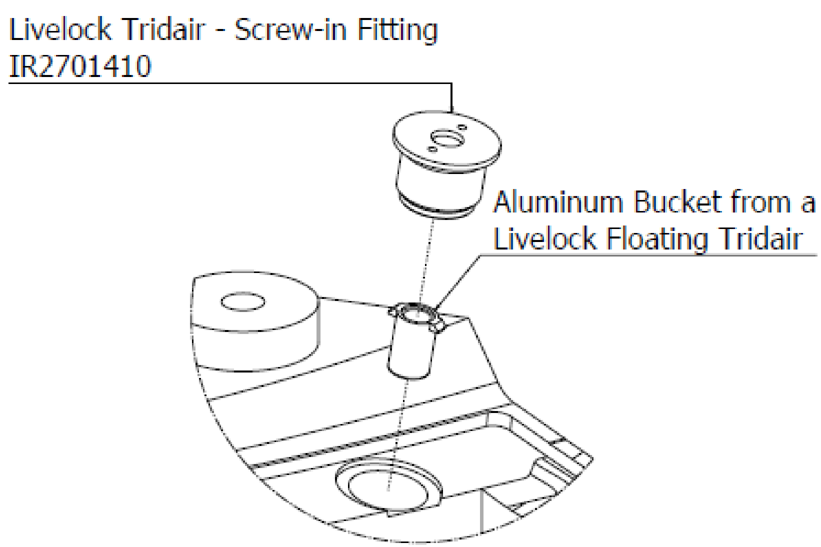

Figure 5: Tridair insert assembly example

3.5.2 Datums

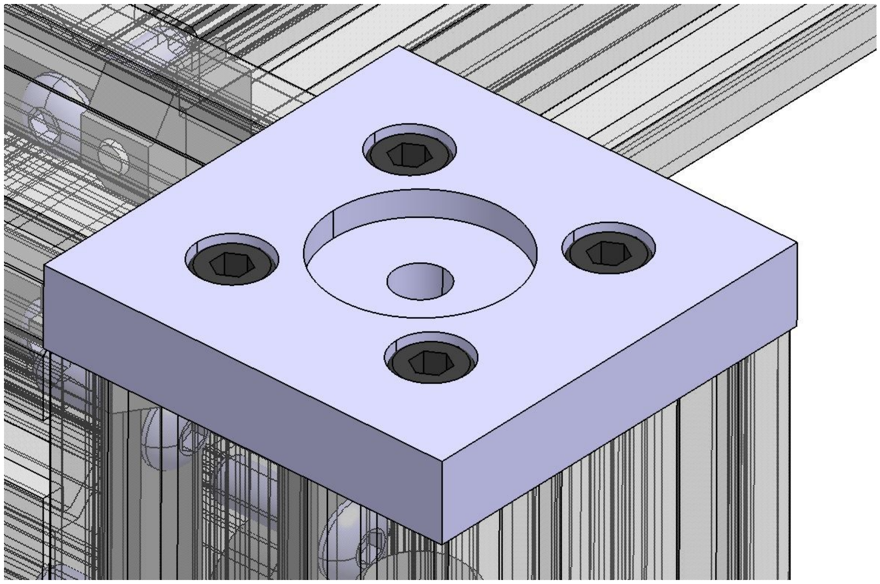

Figure 6: Example of a female-type datum machined on a metal plate

A second standardized feature across the fixture family was the use of dedicated datum elements for scan setup, fixture validation, and long-term traceability. These datums ensured that the inspection coordinate system was established from known fixture references rather than from an arbitrary best-fit alignment of the scanned part. That distinction is especially important in the present methodology because the fixture DRF is intended to reproduce the part DRF inherited from the vehicle coordinate system. Best-fit alignment could mask true positional error by redistributing deviation over the part, whereas a fixture-tied datum structure keeps the scan-to-CAD comparison physically meaningful and compatible with the way the part is mounted on the car [1-3].

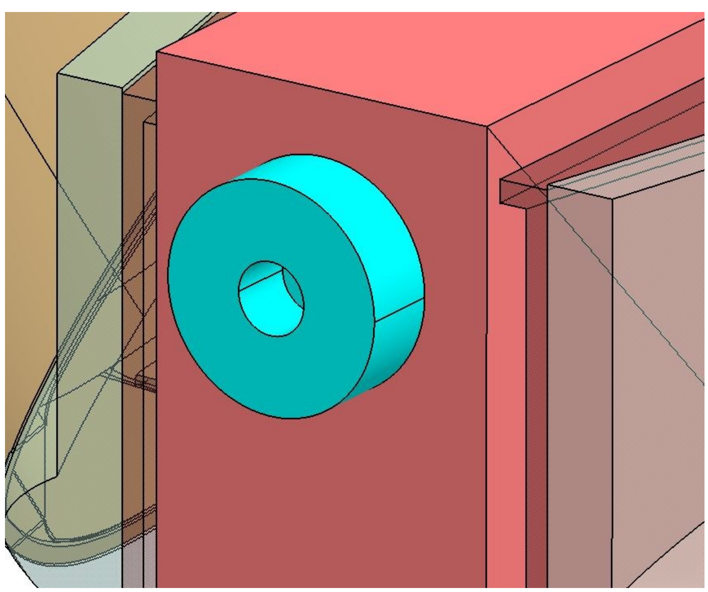

Figure 7: Example of a male-type datum machined on a metal bung

The standard datum geometry adopted throughout the project was a cylindrical feature with a nominal 35 mm outside diameter and a 10 mm central bore. This geometry was large enough to be robust and easy to probe, whether the datum was machined directly into a monolithic tooling-board block or into a welded metal feature on a frame-based fixture. More importantly, the datum set acts as the bridge between the machining frame and the inspection frame: the Belotti machine DRF is used to generate these datum features in the correct relationship, and those finished datum features then define the fixture DRF used during scanning. Standardizing the datum form across fixtures therefore simplified setup, supported repeatable validation, and made the part-fixture-machine relationship explicit in a way that directly supports stack-up definition.

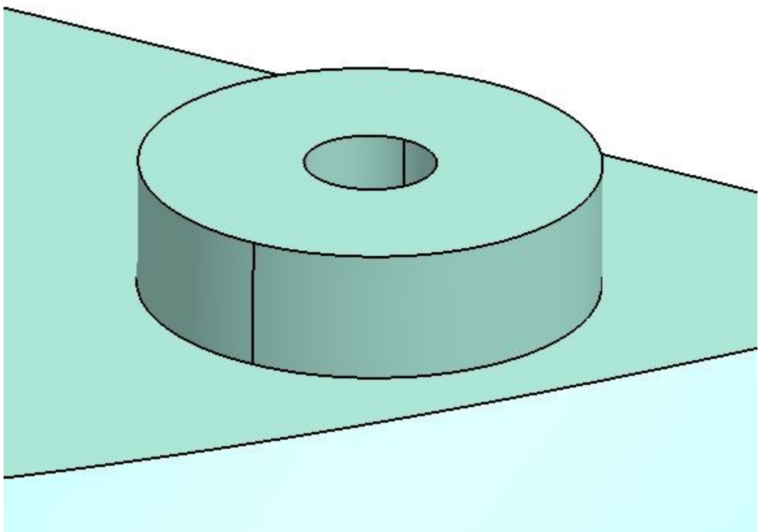

Figure 8: Example of a male-type datum machined directly on fixture

3.5.3 Pads

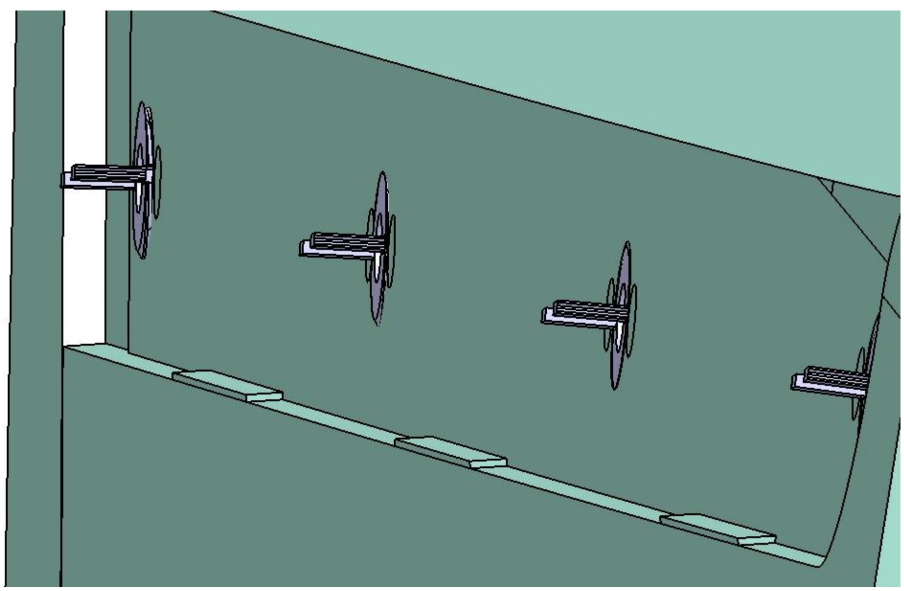

Figure 9: Example of pads used throughout the fixtures

Pads were introduced wherever the CAD definition required a controlled stand-off between the inspected panel and the neighbouring reference geometry represented by the fixture (see figure 8). Their primary function was to establish a hard stop that located the panel repeatably without forcing the edge condition beyond the nominal assembly intent. In this way, the pads helped maintain the gap defined in CAD while also reducing the risk of damage during installation by preventing the operator from driving the panel too far into the fixture.

A secondary benefit of the pads was that they enabled quick physical checks in addition to full scan-based inspection. Where a nominal gap was intentionally preserved, a feeler gauge could be used as a simple go/no-go check for the mating edge, providing a fast qualitative confirmation of fit before or after scanning. Pads were therefore not added indiscriminately to every fixture, but only where they improved locating repeatability, protected the part, or provided a useful physical check of gap and flushness.

3.5.4 CNC and Leveling Feet Mounting

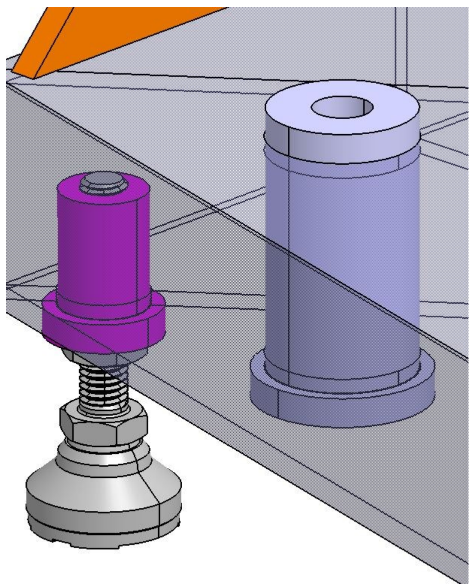

Figure 10: Example of TDM (right) and foot (left) mounting bushings used throughout the fixtures

Although largely invisible during normal inspection use, CNC mounting strategy was an important common requirement across the fixture set because the fixtures had to be manufacturable, re-machinable, and recoverable in-house on the Belotti FLU 2617 (technical specifications shown in *Appendix 9.2*. This supported both cost and maintainability objectives. If a fixture were damaged, worn, or found to be out of tolerance, the released CAD definition could be used to reproduce or rework the fixture internally rather than depending entirely on an external supplier. To support this manufacturing route, all machine-mounting features/bushings (*Figure 9*) were laid out with the Belotti's practical constraints in mind, including compatibility with a 100 x 100 mm mounting grid. The main way the fixtures were fastened to the Belotti was with the use of a Torque, Die & Mold (TDM) clamping system (*Figure 10*). A system mainly designed for mold making but can be used just as well for our intentions.

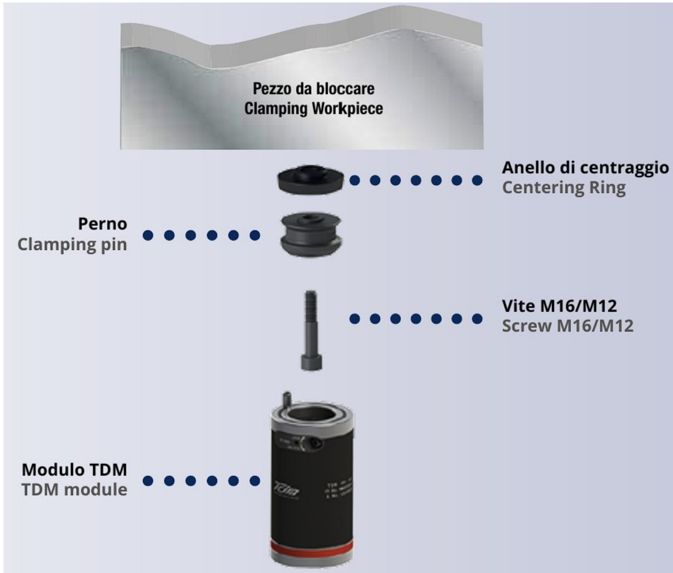

Figure 11: Torque, Mold & Die (TDM) Clamping System

For monolithic tooling-board fixtures, the preferred solution was a counterbored mounting feature combined with an M16 x 2 threaded interface compatible with the TDM clamping system (*Figure 12*). This provided a robust, repeatable way to locate and secure the block during machining. Welded aluminum-frame fixtures required a different solution because the structure should be machined in its true post-weld condition rather than being forced flat during setup. For these weldments, dedicated bushings together with long studs and spherical washers allowed the frame to be clamped securely while accommodating small angular deviations caused by weld distortion (*Figure 11*). This was important because machining a weldment while artificially straightening it would risk producing accurate surfaces in the machine that would shift once the structure was unclamped and relaxed back toward its as-welded shape.

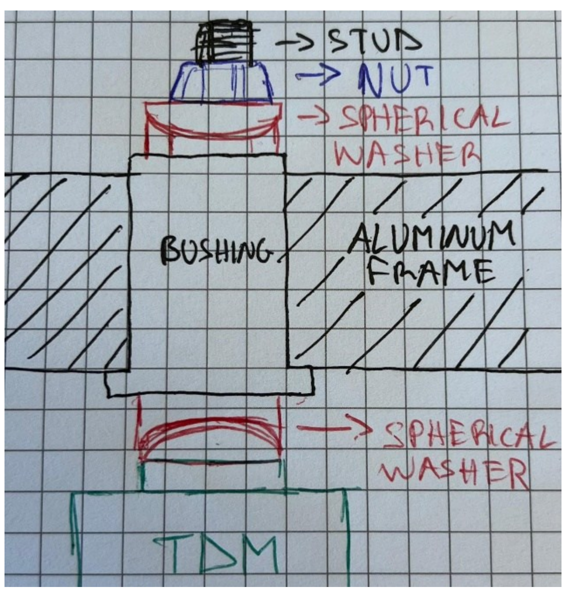

Figure 12: TDM Fixture Mounting System

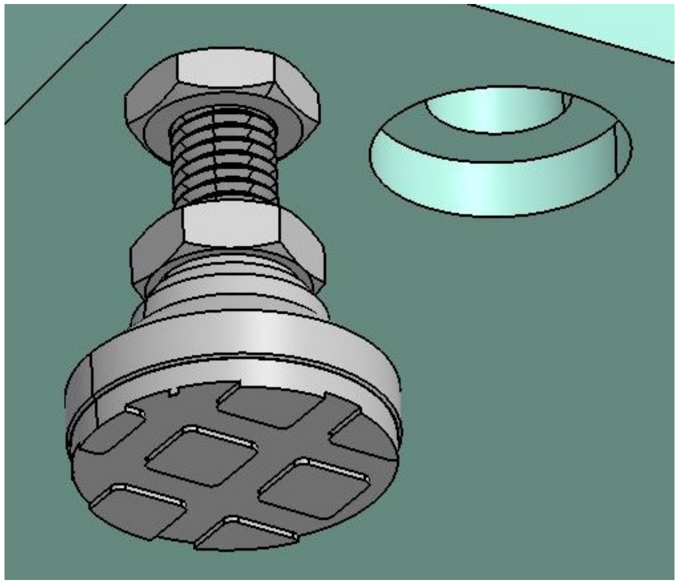

Figure 13: Example of a foot (left) and a machined counterbored hole for the TDM's

3.5.5 Hardware

A final group of common elements consisted of the service hardware required to assemble, disassemble, and refurbish the fixtures without losing positional integrity. Standard fasteners alone are rarely sufficient for this kind of inspection tooling because bolt preload does not guarantee exact re-location after a component has been removed. For that reason, removable joints were supplemented with deterministic locating features such as one-sided threaded studs, dowel-type features, and slotted spring pins wherever future reassembly due to refurbishment was required.

This strategy was particularly useful when a removable machined block had to return to the same position after maintenance or replacement. One-sided threaded studs could hold a block accurately while the remaining fasteners were installed, and spring-pin-based features provided simple but repeatable retention without unnecessarily increasing design complexity. From a lifecycle perspective, these details were important because they allowed wear-prone surfaces, inserts, and local locating elements to be treated as service parts. As a result, the fixture could be repaired or refurbished over time without sacrificing the geometric definition of the main structure, which was consistent with the requirement that the golden fixtures function as durable inspection references rather than one-time-use tooling.

Figure 14: Slotted spring pin (left) One-sided threaded stud (middle) Cap screw (right)

3.6 Design Evolution and Final Designs

The development of the golden fixtures did not proceed as a simple chronological sequence. Multiple panels were studied in parallel, and several concepts had to be revisited as the requirements evolved from a mounting-point-driven philosophy toward broader replication of interface geometry and surface continuity. For that reason, this section is organized by fixture rather than by project timeline.

Although each subsection describes a different component-specific problem, the final solutions consistently resolve into the two fixture architectures defined earlier: either an aluminum structural frame carrying machined locating features, or a monolithic machined RAMPF WB 1256 fixture. Read together, the fixture-specific cases therefore show not only the evolution of individual designs, but also the consolidation of a repeatable methodology across the complete bodywork family.

3.6.1 Underwing

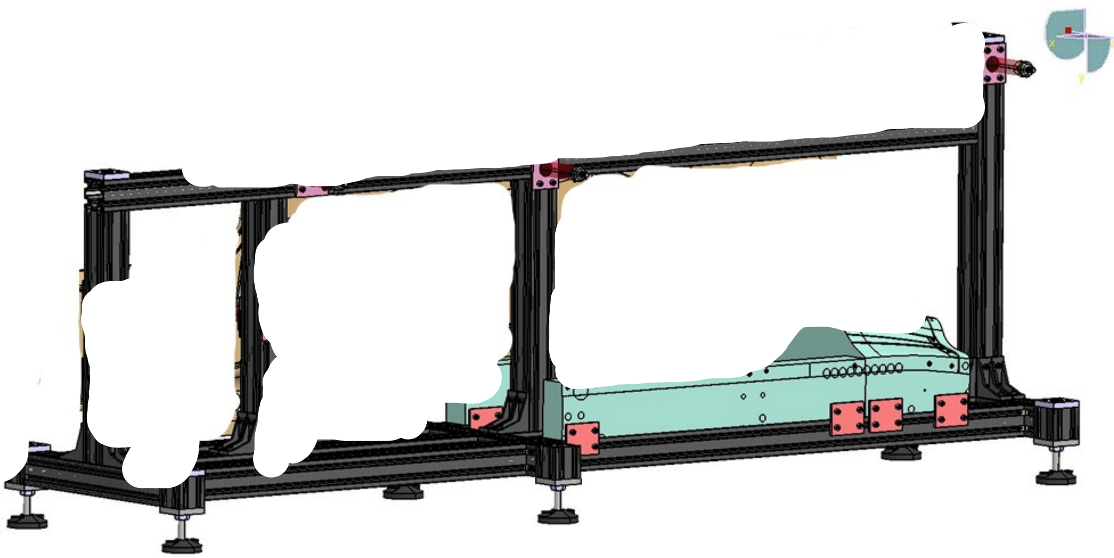

Figure 15: Underwing top side on fixture

The underwing represented one of the most demanding fixture problems because of its size, low thickness, and the practical difficulty of storing, moving, and scanning such a large component. Early concepts attempted to preserve an orientation closer to the installed vehicle attitude so that gravity would act on the part in a more representative way. However, ceiling-mounted and inclined-fixture concepts were quickly judged impractical because they would have complicated mounting, reduced accessibility for scanning, and produced a fixture that would be difficult to transport or store. The design direction that emerged was therefore a 90-degree mounting orientation, which sacrificed some gravity fidelity in favour of a much more manageable inspection and handling solution. This orientation also enabled a narrow fixture envelope relative to part length and allowed the same structure to support both the left-hand and right-hand underwings.

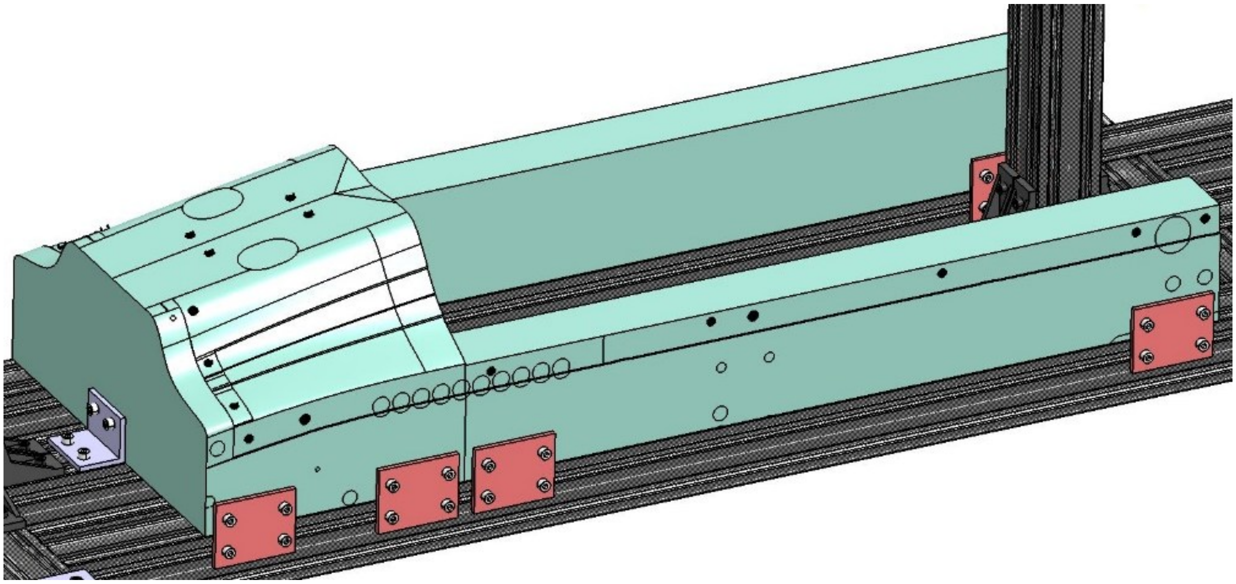

Figure 16: Close up of dummy monocoque/keel machined block

Using that layout as a starting point, and drawing on an earlier Dallara sports-car underwing scanning fixture for reference, the final concept adopted a modular frame built from Robotunits 80 x 80 aluminum extrusion, shown in *Appendix 9.4.1.1*. This choice was technically attractive because the extrusion system offered adequate stiffness, modularity, and ease of assembly, while also reducing internal approval risk by building on a solution already used within the company. The monocoque and keel interfaces were represented by machined RAMPF WB 1256 blocks extracted directly from the vehicle CAD, with a shared center block and handed outer blocks to reduce the number of unique machined parts (*Figure 16*). Inserts used in these blocks were of the fixed kind representing exactly what is on the car, shown in *Appendix 9.4.1.4*. Pads were added where the CAD required a nominal 0.5 mm gap so that the edge condition could be checked physically with a feeler gauge.

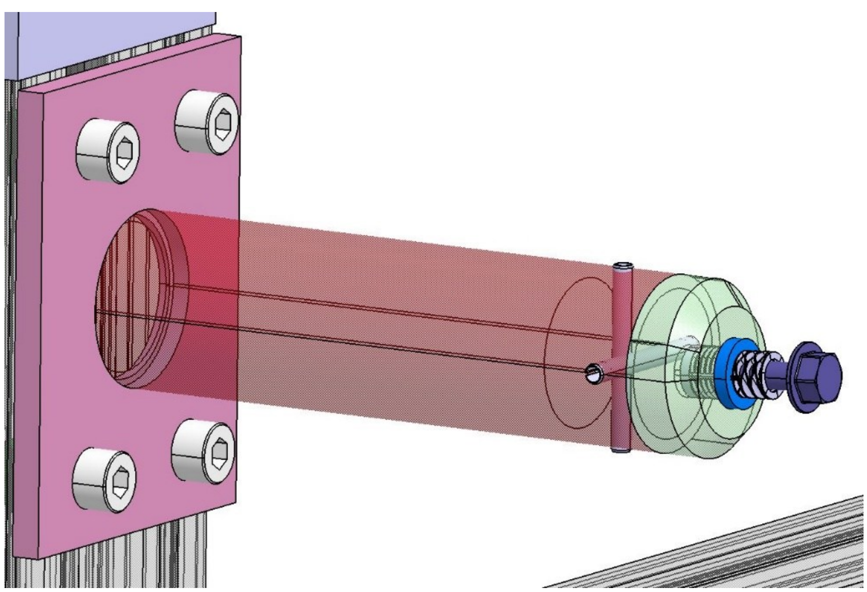

Figure 17: Detail view of simulated stay mounts

The stay interfaces required a different strategy because the associated contact regions were on untooled B-side composite surfaces, whose thickness variation would have reduced measurement consistency if used directly as locating references. Instead, the fixture used a controlled hardware solution based on a custom shoulder bolt, a threaded spacer or washer, and a wave spring so that the stay-related locations could be constrained without making the scan result dependent on unpredictable backside laminate thickness, while still allowing the float required to mimic the real mounting condition (*Figure 18*).

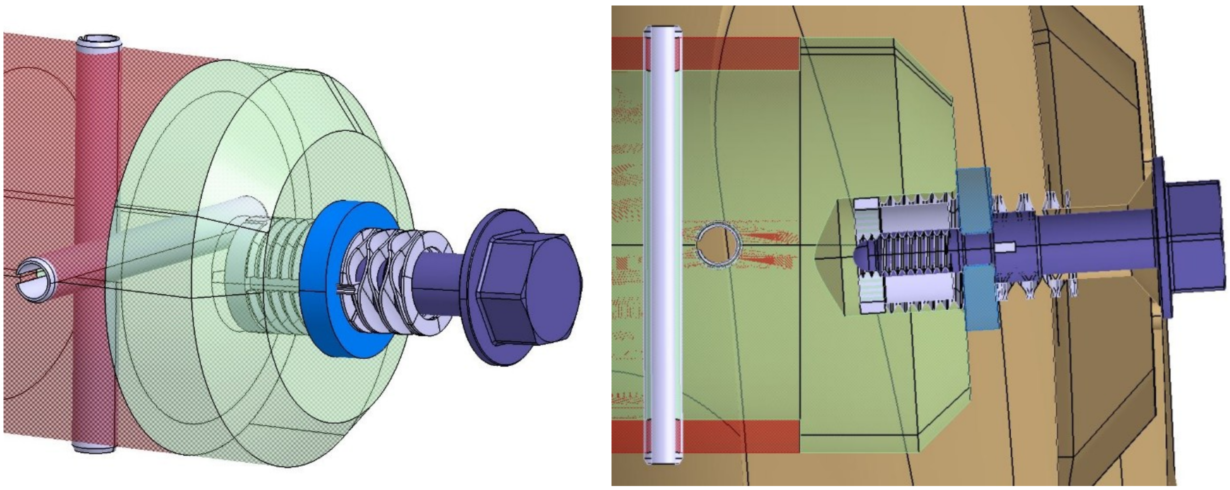

Figure 18: Detail view (left) and section cut (right) of shoulder bolt, wave spring, threaded washer, and floating Keensert assembly

3.6.2 Sidepod Air Inlet

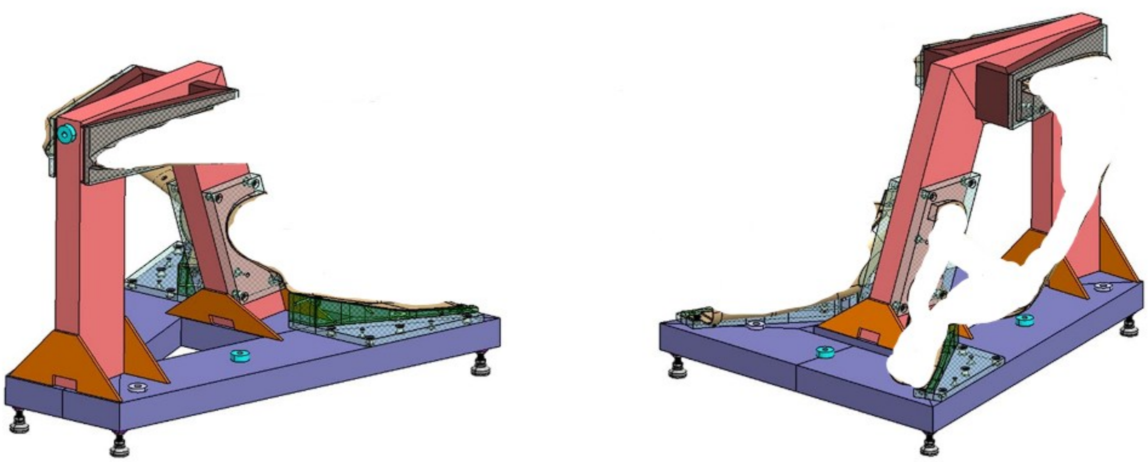

Figure 19: Sidepod Air Inlet scanning fixture

The sidepod air inlet fixture most clearly reflects the mature fixture design language established during the project. It combines an aluminum rectangular-tube frame with machined RAMPF WB 1256 interface blocks and uses symmetry to allow both the left-hand and right-hand components to be mounted at the same time (see figure 19). Three principal interface regions had to be reproduced: the balcony (*Figure 20*), the monocoque (*Figure 21*), and the underwing (*Figure 22*). The balcony and monocoque were each implemented as single machined tooling-board elements fixed to the frame with bolts and positioned repeatably with one-sided threaded studs. In the balcony region, 0.5 mm pads were incorporated to preserve the nominal CAD gap and to allow a quick go/no-go check of edge position during setup, as well as floating Keenserts to copy the floating nut plates used to mount it to the sidepod in the actual car. Like in other fixtures, the monocoque block implements the use of fixed inserts to mount the sidepod air inlet to it.

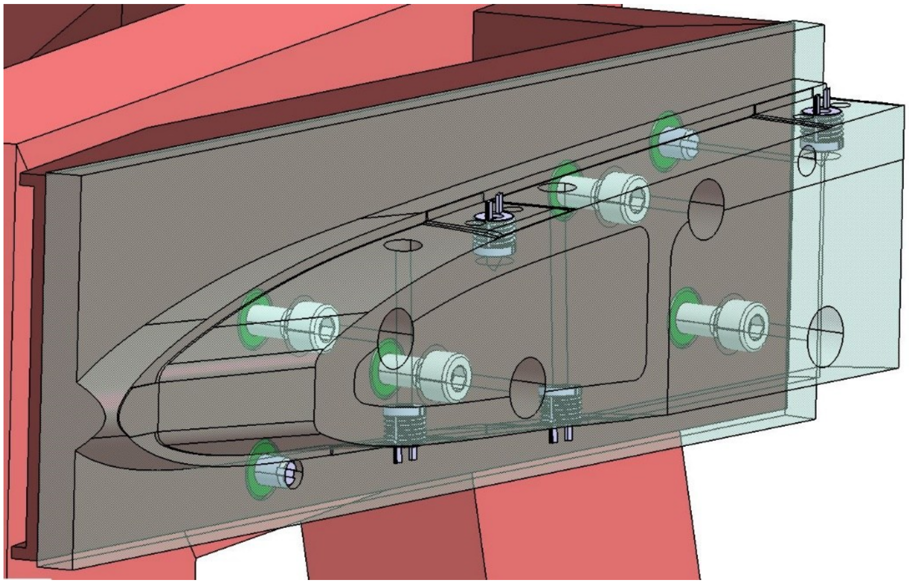

Figure 20: Detail view of machined dummy balcony block

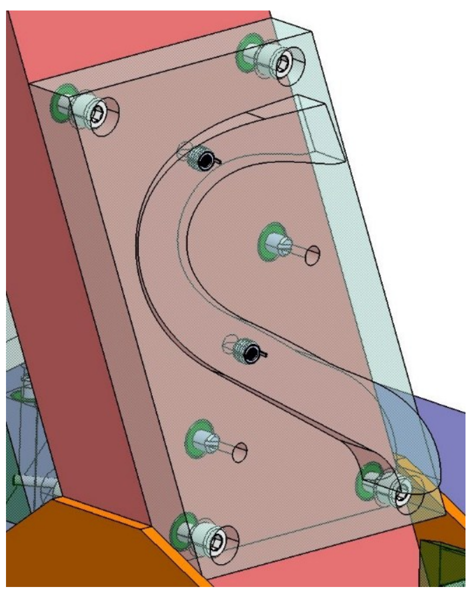

Figure 21: Detail view of machined dummy monocoque block

The underwing-side interface required additional refinement because the sidepod air inlet is relatively stiff and would have been difficult to install safely if the rebate geometry had been represented as one fully rigid block. For that reason, the dummy underwing was split into two pieces: a primary support block (blue) and a removable rebate element (green) as seen in *Figure 22*. The removable section could be taken out during installation and then repositioned with slotted spring pins once the part was seated. This reduced mounting difficulty and lowered the risk of damaging the composite edge while still preserving the local interface condition required for inspection. As a result, the fixture became a strong example of how modular removable contact features could improve both usability and repeatability without undermining the geometric intent of the fixture. Floating Keenserts were used to mimic the floating nut plates that are used to mount the panel to the underwing.

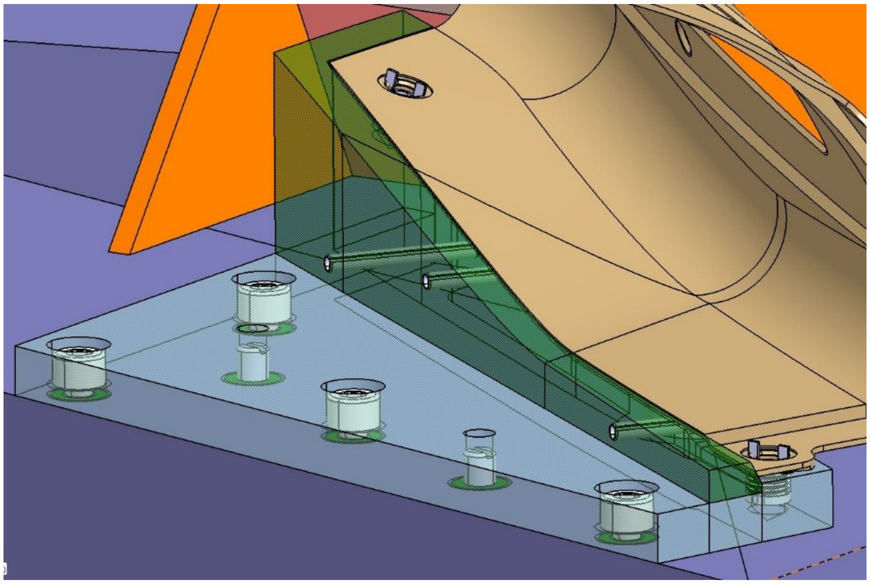

Figure 22: Detail view of machined dummy underwing block and secure mount

3.6.3 Damper Cover

The damper cover was the first fixture for which a monolithic machining strategy in RAMPF WB 1256 was judged both practical and advantageous. Because the part is relatively compact, it was possible to start from a single tooling-board block and machine into it all of the required fixture features, including the extracted mounting surfaces, datums, CNC-mounting features, stiffness ribs, and local weight-relief pockets. Compared with a frame-plus-block architecture, this substantially reduced the number of assembly interfaces within the fixture itself and therefore improved dimensional coherence between the various locating features.

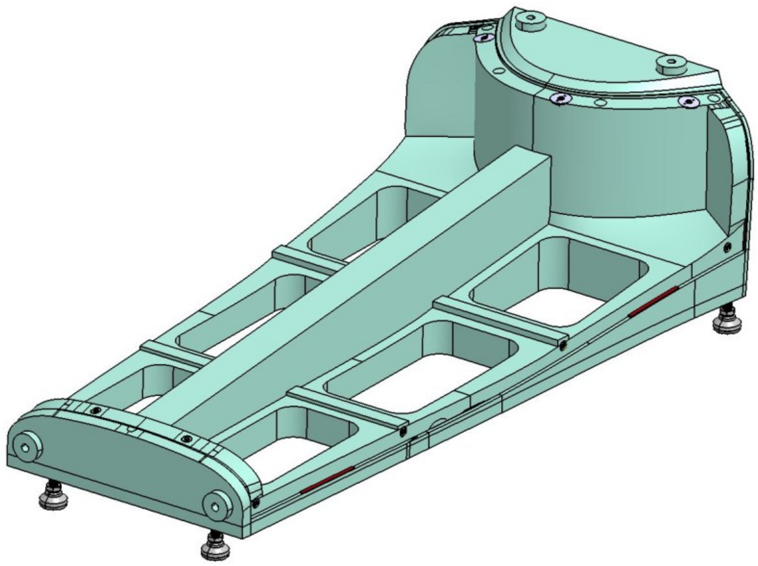

Figure 23: Damper Cover scanning fixture assembly

The fixture geometry was derived directly from the vehicle-side mounting references associated with the monocoque, balcony, front wing, and windscreen. This allowed the damper cover to be inspected under boundary conditions that reflected the adjacent vehicle geometry rather than simply a bolt-hole pattern. The fastening strategy also had to distinguish between non-floating and floating Tridair locations. The side and front mounting points use rigid Tridair-style interfaces, which were reproduced with fixed inserts, whereas the windscreen connections use floating Tridair interfaces and therefore required the dedicated floating insert solution described earlier, as seen in *Figure 24*. A transverse rib was incorporated to improve bending stiffness, the center of the block was relieved where possible to reduce mass, and pads were added in the side regions to preserve the nominal gap and reduce installation damage. Overall, the damper cover fixture demonstrated the benefit of a one-piece architecture where part size and cost made that solution feasible.

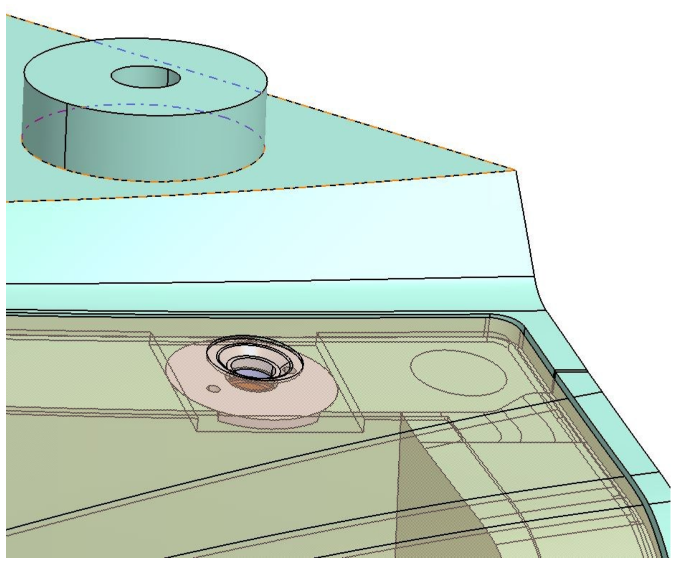

Figure 24: Detail view of Tridair insert and datum used

3.6.4 Lower Gearbox Cover

The lower gearbox cover followed a design logic similar to that of the damper cover in that its symmetry and moderate size made a monolithic tooling-board fixture both realistic and efficient. The principal locating geometry was extracted from the underwing interfaces, which govern how the panel is positioned in the assembled car, while additional features were included to reproduce the way the part mounts to the gearbox itself. Adopting a single machined-block strategy kept the number of internal stack-up contributors low and simplified manufacturing relative to a welded or assembled structure.

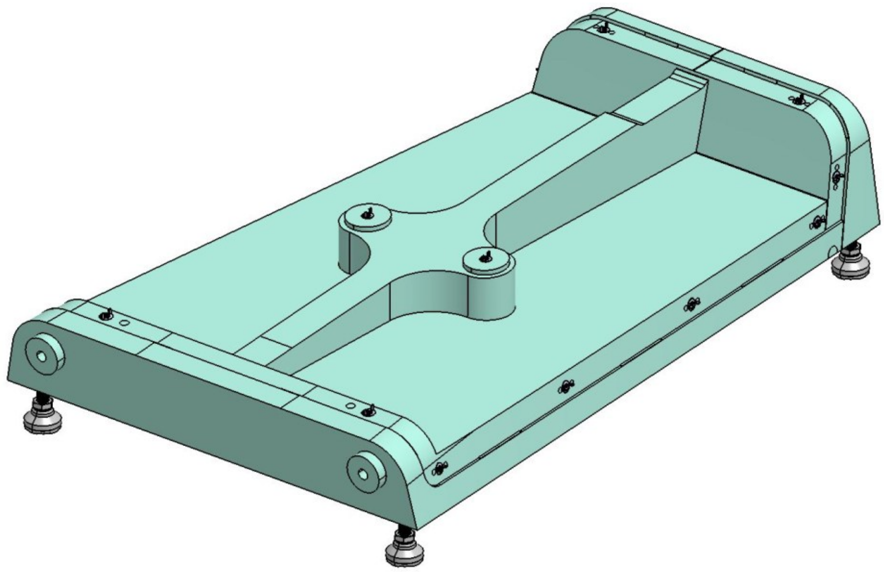

Figure 25: Lower Gearbox Cover scanning fixture assembly

The fastening details again reflected the real assembly condition. The underwing-side locations use floating nut plates on the vehicle, so the fixture employed floating Keensert solutions at those positions in order to preserve the required compliance during installation. Similarly, the gearbox-related interfaces also employ the use of a floating nut plate style mounting and were therefore reproduced with floating inserts. To improve structural performance, the fixture incorporated a stiffening rib that also housed the gearbox-side mounting features. This allowed stiffness and functional interface replication to be addressed simultaneously rather than as separate design problems.

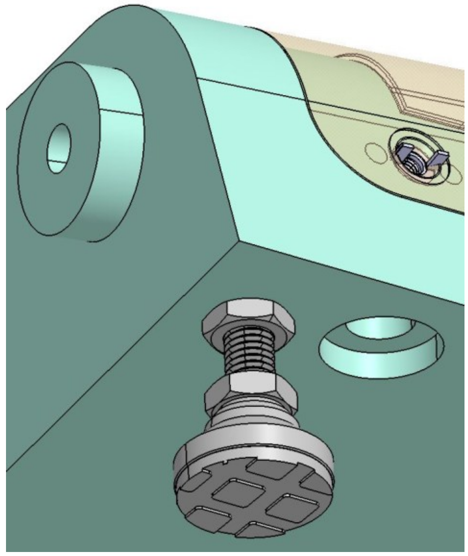

Figure 26: Detail view of datum, foot, TDM counterbore hole, and floating Keensert used

3.6.5 Tyre Wake Conditioner (TWC)

The tyre wake conditioner fixture was comparatively straightforward because the part mounts directly to the underwing and has a relatively simple overall mounting geometry. The design therefore focused on reproducing the local underwing interfaces accurately while keeping the fixture as light, inexpensive, and easy to machine as possible. A monolithic RAMPF WB 1256 block was selected because it offered sufficient stiffness for the component size while minimizing design and manufacturing complexity.

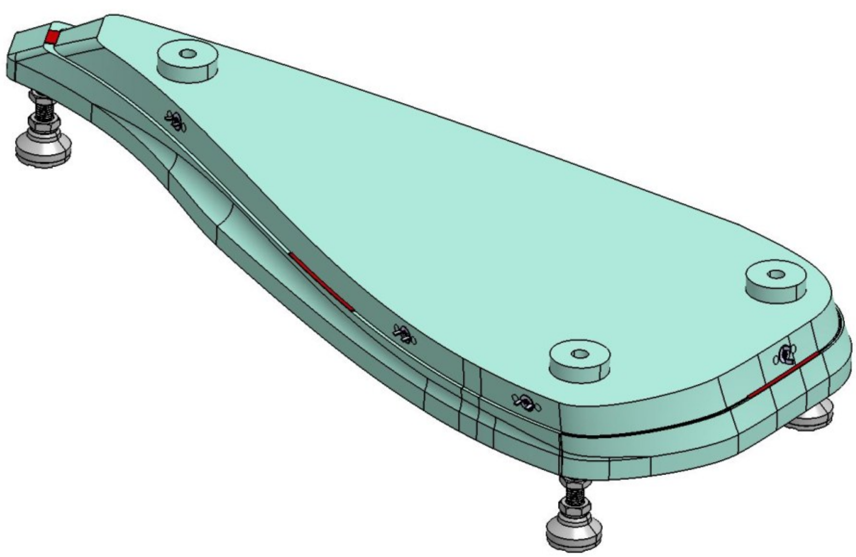

Figure 27: TWC scanning fixture assembly

All mounting points on the vehicle use floating nutplates, so the fixture adopted floating Keensert solutions at each corresponding location. Pads were added where required to preserve the nominal CAD gap and to make installation more forgiving, particularly around the mating edges (*Figure*

28). The Belotti machine-mounting counterbores were distributed with both the 100 x 100 mm grid and the local support needs of the tooling-board block in mind, ensuring that the fixture could be machined without introducing avoidable distortion, as seen on the bottom view of *Figure 29*. The resulting design aligned well with the original requirement for a simple, low-cost, repeatable inspection support.

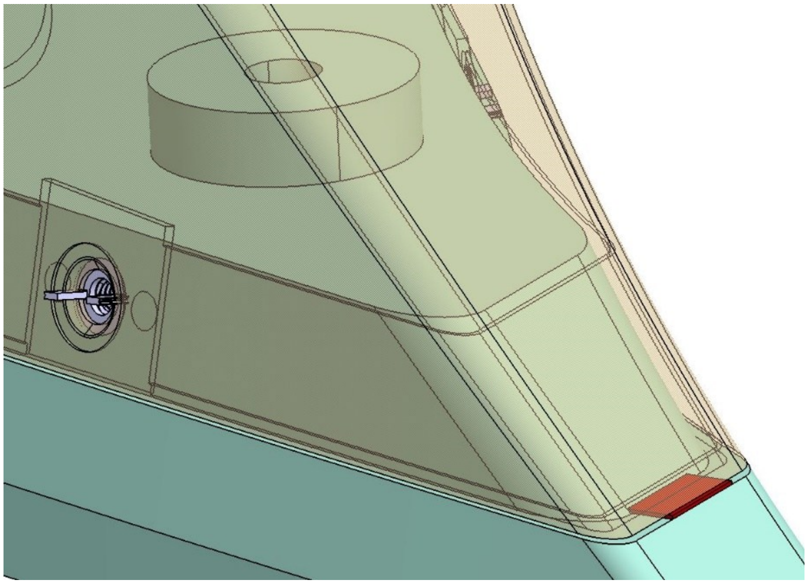

Figure 28: Detail view of pad, floating Keensert, and datum used

3.6.6 Tyre Ramp

The tyre ramp fixture followed the same overall methodology as the TWC fixture, since the part is also relatively small and its mounting logic is governed primarily by the underwing interface. For this reason, a monolithic RAMPF WB 1256 architecture was again preferred in order to minimize part count, reduce manufacturing effort, and keep the fixture lightweight and easy to handle. The surfaces used to define the locating condition were extracted directly from the relevant vehicle geometry so that the part would be supported in a representative CAD position during scanning. Since the underwing doesn't change between speedway and road course configurations, the mounting locations stay and allow both tyre ramps to be scanned on the same fixture.

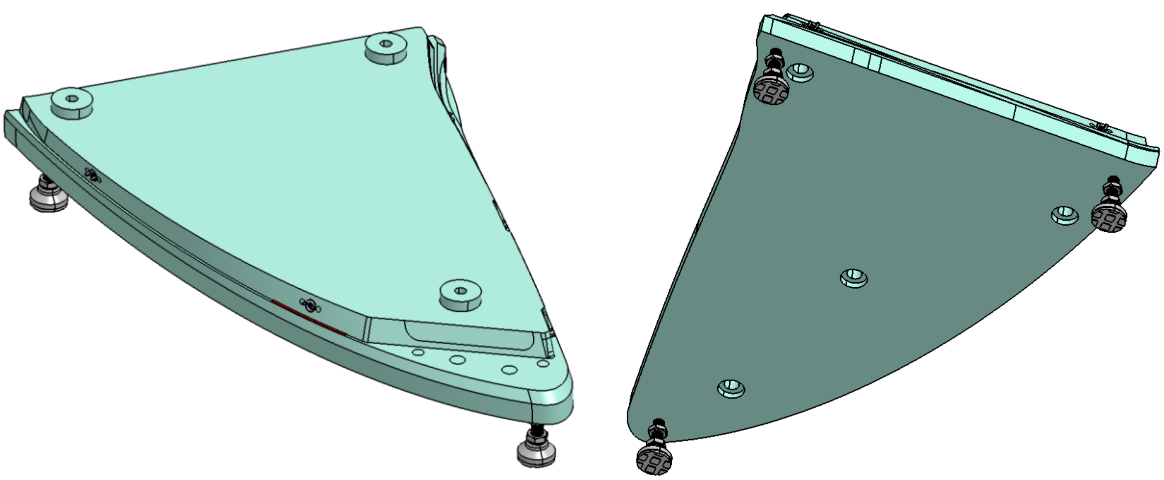

Figure 29: Tyre Ramp scanning fixture

As with the tyre wake conditioner, the fastening strategy respected the floating nature of the real mounting scheme, and pads were incorporated where needed to establish the correct stand-off and protect the composite edge during installation. Although the tyre ramp fixture was not among the most geometrically complex solutions in the project, it was valuable because it confirmed that the common fixture design language could also be applied efficiently to smaller components without unnecessary complication.

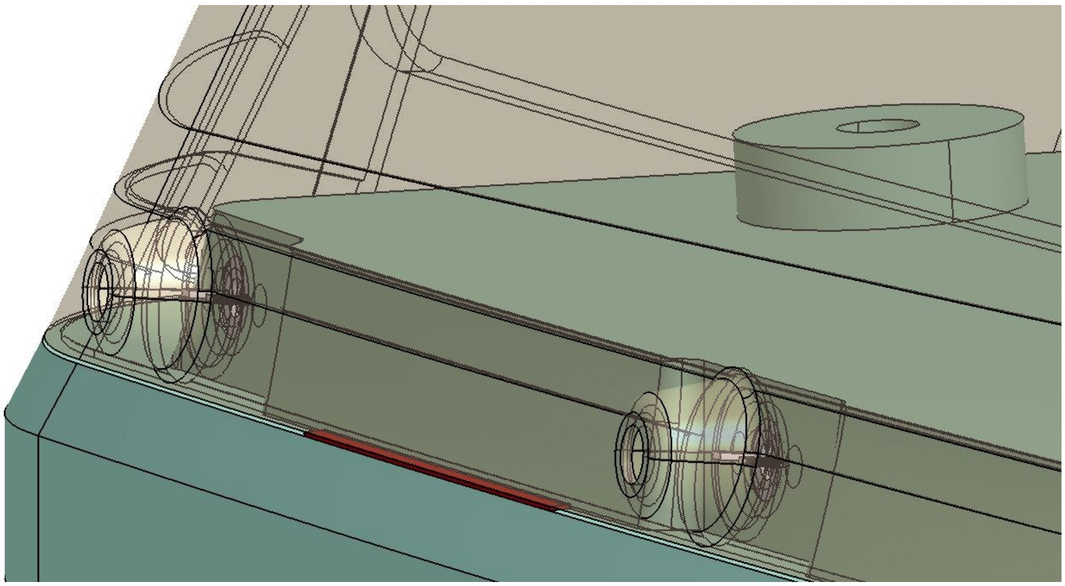

Figure 30: Detail view of pad, floating Keensert, and datum used

3.6.7 Front Wing

As in previous IndyCar generations, there are two front-wing families depending on the type of track: a speedway-specific assembly and a road-course-specific assembly. Speedway assemblies are designed primarily for low drag and maximum speed, whereas road-course assemblies place greater emphasis on downforce. As a result, the speedway assembly comprises five main components - a main plane, two flaps, and two endplates - while the road-course assembly comprises a main plane, twelve flaps, and two endplates. For dimensional validation, the individual airfoils were generally more important than the complete assembly, so the fixture was intended most often for scanning the main plane of both versions. Even so, two requirements remained: both the speedway and road-course complete assemblies had to fit on the fixture, and the fixture had to provide practical access for scanning both the top and bottom sides of the assemblies.

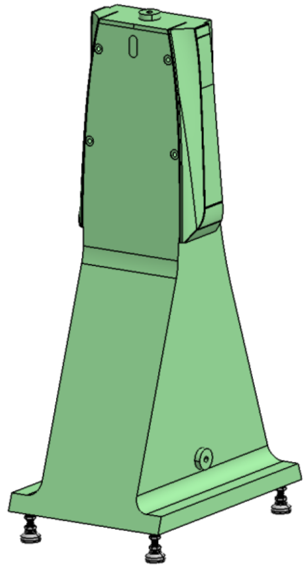

Figure 31: Front wing scanning fixture assembly

Both assemblies mount to the same nosecone interfaces, since the nosecone does not change between the two track configurations. The fasteners are also effectively the same: four rigid studs mounted on the main plane and screwed into the nosecone. Those conditions were represented on the fixture with four fixed Keenserts. The fixture was conceived as a monolithic RAMPF WB 1256 block incorporating the required datums, TDM counterbores, and foot-mounting features.

3.6.8 Roll Hoop Refueling Fairing

The roll hoop refueling panel introduced a different type of design problem because the way the part mounts to the car is not fully representative of the surface-to-surface transitions that ultimately need to be assessed around it. In the vehicle, the surrounding body panels use the refueling-panel region as part of their own attachment logic, meaning that the direct mounting condition of the panel alone is not sufficient to evaluate local rebate height and continuity with adjacent surfaces. As a result, simply reproducing the panel’s direct fastening points would have addressed part location but not the broader interface-quality objective that emerged later in the project.

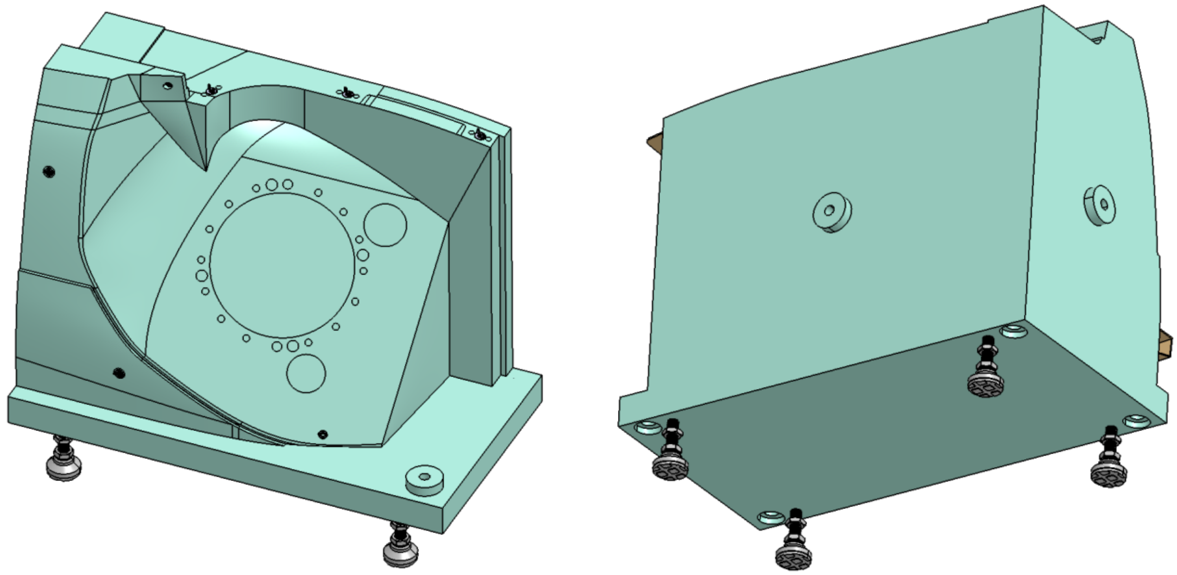

Figure 32: Roll Hoop Refueling Fairing Base Assembly

The final concept therefore combined a monolithic RAMPF WB 1256 base, which reproduced the primary mounting interfaces using representative inserts, with the proposal for an auxiliary carbon skin that would attach to the fixture in the same way as the neighbouring bodywork. This secondary element would not serve as the primary locating feature for the panel itself; instead, it would provide a practical means of evaluating local surface transition and rebate condition relative to the surrounding bodywork. Although this fixture concept remained less mature than some of the other designs, it clearly demonstrated how the methodology had evolved from pure mounting-point replication toward broader interface verification.

3.6.9 Louver Panel

The louver panel was also conceived as a monolithic RAMPF WB 1256 fixture, with the locating geometry extracted from the sidepod interfaces that define its installed condition. The real mounting points on the sidepod use floating nutplates, so the fixture adopted floating Keensert solutions in order to avoid over-constraining the part during installation. In its basic logic, this fixture therefore followed the same philosophy as the other smaller single-block designs.

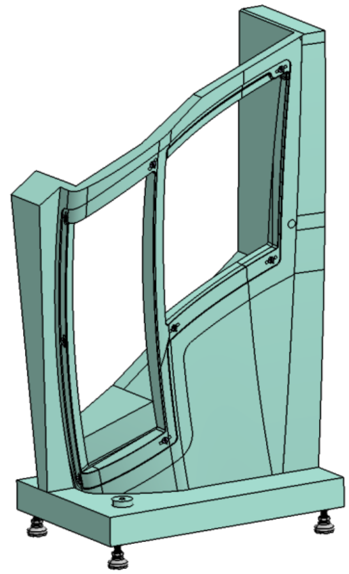

Figure 33: Louver Panel scanning fixture assembly

The main complication came from accessibility rather than from the mounting logic itself. In addition to scanning the upper visible surface, inspection access was also required to the lower region near the leading edges of the louver fins. That requirement reduced the amount of material that could be left in some areas of the fixture and therefore created concerns about local durability and damage tolerance. The final design direction attempted to balance these competing needs by preserving sufficient structural thickness and local support where possible while still leaving the critical scan-access regions open.

3.6.10 Engine Cover

The engine cover fixture was the earliest major development case in the project and effectively served as the methodological test bed from which the wider fixture philosophy emerged. It was selected at the beginning because its symmetry and relatively understandable mounting scheme made it a suitable component on which to establish first principles. In practice, however, the engine cover proved valuable not because it was simple, but because it forced the project to confront several of the core questions that later affected the rest of the fixture family: whether mounting-hole replication alone was sufficient, how much surrounding interface geometry should be represented, and how to balance usability against fidelity to the assembled-car condition.

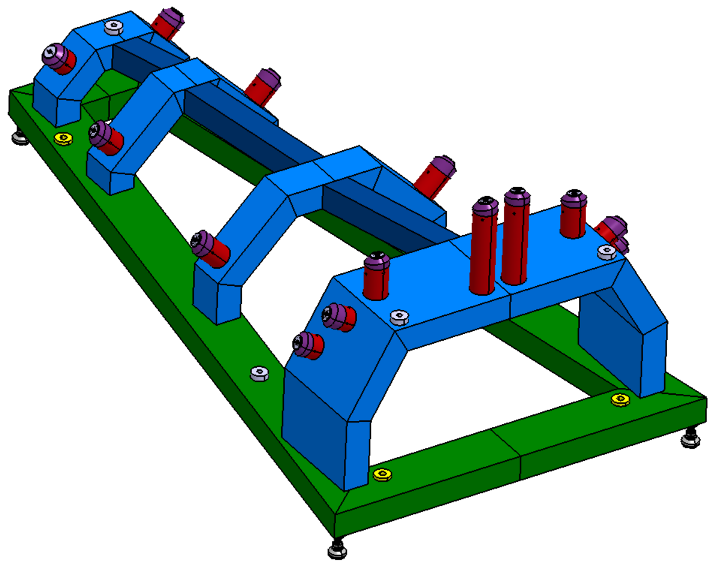

Figure 34: Engine Cover scanning fixture V1 assembly

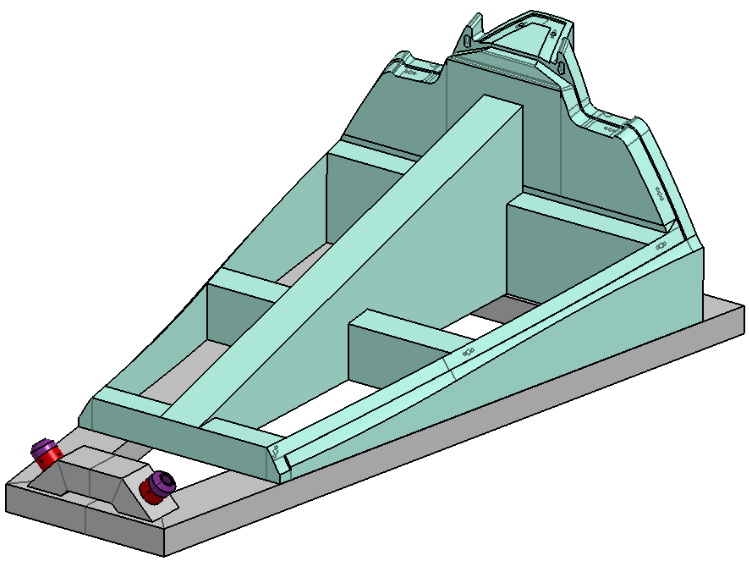

Figure 35: Engine Cover scanning fixture V2 assembly

Two principal design directions were explored during its development. The first focused primarily on reproducing the mounting-hole pattern with the use of Delrin pucks and the custom Tridair screw-in fitting that would be later be used in the damper cover and sidepod, as seen in *Figure 34* and *36*. On the other hand, the second expanded the fixture to include the surface-to-surface transitions between the engine cover and adjacent panels (*Figure 35*). The second approach aligned better with the revised project intent because it extended the fixture's value beyond scanning and allowed quick physical checks of fit and smoothness. Even though the engine-cover fixture was not the first design to converge fully, it established many of the ideas later adopted elsewhere in the project, including the importance of common datums, representative interface replication, and replaceable contact features.

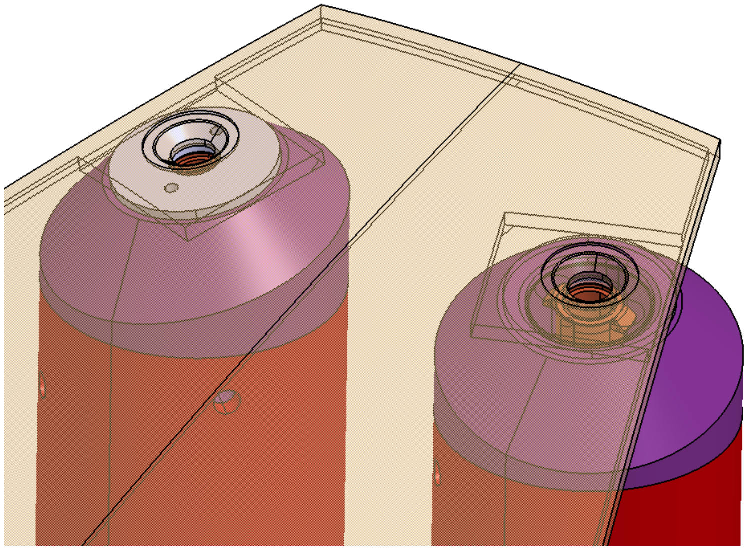

Figure 36: Detail view of Tridair insert

3.6.11 Sidepod

The sidepod fixture was the most difficult to resolve because the component combines a large, irregular external shape with multiple neighbouring interfaces that do not lend themselves to a simple monolithic support strategy. Unlike smaller or more symmetrical panels, the sidepod could not be supported efficiently with one continuous machined block without creating significant weight, accessibility, and manufacturing challenges. The design therefore evolved toward an aluminum rectangular-tube frame carrying multiple machined interface blocks that reproduced the surrounding body-panel conditions in a segmented and serviceable way.

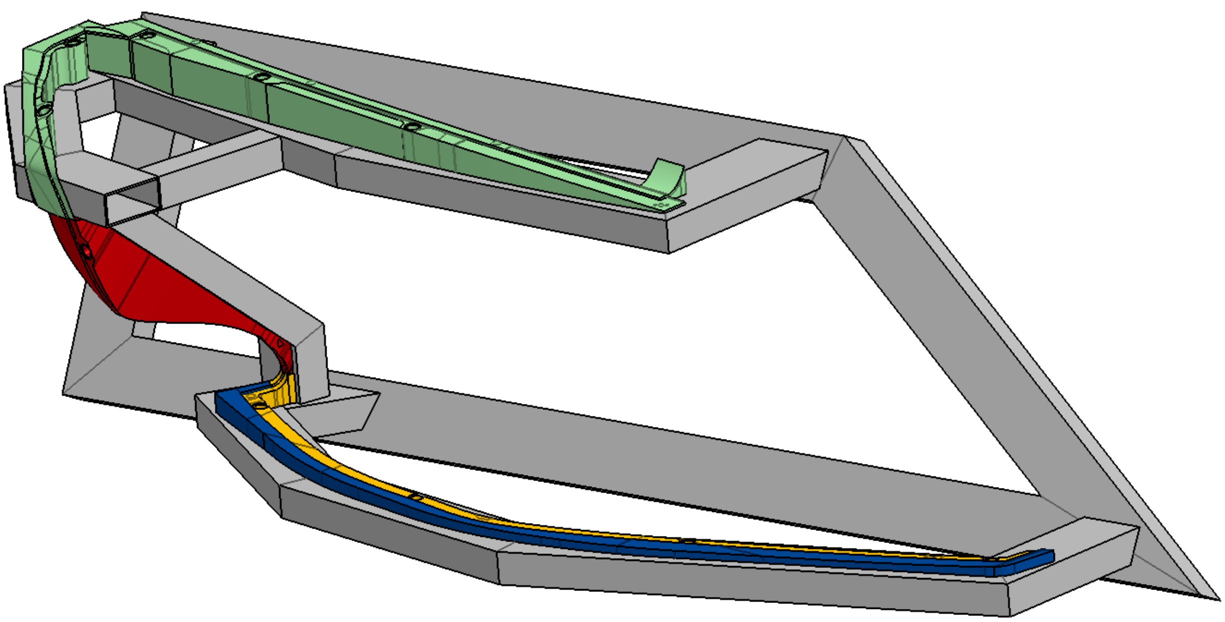

Figure 37: Sidepod assembly scanning fixture

The complexity of the sidepod meant that the key design challenge was not only determining where the part should be constrained, but also deciding how to divide the surrounding reference geometry into manufacturable blocks that could be mounted, adjusted if necessary, and eventually replaced without losing the overall fixture definition. The final design direction addressed this by using a structural frame to establish the global architecture and localized machined blocks to represent the interfaces that most directly influenced part position, seam condition, and scan repeatability. Although this fixture remained one of the most complex cases in the thesis, it showed that the project methodology could still be extended to the most geometrically demanding panels by separating global support from local interface replication.

3.7 Statistical Approach to Stack Up Tolerances

A statistical stack-up review was useful because the golden fixtures were intended to locate semi-flexible composite panels relative to CAD within a narrow tolerance band, while the fixture itself had to consume only a controlled share of that allowable variation. In this thesis, the statistical method was treated as a design-stage engineering tool: it does not replace disciplined structural design, scan-system validation, or physical try-out, but it does provide a rational estimate of whether the proposed fixture architecture is likely to be dimensionally credible before manufacture [10,11].

3.7.1 Why a statistical method was appropriate

For this application, a purely worst-case stack-up would assume that every contributor reaches its most unfavorable limit at the same time. That approach remains useful for checking hard interferences or absolute assembly limits, but it becomes unrealistically severe when applied to an inspection fixture made from several independent manufacturing operations that are each expected to be centered near nominal.

A root-sum-square (RSS) approach is more appropriate when the contributors can reasonably be treated as independent and approximately normal about the target value. Under those assumptions, RSS estimates the probable spread of the response rather than the absolute maximum possible spread. That was the right question at this stage of the project, because the design objective was to confirm that fixture-induced variation would remain comfortably smaller than the panel tolerance being inspected [10,11].

3.7.2 Root-sum-square method

For a one-dimensional response Y written as a linear combination of contributing dimensions,

$$Y = c_1 x_1 + c_2 x_2 + \cdots + c_n x_n$$

Equation 1: Linear response Y

the response mean is

$$\mu_Y = c_1 \mu_1 + c_2 \mu_2 + \cdots + c_n \mu_n$$

Equation 2: Linear response Y influenced by "n" independent contributors

and, if the contributors are independent, the response variance is

$$\sigma_Y^2 = (c_1\sigma_1)^2 + (c_2\sigma_2)^2 + \cdots + (c_n\sigma_n)^2$$

Equation 3: Variance of the response

If each bilateral tolerance T_i is interpreted as a $\pm 3\sigma$ manufacturing spread, then $\sigma_i = \frac{T_i}{3}$ and the resulting $\pm 3\sigma$ assembly tolerance becomes

$$T_{RSS} = \pm\sqrt{(c_1T_1)^2 + (c_2T_2)^2 + \cdots + (c_nT_n)^2}$$

Equation 4: Resulting assembly tolerance in Root Sum Square (RSS) form

For a direct stack in which each contributor acts one-to-one in the same measurement direction, that is $c_i = 1$, the expression reduces to

$$T_{RSS} = \pm\sqrt{T_1^2 + T_2^2 + \cdots + T_n^2}$$

Equation 5: 1D stack simplification

In practice, the equation must be written for a clearly defined response characteristic, such as the position of a simulated mounting hole relative to the fixture datums, the height of a locating surface in the panel-normal direction, or the offset that controls local gap and flush. If a contributor acts through an angle, lever arm, or clearance effect, its sensitivity coefficient c_i must be applied before it is combined in the RSS calculation.

3.7.3 Information and datum logic required to calculate the stack-up

A meaningful statistical stack-up cannot be performed from tolerance values alone; the first requirement is a clearly defined response to be protected. In this thesis, the response is not chosen in the abstract. It is defined from the inspection objective established earlier in the methodology, such as the position of a critical mounting interface, the normal-direction offset of a control surface, or a local gap/flush condition that the fixture is intended to stabilize.

The second requirement is a complete datum-based chain between that response and the references used to create and use the fixture. For these fixtures that means explicitly identifying the part DRF, the fixture DRF, and the machine DRF that was used to generate the functional surfaces. Only once those frames are related can the designer decide which contributors belong in the chain: datum machining, locating-surface machining, insert or bore position, removable-block relocation, and part-seating repeatability during installation.

Because measured process-capability data were not available for every contributor during the thesis period, the calculations below remain design-stage illustrations based on explicit assumptions. The total permitted panel deviation was taken as +/-0.30 mm, and 40 percent of that window was conservatively allocated to fixture-induced variation. This created an allowable fixture budget of:

$$T_{fixture,\ allow} = 0.40 \cdot 0.30 = \pm 0.12\ mm$$

Equation 6: Allowable fixture budget

Any fixture concept whose calculated RSS contribution exceeded +/-0.12 mm would therefore be treated as too sensitive and would require simplification, tighter process control, or relocation of additional features into a shared finishing setup. The value of the calculation was not only numerical; it also forced the datum chain and the design intent to be stated unambiguously before release.

Table 1: Assumed +/-3 sigma contributor values used for the illustrative RSS calculations

Contributor	Monolithic fixture (+/- mm)	Frame + machined mounts (+/- mm)
Datum feature machining	0.03	0.03
Primary locating or mount-surface machining	0.05	0.05
Insert or bore position	0.04	0.04
Secondary interface repeatability	0.03	0.05
Seating / fastener repeatability	0.03	0.04

3.7.4 DRF-based application to the case-study fixtures

The most useful application of the method in this project was to compare the two dominant fixture architectures through representative case studies tied to explicit datum logic. Rather than claiming one universal stack-up for all panels, the analysis was anchored to one monolithic-style fixture and one frame-based fixture so that the effect of additional interfaces could be understood in a realistic way.

For the damper cover, which represents the monolithic RAMPF WB 1256 methodology, the part DRF was taken from the common vehicle coordinate system and the fixture DRF was machined directly into the parent block through the standardized datum features. The response characteristic selected for the illustrative calculation was the positional error of a critical rigid mounting interface relative to those fixture datums. Because datums, locating surfaces, and most functional geometry were generated from one parent body with very few assembled interfaces, the dominant contributors remained limited to datum machining, local locating-surface machining, insert-bore position, insert seating/concentricity, and part-seating repeatability at the controlled interface.

$$T_{monolithic} = \pm\sqrt{0.03^2 + 0.05^2 + 0.04^2 + 0.03^2 + 0.03^2} = \pm 0.079\,mm$$

Equation 7: Tolerance stack for monolithic style fixture

Using the assumed contributor values listed in Table 1, the monolithic case produced an RSS value of +/-0.078 mm. That remained below the allocated fixture budget of +/-0.12 mm and was consistent with the central methodological advantage of the monolithic architecture: reducing the number of internal interfaces that can redistribute error before the part is even installed on the fixture.

For the sidepod air inlet, which represents the aluminum-frame plus machined-interface methodology, the datum chain was more distributed. The part DRF still followed the vehicle coordinate system, but the inspection condition was created by multiple machined interface regions that reproduced the balcony, monocoque, and underwing relationships. The response characteristic for the illustrative calculation was taken as the positional stability of a critical underwing-side locating region relative to the fixture datums, because that interface directly affects both seating and local inspection relevance. In this case the machine DRF on the Belotti was especially important because the structural frame itself was not assumed to be perfect after fabrication. Instead, the methodology assumes that the recovered post-fabrication frame is used as the reference state from which the critical datums and machined mount surfaces are finished. Under that assumption, weld distortion is not inserted directly as an independent inspection contributor; the remaining dominant terms are datum machining, machined mount-surface position, insert or bore position, removable-block relocation, and seating/fastener repeatability.

$$T_{frame} = \pm\sqrt{0.03^2 + 0.05^2 + 0.04^2 + 0.05^2 + 0.04^2} = \pm 0.096\, mm$$

Equation 8: Tolerance stack for aluminum frame-machined mounts style fixture

With the assumed values used in Table 1, the frame-based case produced an RSS value of +/-0.089 mm. This also remained below the +/-0.12 mm fixture budget, although with less margin than the monolithic case, which is exactly what would be expected from an architecture with more functional interfaces and more opportunities for relocation error.

A useful cross-check is to combine the fixture contribution with a conservative scan-system contribution tracked separately from the fixture itself. If a scan-and-alignment contribution of +/-0.05 mm is assumed, the resulting inspection-support variation for the frame-based case becomes:

$$T_{support} = \pm\sqrt{0.096^2 + 0.05^2} = \pm 0.108\, mm$$

Equation 9: Combination of a fixture and a conservative scan-system contribution

This gives a combined RSS value of approximately +/-0.102 mm. That result remains comfortably below the overall +/-0.30 mm inspection target and leaves margin for panel-related contributors. More importantly, it confirms the methodological point made earlier in the thesis: once the DRF chain is defined correctly, reducing contributors is often more powerful than trying to tighten every individual tolerance in isolation.

3.7.5 Extension to 3D statistical simulation

Hand calculations based on RSS are efficient during concept and embodiment design, especially when the dominant behavior can be approximated as a linear stack in one measurement direction. The complete fixture problem, however, is inherently three-dimensional and can include float, angular misalignment, clearance, compliant seating, and interacting datum conditions that are not represented perfectly by a simple hand calculation.

For that reason, a software environment such as 3DCS integrated with CATIA V5 would be the logical next step once the design-stage assumptions are replaced with real process data. In that environment, the required inputs would be the CAD assembly, the datum and constraint scheme, the tolerances assigned to each manufacturing feature and joint, the assumed statistical distributions, and the output measures to be tracked, such as hole position, gap, flushness, or surface offset at critical points. A Monte Carlo study would then allow the fixture and panel to be evaluated as a true 3D variation problem rather than as a simplified scalar chain.

4 Conclusion and Discussion

4.1 Performance Evaluation

The original objective of the project was to design, release, and manufacture the golden fixtures required to support dimensional validation of the 2028 IndyCar bodywork package. Within the thesis timeframe, the work progressed through requirements definition, concept development, CAD design, interface standardization, material selection, drawing release, and design-stage tolerance review. Full manufacturing and physical validation were not completed before the end of the internship period, but the methodology can still be evaluated against the current inspection baseline because the project changed what can be checked, how repeatably it can be checked, and how traceably those checks can be industrialized.

The main gains relative to the current approach are summarized below before the maturity of the individual fixtures is reviewed in Table 2.

Table 2: Current approach to QC

Aspect	Current approach	Proposed methodology	Gain
Inspection coverage	Many body panels are not routinely scanned; some are scanned only if specifically requested.	Dedicated panel-specific fixtures create a defined setup for scan-to-CAD inspection across the bodywork family.	Expands controlled inspection coverage.
Setup condition	Free-state, temporary, or partially mounted setups can be operator-dependent and sensitive to part flexibility.	Fixtures reproduce mounting interfaces and stabilize the part under repeatable boundary conditions.	Reduces setup variability and operator dependence.
Interfaces checked	Checks often focus on local dimensions, visual quality, or isolated features.	Selected fixtures also support gap/flush and edge-condition checks in addition to scanning.	Broader assessment of fit and functional geometry.
Traceability and reuse	Inspection intent is part-specific but not supported by a unified fixture-development method.	Part numbers, staged BOM logic, common datums, and released drawings turn the fixture into a reusable industrial tool.	Improves traceability, refurbishment, and long-term consistency.

Table 2 summarizes the maturity of the documented fixtures and distinguishes between released designs, concept-level definitions, and fixtures not yet physically validated. In every case, the verification completed within the thesis remained limited to CAD fit and interference review together with preliminary analytical tolerance assessment; no dedicated physical validation campaign was completed within the thesis scope.

Table 3: Summary of fixture maturity, verification activities, and validation status

Fixture	Architecture / definition status	Interfaces replicated	Inspection role	Verification activities completed	Physical validation status
Underwing	Aluminum frame + RAMPF WB 1256 machined blocks + Delrin machined pucks; CAD and drawings complete	Keel and monocoque; Delrin pucks represent the stay mounting locations	Scanning fixture	CAD fit check, interference review, and preliminary RSS tolerance stack-up; analytical calculations remain within the allocated fixture budget	Not yet physically validated

Fixture	Architecture / definition status	Interfaces replicated	Inspection role	Verification activities completed	Physical validation status
Sidepod Air Inlet	Aluminum frame + RAMPF WB 1256 machined blocks; CAD complete	Balcony, monocoque, and underwing	Scanning fixture and local go/no-go gauge	CAD fit check, interference review, and preliminary RSS tolerance stack-up; analytical calculations remain within the allocated fixture budget	Not yet physically validated
Damper Cover	Monolithic machined RAMPF WB 1256 block; CAD and drawings complete	Nosecone, monocoque, balcony, and windscreen	Scanning fixture and local go/no-go gauge	CAD fit check, interference review, and preliminary RSS tolerance stack-up; analytical calculations remain within the allocated fixture budget	Not yet physically validated
Lower Gearbox Cover	Monolithic machined RAMPF WB 1256 block; CAD and drawings complete	Underwing and gearbox-side interfaces	Scanning fixture and local go/no-go gauge	CAD fit check, interference review, and preliminary RSS tolerance stack-up; analytical calculations remain within the allocated fixture budget	Not yet physically validated
Tyre Wake Conditioner	Monolithic machined RAMPF WB 1256 block; CAD and drawings complete	Underwing	Scanning fixture and local go/no-go gauge	CAD fit check, interference review, and preliminary RSS tolerance stack-up; analytical calculations remain within the allocated fixture budget	Not yet physically validated
Tyre Ramp	Monolithic machined RAMPF WB 1256 block; CAD and drawings complete	Underwing	Scanning fixture and local go/no-go gauge	CAD fit check, interference review, and preliminary RSS tolerance stack-up; analytical calculations remain within the allocated fixture budget	Not yet physically validated
Front Wing	Monolithic machined RAMPF WB 1256 block; CAD and drawings complete	Nosecone	Scanning fixture	CAD fit check, interference review, and preliminary RSS tolerance stack-up; analytical calculations remain within the allocated fixture budget	Not yet physically validated
Roll Hoop Refueling Fairing	Monolithic machined RAMPF WB 1256 block plus carbon-skin concept; CAD and drawings complete	Monocoque plus proposed surrounding panel references for engine cover, sidepod, and windscreen	Scanning fixture and local go/no-go gauge	CAD fit check, interference review, and preliminary RSS tolerance stack-up; analytical calculations remain within the allocated fixture budget	Not yet physically validated
Louver Panel	Monolithic machined RAMPF WB 1256 block; CAD and drawings complete	Sidepod	Scanning fixture	CAD fit check, interference review, and preliminary RSS tolerance stack-up; analytical calculations remain within the allocated fixture budget	Not yet physically validated
Engine Cover	Aluminum frame concept explored with either RAMPF WB 1256 interface blocks or Delrin pucks; CAD complete	Either surrounding interface surfaces (RAMPF option) or mounting locations only (Delrin-puck option)	Scanning fixture	CAD fit check, interference review, and preliminary RSS tolerance stack-up	Not yet physically validated
Sidepod	Aluminum frame + RAMPF WB 1256 machined blocks; not completed due to design difficulty and internal alignment constraints	Underwing, sidepod air inlet, and balcony	Scanning fixture	CAD fit check and interference review only; formal stack-up not completed	Not yet physically validated

Based on the available design evidence, the most important technical outcome was not simply the existence of individual fixture CAD models, but the establishment of a repeatable and defensible inspection-tooling method. Compared with the previous situation in which several body panels were not routinely scanned, or were inspected only through local dimensional checks, the proposed methodology enables controlled scanning under representative boundary conditions and creates a clearer separation between part variation and setup variation.

At the end of the thesis work, the CAD models and release drawings shown in the appendix were substantially complete for the documented fixtures, and the remaining effort was concentrated primarily in fabrication, fixture validation, and correlation between the manufactured fixtures and the digital design intent. In that sense, the project reached methodological maturity before it reached full industrial validation.

4.2 Key Findings

One of the strongest findings from the project was that inspection tooling for regulated motorsport bodywork is not merely a measurement accessory; it is a critical engineering product in its own right. The fixture defines the boundary conditions under which the part is judged and therefore determines whether scan-to-CAD inspection reflects true part geometry or simply variation in support condition, seating, and alignment. This is why the methodology had to begin with the actual QC problem and the actual part number being sold and inspected, rather than with a purely geometric exercise.

The project also confirmed that no single fixture architecture was optimal across the whole bodywork set. The real methodological innovation of the work was the development of a dual design language in which large or geometrically difficult panels could be supported by lightweight aluminum frames with machined locating features, while smaller or more compact panels could be inspected on monolithic RAMPF WB 1256 fixtures. That selection rule is more valuable than any one fixture because it can be reused as the program evolves.

A second key finding was that datum logic cannot be treated as an afterthought. The thesis showed that the relationship between part DRF, fixture DRF, and machine DRF is what makes the stack-up definition understandable. Once that chain is made explicit, it becomes much easier to justify which features must be machined together, which interfaces may remain removable, and why some architectures naturally offer more margin than others.

Finally, the tolerance stack-up study proved useful not because it delivered a final certified tolerance, but because it forced the methodology to declare a response characteristic, a datum chain, and an allowable fixture budget before release. In that sense, the statistical approach supported design decision-making as much as numerical prediction.

4.3 Recommendations for Future Work

The highest-priority next step is the manufacture and physical validation of the released fixture designs. Once built, each fixture should be inspected against its own CAD definition, mounted repeatedly to evaluate setup repeatability, and used in trial scans to confirm that the datum strategy and support condition produce stable and meaningful scan-to-CAD results. Long-term performance should also be monitored through periodic checks of wear-prone features, replaceable interface blocks, and the stability of the primary reference datums.

A second recommendation is to replace assumed tolerance inputs with measured process data as soon as manufacturing begins. Machining capability, weld distortion, insert installation variation, and scan repeatability should be quantified and fed back into the statistical model. This would convert the current stack-up analysis from a design-stage estimate into a validated predictive tool. Where the fixture behaviour proves too complex for a simple linear stack, a CATIA-integrated

Monte Carlo analysis in 3DCS would provide a more realistic picture of three-dimensional variation and assembly sensitivity.

Finally, the design language developed in this thesis should be applied consistently to the remaining body panels that were not completed within the thesis timeframe. Common datum logic, common serviceability strategy, and common methods for reproducing floating or replaceable interfaces will make the full fixture family easier to manufacture, use, validate, and maintain. As the 2028 bodywork package moves further into production, that consistency will become increasingly important for traceable and repeatable quality control.

5 List of Figures

6 List of Tables

7 List of Formulas

8 References

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[15] McMaster-Carr. Threaded Inserts and related fastening hardware catalog entries consulted during fixture-interface definition.

9 Appendix

9.1 Technical Specifications for Scanners

Key published specifications for the FARO Quantum S and the Creaform MetraSCAN BLACK+|Elite, summarized from official manufacturer documentation, are listed below [4-6].

Environmental

- Operating temperature range: **10 °C to 40 °C**.

Laser Line Probe (ScanArm)

- Laser line width: **150 mm**.
- Frame rate: up to **300 fps**.
- Scan rate: **600,000 points/s** (300 fps × 2,000 points/line).
- Stand-off / depth of field: **115 mm / 115 mm**.
- Laser line probe accuracy: **±25 µm** (with repeatability 25 µm, 2σ).

Contact measurement (Arm), ISO 10360-12 (selected examples)

- Available measurement ranges listed: **1.5 m, 2.5 m, 3.5 m, 4.0 m**.
- Example EUNI (distance error) values (mm):
    - 2.5 m arm: **0.028 (6-axis)** / **0.030 (7-axis)**
    - 3.5 m arm: **0.056 (6-axis)** / **0.070 (7-axis)**
    - 4.0 m arm: **0.068 (6-axis)** / **0.085 (7-axis)**

Non-contact measurement (ScanArm), ISO 10360-8 Annex D (LDIA, selected examples)

- 2.5 m: **0.048 mm**; 3.5 m: **0.080 mm**; 4.0 m: **0.092 mm**.

Key published specifications for MetraSCAN BLACK+|Elite include:

Surface measurement performance

- Accuracy: **0.025 mm**.
- Volumetric accuracy: **0.064 mm (9.1 m³)** and **0.078 mm (16.6 m³)**.
- Automatic Volume Extension accuracy: **0.025 mm + 0.015 mm/m**.
- Measurement rate: **1,800,000 measurements/s**.
- Light source: **30 blue laser lines (+ 1 extra line)**.
- Scanning area: **310 × 350 mm**.
- Stand-off distance / depth of field: **300 mm / 250 mm**.
- Recommended part size range: **0.2–6 m**.

- Setup Assistance tools: **included (Elite)**.

Feature probing capability (HandyPROBE integration)

- Probing accuracy with HandyPROBE Next+: **0.025 mm** (listed alongside MetraSCAN Elite).
- HandyPROBE acceptance test basis: **ISO 10360-12** (and ISO 17025 accredited).

9.2 Belotti technical specifications

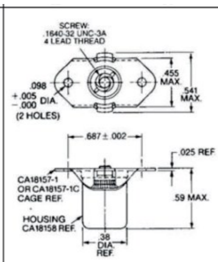
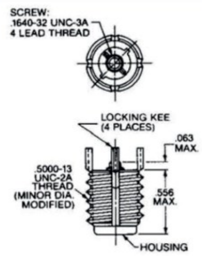
The Belotti data shown in this appendix were taken from the manufacturer's FLU-series documentation [12].

	MAIN TECHNICAL FEATURES		
Structure	Motorized suspended bridge structure sliding on the two extremities		
Axis movement	Brushless motors, movement managed by rack & pinion system, guides with re-circulating runner blocks Gear box ratio 1:10		
Axis stroke and speed	NAME	STROKE	SPEED
	X	8,53 ft	262 ft/min
	Y	5,57 ft	262 ft/min
	Z	4,26 ft	196 ft/min
	C	+/-270°	44 rpm
	A	+/-120°	40 rpm
Working table	Aluminum vacuum table with T slots		
CNC	SIEMENS ONE		
Lubrication	Automatic by grease		
Power supply	3 x 400 V / 50 Hz (+/- 5%) TN-S NETWORK		
Compressed air pressure	6 bar		

	TECHNICAL FEATURES OF PERFORMANCE MACHINING HEAD		
	4° ROTARY AXIS AROUND Z (C AXIS)	5° TILTING AXIS AROUND X (A AXIS)	ELECTROSPINDLE
Max rotation speed	44 rpm	40 rpm	
Max acceleration	2° /sec2		
Nominal and max torque	343 Nm/857 Nm		
Pneumatic clamping torque with 6-bar booster	840Nm	420Nm	
Angle measuring system	ERN180 Heidenhain scale	ERN180 Heidenhain scale	
Positioning accuracy	24 arcsec		
Repeatibility	12 arcsec		
Weight	80 kg		36Kg
Electrospindle			HSK F63
Clamping force			11 kN
Clamping/unclamping control			Inductive sensor
Nominal current			33 A
Nominal power			15 kw
S1 torque			12 Nm
S6 - 40% torque			14.4 Nm
Nominal speed			12.000 rpm
Maximum speed			24.000 rpm

9.3 Technical specifications for various inserts

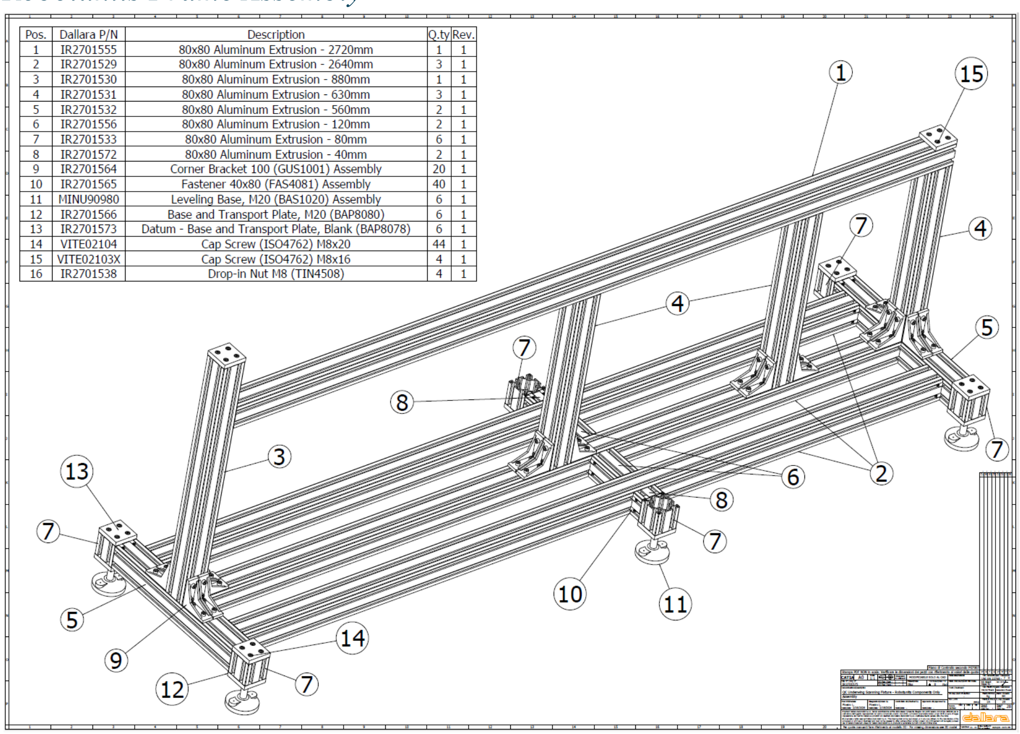
Representative insert and fastening-product information summarized in this appendix was taken from commercial catalog data for key-locking and floating insert systems [13-15].

2-Lug Lightweight Replaceable .025 Radial Float 	 Weight: .011 lbs./ea. approx.	Housing: Aluminium Alloy per QQ-A-225 Screw: Alloy Steel Cage: 17-7PH CRES Heat Treat: Screw: Per MIL-H-6875 Cage: Per MIL-H-6875 Finish: Housing: Blue anodised per MIL-A-8625 Screw: Cadmium plated per QQ-P-416 Type II, Class 2 Cage: Passivated per QQ-P-35	**CA18157**
LiveSert 	 Weight: .018 lbs./ea. approx.	Housing: 300 Series CRES Screw: A286 CRES Heat Treat: Screw: Per MIL-H-6875 Finish: Housing: Passivated per QQ-P-35 Screw: Dry Film Lubed	**CA18062**

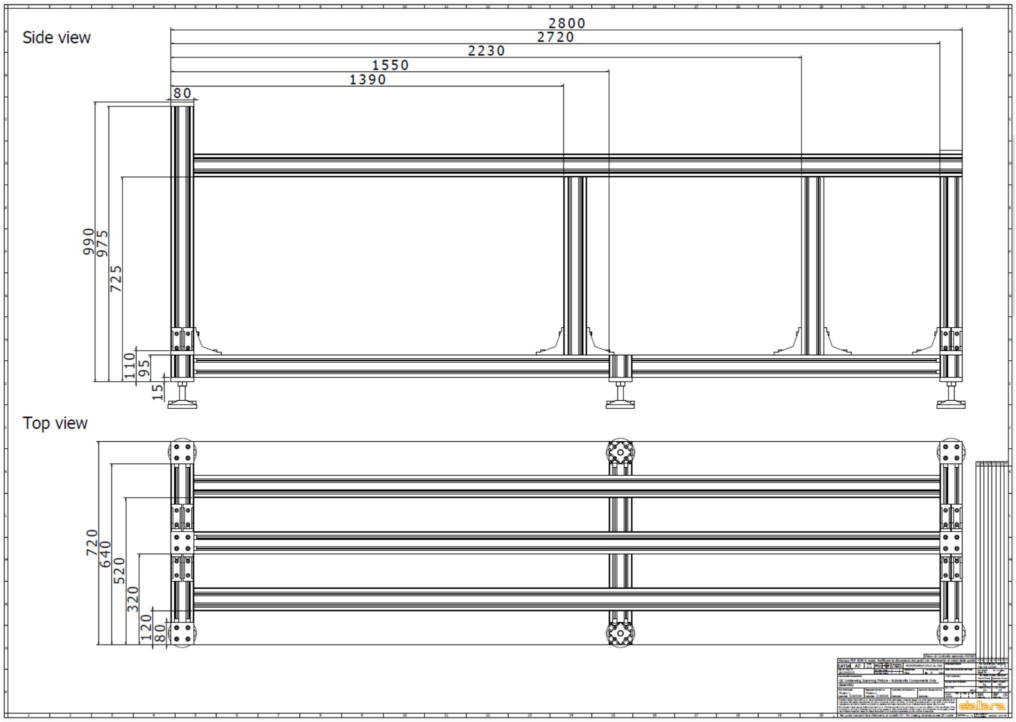
9.4 Drawings of Relevant fixtures

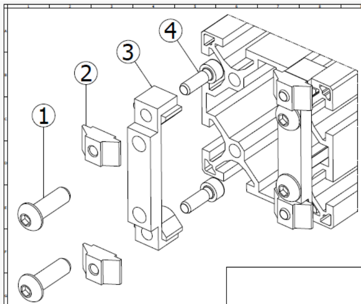
9.4.1 Underwing

9.4.1.1 Robotunits Frame Assembly



Pos.	Dallara P/N	Description	Q.ty	Rev.
1	IR2701555	80x80 Aluminum Extrusion - 2720mm	1	1
2	IR2701529	80x80 Aluminum Extrusion - 2640mm	3	1
3	IR2701530	80x80 Aluminum Extrusion - 880mm	1	1
4	IR2701531	80x80 Aluminum Extrusion - 630mm	3	1
5	IR2701532	80x80 Aluminum Extrusion - 560mm	2	1
6	IR2701556	80x80 Aluminum Extrusion - 120mm	2	1
7	IR2701533	80x80 Aluminum Extrusion - 80mm	6	1
8	IR2701572	80x80 Aluminum Extrusion - 40mm	2	1
9	IR2701564	Corner Bracket 100 (GUS1001) Assembly	20	1
10	IR2701565	Fastener 40x80 (FAS4081) Assembly	40	1
11	MINU90980	Leveling Base, M20 (BAS1020) Assembly	6	1
12	IR2701566	Base and Transport Plate, M20 (BAP8080)	6	1
13	IR2701573	Datum - Base and Transport Plate, Blank (BAP8078)	6	1
14	VITE02104	Cap Screw (ISO4762) M8x20	44	1
15	VITE02103X	Cap Screw (ISO4762) M8x16	4	1
16	IR2701538	Drop-in Nut M8 (TIN4508)	4	1



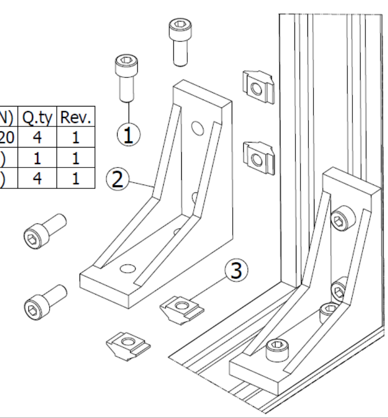


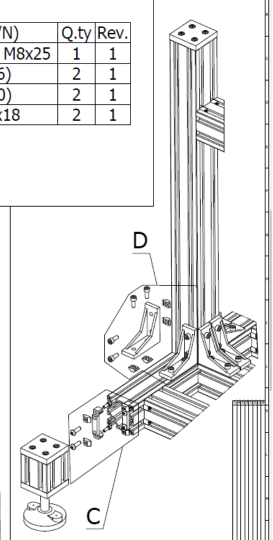
Detail C
Aluminum Extrusion Fastener 40x80 (FAS4081) Assembly
IR2701565

Pos.	Dallara P/N	Description (Robotunits P/N)	Q.ty	Rev.
1	VITE06046	Button-head Screw (ISO7380) M8x25	1	1
2	IR2701540	Drop-in Nut M6 (TIN4506)	2	1
3	IR2701539	Fastener 40x80 (FAS4080)	2	1
4	VITE02940	Cap Screw (ISO4762) M6x18	2	1

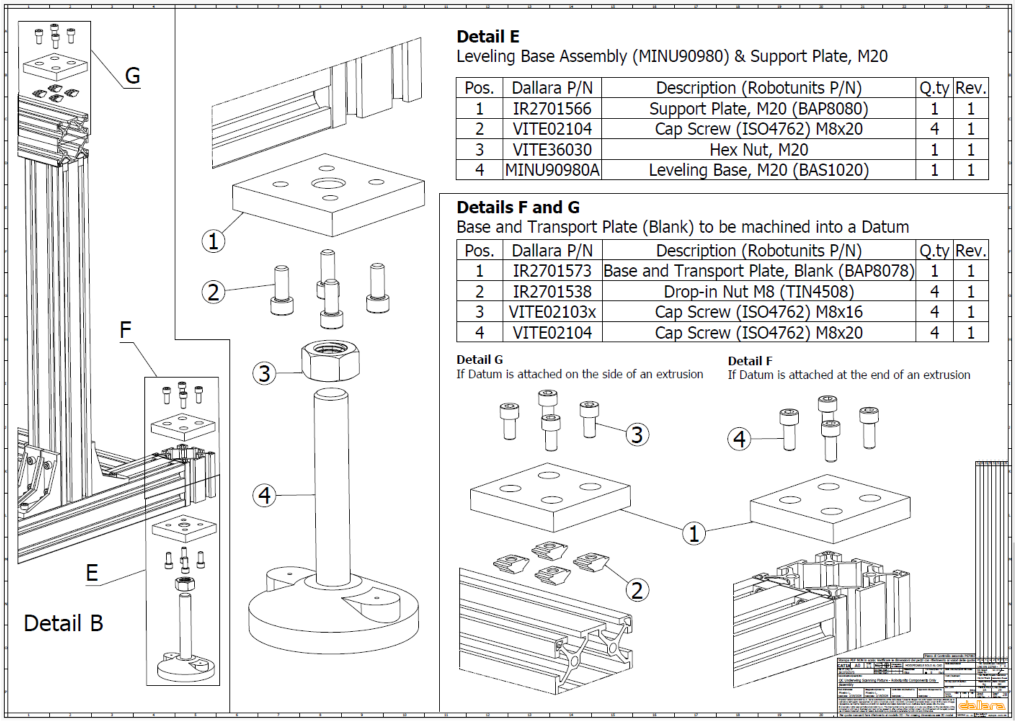
Detail D
Corner Bracket 100 (GUS1001) Assembly
IR2701564

Pos.	Dallara P/N	Description (Robotunits P/N)	Q.ty	Rev.
1	VITE02104	Cap Screw (ISO4762) M8x20	4	1
2	IR2701537	Corner Bracket (GUS1000)	1	1
3	IR2701538	Drop-in Nut M8 (TIN4508)	4	1





Detail A



Detail E

Leveling Base Assembly (MINU90980) & Support Plate, M20

Pos.	Dallara P/N	Description (Robotunits P/N)	Q.ty	Rev.
1	IR2701566	Support Plate, M20 (BAP8080)	1	1
2	VITE02104	Cap Screw (ISO4762) M8x20	4	1
3	VITE36030	Hex Nut, M20	1	1
4	MINU90980A	Leveling Base, M20 (BAS1020)	1	1

Details F and G

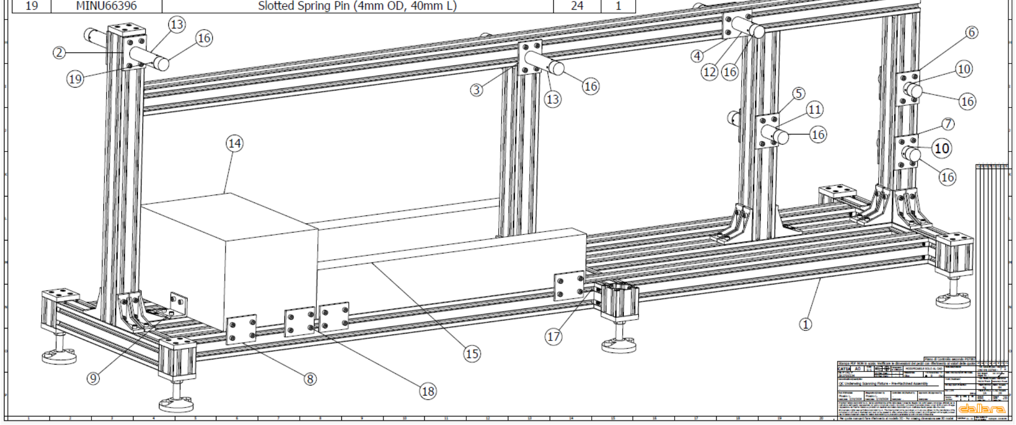
Base and Transport Plate (Blank) to be machined into a Datum

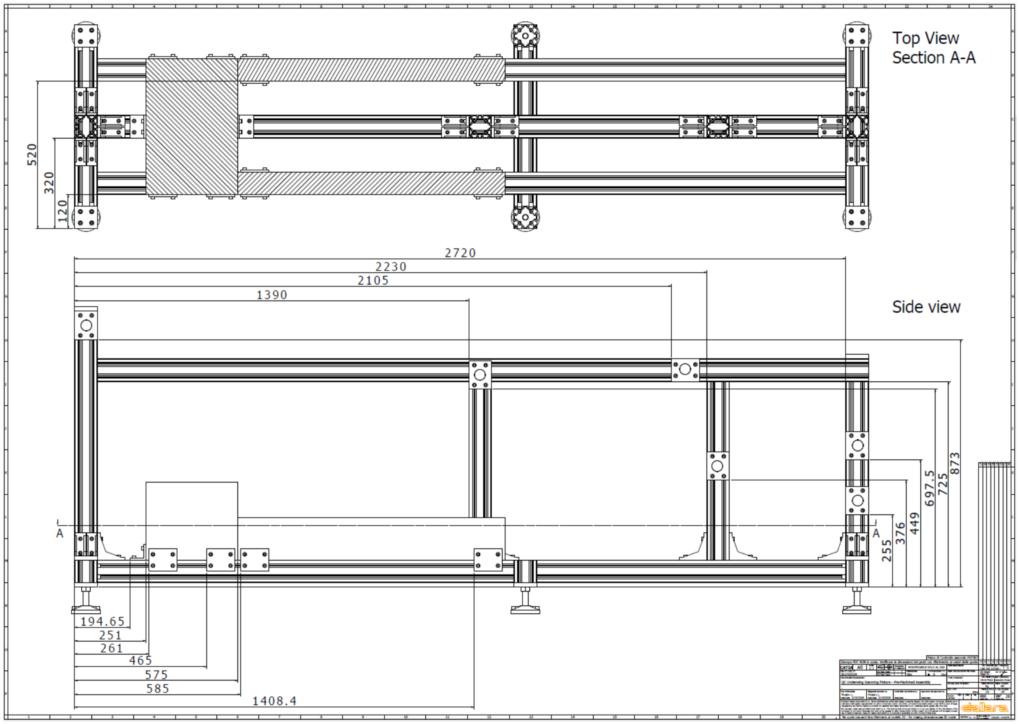
Pos.	Dallara P/N	Description (Robotunits P/N)	Q.ty	Rev.
1	IR2701573	Base and Transport Plate, Blank (BAP8078)	1	1
2	IR2701538	Drop-in Nut M8 (TIN4508)	4	1
3	VITE02103x	Cap Screw (ISO4762) M8x16	4	1
4	VITE02104	Cap Screw (ISO4762) M8x20	4	1

9.4.1.2 Pre-Machined Assembly

Pos.	Dallara P/N	Description	Q.ty	Rev.
1	IR2701575	QC Underwing Scanning Fixture - Robotunits Components Only Assembly	1	1
2	IR2701535	80x100 Aluminum Plate (6.35mm thick) - 1st	2	1
3	IR2701548	80x100 Aluminum Plate (6.35mm thick) - 2nd	2	1
4	IR2701536	80x100 Aluminum Plate (6.35mm thick) - 3rd	2	1
5	IR2701549	80x100 Aluminum Plate (6.35mm thick) - 4th	2	1
6	IR2701550	80x100 Aluminum Plate (6.35mm thick) - 5th	2	1
7	IR2701551	80x100 Aluminum Plate (6.35mm thick) - 6th	2	1
8	IR2701552	80x100 Aluminum Plate (6.35mm thick) - Blank	12	1
9	IR2701588	80x100 Aluminum Plate (6.35mm thick) - Angled	2	1
10	IR2701544	Aluminum Round Tubing (38mm OD, 3mm wall) - 23mm	4	1
11	IR2701543	Aluminum Round Tubing (38mm OD, 3mm wall) - 70mm	2	1
12	IR2701542	Aluminum Round Tubing (38mm OD, 3mm wall) - 100m	2	1
13	IR2701541	Aluminum Round Tubing (38mm OD, 3mm wall) - 135mm	4	1
14	IR2701546	Dummy Monocoque/Keel - Front - Generic	1	1
15	IR2701547	Dummy Monocoque/Keel - Middle - Generic	2	1
16	IR2701545	Derlin Puck - Generic	12	1
17	IR2701538	Drop-in Nut M8 (TIN4508)	76	1
18	VITE02103X	Cap Screw (ISO4762) M8x16	104	1
19	MINU66396	Slotted Spring Pin (4mm OD, 40mm L)	24	1

Isometric view
Jig is symmetrical across its length





Dimensioning and Details of "Delrin Puck - Generic", "Aluminum Round Tubing" sections, and "Dummy Monocoque/Keel"

ALL Aluminum Round Tubing [IR27015(41-44)]
Delrin Puck - Generic [IR2701545]

- The following section represents ALL Aluminum Round Tubing (ART) sections, their lengths represented by Table A.
- ALL have a 38mm OD, 3mm wall thickness (32mm ID) and will follow the hole positioning and dimensions shown:

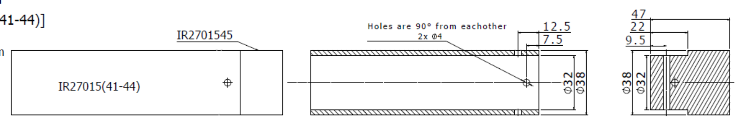
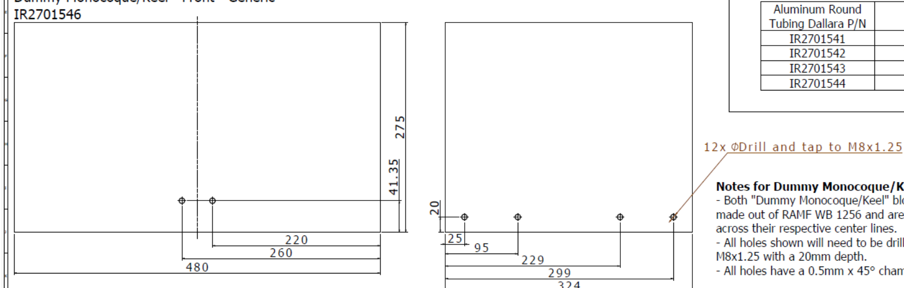


Table A (ART section lengths)

Aluminum Round Tubing Dallara P/N	Length
IR2701541	135mm
IR2701542	100mm
IR2701543	70mm
IR2701544	23mm

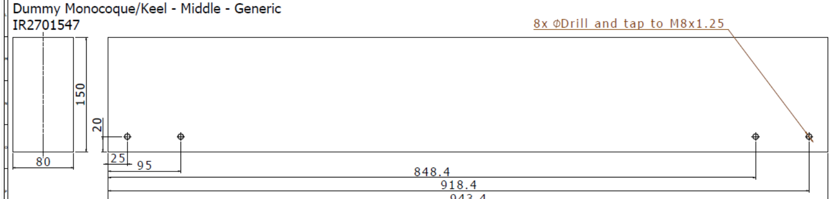
Dummy Monocoque/Keel - Front - Generic
IR2701546



Notes for Dummy Monocoque/Keel blocks:

- Both "Dummy Monocoque/Keel" blocks are to be made out of RAMF WB 1256 and are symmetric across their respective center lines.
- All holes shown will need to be drill and tapped to M8x1.25 with a 20mm depth.
- All holes have a 0.5mm x 45° chamfer.

Dummy Monocoque/Keel - Middle - Generic
IR2701547

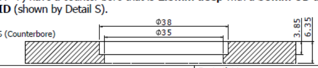


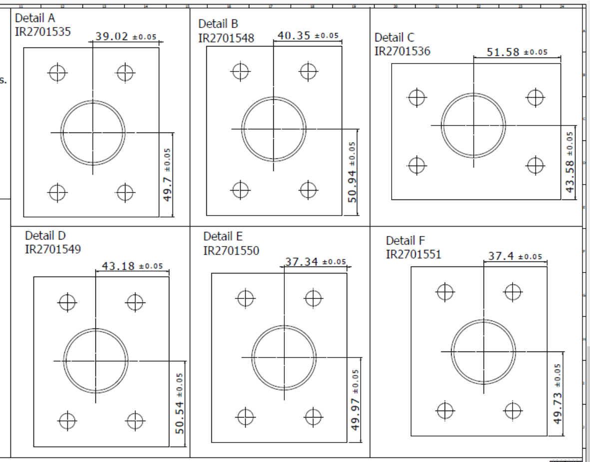
80x100 Aluminum Plate (6.35mm thick) Detailed Sheet

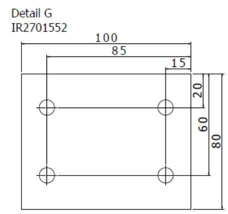
Notes:

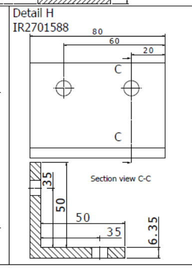
- ALL flat aluminum plates are 80mm x 100mm and 5mm thick, containing 4 x 9mm holes.
- Bent plate (IR2701588) dimensioned in Detail H.
- Positioning of 9mm holes is shown by Detail G (Blank plate).
- ALL plates that will have an aluminum round tubing section welded to it (Details A - F) have a counter bore that is **2.5mm deep** with a **38mm OD** and a **35mm ID** (shown by Detail S).

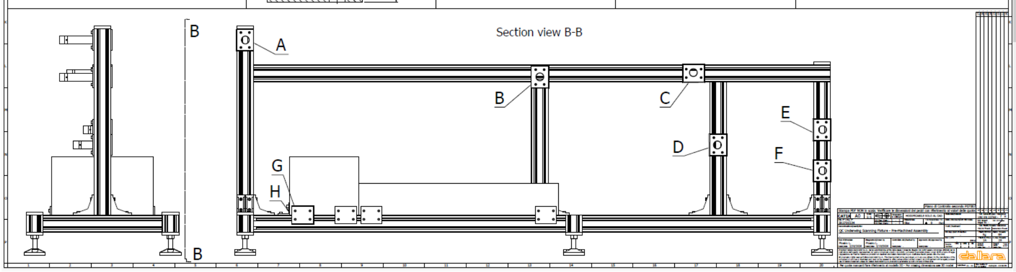
Detail S (Counterbore)







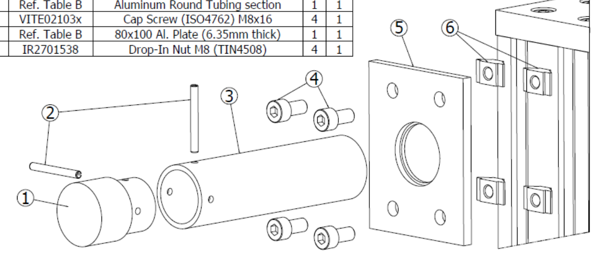




Detail K - Mount for Delrin Puck

Representation of how ALL simulated stay mounts will be attached to the frame

Pos.	Dallara P/N	Description (Robotunits P/N)	Q.ty	Rev.
1	IR2701545	Delrin Puck - Generic	1	1
2	MINU66396	Slotted Spring Pin (4mm OD, 40mm L)	2	1
3	Ref. Table B	Aluminum Round Tubing section	1	1
4	VITE02103x	Cap Screw (ISO4762) M8x16	4	1
5	Ref. Table B	80x100 Al. Plate (6.35mm thick)	1	1
6	IR2701538	Drop-In Nut M8 (TIN4508)	4	1



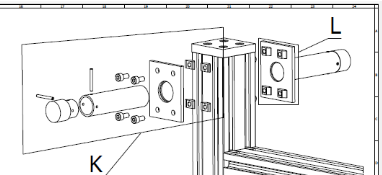


Table B

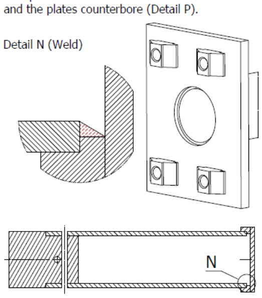
ART-Plate Assemblies

ART (Dallar P/N)	Plate
135mm (IR2701541)	IR2701535
135mm (IR2701541)	IR2701548
100mm (IR2701542)	IR2701536
70mm (IR2701543)	IR2701549
23mm (IR2701544)	IR2701550
23mm (IR2701544)	IR2701551

Detail L

ART sections to be welded to the plate utlizing the lip from the ID difference between the ART and the plates counterbore (Detail P).

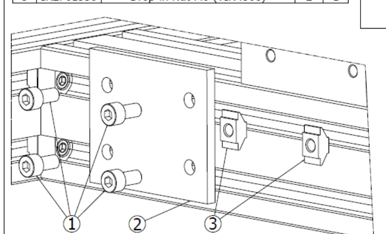
Detail N (Weld)

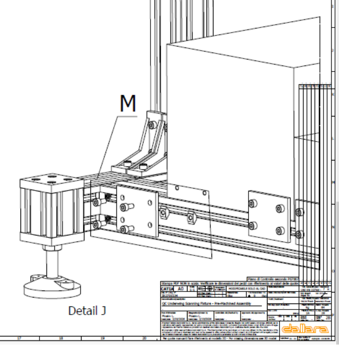


Detail M - Mount for Dummy Monocoque/Keel

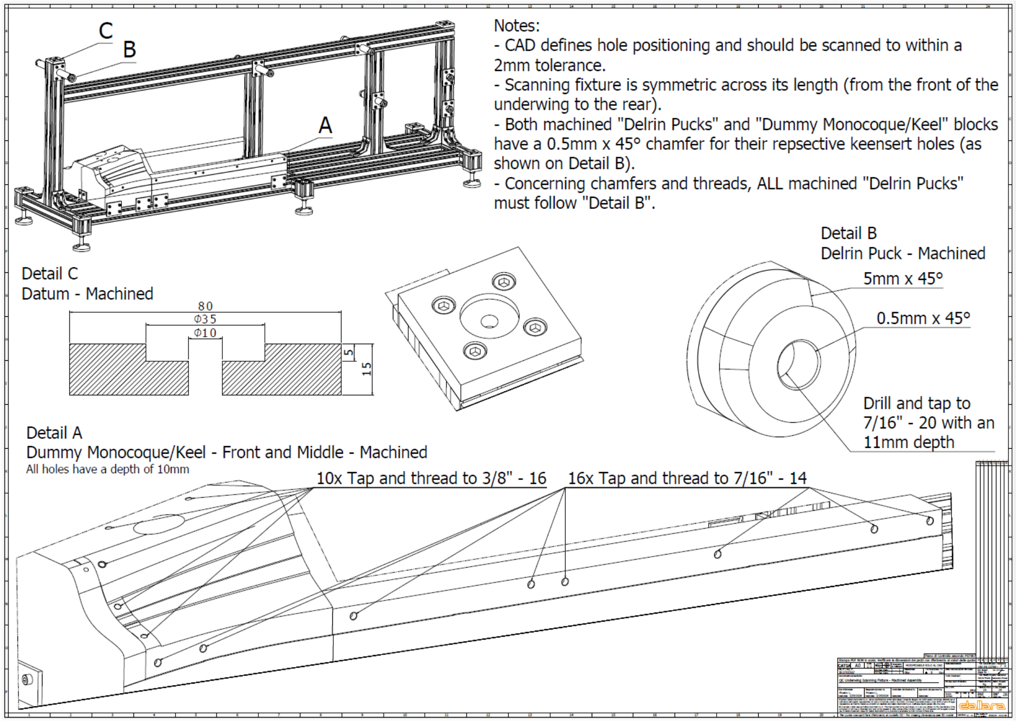
Representation of how the Dummy Monocoque/Keel (Front and Middle) will attach to the frame

Pos.	Dallara P/N	Description (Robotunits P/N)	Q.ty	Rev.
1	VITE02103x	Cap Screw (ISO4762) M8x16	4	1
2	IR2701552	80x100 Al. Plate (5mm thick) - Blank	1	1
3	IR2701538	Drop-in Nut M8 (TIN4508)	2	1

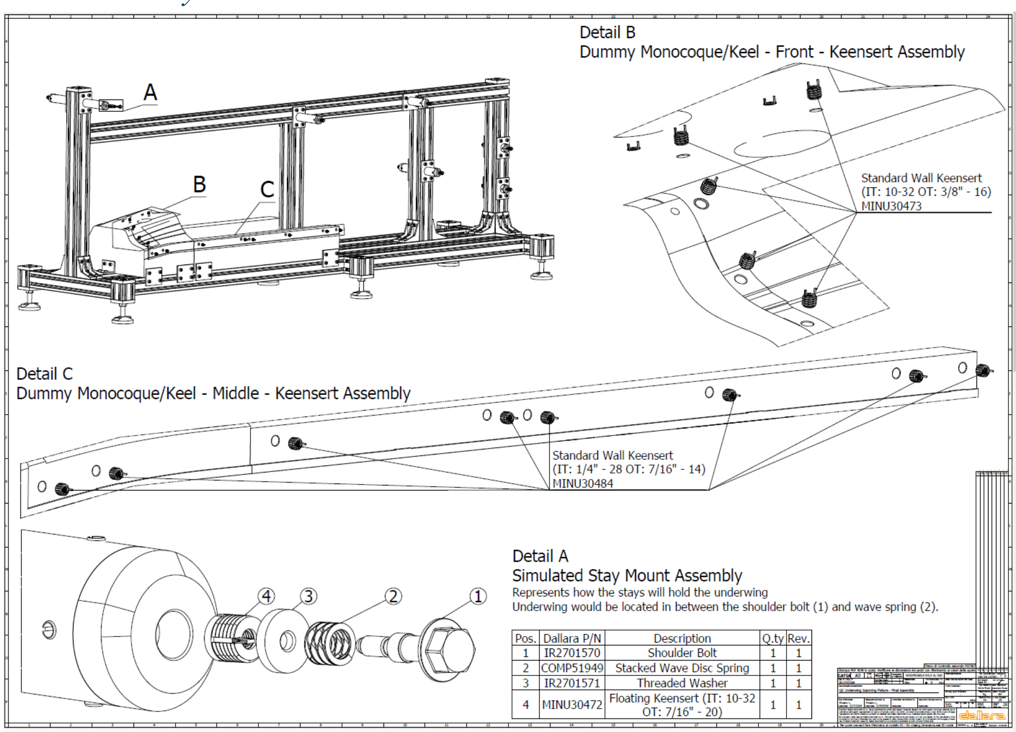




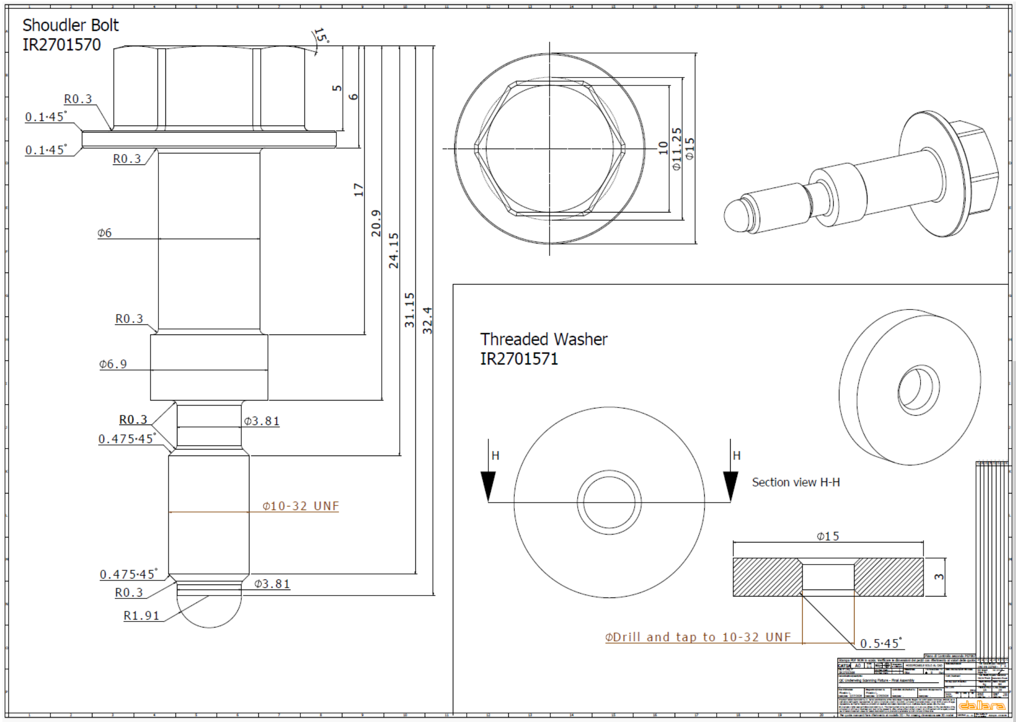
9.4.1.3 Machined Assembly



9.4.1.4 Final Assembly

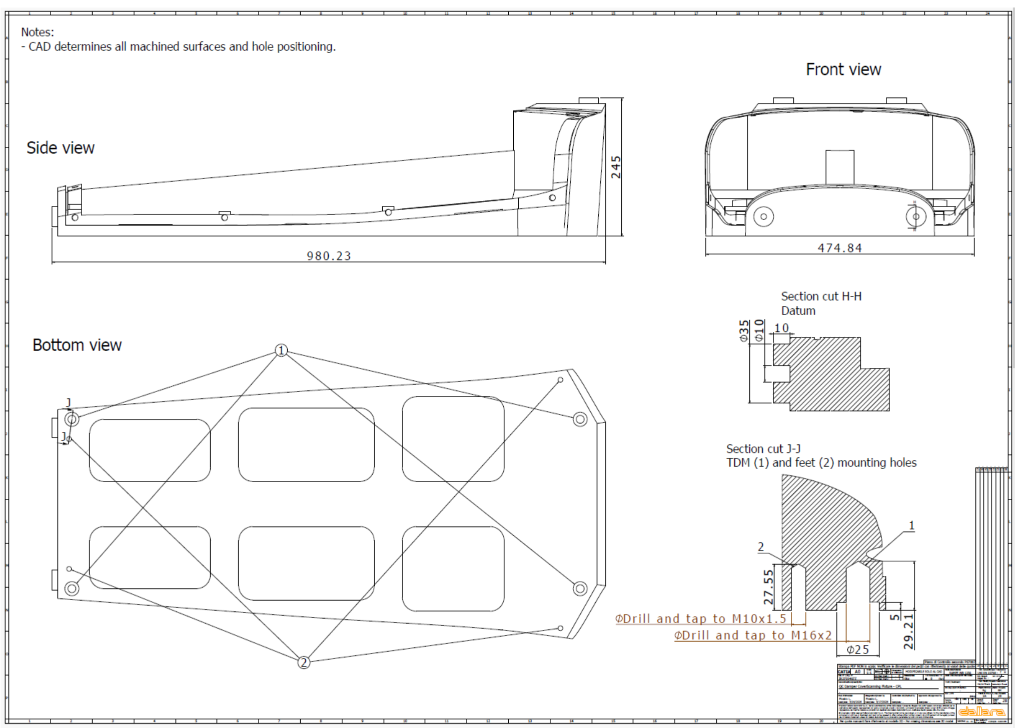


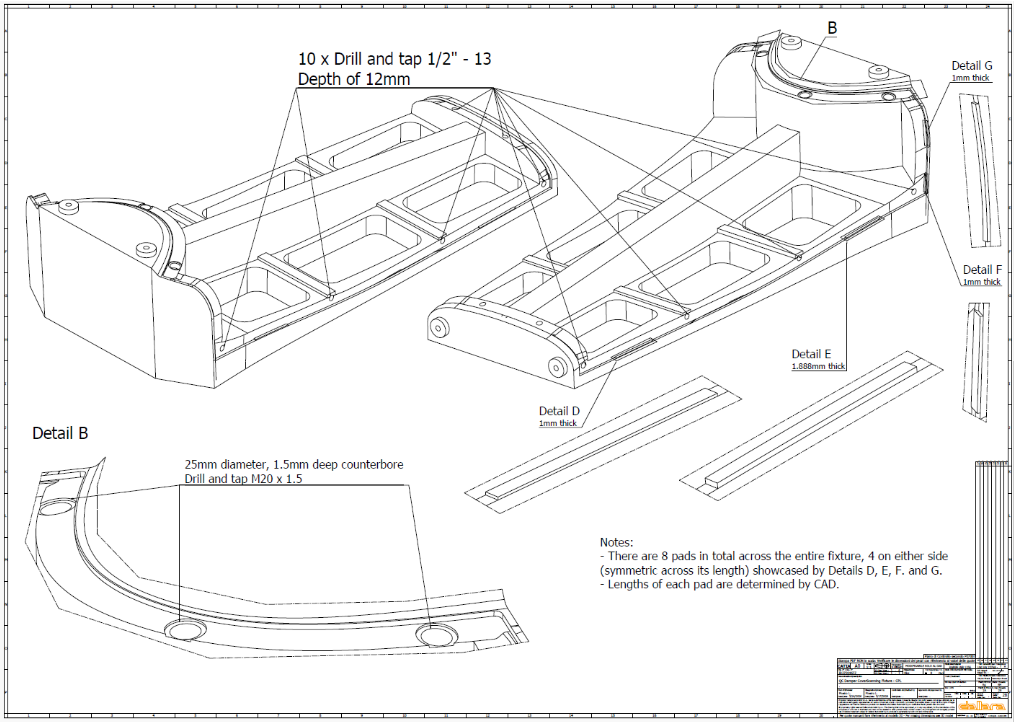
Pos.	Dallara P/N	Description	Q.ty	Rev.
1	IR2701570	Shoulder Bolt	1	1
2	COMP51949	Stacked Wave Disc Spring	1	1
3	IR2701571	Threaded Washer	1	1
4	MINU30472	Floating Keensert (IT: 10-32 OT: 7/16" - 20)	1	1



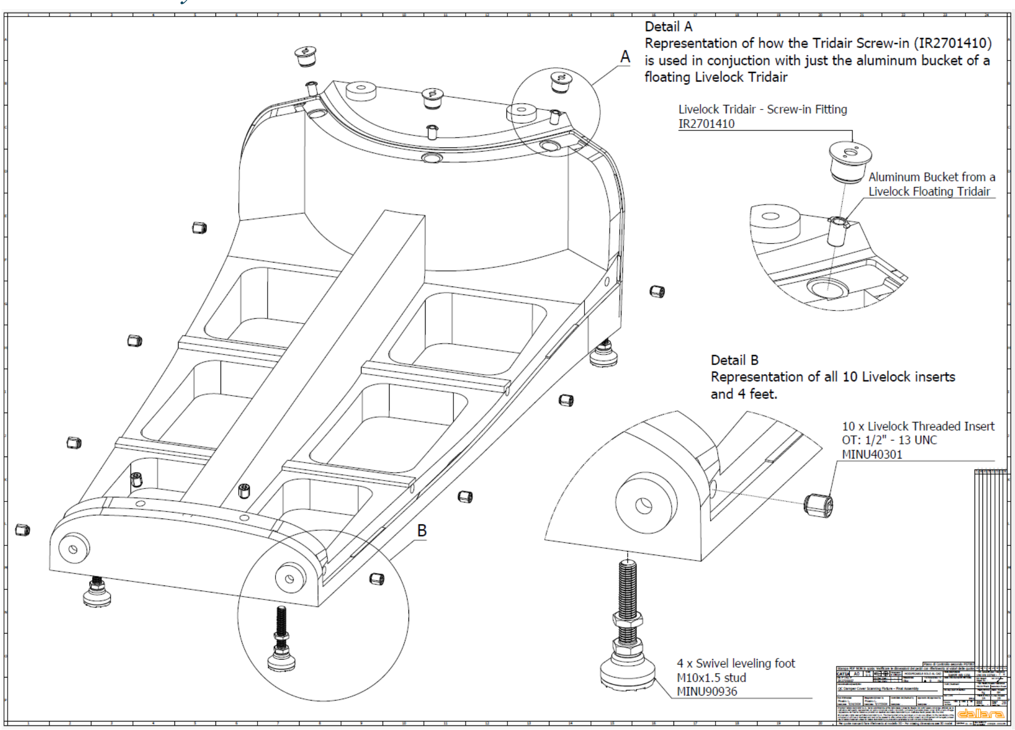
9.4.2 Damper Cover

9.4.2.1 Machined



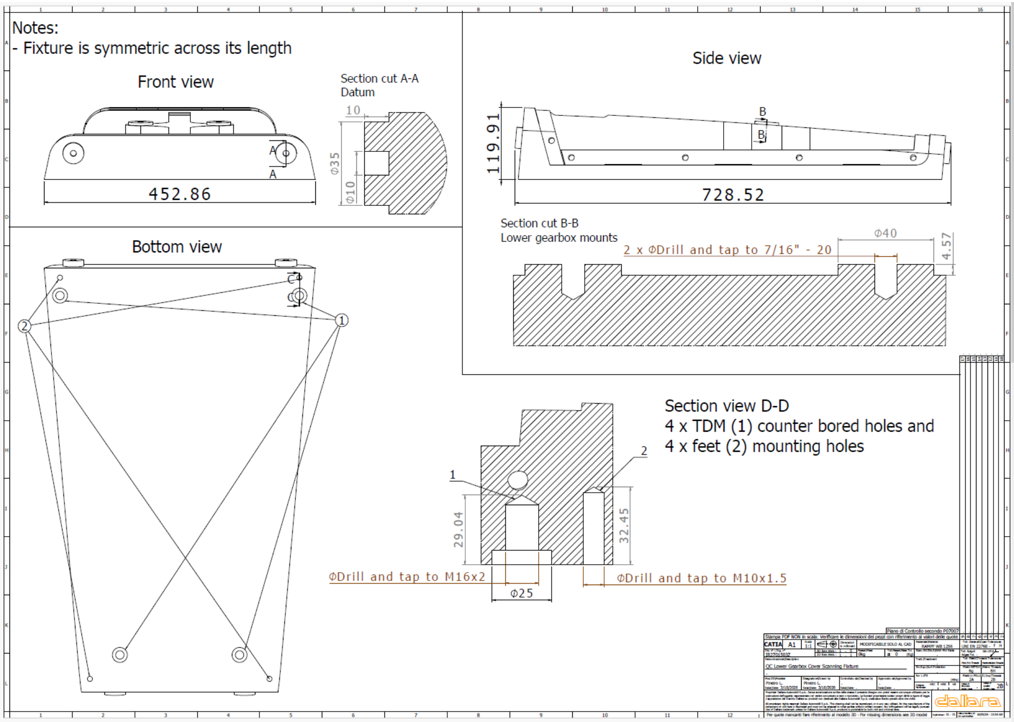


9.4.2.2 Final Assembly

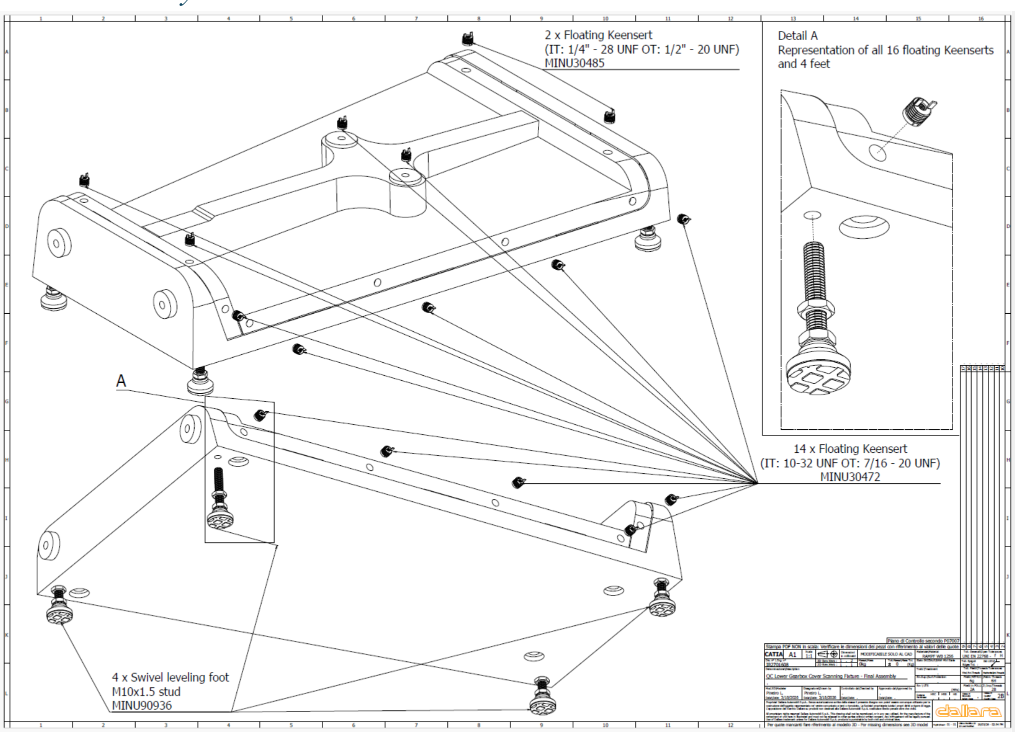


9.4.3 Lower Gearbox Cover

9.4.3.1 Machined

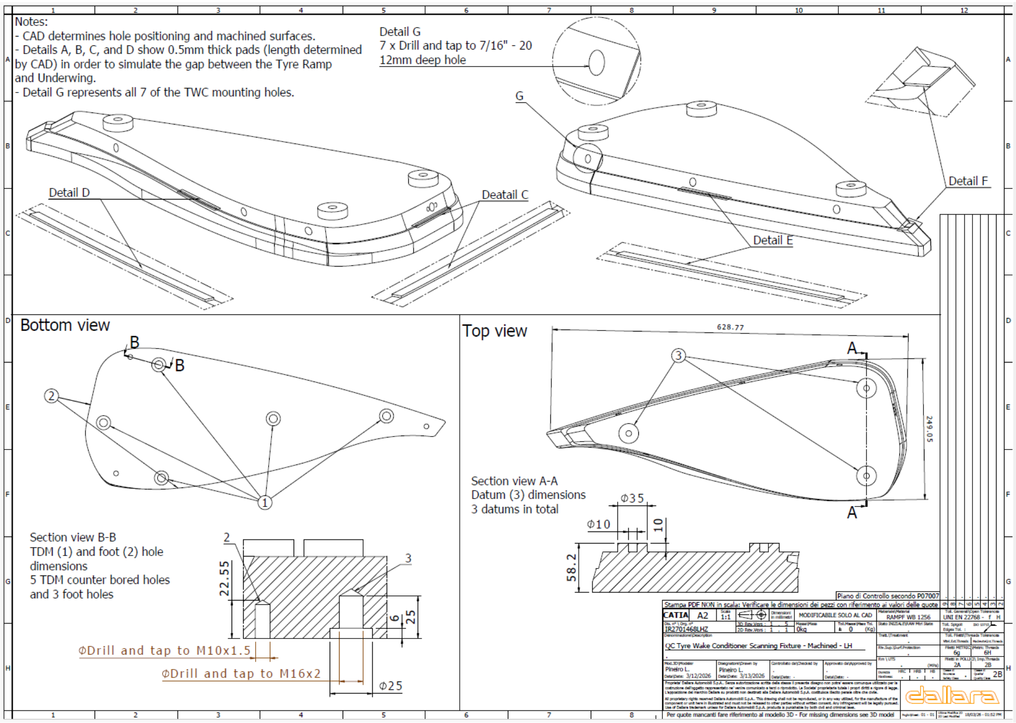


9.4.3.2 Final Assembly

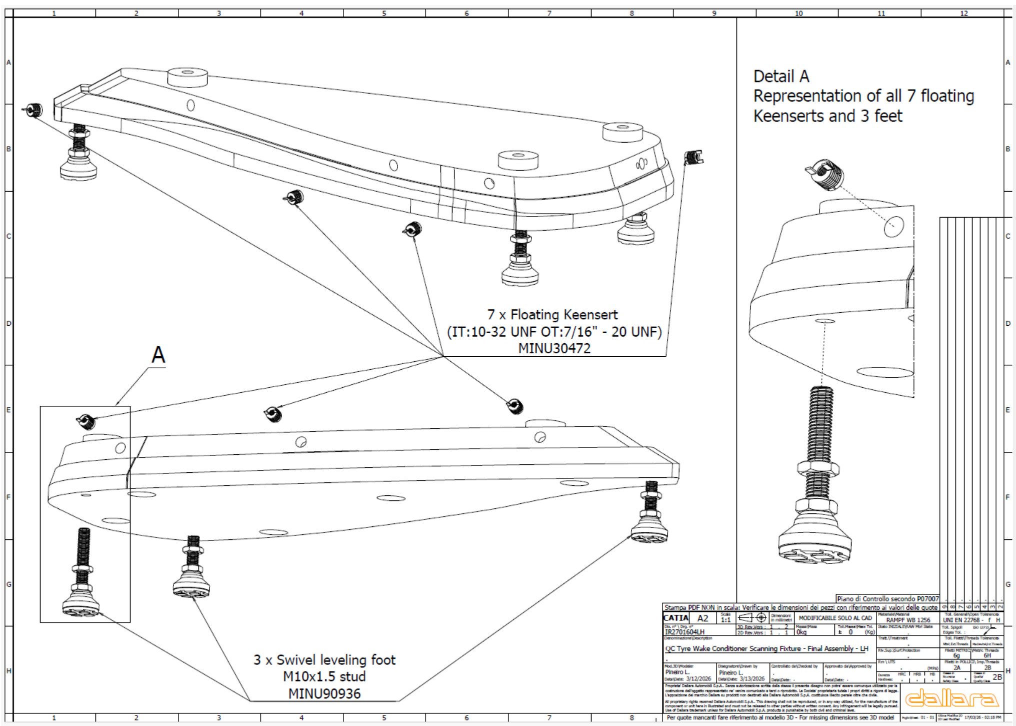


9.4.4 Tyre Wake Conditioner (TWC)

9.4.4.1 Machined

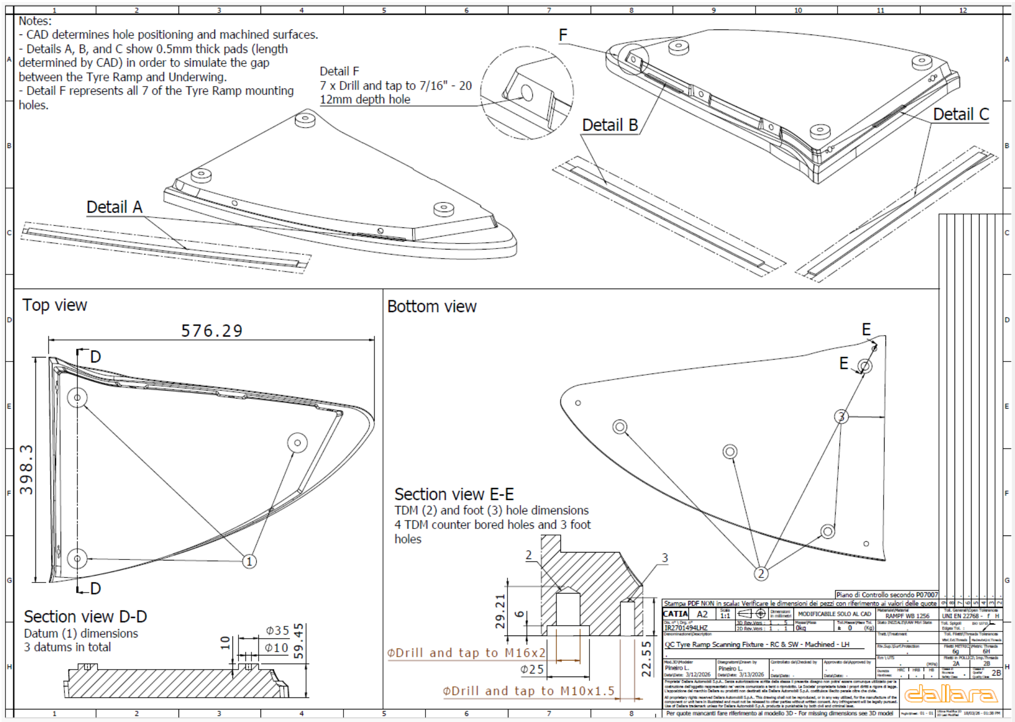


9.4.4.2 Final Assembly

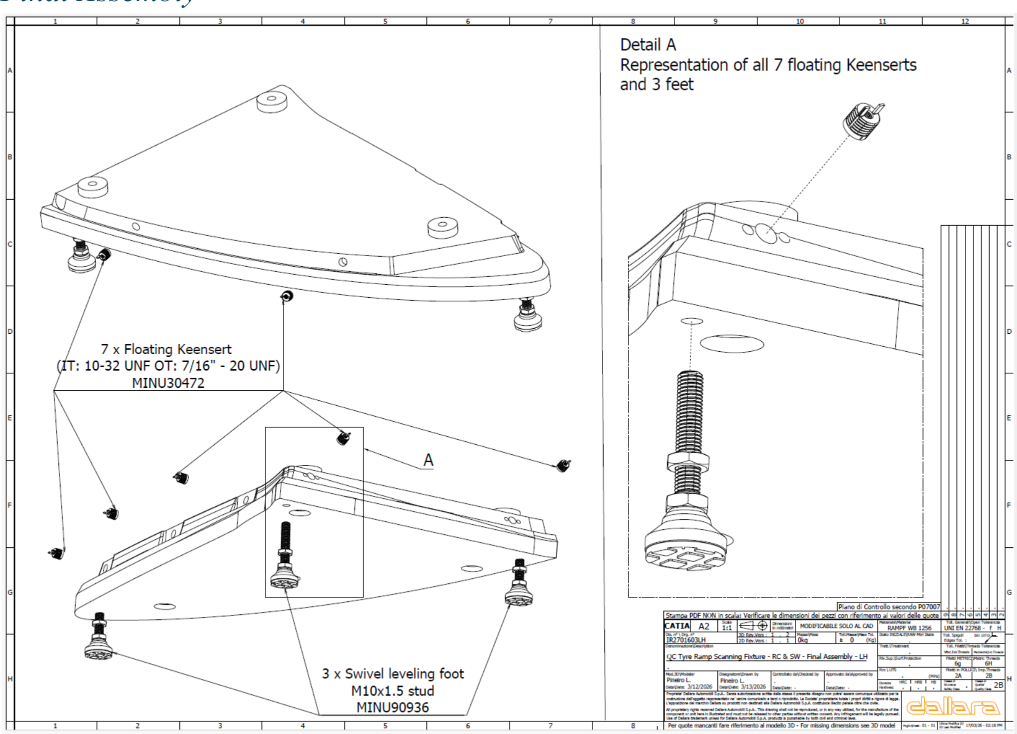


9.4.5 Tyre Ramp

9.4.5.1 Machined

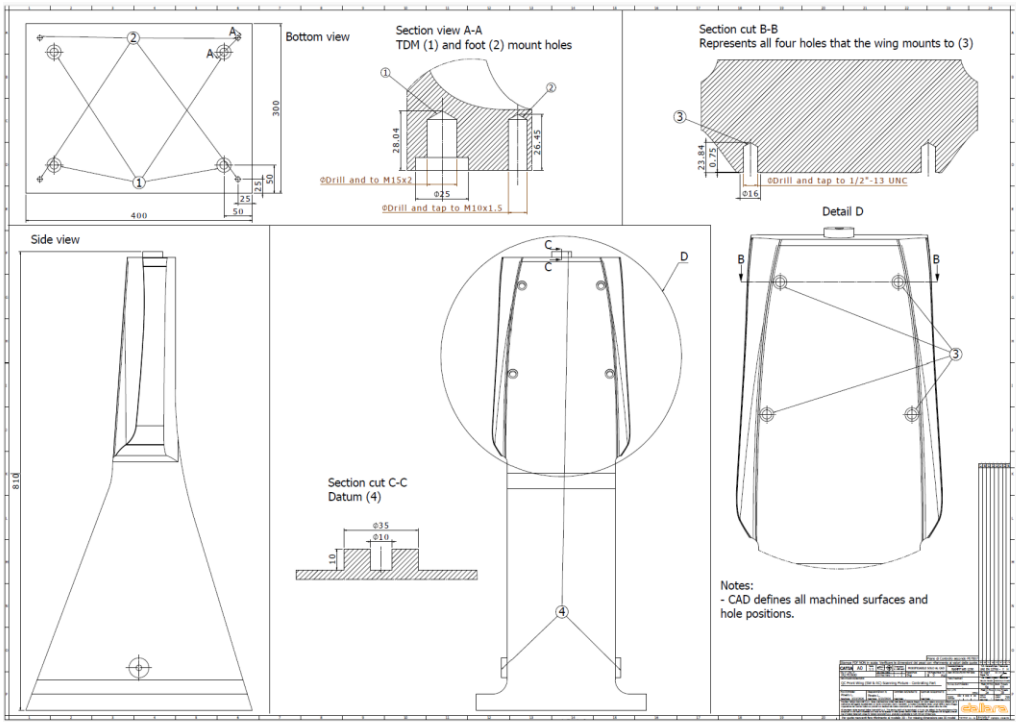


9.4.5.2 Final Assembly

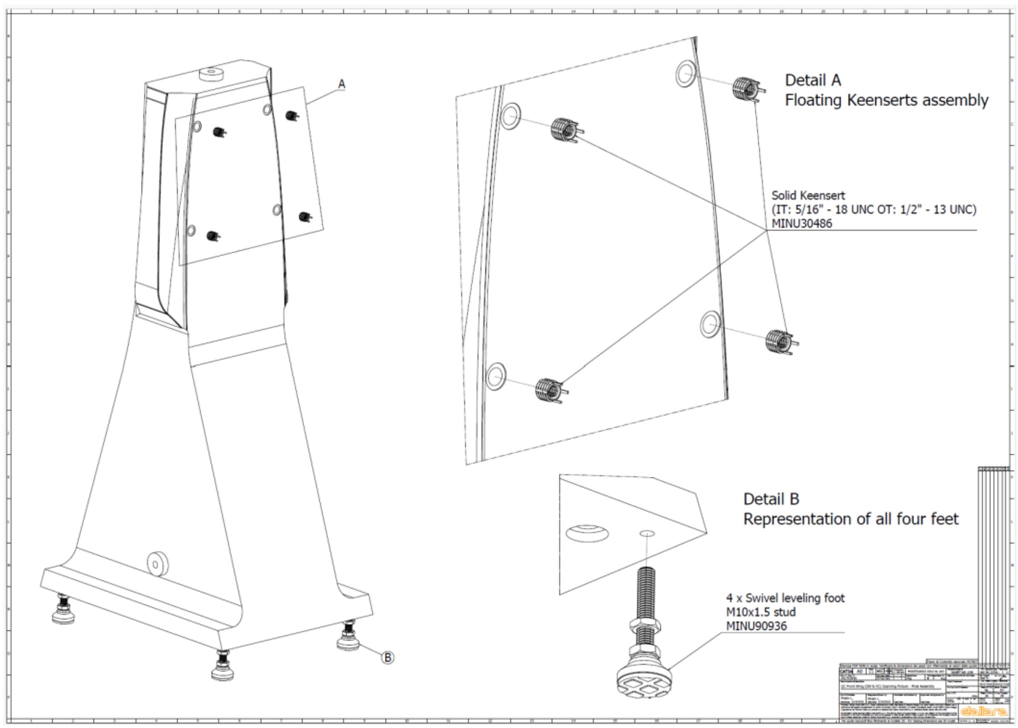


9.4.6 Front Wing

9.4.6.1 Machined

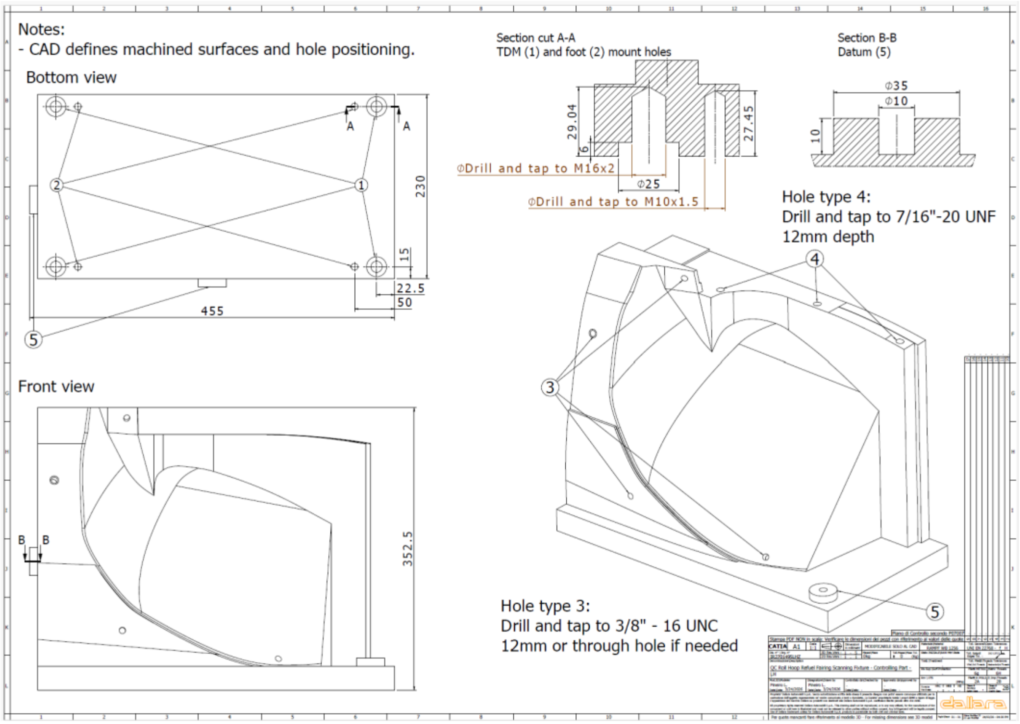


9.4.6.2 Final Assembly

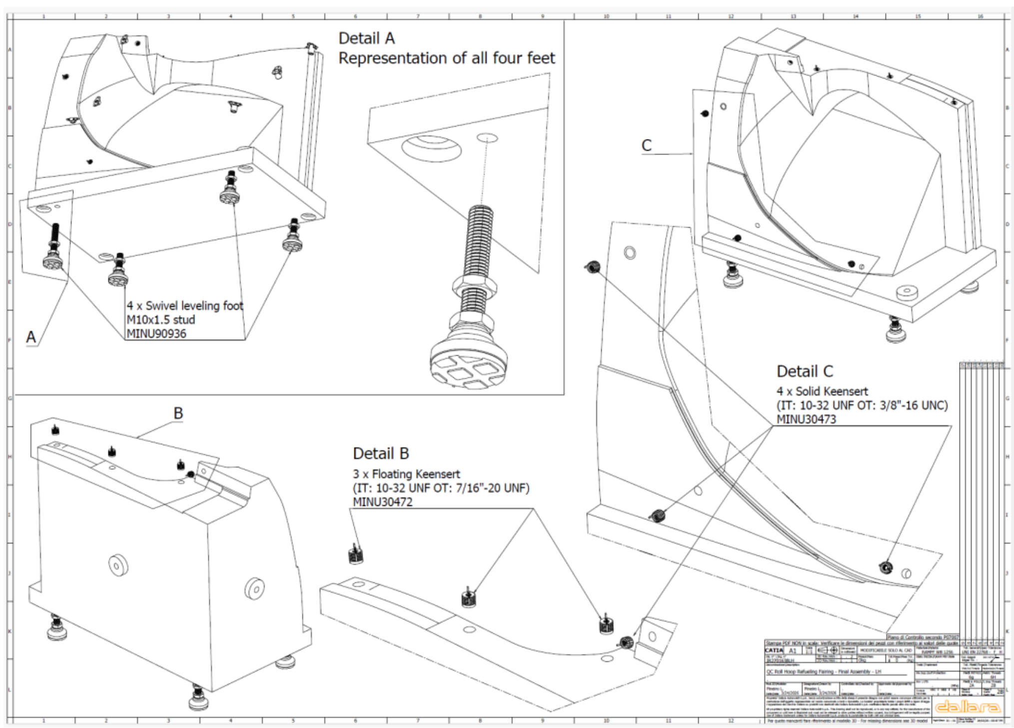


9.4.7 Roll Hoop Refueling Fairing

9.4.7.1 Machined

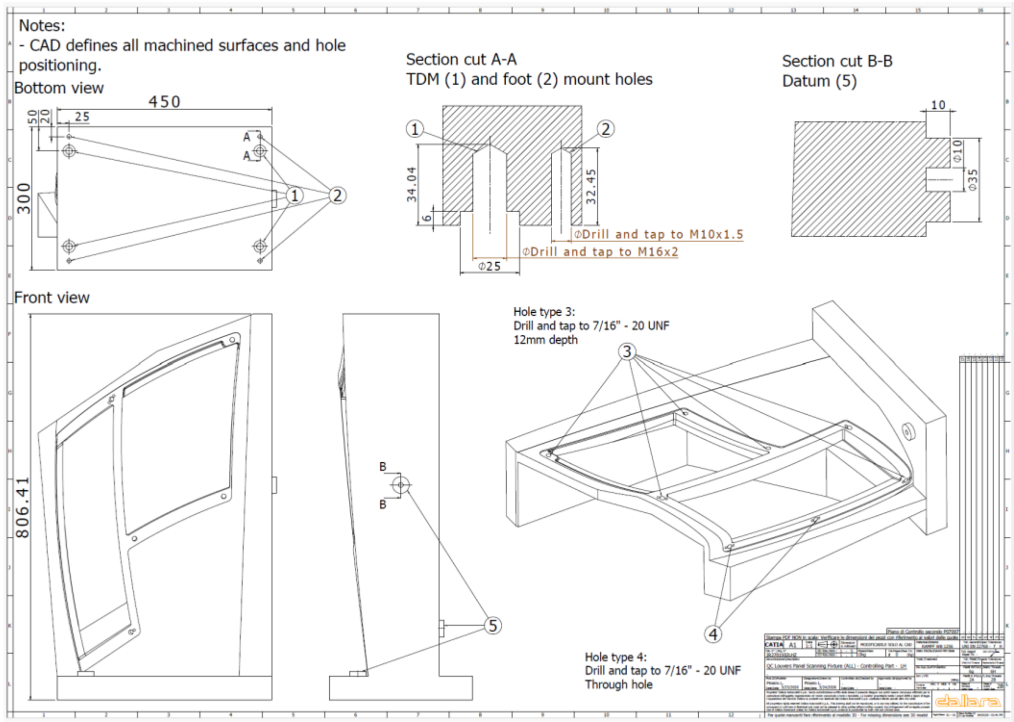


9.4.7.2 Final Assembly



9.4.8 Louver Panel

9.4.8.1 Machined



9.4.8.2 Final Assembly