

Reflections on the Aerospace Engineering Development Programme at the CSIR

Katleho Ramotsabi[1], Lauren Strydom[2] & Lindokuhle Zwane[3]
[1]Council for Scientific and Industrial Research (CSIR) of South Africa, +27 12 841 3315, KRamotsabi@csir.co.za
[2]CSIR, +27 12 841 2911, LStrydom@csir.co.za
[3]CSIR, +27 12 841 3880, LZwane2@csir.co.za

Abstract

The challenges of South Africa's (and Africa at large) engineering skills shortages and 'brain drain' are widely documented, i.e. mass exodus of scarce skills, with insufficient development and retention of such skills. The Aerospace Engineering Development Programme (AEDP) addresses in part such challenges. The AEDP is hosted at the CSIR, and it is a multi-year endeavour that is planned to have cohorts of between 10 to 20 early career engineers. The primary objectives of the AEDP include the provision of experience to early career engineers (participants) within the full scope of aerospace systems/products' lifecycles in an Integrated Product Development Team (IPDT). It also serves to bolster the skills that have been lost in recent years from the South African aerospace and defence industry. The programme seeks to develop engineers to enable them to be productive in an accelerated timeframe. The AEDP is sponsored by the South African Air Force (SAAF) through the Armaments Corporation of South Africa (Armscor). This paper presents the rationale for the establishment of the AEDP, the approach followed, the progress to date, lessons learned, as well as the next steps for phase 1 of the AEDP. Recommendations for future cohorts of the AEDP, as well as other current and future graduate development programmes outside of the AEDP are also provided. The first cohort of the AEDP which commenced in September 2023, has been made up of participants from the CSIR, Armscor, and SAAF. The programme involves the attendance of post-graduate level short courses that focus on topics relevant to aerospace engineering. Some of the courses include material that is not sufficiently addressed during tertiary education but essential for aerospace engineers in industry. The AEDP thereby bridges such gaps. Each cohort of AEDP participants has the further challenge of Designing, Developing, and Demonstration (DDD) of a system that fulfils typical real-world needs. The project for the first cohort of the AEDP involves the DDD of an Unmanned Aircraft System (UAS), whose Unmanned Aerial Vehicle (UAV) is designed to carry a Synthetic Aperture Radar (SAR) payload and to ultimately be powered by a Hydrogen fuel cell module. The detailed design of the airframe, in parallel with procurement of Commercial Off-The-Shelf (COTS) hardware, as well as development of software and firmware are currently underway. Airframe manufacture, integration and ground testing will then follow. Phase 1 of the AEDP is planned to then be concluded with a Flight Test (FT) demonstration of the UAS in 2027, together with the test reporting and documentation of lessons learned.

Keywords: aerospace engineering, brain drain, early career engineer, integrated product development team, unmanned aircraft system

1. Introduction

The CSIR is a South African state-owned entity whose mandate includes bridging the gaps between fundamental research, applied research and industry, such that research outputs and mature technologies are industrialised and commercialised. It does so by undertaking applied research, as well as technology development and demonstrator projects. An upskilled human capital complement is thus key to the CSIR achieving its mandate.

The first cohort of the AEDP commenced in September 2023 with participants from the CSIR,

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Armscor and SAAF. The participants are early career engineers with at least 4-year university degrees in the disciplines of aeronautical, mechanical, mechatronic, electronic, and software engineering. The AEDP involves the attendance of post-graduate level short courses (see Figure 1) that focus on topics relevant to aerospace engineering and related industries/sectors. Some of these courses have assignments and practical (laboratory) elements tailored to equip the participants with the required skills to excel in the aerospace and defence environment. Technical topics within the coursework included SAR fundamentals, Electromagnetic Compatibility, Power Electronics, Data Acquisition and Processing, UAS Design & Technology, Flight Mechanics, Aerospace Manufacturing Methods, and Aerostructures. This is such that some courses would be refreshers for some participants and introductory fundamentals to others given the focus of their respective undergraduate degrees, albeit the need to function within IPDTs when developing aerospace systems.

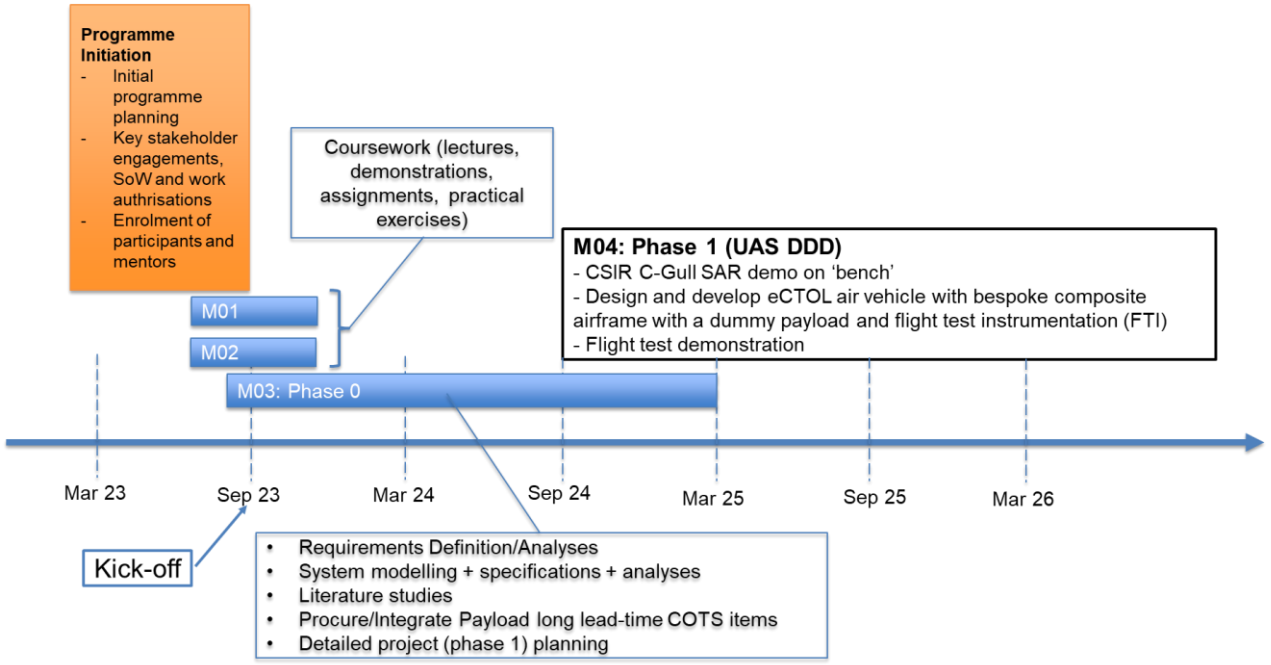


Figure 1: Cardinal milestones for the AEDP

Other courses provided, which are essential for developing aerospace products/systems, albeit not as focused on or addressed at all during undergraduate (and some postgraduate) studies include Project Management, Systems Engineering, Leadership, Organisational Culture & Team Dynamics, Aviation Authorities & Regulations, Product Lifecycle (and Data) Management (PLM/PDM), as well as Configuration and Quality Management.

Each cohort of AEDP participants has a further challenge of DDD of a system that fulfils typical real-world needs within a relatively short timeframe. The project for the first cohort involves the DDD of an UAS, whose UAV is designed to carry a SAR payload and to ultimately be powered by Hydrogen fuel cell module; the end deliverable will involve a flight test demonstration of the UAS. Phase 1 will involve a 'design for but not fitted with' incremental approach that is typical in the development of complex systems, i.e. the first FT demonstration will be with a dummy payload and purely powered by batteries.

2. Literature Review

2.1. Brain Drain

The quality of resources, infrastructure, opportunities, university curricula and research programmes,

as well as remuneration scales outside of Africa have continued to result in her 'brain drain', i.e. the mass exodus of scarce skills for post-graduate research and permanent employment opportunities outside of Africa [1]. It is asserted that "Brain drain has long been a challenge for South Africa as the country continues to lose skilled professionals to other countries, hence, the unsteady growth of its economy" [2]. Sheikheldin and Mohamed further write that "There are currently more African PhD holders outside the continent than inside it; a statement that cannot be said about any other continent of the world. Up to one-third of African scientists and research professionals (excluding other professionals) are said to be lost to what is called 'brain drain'" [3].

2.2. Gaps Between Academia and Industry

Scientific and Engineering education in Africa has been observed to be based primarily on theory and examination, and less so on outcomes and solving problems for the industries that are to absorb the very same graduates once their studies are completed. University curricula in this regard are not seen to continually and timeously adapt to the dynamic market needs. It is argued that while the technical disciplines and theory are vital, tertiary education institutions place little emphasis on interpersonal and professional (communication, analytical, negotiation, business acumen, teamwork, etc) skills, which are also essential for employability. Collaboration between universities and industries in Africa has also been found to have significant gaps with regards to provision of applicable skills to enable the graduates to be readily employable and productive in industry. Vacation work that engineering students undertake in industry is also not alone sufficient to bridge such a gap. Interdisciplinary studies at universities are also found to be lacking, while industry and societal problems rarely require a sole discipline for solutions ([1] and [4]).

2.3. Graduate Engineering Programmes

Employers in the engineering sector often attempt to address the perceived skill gaps among newly recruited graduates by implementing structured mentorship and Engineer-in-Training (EIT) programmes. These initiatives are designed to cultivate competencies that are frequently aligned with the specific operational and technical requirements of the organisation. However, such programmes typically demand substantial investments of time and financial resources, without assurance of a proportional return on investment. Consequently, many firms exhibit reluctance to hire recent engineering graduates. Instead, there is a marked preference for candidates possessing a minimum of five years of professional experience, ideally accompanied by certification or registration with recognised regulatory and/or professional bodies [5]. This further exacerbates the reduced 'pool' of early career engineers that are getting developed to middle and expert levels and thereafter retained in South Africa.

3. Methodology

Informal engagements with experienced industry professionals were undertaken where insights were obtained into previous endeavours towards skills development for early career engineers within the aerospace and defence industry. Such insights were then used to formulate and structure the AEDP. The coursework was developed by in-house (CSIR) experts as well as through consultation with industry/academia experts as needed. The courses were grouped into two sets, i.e. M01 for all the participants, and M02 (see Figure 1 and Figure 2) specifically for aeronautical and mechanical engineers, particularly for expertise that the CSIR is looking to bolster.

Phase 1 of the DDD project (see Figure 1) has the end goal of demonstrating the UAV in flight with a dummy payload. The UAV is intended to be that of a conventional take-off and landing (CTOL) configuration; this, while not a novel configuration, is intended to limit the technical risk given the post-graduate and industry inexperience of the participants. Phase 2 of the AEDP will then involve the

integration of the CSIR C-Gull SAR (thereby replacing the dummy payload) into the phase 1 UAV and then demonstration in flight. A hydrogen primary power plant will also be developed during phase 2 for integration into the phase 1 UAV and then demonstrated in flight. The project (within a programme) was thus designated 'HySAR UAV.' This is intended for the participants to gain experience with the 'design for but not fitted with' (evolutionary acquisition) approach in developing complex systems.

The high-level configuration structure of the AEDP is shown in Figure 2. The configuration structure and nomenclature for the UAS breakdown structure were adapted from the MIL-STD 881C [6]. In the context of the AEDP, the approach to systems engineering was tailored based on the timeline that the team has been negotiated with and given, the experience of the team and the number of participants within the team. The team is following the traditional (albeit tailored) stages and review gates for product or system development, i.e. requirements review, preliminary design review, critical design review, flight test readiness review, etc. The participants were during the commencement of the Phase 1 DDD project provided with a User Requirements Statement (URS) document that was compiled by the CSIR mentors (who emulated a typical client or end-user); the input document called for conformity with NATO STANAG 4703 regulations.

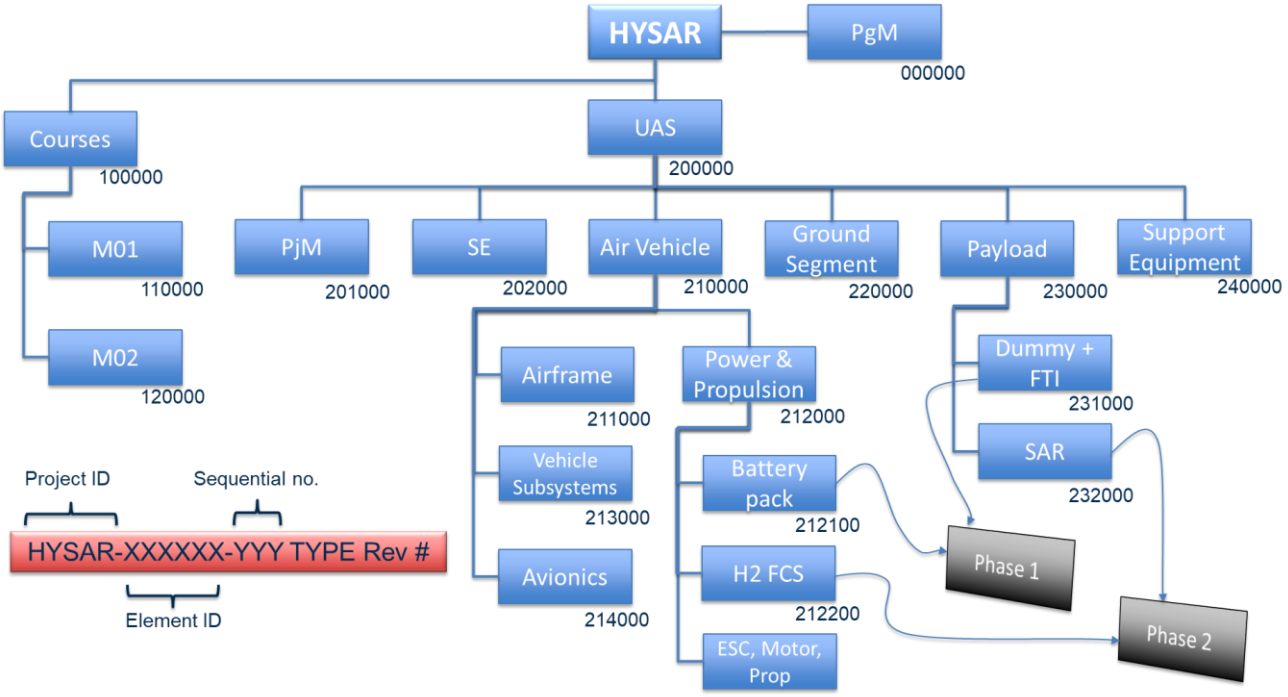


Figure 2: Configuration breakdown structure

3.1. Coursework

The M01 set of courses included overviews of essential 'soft skills' such as part project management, leadership mindset and team building. An introduction to systems engineering addressed technical processes and standards, as well as quality and configuration management. Specialised courses (for 'hard skills') included UASs design, flight mechanics, Guidance, Navigation & Control (GNC), Modelling & Simulation (M&S), Electro-Magnetic Compatibility (EMC), and airborne software considerations. The M02 (specifically for mechanical and aeronautical engineers) set of courses addressed Mechanical Computer Aided Design (MCAD) and product data management, aerospace manufacturing methods, composite materials, structural analysis, and aeroelasticity.

3.2. Project Management and System Engineering

Following the course work, the participants were divided into three sub-teams depending on their disciplines, organisational departments and responsibilities, and areas of interest, namely, i) aeronautical and mechanical engineers, ii) radar engineers, iii) electronic and mechatronic engineers. The aeronautical and mechanical engineers were primarily tasked with the airframe (including aerodynamics, flight performance, structural) design and analyses, as well as project management and system engineering. The radar engineers were tasked with the design updates and development of the SAR payload. The electronic and mechatronic engineers were responsible for the avionics, power and propulsion, and the Ground Segment (GS). This approach further fostered the typical nature of IPDTs.

Using the URS as input, the participants were first tasked during the requirements definition (Phase 0 in Figure 1), with formulating the Project Management Plan (PMP) and System Requirements Specification (SRS). The SRS was required to consider the context (and interfaces) in which the UAS will be operated in as shown in Figure 3. The previously (in another project) compiled SAR Sub-System Specification (SSS) and Interface Control Documents (ICDs) were also updated in parallel. Procurement of known long lead-time items from previous projects was also commenced. The approach was used to foster the typical risk management approach that is usually adopted with concurrent engineering.

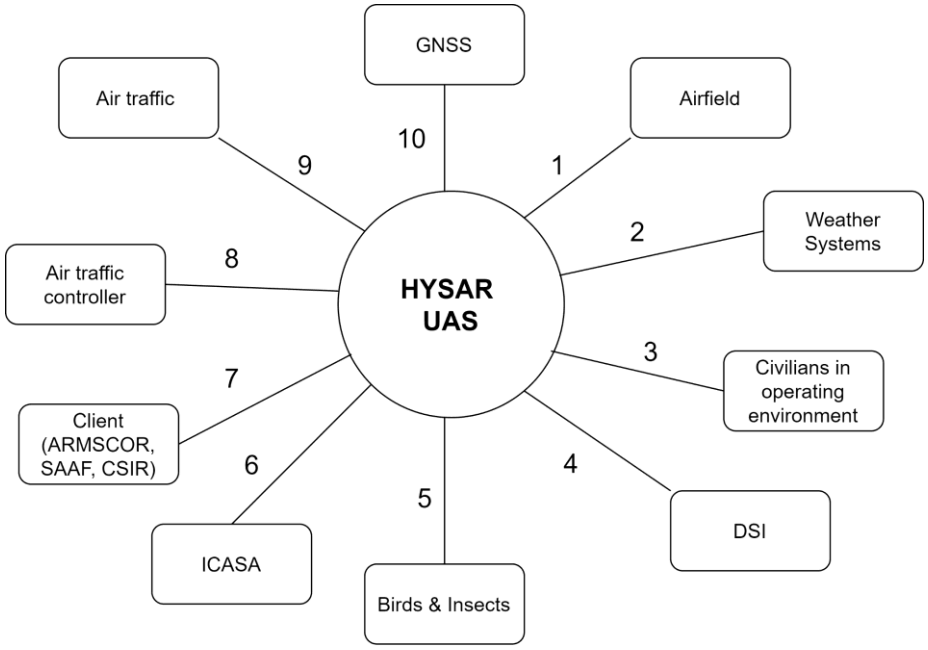


Figure 3: UAS context diagram

As part of the concept design stage, which overlapped with requirements definition, the Test and Evaluation Master Plan (TEMP) and the Functional Hazard Analysis (FHA) were compiled. Concept design was further overlapped with preliminary design, which then overlapped with detailed design as a result of various components and sub-systems of the UAS being at different technology readiness levels.

3.3. Literature and Market Studies

Various studies were undertaken during phase 0 (in Figure 1), during which criteria (such as performance, procurement lead times, cost, and export control considerations) and weights (relative importance) had to be defined. The identification and shortlisting of suitable hardware for flight control and ground control, as well as power and propulsion was performed. Key functions, interactions, sensors, actuators, modes, and safety measures involved in the flight control of a UAV were

evaluated. A functional architecture was also proposed with its related sub system components. The objective of the studies was to guide and inform the initial system's (and subsystems') conceptualisation.

3.4. UAS Design and Development

3.4.1. Aerodynamics and Flight Performance

The HySAR UAV aerodynamic design was developed from the mission requirements outward. The air vehicle was required to operate as a conventional take-off and landing UAV, initially carrying a dummy payload and flight test instrumentation, with later developments planned to integrate the SAR payload and hydrogen fuel-cell propulsion. The aerodynamic design was thus done to meet the flight performance requirements involving take-off distance, climb capability, cruise and loiter efficiency, stall margin, control authority, and static and dynamic stability.

The primary aerodynamic objective was to produce a stable, efficient, low-speed UAV capable of supporting a SAR-relevant mission profile while remaining within the overall aircraft mass and configuration constraints. The air vehicle has a maximum take-off mass of no more than 60 kg and the configuration must be compatible with the Packaging, Handling, Storage and Transportation (PHS&T) requirements as well as later subsystem integration requirements. These constraints influenced the final aircraft layout, but the aerodynamic design was primarily driven by the need to achieve safe and efficient flight over the required mission envelope.

3.4.1.1. Mission and Performance Basis

The aerodynamic design process began with mission modelling. The primary SAR mission (see Figure 4) was represented as a waypoint-based flight profile consisting of straight-line survey segments followed by a holding pattern. This mission definition established the relevant flight phases to be considered during the aerodynamic and performance assessment, including take-off, climb, cruise, loiter, descent and landing. Hydrogen fuel-cell propulsion was deferred to a later phase, allowing the Phase 1 aerodynamic and performance assessment to focus on the battery-electric demonstrator configuration. The placement of components including their mass and volumetric budget considerations, esp. within the fuselage was, however, taken into account throughout the requirements analyses/management and design process. That is for both the Phase 1 and 2 architectures.

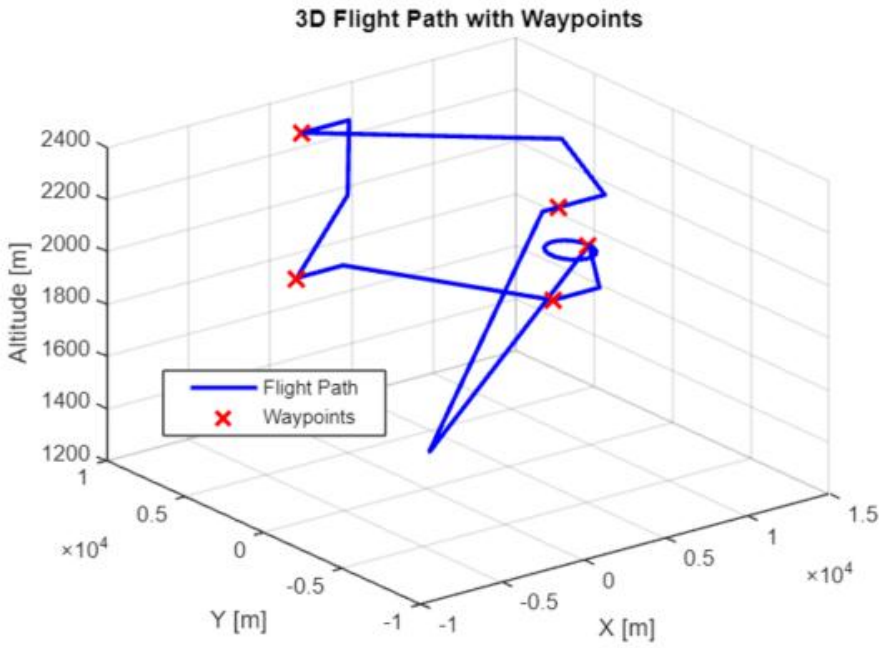


Figure 4: Mission profile

For each flight phase, the aircraft performance was assessed by considering aerodynamic drag, available propulsion power and energy consumption. Drag and thrust curves were developed for the flight envelope and used to simulate climb, cruise at mission altitude, loiter and descent. This allowed key performance parameters to be established including range, endurance and characteristic speeds.

3.4.1.2. Constraint Analysis and Aircraft Sizing

The aircraft sizing was performed using a constraint analysis approach. A constraint diagram was developed to determine the feasible combination of wing loading and required propulsion power. The relevant constraints included take-off run, climb rate, service ceiling and stall speed. This method allowed for a direct link between the aircraft geometry and the flight performance requirements.

From this process, the wing area, wing loading, aspect ratio, taper ratio, and propulsion sizing were established. The selected configuration was consistent with a low speed, endurance UAV. The use of a relatively high aspect ratio wing supports efficient cruise and loiter flight by reducing induced drag while the selected wing loading supports the low-speed operation required for take-off, landing and SAR relevant loiter conditions.

3.4.1.3. Wing Aerofoil Selection

The aerofoil selection was conducted in the low-Reynolds number regime expected for the HySAR UAV. Candidate aerofoils were assessed over an approximate Reynolds-number range of 200 000 to 850 000 with SAR operations concentrated around 300 000 to 450 000. The selection criteria included stable low-Reynolds number behaviour, reduced sensitivity to boundary-layer separation, high lift-to-drag ratio and adequate lift at low angles of attack. These behaviours were favoured for the HySAR as the mission required efficient flight at low speeds with predictable handling and trim characteristics during survey flight. Because of this, the sailplane aerofoil SA7038 was selected for the UAV.

3.4.1.4. Wing planform selection

The wing planform was selected by comparing alternative layouts, including constant chord, semi-tapered, straight leading edge and straight tapered configurations. The 100 m take off run

requirement at the design Maximum Take-Off Weight (MTOW) was treated as the critical sizing driver. This meant that the wing planform could not only be selected for aerodynamic efficiency in cruise, but it also had to generate sufficient lift at low speed to satisfy the take-off and landing constraints. The resulting wing (straight tapered high-aspect ratio) planform represented a compromise between low-speed lift generation and induced drag efficiency, stall behaviour, control surface integration and manufacturability. The high aspect ratio is beneficial for reducing induced drag during cruise and loiter, which supports endurance and range. The moderate taper ratio provides the aerodynamic efficiency benefits without introducing excessive tip loading or undesirable stall progression.

3.4.1.5. Wing Incidence, Twist and Dihedral

The wing rigging (incidence) angle was selected to minimize fuselage pitch attitude in cruise while avoiding unnecessary drag and empennage sizing penalties. This is particularly important for a SAR platform where payload orientation (relative to the scene of interest being imaged) can affect its suitability for the mission.

The wing-tip twist was added to improve the spanwise lift distribution and control the stall progression by preventing undesirable outboard stall, particularly when control surfaces are deflected. This supports safer low-speed handling because it helps preserve aileron effectiveness near stall.

Dihedral was investigated to provide lateral stability. However, due to the high wing configuration as required to allow the SAR adequate visual range, the lateral stability was sufficiently provided for by the high wing and dihedral was thus not required.

3.4.1.6. High-lift device design

The high-lift system was introduced because the clean wing alone could not satisfy the required take-off ground-run constraint. Flaps were therefore required to increase low-speed lift and reduce the take-off distance to below 100 m.

The high-lift design followed a staged analysis process. Initial flap sizing was performed using lower-order aerodynamic tools such as panel methods, which are useful for rapid concept screening and early comparison of configurations. However, because large flap deflections introduce non-linear flow behaviour, separation and increased modelling uncertainty, higher-fidelity computational fluid dynamics (CFD) analysis was then used to assess larger flap deflections. The comparison between clean-wing panel-code results and CFD provided confidence in the modelling approach before the flapped configurations were assessed as shown in Figure 5. From this investigation, the size, location and deflection required of the flaps could be established.

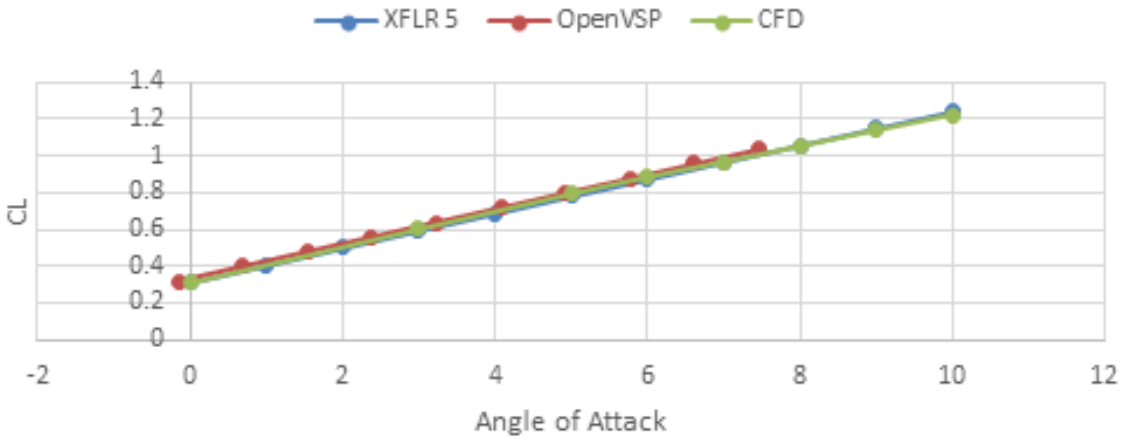


Figure 5: Lift coefficient comparison between panel codes and CFD

3.4.1.7. Aileron and Roll-Control Design

The ailerons were sized to provide sufficient roll authority throughout the mission envelope. The selected aileron geometry had to provide adequate control response while avoiding excessive outboard loading and tip-stall risk. This is particularly important for a high-aspect-ratio UAV wing, where control-surface placement and deflection can strongly influence local stall behaviour.

3.4.1.8. Empennage

3.4.1.8.1. Horizontal Tail and Pitch Stability

The horizontal tail design was driven by longitudinal (static) stability, trim and take-off rotation requirements. It was sized using static-margin and pitch-stiffness criteria. The elevator was sized to provide adequate take-off rotation and trim authority. The design pitch-rate requirement was considered together with the available elevator deflection range. The pitch-control design was also coupled to the landing-gear layout. Take-off rotation depends on the relative positions of the centre of gravity, main landing gear, horizontal tail and elevator. The landing-gear and empennage arrangement therefore had to be considered together to ensure that the aircraft could rotate safely during take-off without excessive elevator demand or tail-strike risk.

3.4.1.8.2. Vertical Tail and Directional Stability

OpenVSP was employed to support the preliminary sizing of the vertical tail, with particular emphasis on directional (static) stability requirements. The placement of the vertical tail was constrained by the available fuselage length, limiting its longitudinal position to the aft-most feasible location. Consequently, the tail was positioned at the end of the fuselage, and its planform area was maximised in accordance with vertical tail volume coefficient guidelines reported in the literature. Despite this, stability analyses conducted within OpenVSP indicated that the resulting configuration did not provide sufficient directional stability. Due to time limitations, it was not feasible to conduct higher-fidelity analyses to confirm or refine this finding. As a risk mitigation method, it was decided that additional stabilisers would be used but manufactured and be designed to be detachable as the FT progresses and the yaw stability is validated. The additional stabilising surfaces were implemented as end plates on the horizontal stabiliser, effectively adding an H-tail configuration. This approach allows for flexibility in validating yaw stability characteristics during the flight test campaign while minimising the risk of over-design in the baseline configuration.

3.4.1.9. Dynamic Stability

Once the aircraft was shown to be statically stable, it then had to be evaluated for dynamically stability. This was done using XFLR5 to compare the aircraft to the levels of acceptable flying and handling qualities as specified in the MIL-STD-1797A. Preliminary estimates of masses and inertias were used as inputs based on analysis from OpenVSP's computation. The phugoid, short period, roll subsidence, spiral and dutch modes were all analysed and shown to be level[1] 1 ratings on the flying and handling qualities scale, with the exception of the phugoid being a level 2. These values are planned to be updated as the project matures.

3.4.2. Structural Design

The purpose of this AEDP is to provide early-career engineers with an opportunity to develop practical skills and experience in the development of aerospace systems. This, for the first cohort, is achieved through the design and manufacture of a functional prototype, with direct involvement from participating engineers throughout the process. In this context, the manufacturing approach avoids the use of advanced or specialized materials and techniques, instead favouring established methods

[1] Levels 1, 2 or 3, with 1 meaning the least workload on the pilot and 3 being the highest (or worst case).

that are more accessible and suitable for rapid prototyping. These choices prioritised manufacturability and availability over structural efficiency, even where this results in weight penalties.

Consequently, the aircraft structure is limited to materials such as basic carbon fibre laminates, wood, and foam. Metallic materials are used only for localized fittings and inserts, and are not employed for skins or internal reinforcement within the fuselage, empennage, or wings.

The structural design follows a philosophy in which loads are carried primarily by an internal arrangement of structural members, while the external skin is idealized as non-load-bearing and serves primarily aerodynamic functions. This approach is less structurally efficient than monocoque or semi-monocoque construction, and therefore results in a higher structural mass. However, it offers simpler and more clearly defined load paths, which facilitates analysis and experimental verification, as the contribution of the skin can be neglected in first-order structural assessments.

The fuselage structure consists of a series of bulkheads, frames, and longitudinal stiffeners linked together to form a continuous load-bearing framework. This framework is encapsulated within a Carbon Fibre Reinforced Polymer (CFRP) skin, which maintains the aerodynamic shape but does not contribute significantly to the primary load carrying structure.

The lifting (wing, empennage and control) surfaces are to be constructed using a polystyrene foam core combined with spars and ribs that carry the primary structural loads. The foam core defines the aerofoil geometry, while an external CFRP overwrap provides surface integrity and maintains the aerofoil shape under operational loading.

All lifting surfaces are designed to be detachable from the fuselage, with the wing further subdivided into three sections. This enables the aircraft to be disassembled and packaged into a configuration suitable for transportation.

3.4.3. Family Tree

The UAS is composed of numerous individual parts, including fasteners, servos, and wiring. The total number of components is substantial, making it challenging to manage both the development and subsequent construction of the aircraft in a controlled manner. Consequently, a family tree was developed to address this complexity.

The family tree provides a hierarchical representation of the aircraft, decomposing the system into assemblies, sub-assemblies, and individual components. It explicitly defines the parent–child relationships between elements, thereby capturing the full assembly architecture of the aircraft. Within the family tree, each component is assigned a unique part number, enabling traceability throughout the design, manufacturing, and assembly phases. This also supports configuration management by ensuring that component definitions, versions, and their relationships are consistently tracked across the lifecycle of this prototype aircraft. A high-level perspective of the family tree is illustrated in Figure 6 (and Figure 2). This structure mirrors the intended assembly and manufacturing process, moving from discrete parts to sub-assemblies, the airframe, and ultimately the complete vehicle. The approach ensures a logical representation of the system architecture and supports efficient management of the design and production workflow.

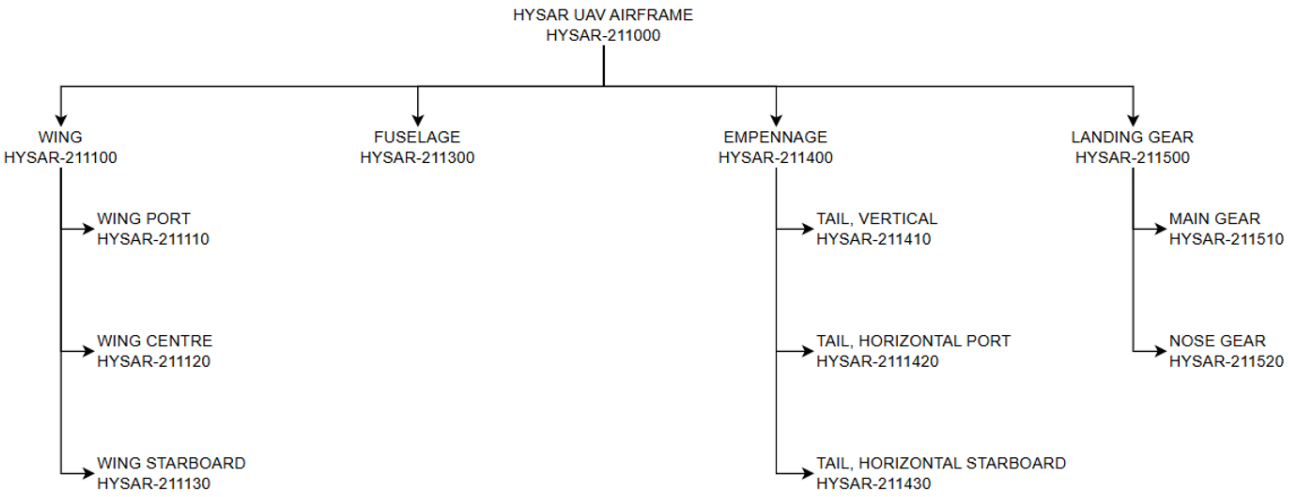


Figure 6: High-level view of the HYSAR UAV family tree

The primary function of the family tree is to assign unique part numbers to every component within the airframe. These identifiers provide consistency across technical documentation, CAD models, engineering drawings, and manufacturing instructions. By establishing a standardized numbering system, the framework enables full traceability of components throughout the design, manufacturing, and assembly lifecycle. This traceability is critical for quality assurance, configuration management, and compliance with engineering standards. In addition, the family tree defines separation points between assemblies, allowing sub-assemblies to be managed independently during manufacturing and during PHS&T. Key identifiers within the system include 103 for the family tree itself, 203 for custom-designed parts, 226 for Commercially Available Off-The-Shelf (COTS) components, and 202 for assemblies. These identifiers provide a clear taxonomy for component classification, supporting both technical integration and logistical management of the air vehicle.

3.4.4. Power and Propulsion

The design of the Power and Propulsion (P&P) subsystem was centred on ensuring reliable generation, distribution, and management of electrical power across all UAV components, including avionics, payload, servos, motors, and propellers. This subsystem plays a critical role in maintaining overall system stability, performance, and mission success. Its scope required careful consideration of both electrical and mechanical interfaces, as well as electromagnetic interference/compatibility/susceptibility to guarantee seamless operation under diverse flight conditions.

The work on P&P included requirements analysis, battery selection and validation to match mission requirements, the design of a robust power distribution architecture, and detailed electrical load analysis to balance peak and steady-state demands. Additional tasks involved component layout and sizing, mass estimations, thermal management and fault detection planning to prevent overheating, structural integration to optimise battery placement and safety, redundancy, and the development of charging and ground support systems. Safety and compliance checks were also integral, ensuring adherence to aviation standards and the incorporation of redundancy and fail-safe mechanisms. Preliminary performance estimation further supported design refinement by simulating UAV behaviour under varying load conditions.

3.4.5. Avionics

The avionics subsystem of the HySAR UAV is tasked with the role guidance, navigation, control, and communications. At its core is the main flight computer, which manages the environment sensing,

data processing, actuator commands to control surfaces, and propulsion motor regulation via the Electronic Speed Controller (ESC). It also facilitates communication with the Ground Control Station (GCS) (a subset of the Ground Segment (GS)). A companion computer supports off-board diagnostics and parachute deployment, thereby enhancing safety. The subsystem's development involves compiling requirements and designing hardware, software, and firmware to ensure seamless integration and reliable operation.

The functional requirements of the avionics subsystem establish its high-level capabilities and operational needs. These include flight management for mission execution, flight control for stability and mode switching, and a sensor suite to provide raw data for navigation and safety monitoring. Guidance and navigation functions enable accurate trajectory computation, while data logging supports post-flight analysis. Additional requirements encompass diagnostics for anomaly detection, safety and emergency management, and a communication subsystem for command execution and data exchange with the GCS. Mission planning and execution are also integral, ensuring alignment between system design and stakeholder expectations.

Prior to integration into the UAV airframe, hardware-in-the-loop simulation (HILS) is required to support firmware and software development and hardware integration. The HILS workbench (see Figure 7), that has been progressively assembled as components are procured, provides a controlled environment for testing and validation. This approach ensures that avionics functions are thoroughly evaluated before physical integration into the UAV, thereby reducing risks and enhancing reliability in the final UAS.

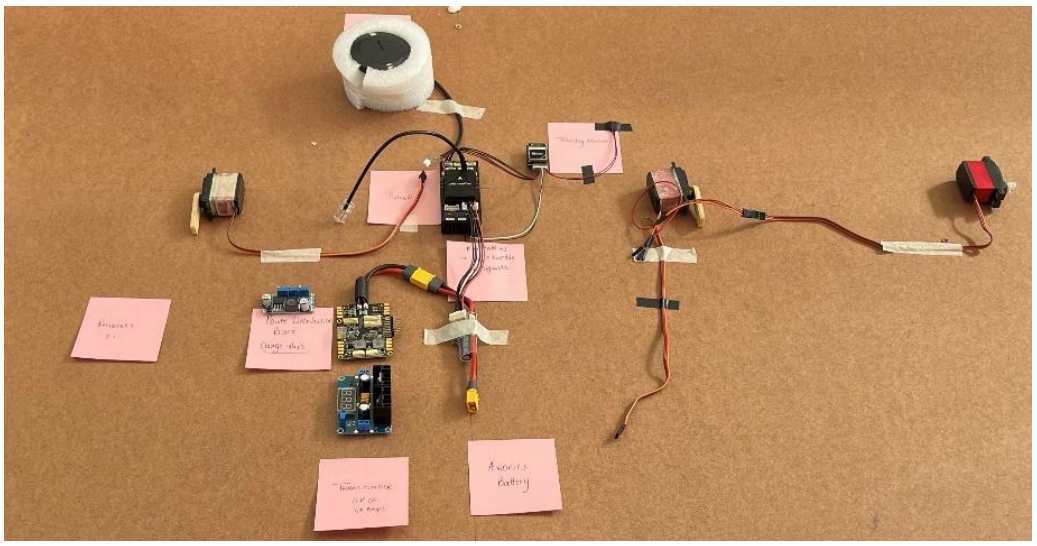


Figure 7: HILS workbench

3.4.6. Ground Segment

The Ground Segment (GS) encompasses all hardware and software required to operate the UAV in both manual and autonomous flight modes. It provides the communication infrastructure between the payload and its ground control workstation through dedicated radio links and networking systems. In particular, a Very High Frequency (VHF) radio ensures compliance with aviation regulations during flight testing. The GS thus serves as the central hub for mission execution, communication, and regulatory compliance.

The objectives of the GS are broad and multifaceted. They include mission planning for autonomous waypoint navigation, manual aircraft control at any stage of flight, and telemetry monitoring to display real-time status information. The GS also supports data processing and analysis by enabling log file

transfer to dedicated workstations for post-flight evaluation. Communication and link management are achieved through dual radio systems—one for UAV command and control, and another for payload communications. Safety and compliance are reinforced through geofencing capabilities and adherence to frequency regulations, while ergonomic human-machine interfaces aim to reduce the pilot workload.

Further objectives extend to logging and documentation of all telemetry data, implementing robust security and access control measures, and integrating environmental data from support equipment. Collectively, these functions ensure that the GS not only enables effective mission execution but also enhances safety, regulatory compliance, and operational efficiency. By combining technical robustness with user-centred design, the GS provides a comprehensive platform for UAV control and mission management.

3.4.7. Verification of Command and Control

The planned HySAR-*α* avionics communications and geofence verification test that is to be conducted at a local (to the CSIR) airfield is meant to verify safety-critical UAV subsystems and UAV, prior to full integration with the airframe. The test is to employ a portable Alpha avionics node (mounted on the roof of a ground vehicle) as a surrogate for the UAV's onboard avionics. This approach is to enable a controlled evaluation of communications and geofence functions in a ground-based environment.

Three procedures are to be executed during the test campaign: assessment of the Command and Control (C2) link range and performance (Test C-1), verification of manual control and telemetry visibility (Test C-2), and evaluation of geofence loading and behaviour (Test G-C-1). Each procedure is directly traceable to the HySAR System Requirements Specification (SRS) and ultimately the User Requirements Specification (URS), ensuring alignment with system- and user-level objectives. The verification discipline followed established systems engineering practices as outlined in the NASA [7] and INCOSE [8] handbooks, thereby providing a structured framework for compliance demonstration.

Key performance parameters verified include the C2 link range, received signal strength, packet loss, command latency, telemetry update rates, and geofence breach detection. All test evidence is to be systematically logged and retained to support the HySAR system-level safety case and to inform subsequent flight-testing activities. This structured verification process is expected to provide confidence in the avionics subsystem's ability to meet derived communications and geofence requirements under operational conditions.

3.4.8. Payload Performance Verification

A bench demonstration was conducted in the SAR laboratory in 2025. This exercise focused on validating the mission planning software, payload controller software, and the live operation of the C-Gull SAR payload. Additionally, the demonstration included testing the real-time processors of the payload through the use of pre-recorded data, thereby providing an initial assessment of system functionality in a controlled environment.

To extend verification beyond laboratory conditions, a vehicle drive test was undertaken to evaluate the operational performance of the C-Gull SAR payload. For this test, the payload was packaged into an ammunition crate, powered by a battery, and mounted on a ground vehicle. This setup enabled the payload to be tested under dynamic conditions while maintaining portability and safety. The drive test facilitated the assessment of multiple payload functionalities in a realistic operational context, complementing the laboratory demonstration. Together, these activities provided critical insights into the performance and reliability of the payload, while also informing software optimisation and system integration strategies for subsequent stages of development.

4. Findings

4.1. Project Management

A central limitation of the programme was the responsibility of project management and air vehicle (airframe-focused) design leadership residing in a single individual. This dual responsibility resulted in neither function receiving sufficient attention. Routine project control activities—such as planning, progress tracking, and reporting—were inconsistently executed, leading to weak schedule discipline and diminished visibility of project status. The situation was exacerbated by the fluctuating team availability (as result of working on multiple projects simultaneously), often with little notice and without clearly defined return timelines. Frequent movement of personnel between projects and reallocation of tasks thus resulted in the loss of tacit knowledge and increased the need for rediscovery of previously completed work. Consequently, task allocation and scheduling became unstable, undermining the reliability of established plans for the AEDP.

The project structure further relied on junior engineers to lead subsystems' development. While this provided valuable developmental opportunities, it also introduced challenges in defining clear, end-to-end task tasks for aircraft design in a highly regulated environment. Although subsystem tasks were initially agreed upon, execution gradually diverged from these plans. As a result, the project schedule as represented in the Gantt chart became misaligned with actual progress. This disconnect contributed to an outdated risk register, delayed tasks, and inaccurate planning forecasts.

As the project progressed, several corrective measures emerged. Clearer task definitions and more realistic duration estimates led to improved planning accuracy. It also became evident that stricter adherence to schedules was necessary, with accountability mechanisms to ensure team members met the agreed deadlines. Importantly, the project manager was required to maintain a working understanding of all technical domains to assess the complexity and interdependencies of tasks effectively. Explicit mapping of task dependencies—identifying prerequisites, parallel activities, and sequencing—was recognised as essential for coherent execution.

A distinctive challenge in teams composed of early-career engineers is the necessity of an adequate upfront learning phase. Engineers require time to explore problems, understand tools, and validate methods before applying solutions effectively. While this process temporarily slows early progress, it is fundamental for ensuring technically sound outcomes later in the project.

4.2. Systems Engineering

The programme encountered significant systems engineering challenges in the lead up to the planned first FT, primarily related to resource constraints, procurement complexity, and late-stage organisational structuring. A persistent issue was the limited number of engineers relative to the programme scope, compounded by inconsistent availability due to competing organisational commitments. This had a particularly pronounced impact on airframe design, where progress depended heavily on a small number of contributors.

Procurement posed a particularly major risk area. Many required COTS components involved long lead-times and complex acquisition procedures. Mandatory procurement protocols, including tendering processes and approval workflows, introduced delays and required engineers to divert time from technical work to administrative support. Additionally, the absence of a formal agreement with an airframe manufacturer restricted early supplier involvement in the design process, limiting opportunities for iterative design-for-manufacture engagement.

Operational readiness challenges also extended to pilot selection/securing for the initial FT, which remained unresolved despite engagements with external organisations. Concurrently, fundamental issues in the design process—such as the late introduction of the airframe "family tree", affected

traceability and project organisation. The family tree, which defines part hierarchies, was only implemented after some design work had already begun. This resulted in inconsistencies in part numbering and increased difficulty in tracking maturity of design artefacts across subsystems.

Despite its delayed introduction, a consistent family tree proved to be a valuable systems engineering tool. It enabled traceability and effective communication between participants who were responsible for CAD models, component and assembly drawings, design and analysis work packages, and design reviews, while also supporting structured task allocation from component level to full assembly. The experience underscored the importance of establishing product architecture and traceability frameworks early in the design process. Although defining an optimal structure at the concept stage was found to be challenging, it was found to be a transferable and essential skill in aerospace engineering projects.

4.3. Air Vehicle Design and Development

The design and development (D&D) of the air vehicle began with mission modelling, performance modelling and conceptual layouts. This was followed by iterative designs of the wing, fuselage, empennage, lifting devices, control surfaces, payload bay and landing gear. The schematics, modelling and simulations, as well as component selections for the avionics, power and propulsion, and ground segment (GS) were also done in parallel. The air vehicle and GS D&D lagged that of the payload as shown in Figure 1, since the latter is centric to executing the system's mission. The initial D&D of the payload thereby resulted in a bench demonstration of the subsystem in 2025. Further refinements of the payload are currently underway to have an optimally packaged and performing payload in the required form factor for integration into the UAV during phase 2 of the HySAR UAV.

The detailed design of the airframe, in parallel with procurement and integration of hardware, as well as development of software and firmware which are currently underway, with the maiden FT for Phase 1 of the HySAR UAV planned for 2027. The model (work in progress) of the air vehicle is shown in Figure 8. The air vehicle is being designed for a 6-metre wingspan and a maximum take-off mass of no more than 60 kg. PHS&T considerations and other 'ilities' (manufacturability, affordability, accessibility, operability, testability, assembly / disassembly considerations, etc.) at large, have thus had to be an essential part of the D&D from the outset. Case in point includes the decision to section the wing into three parts of 2 metres each, as well as keeping the fuselage length to the same 2 metres. Aviation authorities' (military and civil) requirements for approval of flight trials have also been a key driver in the decision-making during the D&D.

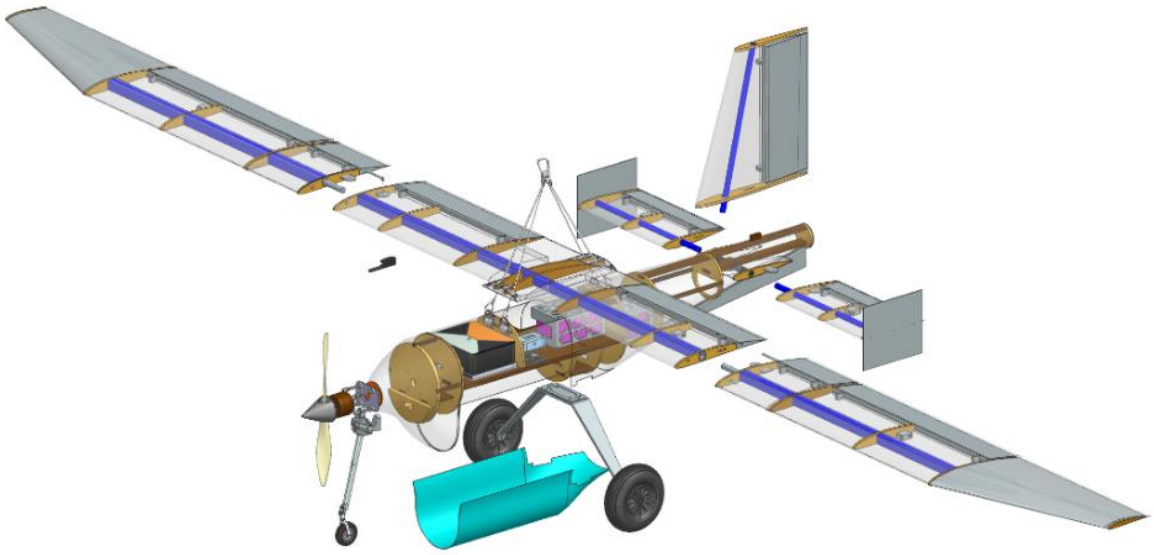


Figure 8: Model (in development) of the HySAR UAV

The primary challenge in airframe development was the lack of continuity in engineering effort. While a nominal 50% participation per team member was initially planned, the actual engagement was inconsistent. In practice, one core engineer carried the majority of the workload, while others contributed intermittently. This resulted in incomplete tasks that could not be seamlessly resumed, as subsequent contributors needed to relearn the context and to validate prior work before continuing with existing or proceeding with new tasks. This discontinuity shifted the project from a parallel workflow model to a sequential one. Critical activities such as aircraft sizing and subsystem integration became tightly coupled, with downstream tasks dependent on the resolution of upstream analyses. Consequently, the system-level progress was delayed despite attempts to distribute workload across the team.

The schedule risks/issues were further amplified by incomplete interface definitions—particularly at wing–fuselage and wing–wing junctions. Any late design changes risked and/or resulted in rework. Additionally, resource availability increased vulnerability to delays arising from unplanned absences or context switching. Rapid decision-making under schedule pressure also introduced quality and airworthiness risks when assumptions and verification strategies would possibly not be adequately documented and verified.

Mitigation strategies included redistributing aerodynamics' tasks across team members and formalising a minimum viable set of interface definitions within an ICD. This approach supports early manufacturing while allowing remaining design work to continue in parallel. Treating variable team availability as a design constraint—through structured handovers and concise documentation—was identified as critical to maintaining progress.

From a technical perspective, ensuring accurate load cases' definition before structural sizing exercises proved essential. Incorrect or incomplete load assumptions could result in unsafe or overly conservative designs. The project also highlighted the importance of coordinating interdisciplinary inputs, as dependencies between aerodynamics, structures, and operational subsystems' design, as well as manufacturing and testing considerations often introduced delays.

Furthermore, practical constraints, such as aerofoil thickness limitations and transport restrictions (e.g., 2 m component length limits) necessitated design compromises, including the introduction of structural joints. These considerations reinforced the need for concurrent engineering, where

structural, manufacturing, and logistical requirements are addressed simultaneously.

Despite these challenges, the programme achieved substantial capability development. Engineers improved in verification and validation practices, numerical reasoning, and professional communication. The project remains viable, provided that execution focuses on interface stabilisation, parallel integration activities, and disciplined systems engineering practices.

4.4. Subsystems: Propulsion, Avionics, Payload, and Vehicle Subsystems

Subsystem development presented a diverse set of technical and logistical challenges. In the P&P domain, difficulty in sourcing a suitable COTS power distribution unit led to a redesign approach in which subsystems were powered by dedicated batteries. This ensured compatibility with ESCs and motor requirements but introduced additional design considerations.

Across subsystems, procurement delays were a recurring issue, largely due to reliance on international suppliers due to limited local availability. These delays were compounded by administrative and legislative requirements, particularly in the avionics' procurement, where approval processes and upfront payment negotiations extended the lead-times and reduced the time available for testing and simulation.

Vehicle subsystems (as per Figure 2) development also faced challenges in component selection and system integration. For example, identifying a suitable servo rail relay unit required design updates, including reducing the servo count and reallocating power responsibilities. These challenges highlighted the importance of early and precise specification of component requirements to streamline procurement and reduce redesign cycles.

The payload (SAR) subsystem encountered technical setbacks related to Printed Circuit Board (PCB) manufacturing inadequacies, as well as firmware and software integration issues. These required iterative redesign and extensive testing. Nevertheless, the team maintained progress by continuing subsystem integration using alternative interim setups and components available in the laboratory from other projects during procurement delays. Key lessons from the payload development included the importance of clear requirements definition, iterative system validation, and continuous stakeholder engagement, particularly for user-interface design. Thorough testing revealed software bugs and optimisation opportunities, reinforcing the value of early and repeated verification activities.

Overall, the development of the payloads underscored the need for proactive procurement strategies, parallel task execution during delays (that were not within the project's delay), and strong communication across teams to ensure alignment during integration of the subsystems, as well as the verification and validation of the UAS.

5. Conclusions and Recommendations

The AEDP provides experience to early career engineers within the full scope of aerospace systems/product lifecycles in an IPDT. It also serves to bolster the skills that have been lost in recent years from South Africa. A balance is struck between the technical (hard) disciplines and soft skills to allow for employable and highly productive individuals in an accelerated timeframe. Sets of short courses are provided and then reinforced with a DDD project that fulfils typical real-world needs. The highly complex and challenging nature of the DDD project that is current and relevant to South Africa's aerospace and defence industry thus contributes to mitigation of her 'brain drain' that is discussed in [1], [2] and [3].

Many of the AEDP coursework providers and DDD project mentors are alumni, external examiners, curriculum reviewers, research supervisors and/or part-time lecturers/researchers of local universities. This allows for closer collaboration between academia and industry as recommended in

[1] and [4]. The selection of participants from various engineering disciplines and the DDD project in an IPDT contributes to bridging the gap between academia and industry (as discussed in [1]) for graduate engineers. Knowledge and experience are thus gained on standards, regulations and best practices on subjects such as configuration and quality management, aviation regulations and product lifecycle management that are essential for industry, but not necessarily a focus area for undergraduates.

The programme illustrates the complex interplay between project management, systems engineering, and technical execution in a resource-constrained environment. While challenges in staffing, procurement, and coordination introduced delays and risks, they also provided critical learning opportunities for the participating early career engineers. The key to future success lies in fundamental role separation between the participants, early systems engineering discipline, proactive risk management, and robust communication processes. By institutionalising these practices, the programme can achieve its dual objective: delivering a functional aerospace system, as well as developing capable, self-sufficient engineers.

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