Fixed Wing Modular UAV Design and Development

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Mini-UAV platforms are quickly becoming a reliable, versatile and effective airborne system. However, they are generally only suitable for a specific mission or small range of missions due to their limited size and payload capability. The objective of this project is to determine if it is feasible to develop a UAV platform that can undertake a variety of missions by variation of the aircraft size and performance capability through a modular concept. A literature review of the current UAV market environment was conducted to investigate the scope and extent of modular UAV’s in use and under development. A comprehensive set of requirements, engineering specifications and targets were developed for the design in order to satisfy a preliminary set of governing requirements for four specific missions in the category of; basic, extended range, extended loiter and extended payload missions. The conceptual design of a modular UAV was undertaken, producing primary outputs of preliminary weights, geometric features including CAD models, performance specifications and estimates for development, production and operational costs for the UAV in two separate configurations; basic configuration and extended range configuration. Recommendations on the feasibility of using a modular concept to satisfy the multi-mission requirements of the design were made based on the merits and shortcomings identified from the conceptual design in terms of performance, engineering merit and financial plausibility. A primary finding of the project identifies that the feasibility of a modular UAV concept would be likely to rely heavily upon the expected percentage of use of the UAV in each modular airframe configuration. Given that the conditions of expected usage by prospective customers meets the recommended range of feasible use of the aircraft in each modular configuration, the modular UAV designed represents a unique and elegant design solution to satisfy all the requirements of the project with a high level of merit and efficiency.

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Nomenclature

\( UAV \) = Uninhabited Aerial Vehicle
\( W_t \) = Takeoff Weight [lb]
\( W_P \) = Payload Weight [lb]
\( W_f \) = Fuel Weight [lb]
\( W_e \) = Empty Weight [lb]
\( AR \) = Aspect Ratio
\( c \) = chord length [m]
\( b \) = Wing Span [ft]
\( S \) = Wing Area [ft\(^2\)]
\( W/P \) = Power Loading [lb/hp]
\( W/S \) = Wing loading [lb/ft\(^2\)]
\( MMH \) = Maintenance Man hours [hr]

I. Introduction

A. Background

The aerial battle space environment is an ever evolving concept due to advances in aeronautical technology and changes to civilian and military objectives. A natural consequence to this effect is the dynamic nature of the requirements defined for aerial platforms such as UAVs in order to deliver various levels of air power capability. “The huge growth in the variety of Uninhabited Air Vehicles (UAVs) and their increasing importance in the contemporary operating environment represent one of the most significant and dramatic advances in air power capability over the past decade” (Torpy, 2009).

Advances in UAV technology have led to many air forces adopting uninhabited aerial vehicles in order to achieve aerial capabilities in a wide spectrum of mission profiles such as surveillance and reconnaissance, close air support and payload carriage. Typically, most of the current UAVs in service today are designed to perform a specific type of mission, and are therefore somewhat limited in terms of the aerial capability and air power they are able to efficiently provide. For many of the smaller organisations and air forces expressing a requirement for UAV platforms to a much wider range of missions (i.e. Multi-mission), it would typically be impractical to acquire and operate multiple UAV platforms in order to fulfil these requirements, primarily due to the high financial penalty and increased logistical and maintenance support required in order to maintain multiple UAV platforms. An alternative to the use of multiple UAV platforms in order to carry out multiple missions has been proposed, in the form of a single, multi-mission modular UAV concept.

The purpose of this paper is to outline the strategy, method and outcomes of investigating the feasibility of the design and development of a modular UAV concept that will fulfil the requirements of multiple missions and therefore serve as an alternative to the purchase and implementation of multiple separate platforms in order to fulfil the multi-mission range of requirements. The modular UAV concept will need to accommodate for quick variations in geometry, power plant and systems in order to be deemed a viable candidate to achieve a diverse range of requirements for changing missions including basic, extended range, extended loiter and increased payload missions. These individual missions have been quantitatively defined by an initial set of governing flight performance requirements, shown below in table 1. For the purpose of the conceptual design process, the modular UAV concept will be named the BU-11 Tycus modular UAV.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Service Altitude (ft)</th>
<th>Range (nm)</th>
<th>Endurance (hr)</th>
<th>Payload (lb)</th>
<th>Payload (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>25000</td>
<td>7620</td>
<td>500</td>
<td>926</td>
<td>1</td>
</tr>
<tr>
<td>Increased Payload</td>
<td>25000</td>
<td>7620</td>
<td>500</td>
<td>926</td>
<td>1</td>
</tr>
<tr>
<td>Extended Loiter</td>
<td>25000</td>
<td>7620</td>
<td>100</td>
<td>185</td>
<td>24</td>
</tr>
<tr>
<td>Extended Range</td>
<td>25000</td>
<td>7620</td>
<td>2500</td>
<td>4630</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1. BU-11 Governing Multi-Mission Requirements
The design component of the project included the development of a comprehensive set of essential and desirable requirements for the UAV system, the conceptual design of a modular UAV platform, development of a modularity concept and generation of detailed 3 dimensional geometric descriptions of the modular UAV concept aircraft in various configurations, in order to fulfil the stated tasks of the project specification shown in Appendix B.

The evaluation component of the project based on the outcomes from the conceptual design process included an analysis of the feasibility of the concept aircraft in terms of financial penalty, engineering merit, manufacturability and general practicality of the designed UAV. All calculations and parameters discussed and presented in this report have been given in imperial units, as is the international convention for aircraft design, metric duplicates have also been provided in tables for moderation.

B. Aim
The aim of the project is to comprehensively detail the conceptual design process undertaken for the BU-11 Tycus modular UAV, and to effectively discuss the feasibility of the designed modular concept. The technical information, design data and material provided in this project suggest a significant opportunity for further development. As such, the key intention of this document along with the highly detailed deliverable project report is to provide a significant level of detail as to the key design considerations and strategy adopted whilst attempting to satisfy the requirements of the project, in order to allow for the successful continuation of this design project by future UNSW@ADFA engineering students.

C. Scope
The beauty of aircraft design is that for any single problem/set of requirements, there may exist an infinite number of possible solutions, all of which are capable of achieving the same outcome. The general goal of any conceptual design is to generate the geometric description of an aircraft that is optimised to fit a given set of requirements as efficiently and effectively as possible. As such, the proposed solution to the modular UAV concept presented in this document represents only a single solution to the set of design requirements detailed in Appendix A, and as such, it is important to note that the feasibility of a modular UAV concept in this study has been assessed based purely on the results and merit of this conceptual design alone.

II. Literature Review
Significant reductions in essential design parameters such as takeoff weight and overall size of a UAV airframe are made by the elimination of the need for human aircrew, through the implementation of remotely controlled and autonomous flight controls. This implies that smaller uninhabited aircraft may be designed to complete similar mission profiles to those of much larger, less efficient manned aircraft. This characteristic alone strongly suggests an advantage of the use of uninhabited aerial vehicles in modern applications over conventional manned aircraft for the completion of a range of civilian and military objectives.

A detailed weights and sizing analysis should reveal a reduction in sized takeoff gross weight of perhaps 10-30 % (Raymer, 2006). This estimate of weight saving due to the absence of a manned aircrew is considerably lower than initially predicted, due to the significant weight penalty induced by the increased avionics and cooling systems required by an uninhabited aerial vehicle over a standard manned aircraft.

Modular concepts exist in current UAV designs on a limited scale. The “IMPULLS” UAV (Innovative Modular Payload UAV – TU LLS), designed and developed by postgraduates of the Technical University of Munich (TU München, 2011), has utilized the concept of modular payload capsules in the aircraft’s fuselage in order to accommodate for various combinations of sensors. “The IMPULLS batteries which drive its single propeller, positioned at the aircraft’s tail, can be moved up or down the body to balance out the weight distribution” (Lewis, 2011). However, this type of UAV is only suitable for use in small scale, civilian operations, comprising of a wing span of 5m, empty weight of 20kg and a maximum endurance of only 75 minutes (TU München, 2011).

One civilian developed UAV with particular relevance to this project in terms of modularity is the Barnard Microsystems InView Unmanned Aircraft System. The InView UAV is a highly demountable system, designed for use in scientific and commercial mission profiles. “The InView is assembled within an hour from modules that can easily be transported in a small vehicle. Individual sections

![Image of InView UAV in disassembled and in-flight conditions.](Images courtesy of Barnard, 2011)
can be upgraded to suit a particular mission, or replaced as part of routine maintenance or as a result of damage sustained” (Barnard, 2011). Figure 1 provides a description of the highly modular nature of the InView UAV. The InView UAV is quoted as capable of completing multiple missions including maritime border patrol, wide area surveillance and reconnaissance, research and development and flight training. This type of highly modular airframe seen in figure 1 is however, again restricted to a small scale and overall size, comprising of a wing span of 4 meters, empty weight of 19.5 kg and total engine power of 4.83 hp.

Yet another small scale modular UAV project of interest to this investigation is the modular UAV development for the South African Council for Scientific Research by (Monk, 2010). The study involves the design and development of a Modular UAV to provide the capability to demonstrate a wide range of novel technologies and/or sub-systems of typically less than 10 kg (Monk, 2010). The UAV has been shown to achieve modularity through variations in payload and avionics capsules, as well as changes to wing and tail geometries.

The review of literature relevant to modular UAV conceptual design and development has shown that modular concepts do in fact exist and have been proven to be plausible on small scale aircraft. The main characteristic of this project that makes it unique from other studies and concepts in this area is the significantly larger scale of defined governing multi-mission requirements, and therefore the considerably larger expected size of the UAV to be designed in order to accommodate them.

A secondary component of the literature review involved a detailed survey of current UAV platforms in service that demonstrated performance capabilities similar to those required for each mission detailed in table 1. A set of four existing aircraft were selected to serve as benchmark aircraft for conceptual design of the Tycus modular UAV. The benchmark aircraft were selected based on the criteria of how closely their specific performance capability matched each of the missions the Tycus was designed to achieve and the level of geometric similarity with the other benchmark aircraft. The four aircraft selected using Jane’s (IHS Jane’s, 2011), were all of the same manufacturer; General Atomics, including the Prowler I, Prowler II, Gnat and the Predator RQ1A. A brief summary of the benchmark aircraft specifications is provided in Appendix C. The specifications of the selected benchmark aircraft were used to provide a mode of comparison and moderation during the setting of engineering specifications and targets for the design, as well serving as a valid reference during the development of the Tycus aircraft geometry.

### III. Modular UAV Conceptual Design

#### A. Quality Functional Deployment

An underlying principle in the context of the design of aerial vehicles is that, “form follows function” (Heslehurst, 2011). Following a review of the initial set of governing multi-mission requirements provided for the modular UAV design, it was evident that a comprehensive set of engineering requirements, specifications and targets was essential in order to effectively drive the conceptual design of the BU-11 modular UAV. In order to ensure efficiency and effectiveness in developing a comprehensive charter of design requirements, the eight-step Quality Functional Deployment (QFD) technique was employed (Heslehurst, 2010). The 8 step process included: Identification of possible customers, development of essential and desirable requirements for the design, ranking design requirements in a hierarchical structure, conducting comparisons with benchmark aircraft, generation of measurable engineering specifications, identifying key relationships and dependencies specifications for the aircraft and the requirements, identification of relationships and conflicts between specifications and setting of engineering targets for the design.

Quality functional deployment was essential to the project in order to expand the initial set of governing mission requirements into a complete set of design requirements and targets that would provide the design with clear boundaries and goals. The requirements charter developed for the design is detailed in Appendix A.

#### B. Advanced Aircraft Analysis Software

The conceptual design of an aircraft is a highly complex and iterative process, requiring the calculation, estimation and design of literally thousands of design parameters in order to generate a design solution to meet a given set of requirements. DARCorporation’s Advanced Aircraft Analysis (AAA) aircraft design software was acquired and extensively used as a primary tool for calculation of conceptual design data for the Tycus UAV concepts. According to (DARCorporation, 2008), “AAA is the industry standard aircraft design, stability, and control analysis software.” AAA offers a powerful and extremely versatile graphical user interface for the input and output of a variety of design data for calculations and design based on the Roskam aircraft design method, published in the literature by Dr. Jan Roskam including; Airplane Design I-VIII, Airplane Flight Dynamics and Automatic Flight Controls, and Airplane Aerodynamics and Performance. The program allows for the calculation of a wide range of aircraft design parameters in the categories of; weight, aerodynamics, performance, geometry, propulsion, stability & control, dynamics, loads, structures and cost. The design of an aircraft using AAA is by no means an automated process. A comprehensive understanding of the principles of
aircraft design, and the calculations the program uses to generate design outputs is essential to ensure that the resulting aircraft concept presents a solution that is both practical and meaningful. As the aim of this document is to provide a concise summary of the methodology used to achieve the desired outcomes of the project, explanations regarding conceptual design for each mission will focus significantly on the details as to what was designed, as opposed to how and why it was designed that way. A complete summary of the design decisions and methodology used in generating each concept has been provided in the project’s deliverable design report. The document has been developed in order to provide a clear and sequential documented process for the development of the Tycus modular UAV, providing a sufficient level of detail to allow compatibility in future continuations of this project.

C. Aircraft Concepts

As no modular UAV platform has been found to exist with the capability to meet the requirements of the project, the conceptual design of a modular system to meet these requirements was an essential component in accomplishing the project objective of determining the feasibility of a modular system.

The conceptual design of the Tycus modular UAV was initiated by developing a number of basic aircraft layout sketches, as is a customary starting point for aircraft design according to (Raymer, 2006). An initial sizing process was conducted in order to establish a preliminary understanding of the likely geometric and performance requirements of the aircraft in various configurations in order to meet the 4 sets of specified mission requirements on an individual basis. The primary output of the initial sizing process was a configuration and airframe concept for the Tycus.

Two modular airframe configurations of universal fuselage, wing and empennage sections were to be developed. The largest airframe configuration was to be designed to satisfy most demanding set of mission requirements; (Extended Range Mission). The smallest airframe configuration was to be designed to satisfy least demanding set of mission requirements; (Basic Mission). The remaining two mission configurations were to be designed to incorporate the extended range airframe configuration geometry. A single engine for both configurations was to be positioned at rear of aircraft. A single mid body positioned wing to be designed for both configurations incorporating a common wing root geometry, sweep angle and airfoil. A single horizontal tail and single vertical tail was to be used for both configurations. The design was to incorporate a standard tricycle configuration landing gear.

The decision to include two main airframe sizes to achieve the 4 sets of mission requirements was driven by specific mission based pairings observed in geometric similarities during the initial sizing estimations for each mission. Initial sizing showed that the airframes sized for the extended range and increased payload missions were of very similar dimensions in terms of wing, fuselage and empennage geometry, and therefore designing individual airframes for each of these missions would be extremely impractical. Likewise, for the basic mission and increased payload mission, similarities in airframe dimensions were observed, which effectively lead to the dual mission airframes concept shown above in points b) and c).

Following the configuration development, the conceptual design of the basic airframe and extended airframe concepts was conducted individually, using the Advanced Aircraft Analysis software. The method employed using AAA for developing both the Tycus extended range and basic mission concepts included the following logically sequential steps;

a) Initial weights sizing;

b) Performance parameter sizing using estimated takeoff weight;

c) Development of specific geometric properties of the aircraft to meet performance parameters;

d) Development of aerodynamic features (lift and drag) based on geometry; and

e) Analysis of the resulting performance characteristics of each concept.

Initial weights sizing calculations generated for each mission based on fuel fraction estimates and statistical regression coefficients based on the empty weight and takeoff weight of the benchmark aircraft produced a takeoff weight of 479 lb for the basic mission configuration and a takeoff weight of 951 lb for the extended range mission configuration.

The two fundamental design parameters with the greatest impact the aircraft’s performance capabilities and limitations are wing loading (W/S) and power loading (W/P). With weight estimates for the aircraft defined, the wing loading and power loading values for both mission concepts were designed based on takeoff weight conditions. The aim of performance parameter sizing in conceptual design generally involves the selection of a

Figure 2. BU-11 Extended Range Mission Performance Matching Plot. (Image courtesy of DARcorp, 2011)
combination of wing loading and power loading values that will allow the designed aircraft to meet specified flight performance capabilities in a number of categories including stall speed, cruise speed, climb performance, landing and takeoff distance, and manoeuvring capability. The primary tool used in the performance parameter sizing for the design was a matching plot generated in AAA. The matching plot shown in figure 2 for the extended range mission case, allows for the selection of maximum required takeoff wing loading and power loading values in order to meet the specific performance in each category described as defined by the user. The design takeoff wing loadings and power loadings are summarised in table 2 at the end of this chapter.

The geometric features of each airframe configuration were developed based on the initial sketches, and were sized in order to satisfy the requirements of the performance parameters set. The geometric design included all major aircraft components including wing, fuselage, empennage, flight controls and landing gear. The wing geometry was designed in order to accommodate the required surface area as defined by each wing loading value set. The fuselage geometry was primarily sized in order to accommodate an engine with the required power output as defined by the set power loading for each configuration. Full details of the Tycus basic and extended airframe geometric features are provided in Appendix E. Figure 3 shows a plan form view of each airframe designed.

Geometric design of each airframe configuration allowed for a detailed analysis of the likely aerodynamic characteristics of the aircraft using AAA. The lift and drag properties were calculated using the specific wing, airfoil and flight control design of each configuration, and were a crucial in calculating the performance characteristics of the aircraft. The main sensitivity in the design identified as a result of aerodynamics analysis was the high stall speed of the extended range mission concept. The maximum lifting characteristics were limited by the airfoil and wing geometry selected to suit both airframe sizes.

Following the development of the basic airframe (developed to meet basic mission requirements), and the extended airframe (developed to meet the extended range mission requirements), concepts were developed to accommodate the increased payload and extended loiter mission requirements, under the critical boundary condition of using the geometric properties of the extended airframe configuration, as determined in the configuration development stage. As such, with the geometric and power plant features fixed according to the extended airframe configuration, the only variation these two concepts showed when compared to the extended range mission was variations in fuel and payloads carried in order to meet the specific mission requirements. The resulting performance characteristics of each configuration were analysed in order to ensure that all engineering specifications and targets for the design were able to be met by each mission configuration concept.

A summary of the resulting performance characteristics of each concept in order to meet each set of mission requirements is shown in table 2. A comprehensive set of design data for the Tycus modular UAV as a result of the conceptual design process described is shown in Appendix E.

According to the findings in Table 2, the Tycus Modular UAV configuration concepts met the requirements for each mission detailed in Table 1. The specifications of the aircraft for each mission compared favourably with the engineering targets set for the design as seen in Appendix A, exceeding targets in most cases. The single specification of concern remains the high clean stall speed of the aircraft in its extended airframe configuration. Although this specification didn’t have a direct impact on any of the requirements and targets set for the design, it has been marked as an area for future analysis in terms of safety risk and flying qualities of the aircraft.

Table 2. BU-11 Conceptual Performance Characteristic Summary
A brief survey of the inherent longitudinal static stability for the aircraft in each configuration was conducted, based on centre of gravity estimates based on the initial weight estimates, and aerodynamic centre of the aircraft calculated using the AAA aerodynamics module based on the wing and fuselage geometry. A static margin range between +11.1% for the basic mission to +15.7% for the extended loiter mission indicated that the aircraft will be longitudinally statically stable. A detailed summary of the aircraft empty and takeoff weight centre of gravity positions was provided in the project specific deliverable design report. The centre of gravity position of the aircraft is likely to be heavily dependent on the internal systems layout and detailed weights estimation for the aircraft. As such, class II centre of gravity calculation and subsequent longitudinal stability analysis is recommended for future preliminary design of the Tycus, in order to confirm the inherent stability characteristics of the aircraft estimated here.

As detailed in the project specification shown in Appendix B, a desirable output of the project was a set of CAD models for the aircraft. DARcorporation’s Shark FX-Aeropack software package was acquired for the task of producing CAD models for the Tycus. “Shark FX-AP integrates DARcorporation AeroPack into Punch Software Shark FX, which is a full-featured application that supports an integrated collection of 2D, 3D, surface, and solid modelling tools, photorealistic rendering and animation” (DARcorporation, 2011). Shark FX-Aeropack was selected for use over programs such as CATIA, primarily due its ability to read geometry files of aircraft concepts generated in AAA, and generate 3D CAD models automatically. This feature offered a significant advantage in terms of time efficiency, as well as offering the versatility for easy changes to be made to the model due to variations made to the design in AAA. A complete set of CAD models were developed for the Tycus basic and extended airframe concepts and have been detailed in the final deliverable project report. An example of the Tycus 3D geometry developed for each airframe configuration is shown in figure 4.

**IV. Modularity Concept**

Figure 5 shows the required modular breakdown developed in order to allow the Tycus UAV to transition between basic and extended airframe configurations. For transition between configurations, a total of 5 major modular aircraft section interchanges will be required. For a transition from the basic to extended airframe configuration these will include:

- a) Addition of two wingtip extensions.
- b) Fitting of a fuselage extension plug section forward of wing root section.
- c) Interchange of empennage sections; and
- d) Re positioning of main and nose landing gear longitudinal positions.

A comprehensive outline of the modularity concept designed for the Tycus UAV has been detailed in the deliverable project report, with a summary of the key features of the design shown here.

Geometric properties designed for the Tycus wing indicate the requirement for a modular variation in the aircraft wingspan of a total of 8.5 ft in order to achieve an effective transition in configuration between the basic and extended airframe concepts. The effective increase in wingspan between configurations will be achieved through wingtip extensions. The wing geometry for each airframe has been designed to incorporate common wing properties such leading edge sweep, trailing edge sweep and airfoil section. This design feature will allow for the incorporation of a simple wingtip extension on each wing of 4.25 ft spanwise length, in
transitioning from the basic to extended configuration airframe wing geometry. A graphical description of the wingtip extension to be designed can be seen in the modular breakdown diagram of the aircraft shown in Figure 5. A primary tool for the structural design of the wingtip extension joint to be conducted during future preliminary design of the aircraft is the wing lift distribution during different missions in the extended airframe configuration. Depending on the maximum lift loading conditions to be determined for the aircraft during future preliminary design, the approximate loading conditions to be experienced by the wingtip extension modular joints will be able to be calculated based on the loading conditions at approximately 74% of the extended configuration wing span. For transition of the Tycus from extended to basic configuration by removing the wingtip extension section, the wingtip will be fitted with an end cap to be designed in order to maintain structural properties such as torsion rigidity of the wing box.

The flight controls requiring design consideration in order to accommodate a modular concept in the Tycus design include the horizontal tail, aileron and flaps. A geometric description of the flap and aileron design for both airframe configurations is shown in figure 6. The use of a wingtip extension had a considerable effect on the design of the aileron and flap geometry. As shown in figure 6, both the basic and extended airframes were designed to share a common flap section. Qualitatively, this implied a necessary compromise in terms of sizing of the flap surface area for each configuration in order to accommodate modularity in the wing design, leading to a slightly oversized flapped wing section in the basic configuration, and likewise, a slightly undersized flapped wing section for the extended airframe configuration. A direct consequence of the lower than optimal percentage of flapped wing delivered for the extended range configuration as a result of this compromise, is the relatively high estimated landing speed of 45 knots required in this configuration. The basic and extended airframes will share a common aileron control horn fitting, with the wingtip extension sections for the extended airframe configuration to include an additional 2.8 foot of aileron span. The primary considerations regarding the sizing and modular integration of aileron surfaces between configurations are expected to be the lateral control characteristics of the aircraft in the extended airframe configuration, and the effective integration of autonomous flight control actuators required for the aileron control horn fitting during wing extension. As such, further analysis of the estimated lateral flight characteristics for the aircraft in both configurations, and the detailed design of the aileron actuation and control system are strongly recommended as a priority during future preliminary design stages of the aircraft.

The Tycus design will incorporate separate modular empennage sections for both the basic and extended airframe configurations primarily to accommodate for different engine and horizontal tail geometries. As such, the horizontal tail surfaces for each airframe were sized as all moving tails in order to provide optimised dimensions for the particular aircraft geometry. The fuselage section of each modular empennage was sized in order to accommodate for the particular engine selected for each configuration. Similar to the modular fuselage plugs to be designed for the aircraft, specific structural design of the attachment point between each empennage and the main fuselage section will be required, in order to ensure an efficient and effective transition method for empennage transitions.

The Tycus shall share universal vertical tail geometry between configurations. The vertical tail was initially sized in order to fit the extended airframe configuration, implying a slight over sizing aspect in terms of the basic configuration geometry. Although the vertical tail requires no specific variation to its geometry during configuration transitions, attention will need to be paid to the structural design of the vertical tail root attachment point to ensure an effective and efficient mounting scheme onto the modular empennage sections to be designed for the Tycus basic and extended airframe configurations.

The Tycus fuselage has been conceptually designed to incorporate a uniform cross sectional geometry between the nose section and empennage section of the aircraft in order to support modular transitions in fuselage geometry between configurations. In order to support an effective total increase in fuselage length between the basic and extended airframe configuration of 5.75 ft, two fuselage extension sections have been designed as shown in figure 5. Including a forward fuselage plug section of 2.5 ft length and a rear fuselage extension fitted to the extended airframe empennage section.

An essential component in the sizing and layout of any aircraft design is the sizing and location of fuel tanks. The primary consideration in fuel tank design for the Tycus was to ensure that the modular variations to the aircraft wing and fuselage geometry had little impact on the fuel system. This requirement implied the need for a single main fuel tank to accommodate for the estimated fuel weight requirements of all four missions as closely as possible. The fuel weight estimates for the four mission profiles ranged from 50.6 lb for the basic
mission to 314.2 lb required for the extended range mission. As the aim was to design an integral fuel tank geometry that would be a part of the basic modular configuration core so as not to be affected by extensions to the airframe through modular concepts, the wing integral tank sizing for both configurations was to be limited to the wing geometry of the basic airframe. The Roskam Method was used to calculate the class 1 maximum fuel tank volume to be designed for an integral wing tank. The method uses two assumptions:

a) The wing fuel is carried in a ‘wet wing’. A wet wing is a wing that has no separate fuel tanks. The wing torque box, which is the part of the wing structure between the front and the rear spar, is sealed and forms the fuel tank (DARcorp, 2011).

b) No fuel can be carried beyond the 85 percent span; a standard design principle for the purpose of fire protection from lightning strikes.

The Roskam method calculates the maximum fuel volume for a wing integral tank based on the specific geometric properties of the designed wing using the following equation:

\[
V_{F,w} = F_F \frac{0.54}{1 + \lambda_{w}} \left( \frac{S_w}{b_w} \right) \left( \frac{L}{C_{max}} \right) \left( \frac{L}{C_{max}} \right) \left( \frac{L}{C_{max}} \right) \left( \frac{L}{C_{max}} \right)
\]

Using the geometric data for the basic mission wing shown in Appendix E to calculate the maximum allowable fuel volume for a core wing integral tank, and subsequently converting the volume to a weight estimate based on the density properties of 100LL Avgas, the maximum fuel weight able to be carried by the single tank was 226.6 lb. This fuel tank would provide sufficient fuel capacity for the basic, increased payload and extended loiter mission fuel fractions as shown in Appendix E, however, in order to allow for sufficient fuel carriage for the extended range mission, an additional fuel tank to support a 87.6 lb fuel capacity was required. The additional tank will be positioned in the wing root section of the fuselage, and is estimated to occupy a volume of 1.97 ft³.

The decision to utilise a universal main and nose landing gear structure in the Tycus design was made in order to increase the simplicity of the design by minimising the number of components required for the system as a whole. Evident advantages of this strategy are a lower overall purchase price of the system and lower logistical support requirement for the system in terms of spare landing gear components. This decision implied the requirement for the gear to be sized according to highest structural requirements to be expected in the extended range configuration. As such, the use of an identical landing gear for the basic mission configuration indicates a less than optimum design in terms of landing gear size and weight in this condition. The main disadvantage to this strategy is an implied lowering in optimisation and efficiency of the basic mission configuration in terms of weight, and hence a slight decrease in expected overall performance capability.

The Tycus basic and extended configuration airframes were sized in order to accommodate separate engines; the AR731 in the basic airframe configuration and the Rotax 582 engine in for the extended airframe. Each engine is to be housed in the modular empennage section designed for its corresponding configuration. One of the primary considerations in sizing of the Tycus fuselage cross sectional geometry was the accommodation of the dimensions of the larger Rotax 582 engine, and as such, the empennage sections for each configuration have been sized in order to allow for the effective installation of each engine. The Rotax 582 and AR731 engine specifications, performance data and technical drawings are detailed in Appendix F.

The expected layout of the major internal systems of the aircraft in each airframe configuration was an essential consideration in terms of the design of the modular concepts. The layout of the major internal aircraft systems including engine, fuel, payload, avionics and cooling unit was to be designed in order to ensure that modular variations to the aircraft geometry shown in Figure 5 would have a minimal impact on the positioning of these systems. As such, the positions of the major internal system components are intended to be positioned in the universal sections of the Tycus fuselage; the nose cone and wing root fuselage sections. An estimate of the proposed systems layout for the aircraft in each airframe configuration is shown in Figure 7. The final positioning of all internal components in the aircraft fuselage will be a function of future preliminary design of the aircraft, and will depend on a number of criteria, including the specific geometry, orientation and special positioning.

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**Figure 7. BU-11 Basic Systems Layout Concept**

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requirements of each system component; and the weight and balance of the aircraft. The longitudinal positioning of systems in the aircraft fuselage will be a strong function of their individual component weight, in order to achieve adequate longitudinal flight stability and control characteristics in each configuration. Provided that an adequate systems layout may be designed in order to satisfy this criteria, the strategy of positioning the major aircraft system components in the universal fuselage sections should provide the best solution in terms of minimising the maintenance man hour penalty paid during configuration transition, by reducing the number of systems to be disconnected, repositioned, remounted and reconnected due to changes in the fuselage geometry.

V. Feasibility Analysis

The determination of the feasibility of a conceptual design such as the Tycus is a relatively complex concept. This is primarily due to the extensive range of variables and requirements to be considered, and secondly, due to the fact that the term ‘feasibility’ implies a significant level of subjectiveness. As such, the definition of feasibility may vary significantly when assessed by different customers of the product due to differences in required functions for the UAV.

The Tycus modular UAV has been designed in a manner such that the performance characteristics important to this type of aircraft such as cruise speed, rate of climb, stall speed, landing and takeoff distance vary as little as reasonably possible between configurations. This is a favourable design feature in terms of uniformity in flying characteristics. However more importantly, it simplifies the conditions for which feasibility is to be based on. By designing a modular UAV with relatively low variation in performance between configurations, feasibility may be determined with a higher weighting on quantitative financial factors and design considerations. However, whilst placing a high weighting on financial factors in assessing feasibility of the Tycus design, it is essential to consider that although financial factors generated from the conceptual design process provide a quantitative analytical tool, they too are have been generated based on educated approximations, and involve a significant number of statistical variables with the possibility of high uncertainties that could potentially alter the outcome of such analysis.

A. Cost Analysis

“Aircraft cost estimation occupies the fuzzy gray area between science, art and politics. Cost estimation is largely statistical, and in the final analysis we predict the cost of a new aircraft based on the actual costs of prior aircraft. However, it is very difficult to determine how much a prior aircraft really did cost in terms that are meaningful to the next aircraft” (Raymer, 2006).

The primary tool involved in generating a baseline cost estimate for the Tycus conceptual design was the Advanced Aircraft Analysis program’s costs module. The program utilises aspects of the aircraft data produced as a result of the conceptual design process in order to develop statistically based cost estimates for the different phases of an aircraft production process including design, development, manufacturing and operation. The primary reference that DARcorp’s AAA cost module uses for calculating these cost estimates is the well published methods by (Roskam, 2002) in the educational text: Airplane Design Part VIII. The cost estimates for the Tycus design shown in Table 3 were generated for each individual airframe configuration, along with conservative projections for the maximum costs of the Tycus as a modular UAV which were produced based on the addition of the costs estimated for each individual configuration.

<table>
<thead>
<tr>
<th>Cost Summary</th>
<th>Basic Airframe Configuration ($US)</th>
<th>Extended Airframe Configuration ($US)</th>
<th>Maximum Complete Modular System Cost ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price per Aircraft</td>
<td>$2.381 Million</td>
<td>$3.647 Million</td>
<td>$6.028 Million</td>
</tr>
<tr>
<td>Operational Cost</td>
<td>$2701 per hour</td>
<td>$3929 per hour</td>
<td>$3622 per hour (average)</td>
</tr>
<tr>
<td>Total R.D.T.E Cost</td>
<td>$20.74 Million</td>
<td>$31.55 Million</td>
<td>$52.29 Million</td>
</tr>
<tr>
<td>Acquisition Cost</td>
<td>$1.345 Million</td>
<td>$2.070 Million</td>
<td>$3.415 Million</td>
</tr>
<tr>
<td>Life Cycle Cost</td>
<td>$18.50 Million</td>
<td>$28.25 Million</td>
<td>$46.75 Million</td>
</tr>
</tbody>
</table>

Table 3. BU-11 Individual Airframe Configuration Cost Estimates.

These estimates are given as a baseline estimate, assuming the incorporation of only basic systems and avionics statistically typical to UAVs. The addition of advanced avionics systems such as sensors, radar and other forms of measuring and guidance equipment are factors that would be expected to significantly increase the overall cost of the system, but have however, for the purpose of conceptual design and feasibility assessment of the Tycus UAV been neglected. Another expected uncertainty in the cost estimation of the Tycus modular design is the increased costs associated with the complexity of manufacturing specifically modular joints and sections.
Like many types of cost projections and financial forecasting techniques, the estimation of the likely cost of an aircraft in various stages of its lifecycle can be considered as a balance between science and art. As such, a sensitivity analysis of the major parameters of the cost calculations made for the design was conducted, in an attempt to quantify the uncertainty involved in the estimated cost figures produced. A summary of the sensitivity analysis conducted for the extended airframe conceptual cost estimates is shown in Table 4, with information regarding the calculation of the major costs shown in Appendix D.

As the Roskam aircraft cost estimation method relies upon key characteristics of the aircraft concept in order to generate statistical cost estimates based on historical design data, the major variables in the conceptual design likely to have the largest impact on the final aircraft costs were assessed for sensitivity including; aircraft weight, aircraft maximum speed and the number of aircraft likely to be produced. The sensitivity analysis indicated that the majority of calculations made for the Tycus cost estimates are insensitive to a relatively large variation in the major input parameters. The most sensitive variables were indicated to be the number of aircraft produced, the number of air crew to operate each aircraft and the number of hours per year the aircraft is expected to be used. Although the results shown in Table 4 could not provide a quantitative uncertainty for the Tycus cost estimates, they were able to highlight the critical assumptions made in the inputs for generating cost estimates, and as such, the greatest uncertainties in the cost estimations model for the Tycus modular UAV lie within the operational cost estimates, with the expected number of aircraft utilised by a customer being the most sensitive parameter. The original cost estimates for the design were generated using an assumption of 20 aircraft to be manufactured and produced, and therefore the hourly operational cost of the aircraft is expected to be highly dependent on how many UAVs the customer will use. The assumption of the number of aircrew required to operate the aircraft shows high sensitivity to the operational hourly cost, however, the original assumption of a maximum of two remote aircraft operators for this type of UAV is expected to be accurate, with the likelihood of 3 or more operators for the one UAV relatively low.

B. Financial Based Recommendations

For a prospective customer with the multiple mission requirements specific to this project in Table 1, 2 main solution option categories have been deemed to exist for the purpose of feasibility analysis:

a) The customer may design and operate a modular UAV system such as the Tycus design described in this project, where different airframe configurations are used to accomplish different portions of the mission requirements.

b) The customer may design/purchase and operate a single configuration UAV system capable of accomplishing all 4 sets of mission requirements.

When assessing the feasibility and merit of the Tycus design based on financial factors, two classes of customers should be considered; customers expecting to use the modular UAV predominantly in its basic airframe configuration, and customers expecting to predominantly utilise the UAV for larger scale missions in its extended airframe configuration. Whilst this form of profiling presents a rather generalised model, the two different types of proposed customers provide the bounds for a useful spectrum to be used in assessment of feasibility.

Using the hourly operational cost estimates projected for the Tycus UAV for each configuration, projections were generated for the total life cycle operational cost of the aircraft. Figure 8 shows a projection of the total estimated operational costs for the Tycus UAV based on a range of hourly percentages of use in the extended airframe configuration. This projection was generated based on the assumptions of 350 flying hours for military aircraft per year, and a typical life of type of 20 years (DARcorp, 2011).

Figure 8 indicates that if the Tycus UAV were to be operated in the extended range configuration 100 percent of the time, implying that a modular concept is not utilised, the total operational cost for a 20 year period for the aircraft is estimated to be $27.43 million US. In order to represent a financially effective solution, the financial advantage gained through lower operational costs by using the Tycus as a modular system is
required to exceed the financial penalty paid due to the higher acquisition cost of the modular UAV airframe when compared to the acquisition cost of the single extended range Tycus system. Using the conservative estimated acquisition cost of the Tycus modular system of $6.02 million per aircraft and the estimated acquisition cost of the individual extended range configuration of $3.65 million per aircraft, the maximum financial penalty of employing the multiple configuration Tycus design over the single extended range configuration was estimated as $2.37 million. Therefore, as shown in Figure 8, in order to represent a financially feasible option, it is recommended that the Tycus modular UAV would be required to be used for missions in its basic configuration for at least 28 percent of its total life hour usage.

As Figure 8 suggests, for customers intending to operate the UAV in the extended airframe configuration above 72 percent of the total flying hours, it is recommended the use of a modular UAV system such as the Tycus would most likely be financially redundant. In this case the penalties associated with the significant number of extra costs and logistical complexities associated with producing and maintaining a modular UAV system such as the Tycus are likely to outweigh the financial benefit gained by operating a modular UAV that may be optimised to suit the smaller scale missions representing 28 percent or less of the total flight hours.

It is expected that a more effective solution to the 4 sets of mission requirements detailed in table 1 could be achieved by designing a single configuration UAV system specifically optimised to meet the requirements of the extended range and extended loiter missions, which is still capable of performing the specified basic and increased payload missions when required. Provided that the inherent penalty of lowered operational cost efficiency paid by operating the UAV overdesigned for basic and increased payload missions can be justified as outweighing the implied advantages of lowered production and maintenance cost of a simpler, single configuration UAV, then the use of a single configuration UAV is deemed to be more viable solution in this specific case.

For customers expecting to design, develop and operate the Tycus modular UAV for use in the extended range configuration for less than 72 percent of the total life of type flight hours, the recommendation is that the Tycus UAV in its conceptual stages would represent an elegant and plausible solution to the requirements for the design. At its current conceptual stage, the design indicates a significant level of simplicity and engineering merit. The conceptual performance specifications for both configurations indicate a high level of conformity to the requirements for the design, and the conservative cost estimates generated based on the conceptual design phase suggest that a modular system such as the Tycus offers the most effective financial solution to satisfy the design requirements in this specific case.

C. Technical Based Recommendations

The Tycus UAV has been designed in an attempt to allow for a simplistic solution to modular transition between airframe configurations. An essential factor in determining the feasibility of a modular concept will be the required maintenance effort in order to flexibly and effectively transition the aircraft from one configuration to another for different missions. The engineering specification developed for the aircraft specifies a required maximum configuration assembly and disassembly time for two people of 5 and 3 hours respectively, producing a required projected maximum airframe configuration transition time of 8 hours.

A specific estimate of the required assembly and disassembly time for the UAV based on the conceptual geometry, systems layout and modularity concepts would be essentially unattainable at this conceptual phase of the aircraft’s design. However, based on the relatively simplistic design of the Tycus UAV, and the growing nature of commercially available aircraft avionics, control and cooling systems in terms of compactness and affordability favour the feasibility of a modular UAV system such as the Tycus. Furthermore, the simplistic nature of the aircraft fuselage should allow for a number of options in designing the detailed systems layout of the UAV in terms of longitudinal internal systems placement, in order to achieve desired centre of gravity characteristics to allow for the aircraft to be feasibly flyable.

The design shows significant potential to provide a feasible option for accomplishing the mission requirements, and as such, further preliminary design is strongly recommended in order to provide a more
refined understanding of the factors critical to the feasibility of the design such as systems layout feasibility, required maintenance effort and stability and control characteristics of the UAV.

VI. Conclusions

The aim of the project was to conceptually design a modular UAV system with the capability to perform multiple missions, and to subsequently assess the feasibility and effectiveness of the concept. The BU-11 Tycus Modular UAV was designed to meet four sets of mission requirements; basic mission, extended range mission, increased payload mission and extended loiter mission. A modularity concept was designed in order to allow for variations to be made to the aircrafts major components to provide two separate airframe sizes to be used to fulfil the multi mission requirements. The resulting concept aircraft met the requirements and targets set for the design with considerable merit. The feasibility of the system was assessed based on factors of financial effectiveness and the engineering merit/practicality. The results of the cost estimations for the design suggested that the use of the Tycus as a modular system to fulfil the multi mission requirements would be more cost effective than using an equivalent single configuration, larger aircraft, provided that the modular UAV system is used in its basic airframe configuration (i.e. Completing basic missions) for more than approximately 28 percent of the aircraft’s total life of type. Sensitivity analysis of the cost estimations showed that the costs associated with the development, acquisition and operation of the concept are likely to be highly dependent on the number of aircraft to be operated, the required maintenance man hours per flight hour to support the system and the number of utilisation hour per year expected, and as such, the financial feasibility of a modular UAV system is likely to be highly dependent on these factors and will therefore depend on the individual circumstances and requirements of each customer. In terms of practicality of the Tycus modular UAV system, recommendations have been made regarding further development of the aircraft structural design, systems layout and stability and control characteristics required to effectively determine whether it is both feasible and effective to operate the Tycus as a modular system. The simplistic and versatile nature of the design is expected to provide future designers with a significant amount of options and freedom to develop a structural design, systems layout and centre of gravity position that will ensure the Tycus Modular UAV is an adequately stable and flyable system, that may be feasibly dismantled and reconfigured between airframes with a minimal maintenance man hour effort.

VII. Future Project Recommendations

It is strongly recommended that this design and development project be continued during future thesis studies by UNSW@ADFA students. The design shows significant merit in its conceptual stages, and the deliverable components of the project including AAA conceptual design data, shark FX CAD models and comprehensive design report will provide a strong basis for continuation of the project by future students. Assuming the decision is made to continue the design and development of the BU-11 Tycus modular UAV system, a number of sequential recommendations for the preliminary design stage of the aircraft have been made, in order to provide future scope to bring the design out of the conceptual stages and in to the preliminary phase of its design.

Further weight estimate refinements for the aircraft are recommended. The AAA program allows for the class I and II detailed weights sizing for an aircraft. Preliminary class I weight sizings were used in order to generate initial estimates for the centre of gravity location for landing gear design for the aircraft its basic and extended range configuration. Further Class I weight iterations will be required in order to improve the accuracy of the aircraft empty weight in each configuration, based on the structural weight estimates of the major aircraft components defined in the conceptual design including the fuselage, wing, empennage, landing gear, power plant and fixed equipment groups. Centre of gravity excursion estimates may subsequently be based on Class I weight estimates, an essential parameter for stability and control analysis of the aircraft.

One vital aircraft component not covered in the conceptual design process of the aircraft was the landing gear strut geometry. The wheel position for the Tycus in both basic and extended airframe configurations has been initially defined and modelled based on initial centre of gravity location estimates, however the sizing and design of the specific strut geometry was omitted, primarily due to the complexity of the structure and its sensitivity to the refined weight and load estimates to be more accurately calculated during future preliminary design.

A detailed systems layout for the aircraft will be required. The general locations of the major aircraft systems including avionics, cooling, payload, engine and fuel were estimated in section IV of the report. The avionics system must include a fully autonomous flight control system as specified in the design requirements. Detailed estimates and selection of such systems to be utilised in the aircraft will allow for a greater understanding of the spatial requirements, installation requirements and subsequent location of the major aircraft systems. The detailed systems sizing, location and installation design will provide a greater understanding of the
maintenance man hour effort required in changing the aircraft’s airframe configuration from basic to extended or vice versa.

An essential component of the future design of the Tycus which will have the potential to make or break the design is the stability and control characteristics of the aircraft. The location of the major aircraft systems in each configuration will have a significant impact on centre of gravity position and subsequently the stability and control of the aircraft. A suitable compromise between the optimum systems location and resulting centre of gravity location and travel for the aircraft will need to be achieved in order to provide a systems layout that is both practical with a low impact on the MMH effort during configuration transition, and that allows for acceptable stability and handling qualities through autonomous control systems.

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