RE-ANALYSIS OF A MULTI-MISSION RE-CONFIGURABLE UAV – REVISED DESIGN CONCEPT

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Abstract

At Present, the range of Unmanned Aerial Vehicle (UAV) missions is met by a large inventory. This has placed operational and logistical challenges requiring the exploration of a new UAV design concept. In this paper a re-configurable UAV (RC-UAV) concept is discussed, presenting a systems approach for mission requirement analysis and identification of design specifications. The design process covers the transformation of a conceptual design process to an intelligent system that produces the viability of module matching to reconfigure a multi mission UAV from a base-design module.

1 Introduction

Due to the growth of UAV technology, several design philosophies exist for future development. UAVs are categorised based on their size, mission payload and flight performance. To cover a wide operational range, the envisaged scope of missions for UAVs presents major design challenges. The Sir Lawrence Wackett Centre is currently focussing research on a Multi-mission Re-configurable UAV (MM-RCUAV) concept, to investigate the merits over other UAVs under design and development. Compared to present uni-mission UAVs, the MM-RCUAV concept has demonstrated a mission and cost effective alternative [1].

The concept aims to provide a high degree of flexibility in payload, range & endurance. The initial approach comprised of a modular concept, that provided flexibility in mission payload, fuselage, propulsion and wing sections. The design concept addressed a wide spectrum of missions with enhanced mission capability [2, 3]. Further investigations later discovered major concept deficiencies in regards to weight & balance and flight mechanics [4].

2 MM-RCUAV Design Process

To identify the multi-mission requirements of UAVs, the design process employs a multi-mission approach [5, 6, 7, 8], which determines mission requirements based on operational and logistical needs. The functional characteristics of state-of-the-art mission systems that provide the required capabilities to the platform were investigated to formulate three multi-mission payloads: a) High Altitude Long Endurance (HALE); b) Medium Altitude Medium Endurance (MAME); and c) Low Altitude Short Endurance (LASE).

A base-line payload was designed for the commonality of mission systems in the three payloads. Further, a base-line UAV platform on a dovetail block system (fuselage and wing extensions and interchangeable tail and engine units) was designed with configuration flexibility to accommodate three classes of payloads and flight performance requirements of HALE, MAME and LASE UAVs.

The design effectiveness of the three MM-RCUAVs was evaluated from the degree to which; the mission capability, flight performance and logistic support are met against the specifications. The mission payload and platform have been redesigned in an iterative aircraft design procedure, to further particularise the aerodynamic and flight-mechanic parameters of the UAV.

Compared to the initial design from 2002, the MM-RCUAV mission spectrum is specified from four mission categories to 53 selected mission types, to cover a wide range of tasks of the MM-RCUAV. The new preliminary design process is based on mission requirements, which are developed for every mission to define its maximum take-off weight (MTOW), fuel and payload weights and the associated volumes. Furthermore the optimum design points of all missions are defined and assessed against each other. The scope of 53 missions leads to an extensive range of mission parameters in terms of speeds, g-loads, endurance and altitude.

The UAV design to cover the entire envelope of 53 missions is deemed as too demanding and the mission scope is hence reduced to missions with high priority (Fig. 1), based on a market analysis of UAVs under development or in operation. Furthermore a performance analysis is conducted to identify limits for selected parameters, comprising of cruise speed, altitude and maximum g-loads.

The newly developed MM-RCUAV mission spectrum is used as the basis for the ongoing design process.

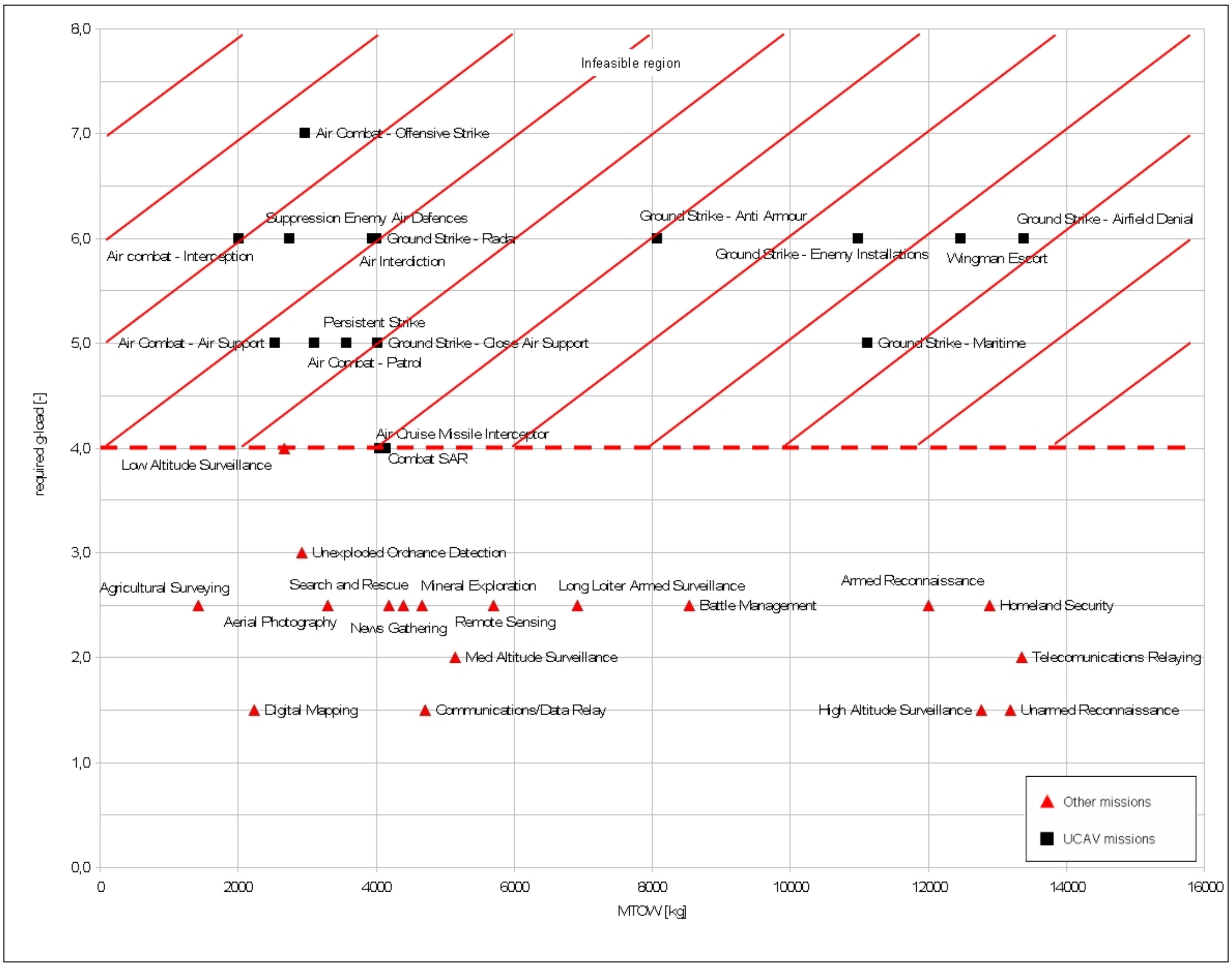


Fig. 1. Multi-mission Groupings of UAVs from an Operational Perspective

Fig. 1 presents the mission-envelope MTOW versus the required g-loads, which illustrates that combat missions (e.g. ground strike) are performing higher loads compared to civil missions (e.g. remote sensing).

The interim result of the mission spectrum standardisation is a MM-RCUAV mission envelope with focus on 30 selected mission tasks. The focussed mission spectrum forms the base for an alternative design point definition, employing a relatively wide range of parameters. The broad weight and velocity envelope of the MM-RCUAV requires a flexible wing area besides fuel and payload volumes to be adaptable to all missions efficiently. For the subsequent discussions, the scope is therefore kept on wing and fuselage redesigns.

3 Wing Design

The preliminary MM-RCUAV design from 2002 focussed on wing extensions to serve a wide range of missions. The wing is designed to serve three main mission categories: HALE, MAME and LASE. The results of these MM-RCUAV investigations were cruise speeds in a range from M0.25 to M0.6 and payload masses from 100kg to 500kg. The wing extensions of the previous design obtain flexibility in terms of wing area, aspect ratio (Λ), wing control surfaces, fuel volume and lift coefficients. The wing extension concept benefits from the elimination of dead weight when the extensions are removed, except a weight penalty caused by the connecting interfaces located in the wing tips.

The original configuration has no morphing capability during flight and the on ground assembly complexity is considered to be higher versus a variable wing sweep or telescopic wing concept. In this investigation, the feasibility and major advantages and disadvantages of a morphing wing concept versus the previous wing extension design concept are discussed.

The advantage of a variable wing aircraft design is a performance increase related to the ability of adapting the wing to various missions, leading to optimum lift and drag characteristics. This relationship is described by the mathematical relation shown in (1), called the 'Breguet Range Equation':

$$R = \frac{V}{c_f \cdot g} \cdot \frac{C_L}{C_D} \cdot \ln\left(\frac{W_1}{W_2}\right) \qquad (1)$$

To achieve high range performance, the quotient C_L/C_D is maximised.

3.1 Morphing Wing Concepts

Several wing morphing concepts have previously been developed and investigated; some found application while others never reached production. To identify the most suitable morphing wing concept for the MM-RCUAV, the benefits and drawbacks are assessed against each other. The most known morphing wing is the variable wing sweep concept, found on the B-1 Lancer, F-111 Aardvark, F-14 Tomcat (Fig. 2) and Panavia Tornado.

Fig. 2. Variable Wing Sweep Concept (F-14 Tomcat)

In the 1960's, the variable sweep wing concept was popular due to the advantages of providing optimum glide values throughout a wide performance envelope with the ability of high supersonic speeds versus low stall speeds, allowing short take-offs and landings. The disadvantages of a large and heavy gearbox and the reduced fuel capacity caused by its pivot mechanism resulted in higher maintenance costs beside a range and endurance penalty. This wing design is therefore slowly disappearing with the retirement of the F-111, B-1 and F-14.

Further investigated wing morphing concepts, e.g. the telescopic wing, are not found on any aircraft designs. The telescopic wing has the advantage of an increased aerodynamic efficiency due to the ability to adapt the shape to changing flight conditions and requirements; reducing fuel consumption during the flight. An increase in aspect ratio (Λ) reduces the induced drag D_i, which is responsible for the endurance (2):

$$D_i = \frac{C_l^2}{\pi \cdot e \cdot \Lambda} \qquad (2)$$

High altitude aircraft (e.g. U-2 and RQ-4 Global Hawk) utilise high aspect ratio (Λ) wings for long range and endurance performance. The telescopic wing design however has a disadvantage of a complex morphing structure resulting in a weight penalty. The structure has to sustain high wing loadings and forces, especially in an extracted position. In retracted configuration, the airplane carries a significant amount of dead weight. Table 1 shows a summary of the presented advantages and disadvantages of each wing morphing philosophy.

In this application, the variable wing sweep design was found inapplicable, related to the low design speeds in the MM-RCUAV flight envelope compared to the optimum design point. Previous investigations [9, 10] with assistance of a weighted evaluation matrix found wing extensions applicable.

The telescopic wing concept was found appropriate for the MM-RCUAV design due to its potential to increase the range and endurance performance by providing a variable Λ with an adaptable wing area versus the variable

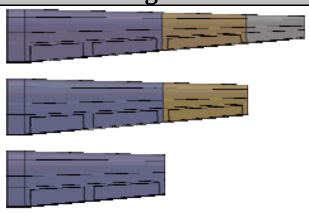
	Wing Extensions	Variable Sweep Wing	Telescopic Wing
Graphic			
Influenced Parameters	S, b, Λ	b, Λ, φ_{25}	S, b, Λ
Advantages	• weight decrease by influencing the MWE for different configurations on ground (e.g. 25% saving for previous RC-RCUAV configuration)	• optimum glide values throughout a wide performance envelope • high supersonic speeds and very low stall speeds (especially for shorter take-off and landing lengths)	• improved aerodynamic efficiency caused by adapting the shape to flight condition requirements • increase of fuel efficiency by reducing drag during flight • significant gain in endurance performance
Disadvantages	• no morphing capability during flight • connecting mechanism complex (structure, hydraulic/ electric and fuel conductions) • high assembly effort on ground and more infrastructure and time needed for flight preparation	• large and heavy gear box • lower fuel capacity caused by pivot mechanism • increased maintenance costs	• morphing structure complex and has to sustain sufficient wing loadings • increased MTOW

Table 1. Advantages and Disadvantages of Morphing Wing Concepts

sweep wing. Further investigations will consider its potential application within the MM-RCUAV project and assess it against the research results of the wing extension concept.

3.2 Telescopic Wing Design

The design factor of a wing is lift (*L*) and drag (*D*) and the relation between both parameters. Furthermore the effect of a variable wing area and span on drag is of interest. Per definition, drag consists of zero lift drag and induced drag, presented in the following correlation (3) for a simplified rectangular wing:

$$D = q \cdot S_1 \cdot C_{Dp} \cdot \left(1 + \frac{2 \cdot \Delta b \cdot c}{S_1}\right) + \frac{L^2}{e \cdot \pi \cdot q \cdot (b_1 + 2 \cdot \Delta b)^2} \qquad (3)$$

The left part of (3) presents the zero lift drag, the right part the induced drag. Δb is defined as the increase or decrease of the wingspan due to the morphing telescopic wing. The optimum span b or the Δb for minimum D increases when the profile drag coefficient C_{Dp} decreases.

Firstly, specific masses as *MTOW*, M_{Fuel}, $M_{Payload}$ and empty weight (*MWE*) are determined for each of the selected 30 MM-RCUAV missions. The scope of this investigation is kept on a morphing wing concept and not on wing extensions; therefore the *MWE* is set as constant for all configurations. The weights are defined through charts, composed from statistical data [11, 12]. The fuel weights are defined for each mission using the fuel fraction method [11]. The required mission ranges, fuel amount and maximum speeds are extracted from the mission analysis. The optimum design points are obtained from a size-matching chart [11] (Fig. 3). The chart allows identifying a suitable combination of the parameters ‘wing loading’ versus ‘thrust to weight ratio’. The design aims on high wing loadings while minimising the vehicle’s thrust to weight ratio. With the help of the size matching chart, new required wing areas for each mission are established. An increase of wing loading while maintaining a constant MTOW causes a decrease of the wing area. This correlation is applied to adapt the wing area for every configuration.

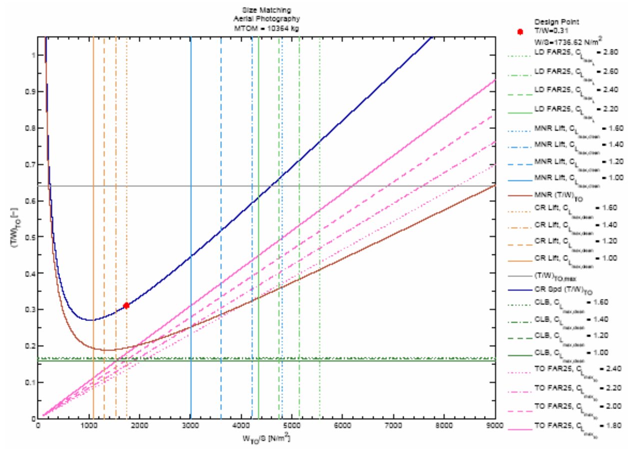


Fig. 3. Size-Matching-Chart

The design point P is determined by solving a two dimensional design problem graphically, while fulfilling all requirements the best possible, e.g. maximum runway length and lift coefficient. After determining the wing area, the required wing plan forms are established within a range of 20m^2, defining the design limits of the morphing wing design. A CATIA V5 model was established to support the further design analysis of the telescopic wing concept. A plan view of the CATIA model is presented in Fig. 4:

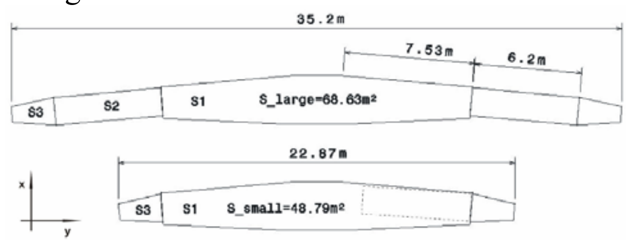


Fig. 4. Telescopic Wing Configuration

4 Fuselage Re-Design

Similar to the initial wing design [2], the MM-RCUAV fuselage was designed to provide flexibility through modular extensions, consisting of two nose sizes, two fuselage centre-sections and two tails. This design furthermore provided additional payload capacity through fuselage extensions. Fig. 5

shows a 3D isometric view of the MM-RCUAV conceptual design from 2002 [2]:

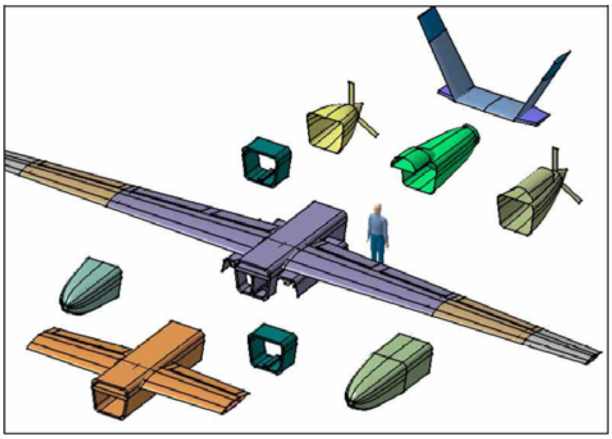


Fig. 5. Modular MM-RC UAV System

The design offers a broad payload range, including a weapons bay and three individual propulsion-systems to meet the requirements of a wide mission envelope. This particular configuration faces weight penalties due to the structural interfaces and connectors for each module. Furthermore stability- and balance-issues due to centre of gravity (CG) shifts besides challenging flight mechanics present design problems which need to be addressed [10, 13, 14].

Thus, an alternative MM-RCUAV fuselage design is investigated. The 30 previously identified missions require a broad range of payloads and fuel, which pose a major challenge for fuselage design. As an alternate option for the MM-RCUAV fuselage, the theoretical and practical suitability of a standardised fuselage with removable equipment bays and fuel tanks is investigated. This concept reduces its system complexity while addressing the weight and balance issues due to the standardised fuselage length.

To design a suitable alternative to the previously investigated modular concept, a mission requirement analysis and definition was conducted in parallel and similar to the mission analysis applied prior to the wing re-design. Based on the slated requirements, fuselage design concepts were investigated with the identification of their characteristics, advantages and disadvantages followed by an evaluation. The main parameters influencing the selection were the size of the fuel tanks and their design besides the layout and location of the interchangeable systems, engine and vertical wing position including the empennage configuration.

The initial step in the re-design process was to assess and define the fuel volume requirements for all missions; these were obtained using the fuel fraction method. Internal fuel tanks satisfy the fuel requirements for over 70% of the missions and can accommodate 80% of the maximum required fuel. However to maintain flexibility additional fuel tanks are required.

The payload dimensions and weight of all 30 missions were identified, separated into base-line payload and optional payload. To reduce the risk of a CG travel, the internal main tanks were located close to the CG of the overall configuration. The final design and location of the fuel tank was obtained by the requirement of a continuous wing box for stability and the shape of the jet engine air intake.

Two preferred UAV-design philosophies exist for engine positioning: a) an internal or b) high mounted engine configuration, both are currently in service, e.g. with the Shadow UAV and RQ-4 Global Hawk respectively. Within the MM-RCUAV application, an internal configuration is identified as more favourable, due to drag benefits, the lack of a pitching moment related to the offset from the longitudinal axis, a decreased radar cross section and better CG control. However, this configuration reduces the internal space for payload accommodation and faces operational disadvantages e.g. maintenance access.

Similar to the initial MM-RCUAV design, a high mounted wing was evaluated as the preferable option in this application, related to the design advantages of a continuous wing box, lower interference drag and greater ground clearance.

Following the selection of the favoured concept, the fuselage design was implemented in a CATIA V5 model to support the final design analysis and evaluation, including aerodynamic investigations using Computational Fluid Dynamics (CFD).

This revised fuselage design poses flight mechanical problems for the empennage design due to the short fuselage length. A dove tail was evaluated as the preferable option due to its low weight and radar signature, however requiring large control surfaces to provide sufficient stability and control.

Fig. 6 and Fig. 7 illustrate the conceptual design of the fuselage re-design, including dove tail and the preliminary telescopic wing design in a retracted position.

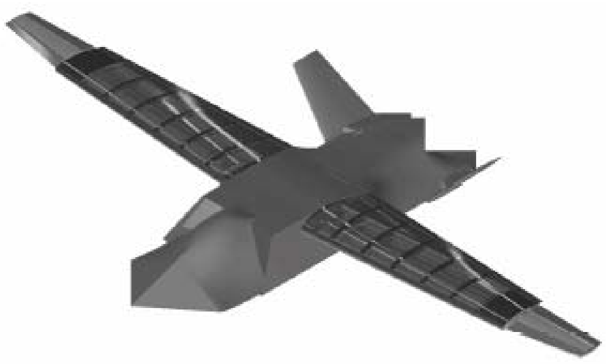


Fig. 6. MM-RCUAV Front View

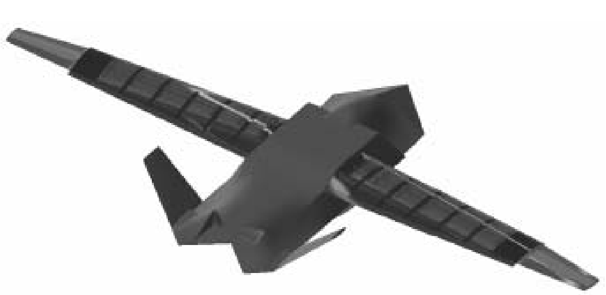


Fig. 7. MM-RCUAV Rear View

Further research is being undertaken using CFD software to determine the lift and drag coefficients for all envisaged missions to conclude if the stealthy design imparts any major drag penalties. Fig. 8 presents a CFD calculation using Fluent. This simulation was run under the atmospheric conditions of 20000ft altitude and a cruising speed of Mach 0.5 with observations of pressure and airflow, giving estimates of the overall drag and airflow separation.

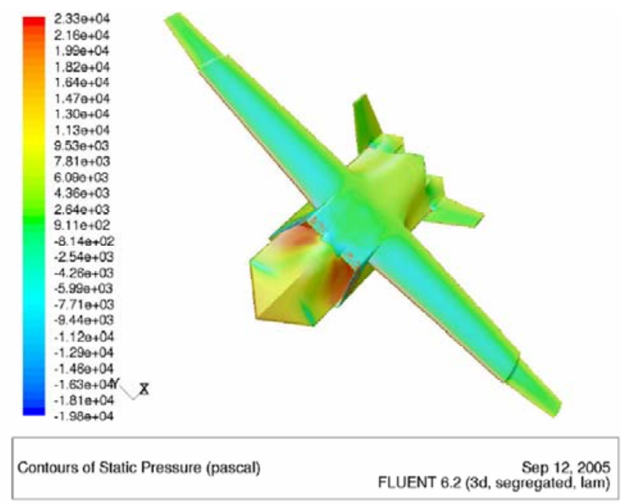


Fig. 8. Static Pressure [Pa] Distribution at 20000ft and M0.5

5 Results and Discussion

5.1 Wing Design

The morphing wing concept demonstrated its application in a broad range of mission requirements of the MM-RCUAV. The parameters of interest are the wing area *S*, aspect ratio Λ, lift C_L and drag coefficient C_D, wing loading, lift *L* and wing span *b*. This concept is evaluated as a feasible option to meet the MM-RCUAV requirements. However, the telescopic wing faces challenges in its practical application.

The CATIA model has shown that the mechanical mechanism in the wing leads to a weight penalty combined with reduced fuel capacity. The wing increases its efficiency when being extended, however with retracted wingtips; the wing carries dead structural weight. Furthermore the vertical loadings in a fully extended position on the overlap positions of the outer and inner wing are significant and will need advanced materials to sustain the forces. Therefore the structure poses the greatest design challenge on the MM-RCUAV telescopic wing, related to issues in placing a main spar conventionally.

5.2 Fuselage Design

Considering the advantages and disadvantages of the initial MM-RCUAV modular concept, the new design has proven to be a suitable alternative. The new design has utilised the experience gained from previous investigations and has addressed the identified problems, including limitations of the CG movement.

Payload flexibility is now obtained through an alternative approach by designing interchangeable equipment bays. Similar to previous designs, it is not free of disadvantages. The empennage size, design and layout are presently being further investigated, as the short lever arm from the neutral point results in large control surfaces. Fig. 9 illustrates the principle of the investigated dovetail empennage configuration.

The landing gear configuration is to be further investigated; a high mounted wing increases the complexity and weight.

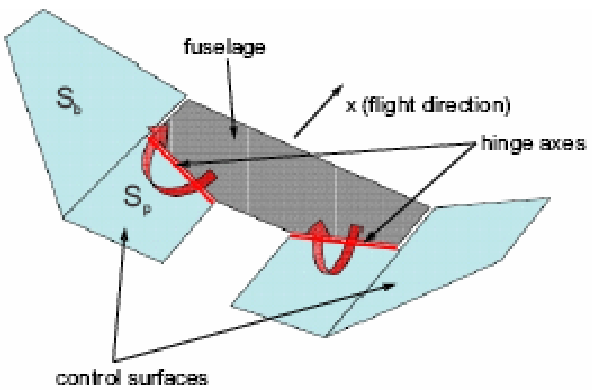


Fig. 9. Dovetail Configuration [16]

6 Concluding Remarks

The mission analysis resulted in stipulating the mission profile and the identification of missions systems to formulate the mission payload. The design analysis involved comparative analysis with UAVs in service to slate the design benchmarks. The iterative design process resulted in the design of the shown MM-RCUAV for a broad mission envelope and the iterative design process was executed on computational format in Microsoft Excel. It is important to note that the results obtained at each stage of the design were compared against the benchmark and re-iterated to meet the stipulated requirements. CFD simulations assist in the evaluation of the design.

The MM-RCUAV project has reached a new stage of design, while the morphing wing and the fuselage, using interchangeable equipment bays, and have demonstrated to be promising approaches. Several issues and challenges of the modular concept were addressed and partly solved. However, due to the early design stage of the MM-RCUAV project, further iterations steps are required in order to evaluate more concepts and designs for suitability and evaluation against each other. Current research focus is kept on a more detailed empennage design, wing design and the next iteration step for more accurate design points and therefore dimensions and weights.

7 Glossary

b	Wing Span
c	Wing Chord
CFD	Computational Fluid Dynamics
CG	Centre of Gravity
C_D	Drag Coefficient
C_{Dp}	Profile Drag Coefficient
C_L	Lift Coefficient
D	Drag
e	Oswald Factor
HALE	High Altitude Long Endurance
Λ	Aspect Ratio
L	Lift
LASE	Low Altitude Short Endurance
M	Mach Number

MAME	Medium Altitude Medium Endurance
MM-RCUAV	Multi-Mission Re-Configurable UAV
MTOW	Maximum Take-Off Weight
MWE	Empty Weight
P	Design Point in Size-Matching-Chart
Pa	*Pascal*
S	Wing Area [m^2]
SATCOM	Satellite Communication
t	Mission Duration (Time)
UAV	Unmanned Aerial Vehicle
W	Weight
φ_{25}	Sweep Angle 25% Chord

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