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Cite as: AIP Conference Proceedings **2233**, 020020 (2020); https://doi.org/10.1063/5.0001359
Published Online: 05 May 2020

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Development of a Hybrid Vertical Take-off and Landing Unmanned Aerial Vehicle for Maritime Application

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Abstract. An unmanned aerial vehicle (UAV) that is able to take-off and land on a medium sized ship, have greater endurance and range as compared to the previous iteration, and the ability to achieve all three flight modes – vertical, transition and horizontal flight modes is to be designed, built and tested. In this paper a comprehensive review is given on various VTOL planform configuration and a tilt-rotor configuration is selected for Minerva 2.0 for its high stability and increased efficiency. This paper covers the selection analysis of different vertical take-off and landing (VTOL) airframe as well as mechanical and electronic hardware design with the intention of increasing flight efficiency for surveillance purposes on wide sea area. This paper presents Minerva 2.0, a novel aerial platform with VTOL capabilities. Numerical and analytical analysis results are discussed. The previous iteration, Minerva 1.0 was built and tested as a QuadPlane configuration and an increased efficiency of 25 to 58.7% is achieved in this paper.

INTRODUCTION

The motivation of this development came from the desire to solve the problem of cross-border attacks that have been ongoing in Sabah since 1963 until now. Though with enhanced border security such as enhanced patrols by marine police and the establishment of Eastern Sabah Security Command (ESSCOM) in 2013 in effort to counter further Filipino militant infiltrations [1]–[3], cross border attacks are still ongoing. It is thought to be impossible to mitigate this issue due to the geographical location of Sabah with its vast 1400 km coastline and proximity to the impoverished Sulu archipelago, swarming with terrorist groups [4], [5].

With large scale fixed wing unmanned aerial vehicles (UAVs) like Global Hawk [6], [7] and Predator [8] demonstrating huge success in action throughout the recent years, they have showcased the advantages of UAVs in critical circumstances. However, these UAVs are unable to conduct observations in confined scenarios, resulting in the need of ground-based troops. An important factor for UAVs to be deployed in such situations is the need of infrastructure support, such as a take-off and landing runways. A conventional fixed wing UAV would require these infrastructures or some form of launch and recovery systems at the very least. Examples of launching and recovery equipment are catapults and hooks, as well as sufficient space to acquire airspeed and altitude. Hence, large space and external infrastructures are a must to deploy these UAVs.

Maritime application contributes to added challenges for UAV design and operations due to sea state conditions. The immense maritime space without physical or functional boundaries imply the necessity of greater UAV endurance and range and custom-made maritime vessels with sufficient space for external infrastructures.

While rotorcraft is small and agile, a rotorcraft has an average endurance of 20 minutes due to the lack of aerodynamic structure [9]. Hence, a hybrid vertical take-off and landing (VTOL) UAV that combines VTOL capability of a rotorcraft with the endurance capability of a fixed wing is deemed to be optimal for maritime application will be developed in this project. This is because these abilities not only allow the UAV to have increased endurance and range which is required for surveillance purposes on wide sea area, it also allows the UAV to take-off and land on the ship, increasing its mobility, as well as to hover and investigate a specific area when needed, which increases their

13th International Engineering Research Conference (13th EURECA 2019)
AIP Conf. Proc. 2233, 020020-1–020020-13; https://doi.org/10.1063/5.0001359
Published by AIP Publishing. 978-0-7354-1992-6/$30.00

maneuverability. A schematic diagram of conventional take-off and landing (CTOL) against VTOL flight path is shown in Figure 1.

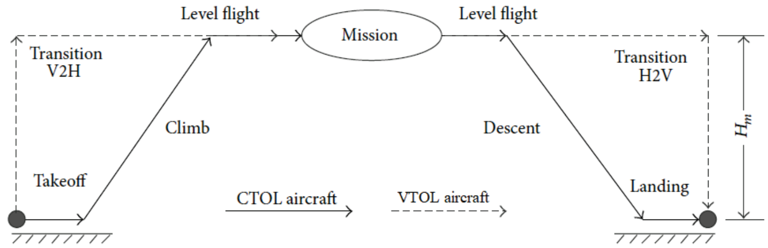
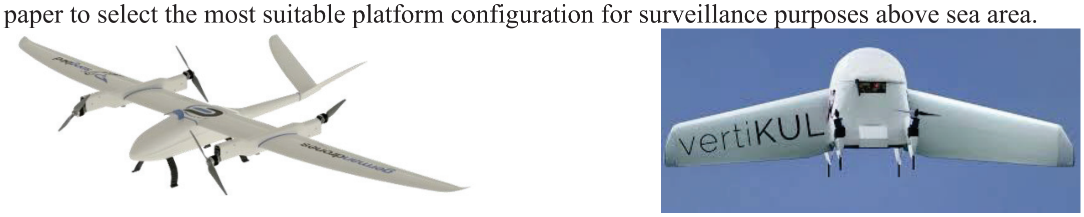


FIGURE 1. CTOL versus VTOL fight path.

Many platform configurations have emerged and are researched on throughout the decades. Typically, hybrid VTOL configuration can be categorized into two types: convertiplanes and tail-sitters. Figure 2 shows examples of a tilt-rotor convertiplane and a tail-sitter. Depending on the transitioning mechanism and the configuration of the airframe, each may be further classified into a few sub-types. An extensive review of these configurations is included in this paper to select the most suitable platform configuration for surveillance purposes above sea area.



(a) (b)

FIGURE 2. (a) Tilt-rotor convertiplane [10]. (b) Tail-sitter [11].

The objective of this paper is to develop a marine hybrid VTOL UAV to provide surveillance of the penetration of any sea borne hostile intruder during peace time and to assist in search and rescue operations when needed. In this paper, comparisons between two platform designs of hybrid VTOL UAVs will be done according to the needs to execute long range and high endurance surveillance above the vast sea area while finding a balance between the requirements and power efficiency. An efficient aircraft would mean the UAV can cover a broader area per flight, increasing operational hours while decreasing preparation hours. This is beneficial for surveillance aircraft as minimal man hours is required for servicing and coordination of landing and take-off sequences, allowing more hands on-deck to work on more vital tasks while reducing empty windows where the area is not under surveillance. The current work will be based on the first iteration of the hybrid VTOL UAV – Minerva 1.0 as manufactured by FourFang Sdn. Bhd. A prototype of the optimal design shall then be selected, designed, built and verified at the end of this paper.

REVIEW AND SELECTION OF VTOL PLATFORM CONFIGURATIONS

Convertiplanes are generally aerial vehicles that maintain its airframe orientation throughout all flight operations, namely take-off, transition, cruise and hover. Various mechanisms are then employed to transition from vertical to horizontal flight mode and vice versa. Hence, convertiplanes are then further categorized into three sub-types according to their tilting mechanisms. These include tilt-rotor, tilt-wing and dual systems, more commonly known as QuadPlanes. Contrary to convertiplanes, a tail-sitter takes off and lands on its tail, tilting the entire aircraft from vertical to horizontal while transitioning from vertical to forward flight using either control surfaces or differential thrust. This configuration is also known as tilt-plane as the entire plane tilts while transitioning.

A tilt-rotor configuration is equipped with rotors that can be tilted by a servo motor, either to provide vertical lift force (i.e., take-off, hover and landing) or forward flight thrust [12], [13]. The tilt-wing idea is much like the tilt-rotor, with the exception that the entire wing tilts instead of the rotors alone [14]–[16]. Even though both tilt-wing and tilt-rotor configurations require complex mechanical structures, tilt-wing is more sensitive to wind gust than tilt-rotor and requires servo motors with much higher torque to tilt the entire wing. This means that the tilt-wing configuration is unsuitable for maritime purposes due to the harsh wind sea condition. The wing tilting requirement also causes it to be much more mechanically complex, causing it to be more prone to failure, let alone more expensive.

The third type of configuration, a QuadPlane uses distinct rotors for vertical and forward flight. The design, modelling and control of a QuadPlane are comparatively easier than the other configurations as it has separate control systems for vertical and forward flights [17], [18]. However, it is not as energy efficient as all other configurations as it uses separate rotors for vertical and level flight and that the lifting rotors will not be in used during forward flight, resulting in unnecessary dead weight while in forward flight [19]. Hence, tilt-rotors and tail-sitters were selected for comparison and tabulated in Table 1.

TABLE 1. Comparison between tilt-rotor and tail-sitter.

	Tilt-rotor	Tail-sitter
Mechanical complexity	High mechanical complexity – decreases reliability of aerial system.	Does not involve tilting mechanism and less actuators, mechanically simpler and lighter than convertiplanes – less prone to failures.
Weight	Requires actuators resulting in extra weight. Less efficient during forward flight as number of rotors of more than two is required for stable vertical flight but fixed-rotors are redundant during forward flight and induces dead weight.	Does not require actuators hence less weight and all rotors are utilized for thrust generation of forward flight.
Aerodynamic performance	Unused rotors during forward flight increases drag unless more actuators are added to tilt the excess rotors, which reduces drag but increases weight and mechanical complexity.	Streamlined shape favours drag reduction.
Controllability and stability	Good controllability and stability.	Requires complicated control mechanisms and high power to maintain stability. Inaccuracy in attitude control.
Susceptibility to cross wind and wind gust.	Less affected by cross-wind and wind gust.	Highly vulnerable to cross wind and wind gust during vertical flight due to vertical orientation and bigger surface area of aircraft.
Ease to land on moving deck	Easy to land on moving deck due to its stability.	Difficult to land on moving decks.

As per paper's objective, a hybrid VTOL UAV of greater efficiency for maritime purpose is to be developed. Hence, tilt-rotor is selected as the most suitable configuration for this project. Though with a moderate power efficiency as compared to tail-sitter and quadcopter configurations, a tilt-rotor excels in maritime conditions by having great resistance to cross-wind and a moderate controllability and stability and capability to land on moving deck, second to quadcopter but top of tail-sitter configuration.

HARDWARE ARCHITECTURE

The airframe was designed according to flight requirements as shown in Table 2. These requirements were set according to the average flight conditions of a fixed wing UAV with surveillance purposes as well as Minerva 1.0, the first iteration of this UAV. The flight specifications of the first iteration were also included in Table 2.

TABLE 2. Flight requirements.

Parameter	**Value**	
	Minerva 1.0 (Quadplane)	**Minerva 2.0 (Tilt-rotor)**
Maximum take-off weight, MTOW/WTO	3.4 kg	4.4 kg
Desired stall speed, Vs	10 m/s	< 15 m/s
Desired cruising speed, $V\infty$	13.7 m/s	20 m/s
Desire maximum speed, V_{max}	18 m/s	30 m/s
Desired cruising altitude, h	89 m	100 m
Endurance	48 min	> 60 min

Number of rotors

A tilt-rotor configuration can be further categorized into a few sub-types according to the number of rotors, each giving different effects on the flight condition and stability in different modes (vertical flight, horizontal flight and transition).

In this paper, a quad-rotor design was chosen. The main advantages of quad-rotor designs are that they do not require variable pitch propellers, hence mechanically simpler, while allowing smaller rotor diameters as they possess less kinetic energy during flight. This allows them to be safer, and still maintain flight capacity if one of the rotors fail, causing higher chances of surviving a crash. Moreover, due to more actuators present, they also have better maneuverability, are easier to control, and generally more stable. Distribution of mass is also much easier as the mass point can in the center.

Although with increased weight when compared to a bi-rotor or tri-rotor, it results in better aerodynamic profile as compared to bi-rotor and greater stability, less mechanical complexity and simpler control system as compared to tri-rotor. As bi-rotor is mounted on the wing tip due to the need to counteract the constant rolling torques applied by the wing tip mounted rotors on the both wings and fuselage, it causes bad aerodynamic in terms of aspect ratio and drag due to shorter wing span and thicker airfoil. Attitude stabilization in hover mode becomes challenging as well due to the lack of counter torque with only two rotors. While for tri-rotors, although it is more stable than bi-rotor designs, it is still highly unstable during hover as compared to other multirotor designs. An additional servo has to be added onto the single rotor along with highly advanced control system to maintain its stability while hovering. Failure also tends to be more catastrophic as the copter will not be able to save itself if one rotor fails.

Hence, quad-rotor design was concluded as the most suitable design as stability is a crucial factor to take off and land vertically above sea condition with possible wind gust along with other advantages discussed.

Aerodynamics

The aerodynamic of the UAV was designed according to the flight requirements to be achieved through analytical and numerical methods. The airfoil selected in this paper would be the same as the first iteration which is MH114 as analysis was made during the research and development of Minerva 1.0 and performance was verified through real flight test result. Other aspects relating to aerodynamics such as wing area, aspect ratio, disc loading and tail design were included in mechanical design to allow chronological explanations.

Mechanical Design

The design maximum take-off weight (MTOW) was estimated to be 4.4 kg. This value is obtained through a weight estimation of total electronics weight to non-electronics weight of Minerva 1.0, which in this case is 1.26 to 1. A rough estimation of total electronics weight of Minerva 2.0 is 1.92 kg. Using the historical data as a starting point, the estimated MTOW for this project is around 4.4 kg. Taking 20% tolerance to this weight estimated, the allowable UAV weight was between 3.2 kg to 5.28 kg.

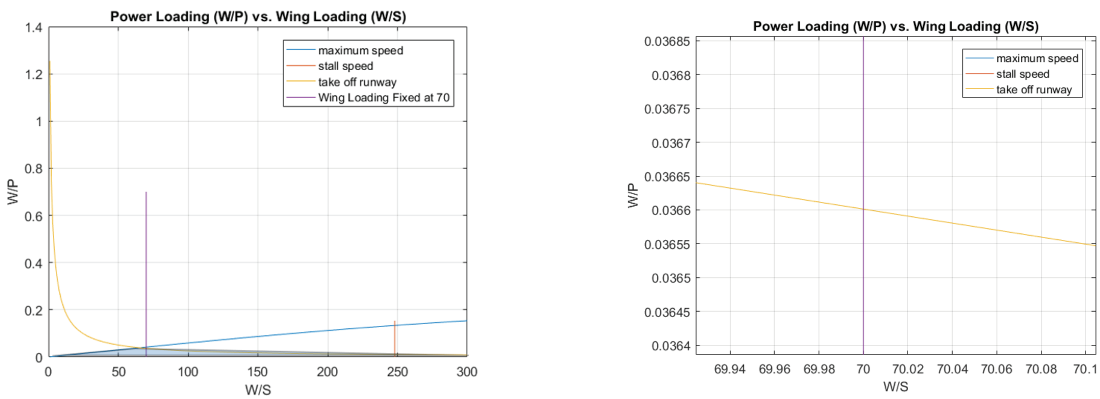
Wing area design was done through investigating the three contributing factors to obtain the ideal wing loading and power loading. Ideally, the planform area of the aircraft should coincide with the best probable power loading. The three selected performance equations to generate a matching plot were maximum speed (V_{max}), stall speed (V_S) and take-off run (S_{TO}). These equations can be obtained from [20]. Using the aircraft specifications as well as the necessary parameters and utilization of MATLAB software, a series of graphs were generated. The acceptable region was then identified and the design point was selected. While this project involves improvement of current design, wing loading was set as geometry similarity between the two designs. Hence, the same wing loading of 70 kg/m^2 will be used and the minimum power in the acceptable region corresponding to wing loading of 70 kg/m^2 was selected.

From Figure 3, the minimum power, corresponding to the maximum wing loading at wing loading of 70 in the acceptable region is 0.0366. After obtaining the design point, the final wing reference area and power required for forward flight can be calculated using simple wing loading and power loading equations as shown in Eqs. (1) and (2).

$$S_w = \frac{W_{TO}}{\left(\frac{W}{S}\right)_d} \tag{1}$$

$$P = \frac{W_{TO}}{\left(\frac{W}{P}\right)_d} \tag{2}$$

where S_w is the wing reference area required for forward flight, $(W/S)_d$ is the desired wing loading obtained from matching plot generated, P is the power required for forward flight and $(W/P)_d$ is the desired power loading obtained from matching plot generated.



(a) (b)

FIGURE 3. (a) Matching plot for fixed-wing part of hybrid UAV. (b) Design point extracted.

Using MTOW of 4.4 kg, desired wing loading of 70 and desired power loading of 0.0366, the wing reference area, S_W was calculated to be 0.6 m^2 with maximum power at 1.26 kW at maximum speed of 30 m/s.

The tail to be a boom-mounted tail with a horizontal tail span of 55.72 cm and a tail chord of 11 cm, with an aspect ratio of 5. A high tail boom-mounted configuration was selected instead of conventional tail design such as Minerva 1.0 as the propellers behind the fuselage are rather large and would decrease the efficiency of flow profile hence increasing drag due to inference between propeller flow and the tail. Aspect ratio used was according to the typical tail aspect ratio of 3 to 5 that prioritizes structural weight to drag coefficient. Tail aspect ratio of 5 will be selected, to allow a slim tail with minimum weight and drag. Then, the other defining parameters such as the tail span and chord as well as the arm length were obtained through iterative method and known parameters using the most important factor in tail design which were the tail volume ratios for both vertical and horizontal tails, equations which can be obtained from [20]. For example, the known parameters were such as wing span and wing chord length, the arm length and tail area can then be obtained by constraining the tail area within a standard value of 20~30% of wing area.

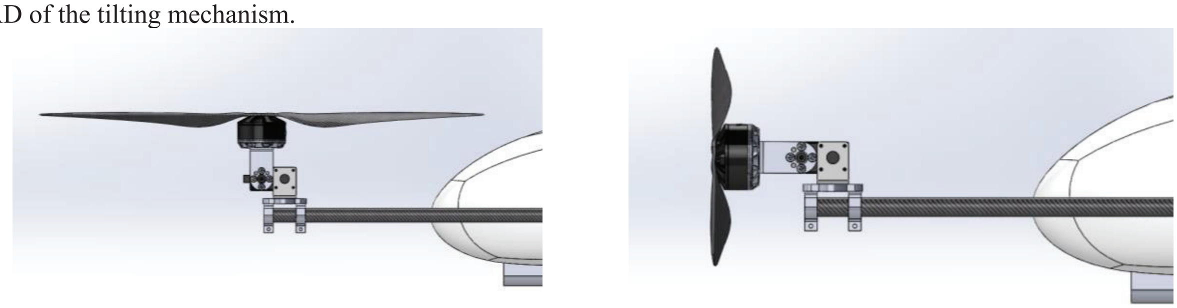
Main function of the fuselage was to contain avionics while minimizing its effect on the lift and drag profile. Hence, a fuselage that is similar to an airfoil profile with sufficiently large space was designed to reduce drag and increase lift of the fuselage. A side view of the fuselage is shown in Figure 4 (a) and a full CAD drawing is shown in Figure 4 (b).

(a) (b)

FIGURE 4. (a) Side profile of fuselage. (b) Complete CAD drawing of the UAV.

Transition Mechanism

The transitioning mechanism design will essentially tilt the front two motors of the QuadPlane design and eliminate the forward propulsion motor. Through this method, the powerplant of the aircraft was simplified from a set of five motors to four motors. A visual concept of the design is shown in Figure 5 (a) and (b), which are side view CAD of the tilting mechanism.



(a) (b)

FIGURE 5. (a) Tilting servo in vertical flight mode. (b) Tilting servo in forward flight mode.

The main moving parts for the transitioning mechanism were the servo motors which manipulate the front propulsion units. As such, they need to have sufficient holding torque to hold the motors in place during all stages of flight, while having sufficient speed to reach angular setpoints as demanded by the flight controller. The propulsion mounting design will be like Minerva, in which support beams will be placed on the wing, longitudinally. To compute the torque, T required to hold the propulsion units, Eq. (3) was used, where W_{motor} represents motor and propeller's weight and l_{sa} represents servo arm length.

$$T = W_{motor} l_{sa} \tag{3}$$

The allowable motor weight limit was 0.2 kg, and most servo motors have a typical arm length of 0.05 m. Hence, the minimum torque requirement was 0.01 Nm, which translates to 10 kg·cm in servo motor specification terms. Applying an aircraft required factor of safety of 2, the required servo motor specification was to have at least 20 kg·cm. Based on available market options, the selected servo motor is DSSERVO DS3235 Coreless Servo Motor, with 35 kg·cm of torque, or 0.035 N m.

Avionics

The most important component of a UAV is the flight controller (FC), which acts as the brain of the UAV that receives commands from user and direct them through pulse width modulation (PWM) signals to respective actuators and in turn controls the flight. The FC used in Minerva is PixHawk 2. Several main components to support the UAV system includes actuators, power distribution board, GPS module and telemetry.

There were total of 10 actuators present – four brushless motors with 15-inch propellers, 2 tilting servos for transition mechanism and four servos for control surfaces actuation. All actuators were connected to PWM output channels of the flight controller. PWM signals are standard protocol used to command radio controlled (RC) actuators, enabling simple signals control. Each of the brushless motors were connected to an electronic speed controller (ESC) which controls the speed of the motors. These ESCs were then connected to a power distribution board (PDB) that is connected to the main power supply. The PDB was used to distribute electricity supply to subsidiary circuits, which in this case are the ESCs. The PDB acts as a safety fuse to the respective subsidiary circuit, protecting them from damaging in case of current overload.

GPS module was necessary to measure ground speed of the UAV and telemetry is a long-ranged radio modem used to transmit real time flight data back to ground control station, enabling instant monitoring of the flight status. Flight data that can be monitored were ground speed, altitude, attitude, battery information, flight mode and so on. These are important for data collection and verification after real flight test. Real time monitoring and adjustment also act as a safety feature as any unusual flight status can be detected and adjusted instantly.

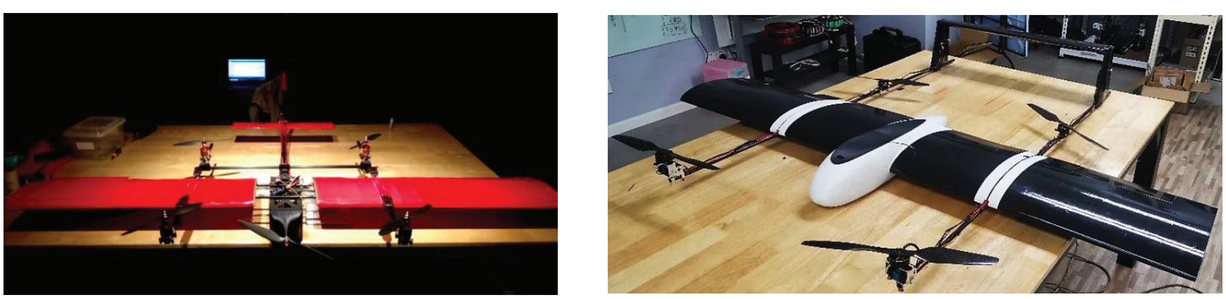
PROTOTYPING

Other than electronics, all components of Minerva were manufactured using rapid prototyping, 3-axis CNC milling machine and laser cutting. For example, fuselage casing is 3D-printed using ABS material due to its heat resistant and light weight properties. This minimizes the weight and keeps the weight of the aircraft under the designed MTOW. It also prevents the fuselage from deforming if the UAV was flown in the afternoon under the sun as opposed to the typical 3D printing material – PLA with low heat resistance. Other parts such as tube clamps were manufactured using CNC milling of aluminium for its strength and light weight and parts that requires specific shapes such as wing ribs using foam boards were cut using laser cutter.

A twin-spar configuration was selected for wing as load bearing structural members as the MTOW is rather high for an aircraft. The wing was manufactured using a novel method where foam boards were used as ribs to provide airfoil shape, carbon fiber tubes as spar for structural reinforcement and PVC foam boards as skin. Foam was used as the main materials due to its light weight. Though foams are brittle, PVC foam boards have exceptional strength with impact strength greater than 800 N. Carbon fiber tubes also act to increase structural strength of the overall wing while being light-weight. A section of the rib-spar structure is shown in Figure 6. As opposed to conventional methods where balsa wood was used as ribs and shrink wrap as skin, the foam method is more ductile and durable, making it more impact resistant than the conventional method.

FIGURE 6. Ribs and spars.

An important factor to be considered while building the prototype is the center of gravity and neutral point placement. To ensure the prototype's stability, neutral point (NP) and center of gravity (CG) positions were calculated to ensure that the NP is aft of CG. Equations can be obtained from [21]. All avionics and components placement were then done to ensure center of gravity coincides with calculation results which is 10 cm from the trailing edge of wing in this case. The final prototype along with Minerva 1.0 were shown in Figure 7 (a) and (b).



(a) (b)

FIGURE 7. (a) Minerva 1.0. (b) Final prototype of Minerva 2.0.

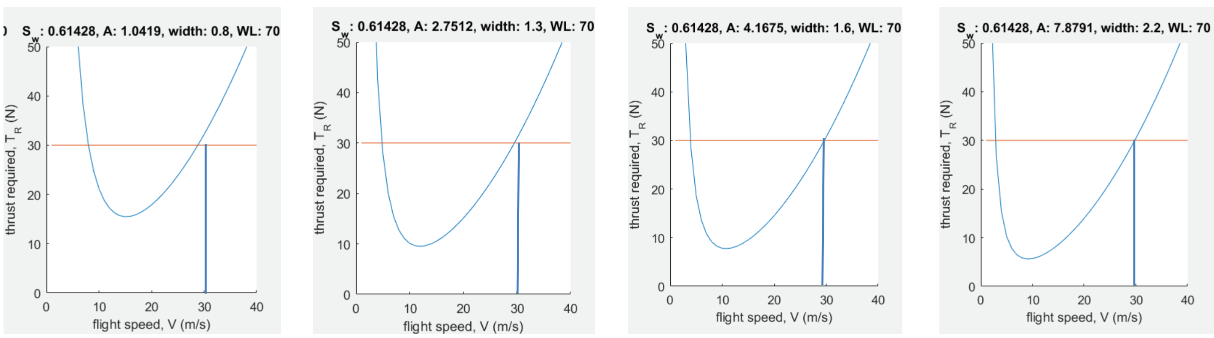
RESULTS AND DISCUSSION

Aspect Ratio

Aspect ratio is one of the most important factors in dictating aerodynamic efficiency of an aircraft. In present study, momentum theory was used for analysis for the optimum aspect ratio. It states the power required for lift decreases with an increase in aspect ratio. However, the minimum power flight speed, states that the flight speed of best efficiency tends to decrease with increasing aspect ratio. Both formulas can be found in [21].

Based on the minimum power flight speed equation and the selected wing loading of 70, the optimized aspect ratio is computed as $A = 1.034$. However, this is not possible nor is it logical as this would result in a square wing.

Hence, the analysis is approached with another method using the thrust required at level flight speed. Equation can be referred from [21]. An iterative method is used and the data is computed using MATLAB at different aspect ratio, part of the results is shown in Figure 8.



(a) (b) (c) (d)

FIGURE 8. Thrust required against flight speed for wing aspect ratio of (a) 1, (b) 3, (c) 4 and (5) 8.

In Figure 8, the red line corresponds to the aircraft estimated thrust available and is added purely for visualization of flight envelop. Region below the red line indicates speeds where the aircraft can fly. It can be seen that an aircraft with higher aspect ratio is able to sustain a lower top speed than an aircraft with lower aspect ratio but is able to cruise more efficiently within its flight envelop. Based on this, there appears to be no optimum wing aspect ratio. Hence, Table 2 was referred to find the ideal wing size based on maximum speed and cruising speed. The first criterion is that maximum speed of 30 m/s, as indicated by the blue line in Figure 8 must be available at the estimated thrust. Therefore, aspect ratio of less than 4 is eliminated as curves in Figure 8 (a) and (b) do not intersect a maximum flight speed of 30 m/s as shown in Figure8 (b) and (c). Aspect ratio between 4 to 15 requires between 13 to 15 N of thrust for sustained flight at cruising speed. Hence, all the aspect ratio in this range is accepted. For this reason, narrowing down the aspect ratio selection would be based on practicality purposes. In this case, an aircraft with smaller aspect ratio is easier to transport and has wings that are more rigid. In consequence, the aspect ratio of 4 is selected and this causes the preliminary wing design to have 0.39 m chord and 1.57 m wingspan. This decrease in aspect ratio allows the aircraft to have higher specification requirements than Minerva while maintaining the same wingspan of approximately 1.6 m.

However, after further analysis of centre of gravity and neutral point, it was found that an aspect ratio of 4 would result in the chord being too lengthy and falls right below the rear propellers. This would result in reduced efficiency and instability in transition flight as the wing would be directly affected by the downwash of the propellers. Hence, the aspect ratio was modified to be 5, with 0.346 m chord length and 1.732 m wingspan.

Moreover, based on historical data, the conventional value of aspect ratio for home-built aircraft lies within 5~7 [20]. Based on the information, the aspect ratio of 5 is the most optimum aspect ratio.

Disc Loading

The same propulsion system would be used throughout all flight modes as same motors and propellers used for vertical flight will be tilted for forward flight. Hence, the propulsion system needs to be able to accommodate both vertical and forward flight, as well as transition mode. It was proven that vertical flight requires higher thrust to weight ratio as compared to forward flight [22]. Therefore, the motor selection and hence the propeller selection was done according to vertical mode, which is the rotorcraft mode. For a typical quadrotor UAV, a thrust to weight ratio of 2 would be required for proper functionality [23]. The total thrust needed was distributed among four motors. Taking that into consideration, an aircraft with maximum weight of 3.5 kg would require a total thrust of 7 kg. Hence, each motor must provide a minimum of 1.75 kg thrust. This metric also justifies the selection of wing aspect ratio, as a minimum thrust of 30 N is required for achievement of 30 m/s flight speed. The selection of to provide 35 N of thrust allows the aircraft to be able to reach that target top speed, while allowing a typical value of 17% loss of efficiency to aerodynamic drag from the fuselage and tail.

After the motor is selected, suitable propeller will be selected from the specification sheet of the motor selected. A graph of power loading against disk loading as shown in Figure 8 is generated in MATLAB using Eq. (4) [24].

$$\left(\frac{W}{P}\right)_h = FoM\sqrt{\left(\frac{2\rho}{W/A}\right)} \tag{4}$$

where FoM which is figure of merit corresponds to P_i/P, P_i indicates ideal power, P indicates real power, ρ indicates density at specific altitude, $(W/P)_h$indicates power loading due to hover altitude and (W/A) indicates disc loading.

According to Figure 9, minimize disc loading maximizes power loading. This means that larger propeller sizes are beneficial to the efficiency of the aircraft. However, the general trend is that larger propeller sizes are paired to more powerful and larger motors, and this generally means propulsion system that increase in available thrust as disc loading decreases. Hence, propeller sizing that is too large is not ideal as larger motors have bad control bandwidth when operated at low throttle points. In simple terms, motors have sluggish response when not operating within an expected operating range.

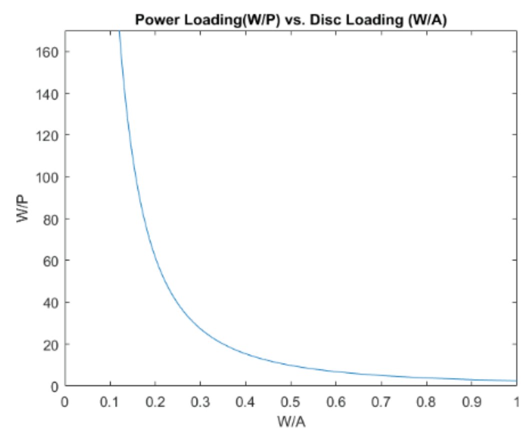


FIGURE 9. Graph of power loading against disc loading.

For this case, the largest available propeller size for the thrust requirement of the aircraft is chosen from the market. Based on market survey of available propeller and motor combinations, the largest propeller size for the thrust requirement is APC 1506 paired with EMAX MT3510 600kv motors operating with a voltage of 14.8 V, which corresponds to a 4-cell Lithium Polymer battery. The total thrust available for forward flight for this motor selection is 35 N, which is more than enough to allow achievement of the maximum flight speed of 30 m/s, while allowing 17% for drag and aerodynamic inefficiency.

Aircraft Numerical Analysis

MATLAB

Unlike conventional aircrafts where only wing loading and power loading are considered, a transitional aircraft (TA) comprises a three-axis relationship between wing loading, power loading and rotor disc loading. A set of curves were obtained at the end of design stage to allow the sizing of propulsion system (power loading), wing area (wing loading) and rotor disc area (rotor disc loading). This stage comprises three main elements:

1. Conventional fixed-wing preliminary design (sizing of power loading and wing loading).
2. Enhance performance equation of rotorcraft system (sizing of rotorcraft system and rotor disc area according to required performance).

3. Combination of fixed wing preliminary design with rotorcraft while integrating transition performance requirement (sizing verification).

Transition flight contribution was computed using available data in MATLAB. Combining Equations used to generate graphs in Figures. 2 and 8, a three-axis relationship plot of wing loading and disc loading against power loading as shown in Figure 10 is obtained using MATLAB, the shaded area shows the final design region.

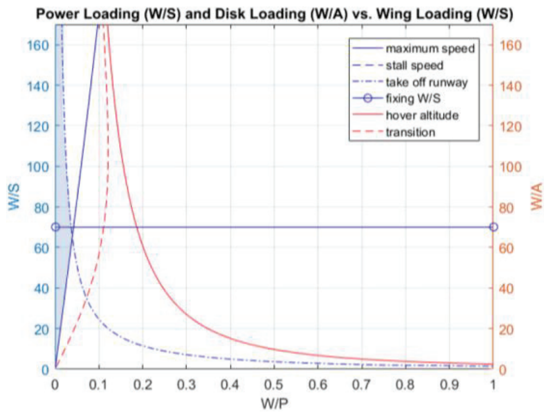


FIGURE 10. Three-axis matching plot.

The final design region is the region enveloped by all the contributing curves and is shaded in Figure 10. This final 3-axis matching plot verified that the design point and the motors selected are within the region of fixed-wing, rotorcraft and transition mode. This is crucial to ensure that the wing area, power needed and disc loading chosen were able to accommodate all three flight modes.

XFLR5

A software that was utilized to obtain computational fluid dynamics (CFD) results of an aircraft is the XFLR5. In order to simplify the simulation, only the wing and empennage are included as they are the main contributing components of the aerodynamic lift and drag while the other components are negligible. Figure 11 shows the visual simulation result of streamline, lift and drag profile on the UAV while Figure 12 shows the lift and drag polar curves generated for the UAV.

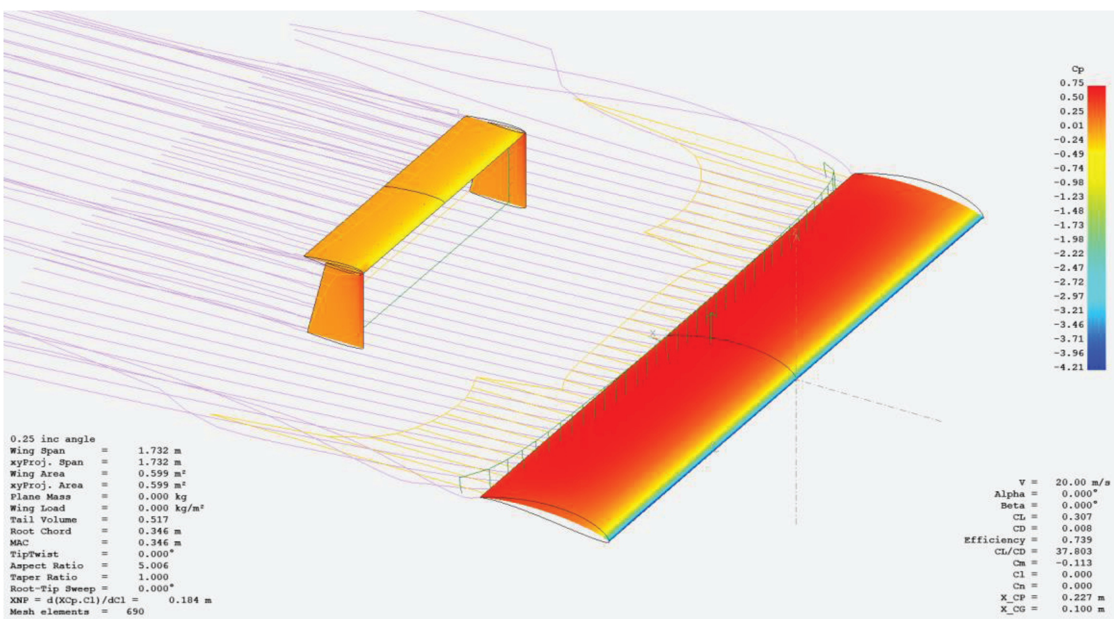


FIGURE 11. Simulation result of Minerva 2.0.

From Figure 11, the color distribution on the aircraft surface shows the pressure coefficient distribution. It was this factor that contributes to lift and drag forces. Lift and drag forces can be calculated from this parameter through simple equations in [25]. However, since lift and drag are computed by this software, no calculation has to be made. The yellow distribution lines show the drag profile while green distribution line shows the lift profile when the UAV is cruising at 20 m/s at 0° angle of attack. The lift profile concentrates around three-quarter-chord of the wing while the induced drag increases further away from mid-span. These were expected results as taper ratio of 1 was selected for the wing configuration for its mechanical feasibility. To improve this, taper ratio can be lowered and dihedral angle can be added. However, due to mechanical complexity and limited time frame, improvements will be done in the next iteration. Furthermore, the purple lines show the streamline of airflow across the UAV in flight. From the streamline profile, it can be observed that there is little to no vortex that forms at the wing tip due to the low aspect ratio, hence no external accessory such as winglet is necessary.

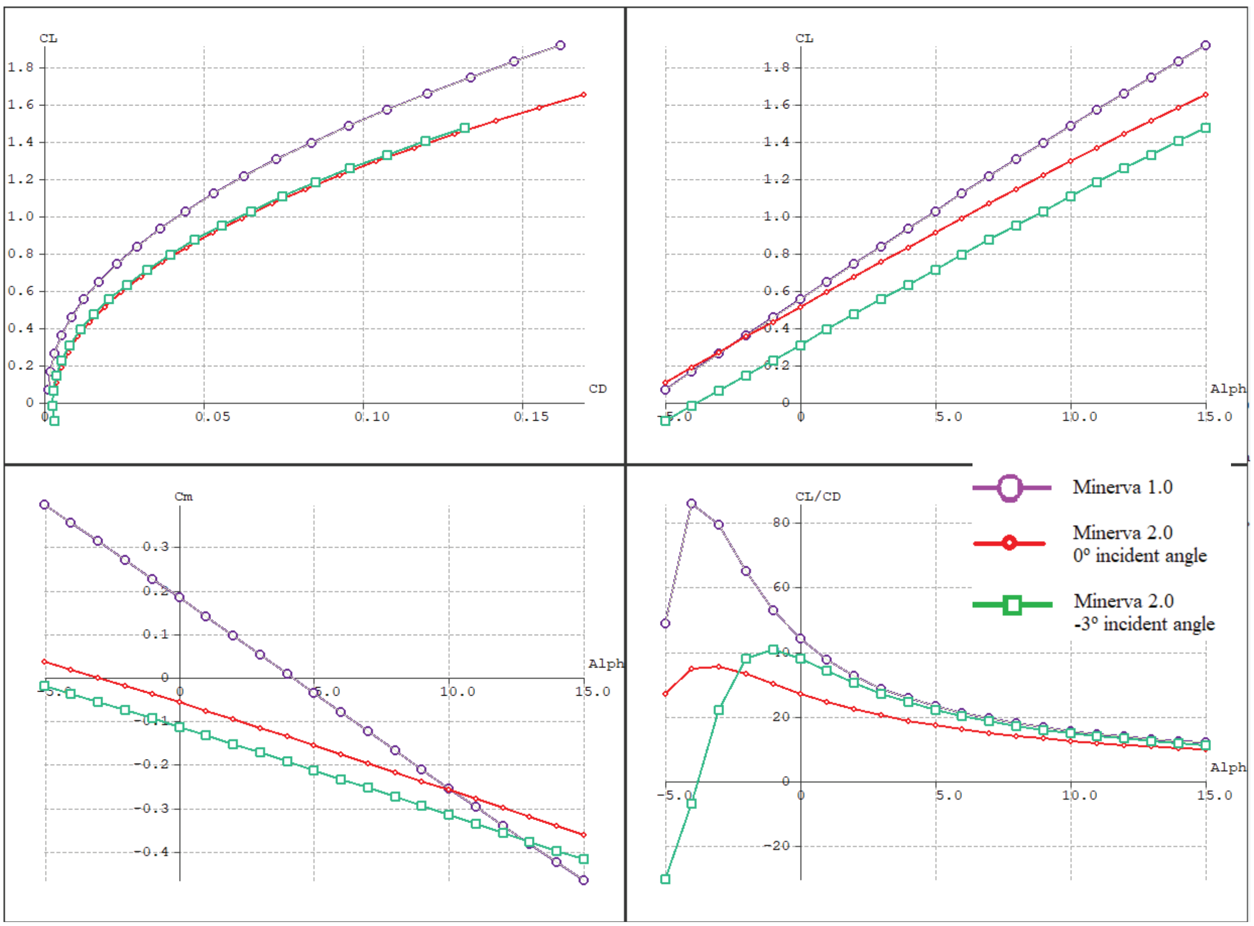


FIGURE 12. Aircraft polar curves.

Figure 12 shows the polar curves of aircraft obtained through the software- XFLR5. The purple line with big circles indicates Minerva 1.0 and red line with small circles indicates the first design of Minerva 2.0, where incident angle of the wing is at 0°. During cruising, the UAV was assumed to fly at a 0° angle of attack. Hence, cruising speed of each model can be calculated using simple lift equation found in [21] and lift coefficient obtained from the curves. Taking weight as lift during steady level flight at 0° angle of attack, lift coefficient of Minerva 1.0 as 0.55 and of Minerva 2.0 as 0.5, cruising speed was calculated to be 12.6 m/s, which corresponds to the flight data obtained. However, for Minerva 2.0, the cruising speed was calculated to be only 16.0 m/s, which is below the desired cruising speed of 20 m/s. Hence, using reverse calculation, it was found that the lift coefficient at 0° has to be 0.32 in order to achieve a cruising speed of 20 m/s. It was found from the graph that lift coefficient of 0.32 corresponds to an angle of attack of $-3°$. Hence, to prevent the UAV from flying at a negative angle of attack, $-3°$ was included as incident angle of the wing. A third simulation with incident angle was added and shown on the polar curves as green lines with squares. Table 3 shows the tabulated results.

TABLE 3. Cruising speed calculated for different models according to lift coefficient simulated.

Model	Lift coefficient, C_L	Cruising speed, V_∞ (m/s)
Minerva 1.0 (blue)	0.55	12.6
Minerva 2.0 first design (yellow)	0.5	16
Minerva 2.0 second design (green)	0.32	20

The main reason to this issue was because the lift generated is beyond the required amount for cruising as lift coefficient is inversely proportional to the square of speed. This would be appreciated on a fixed wing or a glider where high lift and a runway is required to take off. This is evident in [26], where a glider airfoil is designed to have a high lift profile so that high lift can be generated for take-off and landing. However, since the cruise speed is the limiting design criteria, the cruising lift coefficient should be carefully tuned or the aircraft would climb at the desired cruising speed. An example is such as in literature [27], where sweep wings and thin airfoil design was used to provide a low cruising lift coefficient. Similar method can be used to solve this issue which is to incorporate sweep wing design or changing the airfoil profile so that lower lift is generated at the same angle of attack. However, a simple approach is used in this study where negative incident angle is integrated.

Theoretical Analysis

Since the main determining factor of power efficiency is the endurance and range of the UAV, theoretical results can be estimated using equations as shown in Eqs. (5) and (6).

$$Endurance = \frac{Battery\ capacity\ (\text{Ah})}{Current\ draw\ (\text{A})} \tag{5}$$

$$Range = \frac{kV \times V \times 60 \times pitch}{12 * 5260} \times endurance \tag{6}$$

where kV is the number of revolutions per minute per volt of the motor used and V is voltage drawn.

Using estimated value of current draw from historical data, the endurance of Minerva 2.0 can achieve 60 min while the range is 75 km as compared to Minerva 1.0 that has an actual endurance of 48 min and range of 50 km. Hence, theoretically, Minerva 2.0 should have a greater flight efficiency of 25 to 50%. However, these values have to be verified through experimental result – the actual flight test before a solid conclusion can be made. This is due to the high percentage of random error during a UAV flight such as the fluctuating environmental condition, surface finish of the actual prototype and varied piloting skills.

CONCLUSION

The objectives were achieved where a review was done on different planform configurations of hybrid VTOL UAVs and the best design selected. The prototype was also design, simulated and built. Final selected planform configuration is a tilt-rotor in quadrotor configuration. Aircraft is designed to have single wing with aspect ratio of 5 and wing area of 0.6 m^2 with boom mounted high-tail. The propulsion system would use a quad-rotor configuration using EMAX MT3510 600kv motors paired with APC 1506 operating with a voltage of 14.8 V, which corresponds to a 4-cell Lithium Polymer battery, providing a minimum thrust-to-weight ratio of 2 for vertical flight and 0.74 for forward flight, which is a copious amount of thrust generation in both modes. The two servomotors used for transitioning will be DSSERVO DS3235 Coreless Servo Motor, supplying 3.5 Nm of torque per motor. Numerical and theoretical analysis proved that the current design is more efficient than the previous design where it is able to fly at an increase of 58.7% cruising speed, 25% endurance and 50% range of Minerva 1.0. Further flight test will be done on the prototype to obtain accurate flight data and test its ability in different flight modes. Future improvements can be done on changing the airfoil profile to better suit the application so that it can achieve cruising speed without negative incident angle is not needed as it reduces aerodynamic efficiency. Furthermore, dihedral and sweep angle can be added on the wing so to further improve aerodynamic efficiency.

ACKNOWLEDGMENTS

This research is co-funded by the School of Engineering, Taylor's University and FourFang Sdn. Bhd. The authors would also like to acknowledge FourFang Sdn. Bhd. for providing certain materials to support the research.

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