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Design of Separate Lift and Thrust Hybrid Unmanned Aerial Vehicle

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Abstract— Hybrid UAV is a new platform of UAV which is an integration of fixed wing and multirotor to get vertical takeoff and landing capability with high range and long endurance. Thus it has the benefit of both fixed wing and multirotor platform. The design methodology of hybrid UAV is by resembling fixed wing aircraft with modification at some part due to augmentation of multirotor. This Hybrid UAV has been manufactured and on testing phase.

Keywords— Hybrid UAV, VTOL, fixed-wing, multirotor.

I. INTRODUCTION

MULTIROTOR is a rotorcraft with more than two rotors. Control of vehicle motion is achieved by varying the relative speed of each rotor to change the thrust and torque produced by each rotor. Fixed wing UAV is an UAV which is capable of flight using wings that generates lift caused by the vehicle forward airspeed and the shape of the wings.

The concept of hybrid UAV enables designers to deliver air vehicle with longer mission endurance while eliminating the need for runway during take-off and landing. It combines the vertical take-off and landing (VTOL) capabilities of a multirotor and the efficiency, speed, and range of a normal fixed-wing aircraft.

Here are the major challenges that have to be carefully considered when designing hybrid UAV:

- Higher energy consumption
- Vibration
- Aerodynamic efficiency decrease
- Maximum take-off weight increase
- Difficulty in transition, both from hover-to-forward flight and forward flight-to-hover

II. DESIGN METHODOLOGY

A. Literature Study and Specifying Requirements

Comparing existing UAV with VTOL capability resulted in the selection of configuration to comply with the DRO (Design Requirements and Objectives). A number of hybrid UAVs were studied, providing valuable information to start design process. Basically, there are 3 types of hybrid UAV which are:

1) *Separate Lift and Thrust (SLT)*

This type has a number of motors with 2 different functions. One or more motors produce horizontal thrust like a normal fixed wing to generate lift for forward flight. The others motors produce vertical thrust like a multirotor.

The benefit of this type is it does not need mechanism to tilt the rotor. But this SLT type will produce more weight and more drag than the other type. Since it produces 2 kind of thrusts with different direction (horizontal and vertical thrust), there will be overlapped thrust during the transition, when switching flight mode from hover to forward flight and vice versa.

Figure 1 Separate Lift and Thrust (SLT)

Figure 2 Tilt-rotor

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Figure 3 Aerobatic plane

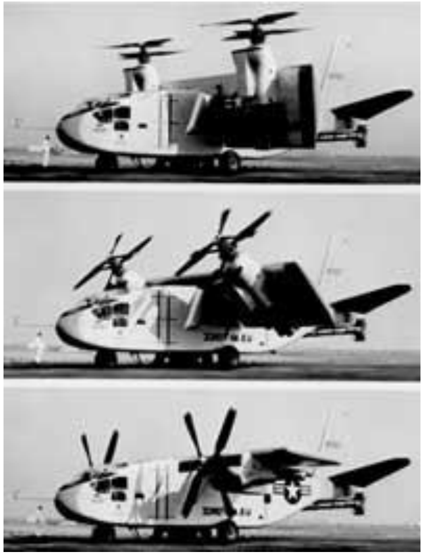

Figure 4 Tilt wing

2) Tilt Rotor

Hybrid UAV with VTOL capability can be obtained using tilt rotor (**Figure 2**). For vertical flight, the rotors are angled so the plane of rotation is horizontal, lifting the way helicopter does. As the UAV gains speed, the rotors are progressively tilted forward, with the plane of rotation eventually becoming vertical so the wing provides the lift.

3) 3D Aerobatic

Aerobatic UAV (**Figure 3**) designed to operate even under fully stalled conditions. In particular, this UAV can fly in trim condition at high angle of attack near 45 degrees even with flight speed below the stall speed. Large control surfaces with large deflections in the presence of strong propeller wash give adequate authority even when the speed of the UAV is much lower than the stall speed. This enables an aerobatic model UAV to be maneuverable in the deep wing-stall condition.

4) Tilt-Wing

A tilt-wing UAV (**Figure 4**) features a wing that is horizontal for conventional forward flight and rotates up for vertical takeoff and landing. The tilt-wing design offers certain advantages in vertical flight relative to a tilt-rotor because the slipstream from the rotor strikes the wing on its smallest dimension. The tilt-wing is able to apply more of its engine power to lifting the UAV.

Based on literature study result, the selected configuration is tail-boom with separate lift and thrust. Separate lift and thrust means that the UAV equipped with a number of motor with different function. One motor is placed horizontally for lift generation and the others generate vertical thrust. The motors are fixed, not tilting. Total motors used in this hybrid UAV are 5 motors, one motor for horizontal thrust and 4 motors for vertical thrust. Separate lift and thrust model is selected to simplify the control and mechanism which is absent in tilting rotor model.

The basic requirements for design process are:

1. The main feature is VTOL capability.
2. The UAV should be capable of carrying payload of 1 kg.
3. The cruise speed should be approximately 100 km/h.

B. Weight estimation

Weight of the UAV can be estimated by weight fraction of the historical trends of aircraft. The weight estimation must be higher to give tolerance to manufacturing limitation. Therefore the weight estimation of this UAV is:

1. Maximum take-off weight (Wto) = 6 kg
2. Payload weight (Wp) = 1 kg
3. Airframe weight (Wa) = 2 kg
4. Avionic system weight (Ws) = 2 kg
5. Quadrotor weight (Wq) = 1 kg

C. Selection of thrust-to-weight and wing loading

Thrust-to-weight ratio (T/W) indicates power efficiency of aircraft. There are two types of T/W in hybrid UAV, T/W for hover and T/W for forward flight. Wing loading (W/S) affects stall speed, climb rate, takeoff and landing distances, and turn performance.

Wing loading and thrust-to-weight ratio must be optimized together. This hybrid UAV has thrust-to-weight ratio of 2.13 for hover, thrust-to-weight ratio of 0.3 for forward flight, and wing loading of 14.5 kg/m^2.

D. Geometry sizing

Once the maximum take-off weight and wing loading have been estimated, the fuselage, wing, and tails can be sized. In this sizing, iteration process is important to do to get optimal design. First step is sizing wing geometry by calculating wing area using Wing loading (W_l) formula:

$$W_l = \frac{W_{to}}{S} \tag{1}$$

Generally, normal aircraft have aspect ratio around 5-10. Hence to get high stability and to avoid structural problem, the AR selected is 8.6. This value obtained by iteration process to get optimal AR for this hybrid UAV.

After defining AR, the wing span can be calculated by equation (2):

$$AR = \frac{b^2}{S} \tag{2}$$

The next step is considering some parameters, such as: taper ratio, dihedral angle, sweep angle, wing incident, and vertical wing position (low wing, mid wing, and high wing). These parameters should be considered to meet the requirements and the mission of flight.

Wing airfoil selection was started by calculating lift (*L*) and Reynolds number (*Re*) by these formulas:

$$L = \frac{1}{2}\rho\, V^2 S C_L \tag{3}$$

$$Re = \frac{\rho\, V\, C_r}{\mu} \tag{4}$$

where ρ, V, CL, and Cr are air density (kg/m^3), velocity (m/s), coefficient of lift, chord at root (m), respectively, and $\mu = 1.7875 \times 10^{-5}$ Ns/m.

Based on the requirement, the selected wing airfoil is FX60-100. This airfoil meets the need of this Hybrid UAV.

The primary purpose of tails is to counter the moments produced by the wing. Thus the tail size is related to the wing size. A good starting point is by using “tail volume coefficient” method for initial estimation of tail size. Typical value for volume coefficient for sailplane is 0.5 for horizontal tail, and 0.02 for vertical tail.

$$c_{VT} = \frac{L_{VT} S_{VT}}{b_w S_w} \tag{5}$$

$$c_{HT} = \frac{L_{HT} S_{HT}}{C_w S_w} \tag{6}$$

where C_{VT}, L_{VT}, S_{VT}, b_w, S_w, and C_w are moment arm (m), vertical tail area (m^2), wing span (m), wing area (m^2), and wing chord (m), respectively.

The fuselage design is basically related to carry the payload and avionic system. It should be aerodynamically shaped to produce drag as low as possible.

E. 3D modeling

The 3D modeling of this hybrid UAV uses PTC Creo Parametric version 2.0. This 3D modeling helps to visualize the geometry of the UAV. It also helps to estimate airframe weight and to calculate weight and balance.

This 3D modeling can be imported as .stp file to other software, such as ANSYS to analyze air flow over the airframe.

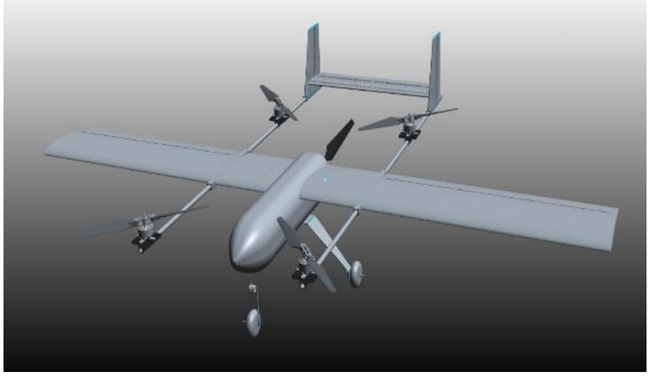

Figure 5 3D modelling

TABLE I GEOMETRY SIZE OF HYBRID UAV

Wing	
Span (m)	1.9
Taper Ratio	1
Chord (m)	0.22
AR	8.6
Airfoil	FX60-100
Horizontal Tail	
Span (m)	0.5
Taper Ratio	1
Chord (m)	0.13
Airfoil	NACA 0010
Vertical Tail	
Span (m)	0.18
Root Chord (m)	0.15
Tip Chord (m)	0.09
Airfoil	NACA 0010
Fuselage	
Diameter (m)	0.1
Overall Length (m)	1.15
Cross Section	Round-edge-square

III. PERFORMANCE AND STABILITY ANALYSIS

Performance and stability analysis carried out using XFLR-5. It provides a good starting point for constructing a nonlinear model simulation. Basic performance analysis can be seen in **TABLE II**.

TABLE II PERFORMANCE

Performance	
Cruise Speed (km/h)	100
Stall Speed (km/h)	44.7
Max. Speed (km/h)	125
Climb Rate (km/h)	55.92
Wing Loading (kg/m^2)	14.5
CG Position (x-axis)	27.7% chord

The center of gravity (CG) position is located at the front of the wing aerodynamic center for safety reason, keeping the UAV stable during transition flight (hover to flight forward and vice versa).

This hybrid UAV needs to be adjusted for performance, but also needs to be stable and controllable. The purpose of stability analysis is to evaluate the static and dynamic stability of UAV for such a perturbation.

Both **Figure 6** and **Figure 7** describe static longitudinal stability. Graphic C_m vs Alpha tells us that this hybrid UAV is statically stable in longitudinal direction because of the slope of the curve is negative. The more negative the slope is, the more stable the aircraft. Graphic C_m vs C_L shows us that at zero pitching moment, the lift is slightly positive.

Aerodynamic efficiency can be obtained by calculating C_L/C_D. It affects power consumption during flight. For hybrid UAV, it is difficult to get high aerodynamic efficiency because of the augmentation of the multirotor equipment produced more drag compared with conventional UAV.

The values of the aerodynamic derivatives obtained (**TABLE III**) are reasonable compared to fixed wing aircraft. These values have been validated by flight test and can be categorized as good handing UAV.

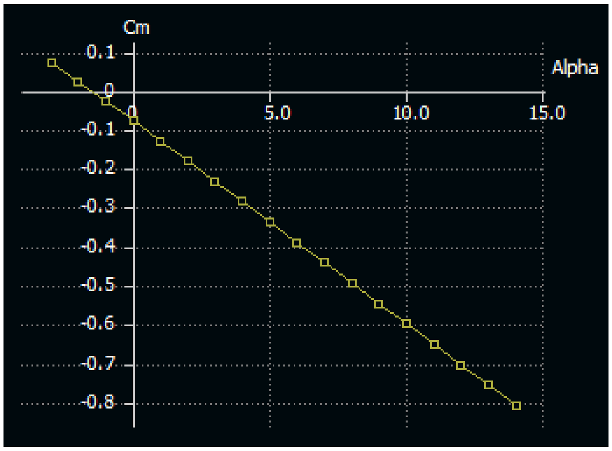

Figure 6 C_m vs. Alpha

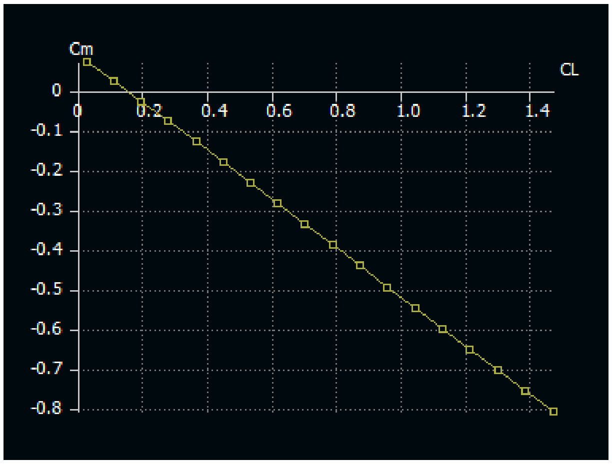

Figure 7 C_m vs. C_L

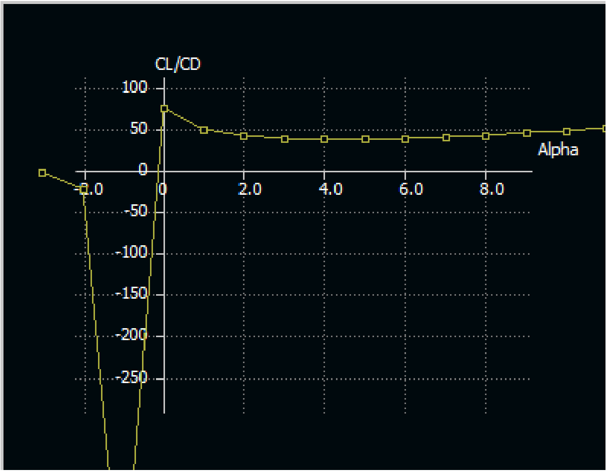

Figure 8 C_L/C_D vs. alpha

TABLE III STABILITY DERIVATIVE

Longitudinal Derivative	
Trim Angle of Attack (deg)	4
Neutral Point Position (m)	0.15233
Cla	5.0651
CLq	8.321
Cma	-2.0982
Cmq	-14.17
Lateral Derivative	
Cyb	-0.2892
Cyp	0.040145
Cyr	0.20412
Cnb	0.10438
Cnp	-0.0628
Cnr	-0.074

IV. COMPUTATIONAL FLUID DYNAMICS ANALYSIS

Computational Fluid Dynamics (CFD) is a tool to analyze air flow around this hybrid UAV. It is based on the Navier-Stokes equation which describes how the velocity, pressure, temperature, and density of a moving fluid are related. In case of hybrid UAV, it is important to know the effect of integrating multirotor equipment to the fixed wing UAV. The very basic information by computational fluid dynamic is the forces difference (side force, lift, and drag) of UAV with propeller and without propeller as seen in **Figure 9** and **Figure 10**. Therefore there are two main cases in this analyze, these are:

1. Case 1: airframe without propeller
2. Case 2 : airframe with propeller

TABLE IV is the result of CFD analysis using ANSYS. Side forces on the case 1 and case 2 are not symmetric because of the propellers are not in same direction and maybe caused by asymmetric element built by unstructured meshing method. Lift on case 2 is lower than case 1, but the drag on case 2 is much higher than case 1. One of the solutions for minimalizing the drag by propellers for hovering is by using folded propellers.

TABLE IV COMPARISON OF FORCES

Forces	Case 1	Case 2
Side Force (N)	0.2079	1.699
Lift (N)	50.66	45.57
Drag (N)	8.401	33.45

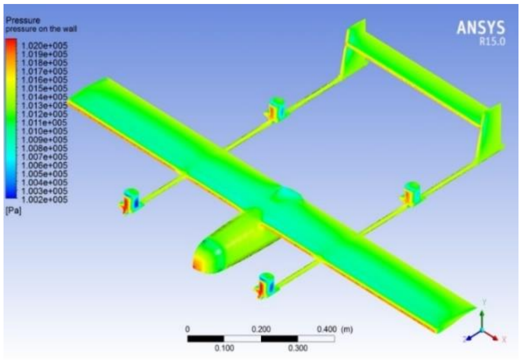

Figure 9 Pressure distribution of case 1

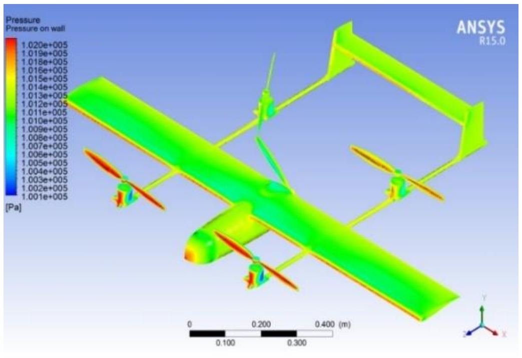

Figure 10 Pressure distribution of case 2

V. TRANSITION SCENARIO

In separate lift and thrust model of hybrid UAV, there is no tilting rotor during transition from hover to forward flight, and vice versa. **Figure 11** is the illustration of transition scenario during take-off (hover to forward flight) and landing (forward flight to hover). It is important to simulate the behavior of UAV during transition before flight test. It can be done using MATLAB and SIMULINK. For algorithm of transition process, the following considerations should be taken into account:

1. Overlap thrust by all active motor, one is producing horizontal thrust, and the others producing vertical thrust.
2. UAV behavior as function of increment or decrement of drag by rotary propeller of multirotor. It influences the stability of the hybrid UAV during transition.
3. Transition speed and angle of attack. It is better to design the transition speed as low as possible to avoid stall.

The flight profile of this hybrid UAV is hover/take-off → transition → forward flight/cruise → transition → hover/landing. There are five motor used to complete flight mission, one horizontal motor and four vertical motor. This hybrid UAV flies semiautonomous.

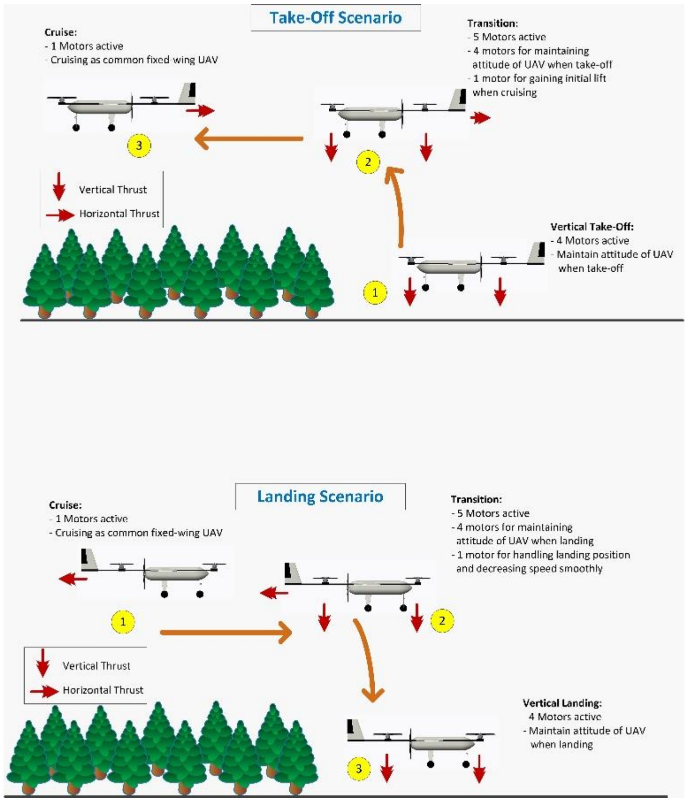

Figure 11 Transition mode illustration

In hover mode, four vertical motors are activated to deliver the UAV vertically. At specific altitude, the horizontal motor is activated for gaining lift. Those four vertical motor will maintain the attitude and the throttle will decrease gradually to zero until the UAV produces enough lift by horizontal motor only and ready to cruise like a normal fixed wing.

VI. MATERIAL SELECTION

Wing, fuselage and tails of this hybrid UAV is using glass fiber reinforcement plastic (GFRP) with extra carbon fiber layer on the control surface. Carbon tube is used to avoid high displacement at the twin boom while the quadrotor activated. Aluminum 2024 is used for wing-twin boom joint.

The rotation of multirotor causes vibration to airframe, especially to the twin boom. The highest vibration appears at low RPM (low throttle). Therefore, structural rigidity must be considered in structure design.

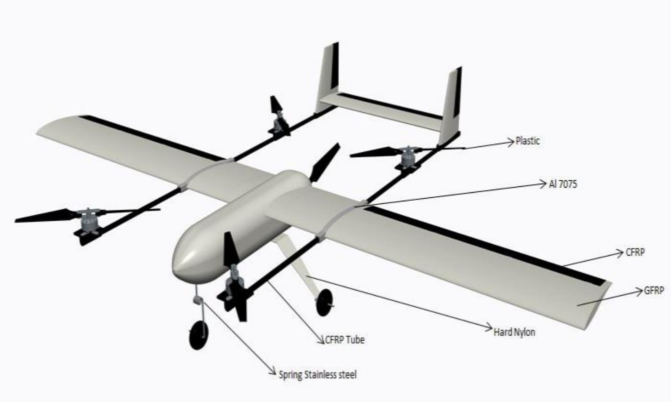

Figure 12 Material selection

VII. TESTING

The test is divided into two major part, ground test and flight test. Ground tests include checking static thrust, inspection of structural integrity, verification of weight and balance, loading test, and observation of UAV behavior due to motor respond at transition stage.

The purpose of the flight tests are to validate the result of theoretical and computational analysis of UAV, and to provide data where no quantitative prediction can be made. Flight tests are divided into 3 parts, hover test, forward flight test, and transition (hover to forward flight, and vice versa) test. It is important to ensure each phase (hover and forward flight) to be successful before continuing to transition test.

VIII. FUTURE WORK

The result of this hybrid UAV will be applied into bigger hybrid UAV which carry 20 kg payload, especially for the transition algorithm. The appropriate flight control will be installed to make the UAV fully autonomous. All of the evaluation of this hybrid UAV will be used for design optimization of the 20 kg payload-UAV.

IX. CONCLUSION

This concept of hybrid UAV is a potential to be developed, considering it has wide application, both in military and civilian need. But compared to normal fixed wing UAV, this hybrid UAV is significantly heavier and significantly less aerodynamic.

When designing hybrid UAV, drag of the four propellers must be taken into account because they create moment toward center of gravity and will cause the UAV to nose up during flight. The drag of propeller can be reduced by using folded propeller.

Drag produced by wing during vertical take-off and landing cannot be neglected in selection of multirotor, thus the thrust to weight ratio for multirotor must be higher than 2.

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