Design of Avionics System and Control Scenario of Small Hybrid Vertical Take-Off and Landing (VTOL) UAV

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Abstract— In this paper, design of avionics system and control scenario of small hybrid Vertical Take-Off and Landing (VTOL) UAV will be presented. The UAV configuration is a hybrid-UAV configuration combining feature of rotary-wing UAV and fixed-wing UAV. There are two topics that will be discussed in this paper. Firstly, avionics system of the UAV including its power system and its peripherals interfacing. Secondly, control system design of the UAV including flight scenario when the UAV is on transition mode/stage. Rotary-wing UAV configuration has advantages such as easy-and-stable when take-off and landing. Rotary-wing UAV also does not need special area to do take-off and landing. While Fixed-wing UAV configuration has advantages such as high maneuverability and high endurance. This hybrid UAV is designed to obtain all of these advantages.

Keywords—VTOL, hybrid UAV, avionics system, control system.

I. Introduction

NOWADAYS Unmanned Aerial Vehicle (UAV) has been developed and used for myriad practical purposes, from civilian tasks [1] into military missions [2]. UAV is widely used because it is safer and more convenient than manned aerial vehicle [3]. There are two common types/configurations of UAV, rotary-wing UAV and fixed-wing UAV. Rotary-wing UAV configuration has advantages such as easy-and-stable when take-off and landing. Rotary-wing UAV also does not need special area to do take-off and landing. However, Rotary-wing UAV draws much energy so that it has low endurance. Contrary, Fixed-wing UAV configuration has advantages such as high maneuverability and high endurance. Nevertheless, when Fixed-wing UAV has big size, it will need special area for take-off and landing.

It is important to make an optimized UAV design that can obtain both of these advantages. The trade-off of these two types of configurations has to be discovered, so that the advantages of both configurations can be achieved but the disadvantages can be minimized or even can be vanished.

In this paper, avionics and control system of VTOL UAV will be presented to show avionics system design and control scenario of this hybrid UAV. The overview of UAV airframe design will be shown in Section II. In Section III and IV, avionics system and control system of this UAV will be detailed. Then, result and test of this hybrid UAV will be presented in Section V. Finally, the conclusion of this paper will be shown in Section VI.

II. Airframe Design

This UAV's airframe is dominantly made of foam and laminated by fiber glass but in some parts it is laminated by CFRP (Carbon Fiber Reinforced Plastic). This UAV is also strengthened by carbon tube for its wing spar and tail spar. Aluminum alloy 7075 is also used for strengthening wing joint. Foam is chosen because it is not too heavy and adequately easy-to-manufacture [4]. Based on our goal to gain the advantages of rotary-wing platform and fixed-wing platform we calculate the desired basic performance of the UAV using Excel software. Subsequently, the numbers will be simulated using the other software, such as XFLR5. Here, the basic performance of this UAV is showed in **Table I**.

Table I Basic Performance

Basic Performance	
MTOW (kg)	6
Cruise Speed (m/s)	27.7
Stall Speed (m/s)	12.41
Max. Speed (m/s)	34.72
Climb Rate (m/s)	15.53
Wing Loading (kg/m^2)	14.5
CG Position (x-axis)	27.7% chord

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This UAV configuration is customization of common double tail boom fixed wing UAV. Figure 1 shows 3D drawing of this UAV in CAD (Computer-Aided Drafting) format. The dimension of this UAV design is illustrated in **Figure 2**.

Figure 1 CAD design of the UAV

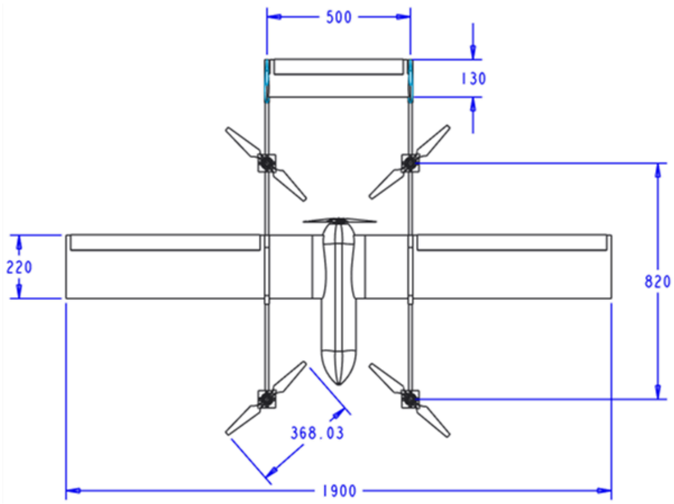

Figure 2 Dimension of airframe (top view)

III. Avionics System

The important components of this UAV are a Li-poly battery 6 cells 8000mah, Voltage-Current sensor, an Autopilot board, an airspeed sensor, a compass sensor, a GPS Sensor, an IMU sensor, actuators (Motor Brushless and Servos), Telemetry, and GCS (Ground Control Station) System.

The illustration of interfacing system design of avionics system of the UAV is described in **Figure 3** [5]. From this diagram it can be known that there are two kinds of signal frequencies to handle wireless communication between UAV and GCS. Signal with frequency 2.4 GHz is used for remote RC (Radio Control) by which pilot can give direct command to UAV, while signal with frequency 433 MHz is implemented in telemetry for sharing data between UAV and GCS. This second wireless communication is duplex communication using Mavlink protocol [6].

Power distribution system of the UAV is described in **Figure 4** [1]. There is only one battery (Li-poly 6 cells 8000 mA·h) that powers all of the system. However, power from this battery will be distributed to several voltage regulators and by default power for main processor (autopilot) and actuators is electronically separated by autopilot board. This power separation is implemented to avoid direct back EMF (Electromotive Force) effect from brushless motors which can impact voltage level in the other peripherals [7]. And if this EMF effect is occurred on essential component like autopilot it will make profound problem to UAV because the autopilot will get restarted automatically.

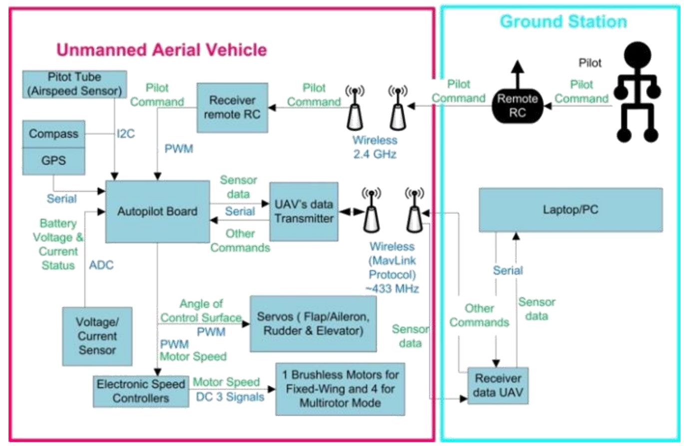

Figure 3 Interfacing system diagram of the UAV

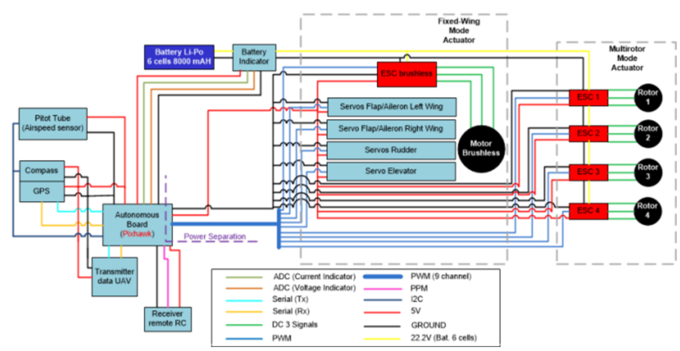

Figure 4 Power Distribution system diagram of the UAV

One of crucial design process in avionics system is choosing capacity of the battery, its weight, and also specification of brushless motors which is used to embody vertical take-off and landing feature of this UAV. Empirically, total of maximum thrust of 4 motors (F1-F4) should be more than twice of UAV's weight (W) [8]. Thus, end up this formula becomes the following equation:

$$2\mathrm{W} \leq \sum_{k=1}^{4} F_k \tag{1}$$

From **Table I** it is known that MTOW of the UAV is 6 kg so that each motor brushless should have maximum thrust up to 3 kg. Fortunately, we have brushless motor with maximum thrust ~ 3.3 kg so that the thrust to weight ratio becomes 2.2:1. Therefore, this avionics system design is approvable by calculation.

Figure 5 is the configuration of all quadrotor's motors with its numbering of every motor. The collective thrust of these four rotors accelerates the quadrotor along its normal direction. In order to balance the yawing torque, rotor 1 and rotor 2 rotate in counter-clockwise direction, whilst rotor 3 and rotor 4 rotate in clockwise direction. As a result, the difference of collective torques between these two directions produces a yawing torque. Similarly, differences of thrusts between rotor 1 plus rotor 3 and rotor 2 plus rotor 4 produce a pitching torque. Subsequently, differences of thrusts between rotor 1 plus rotor 4 and rotor 2 plus rotor 3 will produce a rolling torque. Therefore, four control inputs can be defined as

$$U_1 = F_1 + F_2 + F_3 + F_4 \quad (2)$$

$$U_2 = (F_1 + F_3 - F_2 - F_4)\mathrm{L}_1 \quad (3)$$

$$U_3 = (F_1 + F_4 - F_2 - F_3)\mathrm{L}_2 \quad (4)$$

$$U_4 = M_1 - M_4 + M_2 - M_3 \quad (5)$$

where U_1 is total thrust, U_2 is pitching torque, U_3 is rolling torque, U_4 is yawing torque, L_1 and L_2 is the length from the rotor to the center of the mass of the quadrotor, F_k is the generated thrust, and M_k is the generated torque [9].

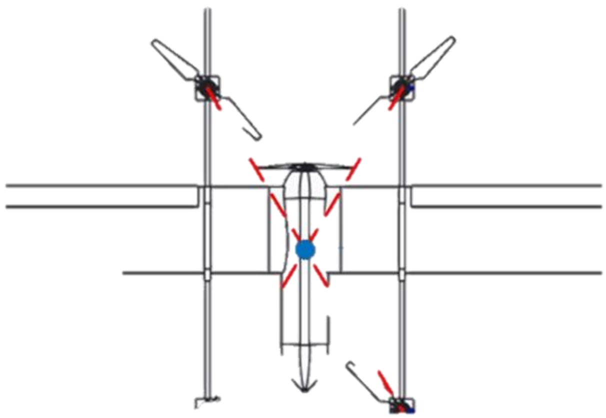

Figure 5 Quadrotor motors' configuration

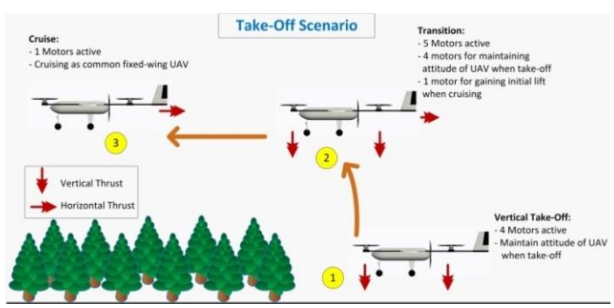

Figure 6 Take-off scenario

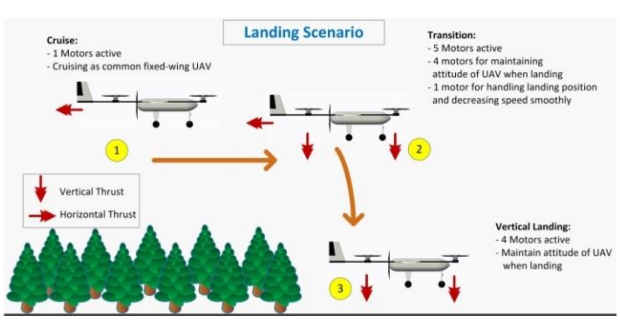

Figure 7 Landing scenario

IV. Control Scenario in Transition Mode

The most crucial control system of this UAV is control scenario for maintaining transition stage/mode. Transition stage/mode happens when the UAV change flight mode from hovering to cruising (take-off) or from cruising to hovering (landing). The scenario of this transition mode can be seen in **Figure 6** and **Figure 7**. As can be seen from these illustrations, that when UAV is in transition mode all of 5 motors will be activated. One motor is used to maintain UAV's speed while the 4 motors are used to maintain UAV's stability when the UAV is in transition mode.

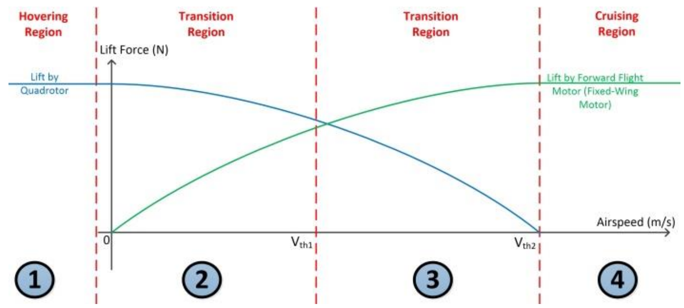

Figure 8 Details of control scenario in transition mode

Figure 8 shows the details of control scenario in transition mode. There are four critical states embodied in this transition mode scenario. Actually, there are only three regions/modes that will happen in this transition condition. However, because there are two additional constraints applied in transition region to make sure the transition flight happens smoothly, it will be easier if we break down the states to become four states. These two constraints (Vth1 and Vth2) are boundary between states which are based on UAV airspeed. Below are the detail control actions of UAV in every state.

A. *State 1*

- Lift force gained by UAV is only from quadrotor thrust. The thrust is used to gain sufficient and safe altitude for applying transition stage/mode. Besides, the UAV is stabilizing its attitude whilst gaining certain altitude.
- Gain of quadrotor attitude control from Ground Control Station is fully applied to the UAV.
- Control surfaces (aileron, rudder, elevator) are still inactivated.
- Forward flight motor (for fixed-wing mode) is still inactivated.

B. *State 2*

- Lift force combination of quadrotor thrust and fixed-wing (wing and tail) lift. These combination forces are applied to maintain altitude and attitude of the UAV. The value of quadrotor thrust can be adjusted by the operator or automatically adjusted by the autopilot if the altitude hold mode is activated.
- Gain of quadrotor attitude control from Ground Control Station is fully applied to the UAV.
- Control surfaces (aileron, rudder, elevator) are still inactivated.

- Percentage throttle of forward flight motor is initially activated and fixed in 75% of full throttle (cannot be adjusted). The thrust is used to initialize forward speed of UAV.

C. State 3

- Lift force combination of quadrotor thrust and fixed-wing (wing and tail) lift. These combination force are applied to maintain altitude and attitude of the UAV. The value of quadrotor thrust can be adjusted by the operator or automatically adjusted by the autopilot if the altitude hold mode is activated.
- Gain of quadrotor attitude control from Ground Control Station applied to UAV is attenuated. The attenuation value is proportional with the increment of UAV airspeed.
- Control surfaces (aileron, rudder, elevator) are activated.
- Percentage throttle of forward flight motor is still activated and fixed in 75% of full throttle (cannot be adjusted).

D. State 4

- Lift force gained by UAV is only from fixed-wing (wing and tail) lift.
- Quadrotor motors are inactivated.
- Gain of quadrotor Attitude Control is inactivated.
- Control surfaces (aileron, rudder, and elevator) are still activated. Attitude of the UAV is fully controlled by control surfaces of the UAV only.
- Percentage throttle of forward flight motor (for fixed-wing mode) can be adjusted.

In our experiment, we assigned Vth1 as 12 m/s and Vth2 as 18 m/s. These values are considered based on the basic performance of the UAV.

V. Result and Test

A. Result

Here is result of UAV manufacturing. **Figure 9a** shows its perspective view while **Figure 9b** shows its front view.

B. Fixed-Wing Test

We have tested the UAV in fixed-wing mode (take-off, cruise, and landing). **Figure 10** shows that the UAV was being tested in fixed-wing mode, and though it was only fixed-wing mode testing, the 4 brushless motors (for hovering mode) have been already mounted in the UAV because we wanted to know drag effect caused by these 4 motors and also performance of the UAV in the total weight.

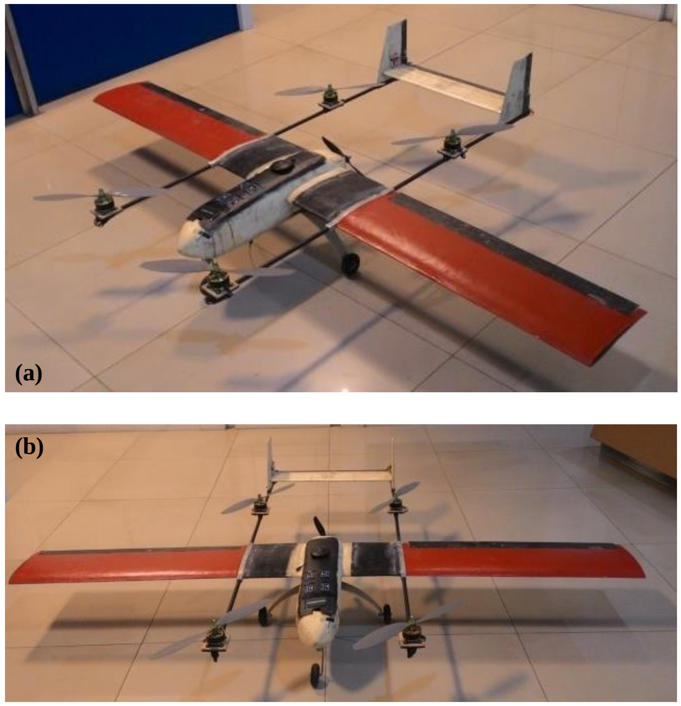

Figure 9 Airframe result of the UAV: (a) Perspective view, (b) front view

Figure 10 Take-off, cruise, and landing test of the UAV (Fixed-Wing mode)

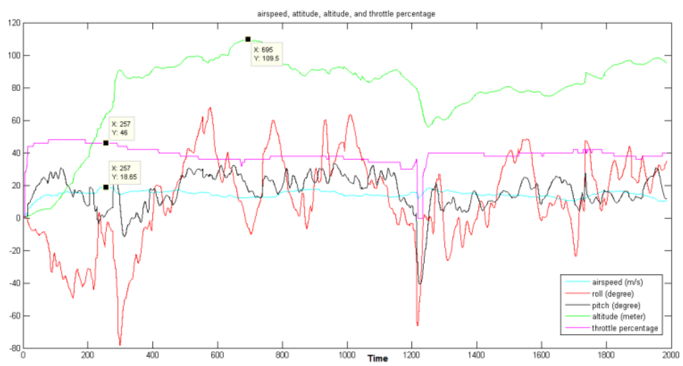

Figure 11 Flight data plot of Fixed-Wing mode testing

Figure 11 shows flight data plot of fixed-wing mode testing. We have tested the UAV to fly within 109.5 meter altitude (measured from take-off area). From **Figure 10** we can also know that when the pilot adjusts the throttle only 46%, airspeed of the UAV has reached 18.65 m/s while the stall speed of the UAV is 12.41 m/s. Therefore, we can assume that this UAV can gain initial lift when the UAV is in transition mode.

Figure 12 Hovering test of the UAV (Multirotor mode)

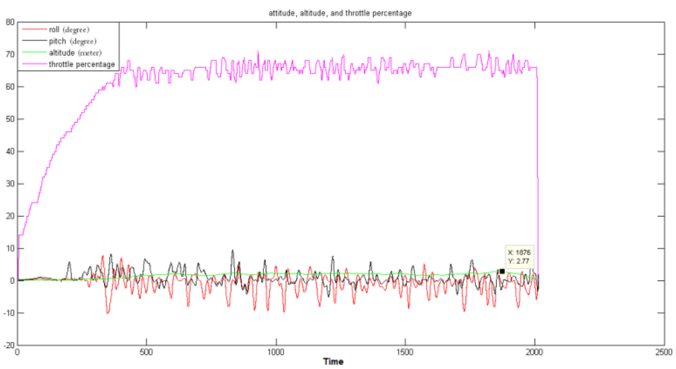

Figure 13 Flight data plot of Multirotor mode testing

C. Multirotor

We have tested the UAV in multirotor mode (hovering). Figure 12 shows that the UAV was being tested (hovering) in indoor although we also have tested the UAV (hovering) in outdoor. When we tested the UAV in hovering mode, we also mounted the brushless motor (for cruising/fixed wing mode) in the UAV so we could get performance of the UAV (in multirotor mode) in its real weight.

Figure 13 shows flight data plot of multirotor mode testing. We have tried to make the UAV hovering within 2.77 meter altitude (measured from take-off area). From roll and pitch data, we know that the UAV was quite stable in its hovering testing.

We have not tested the UAV in transition mode or even in entire feature of VTOL UAV because we have been trying to discover optimum control and algorithm of this feature so that the UAV can obtain its stability and agility.

VI. Concluding Remarks

The VTOL UAV has been designed based on the dynamics calculation. Then this design has been embodied and it is manufactured well. This UAV has also been tested in both of fixed-wing mode testing and multirotor mode testing. And from the flight data record, it is known that this UAV is possible to be skilled up becomes VTOL UAV that can obtain both of feature of fixed wing UAV and rotary wing UAV. Therefore, the future work is optimizing the control and algorithm of this UAV so that this UAV can become VTOL UAV with good stability and agility.

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