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Research paper

Development of attitude control system for hybrid airship vehicle

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Abstract

This paper documents and presents the development of attitude control system of Hybrid Airship Unmanned Aerial Vehicle (HAU) that should be able to change its attitude condition based on the response processed from the provided input. This is accomplished by data acquisition method that retrieves data from a flight controller and processes it into the control system without looking in deep on the mathematical model of the airship. Besides that, PID controller is used in order to create a good stable response for the hybrid airship. A working hybrid airship prototype was successfully developed and built, which is five meters in length and has four propellers that is symmetrically distanced to each other. A quadcopter attitude control mechanism is adopted into the hybrid airship to allow for good hovering capability and direct pure attitude control. Outdoor flight tests have been conducted to prove its stability in responding to attitude input given to the hybrid airship attitude controller. A data monitoring software is also written to make the data observation on the behaviour of the hybrid airship response to be easier and understandable. Result demonstrates that the hybrid airship does response to pitch, roll and yaw input from the operator, albeit the lack response stability and speed which can be improved in conservative continuation of research on the airship attitude control system.

Keywords: *hybrid Airship; PID controller; quadcopter attitude control; data acquisition.*

1. Introduction

Several centuries before the first sustainable flight of an airplane by the famous Wright Brothers, people have been researching and developing many different approaches of providing lift to aircraft. An example of the approaches is to use static lift by utilizing the difference between the air and aircraft density, which produces a buoyancy. This type of aircraft is called an airship. However, due to its sheer size to provide a similar lift compared to conventional aircraft, the development of the airship getting slower. Therefore, people had come up with hybrid airship design to compensate for its weaknesses and allow for it to be used practically in any suitable application, which might exceed the capability of current aircraft in certain fields [1].

The hybrid airship is a type of airship that utilizes the lighter-than-air principle together with the aerodynamic principle of producing lift like those applied for fixed-wing and rotorcraft. Most airships have greater endurance compared to other conventional aircraft as its lift is produced by the buoyant force from the gas used as lifting gas, which does not require any incoming airflow or power to maintain its lift. Therefore, theoretically, an airship should be able to float or hover midair for a long period of time. However, due to its huge body size, an airship will experience great amount of drag when it tries to change its attitude. Therefore, a huge propeller and control surface are required. Despite that, finding the right balance between the application of static lift, aerodynamics, airship design and attitude control system in the hybrid airship proves to be the solution to the problem that is currently faced by the conventional airship.

Airships, like any aircraft in general, are free to rotate in all three axes that perpendicularly intersect at the centre gravity of the airship, which will act as the origin point of the body axes [2]. Therefore, any force that is exerted around the body of the airship will contribute to the moment of the airship. In turn, it provides rotational forces on the airship to control its attitude based on its roll, pitch and yaw. Figure 1 demonstrates how the body axes of airship relates with the center of gravity, which defines the condition of rotation for each axis.

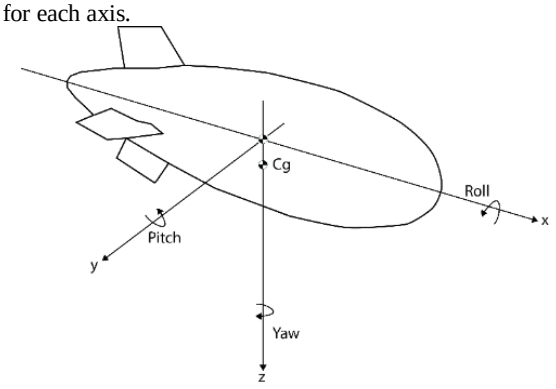


Fig. 1: Airship body axes

For hybrid airship, multirotor flight dynamic can be implemented to allow the airship to rotate only by using propeller thrust as it is hovering in midair. The usual term used for propeller in multirotor is rotor. Based on Figure 2, typical multirotor will consist of four rotors, which by manipulating the speed of each rotor can change its roll, pitch and yaw. The speed of each rotor affects the thrust vector it produces and therefore contributing to the pitching, rolling and yawing moment of the airship, respectively, to the combi-

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nation of speed variation of all rotors [3]. Specifically, the type of hybrid airship that utilizes this type of control mechanism is called a rotastat. The advantages in using this method is that the Vertical Take-off and Landing (VTOL) capability is maintained. Nonetheless, the cruise efficiency and power requirement will be affected with this configuration [1].

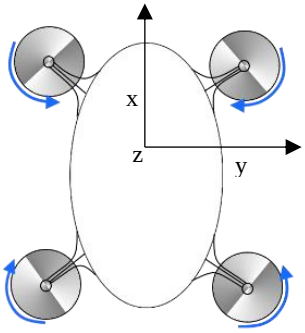


Fig. 2: Rotor configuration for multirotor rotastat airship

In a previous study, two different control strategies taken to stabilize the attitude of the airship, which is linear H_∞ control and nonlinear backstepping control [4]. From the obtained result, the controller based on nonlinear backstepping technique exhibites a good control performance. Other researchers have investigated autonomous trajectory tracking control system of the AURORA airship using the PID and H_∞ control algorithm [5-6]. The PID controller consists of a classical inner-loop and outer-loop structure, with the inner loop is controlling the airship heading and the outer-loop is used for trajectory tracking. The control method of the AURORA airship is then validated in flight test. Besides that, Linear Quadratic Regulator (LQR) controller is utilized in combination with a vision system to track optical flight path [7]. The control system performance is then verified by using a simulation where no wind disturbance is included in the simulation. Instead of using linear control algorithms, non-linear control approach is implemented to stabilize and control the airship motion due to the high level of nonlinearity in the equations of motion. To enable the AURORA airship to follow a predefined path at a given altitude and forward speed, feedback linearization is used [8]. The controller performance is then validated in a simulation that includes the wind disturbance. Note that all the airships stated here are of conventional type where they use rudder and elevator control surfaces to stabilize. The finless airship type that uses PID and motor mixing control technique has not yet been studied.

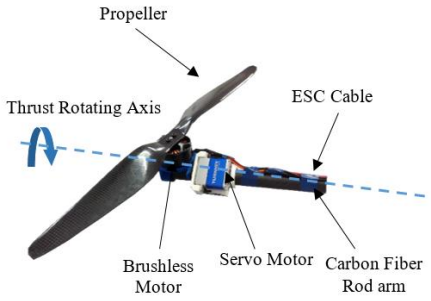
2. The hybrid airship platform

Hybrid Airship Unmanned Aerial Vehicle (HAU) development is done in the Faculty of Engineering, Universiti Putra Malaysia. The HAU is equipped with several essential electronic components in driving its attitude control system such as flight controller, motor, propeller and communication. In addition, few software are being used to develop the attitude control system, including e-calc web software, which is used to calculate the estimated performance of the UAV system, and MATLAB, which is applied to illustrate the attitude control system responses. In parallel with the development of the HAU attitude control system, the fabrication of HAU is also being carried out by a group of students with their individual section of the development project such as HAU design and altitude control. Figure 3 shows the Hybrid Airship UAV that utilizes the quadrotor and tilt rotor thruster configuration that are made from 1.8mm Polyvinyl chloride (PVC) with heat seaming. Table 1 described the specification of the hybrid airship.

A multirotor control system is adopted as the control system reference for HAU due to its ability to maintain hovering position hold. This particularly beneficial to HAU target applications such as for surveillance and geographical monitoring. Hence, for simplicity in term of the fabrication and control system development, four-rotor configuration is used for HAU with tilt mechanisms, the assembly details of the thruster as shown in Figure 3. Four servos are added to the control system to enable the motor to be facing downward and upward at certain condition to produce downward and upward vector thrust. All the actuators are manipulated by the Pulse Width Modulation (PWM) output using the constructed attitude control system in Arduino Mega 2560 Microcontroller. In the meantime, the attitude controller output is extracted from the flight controller through direct interpretation of four motor outputs to aircraft motion in real time data transmission from the flight controller. This is used for input and feedback mechanism in the control system. Furthermore, RC receiver and transmitter are also used to provide the manual input from operator to the flight controller and a RFD 900+ Modem is used as telemetry module that transmits real time data to the ground station that uses 3DR 900MHz telemetry module. The hybrid airship is powered by two Li-Po battery and the servo is powered by independent 7.4V Li-Po Battery. The hardware configuration and integration for HAU is shown in Figure 4.



(a)



(b)

Fig. 3: (a) Hybrid Airship UAV (HAU) prototype, (b) the thruster with tilt mechanism

Table 1: Hybrid airship prototype specification

Hybrid Airship Specification	Dimensions
Height	5.0 m
Width	2.1 m
Length	1.4 m
Surface Area	24.941 m^2
Volume	8.296 m^3

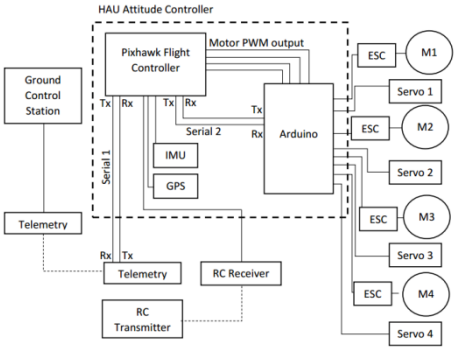


Fig. 4: Hardware configuration and integration for HAU

3. The attitude controller

Generally, the attitude control system consists of three main pure motions, which are pitch, roll and yaw. In making the design process more organized and simpler, the control system is established

for each of the pitch, roll and yaw motion. The output from every control system is mixed in a process called motor mixing where every motor will have different responses to the output of the control system. In the case of this project, a simpler approach to control system is used, which is by incorporating Proportional, Integral and Derivative (PID) controller and sensor feedback.

3.1. HAU flight dynamics

The rotor configuration used by the hybrid airship is by adopting quadcopter with X-frame configuration as shown in Figure 5. Like other aircraft, the airship is defined by three basic Euler angles, namely pitch (θ), roll (ϕ) and yaw (ψ). Figure 5 provides the illustration on the body fixed axes and Euler angle representation on the HAU. Moreover, the angular velocity transformation between earth frame (Fixed Frame) – also referred to as North East Down (NED) – and the body fixed frame *(p, q, r)* can be expressed in matrix notation as in Eqn. 1, where *(p, q, r)* is the angular rate referring to the fixed body of the HAU and $(\dot{\phi}, \dot{\theta}, \dot{\psi})$ refers to the earth frame where the inertial component lies. The body fixed coordinate system and Euler angle representation of HAU is shown in Figure 6.

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \cos\theta \sin\phi \\ 0 & -\sin\phi & \cos\theta \cos\phi \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (1)$$

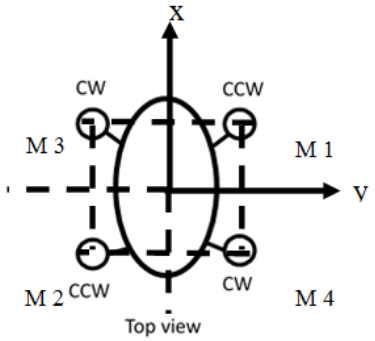


Fig. 5: X-Frame rotor configuration used on HAU

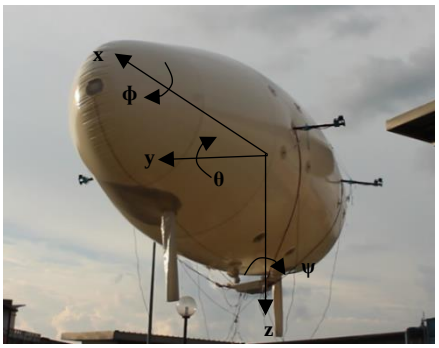


Fig. 6: Body fixed coordinate system of HAU

3.2. Attitude control system

The attitude control system works by reading input from operator through the stick input. By direct proportional, the stick inputs are read as the desired angle for HAU attitude control system. Next, attitude angle error is calculated from the difference between desired attitude and current HAU attitude angle, which is limited to 45 degrees of rotation to ensure safety. The attitude angle error is given a proportional gain for respective flight mode. For this project, it is using the stabilize mode that will give out a desired attitude angular rate. The stabilize mode is used because it serves as the most basic flight mode for attitude control. Later, the attitude angular rate is fed into the PID controller in the inner loop of the attitude control system. Finally, the PID controller results in output of the desired torque, which can be translated into PWM value that is then sent into the motor speed controller to provide thrust to change the attitude of the airship.

3.2.1. Pure pitch control system

The pitch control system reads the pitching stick input to calculate the pitch error, which is then multiplied with the proportional gain for stabilize mode of the airship. The output is fed into the inner loop where PID controller will control the rate of pitch based on pitching rate error. The output torque required is converted into a PWM signal, which is given to the motor speed controller after the motor mixing. The whole pitch control system is summarised by using the block diagram as shown in Figure 7.

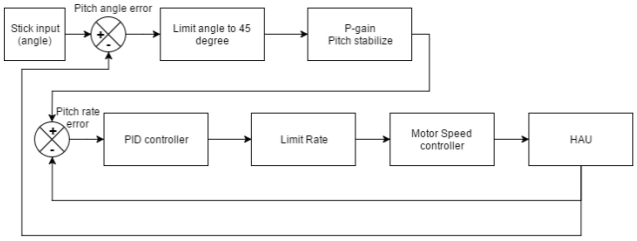


Fig. 7: Pure pitch controller block diagram

3.2.2. Pure roll control system

Figure 8 shows the block diagram of pure roll control system used for HAU. Similar to the pure pitch control system, roll stick input value is read and translated into the desired angle value as to calculate the roll error. It is then multiplied with the proportional gain for the stabilize mode to give out the value of desired roll rate. The roll rate is then transferred into the inner loop of the control system where PID controller is placed to control the rolling rate of the system. Finally, it will give out the value of rolling torque desired, which is translated into PWM for the motor speed controller after motor mixing.

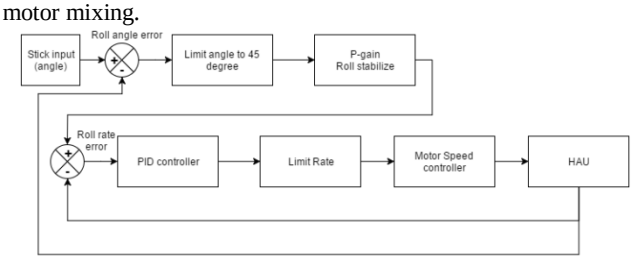


Fig. 8: Pure roll controller block diagram

3.2.3. Pure yaw control system

Yaw controller is slightly different compared to the pitch and roll controller. This is because yaw controller reads the yaw stick input as yaw rate instead of yawing angle. The reason behind this is that the yaw needs to be able to rotate at a continuous rotation. Therefore, the stick input only can go up to a certain limit and it is read as yawing rate. The yawing rate is then converted to yawing angle by using an integrator. Using desired yawing angle value, the yawing angle error is calculated from the sensor. Similar to the roll and pitch controller, the yawing angle error is multiplied with the proportional gain for yaw stabilize. Then, the yawing rate output is added with the value of stick input. The sum of the desired yawing rate is fed into the inner loop of the control system where the PID controller is used to control the yawing rate. The output from the controller gives out the required yawing torque that is converted into PWM for the motor speed controller after motor mixing. The whole yaw control system is summarised using the block diagram as shown in Figure 9.

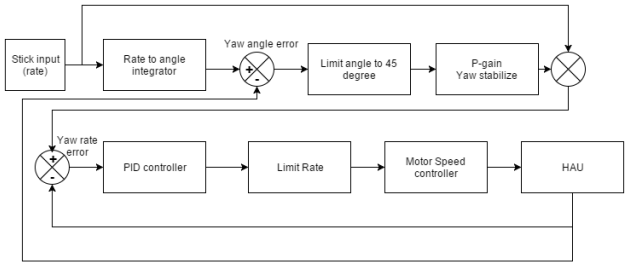


Fig. 9: Pure yaw controller block diagram

Finally, Figure 10 shows the block diagram of the overall attitude control system that can be used for HAU in stabilized mode. This is constructed by compiling all pitch, roll and yaw control system into one control system. The main addition to the system is that it should have an earth to body fixed transformation of the angular rate from the outer loop controller to the inner loop controller.

3.3. Motor output mixing for fixed rotor

As the desired torque is produced from the control system, it can be properly translated into the thrust of propeller motor in the X-configuration through motor mixing methodology. Therefore, it is done by motor mixing of each of the pure attitude motion and then summing it up together to form a mathematical expression for the thrust required for each motor. However, it is vital to note that the airship is not affected much by gravity. Hence, a discrete effect of thrust to every side motor configuration of the hybrid airship has to be made, which is unlike the conventional multirotor concept. This is to ensure that the resultant thrust will not cause the airship to drift upwards as attitude control is commenced.

For pitch, it is crucial to understand the direction of rotation and the position of the motor with regards to that. Figure 11 illustrates the instance pitching motion occurring in HAU. As viewed from the side view, it is assumed that when HAU is pitching and facing backwards, the pitching error is positive. Otherwise, pitch error is negative. Using that as an assumption, the respective motor relationship can be laid down into a series of motor state during pitching motion as expressed in the matrix notation below, where the motor state is approximate to the desired parameters. The following matrix notation in Eqn. 2, which shows the relationship of the motor output $(T_{m1}, T_{m2}, T_{m3}, T_{m4})$ with thrust needed for pitching motion $(T_\theta, T_{-\theta})$.

$$\begin{bmatrix} T_{m1} \\ T_{m2} \\ T_{m3} \\ T_{m4} \end{bmatrix} = \begin{bmatrix} 0.5 & 0 \\ 0 & 0.5 \\ 0.5 & 0 \\ 0 & 0.5 \end{bmatrix} \begin{pmatrix} T_\theta \\ T_{-\theta} \end{pmatrix} \quad (2)$$

For roll, it is similar to that of the pitching motor output but with a difference in the position where the roll error occurs. Hence, by understanding the direction of rotation and position of the motors with regards to that, the motor state for roll can be laid out. Figure 12 shows the instance rolling motion occurring for HAU. From the front view, it is assumed that when HAU is rolling to clockwise direction, it has a positive roll error while otherwise negative roll error. So, any motor the side of positive roll error will have relationship to that condition.

With that assumption, the motor state of HAU during rolling can be expressed using matrix notation that shows the relationship of motor output $(T_{m1}, T_{m2}, T_{m3}, T_{m4})$ with thrust needed for rolling motion $(T_\phi, T_{-\phi})$.

$$\begin{bmatrix} T_{m1} \\ T_{m2} \\ T_{m3} \\ T_{m4} \end{bmatrix} = \begin{bmatrix} 0 & 0.5 \\ 0.5 & 0 \\ 0.5 & 0 \\ 0 & 0.5 \end{bmatrix} \begin{pmatrix} T_\phi \\ T_{-\phi} \end{pmatrix} \quad (3)$$

For yaw, the motor output mixing will make use of propeller rotation to create torque motion to the body of the HAU as shown in Figure 13. Hence, by understanding the direction of propeller spin, the motor state for each direction of yaw can be made. Before that, it is assumed that the yaw error of the HAU is positive if it is rotating clockwise while it is negative if it is rotating counter clockwise. Therefore, for yaw, the motor is paired according to its spin direction and yaw error.

Using that assumption, the relationship of the motor state and the yawing condition can be made and expressed in the matrix notation in Eqn. 4, where the motor state is approximated to the desired parameters. The matrix notation below shows the relationship of motor output $(T_{m1}, T_{m2}, T_{m3}, T_{m4})$ with thrust needed for yawing motion $(T_\psi, T_{-\psi})$. The negative value of yaw thrust factor due to the configuration of the thruster that is fasing in opposite direction.

$$\begin{bmatrix} T_{m1} \\ T_{m2} \\ T_{m3} \\ T_{m4} \end{bmatrix} = \begin{bmatrix} 0.5 & 0 \\ 0.5 & 0 \\ 0 & 0.5 \\ 0 & 0.5 \end{bmatrix} \begin{pmatrix} T_\psi \\ T_{-\psi} \end{pmatrix} \quad (4)$$

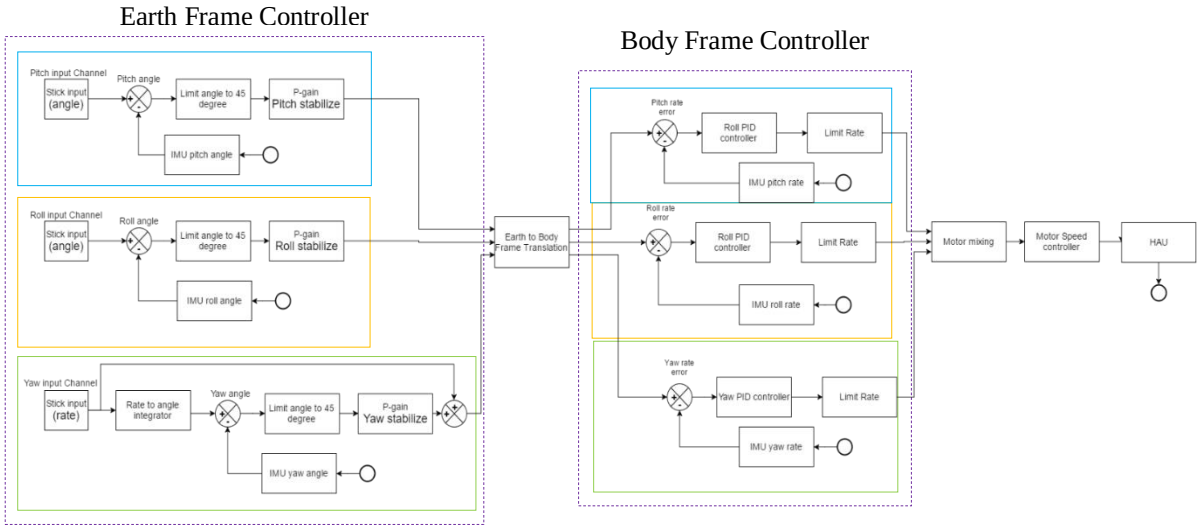


Fig. 10: Overall HAU attitude control system

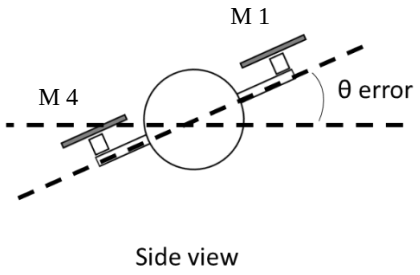


Fig. 11: Pitching motion on HAU

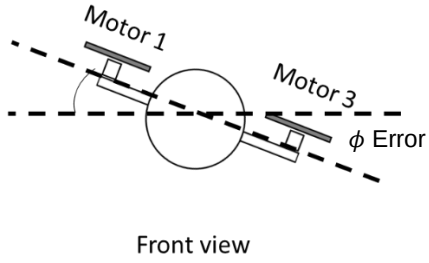


Fig. 12: Rolling motion on HAU

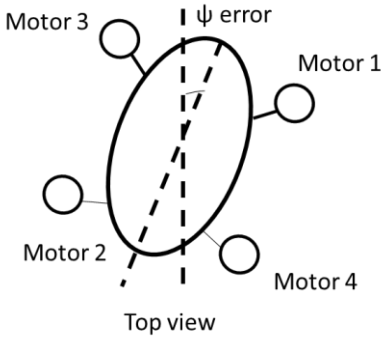


Fig. 13: Yawing motion on HAU

Generally, motor mixing for all motions can be summarised into one expression where the required motor thrust for every motion is added to form a total respective motor thrust. Mostly, the expression for total is as in Eqn. 5.

$$T_m=T_T+T_\theta+T_\phi+T_\psi \quad (5)$$

Definition 3.1: T_m is the total motor thrust, T_T is throttle thrust, T_θ is the thrust required for pitch, T_ϕ is thrust required for roll and T_ψ is the thrust required for yaw. Hence, by adding all the required thrust for attitude motion, the respective motor thrust required can be expressed. Therefore, the following matrix notation in Eqn. 6 is the expression for motor output mixing of HAU with fixed rotor configurations.

$$\begin{bmatrix} T_{m1} \\ T_{m2} \\ T_{m3} \\ T_{m4} \end{bmatrix} = \begin{pmatrix} 1 & 0.5 & -0.5 & 0.5 \\ 1 & -0.5 & 0.5 & 0.5 \\ 1 & 0.5 & 0.5 & -0.5 \\ 1 & -0.5 & -0.5 & -0.5 \end{pmatrix} \begin{bmatrix} T_T \\ T_\theta \\ T_\phi \\ T_\psi \end{bmatrix} \quad (6)$$

Definition 3.2: T_{m1} is the total motor 1 thrust, T_{m2} is the total motor 2 thrust, T_{m3} is the total motor 3 thrust and T_{m4} is the total motor 4 thrust.

3.4. Yaw motor mixing using tilt rotor

For yaw motor output, the motor state has to change accordingly. This is because using motor spin will not work at all time as the rotor incidence angle can be changed at any time and this makes it undesirable. Therefore, using the tilting motion of each motor, the resultant force can be used to make it provides thrust according to the desired thrust for yaw movement. By referring to Figure 13, a clockwise rotation will provide positive yaw error and vice versa. Therefore, to create torque for HAU to move in a positive yaw, the left side motors (i.e. motor 2 and motor 3) have to provide thrust by using the tilt mechanism to change the incidence angle of those two motors. This work is similar to the negative yaw error. Hence the new motor state for yawing motion can be expressed by the matrix notation in Eqn. 7 that shows the relationship of the motor output $(T_{m1}, T_{m2}, T_{m3}, T_{m4})$ with thrust needed for yawing motion $(T_\psi, T_{-\psi})$.

$$\begin{bmatrix} T_{m1} \\ T_{m2} \\ T_{m3} \\ T_{m4} \end{bmatrix} = \begin{bmatrix} 0.5 & 0 \\ 0.5 & 0 \\ 0 & 0.5 \\ 0 & 0.5 \end{bmatrix} \begin{pmatrix} T_\psi \\ T_{-\psi} \end{pmatrix} \quad (7)$$

For tilt angle, it is desirable that when there is no required thrust for pitch and roll, the incidence angle should be facing forward, which is at 90° angle. Therefore, the following expression in Eqn. 8 can be made for incidence angle, i.

$$i = \begin{cases} 90\text{-}\tan^{-1}\left(\frac{(T_\theta+T_\phi)}{T_\psi}\right), T_\psi>0 \\ 0, T_\psi \le 0 \end{cases} \quad (8)$$

3.5. Motor output mixing with tilt rotor

The expression of the required resultant force needs to be made to ensure that the resultant force will create similar thrust that is respective to the direction of the thrust pitch, roll and yaw. Figure 14 shows how the resultant thrust vector relates to the pitch and roll thrust with yaw thrust and the consideration to the placement incidence angle that is less than 90°. Furthermore, it needs to consider the condition when the rotor is facing downwards, which is where the incidence angle is at more than 90°. Figure 15 shows the tilt resultant force when the incidence angle is more than 90°.

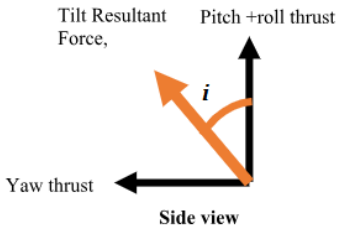


Fig. 14: Illustration of thrust vector for tilt resultant force

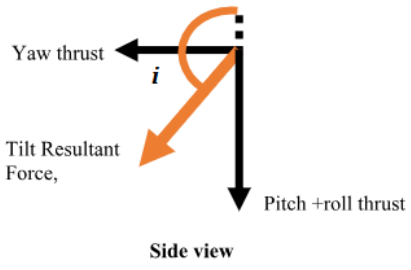


Fig. 15: Illustration of thrust vector for tilt resultant force when i> 90°

Therefore, based on the illustration, the general expression for the resultant thrust is given in Eqn. 9.

$$T_R=\sqrt{(T_\theta+T_\phi)^2+T_\psi^2} \quad (9)$$

Using the general expression, several set of equations can be made for each of the thrust for resultant thrust of each motor. The following Eqn. 10 is the expression for the resultant thrust for each motor.

$$T_{R_1}=\sqrt{(T_\theta-T_\phi)^2+T_\psi^2}$$
$$T_{R_2}=\sqrt{(-T_\theta+T_\phi)^2+T_\psi^2} \quad (10)$$
$$T_{R_3}=\sqrt{(T_\theta+T_\phi)^2+T_\psi^2}$$
$$T_{R_4}=\sqrt{(-T_\theta-T_\phi)^2+T_\psi^2}$$

The throttle thrust can be added to the expression. This is important to spate the throttle thrust by considering it as a thrust component for translation motion instead of the attitude control motion. Thus, the general expression is given in Eqn. 11.

$$T_{R_M}=T_T+T_{R_{\theta,\phi,\psi}} \quad (11)$$

Using the general expression for the resultant thrust, the respective motor thrust components can be expressed. The following Eqn. 12 is the expression of motor output thrust.

$$T_{R_{M1}}=T_T+\sqrt{(0.5T_\theta-0.5T_\phi)^2+(-0.5T_\psi)^2}$$
$$T_{R_{M2}}=T_T+\sqrt{(-0.5T_\theta+0.5T_\phi)^2+(0.5T_\psi)^2} \quad (12)$$
$$T_{R_{M3}}=T_T+\sqrt{(0.5T_\theta+0.5T_\phi)^2+(0.5T_\psi)^2}$$
$$T_{R_{M4}}=T_T+\sqrt{(-0.5T_\theta-0.5T_\phi)^2+(-0.5T_\psi)^2}$$

When the incidence angle is more than 90^o, the usual expression for motor output mixing will not work. In this case, the sign convention has to be flipped to create a reverse response. Hence, the following expression in Eqn. 13 of total desired motor thrust with tilt rotor has to be used.

$$T_{R_{M1}}=T_T+\sqrt{(-0.5T_\theta+0.5T_\phi)^2+(-0.5T_\psi)^2}$$
$$T_{R_{M2}}=T_T+\sqrt{(0.5T_\theta-0.5T_\phi)^2+(0.5T_\psi)^2} \quad (13)$$
$$T_{R_{M3}}=T_T+\sqrt{(-0.5T_\theta-0.5T_\phi)^2+(0.5T_\psi)^2}$$
$$T_{R_{M4}}=T_T+\sqrt{(0.5T_\theta+0.5T_\phi)^2+(-0.5T_\psi)^2}$$

Definition 3.3: T_R is the resultant thrust and T_{R_M} is the motor resultant thrust for each motor.

3.6. Flight controller integration

In order to translate the motor output from the flight controller that uses quadcopter firmware of which HAU will adopt, the roll, pitch and yaw PID controller outputs are required. The attitude controller PID output is then can be used to provide motion to HAU with respect to the motor response needed for the HAU attitude control motion. The first step to adopt the flight controller system is to extract motor output from it and translate it into an expandable value such as value of thrust in percentage. Figure 16 shows the flow of the motor output extraction that is applied to get the required data to decode the value of PID output from the flight controller.

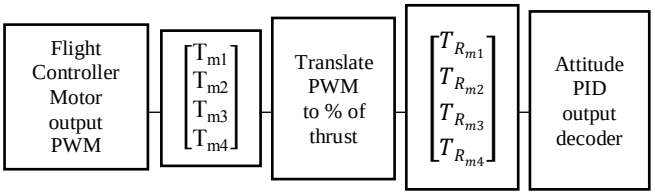


Fig. 16: Motor output extraction flow from flight controller

For this project, the quadcopter control system is downloaded into the flight controller and it is adopted for the HAU control system. Hence the quadcopter control system will have four motor outputs. Using previous expression of motor thrust that is made, the desired attitude thrust, respective value of thrust for pitch, roll, yaw and throttle can be derived. Hence, the following equations are the derivation from motor mixing technique.

For pitching thrust from flight controller output:

$$T_\theta=-\frac{(T_{R_{M4}}-T_{R_{M3}}-T_{R_{M2}}-T_{R_{M1}})}{4} \quad (14)$$

For rolling thrust from flight controller output:

$$T_\theta=\frac{(T_{R_{M1}}-T_{R_{M2}}-2T_\theta)}{4} \quad (15)$$

For yawing thrust from flight controller output:

$$T_\theta=\frac{(T_{R_{M2}}-T_{R_{M3}}+2T_\theta)}{4} \quad (16)$$

For throttle thrust from flight controller output:

$$T_\theta=\frac{(T_{R_{M1}}+T_{R_{M2}}+T_{R_{M3}}+T_{R_{M4}})}{4} \quad (17)$$

Finally, having separated the thrust value respective to the attitude motion, the thrust component can be remixed according to HAU motor mixing expression that is derived in previous section 3.3. This will translate the quadcopter motor output into a specialized HAU motor output. After that, the thrust values are converted into PWM and sent to HAU motor speed controller. Figure 17 shows exactly what has been explained for the HAU motor output translation.

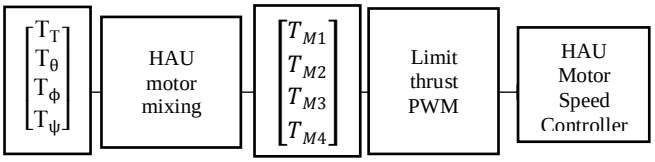


Fig. 17: HAU attitude control translation flow

4. Results and discussion

4.1. Motor output validation using pure multirotor motion

The motor output of the attitude controller of HAU is evaluated through a software specially made for the HAU monitoring, which works by communicating with Arduino microcontroller to request system data. Figure 18 shows the HAU monitoring software. In the software, the value of motors output is shown in PWM. This is because PWM value is used to fed into the motor speed controller. Respective arrangement of motor is motor 1 is at top right, motor 2 at bottom left, motor 3 at top left and motor 4 at bottom right. Along that line, servo angle is also shown in the software to observe the tilt angle changes when the desired condition is given by manual trigger, yaw response and altitude controller response. The motor output response can be validated by changing the desired attitude input and observing the response to ensure that the value

change accordingly. For pitch response, a pure pitch input is given to the system and the respective motor output value is observed.

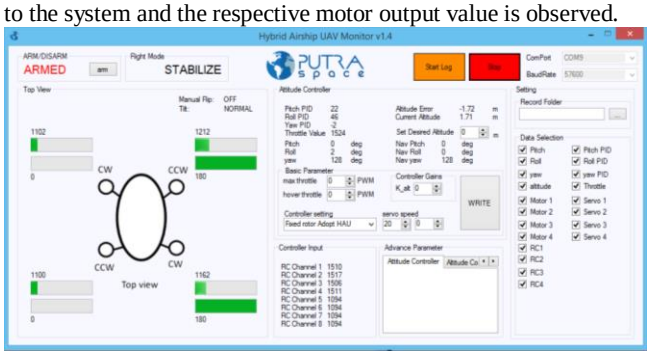


Fig. 18: Hybrid airship UAV monitor software

Figure 19 demonstrates the motor output value when desired negative pitch is given to the system while Figure 20 demonstrates the motor output response when a desired positive pitch is given to the system. From these figures, it can be said that the designed pitching system responds accordingly to the input given. On the other hand, the motor output response for roll input can be validated by changing the desired roll input and observing the response to ensure that the value changes accordingly due to the pitching contribution of moment.

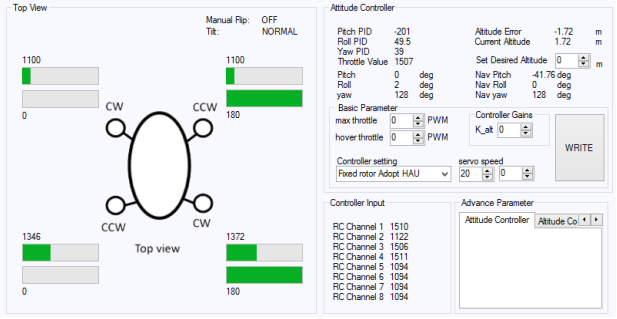


Fig. 19: Pitch down response

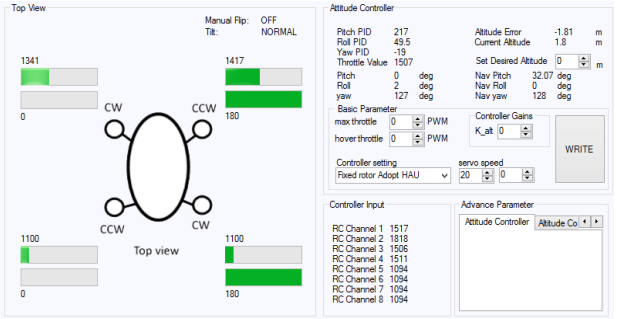


Fig. 20: Pitch up response

Like the previous test, the roll motor output response can be observed by providing pure roll stick input to the system to see the changes it gives to the motor output. Figure 21 demonstrates the motor output when pure left roll is given to the system and Figure 22 shows that the motor output response when the stick input to roll the HAU to the right is given. From observation, it can be seen that the system responds accordingly to the given input due to the difference value of PWM for each cases. The difference of PWM value makes HAU rolls due to the contribution of moment to the right and left.

4.2. Attitude control system responses from flight test

Indoor flight test for the HAU has been conducted and data of the input and output of the attitude controller is obtained. The input data is from the stick input with accordance to the attitude control. The stick input is then processed into a desired attitude angle for a proper data analysis and comparison. The output is the value of HAU attitude angle as it responds to the output provided by the attitude controller. The attitude angle is extracted from the value of the IMU sensor that is embedded in the flight controller. Therefore, the flight test consists of three segments namely the pure roll test, pure pitch test and pure yaw test.

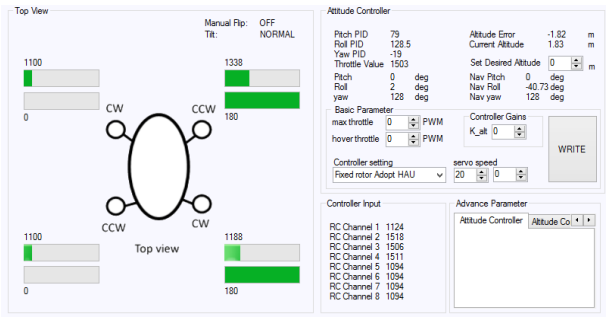


Fig. 21: Rolling to left response

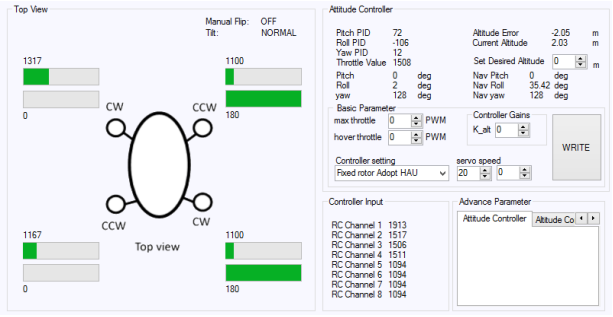


Fig. 22: Rolling to right response

The flight path consists of four points and the airship is manually controlled to follow the designed path. Figure 23 demonstrates the comparison between the desired flight path and the actual airship flight path during the flight test. The objective is for the airship to follow a straight line connecting all four 'blue points' describing a parallelogram. From the data, the airship performance can be considered as satisfactory in performing all four-point manoeuvre during the flight test. However, it can be seen that the airship has a bit of difficulty in following 'short sides and sharp corners' (from point 2 to 3, and from point 4 back to 1). The overshoots in those two points are due to the difficulties of piloting and controlling the airship's forward momentum at the short sides, which are about 10 meters in length. Observing the performance on the longer sides (point 1 to 2, and point 3 to 4), it is believed that the patrol area needs to be bigger for the size of the airship for practical application such as surveillances application.

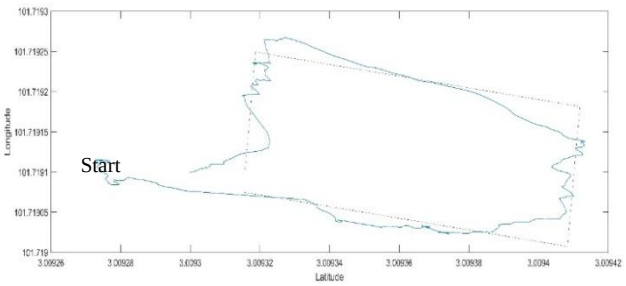


Fig. 23: Flight path of indoor flight test of HAU following point 1-4 (starting from bottom left going counter-clockwise)

For pure roll test, the stick input is given to the system to see its response and stability as it reacts to the input. The stick input is held for a period of time to ensure that the desired attitude will be able to be reached. Figure 24 demonstrates the comparison of the desired roll and the actual HAU roll angle during flight test. Immediately from the response graph, it can be seen that the airship does oscillate by a huge amount. From observation, it can be seen that the HAU roll angle is unable to properly reach the desired roll angle, mostly because of the output limitation and scaling that is

placed on the attitude controller to ensure safety of the surroundings and the operator are under control.

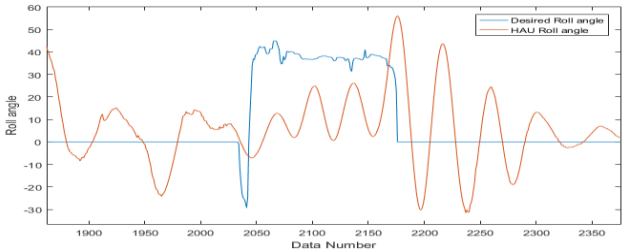


Fig. 24: Roll angle during flight test. Blue line is the desired roll angle and brown line is the actual roll angle

From Figure 25, it illustrates that poor performance of pitch compared to the yaw performance. The actual HAU pitch is unable to track the desired pitch from the stick input, particularly when the desired pitch is zero degree. Besides that, the pitch response also oscillates by an amount of ±20 degrees and takes times to come to the zero degree pitch angle. This poor performance is caused by the error in determine the centre of gravity and centre of buoyancy of the airship. It is also noticed that the gondola should be fixed on the hull skin of the airship rather than hanging on the bottom of the airship hull. This is to make sure that the gondola is not moving and changes the location of centre of buoyancy of the airship. The roll and pitch responses are also influenced by the pendulum mode in lateral-direction and longitudinal-direction, respectively. In order to reduce the pendulum mode of the airship, the PID controller should be able to damp this oscillation amplitude. Besides that roll and pitch, it also has slow response to react to the desired input because the current gain for PID is considerably low. Thus, in future flight test, the gain and the limitation on the thrust value can be increased to ensure that the airship will be able to reach the desired attitude.

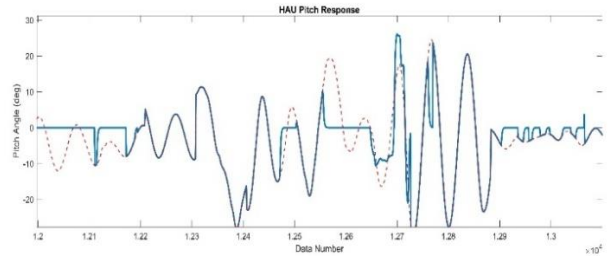


Fig. 25: Pitch angle during flight test where blue line is desired pitch and red line is the actual pitch

For pure yaw test, similar to roll and pitch, the stick input is given to the system to evaluate the performance. Figure 26 illustrates the comparison between desired yaw and actual yaw response of the HAU. From the figure, it can be seen that HAU is able to track the desired yaw with minimal error as compared to pitch and roll responses. Thus, it can be said that the yaw PID controller gain considerably satisfied.

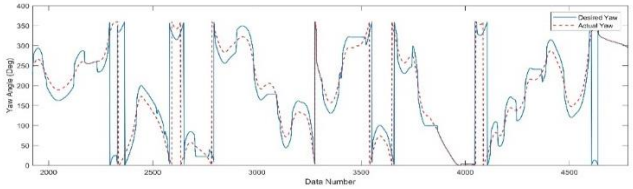


Fig. 26: Yaw angle during flight test where blue line is the desired yaw angle and red line is the actual yaw angle.

5. Conclusion

The attitude control system for HAU has been designed and developed to complete the first project's objective. Two approaches have been carried out to implement the attitude control system onto HAU. The first is flight controller data extraction and control integration of which the control input from operator is fully processed in the flight controller while HAU attitude control system will translate the existing quadcopter output into desirable HAU output. Meanwhile, the second approach is embedding the HAU attitude PID controller into an Arduino microcontroller. This approach only requires processed sensor data from flight controller such as navigation pitch, roll and yaw angle. The second objective of this study has been fulfilled through conducting flight test to see whether the airship correctly responds to attitude control input. The flight tests are conducted in two segments: static and dynamic flight tests. The static flight test is to provide confirmation that the output value is correctly given to the actuators while the dynamic flight test is a test where the airship is properly flown to observe the attitude PID controller response and whether its gain is adequate. Generally during flight test, the HAU does indeed respond correctly to the provided attitude input. Nevertheless, it does have unsatisfactory stability as the optimum gain value has not yet obtained from PID tuning, especially in yaw attitude control.

During the development of HAU attitude control system, there is a lot of limitation and difficulties faced. Hence, it is advisable that a more in-depth research study on the mathematical model of HAU, especially the nonlinear model, is required to ensure that the airship can be flown safely knowing that the control system is properly simulated in the computer with all surrounding variables in mind such as drag, wind and shift of distribution of lift of the helium on elastic skin [9]. Moreover, for attitude control system, an actual nonlinear system of an airship has to be studied. For example, this can be done by using black box methodology where the data of input and output of the airship is logged. Input data can be the desired attitude angle and output data is the attitude angle [10]. The data is then transferred into MATLAB using system identification toolbox, which calculates the linear and nonlinear mathematical models by relating the two data. By using the mathematical model, a more specific control system can be designed for the airship.

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