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Development of Flight Control for UGS Tri-copter MAV

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Abstract— This paper presents our flight control development for the University of Glasgow Singapore (UGS) tilting tri-copter. The tilting tri-copter has the capability of high cruising speed by tilting the main rotors. The drawback of this design is that it causes instability during rotors transition and flight stability. As such, the development of a new flight control system is required to make this system stable. The first phase involves the designing & building of the tilting tri-copter for the investigation of its flight behaviour, and researching on different control systems to select the suitable control system for the tri-copter. The next phase is be to design the flight control system using the Simulink program. The final phase is to analyses and discuss the simulation result and compare with the test flights. There are discovery from the simulation result that after the main rotor had titled, the roll effect become less responsive and the roll mode will caused the tri-copter to yaw. This can be resolved by changing the design of the main rotor tilting into an independent tilting rotor system to improve the performance. With the new develop flight control system, it can use for future in deep research or even use it to combine with other controller such as LQR controller.

***Keywords*—Tri-copter, PID Control, Simulink**

I. Introduction

RECENTLY, unmanned aerial vehicles (UAV) are largely seen as an alternative to replace manpower to accomplish various missions. For example, surveillance over disaster areas and search and rescue. Thus, researchers have been looking into aerial vehicles which are capable of hovering and are capable to fly in longer endurances. This creates a demand in many industries for the UAV to perform a wider range of missions with better performances. Some examples of successful large scale tilt-rotor vehicles are the Boeing's V22 Osprey [1] and Bell's Eagle Eye [2].The development of tilting tri-copter UAV is one-to-itself whereby the tilt rotor has the capability to enhance its forward cruising speed and range as compared to an existing conventional UAVs (fixed-base quad-copters and tri-copters). The new tilting mechanism of the tri-copter allows the front rotors to tilt, thus achieving a faster response to flight acceleration. The conventional UAV achieves forward flight by pitching itself downwards, thus producing a forward thrust force component which causes it to accelerate. However, the tilting tri-copter does not need to pitch itself, it rotates the front two propellers forward to create forward flight motion.

The aim of this project is to develop the flight control for the new UGS tilting tri-copter UAV during maneuvering flight. The analysis and information obtained from this study can aid in the research and development of future transition flight models.

The focus of this study is to study the maneuvering flight characteristics, for example; roll, pitch and yaw control input and outputs of the UAV. A control system will be developed to accommodate these flight controls to exhibit the necessary flight characteristics of the tilting tri-copter. The analysis may be carried out through means of experimental flight tests or by using MATLAB Simulink software.

Figure 1 Overview of UGS Tilting Tri-copter.

The main objective of this work is to develop the flight control system for the UGS tilting tri-copter which is equipped with forward tilting rotors to enable the tri-copter to achieve forward flight without pitching of the main body. In order to achieve forward flight using tilted rotors, research and comparing different types of controllers are required. The suitable controller for the FCC (Flight Control Computer) will be used to develop the flight control. After constructing the tri-copter, the study of real-time flight behavior of the tri-copter is used to compare with simulated results.

II. Review Of Controller Types

There are various types of controllers designed for an UAV to exhibit vertical take-off and landing (VTOL) and tilt-rotor characteristics. The Proportional-Integral-Derivative (PID) controller and the Linear Quadratic Regulator (LQR) are the most commonly used for linear control systems. Whereas back-stepping, gain-scheduling and dynamic systems are mainly used for non-linear control.

A. *Proportional-Integral-Derivative (PID)*

The PID control law consists of proportional, integral and derivative elements. When using the PID control law algorithms, it is important to decide which of these elements are used since each has a particular effect on the control signal [3] [4]. The controller gain values are determined by experiential tuning till ideal response of the system is achieved. PID controllers can be implemented onto the UAV's altitude, attitude angles and velocity controls outputs by changing the control gain accordingly.

The strategy to tune a PID controller requires appropriate adjustment of the control gains, it also serves as a preliminary design setting for many UAVs. The advantages for using PID control is that, it is a widely used control scheme design in real life applications and it does not require extensive knowledge of the model. The disadvantage for PID controller is applicable only for single-input single-output (SISO) system It does not account for the cross coupling effects present in UAVs. Therefore, multiple independent PID controllers are used in UAVs [3] [4].

B. Linear Quadratic Regulator (LQR)

LQR controller requires a state vector, control input vector, system matrix, control influence matrix, real positive weighting matrices and feedback control input well known as Riccati matrix to find a control input of the form. The approach towards using this control is choosing a suitable weighting matric. Brysons Rule is commonly used to find these weighting matrices based on normalizing the signals [3] [5]. The advantages of using a LQR control is that it is able to handle complex dynamic systems and multiple actuators. It can process infinite value and provide the system for at least controllable and has very large stability margins to errors in the loop [3] [6]. The disadvantage for LQR is that it requires access to the full state which is not always possible [3].

C. Back-Stepping

The back-stepping controller is constructed based on Lyapunov stability and it provides a reputational approach for nonlinear systems that transforms into triangular form. The main idea is to let certain states act as virtual controls of other states [7] [8]. This method will be beneficial for more complex UAVs, where the control system takes into considerations of all the states and accounts for those nonlinearities that are present in the model. From previous studies, the back-stepping control are coupled with Euler-Lagrange approach for the dynamic modeling [9] [10].

D. Non-linear Dynamic Inversion (NDI)

The NDI dynamic model of a SISO system are using the functions of the state vector which linearize only the state affected by the input. All other elements of the state vector derivative are linear. Similar to the back-stepping approach, a virtual control input which is a linear relation and therefore can be used to control the system easily. However, NDI can be generalized for multiple-input and multiple-output (MIMO) system [11]. The NDI linearizes the inner loop system making the dashed box a linear system [8].

The advantage of using NDI is that it does not require a single controller for the full flight envelope as compared to gain-scheduling. NDI closed loops system can be easily tuned like a PID controllers. As for the disadvantage of using NDI, there is a need for accurate knowledge of the aerodynamic coefficients [8].

With this, LQR, back-stepping, gain-scheduling and NDI had been listed out, reason being is that the LQR control method is required to access to the full state as stated in [3], which is not available at this design phase of the UGS tilting tri-copter. The back-stepping and gain-scheduling control method are too time consuming as stated in [3] [8] [9] [10] for an individual project. Lastly, NDI requires accurate knowledge of the aerodynamic coefficients [8].

Therefore, the PID controller has been chosen for this tilting tri-copter application as a flight control system. Although, PID has poor aptitude as compared with other controllers which can perform MIMO, it is easy to apply and widely used for real life applications. Lastly it does not require the knowledge of the UAV model.

III. DESIGN OF TRI-COPTER

The Tri-copter that was used for actual flight testing is built with the following main items:

Item (s)	Description
Flight Control Units system with GPS	PixHawk by 3DR (configure via MissionPlanner)
Electronic Speed Controller (3)	Max 40Amp, 30V by HobbyWing
Brushless Motor (3)	400KV Motor by SunnySky
Propeller (2 anticlockwise & 1 clockwise)	Carbon Fiber,15inchs with 5.5pitch
Main Servo (2)	MG958 Servo, torque 18kg/cm
Main tilting rod	Carbon Fiber rod, diameter 16mm
Frame	3cm Carbon Fiber broad, design and cut by water jet
Tail servo	MG958 Servo, torque 18kg/cm
Battery Eliminator Circuit (2)	Hobby Wing 2-6s, MAX 3Amp
Battery	24v, 6cells Li-Po battery, 3200mAh

Table 1 Tri-copter Components.

In our case, we deal with a force division problem combining relative deadline and visibility clustering. Given a set of N locations and K different types of agents (which are available for patrol at a given moment), Our method focus on finding a patrolling strategy, where each route for an agent passes through a number of locations. Patrolling strategy aims to minimize cost function, which is based on 3D visible volumes and meets the relative deadline constraints.

The main distinct feature for the Tri-copter is the forward tilting capability. The servo will rotate the main carbon fiber rod which directly tilts the main rotors that were mounted on the rod's ends. When the main rotors are tilted forward, the thrust is divided to lift and forward thrust components. The forward thrust component is the main reason that create the faster cruising speed.

Figure 3 shows the circuit of the Tri-copter. For the signal input is from the RC Transmitter via a 2.5Hz frequency connection to the on board receiver, the receiver will transfer

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the input command to the flight control unit for processing. During the production of this prototype, the control system was not made ready, the author created a direct link to the main servo to control the main tilting.

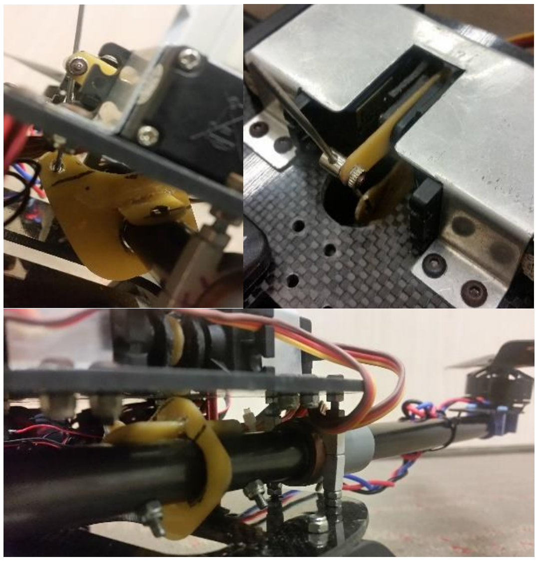

Figure 2 Tilting Mechanism.

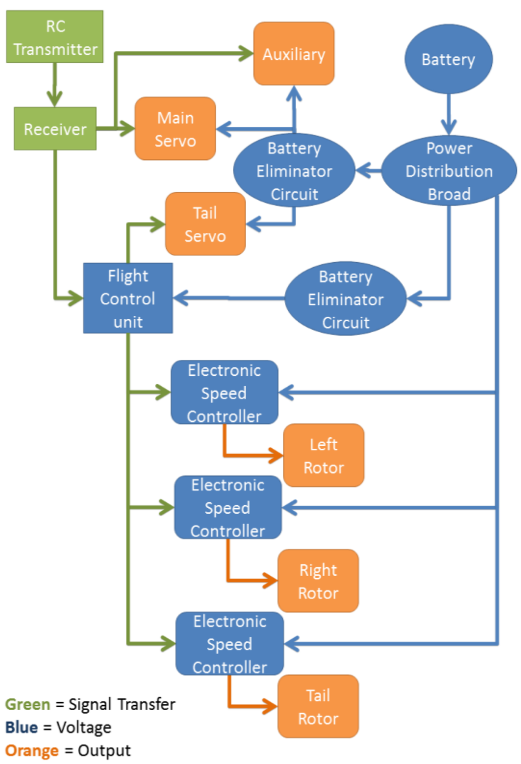

Figure 3 Tilting Tri-copter System Overview.

As mention, the flight control unit for this system will be using PixHawk. The flight control unit assists in processing the input command and control the required for the tail to tilt in order to produce counter torque and it also controls motor speed and records these flight data as show in Appendix-A.

The Auxiliary port in the layout is for other equipment that might be needed to be built on based on mission requirement.

These equipment such as video transmitter, dropping device or any surveillance equipment (camera and etc.).

The system consists of 2 Battery Eliminator Circuit (BEC). The purpose of the BEC is to step down the voltage, as the battery used provides 24 volts input to the system, some of the other components in the system will burn out if the voltage is not stepped down. The BEC powers down the input for the servos to 6 volts. Similarly, the input received by the flight control unit is powered down to 5 volts.

IV. DESIGN OF TRI-COPTER

With the components as stated previously, the following are the tested performance results. The actual empty weight of the tri-copter for this test was 2.6 Kg. For the following test, a battery was added on to which the total Tri-copter weight is 3 Kg. All these values mentioned in Table 2 are values extracted from the flight control unit (PIXHAWK) data logs during testing.

Maximum Take-Off Weight is tested by adding additional weights for a takeoff flight. Max endurance and range is tested by allowing a fully charged Tri-copter to cruise around a track. And takeoff and forward speeds are tested by full throttle. All the test were conducted 5 times and the following are the average values of the test.

Maximum Take-Off Weight (MTOW)	8.7kg
Max Endurance	20 min
Hover Flight Duration	15 min
Max Range	6.322 km (Point To Point)
Max speed (Take off)	25m/s (fastest tested)
Max Speed (Forward speed)	10 m/s (no Main Tilting) 25m/s (Main Tilted 60Degree)
Cruising speed	5 (no Main Tilting) 10m/s (Main Tilted 45Degree)
Max Operation Altitude	3000m (Tested)

Table 2 Tri-copter Performance.

A. Frame of reference & Moments of inertia

The body frame of reference is with respect to the fixed frame of reference to determine the orientation of the tri-copter as shown in Figure 4.

The moment of inertia determines the torque required for desired angular acceleration about a rotational axis. The moment of inertia is the sum of all the components multiplied by distance of the component from the Center of Gravity.

Table 3 lists the components, mass and distance away from the Center of Gravity (C.G). These are used to calculate the moment of inertia. The listed components have a greater influence on the moment of inertia, thus chosen. Whereas other components are negligible as they are too light or close to the C.G. For example, components such as screws, bolts, nuts and electrical wires etc.

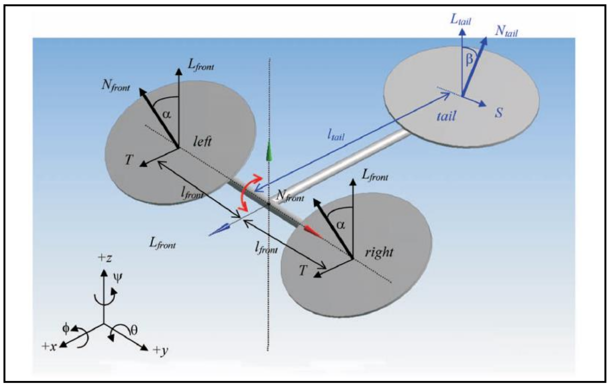

Figure 4 Fixed and Body Frame of Reference.

There are a few assumptions made for this calculation. The assumptions are:

- The components along the z-axis are too negligible and assume to be zero displacement.
- The tilting tri-copter is symmetrical along x-axis.
- The tilting tri-copter has a rigid body.

Component	Mass (kg)	Distance (x,y,z) (m)
Front Motor (each)	0.149	(0.161, 0.3075, 0)
Rear Motor	0.149	(0.4285, 0, 0)
Front Servos (2x)	0.130	(0.146, 0, 0)
Flight Controller	0.038	(0.002, 0, 0)
Rear Servo (1x)	0.042	(0.345, 0, 0)

Table 3 Component Mass and distance away for C.G.

$$\begin{vmatrix} I_{xx} & 0 & I_{xz} \\ 0 & I_{yy} & 0 \\ I_{xz} & 0 & I_{zz} \end{vmatrix} = \begin{vmatrix} 0.2764 & 0 & 0 \\ 0 & 0.4194 & 0 \\ 0 & 0 & 0.6958 \end{vmatrix}$$

In the theory of moment of inertial, having values on I_{xz} would mean that the vehicle would be unstable.

B. Agents

The equation of motion of tilting tri-copter are presented in this section. These equations will be used in the PID control system. The tri-copter has a rotating boom which allows the tilting of the two front rotor forward and backwards about the y-axis. Alpha (α) will be used to represent the tilting angle from the vertical axis for the front rotors as shown in **Error! Reference source not found.**. During the hovering condition, α = 0°. As for the tail rotor, Beta (β) will be used to represent the tilting angle from the vertical axis. The tail rotor is mounted with a servo to tilt it about the x-axis. In this configuration, tilting the side force (S) for yawing motion as shown in figure 7**Error! Reference source not found.**. During hovering condition, the tail rotor will be tilted in a small angle to provide an anti-torque and the angle varies when the speed of the rotor increase or decrease, thus by default β will not be zero.

Pitching Moment, (θ)

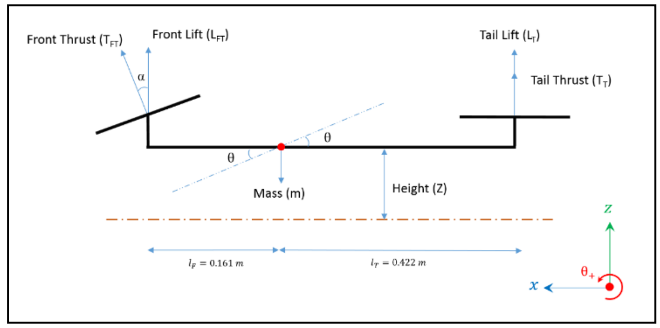

Figure 5 Free-Body Diagram for Pitching Moment.

$$\ddot{\theta} = \frac{-(L_{FT} \times l_F) + (L_T \times l_T) - c\dot{\theta}}{I_\theta} \tag{2}$$

Rolling Moment, Ø

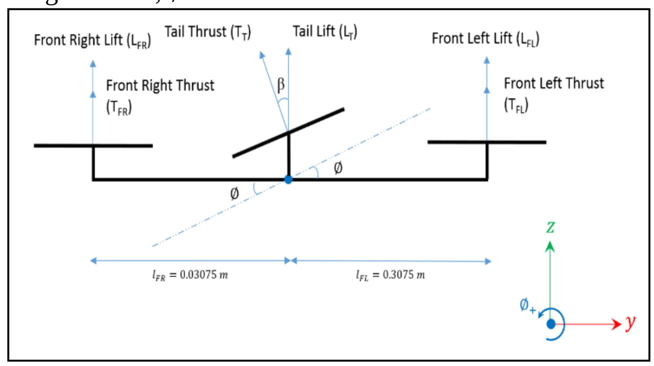

Figure 6 Free-Body Diagram for Rolling Moment.

$$\ddot{\emptyset} = \frac{(L_{FL} - L_{FR}) \times l_{F(L/R)} - c\dot{\emptyset}}{I_\emptyset} \tag{3}$$

Yawing Moment, φ

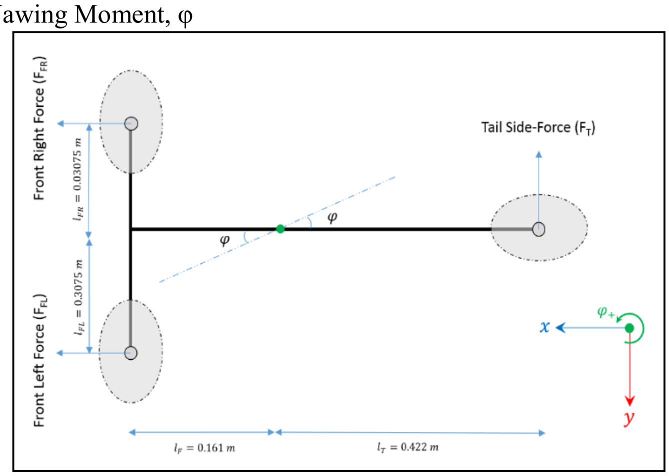

Figure 7 Free-Body Diagram for Rolling Moment.

$$\ddot{\varphi} = \frac{(L_{FR} - L_{FL}) \times l_F + (L_T \times l_T) - c\dot{\varphi}}{I_\varphi} \tag{4}$$

Vertical Displacement, Z

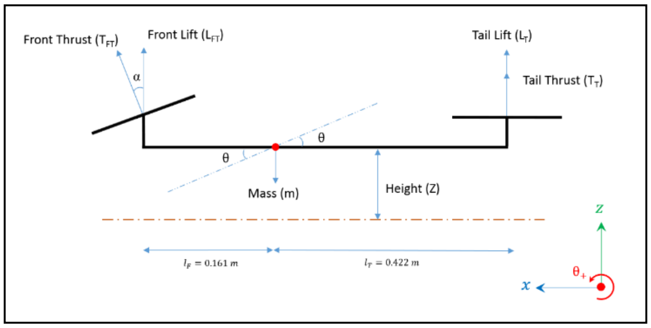

Figure 8 Free-Body Diagram for Vertical Displacement.

$$\ddot{z} = \frac{(L_{FR} + L_{FL}) \times l_F + (L_T \times l_T)}{m_T} \quad (5)$$

C. SIMULINK

In this project, MATLAB – Simulink software is used to create the flight control system for the tilting tri-copter. The equations (1)-(5) used are those developed from the previous section. The results generated from the Simulink were analyzed and used to investigate behavior and responses of the tilting tri-copter. The following chapter will show block diagrams of the flight control system.

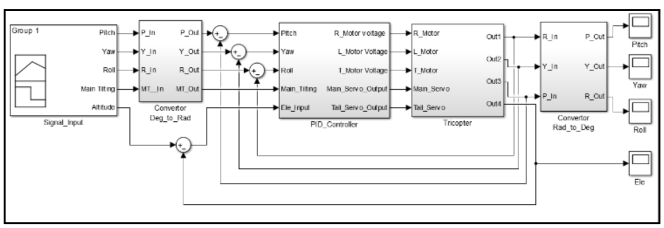

Figure 9 Overview of Tilting Tri-copter Block Diagram.

Figure 9 shows an overview of the entire system. It consists of an input signal to simulate as a transmitter input, PID controller and the characteristics of the tri-copter in the "Tricopter" block. The characteristics of the tri-copter consist of pitch, roll, and yaw and elevation sub-system.

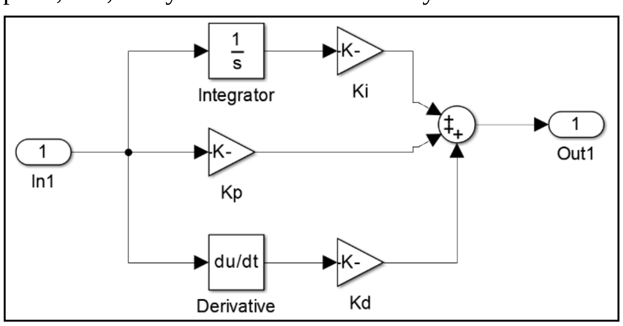

Figure 10 PID Controller Model for Pitch, Roll and Yaw.

In figure 10**Error! Reference source not found.**, it shows the basic model of the PID controller model created in Simulink. The PID controller model consists of Proportional Gain (K_p), Integral Gain (K_i) and Derivative Gain (K_d) elements. These are commonly used in feedback controls of general processes.

The Steady-State Error (SSE) from the feedback loop will feed into the PID controller. For a PID control to establish outputs, there must be a non-zero input (error). Thus, the SSE allows the system to run itself.

The UGS PID controller gain values are shown in Table 2**Error! Reference source not found.**

	K_p Value	K_i Value	K_d Value
Pitch	40	42	12
Roll	60	0.1	10
Yaw	12	12	4.9

Table 2 UGS Flight Controller Gain Value.

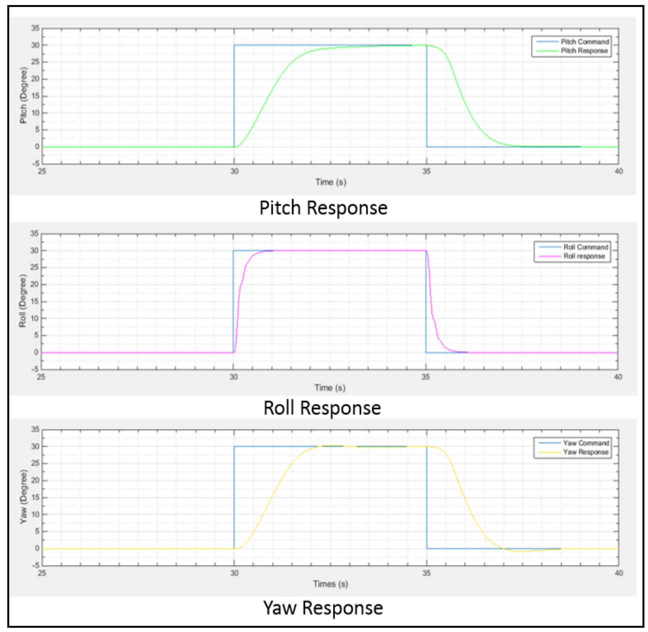

Figure 11 UGS Flight Control Responses.

Figure 11 shows that the design PID controller are able to behave like the ideal response. The ideal response result took 4-5 seconds to establish the first settling time. This proves that the controller are stable and is able to control the UGS tilting tri-copter. Figure 11 result took 1-4 seconds to reach the first settling time.

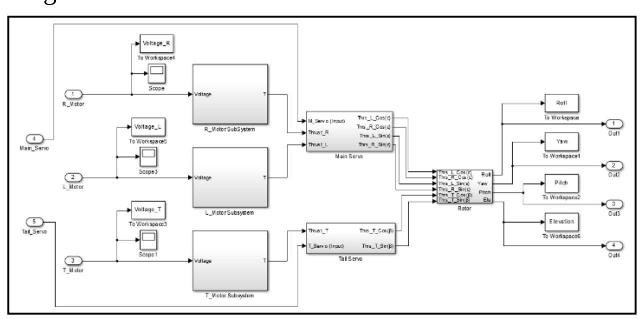

Figure 12 Over-View of Tri-copter Block Diagram.

In **Error! Reference source not found.**12, it shows the characteristic of the tilting tri-copter. It consists of the motor sub-system and sub-systems for Pitch, Roll and Yaw in "Rotor" block.

V. RESULT & DISCUSSION

Physical test flight was conducted to validate the simulation. The condition of the main rotor was tilted at 45 degree angle, altitude held constant and throttle control with a pre-set altitude were used for both test flight and simulation. During the test flight, the tri-copter showed a loss of altitude (when tilted) and rapid rise of altitude (back to neutral), which shows that it could not maintain its pre-set altitude. Thus, the system was tuned. Since altitude holding is the current major problem, the altitude results from the simulation will be monitored with a different test response.

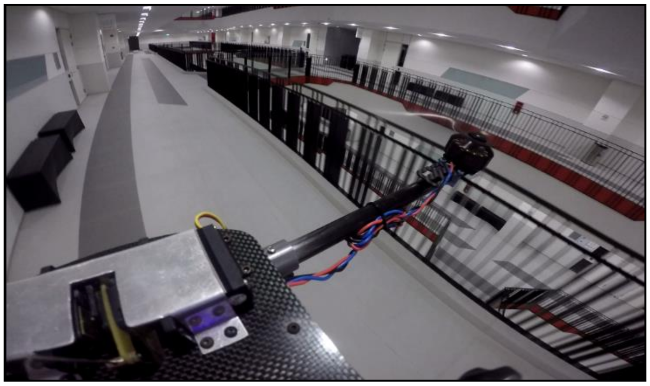

Figure 13 Tilting Test-Flight On-board View.

The development of MATLAB-Simulink was built on the following assumptions:

- No Anti-Torque
- No disturbance (such as ground effect, side-slip and vortex)
- Ideal condition (such as constant temperature and air density)
- Point load (the model mass is acting on the C.G)

The following results are based on the simulations for a steady hovering condition at an altitude of 1 meter above sea-level. This was done before each new parameter of input commands was executed. Each input command will be executed 20 seconds after, whereas the first 20 second duration were will be used for the tri-copter to take-off and climb to it desired altitude, while stabilize itself as shown in Figure 13.

The main rotor was then tilted to the maximum angle of 45 degree position. The reason for the configuration of 45 degree angle is because for an average flight controller, the maximum available setting for the pitch and roll angle are a maximum of 45 degrees. Therefore the main tilting rotor will be set at its maximum leading angle of 45 degree.

Figure 13 is used to illustrate the taking-off of the tri-copter. This control uses step-input to attain 1m altitude and a total of 4-5 seconds for the process. When it reaches the desired altitude, it took 7 seconds to reach its steady-state. This shows the system made a stable take-off and achieve this process before the 20 second mark.

Elevation hold (hovering)

From Figure 14, the graph plotted with the input signal (in blue) and the response of the tri-copter (in red). There was a slide delay as shown in the Figure 15, the delay is because of the start-up of the motor, and this will take about 1.5 seconds to overcome the motor inertial and produce sufficient thrust to overcome the tri-copter's weight.

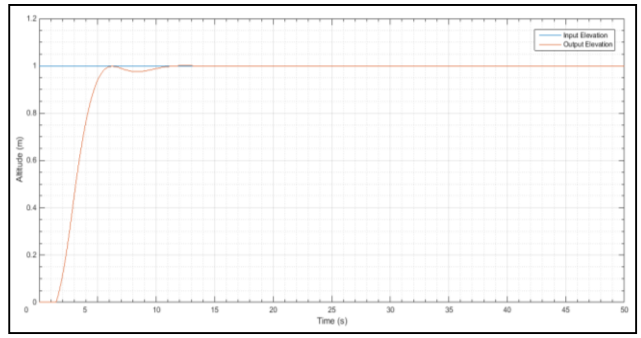

Figure 14 Tilting Test-Flight On-board View.

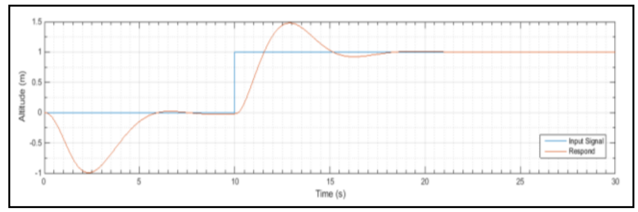

Figure 15 Tilting Test-Flight On-board View.

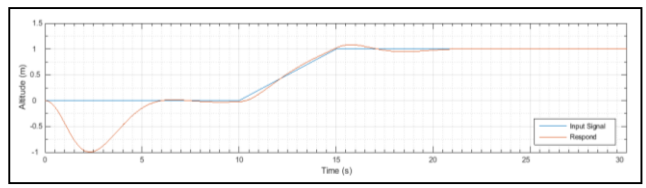

Figure 16 Tilting Test-Flight On-board View.

In Figure15 is using the step-input and Figure 16 is using ram-input. The step-input results show that it requires 2 seconds to reach the desired altitude and about 6.5 seconds to allow it to reach it steady-state. There will also be a higher overshoot than the ram-input, the difference of 0.4m. Although a time of 5 seconds for the ram-input is needed to reach the desired altitude, it took 5.55 seconds to reach steady-state. The response showed that stability improves at the cost of a longer time to reach the desired altitude. For the UGS tilting tri-copter the altitude that is lost during the transition are considered very minor, thus using step-input recovery from perturbation will not be as effective.

Tilting of main rotor (Forward flight)

In Figure 16, the graph represents altitude responses followed by the pitch responses. Similar to Figure 6, both sets of simulation results has two tilting command input signal, the commands are 45 degrees positive from neutral position and held for about 5 seconds. After of which, which, it will return to its neutral position.

The difference between the two figures is that in Figure 17, the main rotors tilting input while using a step input and for Figure 6 are the main rotors tilting while using a ram. The main rotors are tilted at an angle of 45 degrees for both simulations. Pitch inputs will be maintained at neutral and altitude input will be maintained at the set height to simulate an altitude-hold condition. This is done to compare the responses by the systems.

The following results for positive pitch angle represents nose down (tri-copter facing downwards), and negative pitch angle represent nose up (tri-copter facing upwards).

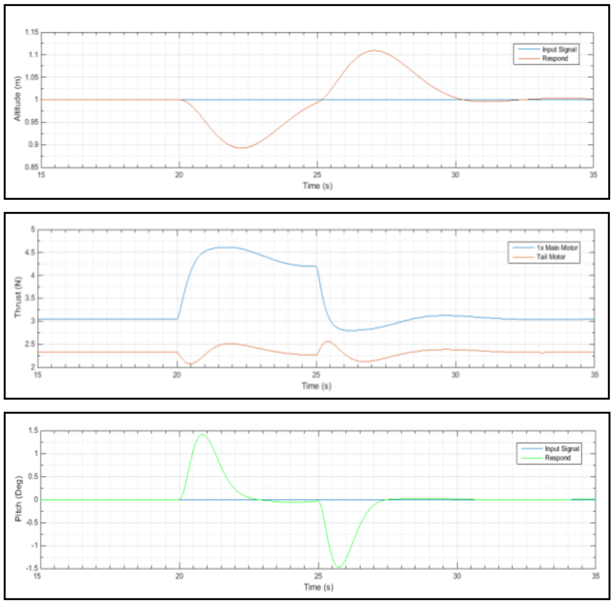

Figure 17 Main Rotor Tilting with Step Input Response.

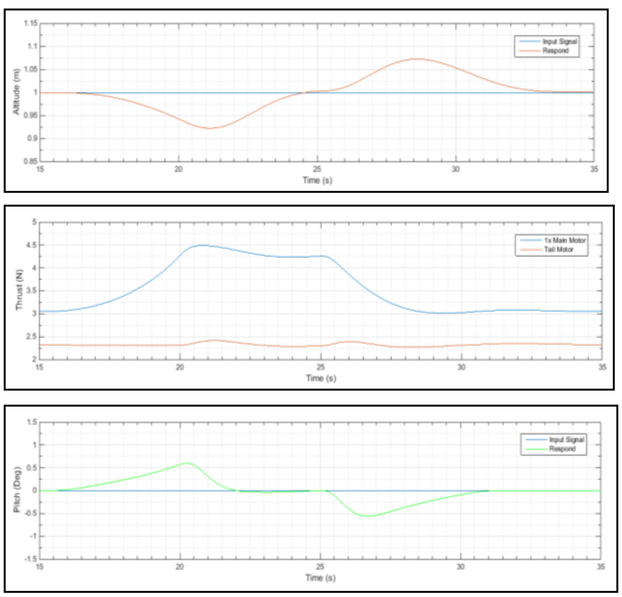

Figure 18 Main Rotor Tilting with Ramp Input Response.

The two sets of results shows the difference in responses by both simulations as displayed in Figure 17 and 18. In Figure 19, the altitude shows an extra of 0.03 m (-/+) overshoot of altitude and the pitch shows an extra of 1 degree overshoot of pitch. Though the thrust required from both result is similar, Figure 20 thrust graph shows that the forces are unbalanced on the pitching axis. This might be the major cause of the overshoot.

Tilting of main rotor will cause a loss in altitude and pitching motion, due to the sudden loss of vertical lift when the main two rotor are tilted at an angle. When it returns to its neutral position, the excess thrust causes the tri-copter to climb and pitch nose up.

From Figure 19, a step input tilting will cause a rapid descend and climb of 11 cm (-/+) and nose down and up angles of 1.45 degree (-/+). in Figure 18 shows the ramp input of 5 seconds input, which produces shows a better result of 7.5 cm (-/+) descend and climb, with a 0.55 degree (-/+) nose down and up.

Figure 19 shows that the main motor has a similar magnitude of thrust change as compared to as compared to Figure 18. However, in Figure 19, the shows that the tail motor has a higher magnitude thrust change than Figure 18. This shows that there is a there was a sudden loss of lift from the main motor, therefore the tail motor to compensate it by reducing its thrust so the tri-copter can maintain its desired angle. This will cause the higher loss of lift as shown in Figure 19.

Nevertheless, both step-inputs and ramp inputs are acceptable to be applied into the control system. Since both input are able to attain its steady-state within 3 seconds and maintains the pitching angle as close as zero.

The only visible difference is in Figure 20, where it receives a yaw response while in Figure 19, there is no response in yaw. This is due to the force imbalance when the main rotor is tilted, causing the tail to create a side force which causes the tri-copter to yaw. The yaw motion will then be countered by the tilting tail rotor, and within a short period of 0.5 seconds, it gets corrected. The response displays a fast response whenever there is an error, with a longer period required to recover to steady-state. This acts like a damper system and it also provide a better lateral stability to avoid a Dutch Roll.

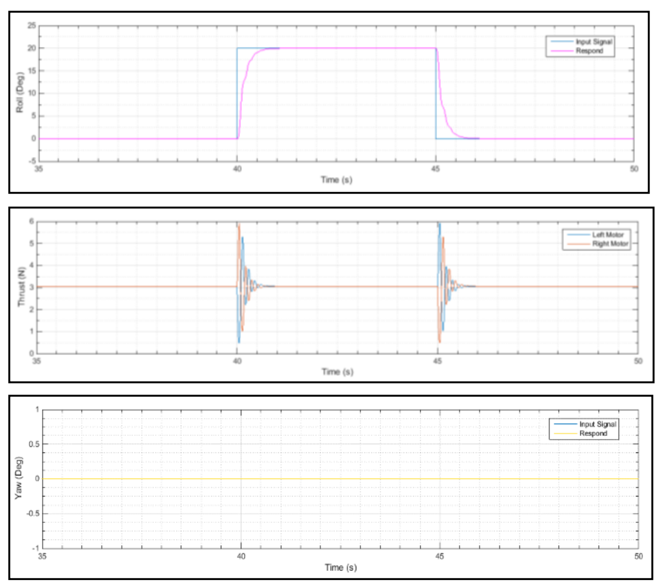

Figure 19 Rolling without Main Rotor Tilt.

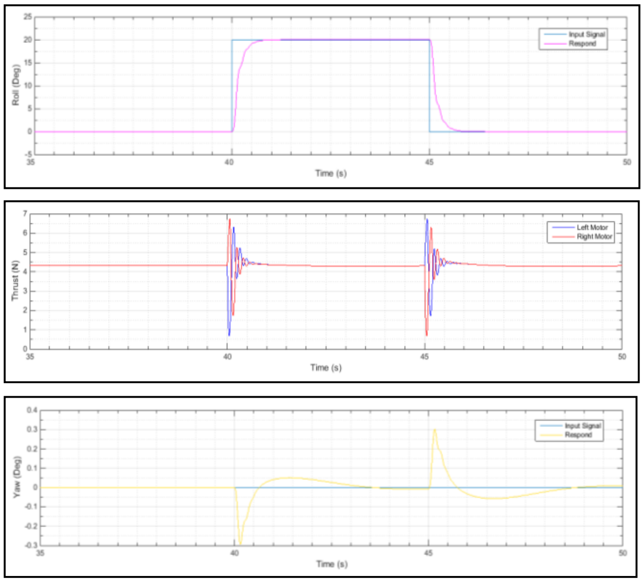

Figure 20 Rolling with Main Rotor Tilted.

However, there a disadvantage for a roll input when the main rotor are tilted, it requires more thrust to perform the roll motion than non-tilted rotors. This is concluded by comparing the difference of first upper and lower peaks of each thrust graph magnitude. It shows that the tilted rotors requires six times more thrust than the non-tilted rotors to perform a roll motion.

Although the tri-copter UAVs are highly manoeuvrable, this system shows that it is inefficient for it to be manoeuvrable.

VI. CONCLUSION

In This work presents the development of UGS tri-copter. We also present the control algorithm for vertical take-off, followed by transitioning to forward flight and back to landing. A linear dynamic model has also been developed for the tilting tri-copter UAV. The PID controllers are designed to stabilize the aircraft during take-off, hovering, landing and transition to forward flight phases. The success of the designs are demonstrated through the linear control simulations by the use of PID controller created in Simulink and observing the actual flight behavior and result of the tilting tri-copter during test-flight.

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