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Switching Control Approach for Stable Transition State Process on Hybrid Vertical Take-off and Landing UAV

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Abstract**—**In this paper, switching control approach for Stable Transition State Process on Hybrid Vertical Take-off and Landing UAV will be presented. The UAV configuration is a hybrid-UAV configuration which combines feature of rotary-wing UAV and fixed-wing UAV. Rotary-wing UAV configuration has advantages in easy-and-stable when take-off and landing, and also does not need special area to do take-off and landing. In the other hand, Fixed-wing UAV configuration has advantages in high maneuverability and high endurance. This hybrid UAV is designed to obtain all of this advantages. The most difficult part of control system of the VTOL UAV is designing control scenario of VTOL UAV in transition state. Therefore, there are two topics that will be discussed in this paper. First, control scenario design of the UAV in transition state which will describe the idea of switching control to achieve stable transition state. Second, the implementation details of the switching control scenario of the VTOL UAV's control system.

Keywords**—**VTOL, hybrid UAV, switching control, transition state.

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I. Introduction

Nowadays Unmanned Aerial Vehicle (UAV) has been researched and applied for vast practical used, from civilian purposes, such as for payload dropping [1], into military missions [2]. Based on their airframe configuration, most UAVs can be classified into one of the following categories: rotary-wing UAV and fixed-wing UAV. Both configurations have their respective advantages and limitations. With the expense of higher fuel consumption rate, the rotary-wing configuration allows the UAV to have low-speed maneuvering and vertical flight capabilities. UAVs with such configuration do not need spacious area for take-off and landing, and provide ideal observation platform as they can perform steady hover flight. On the other hand, the fixed-wing configuration is efficient for flying long range and for flying long endurance. The shortcoming of this configuration is that it requires runway for take-off and landing. The design of a hybrid UAV configuration seeks to obtain the beneficial traits of both rotary-wing UAV and fixed-wing UAV by having the beneficial traits of one configuration fullfill the shortcomings of the other configuration. Figure 1 shows the top-view of our hybrid VTOL design.

This paper is the continuation of our work in [3] to enhance the performance of our VTOL UAV. Control method of the hybrid UAV is presented by implementing control scenario during flight. We begins by describing the mathematical model of the UAV in section II followed by the control scenario in section III. The detailed control system based on the control scenario is described in section IV. In section V, test and result are presented. Conclusion is presented in section VI.

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II. UAV Mathematical Model

A. *Rotary-Wing Model [5]*

We use ordinary rotary-wing equation of motion as follows.

Equation of Translational Acceleration

$$\ddot{X} = (\cos\varphi\,\sin\theta\,\cos\psi + \sin\varphi\,\sin\psi)\frac{1}{m}U_1 - \frac{1}{2}C_x A_x \rho \dot{x}|\dot{x}| \quad (1)$$

$$\ddot{Y} = (\cos\varphi\,\sin\theta\,\sin\psi - \sin\varphi\,\cos\psi)\frac{1}{m}U_1 - \frac{1}{2}C_y A_y \rho \dot{y}|\dot{y}| \quad (2)$$

$$\ddot{Z} = (\cos\varphi\,\cos\theta)\frac{1}{m}U_1 - g - \frac{1}{2}C_z A_z \rho \dot{z}|\dot{z}| \quad (3)$$

where X, Y, and Z are position in x-y-z axis respectively while $\varphi, \theta,$ and ψ are Euler angle (roll, pitch, yaw respectively).

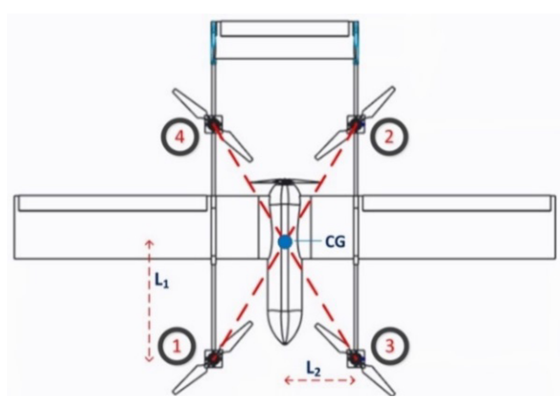

Figure 1 Appearance of the VTOL UAV [3]

Equation of Rotational Acceleration

$$\ddot{\varphi} = \dot{\theta}\dot{\psi}\left(\frac{I_{yy} - I_{zz}}{I_{xx}}\right) + \frac{U_2}{I_{xx}} - \frac{mgl}{I_{xx}} \quad (4)$$

$$\ddot{\theta} = \dot{\varphi}\dot{\psi}\left(\frac{I_{zz} - I_{xx}}{I_{yy}}\right) + \frac{U_3}{I_{yy}} - \frac{mgl}{I_{yy}} \quad (5)$$

$$\ddot{\psi} = \dot{\varphi}\dot{\theta}\left(\frac{I_{xx} - I_{yy}}{I_{zz}}\right) + \frac{U_4}{I_{zz}} \quad (6)$$

where $C_x, C_y,$ and C_z are drag coefficient while $A_x, A_y,$ and A_z are propeller area. $I_{xx}, I_{yy},$ and I_{zz} are inertia in x-y-z axis respectively.

Equation of Control Input

Figure 1 is the configuration of every 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 of the rotors can be defined as:

$$U_1 = F_1 + F_2 + F_3 + F_4 \quad (7)$$

$$U_2 = (F_1 + F_3 - F_2 - F_4)L_1 \quad (8)$$

$$U_3 = (F_1 + F_4 - F_2 - F_3)L_2 \quad (9)$$

$$U_4 = M_1 - M_4 + M_2 - M_3 \quad (10)$$

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.

B. *Fixed-Wing Model [6]*

In modeling the fixed wing UAV model we use conventional aircraft equation of motion as follows.

Translational Equation

$$\dot{u} = -g\sin\theta + \frac{X}{m} - qw + rv \quad (11)$$

$$\dot{v} = g\cos\theta\sin\varphi + \frac{Y}{m} - ru + pw \quad (12)$$

$$\dot{w} = g\cos\theta\sin\varphi + \frac{Z}{m} - pv + qw \quad (13)$$

where X, Y, and Z are the aerodynamic and thrust forces. And u, v, and w are the velocity of the body in x-y-z axis respectively.

Rotation Equation

$$\dot{p} = (c1r + c2p)q + c3L + c4N \quad (14)$$

$$\dot{q} = c5pr - c6(p^2 - r^2) + c7M \quad (15)$$

$$\dot{r} = (c8p - c7r)q + c4L + c9N \quad (16)$$

$$c1 = \frac{(I_y - I_z)I_z - J_{xz}^2}{I_xI_z - J_{xz}^2}\ ;\ c2 = \frac{(I_y - I_yI_z + I_z)J_{xz}^2}{I_xI_z - J_{xz}^2}\ ;$$

$$c3 = \frac{I_z}{I_xI_z - J_{xz}^2}\ ;\ ;\ c4 = \frac{J_{xz}I_z}{I_xI_z - J_{xz}^2}\ ;\ c5 = \frac{I_z - I_x}{I_y}\ ;\ c6 = \frac{J_{xz}}{I_y}\ ;$$

$$c7 = \frac{1}{I_y}\ ;\ c8 = \frac{(I_x - I_y)I_x - J_{xz}^2}{I_zI_x - J_{xz}^2}\ ;\ c9 = \frac{I_x}{I_xI_z - J_{xz}^2}$$

where p, q, and r are the rotation in x-y-z axis respectively and L, M, and N are the moment in x-y-z axis respectively

Kinematic Relation

$$\dot{\psi} = q\frac{\sin\varphi}{\cos\theta} + r\frac{\cos\varphi}{\cos\theta} \quad (17)$$

$$\dot{\theta} = q\cos\varphi - r\sin\varphi \quad (18)$$

$$\dot{\varphi} = p + q\sin\varphi\tan\theta + r\cos\varphi\tan\theta \quad (19)$$

In this model we make assumption that the UAV is considered as rigid body. For further study we prefer to simplyfy the equation above by linearizing the non linier aircraft equation of motion which is stated before.

In linearizing the equation of motion we make another assumption that the aircraft only experience small disturbance. So that we can write down all the equation above in term of state space form below.

$$\dot{x} = Ax + Bu \quad (20)$$

where A is state matrix and B is input matrix.

The symetrical variable is independent to asymetrical variable and because of that we can decouple the linier equation of motion into two type of motion as longitudinal motion and lateral directional motion.

III. CONTROL SCENARIO

The VTOL UAV has 4 motors (1 motor for fixed-wing state, 4 motors for rotary-wing state). And as ordinary fixed-wing UAV, it also has some control surfaces (aileron, elevator, and rudder).

For efficiency, we have to control every actuators (motors and control surfaces) properly in every state. Therefore, we have made control scenario for every state. This control scenario is shown in **Figure 2**.

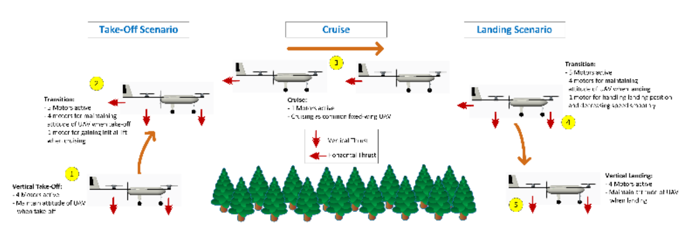

Figure 2 Control scenario in transition state

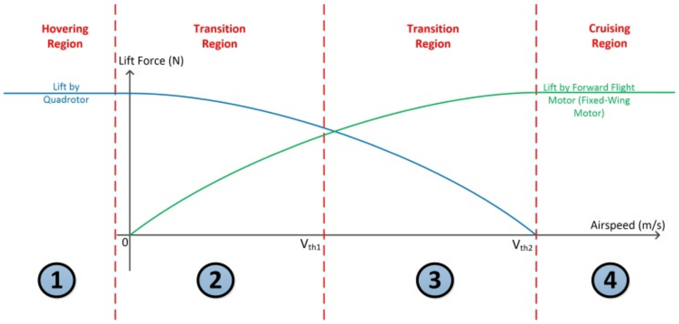

Figure 3 Details of control scenario in transition mode

Figure 3 shows details of control scenario in transition mode. There are four critical states embodied in this transition mode scenario. Of the four critical states, there are only three regions/modes that will actually occur in this transition condition. However, there are two additional constraints applied in transition region to make sure the transition flight happen smoothly hence it will be easier if we break down the states into four states. These two constraints (V_{th1} and V_{th2}) are boundary between states which are based on UAV airspeed. The detailed control actions of UAV in every state are described as the following.

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. During this state, the UAV is stabilizing its attitude whilst gaining certain altitude.
- Gain of quadrotor attitude control from Ground Control Station (GCS) is fully applied to the UAV.
- Control surfaces (aileron, rudder, and elevator) are still *inactivated*.
- Forward flight motor (for fixed-wing mode) is still *inactivated*.
- Flight Mode: altitude hold for quadrotor.

B. State 2

- UAV lift force is the combination of quadrotor thrust and fixed-wing (wing and tail) lift. Altitude and attitude is maintained using this combined force.
- The value of quadrotor thrust can be adjusted by either operator or automatically adjusted by the autopilot because the altitude hold mode is *activated*.
- Gain of quadrotor attitude control from Ground Control Station (GCS) is fully applied to the UAV.
- Control surfaces (aileron, rudder, and elevator) are still *inactivated*.
- Forward flight motor is initially *activated automatically* to last value of the throttle level on remote control, while throttle of quadrotor is fully automatic to maintain altitude and attitude.
- Flight Mode: altitude hold for quadrotor and stabilize for fixed-wing.

C. State 3

- UAV lift force is the combination of quadrotor thrust and fixed-wing (wing and tail) lift. Altitude and attitude is maintained using this combined force.
- The value of quadrotor thrust can be adjusted by either the operator or automatically adjusted by the autopilot because the altitude hold mode is activated.
- Gain of quadrotor attitude control from Ground Control Station (GCS) applied to UAV is attenuated. The attenuation value is proportional with the increment of UAV airspeed.
- Control surfaces (aileron, rudder, and elevator) are activated.
- Throttle level of forward flight motor automatically switches to stabilize mode (can be adjusted by operator).
- Flight Mode: altitude hold for quadrotor and stabilize for fixed-wing.

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 surface (Aileron, Rudder, Elevator) are still activated. Attitude control of the UAV is fully controlled via control surfaces of the UAV only.
- The throttle level of forward flight motor (for Fixed-Wing mode) can be adjusted manually.
- Flight Mode: Stabilize for fixed-wing.

In our experiment, we assigned V_{th1} as 12 m/s and V_{th2} as 18 m/s. This values are considered based on the basic performance of the UAV.

IV. Control System Based on Control Scenario

Figure 4 shows the detail of control system design based on control scenario which has been presented in the previous section. Summarily, there are two PID control systems (for rotary-wing and for fixed-wing) combined into one big control system. The most distinguished part is the transition state algorithm block. This block/part consists the logics that decide which control mode to undertake (rotary-wing state, fixed-wing state, or transition state). This decision depends on both input from user and the airspeed feedback. This block also regulates the gain input in both rotary-wing control system and fixed-wing control system when the VTOL UAV is in transition state so that every actuators (motors and control surfaces) would work efficiently.

Figure 5 shows the gain value in rotary-wing control system based on airspeed threshold. As mentioned before there are two constraints/thresholds (V_{th1} and V_{th2}) which mark the mode boundaries. Based on our real test, the V_{th1} is 12 m/s and the V_{th2} is 18 m/s. More detailed descriptions are shown in Figure 6-9 and section III.

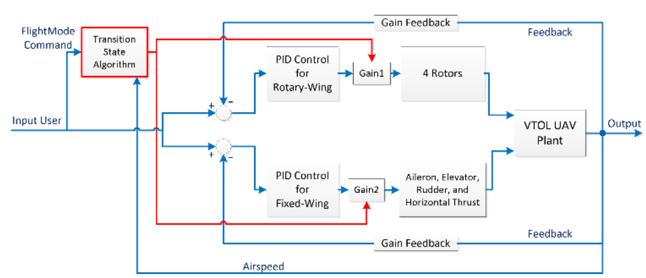

Figure 4 Control system design based on control scenario

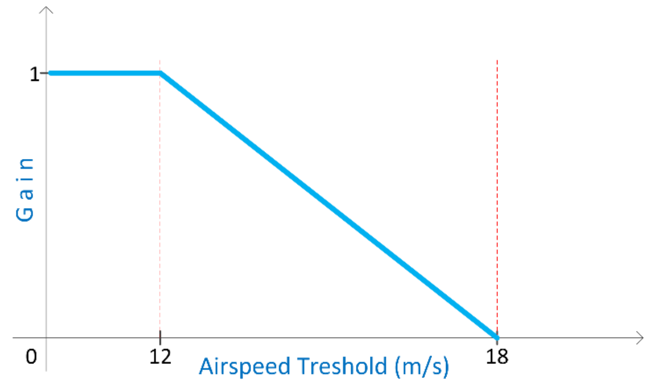

Figure 5 Airspeed threshold in transition state (Rotary-Wing System)

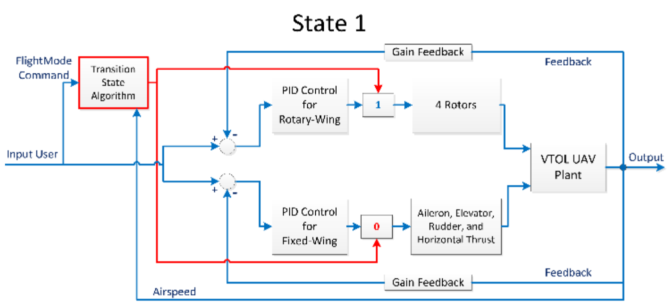

Figure 6 Control system design in State 1

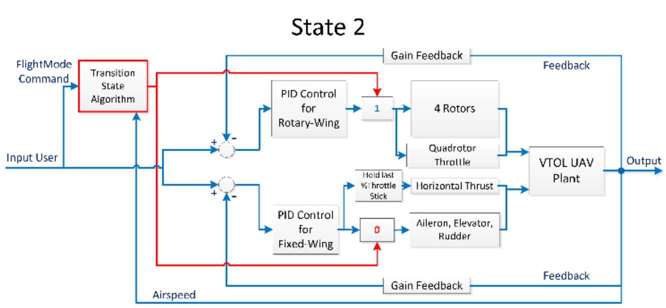

Figure 7 Control system design in State 2

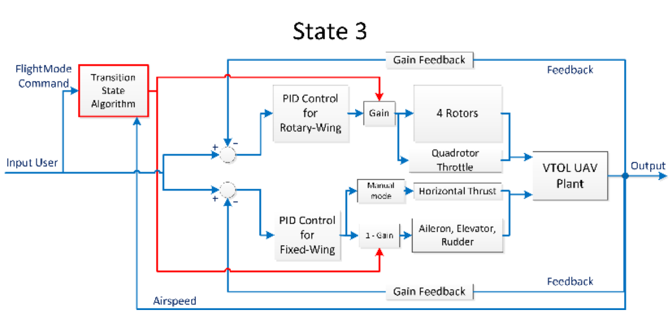

Figure 8 Control system design in State 3

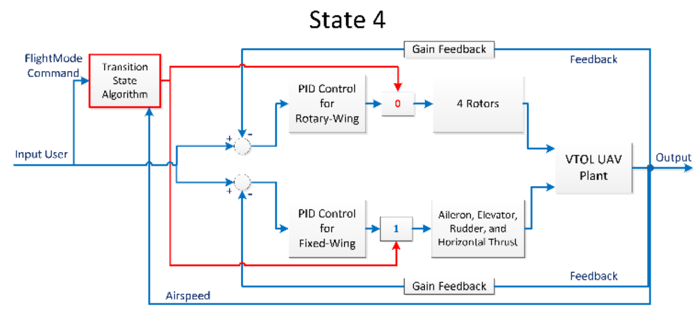

Figure 9 Control system design in State 4

V. RESULT

Figure 10 and **Figure 11** are data plot of flight test log. We divide the data plot into 6 sections which also correlate with 6 stages in the real flight test. These 6 stages are:

- **Stage 1 and Stage 2:** Stage 1 is manual mode and stage 2 is altitude hold mode. Both modes are in hover flight (rotary-wing). Based on our experiment, the duration of stage 1 and stage 2 are *68.75 seconds.*
- **Stage 3:** Stage 3 is transition state from hover to forward flight (fixed-wing). In this fixed-wing section, the UAV is set into stabilize mode. The duration is *10.75 seconds.*
- **Stage 4:** Stage 4 is also stabilize mode, the UAV has been totally in forward flight mode (fixed-wing). In our experiment, we maintained this stage for *106.375 seconds*.
- **Stage 5:** Stage 5 is transition state from forward to hover flight (rotary-wing). In this rotary-wing section, the UAV is set into manual mode. The duration is *2.125 seconds*, which is shorter than transition from hover to forward flight.
- **Stage 6:** Stage 6 is manual mode in totally hover flight, which is also in preparation for vertical landing. The duration is about *52 seconds.*

Figure 10 shows that there is correlation between the change of flight mode and the airspeed sensor output [7]. We can see that in stage 3 the black line shows that the fixed-wing throttle starts from fixed value around 50% of total power. After the airspeed sensor output reach threshold V_{th1}, the fixed-wing throttle becomes adjustable in stabilize mode. Transition state from forward to hover flight occurred in a short time thus it cannot be easily analyzed based on this data plot.

From **Figure 11** we can see that the attitude (red line: roll, and black line: pitch) data shows that the UAV motion is adequately stable in rotary-wing mode (stage 1, stage 2, and stage 6). In fixed-wing mode (stage 3-5) the UAV gets more oscillation because of the critical stage in transition state (stage 3 and stage 5). Meanwhile, oscillation in stage 4 is intentional; we want to test the UAV's maneuverability by maneuvering the UAV with extreme roll or pitch.

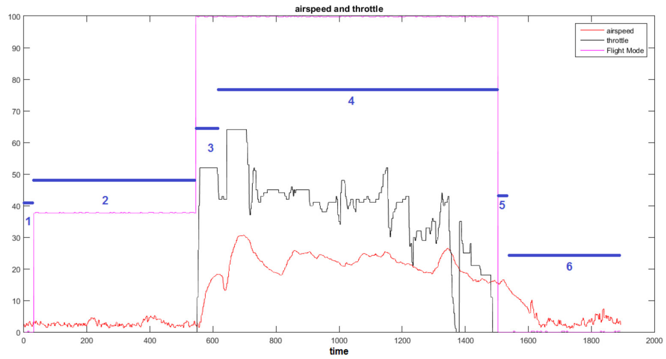

Figure 10 Flight data plot (airspeed and throttle) of full-mode testing

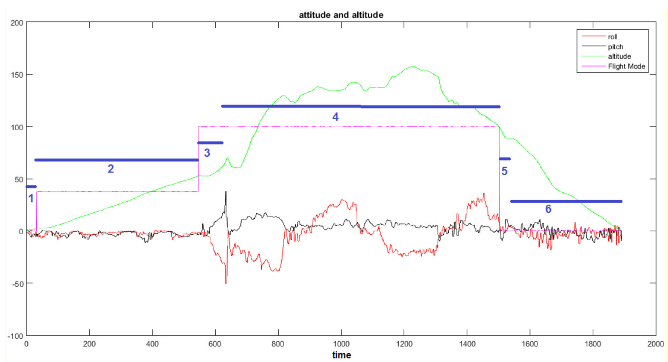

Figure 11 Flight data plot (attitude and altitude) of full-mode testing

Figure 11 (green line: altitude) also shows that we start to activate the transition state from hover to forward flight at 50-meter altitude while we start to activate the transition state from forward to hover flight at 100-meter altitude. This altitude constraint is part of safety measures in our flight test procedure. With this procedure, the UAV is brought to a safe altitude before activating the most critical stage (transition state) so that we still be able to recover the UAV before it crashes with ground if the transition scenario is failing. In this experiment, we have tested the VTOL UAV to fly up to 150 meters above ground level.

VI. CONCLUDING REMARKS

Control system of the VTOL UAV is basically the combination of the rotary-wing control system and fixed-wing control system. Both of these control system is integrated into one big control system design and governed by transition state algorithm block that can make every actuators (motors and control surfaces) work efficiently in every state, especially in transition state.

The switching control approach which has been designed to govern every change of gains in every state works well. It can be seen from the result that the UAV can pass every stage in our flight test, especially the transition state, with adequate stable response.

However, there are still some of instabilities we still have to cope with in the control system. Since the most critical stage of the hybrid UAV's flight phase is transition state, in the next improvement we should consider carefully when we design the transition algorithm. It also important to prove rotary-wing and fixed-wing mode are going well before taking transition test.

FUTURE WORK

The airframe and avionics systems will be improved to achieve optimal performance [8,9,10], and the enhanced flight control will be developed and installed to make the UAV fully autonomous and to make the UAV more robust and agile.

Electric-powered propulsion system can be substituted by combustion engine to lengthen flight endurance. We also want to solve high current problem during the transition from hover to forward flight (when all of the motor are activated) by adding cooling system in UAV since this problem can cause overheat and may melt the tin-soldered component. The overheat problem may be reduced by letting the freestream air to flow inside fuselage where all of the systems are located and have that air be sucked out using a portion of power output of the propulsion system.

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REFERENCES

[1] Ghozali Suhariyanto Hadi, Rivaldy Varianto, Bambang Riyanto Trilaksono and Agus Budiyono, "Autonomous UAV System Development for Payload Dropping Mission," Journal of Instrumentation, Automation and Systems, vol. 1, no. 2, 2014, pp. 72-77. https://doi.org/10.21535/just.v4i2.944

[2] Department of Defense USA, Unmanned Aircraft System Roadmap, Office of the Secretary of Defense, 2005.

[3] Puspita Triana Dewi, et. al.,"Design of Separate Lift and Thrust Hybrid Unmanned Aerial Vehicle," Journal of Instrumentation, Automation, and Systems, vol. 2, no. 2, 2015, pp. 45-51. https://doi.org/10.21535/jias.v2i2.697

[4] Ghozali Suhariyanto Hadi, Muhammad Ramadhan Kusnaedi, Puspita Dewi, Aris Budiyarto, Agus Budiyono, "Design of Avionics System and Control Scenario of Small Hybrid Vertical Take-Off and Landing (VTOL) UAV," Journal of Instrumentation, Automation and Systems, vol. 2, no. 2, 2015, pp. 67-71. https://doi.org/10.21535/jias.v2i2.698

[5] Wei Dong, Guo-Ying Gu, Xiangyang Zhu, Han Ding, "High-performance trajectory tracking control of a quadrotor with disturbance observer," Elsevier: Sensors and Actuators A 211, 2014, pp. 67–77. https://doi.org/10.1016/j.sna.2014.03.011

[6] Hari Muhammad, Fuad Surastyo, Rianto Adhy Sasongko, " Simulation, Parameter Identification and Control System Design of An Aircraft Using Unified Mathematical Model," ASEAN Engineering Journal Part A, vol. 3, no. 1, 2013, pp. 5-26.

[7] M. L. Fravolini et al., "Model-based approaches for the airspeed estimation and fault monitoring of an Unmanned Aerial Vehicle," 2012 IEEE Workshop on Environmental Energy and Structural Monitoring Systems (EESMS), Perugia, 2012, pp. 18-23. https://doi.org/10.1109/EESMS.2012.6348401

[8] Fredericks, William J., "Conceptual Design of A Vertical Takeoff and Landing Unmanned Aerial Vehicle with 24-HR

[9] Endurance", NASA Langley Research Center, Hampton, VA 23681, 2010.
[10] Soojung Hwang, Yushin Kim, and Myeong Kyu Lee, "Tilt Rotor-Wing Concept for Multi-Purpose VTOL UAV", KSAS International Journal, 2007, vol. 8, no. 1, pp. 87-94. https://doi.org/10.5139/ijass.2007.8.1.087
[11] Aslihan Vuruskan, Burak Yuksek, Ugur Ozdemir, Adil Yukselen, Gokhan Inalhan, "Dynamic Modeling of A Fixed-Wing VTOL UAV", 2014 International Conference on Unmanned Aircraft Systems (ICUAS), 2014, pp. 483-491. https://doi.org/10.1109/icuas.2014.6842289