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Dynamics and Fuzzy Logic Method for Controlling Quadcopter

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Abstract: A controlling aerial robot with four rotors called quadcopter with intelligent system; combine with dynamical model is difficult. In this study, mathematic formulation and implementation quadcopter with simple trajectory is shown. In detail, this study aims to calculate the moment of inertia of the body and the rotational of the quadcopter, then calculating the thrust factor, the drag factor as well as the acceleration of aircraft and also to simulate the trajectory of quadcopter. The research method used in this study is modeling, simulations and experiments. So that, in the modeling and simulation methods consist of calculating statics, dynamics, kinematics and fuzzy logic control. While the experimental method consisted of quadcopter tests process and processing of GPS data showing the actual position of the aircraft. Simulation of aerial robots showed that the maximum error value between theoretical and actual movement can get minimum errors. Trajectory simulation results and error values are affected by setting the range of membership functions of fuzzy logic control system.

Key words: Quadcopter, inertia, control system, fuzzy logic method

INTRODUCTION

One type of robot that much attention is the best mini unmanned aerial UMAVs, mainly because of its ability to perform rescue tasks in hazardous locations and difficult to reach. These types of helicopter flying robots have advantages over other flying vehicle that can maneuver in the narrow area and perform takeoff and landing Vertically (VTOL) (Claudia *et al*., 2010). As this study will discuss a type of mini unmanned aircraft with wing-type rotating RUMAV called quadcopter. Quadcopter is a flying robot that has four independent propellers installed at each end of a cross frame.

Quadcopter aircraft first made in 1907 in France by Louis and Jacques Breguet named Gyroplane No. 1. Test fly the plane does not end well because it is still too difficult for controlling. Therefore, quadcopter concept is not developed further until the introduction of the control system for controlling an aerial robot. In the early 21st century, a number of researchers such as (Hamel *et al*., 2002) began to conduct research on the design and control of unmanned mini helicopter with four rotor (Kivrak, 2006; Watanabe *et al*., 2009). Here is an example of some of the best designs aerial robot quadcopter from various universities and companies.

With these advantages allow this plane can be widely applied in various fields, among others in the military sphere is useful to conduct reconnaissance, border patrol, mine detection, delivery of equipment by air. Whereas in the civil field is useful for mapping, photography, television and cinema shooting, search and rescue, monitoring disaster areas such as flood or forest fire, traffic monitoring (Scmidth, 2011) and its applications for military aircraft .

Quadcopter at this time is not only manufactured by companies that are related to robotics but also created by academics for research purposes on quadcopter system. With so many advantages in capabilities and fields of application, then quadcopter have very extensive development opportunities. The studies centered on Quadcopter generally discussed ranging from basic concepts, simulation and control action on quadrotor use. From the results of these studies concluded that by doing modeling and simulation before the design would save time and cost.

In Fig. 1 shows the block diagram of the design process in outline. Selection of the mass, size and layout aircraft components will determine the moment of inertia and moment of inertia rotational body aircraft and will

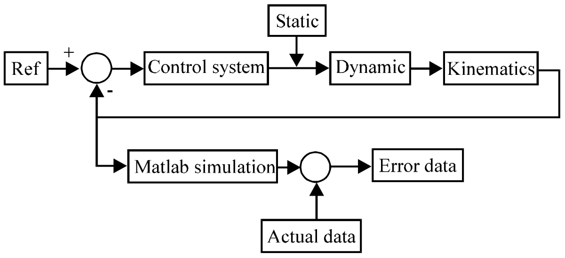


Fig. 1: Block diagram of quadcopter control system

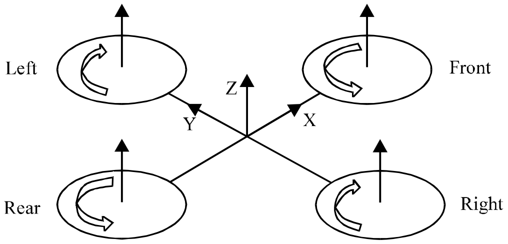


Fig. 2: Quadcopter configuration of propeller motion of hovering condition

further affect the overall aircraft moving process. Therefore, the moment of inertia is included in the formulation of the problem and research purposes.

In this study formulated how to get great moment of inertia caused by the aircraft and also to calculate acceleration, velocity and distance traveled by system respect to the time and further more to get mileage vs time graph, either theoretical or actual methods.

Basic motion of quadcopter: To learn the basic motion of a quadcopter described simply as four rotors that are in a cross configuration as shown in Fig. 2. This model consists of a thin cross structure with four propellers in the four corners thereof (Bresciani, 2008).

Quadcopter front and rear propeller rotates anti-clockwise direction, otherwise right and left propeller rotates clockwise. This causes differences in the direction of rotation reverse torque of the motor 1 and 2 will be eliminated by turning the torque of the motor 3 and 4. This configuration allows the removal tail?rotor as found in traditional helicopter. Figure 1 shows a model structure in a state where the linear acceleration quadcopter drift upward offset the acceleration of gravity and all have the same speed propellers.

Coordinate system used involves two separate coordinate systems. The first is a system of geographic information systems (E frame) which is a coordinate system relative to the earth's surface. The second is a coordinate system which is the body quadcopter coordinates system attached to the frame quadcopter (B frame).

There are four targets relating to the four basic movements that allow the helicopter reached a height, altitude and the angular position specific. Here is an overview of the basic movements.

Vertical translation up and down-thrust (U_1 [N]): In Fig. 3 shows the translational movement vertically upwards. Movement of quadcopter to up or down is obtained if the speed of Ω_H [rpm] for all the propeller is increased or reduced by $\Delta\Omega$ [rpm] so that result vertical thrust forces U_1 [N] relative to the B Frame. Δ_A [rad/s] is a positive variable that indicates the increase of the constants Ω_H (angular speed of hovering condition). The Δ_A cannot be too large because the model will be affected by the nonlinearity.

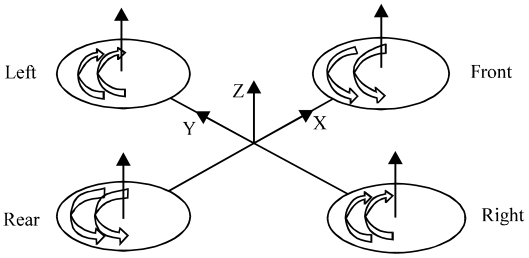


Fig. 3: Vertical translation movement

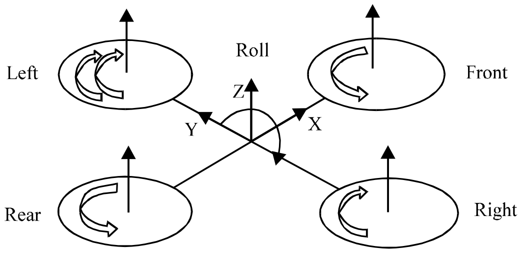


Fig. 4: Rotation to the right (Roll)

Rotation to right and left (roll)-torque U_2 [N m]: In Fig. 4, shows the rotational movement of the roll to the right. Movement of quadcopter to the right or left is obtained when the propeller speed is increased or decreased left and right propeller speed reduced or increased so as to produce rotation about the axis x_B. Overall thrust together on the condition of hovering or float, so that this movement only to produce in a continued acceleration in the direction of the roll; on the first approach. The Δ_A and Δ_B [rad sec^{-1}] is selected to maintain the vertical force unchanged. It can be demonstrated to a small value Δ_A, $\Delta_B \approx \Delta_A$. In the previous case Δ_A and Δ_B cannot be too large because the model will be affected by the nonlinearity.

Rotation to the forward and backward (pitch)-torque U_3 [N m]: The driving force is the same as the overall condition of hovering or float, so that the movement is only produced an acceleration in the direction of the pitch (in the first approximation). Figure 5 shows the rotational movement of the pitch to upward. Like the previous case ΔA and ΔB [rad sec^{-1}] is selected to maintain the vertical force unchanged and should not be too big. For small value Δ_A, $\Delta_B \approx \Delta_A$.

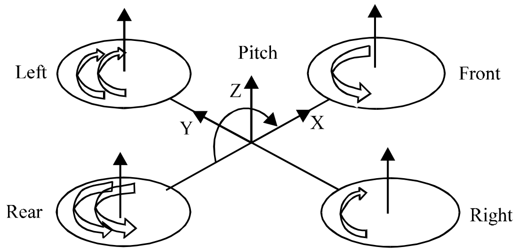


Fig. 5: Rotation for Pitch motion, forward movement

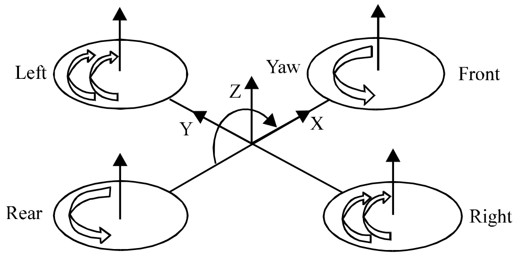


Fig. 6: Rotation to z-Frame (Yaw)

Rotation to the z-frame (yaw)–torque U_4 [N m]: The total zero-lift drag coefficient of the body is usually considered to be of three components; friction drag, wave drag and base drag as shown in Eq. 1. These different components are further discussed in the following sub-sections.

In Fig. 6 shows the movement of the z-axis yaw rotation. Yaw motion clockwise or counter-clockwise obtained if the front and rear propeller speed is increased or decreased and the left and right propeller speed reduced or increased so as to produce rotation about the axis z_B. When the overall torque is unbalanced, the helicopter will rotate itself towards the axis z_B.

The driving force is the same as the overall condition of hovering, so that the movement is only produced an acceleration in the yaw direction; the first approach. Like the previous case Δ_A and Δ_B [rad sec^{-1}] are selected to maintain the vertical force unchanged and should not be too big, then for small value Δ_A, $\Delta_B \approx \Delta_A$.

MATERIALS AND METHODS

Equation motion of quadqopter

Kinematics of Quadcopter: The issues of aircraft kinematics describe the condition of an aircraft on the position vector and velocity vector defined in a vector state of X_H dan $\dot{x}_H$. Each of these vectors consist of linear and angular position and linear velocity and angular. Fig. 7 shows the best linear position against E-Frame.

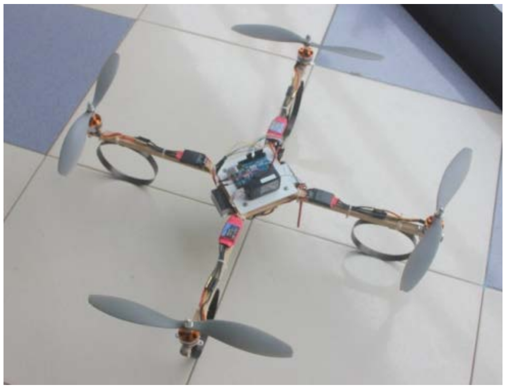


Fig. 7: Coordinate system is a frame of Quadcopter

If X^E_{LIN} is linear position vector comprising a position component in the direction of the axis x, y, z (x, y, z) and X^E_{ANG} is vectors comprising the angular position of the component position angle to the axis x, y, z (?, θ, Ψ) then position vector of quadcopter become $X_H = [\, X^E_{LIN} \quad X^E_{ANG} \,]^T = [x, y, z\ ?, \theta, \Psi]^T$.

If X^E_{LIN} is linear velocity vector comprising velocity component in the direction of the axis x, y, z ($\dot{x}, \dot{y}, \dot{z}$) and angular velocity vector comprising the axis angular velocity component x, y, z (p, q, r) then velocity vector is $\dot{x}_H = [\, \dot{x}^E_{LIN} \ \dot{x}^E_{ANG} \,]^T = [\, \dot{x}, \dot{y}, \dot{z} \ \ p\ q\ r]^T$.

Furthermore, initial of the state vector and the sate vector e after being given the acceleration in time t, respectively notated X_{H0}, $\dot{x}_{H0}$, dan $\dot{x}_{Ht0}$:

$$X_{H0} = [x_0 \ y_0 \ z_0 \ \phi_0 \ \theta_0 \ \psi_0]^T \tag{1}$$

$$\dot{X}_{H0} = [\dot{x}_0 \ \dot{y}_0 \ \dot{z}_0 \ p_0 \ q_0 \ r_0]^T \tag{2}$$

If the plane is given an acceleration of the state will change its position and velocity. If $\bar{X}$ is the acceleration vector consisting $\bar{x}\,\bar{y}\,\bar{z}$ of components ($\bar{x}\,\bar{y}\,\bar{z}\,\dot{p}\,\dot{q}\,\dot{r}$) and t is the time, the new velocity vector at time t is obtained by integral acceleration vector quadrotor against t:

$$\dot{X}_{Ht} = \int \bar{X}\, dt = \bar{X}_t + c_1 \tag{3}$$

Initial boundary condition, $X_H(0) = x_0$ at time t = 0 then:

$$\dot{X}_{Ht}(t) = [x_t \ y_t \ z_t \, p_t \, q_t \, r_t]^T = X_0 + \bar{X}_t \tag{4}$$

The new position vector at time t is obtained by integration of velocities vector against to t:

$$\dot{X}_{Ht} = \int \bar{X}_{dt} = \bar{X}_0 t + 0.5\, \bar{x} t^2 + c_2 \tag{5}$$

Then, initial boundary condition awal, $X_H(0) = X_0$ at time t = 0 then:

$$X_{Ht} = [X_t\ y_t\ z_t\ \phi_t\ \theta_t\ \psi_t]^T = X_0 + \dot{X}_0 t + 0.5\ \bar{X}_{t^2} \tag{6}$$

Dynamics of quadcopter: Acceleration of the quadcopter influenced of the force or torque acting on the aircraft. On the issue of the dynamics of these aircraft will be analyzed the dynamic equilibrium of the plane so they will know the forces and moments that can work on the aircraft. Furthermore, from the forces and moments acting on the frame will be known acceleration occurs. Figure 8 shows the illustration of the dynamics of aircraft motion.

If M_H inertia moment matrix, $\ddot{X}_H$ acceleration matrix, C_H Centripetal-Coriolis matrix, $\dot{X}_H$ velocities matrix, G_B gravitational vector and A vector motion action then the dynamics model from a quadcopter could be be defined in the following matrix form (Hamel *et al*., 2002; Rodic and Mester, 2011):

If the action of the motion vector U_H, matrix of gyroscopic propellers O_H and propeller angular velocity vector Ω then the action vector for general motion is:

$$\Lambda = U_H + O_H.\ \Omega$$

Or both of the above equation can be written in the following form:

$$M_H.\bar{X}_H = -C_H.\ \dot{X}_H + G_H + O_H.\Omega + U_H \tag{7}$$

Subscript H indicates that the variable in question relative to the H-Frame. If m (kg) is a mass of a quadcopter and I (N m sec^2) is a inertia moment of matrix then it can be obtained as follows:

$$\begin{aligned} M_H &= [(m I_{3\times 3}\ \&\ O_{3\times 3} @ O_{3\times 3}\ \&\ I)] \\ &= [m \& 0 \& 0 \& 0 \& 0 \& 0 @ 0 \& m \\ &\quad \& 0 \& 0 \& 0 \& 0 @ 0 \& 0 \& m \& 0] \end{aligned} \tag{8}$$

It appears that M_H is a diagonal matrix and is a constant. It appears that the matrix M_H is diagonal and constant variable. Centripetal-Coriolis Matrix:

$$\begin{aligned} C_H &= \begin{bmatrix} O_{3\times 3} & O_{3\times 3} \\ O_{3\times 3} & S(I.X^B_{ANG}) \end{bmatrix} = [0 \& 0 \& 0 \& 0 \& \\ &0 \& 0 @ \& 0 \& 0 \& 0 \& 0 \& 0 @ 0 \& \\ &0 \& 0 \& 0 \& 0 \& 0 @ 0 \& 0 \& 0 \& 0 \& \\ &0 \& 0 \& 0 \& 0 \& 0 \& I_{zz} r \& 1 I_{yy} q @ 0 \&] \end{aligned} \tag{9}$$

Gravitasional vector:

$$G_H = \begin{bmatrix} F^E_G \\ O3\times 1 \end{bmatrix} = \begin{bmatrix} C \\ 0 \\ -mg \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{10}$$

If J_{TP} (N m sec^2) is a total of rotational inertia moment against to axis of propeller and $\mathbf{\Omega}$ (rad sec^{-1}) is angular velocity vector of propeller then the gyroscopic propeller matrix as:

$$O_H\Omega = J_{TP} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ q & q & q & q \\ p & p & p & p \\ 0 & 0 & 0 & 0 \end{bmatrix} \Omega \tag{11}$$

If b (N s^2) is thrust factor and d (N m s^2) is drag factor then motion of matrix can be written as:

$$E_H = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ q & b & 0 & b \\ b & 0 & b & 0 \\ d & d & d & d \end{bmatrix} \tag{12}$$

If U_1(N), U_2(N m), U_3(N m) and U_4(N m) are thrust, torque of roll motion, torque of pitch motion and torque of yaw motion also thrust factor b (N s^2) and draf factor d (N m s^2) then relative motion vector respect to B-frame:

$$\begin{aligned} U_B = E_B\,\Omega^2 &= [(0 @ 0 @ U_1 @ U_2 @ U_3 @ U_4)] \\ &= [(0 @ 0 @ b(\Omega_1^2 + \Omega_2^2))] \end{aligned} \tag{13}$$

If R_θ rotational matrix then the action reative vector vektor of H-frame:

$$\begin{aligned} &(s_\psi s_? + c_\psi s_\theta c_?)U_1 @ \\ &(1c_\psi s_? + s_\psi s_\theta c_?)U_1 @ (c_\theta c_?)U_? \end{aligned} \tag{14}$$

If $c_k = \cos k$, $s_k = \sin k$ then rotational matrix as:

$$\begin{aligned} R_\theta = [(&c_\psi c_\theta \& 1\ s\ 1\ \psi c_\phi + \\ &c_\psi s_\theta s_\phi \& s_\psi s_\phi + c_\psi s_\theta c_\phi @ s_\psi c_\theta)] \end{aligned} \tag{15}$$

If $t_k = \tan k$ then transfer matrix is:

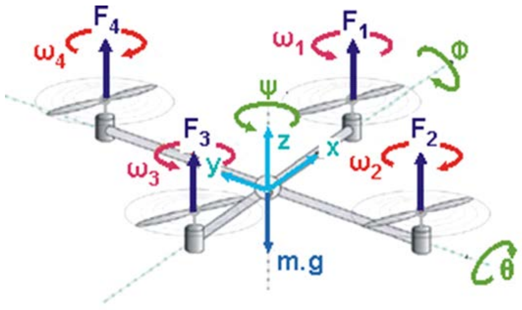


Fig. 8: Dynamic motion of Quadcopter (Claudia, 2010)

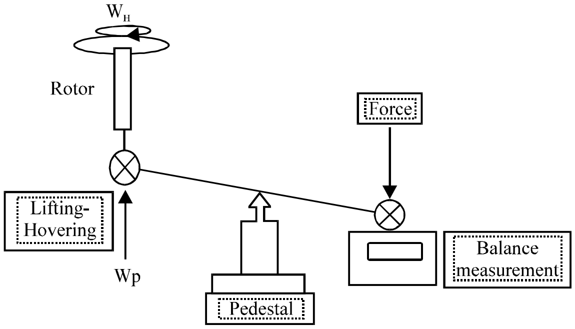


Fig. 9: How to get thrust of quadcopter and determine b factor (Syam *et al.*, 2015)

$$T_\theta = \begin{bmatrix} 1 & s_? t_\theta & c_? t_\theta \\ 0 & c_? & l s_? \\ 0 & s_? / c_\theta & c_? / c_\theta \end{bmatrix} \tag{16}$$

Acceleration vector of quadcopter respect to H-frame, could be obtained from the following Eq. 17:

$$\begin{aligned} \ddot{X}_H &= [\ddot{x}\ \ddot{y}\ \ddot{z}\ \dot{p}\ \dot{q}\ \dot{r}] \\ &[(C_H \dot{X}_H + G_B + O_H \Omega + U_H) M_H^{-1}] \end{aligned} \tag{17}$$

Be simplicity Eq. 17 can be shown as:

$$\begin{aligned} x &= (\sin ?\ \sin ? + \cos ?\ \sin\theta \cos ?)\frac{U_1}{m} \\ \dot{p} &= \frac{(I_{yy} ? I_{zz})qr - J_{TP} q\Omega + U_2}{I_{xx}} \\ &\frac{q = (I_{zz} ? I_{xx})pr - J_{TP}\, p_\Omega + U_3)}{I_{yy}} \end{aligned} \tag{18}$$

The thrust factor b in Eq. 13 obtained from testing of quadcopter thrust as shown in Fig. 8. It is performed a linear regression to obtain a linear relationship between the thrust of an F_P propeller and propeller angular velocity squared ω_p^2 as shown in Fig. 9 and 10.

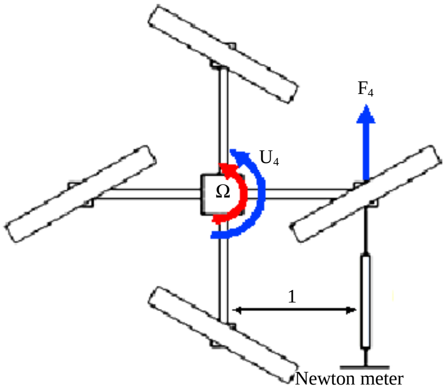


Fig. 10: Torque testing for yaw motion, to determine d factor

The thrust factor b value may also be sought from the relationship between thrust an propeller F_P and angular velocity of propeller ω_H^2 in a state of hovering as follows:

$$F_H = b\,\omega_H^2 \text{ atau } b = \frac{F_P}{\omega_H^2} \tag{19}$$

Because quadcopter in a state floated the thrust of the fourth F_P propellers must be equal to the weight of the quadcopter:

$$4 \times F_H = mg \text{ atau } F_P = \frac{mg}{4} \tag{20}$$

Furthermore, the value of drag factor d can be obtained from the experiment by testing torque of yaw motion of quadcopter, by observing the linear relationship between torque yaw U_4 and angular velocity squared, yaw quadcopter Ω_{yaw}^2 :

$$U_4 = F_4.1 = d.\,\Omega_{yaw}^2 \tag{21}$$

Moment of inertia of quadcopter: A moment of inertia describes the dynamic behavior of an object when rotated about an axis. There are two kinds of inertia to be used in calculating the dynamics of quadrotor, i.e., rotational moment of inertia and inertia moment of body.

The first calculation aims to get a total rotational moment of inertia of the motor axis. This moment is composed of a rotational moment of inertia of the motor axis J_{M1} and rotational moment of inertia about the axis propeller J_{P1}. If the motor has a gear, the moment J_{M1} will consist of rotational moment of inertia J_{M0} and the rotational gear motors moment of inertia J_{GM}. These two components are considered to be a solid cylinder, if m_{MO}, m_{GM}, R_{MO} and R_{GM} is the mass and radius of the motors and gear motors, the rotational moment of inertia (Fig. 11 and 12):

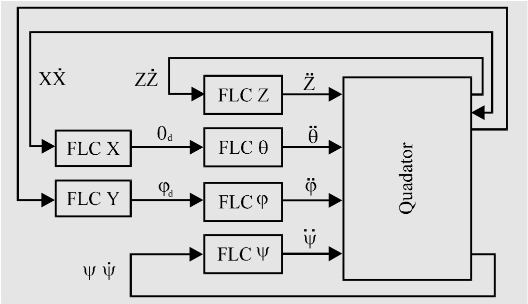


Fig. 11: Diagram block of control system

Fig. 12: Quadcopter and RC 9 channel (Syam, 2015)

$$J_{MO} = \frac{1}{2} m_{MO} R_{MO}^2 \tag{22}$$

$$J_{GM} = \frac{1}{2} m_{GM} + R_{GM}^2 \tag{23}$$

$$J_{M1} = J_{MO} + J_{GM} \tag{24}$$

If the propeller has gears then moments J_{P1} will consist of a propeller rotational moment of inertia J_{P0} (without gear) and rotational moment of inertia of the propeller gear J_{GP}. Propellers regarded as a plate while the gears are considered as a cylinder. If the m_{PO}, W_{PO} and L_{PO} is the mass, width and length of the propeller and the m_{GP} and the R_{GP} are the mass and radius of the propeller gear, respectively can be written as:

$$J_{PO} = \frac{1}{12} m_{PO}(W_{PO}^2 + L_{PO}^2) \tag{25}$$

$$J_{GP} = \frac{1}{2} m_{GP} R_{GP}^2 \tag{26}$$

$$J_{P1} = J_{PO} + J_{GP} \tag{27}$$

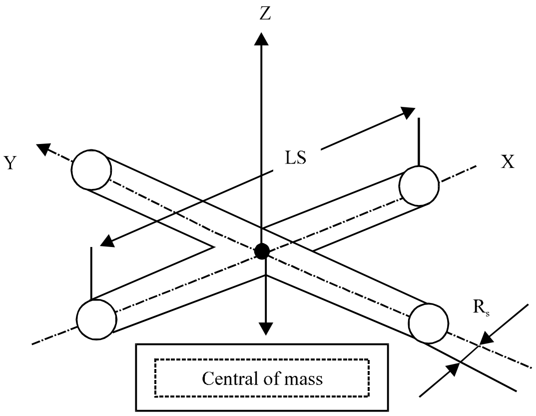


Fig. 13: Components of cross structure

If η and N are the efficiency of the gear box and the ratio of the reduction gear box, so that:

$$J_{TM} = J_{M1} + \frac{J_{p1}}{\eta N^2} \tag{28}$$

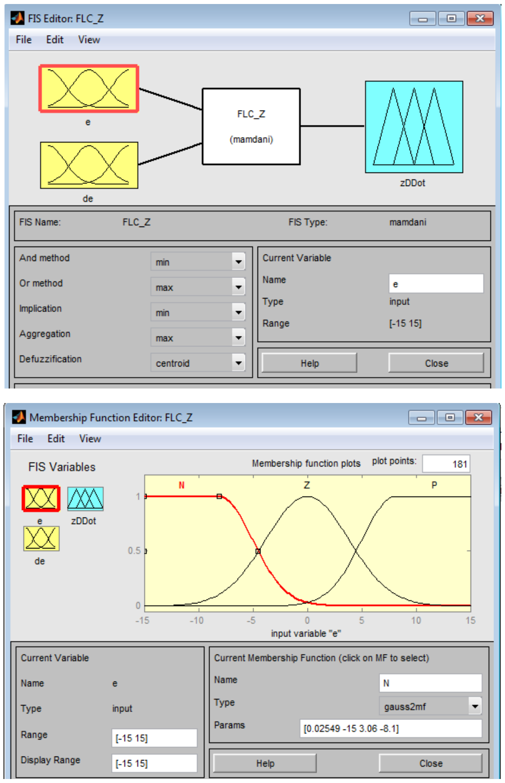
$$J_{TP} = J_{P1} + \eta N^2 J_{M1} \tag{29}$$

In the calculation of the inertia moment of body aims to identify the dynamic behavior of the overall quadcopter rotation about the axis defined. Because of its structure, the symmetry of the inertia moment of tensor can be reduced to a diagonal matrix. The moment of inertia tensor is a way to conclude all the moments of inertia of an object in one price. If I_{xx} [N m s^2] denotes the moment of inertia about the axis-x when an object rotates on the x-axis as well as I_{yy} and I_{zz} accordance with their respective rotational axis, then:

$$I = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} \tag{30}$$

To determine the moment of inertia of a motor and propeller on quadcopter then the shape can be simplified as a cylinder. The following will explain the moment of inertia of the components quadcopter (Fig. 13).

Fuzzy logic control sytem: Study on fuzzy logic control can be found at (Syam and Fuzzy, 2015), it describes simple application for FLC method. When using the RC device for controlling the motion shows in Fig. 14. Otherwise, the quadcopter motion system can be shown



FIS Name: FLC_Z
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: e
Type: input
Range: [-15 15]

plot points: 181
Current Variable
Name: e
Type: input
Range: [-15 15]
Display Range: [-15 15]
Current Membership Function (click on MF to select)
Name: N
Type: gauss2mf
Params: [0.02549 -15 3.06 -8.1]

Fig. 14: Membership function of input and output of z-axis and error positions

that the rotational motion is not affected by the translation movement. Quadcopter motion as subsystems can be controlled independently of the subsystem translation. The output of the angular subsystem will be input to the system together with the input control. Angular stabilization subsystem will be obtained by using FLC. Height control will be obtained by using an FLC. The X and Y motion of quadrotor will be controlled by the angle θ and Ψ. This angle changes will increase for the total lifting force of the components X and Y.

Control system of FLC for controlling altitude axis-Z Z of quadcopter. The method of control systems FLC θ, FLC Ψ and φ is used to control the angle as reference angle. FLC X and FLC Y control the direction of X and Y movement through the angle θ and Ψ, see Fig, 11. Still in that Figure that is two input controllers are error e and $\dot{e}$ and one output. The addition of the rules will increase the calculation time.

The research method is experimental work and simulation with Matlab software in a computer. First of all do the selection of components that fit the needs of a quadcopter. Furthermore, calculation of the statics of the quadcopter that analyzes the influence of the size, mass and laying of the moment of inertia of the aircraft. Then testing factors pushing force and air drag factor. After that is done planning fuzzy logic control which will regulate the movement of aircraft theoretically. The process is continued with the dynamics and kinematics calculations plane. If theoretically already considered good planning is carried out assembly and testing aircraft. Based on the data of statics, dynamics and kinematics calculations made simulated theoretical plane. Experimental test generates GPS data showing the actual position of the aircraft, based on these data is analyzed.

RESULTS AND DISCUSSION

In a design prototype quadrotor, value moment of inertia, thrust factors and drag factors is important to decide because it is required in the calculation of force, torque and acceleration of the plane, Eq. 18. Selection of the components are made in the design will determine the value of these magnitudes. Below is shown an example of the calculation of the moment of inertia, thrust factors and drag factors based selection of materials, mass, the size and layout of the components that have been designed in a quadcopter as unmanned aircraft. Calculation results obtained will be used in the simulation of aircraft movement quadcopter controlled by fuzzy logic controller.

Calculation of inertia moment of body: If m_S(kg) mass of cross structure, W_S(m) wide cross-section, H_S(m) sectional height and L_S (m) length of cross structure, then moment of inertia of cross structure component against to frame x, y and z:

$$I_{sx} = m_s\left(\frac{w_s^2}{12} + \frac{H_s^2}{12}\right) \tag{31}$$

$$I_{sy} = m_s\left(\frac{L_s^2}{12} + \frac{H_s^2}{12}\right) \tag{32}$$

$$I_{sz} = m_s\left(\frac{L_S^2}{12} + \frac{W_S^2}{12}\right) \tag{33}$$

Model of cross structures from two thin cylinders solid united in the center and a cross formation. The moment of inertia I_s (N m sec^2) structural components cross the x-axis, y and z, using (Eq. 33) and parameter at (Syam, 2015) s obtained as $I_{sx} = 8,7843.\ 10^{-6}$, $I_{sy} = 8,7843.\ 10^{-3}$ and $I_{sx} = 8,7843.\ 10^{-3}$ N m sec^{-1}.

Table 1: Rule base of FLC

Ede	P	Z	N
P	P	P	Z
Z	P	Z	N
N	Z	N	N

Calculation of moment of inertia of the rotational axis of the propeller: Rotational moment of inertia, J_{TP} [Nms^2] is the moment of inertia generated by the rotating parts, namely the propeller and the motor rotor to the axis of the propeller. This moment of inertia will generate gyroscopic torque which will affect air acceleration (Scmidth *et al*., 2011).

For the calculation of rotational inertia, the propeller is modeled as a thin beam, the propeller rotational moment of inertia against to the axis propeller:

$$J_P = \frac{1}{2} m_P (L_P^2 + W_P^2) \tag{34}$$

Rotational moment of inertia of the motor rotor to the axis of the motor:

$$J_M = \frac{1}{2} m_{RM} R_{RM}^2 \tag{35}$$

Rotational moment of inertia of the motor rotor and propeller on the propeller axis:

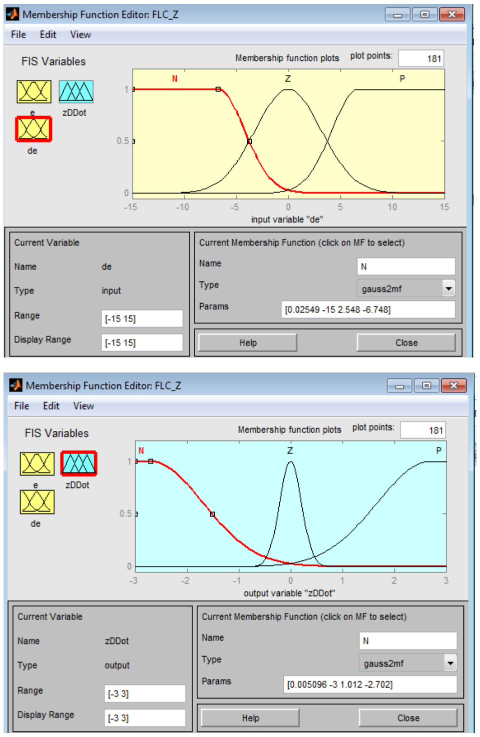
$$J_{TP} = J_M + J_P \tag{36}$$

Using Eq. 35 and 36 and parameter at (Syam, 2015), the calculation result of rotational inertia of the propeller can be written as $J_P = 0.857.10^{-3}$, $J_M = 0.0174.10^{-3}$ and $J_{TP} = 0.1031.10^{-3}$ N m sec^2. Where, Drag factors $d = 3.4431\times10^{-6}$ and Thrust Factor $b = 72{,}0811.10^{-6}$.

Trajectory simulation of quadcopter: In these simulations for flight trajectories are using Matlab software. The data input to the program using the results of measurement and calculation of the previous section. The program consists of Fuzzy Logic Control program and aircraft trajectory simulation program.

FLC program to control the acceleration $\ddot{X}$ of quadcopter accordance to the given input position, there is the difference e and the difference in speed de. An Output acceleration obtained will be used to calculate the force and torque ($U_{1\text{-}4}$).

FLC Z is used to control altitude of quadcopter. FLC for θ, Ψ and φ are used to control the angles of a plane. FLC X and Y are used to control the direction of X and Y through angles θ and Ψ. FLC configuration is follow for nine rules listed in Table 1. The addition of the rules will increase the calculation time. There are two control inputs, the position error e and its derivative.



plot points: 181

Current Variable

Name: de

Type: input

Range: [-15 15]

Display Range: [-15 15]

Current Membership Function (click on MF to select)

Name: N

Type: gauss2mf

Params: [0.02549 -15 2.548 -6.748]

plot points: 181

Current Variable

Name: zDDot

Type: output

Range: [-3 3]

Display Range: [-3 3]

Current Membership Function (click on MF to select)

Name: N

Type: gauss2mf

Params: [0.005096 -3 1.012 -2.702]

Fig. 15: Membership function of input and ouput

Mamdani type is used in this control system, by max-min composition and using center of gravity deffuzification. Furthermore, two types of membership function they are gussian function type 1 and Gaussian function type 2. By using fuzzy toolbox of Matlab can be determined the relationship between the input e, de and the output. For example, the input and output variables as well as the FLC control membership function Z (Z-axis direction of the movement) is shown in Fig. 14-15.

Data on calculations e, $\dot{e}$ and $\ddot{z}$ can be seen at Fig. 14-16. Based on the calculation and graphical display on trajectory simulation, showed that the acceleration $\ddot{X}$ generated from fuzzy control is not constant but varied to adjust the position difference e and the difference in the speed of the aircraft de reference position X_d and speed reference $\dot{x}_d$.

The program displays the motion of experimental and simulations using matlab software. Movement as a theoretical approach that resembles the actual movement obtained from the formula statics, dynamics, kinematics and fuzzy logic control. Movement in the x-axis direction is limited to a distance of 5 m. The movement in the y-axis direction is limited within 4.5 m. The movement in the z-axis direction is maintained at a height of 5 m, Fig. 16-19.

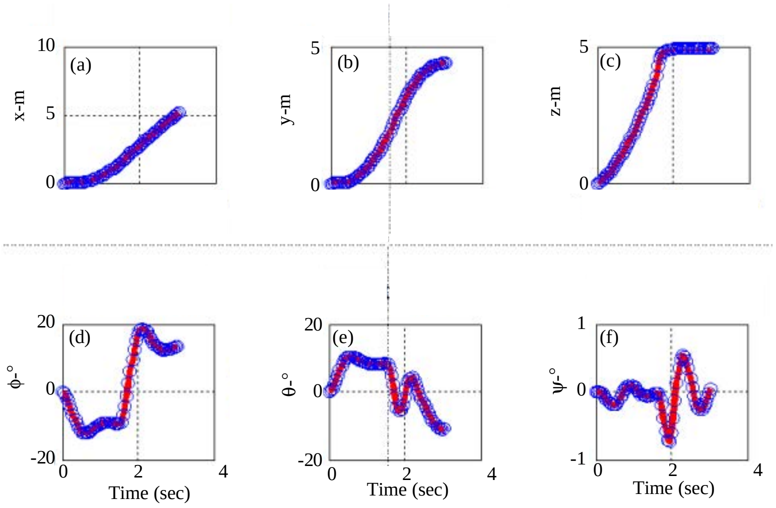


Fig. 16: Experimental and Simulation of Distance, x (m) Time (sec): a) Vertical transaction; b) Translation B-F; c) Translation L-R; d) Rotation L-R; e) Rotation B-F; f) Roatation B_{jj}-S_{jj}

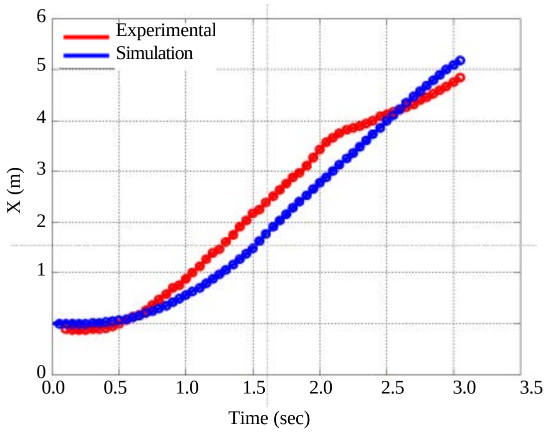


Fig. 17: Graphics distance, x (m) and time, t (sec), simulation and experimental

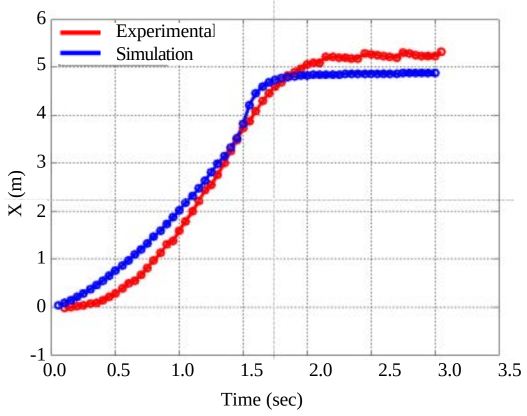


Fig. 18: Graphics distance, y (m) and time, t (sec), simulation and experimental

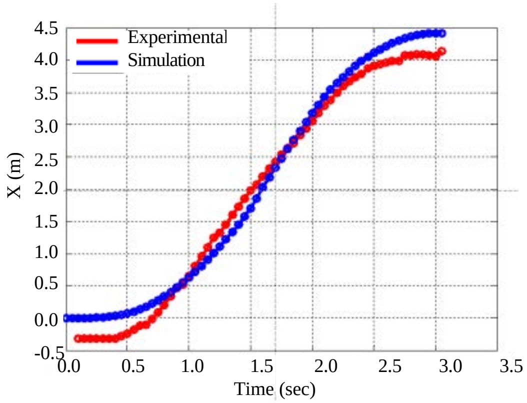


Fig. 19: Graphics distance, z (m) and time, t (sec), simulation and experimental

CONCLUSION

Base on the result and discussion can be concluded as follows: moment of inertia caused by aircraft show that the Izz>Iyy>Ixx so that the angular acceleration of quadcopter will be inversely proportional to that p>q>r or in other words the required acceleration r (yaw) are great to produce the same angle movement.

Acceleration acting on the aircraft is large enough that = 1,7509 msec^{-2}, =2,0377 m sec^{-2}dan = 1,6371 m s^{-2} mileage for each is x = 0,5565 m, y = 0,6307 m and z = 1,9700 m. Thereby indicating that the aircraft is quite agile in maneuvering

Simulation of aircraft movements showed that the maximum error value (error value) between theoretical and actual movement is ex = 0.683 m; ey = ez = 0.353 m and

0.546 m. Theoretical of Quadcopter pattern of movement and variable of the error value are influenced by membership function of the fuzzy logic control design. A theoretical movement pattern already resembles the actual movement

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