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Sensor Fusion for Attitude Estimation and PID Control of Quadrotor UAV

Aminurrashid Noordin, Mohd Ariffanan Mohd Basri, and Zaharuddin Mohamed
Universiti Teknologi Malaysia, Skudai, Malaysia
Email: aminurrashid@utem.edu.my; {ariffanan; zahar}@fke.utm.my

***Abstract*—This paper presents sensor fusion algorithm using nonlinear complementary filter (NCF) for attitude estimation and a proportional-integral-derivative (PID) controller for small-scale quadrotor unmanned aerial vehicle (UAV) stabilization. From inertial measurement unit (IMU) data, gyroscope as a main sensor is fused to another two sensors; accelerometer and magnetometer to correct drift error of gyroscope to obtain reliable attitude estimation. In this paper, the performance of NCF is implemented on real-time while applying PID controller for attitude stabilization of quadrotor UAV during hovering. Experimental results show the effectiveness of PID controller for quadrotor UAV stabilization during attitude control .**

***Index Terms*—nonlinear complementary filter, quadrotor, PID, UAV.**

I. INTRODUCTION

Microelectromechanical systems (MEMS) is a combination of mechanical and electrical components into microscale objects. In advanced of MEMS technology, components being small size, less expensive, and low power consumption, sensors such as inertial measurement unit (IMU) are redesigned to include onto devices such as smartphone, automotive industries and others application.[1]-[4].

In robotics, IMU is the main of attitude and heading reference system (AHRS) to determine rotation, motion, location and direction (generally called attitude estimation) of mobile robots for automated navigation, autonomous underwater vehicle (AUV) for global localization systems and unmanned aerial vehicle (UAV) in aviation [1], [4]-[6]. Hence, research community and DIY hobbyist take this opportunity, utilizes small scale IMU and focus on development of unmanned aerial vehicles (UAV) which is very promising vehicle for navigations, surveillances, and as well as educational purposes [7]-[10].

However, IMU sensor performance is commonly effected by biases and noises which tend to drift over time for especially gyroscope and reduce the accuracy of measurement. Therefore, most researcher applied sensor fusion algorithms techniques to overcome the measurement errors and obtaining accurate reading [1], [4], [5], [11].

Quadrotor UAV is an aerial vehicle that has capabilities in vertical take-off and landing (VTOL), omni-directional flying, and easy hovering performances in limited spaces and always being considered in research due to the simplest electronics and mechanical structures design. However, quadrotor UAV is an under-actuated and dynamically unstable system which possess with complex behaviours. Many presented work in literatures use '+' configuration and simplified model, where non-linear effect is neglected. Several literatures have mentioned of proportional-integral-derivative (PID) control a quadrotor [12]-[15] but using linearize model.

Thispaper focus on low cost IMU fusion using nonlinear complementary filter for attitude estimation of quadrotor UAV and PID controller for highly nonlinear quadrotor UAV. The system comprises of quadrotor F450 frame (x configuration model), and APM2.6 flight controller with built in IMU (MPU6000) and external HMC5833L compass sensor. Data from low frequencies parts of accelerometer and magnetometer are fused to the high frequency part of the gyroscope signal. Drift error by the main source (gyroscope) is corrected by accelerometer and magnetometer. A PID controller is used for attitude stabilization during quadrotor hovering. A flipped test is conducted to observed quadrotor performance during initial start on a rotating test-bed fixed on one axis to ensure its stabilization before free test on 3dof experimental platform with k_p, k_i, and k_d parameter setting.

This paper is structured as follows. Section II briefly described the nonlinear quadrotor UAV modelling in Newton-Euler formulation. Section III explained regarding sensors used in IMU such as gyroscope, accelerometer and magnetometer. Section IV mentioned sensor fusion algorithm technique used in this research. Section V shows the PID controller design method for attitude stabilization of quadrotor UAV. Section VI gives the experiments results and conclusions are stated in Section VII.

II. QUADROTOR MODEL

Quadrotor UAV is a type of helicopter that can be controlled by varying the rotor speeds. It is an under-actuated, dynamic vehicle with four input forces and six output coordinates. Quadrotor UAV composed of four rotors with symmetrically arrangement where two

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diagonal motors (1 and 2) are running in the same direction whereas the others (3 and 4) in the other direction to eliminate the anti-torque [10], [14], [16].

Quadrotor UAV have been designed with symmetrically structure in either ‘x’ mode configuration or ‘+’ mode configuration. This research used ‘x’ mode configuration quadrotor as illustrated in Fig. 1, where the coordinate systems of two reference frames describe the dynamics of a quadrotor; an earth fixed initial reference frame, {E} and a body fixed reference frame {Q} located at the center of gravity (COG) of quadrotor body frame which is a rigid body in free motion with six Degree of Freedom (DOF) consist of three translational and three rotational.

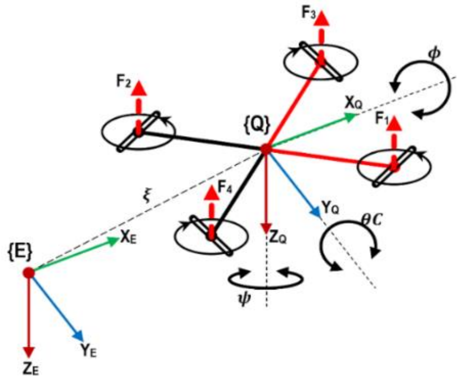


Figure 1. Inertial coordinate systems and body-fixed frame for x configuration quadrotor

For the modelling, the following assumption is defined for simplification [17]:

1. The quadcopter is assumed as a rigid body.
2. The quadcopter’s structure is assumed as symmetric with respect to the XY-axis.
3. The centre of mass and the origin of the body fixed frame are coinciding.
4. The propellers are considered as rigid; no blade flapping occurs.
5. The four propellers work under the same conditions at any time, meaning that thrust coefficient, and reaction torque coefficient, are the same for all propellers.

The generalized coordinates for the quadrotor based on Fig. 1 can be described as follow:

$$\xi = [x, y, z]^T \in \mathbb{R}^3, \quad \eta = [\phi, \theta, \psi]^T \in \mathbb{R}^3 \tag{1}$$

whereas, in (1) vector ξ, denotes the position of the quadrotor relative to inertial frame, vector η, denotes the attitude of the quadrotor. The relation of body fixed reference frame, {Q} respect to earth fixed initial reference frame, {E} satisfy as $\{Q\}^T = R_T \times \{E\}^T$. Equation (2) defines the rotation matrix R_T, where, S and C stands for trigonometric operators ‘sin’ and ‘cos’ respectively.

$$R_T = \begin{bmatrix} C\psi C\theta & -S\psi C\phi + C\psi S\theta S\phi & S\psi S\phi + C\psi C\phi S\theta \\ S\psi C\theta & C\psi C\phi + S\psi S\theta S\phi & -C\psi S\phi + C\phi S\psi S\theta \\ -S\theta & C\theta S\phi & C\theta C\phi \end{bmatrix} \tag{2}$$

From general Newton-Euler translational and rotational dynamics, the quadrotor dynamics, is described as (3) and (4) respectively, where, g is gravitational coefficient, E_z is vector matrix of z-axis defined as $[0\ 0\ 1]^T$, U_1 is total thrust force generated by four rotors. I is the moments of inertia for the quadrotor, a diagonal matrix 3-by-3 and defined as $I = \text{diagonal}\left[I_{xx} I_{yy} I_{zz}\right]^T$. J_r is rotor inertia, $\Omega_d$is total rotor speeds generated from the two pairs of rotor. U_2, U_3 and $U_4$are total torque, τrelated to quadrotor as of total summation of Coriolis torque, τ_c, and Gyroscopic torque, τ_g and quadrotor body frame torque, τ_a.

$$m\ddot{\xi} = mgE_z + U_1 R_T E_z \tag{3}$$

$$I\ddot{\eta} = -\eta \times I\eta - J_r(\eta \times E_z)\Omega_d + [U_2 U_3 U_4]^T \tag{4}$$

Finally, from (3) and (4), the final equation for quadrotor translation dynamics and rotational dynamics can be formulated as

$$m\ddot{x} = U_1(S\psi S\phi + C\psi S\theta C\phi)$$
$$m\ddot{y} = U_1(-C\psi S\phi + S\psi S\theta C\phi)$$
$$m\ddot{z} = mg + U_1(C\theta C\phi) \tag{5}$$

$$I_{xx}\ddot{\phi} = \left(I_{yy} - I_{zz}\right)\dot{\psi}\dot{\theta} - (J_r\Omega_d)\dot{\theta} + lU_2$$
$$I_{yy}\ddot{\theta} = (I_{zz} - I_{xx})\dot{\psi}\dot{\phi} + (J_r\Omega_d)\dot{\phi} + lU_3$$
$$I_{zz}\ddot{\psi} = \left(I_{xx} - I_{yy}\right)\dot{\theta}\dot{\phi} + U_4 \tag{6}$$

III. INERTIAL MEASUREMENT UNIT

With advanced in MEMS, 3-axis gyroscopes are often implemented with a 3-axis accelerometer to provide a full 6 degree-of-freedom (DOF) motion tracking system for many applications such unmanned aerial vehicles (UAV), mobile robot and smartphone. With 3-axis digital compass additional of 3-DOF can assist on a heading for a system for correct orientation during locomotion. Fig. 2 shows 6-DOF MPU6000 comprise of gyro and accelerometer. 3-axis compass can be attached as auxiliary sensor for attitude estimator system such used in APM2.6.

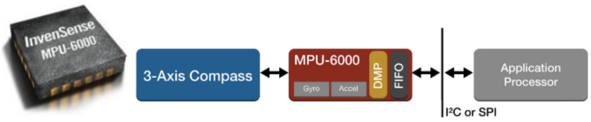


Figure 2. A 6-DOF – Gyro/Accelerometer

A. *Gyroscope*

A gyroscope is a device typically used for navigation by measurement of angular velocity and estimated changing in orientation [18]. However, for a long term, Gyroscope reading tend to drift from static condition. Gyroscopes can measure rotational velocity up to three directions. In IMU, a gyroscope or gyros sensor as shown in Fig. 3 is used to detect rotation speed to measure angular velocity or in other term called angular rate with measurement unit degree per second (°/s) or revolution per second (RPS).

Figure 3. A 3-Axis Gyro Sensor (Source: Adafruit Industries, 2017)

By integrating the angular rate (reading from sensor) of each axis, the roll angle (ϕ), the pitch angle (θ), and the yaw angle (ψ) can be obtained using (7) as follow

$$\phi = \int \omega_x \, dt$$

$$\theta = \int \omega_y \, dt$$

$$\psi = \int \omega_z \, dt \tag{7}$$

Standard control range of angle in aviation system is between −180 to 180 degrees. Therefore, result from (7) need to be adjusted within this range.

B. Accelerometer

An accelerometer sensor as shown in Fig. 4 is a dynamic MEMs sensor used to measure acceleration forces up to three orthogonal axes. Measurement unit of accelerometer typically in gravitational motion (g) where 1g is equivalent to 9.8m/s2 which is acceleration cause of earth gravity. However, for linear displacement measurement, recorded data need to be integrated two times which tend to drift over a time and very sensitive to environmental noise [3], [19].

In other way, from an accelerometer, a tilt angle can be sense and estimate as described on Freescale Semiconductor Application Note used by [20].

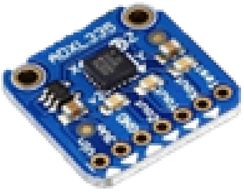
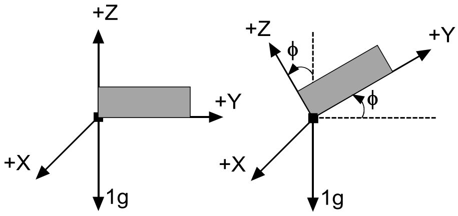
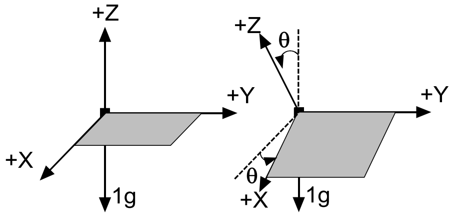


Figure 4. A 3-Axis Accelerometer Sensor (Source: Adafruit Industries, 2017)



(a) Rotate about *x*-axis



(b) Rotate about *y*-axis

Figure 5. Three Axes tilt sensing for (a) Roll angle and (b) Pitch angle

For three axes rotation, the same concept is applied as shown in Fig. 5 where roll angle (ϕ) and pitch angle (θ) can be computed as (8) and (9) respectively. The rotation follows typical right-hand rules law:

$$\phi = \tan^{-1}\left(A_y / \sqrt{A_x^2 + A_z^2}\right) \tag{8}$$

$$\theta = \tan^{-1}\left(A_x / \sqrt{A_y^2 + A_z^2}\right) \tag{9}$$

C. Magnetometer

A magnetometer as shown in Fig. 6 can sense where the strongest magnetic force is coming from, generally used to detect magnetic north. Therefore, as for digital compass, magnetometer sensor is used to provide heading information where the heading system calculation depending to magnetic data (*X*, *Y*, *Z*) therefore the compass orientation can be mathematically rotated to horizontal plane as show in Fig. 7. Based on this figure, *X*, *Y*, and *Z* from magnetic sensor reading can be transformed to the horizontal plane (X_h, Y_h) by applying the rotation as (10) with aided from tilt sensing roll (ϕ) and pitch (θ) from an accelerometer sensor. As such it is useful to determine absolute orientation in the NEWS plane of any systems during navigation [20].

$$X_h = m_x \cos(\phi) + m_y \sin(\phi) - m_z \cos(\theta) \sin(\phi)$$

$$Y_h = m_y \cos(\theta) + m_z \sin(\theta) \tag{10}$$

From (10) then, the heading information can be calculated as

$$\text{Heading} = \psi_h = \text{atan2}\left(\frac{Y_h}{X_h}\right) \tag{11}$$

Figure 6. A 3-Axis Magnetometer Sensor (Source: Adafruit Industries, 2017)

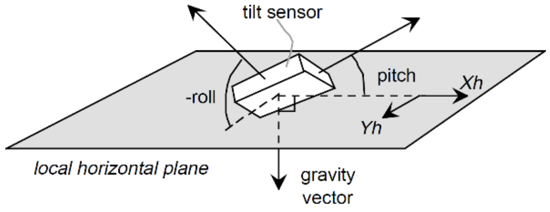


Figure 7. Tilt sensing angle in local horizontal plane defined by gravity (Caruso, 2000)

IV. SENSOR FUSION ALGORITHM

Based on [20] and [21], in this sensor fusion, gyroscope signal is used as references for orientation of the UAV to update the direct cosine matrix (DCM). Accelerometer and magnetometer are used to correct drift error from gyroscope and heading error. A feedback proportional integral (PI) controller is used to eliminate the steady state error in this system.

DCM for rigid body frame respect to earth frame expressed in Euler angles is described as (3). For small angle rotation, $S\phi \rightarrow \phi, S\theta \rightarrow \theta, S\psi \rightarrow \psi$ and the cosines of these angles approach unity. By neglecting the products of the angles because become small, the DCM can be simplified to the skew symmetric form shown as below:

$$R_B^E \approx \begin{bmatrix} 1 & -\psi & \theta \\ \psi & 1 & -\phi \\ -\theta & \phi & 1 \end{bmatrix} \tag{12}$$

In kinematics, the rate of change in rotating vector gives by

$$\frac{dr(t)}{dt} = w(t) \times r(t) \tag{13}$$

where $w(t)$ is angular rate vector and r(t) is rotating vector with same reference frame. By assuming signals of gyroscope not affected by drift, the matrix to update DCM from gyroscope signals can be described as

$$R(t + dt) \approx R(t) \begin{bmatrix} 1 & -d\psi & d\theta \\ d\psi & 1 & -d\phi \\ -d\theta & d\phi & 1 \end{bmatrix} \tag{14}$$

To maintain the orthogonality of rotating frame, renormalize is needed. The first step is to obtain the error that measures the rotation of X and Y toward each other by dot product

$$\mathrm{err} = X \cdot Y = X^T Y = [r_{xx} \quad r_{xy} \quad r_{xz}] \begin{bmatrix} r_{yx} \\ r_{yy} \\ r_{yz} \end{bmatrix} \tag{15}$$

Then the orthogonal value of X, Y and Z can be computed as

$$\begin{gathered} X_{orthogonal} = X - \frac{error}{2} Y \\ Y_{orthogonal} = Y - \frac{error}{2} X \\ Z_{orthogonal} = X_{orthogonal} \times Y_{orthogonal} \end{gathered} \tag{16}$$

The final step is to ensure magnitude of each row of R matrix is equal to one. This is done by scaling the row of the R matrix using Taylor's expansion as

$$\begin{aligned} X_{norm} &= \frac{1}{2}\left(3 - X_{orhtogonal} \cdot X_{orthogonal}\right) X_{orthogonal} \\ Y_{norm} &= \frac{1}{2}\left(3 - Y_{orhtogonal} \cdot Y_{orthogonal}\right) Y_{orthogonal} \\ Z_{norm} &= \frac{1}{2}\left(3 - Z_{orhtogonal} \cdot Z_{orthogonal}\right) Z_{orthogonal} \end{aligned} \tag{17}$$

The roll-pitch error is computed by taking the cross product of the reference measurement of gravity with the Z row of DCM and can be described by

$$e_{roll-pitch} = \left[r_{zx}\, r_{zy}\, r_{zz}\right]^T \times g_{ref} \tag{18}$$

The yaw error in the earth frame is the z component of the cross product of the Heading vector and the x column of the R matrix

$$e_{yaw(earth)} = r_{xx} Heading_y - r_{yy} Heading_x \tag{19}$$

Then, the yaw error in body frame can be computed as

$$e_{yaw} = e_{yaw(earth)} \begin{bmatrix} r_{zx} \\ r_{zy} \\ r_{zz} \end{bmatrix} \tag{20}$$

Finally, the total error vector can be written as

$$e_{total} = W_{rp} e_{roll-pitch} + W_Y e_{yaw} \tag{21}$$

V. PID CONTROL

Proportional Integral Derivative (PID) controller is a classical controller that have proven to be robust and tremendously beneficial in many linear or non-linear applications. The PID design are pointed out in many references, such as [13], [22]-[25]. The controller attempts to minimize the error over time by adjustment of a control variable $u(t)$. The mathematical representation of PID controller is given as

$$u(t) = k_p e(t) + k_i \int e(t) + k_d \frac{d}{dt} e(t) \tag{22}$$

where, $u(t)$ is the input signal and the error signal $e(t)$ is defined as

$$e(t) = desired\_input(t) - actual\_output(t) \tag{23}$$

On the other hand, a PID controller continuously calculates an error value $e(t)$ then applies a correction based on proportional, integral, and derivative terms as shown in Fig. 8.

The proposed controllers for attitude and altitude stabilization in this experiment are shown as Fig. 9, where a cascade PID is used. For attitude stabilization in the inner loop PID controller, angular rate $\dot{\phi}$, $\dot{\theta}$, $\dot{\psi}$ and velocity of $\dot{z}$ are used as references input and have its own gain. For altitude control in outer loop PID controller, desired z, ϕ, θ, and ψ is set as desired input/reference.

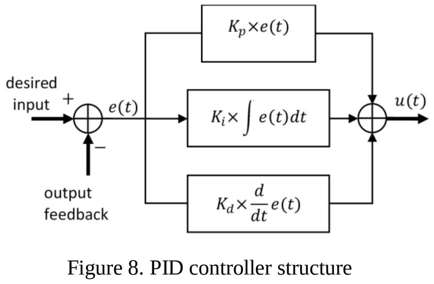


Figure 8. PID controller structure

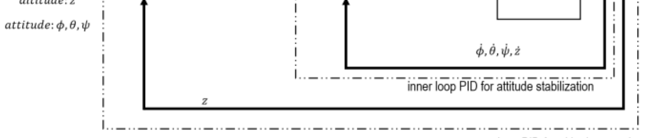


Figure 9. Cascade PID in nonlinear quadrotor's attitude stabilization and altitude control

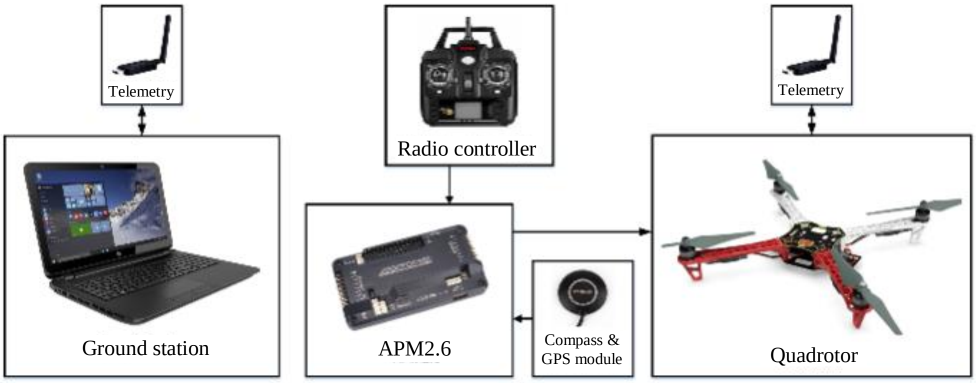
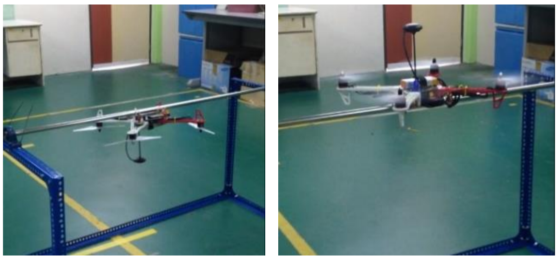


Figure 10. Avionics system for quadrotor



a) Initial condition b) On going experiment

Figure 11. Single axis platform for flipping

TABLE I. PID PARAMETERS FOR QUADROTOR UAV

	Angles	K_p	K_i	K_d
Stabilize	$\boldsymbol{\phi}$	5	0.003	0
	$\boldsymbol{\theta}$	5	0.003	0
	$\boldsymbol{\psi}$	7	0.02	0
Rate	$\dot{\boldsymbol{\phi}}$	0.2	0.004	0.003
	$\dot{\boldsymbol{\theta}}$	0.2	0.004	0.003
	$\dot{\boldsymbol{\psi}}$	0.13	0.02	0

VI. EXPERIMENTAL RESULTS

Fig. 10 shows flight control system for the quadrotor that used in this experiment consist of APM2.6 (based on Arduino MEGA) with built in IMU (accelerometer and gyroscope) and external compass with GPS module.

Several experiments have been conducted to test quadrotor UAV stabilization while tuning the PID parameters. For the first test, the quadrotor UAV is tied up on a single road testbed platform. Fig. 11 (a) and Fig. 11 (b) shows the quadrotor UAV condition tied up on the testbed before and during the experiment. In this experiment, the quadrotor UAV is only allowed to rotate on roll, ϕ angle. The PID parameters is tuned until the quadrotor UAV able to flip 180° and stabilized at 0°. The chosen PID parameter is stated on Table I.

Fig. 12 shows roll angle performance during flipping test. Initially, the quadrotor UAV is at 180° position and after the throttle is set about 50% of maximum speed, it immediately rotates to 0° in 1 to 2 seconds and try to be stabilized until at 13 seconds before the throttle is set to zero. Since quadrotor UAV still has momentum, it still rolling for a few second before stabilized until 26 seconds before the throttle once again is set about 50% of maximum speed. The quadrotor UAV once again able to be flipped from 180° to 0° and stabilized. It shows that with the chosen PID parameter, the quadrotor UAV able to maintain it stability during hovering.

Then the experiment continues with 3dof testbed platform as shows in Fig. 13. Here, the quadrotor UAV being test to response on roll, pitch and yaw angle input from radio controller.

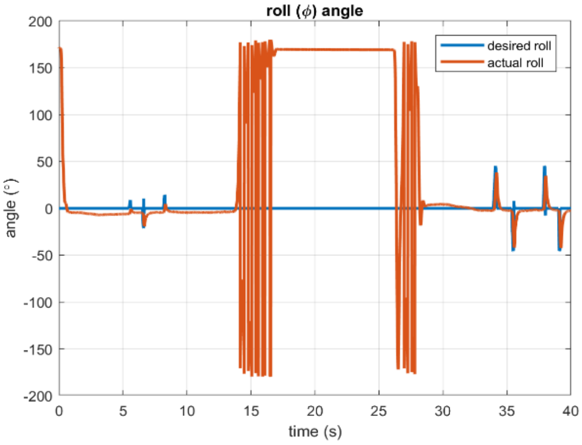


Figure 12. Roll, ϕ angle performance during flipping test

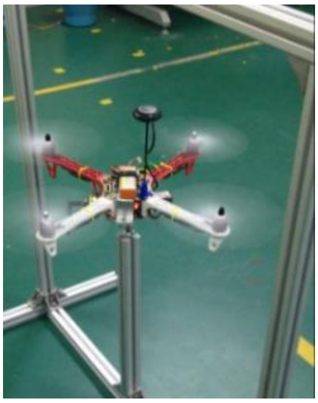


Figure 13. 3dof experimental platform

Fig. 14, Fig. 15 and Fig. 16 show roll, pitch and yaw response to the input from radio controller respectively. During this experiment, the throttle is set about 50% of maximum input. The roll and pitch from radio controller are push right and left, upward and backward respectively to see quadrotor UAV response for stabilization during hovering.

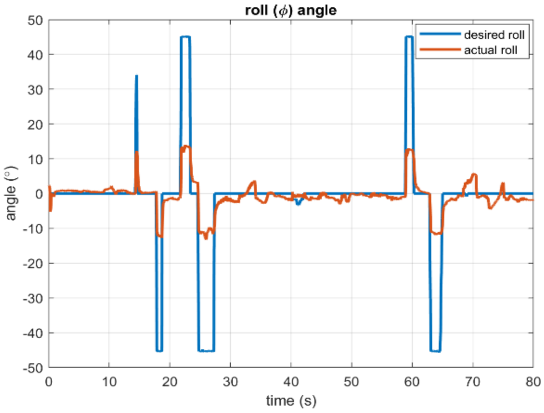


Figure 14. Roll angle response

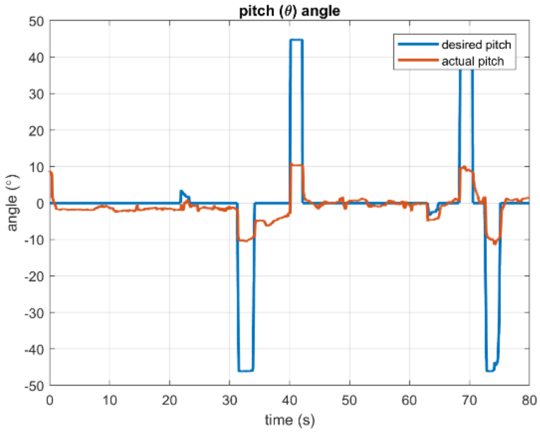


Figure 15. Pitch angle response

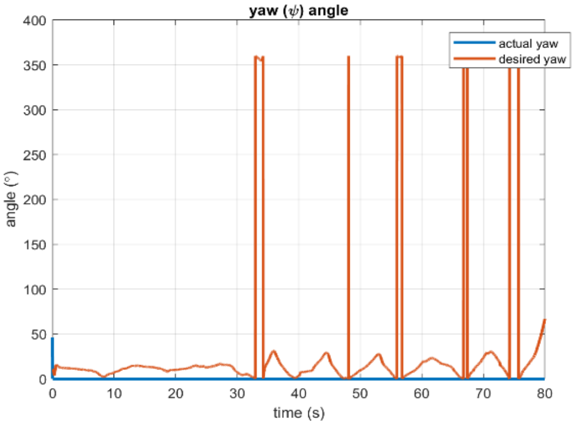


Figure 16. Yaw angle response

As shown in Fig. 14, at 30 seconds, the quadrotor UAV try to stabilize at zero (0) degree after being push to right and left. The positive and negative spikes show the quadrotor UAV angle response to the radio controller input from roll. Similarly, as shown in Fig. 15, where at 50 seconds, the quadrotor UAV try to stabilize at zero (0) degree after being upward and backward. The positive and negative spikes show the quadrotor UAV angle response to the radio controller input from pitch.

Fig. 16 shows a response from yaw direction where the quadrotor UAV able to rotate right and left between zero (0) to 360-degree angle response to the radio controller input from yaw.

VII. Conclusions

This paper has presented a sensor fusion based on nonlinear complementary filter algorithm and PID controller design for the quadrotor UAV for attitude estimation and stabilization during hovering. The sensor fusion algorithm used gyroscope data (high frequency part) as the main source and the drift corrected by accelerometer and magnetometer data (low frequencies part).The proposed PID controller is designed based on the cascade control approach where, for attitude stabilization in the inner loop PID controller, angular rate $\dot{\phi}$, $\dot{\theta}$, $\dot{\psi}$ and velocity of $\dot{z}$ are used as references input and have its own gain. For altitude control in outer loop PID controller, desired z, ϕ, θ, and ψ is set as desired input/reference. Two experiments have been conducted for flipped and attitude stabilization. PID parameters is tuned to ensure the quadrotor UAV able to flip and stabilize from 180-degree initial position for roll axis. Then the quadrotor was tested on 3dof experimental platform for attitude stabilization respond to input from radio controller. Experimental results demonstrated the effectiveness of the proposed approach throughout the test.

Further research needs to be done to extend the results shown in the present paper with input disturbance such as wind while outdoor flight test. Different type of controller can be further investigated to improve system performances.

Acknowledgment

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Aminurrashid Noordin received the B.Eng. and the M.Eng. Degree in Mechatronics Engineering from Universiti Teknologi Malaysia in 2002 and 2009 respectively, where he is currently working toward the Ph.D. in the Department of Control and Mechatronics Engineering of Universiti Teknologi Malaysia (UTM). Since 2011, he has been with Department of Electrical Engineering Technology, Faculty of Engineering Technology of Universiti Teknikal Malaysia Melaka where he is currently a Lecturer. His research interests include Nonlinear Control System, Robotics and Embedded System.

Mohd Ariffanan Mod Basri received the B.Eng. and the M.Eng. Degree in Mechatronics Engineering from Universiti Teknologi Malaysia in 2004 and 2009 respectively. He also received the Ph.D. in Electrical Engineering from Universiti Teknologi Malaysia in 2015. He is currently a Senior Lecturer in Department of Control and Mechatronics Engineering of Universiti Teknologi Malaysia. His research interests include intelligent and Nonlinear Control Systems.

Zaharuddin Mohamed received his B.Eng in Electrical, Electronics and Systems from Universiti Kebangsaan Malaysia (UKM) in 1993, M.Sc. in Control Systems Engineering from The University of Sheffield in 1995 and Ph.D. in Control Systems Engineering from The University of Sheffield in 2003. Currently, he is an Associate Professor in Department of Control and Mechatronics Engineering of Universiti Teknologi Malaysia (UTM) and his current research interest involve the control of Mechatronics systems, flexible and smart structures.