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Development of a Control System for Human Follower Quadcopter

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Abstract **– The purpose is to develop a control system in a quadcopter that has two modes of flying systems, firstly controlled by remote control and the other one automated quadcopter that can follow human movement. For the human following capability of the quadcopter, ultrasonic is used to help identify the human position and movement by knowing the distance between the quadcopter and the person with an ultrasonic Thus, in order to create a good performance in both modes, flight control is developed by using PID control system and Inertial Measurement Unit (IMU) sensor. The lift capabilities experiment results the relation between input PWM and the lift force of the motor RF module is used in the distance estimation process to synchronize the microcontroller's time in the human and quadcopter. Therefore, the human movement and human position can be estimated by using triangulation method.**

Keywords—Triangulation method, IMU Sensor, Human-following Quadcopter, PID controller, Ultrasonic sensor.

I. INTRODUCTION

Quadcopter has become one of the most interesting topics in the research and development of aerial robot. This is because there are still many opportunities to create new inventions that can be implemented on Quadcopter. In this research study the target is to develop a stable flight quadcopter that can follow a walking-speed human movement.

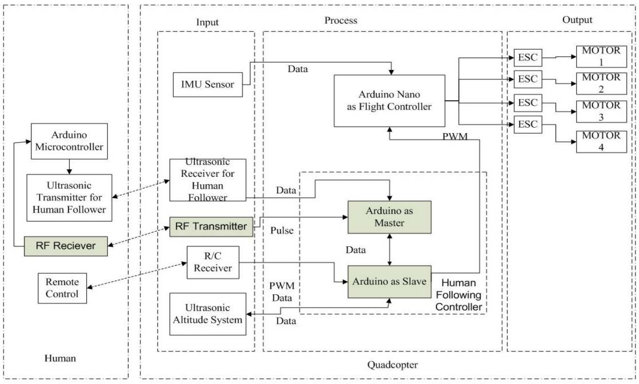

Fig. 1. System Overview of Human Following Quadcopter

The overall system block diagram shown in Fig. 1, it shows the system between the human and the quadcopter for human follower system. The human will bring a microcontroller to control the ultrasonic transmitter, which will give a signal burst to the ultrasonic receiver in the quadcopter. For estimating the distance between the ultrasonic receiver and transmitter, RF module receiver is installed to have communication to the microcontroller in quadcopter, while the remote control is also carried by the human.

II. MATHEMATICAL MODEL DERIVATION AND SIMULATION

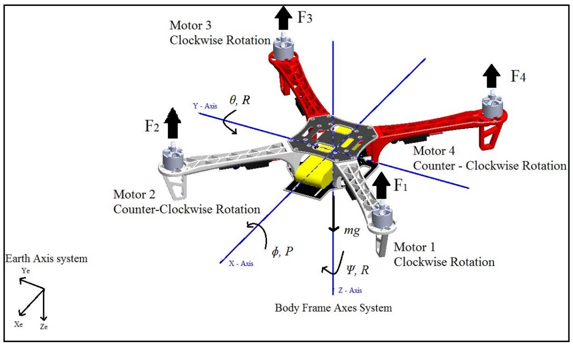

Fig. 2. The Force Diagram and the Configuration of Quadcopter

A mathematical model is developed to find and to simulate the behaviour of the system. Knowing the behaviour of the system can be used to obtain the appropriate control parameters of the system because quadcopter is moving in 3 dimensions and able to revolve around all three (3) axes.

Fig. 2 shows that the axes system is divided into two system earth axes system and body frame axes system. In the body frame axes system, there are several parameters that will be used for the mathematical calculation. The force of $\mathbf{F_1}$, $\mathbf{F_2}$, $\mathbf{F_3}$ and $\mathbf{F_4}$ represent the thrust produced by the motors while ***mg*** represents the gravitational effect on the quadcopter. The orientation angle of this quadcopter is based on the Euler angle ϕ, θ, ψ which represent rotation angle, **while P, Q, R** represent the rotation angle rate in the x-axis, y-axis and z-axis.

From the explanation of the theoretical of Euler rotational angle, matrix of **D** can be obtained from the direction cosine matrix of rotation in the $z \rightarrow y \rightarrow x$ axes. The **D** matrix as it is shown in equation 1, describes the transformation from earth-fixed coordinates to body-fixed coordinates.

$$\boldsymbol{D} = \begin{bmatrix} \cos\theta\cos\Psi & \cos\theta\sin\Psi & -\sin\theta \\ \sin\phi\sin\theta\cos\Psi - \cos\phi\sin\Psi & \sin\phi\sin\theta\sin\Psi + \cos\Psi\cos\phi & \sin\phi\cos\theta \\ \cos\phi\sin\theta\cos\Psi + \sin\phi\sin\Psi & \cos\phi\sin\theta\sin\Psi - \sin\phi\cos\Psi & \cos\phi\cos\theta \end{bmatrix} \quad (1)$$

A. Linear Motion

The linear acceleration of the quadcopter can be obtained by using Newton's Second Law with a result in an earth axes system.

$$\sum F = F\_translation + F\_Centrifugal \quad (2)$$

$$\sum F = m \,.\, \dot{v} \quad (3)$$

$$\sum F = m\frac{d}{dt}(V_T)_{body\,frame} + m.\omega \cdot V_T \quad (4)$$

In the body fixed frame ***U, V** and **W*** variables are used to represent the speed while $\dot{u}$, $\dot{v}$ and $\dot{w}$ are used to represent acceleration in the x-axis, y-axis and z-axis. Forces in the quadcopter consist of $\Delta \boldsymbol{F_x}$, $\Delta \boldsymbol{F_y}$ and $\Delta \boldsymbol{F_z}$ which exist in the x-axis, y-axis and z-axis. All of the forces occur in the earth axes system. Therefore, the equation *5* is the result of substituting the speed and the acceleration in the body fixed axes to V_T and $\dot{V}_T$ while the all the force to the $\sum F$ in the *equation 4.*

$$\begin{bmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_z \end{bmatrix} = \begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix} + \begin{bmatrix} P \\ Q \\ R \end{bmatrix} \cdot \begin{bmatrix} U \\ V \\ W \end{bmatrix} \quad (5)$$

In the quadcopter the force of $\Delta \boldsymbol{F_x}$ is equal to $\boldsymbol{W_x}$, $\Delta \boldsymbol{F_y}$ is equal to $\boldsymbol{W_y}$ and $\Delta \boldsymbol{F_z}$ is equal to $\boldsymbol{W_z}$ - ***Lift.*** $\boldsymbol{W_x}$, $\boldsymbol{W_y}$ and $\boldsymbol{W_z}$ are all the weight forces which are generally represented in the earth axes system while lift force is the ability of the motor to counter the weight force so that the quadcopter can fly which is represented in body fixed axes system.

The conversion is done by multiplying matrix weight force with rotational matrix of ***D***, therefore the complete equation will be calculated all based on the body-fixed axes system as shown in equation 6.

$$D\begin{bmatrix} W_x \\ W_y \\ W_z \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix} = m.\left(\begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix} + \begin{bmatrix} WQ - VR \\ UR - WP \\ VP - UQ \end{bmatrix}\right) \quad (6)$$

Under the assumption that there is no weight produced in the x and y –axes but the actual weight of the quadcopter represent the weight force in the z-axis that can be seen in equation *7*.

$$\begin{bmatrix} 0 \\ 0 \\ m.g \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix} = m.\left(\begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix} + \begin{bmatrix} WQ - VR \\ UR - WP \\ VP - UQ \end{bmatrix}\right) \quad (7)$$

Equation 8 shows the result of the multiplication between the matrix ***D*** with the weight force.

$$\begin{bmatrix} m.g. - \sin\theta \\ m.g.\sin\phi\cos\theta \\ m.g.\cos\phi\cos\theta \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix} = m.\left(\begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix} + \begin{bmatrix} WQ - VR \\ UR - WP \\ VP - UQ \end{bmatrix}\right) \quad (8)$$

Equation 9 is derived by dividing the *equation 7* with the mass of m. Therefore, equation of acceleration in body fixed axis system can be obtained.

$$\begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix} = -\begin{bmatrix} WQ - VR \\ UR - WP \\ VP - UQ \end{bmatrix} + \begin{bmatrix} g. - \sin\theta \\ g.\sin\phi\cos\theta \\ g.\cos\phi\cos\theta \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ \frac{T}{m} \end{bmatrix} \quad (9)$$

B. Angular Motion

Angular momentum is characterized as rotational inertia of a rigid body in axes that may or may not pass through the object. Where $\boldsymbol{\omega}$ is rotational velocity change of the altitude and ***I*** is the moment of inertia of the quadcopter. The rigid body of quadcopter is symmetric about its xz and yz plane, and the principal axes coincide with the rotation axes, therefore the moment inertia of quadcopter can be described as equation 11.

$$\boldsymbol{H} = \boldsymbol{I} \,.\, \boldsymbol{\omega} \quad (10)$$

$$\boldsymbol{I} = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \quad (11)$$

The rotational moment equation of motion can expressed in the vector:

$$\boldsymbol{M} = \boldsymbol{I}.\dot{\omega} + \omega \times \mathbf{I}.\omega \quad (12)$$

The angular velocity of ω in x-axis, y-axis and z-axis is symbolized as *P, Q and R* while the angular acceleration of $\dot{\omega}$ is symbolized as $\dot{P}$, $\dot{Q}$ *and* $\dot{R}$. In equation 13*,* moment of inertia, the angular velocity and angular acceleration are substituted to equation 12.

$$M = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} . \begin{bmatrix} \dot{P} \\ \dot{Q} \\ \dot{R} \end{bmatrix} + \begin{bmatrix} P \\ Q \\ R \end{bmatrix} \times \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} . \begin{bmatrix} P \\ Q \\ R \end{bmatrix} \quad (13)$$

Equation 14 is the result of matrix dot product and matrix cross product from the equation 13.

$$M = \begin{bmatrix} \dot{P}.I_x & 0 & 0 \\ 0 & \dot{Q}.I_y & 0 \\ 0 & 0 & \dot{R}.I_z \end{bmatrix} + \begin{bmatrix} QR(I_z - I_y) \\ PR(I_x - I_z) \\ PQ(I_y - I_x) \end{bmatrix} \quad (14)$$

The propellers of the quadcopter produce external torque because of the thrust and drag forces. By neglecting the aerodynamic torque and inertia of quadcopter, the external vector torque can be written as

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} R\,.\sin 45^o\,.(F_2 - F_4) \\ R.\ \sin 45^o\,(F_1 - F_3) \\ (-F_1 - F_2 + F_3 + F_4)Tq \end{bmatrix} \quad (15)$$

The equation of angular motion as shown in equation 16 can be obtained by substituting the equation 14 and equation 15.

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{R.\sin 45^o(F_2 - F_4)}{I_x} \\ \frac{R.\sin 45^o\,(F_1 - F_3)}{I_y} \\ \frac{(-F_1 - F_2 + F_3 + F_4)Tq}{I_z} \end{bmatrix} - \begin{bmatrix} \frac{QR(I_z - I_y)}{I_x} \\ \frac{PR(I_x - I_z)}{I_y} \\ \frac{PQ(I_y - I_x)}{I_z} \end{bmatrix} \quad (16)$$

C. Human Follower Calculation

The human follower system uses the basic principle of the ultrasonic sensor to approximate the distance. The basic calculation is used to support the calculation of the human follower system is cosine rule as it is shown in Fig. 3.

The equation 17 is derived for finding the side length (a, b and c) of triangle while equation 18 is the equation that is derived for finding the angle value (A, B and C) in the triangle. The ultrasonic receiver position A and ultrasonic receiver position B can calculate distance to the transmitter based on the travel time calculation which are Distance A and Distance B.

$$a^2 = b^2 + c^2 - 2\,.\,b.c\ \cos A \quad (17)$$

$$\cos A = \frac{b^2+c^2-a^2}{2.b.c} \quad (18)$$

The distance D', the angle α, β and γ can be calculated by using the *equation 19* up to equation *22* which are derived from the basic cosine rule. As a result, the distance D' shows the distance between the quadcopter to the object based on known distance A and distance B so that the quadcopter can know whether to move forward or backward. The angle γ is used to know the moving orientation of human based on the quadcopter position so that the quadcopter can identify whether to rotate in z-axis to the right or left.

$$\alpha = \cos^{-1}\left(\frac{d^2+Distance\ A^2-Distance\ B^2}{2\,.d.\ Distance\ A}\right) \quad (19)$$

$$D' = \sqrt{\frac{d^2}{2} + Distance\ A^2 - d.Distance\ A\,.\cos\alpha} \quad (20)$$

$$\beta = \cos^{-1}\left(\frac{D'^2+\frac{d^2}{2}-Distance\ A^2}{d.D'}\right) \quad (21)$$

$$\gamma = 90^0 - \beta \quad (22)$$

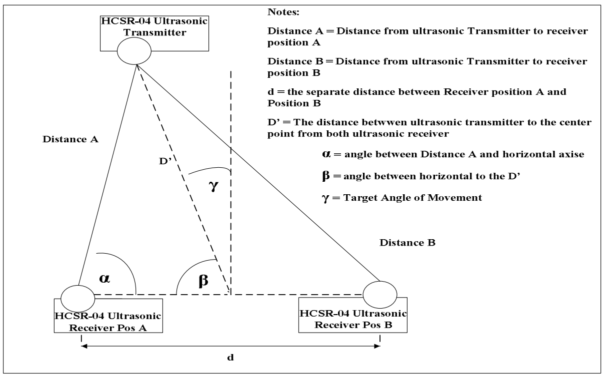

Fig. 3. Human Follower Ilustration

D. Human Follower Program Design

In this research, the controller is divided into 2 parts (master controller and slave controller). The master controller will only be used for sensing the distance between both ultrasonic receivers in the quadcopter to the ultrasonic transmitter in the human. Both measure the distance that will be sent to the slave controller via *I2C* communication.

The slave controller will receive the distances from the master then process them to calculate the approximate distance and angle from the quadcopter to the human which can be used to estimate the human movement. In this research the human speed is limited to slow walking speed around 0.5m/s The results of the estimate distance and angle will be converted into PWM for moving in the pitch and yaw rotation. The PWM will be directly sent via hard wired to the flight controller, which converts it into real movement in the quadcopter.

E. Triangulation Calculation Program Design

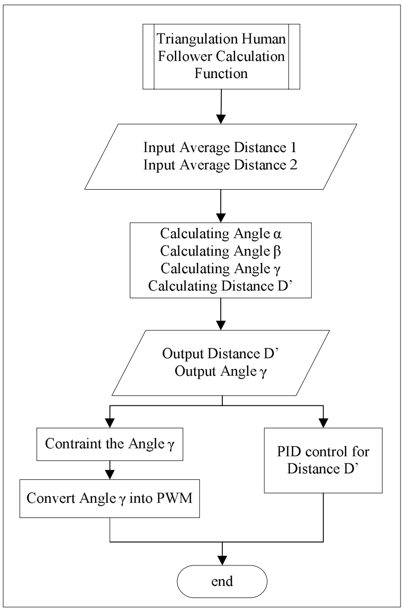

Fig. 4. Triangulation Calculation Sub-Function Programming Flowchart

Triangulation calculation is sub-function in the human follower system that calculates the two parameters that are needed to know the movement and position between the human and the quadcopter. The result of this calculation is D' which is the distance between human and quadcopter and gamma (γ) for the rotation movement. The flow process of the triangulation calculation can be seen in the Figure 4.

F. Flight Controller Design

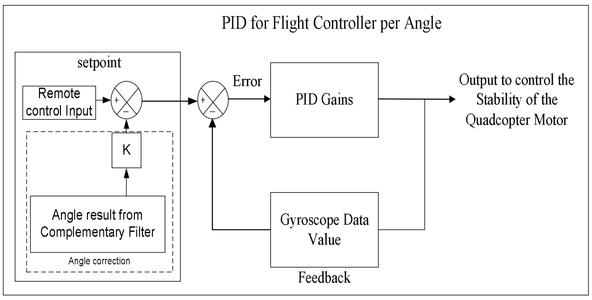

Fig. 5. PID Block Diagram per Axis Rotation

The control system to control the quadcopter in this project is done by using a PID controller. The quadcopter has 3 PID controllers for every tilt and rotation rate angle in the x-axis, y-axis and z-axis because the quadcopter can fly hover when the system is stable in all rotational axes.

G. Digital Filter for IMU Sensor

The digital filter estimates the angle of the system, so complementary filter is used to combine the data from the gyroscope and the accelerometer.

$$angle = \alpha . (angle + gyro.dt) + (1 - \alpha).(acc_{data}) \quad (23)$$

When the filter coefficient α is set to 0.98 and assumed that the running loop executes 100 times per second, the time constant $\boldsymbol{\tau}$ for both the low pass and the high pass filter can be calculated by using equation 24.

$$\boldsymbol{\tau} = \frac{\alpha.dt}{1-\alpha} = \frac{0.98\times0.01sec}{0.02} = 0.49\ sec \quad (24)$$

H. Electronic Speed Control Calibration

Calibration in each ESC is needed for setting the minimum and the maximum value of the PWM so each ESC has equal value. Thus, the motor will start at the same time in the same value. The transmitter and the receiver of the remote control shoud be turned on before turning on the arduino or the flight controller then it moves the throthle channel to the maximum position. The controller is turned on until the ESC will be beeping two times. Finally, the throthle channel is moved to the minimum position and waits until the ESC beeping once; This process marks the end of calibration process of the ESC.

III. Testing, Result And Discussion

A. Human Follower Ultrasonic Sensor Test

The human follower system is developed through an experiment of two types of ultrasonic sensors: beacon ultrasonic sensor and modification of HCSR-04 ultrasonic sensor

A.1 Beacon Ultrasonic Sensor

An ultrasonic beacon and an ultrasonic receiver as it is shown in Fig. 6 are generally similar to a beam barrier circuit. This system tries to locate the ultrasonic beacon by moving the ultrasonic receiver when an object breaks the ultrasonic path.

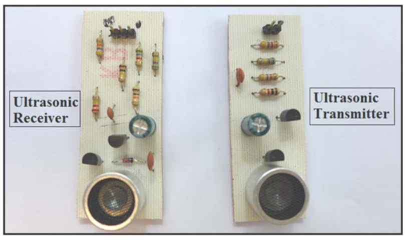

Fig. 6. Beacon Ultrasonic Sensor Module

The beacon system needs an oscillator set for a 35-45 kHz frequency. Generally, the frequency can be altered by using a 555 timer but in this beacon ultrasonic only use of a transistor even though it lacks of control over the signal frequency. The signal shape of the output emitter of the circuit can be seen in Fig. 7 with the result of frequency approximately 35 kHz.

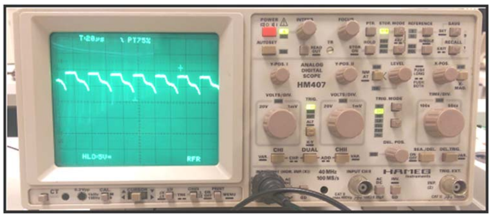

Fig. 7. The Signal Shape at the Output Emitter on the Circuit

The output pin header or signal pin of the sensor on receiver module can be hooked up directly to a microcontroller ADC port. The value of the ADC can also be used for estimating the distance between the beacon and the receiver. The output itself will provide approximately 0 to 5V depending on the power level of the detected ultrasonic signal.

A.2. Modification HCSR-04 Ultrasonic Sensor and Testing

Modification of ultrasonic HCSR-04 is the main sensor used for the human follower system. The experiment process as shown in Fig. 8 will be conducted in three different distances: 1.5 m, 2 m and 2.5 m. Those three distances were chosen to find out the maximum distance of the object, which still can be measured by the ultrasonic. For every step of the distance, the ultrasonic transmitter will be moved 80 cm to the left and right which can be used for finding the window frame that the sensor can still be readable.

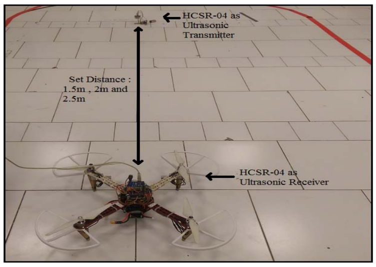

Fig. 8. The Process of Testing for the Human Follower Ultrasonic system

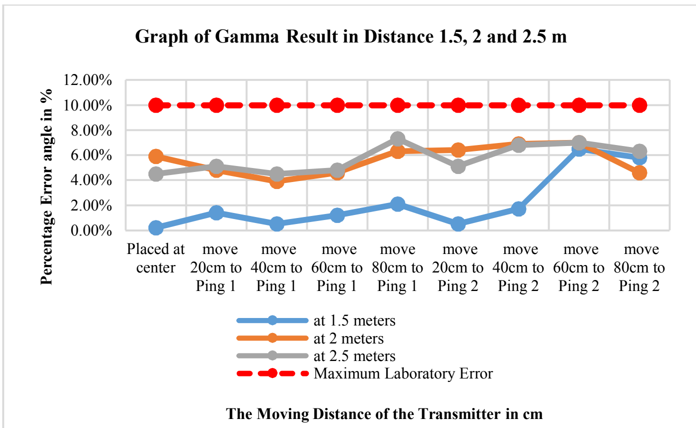

Fig. 9. The Graph Result for the γ angle from distance 1.5, 2 and 2.5 meters

Figure 9 shows the result of the angle gamma (γ) based on the calculation. The gamma result is based on distance from the ultrasonic transmitter in the human and two ultrasonic receivers in the quadcopter.

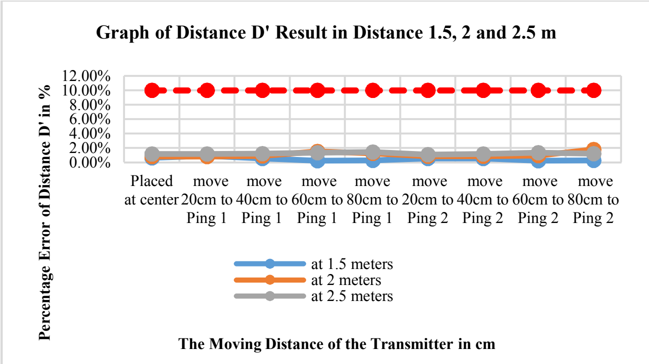

Fig. 10. The Graph Result for the distance D'

The result of the Distance D' can be seen in Fig. 9 and Fig. 10 which are based on the theoretical calculation. As a result of the experiment, the error calculation of distance D' was below 2%.

B. The Complementary Filter Test

The complementary filter test was done by using pprocessing software to represent the result of the angle. The process of development of the complementary filter which combines the value of the accelerometer and gyroscope that can be used for estimating the angle of the object.

In the pprocessing software user, interface will be divided into 3 blocks the gyroscope block, accelerometer block and result of the filter block as it is shown in Fig. 11. In conclusion, the complementary filter that is developed in this study works well because when the gyroscope data is start to drift, where the result of degree in the complementary filter is back to the initial position (0 degree in x and y axes).

C. PID Gain Test

The PID gain test explains about how the PID gain is achieved to make the quadcopter fly in a stable way. Basically, the process of finding the gains uses a Ziegler-Nichols method. The period of the oscillation of the system is the information needed in the Ziegler-Nichols methods to have the appropriate tuning. However, there is limitation of the measurement tools; it is not possible to get the exact period if the oscillation. Therefore, manual tuning or tuning based trial and error method is implemented to tune the system.

The tuning process starts with P gain, I and then D gain. When the quadcopter becomes more stable, then PID gain needs to be fine-tuned to get the best stability of the system. For the first method in the manual tuning, the integral and derivative gain is set to zero. Afterwards, the proportional gain is increased until it produces an oscillation to the system. After the oscillation occurs, the proportional gain can be reduced to a certain point where the system is not sluggish and the oscillation does not occur anymore.

The next part is tuning the integral gain. The integral gain is started from low value and then slowly increased. During the increasing value of integral gain, the quadcopter must be moved in the roll and pitch angle, so that the time of quadcopter to stop moving and start to stabilize can be calculated.

For the derivative gain, it found out that the derivative gain can get a complicated interaction to the proportional and integral gain. Therefore, after the D gain is achieved then fine tune P and I should be tested again to keep the plant stabilized well.

As a result of the tuning testing, the quadcopter starts to oscillate when the proportional gain increased above Kp = 5; when the proportional gain reduced below Kp = 0.5 the quadcopter get more sluggish. In conclusion, the best value of the PID pitch and roll gain in this study is Kp = 1.3, Ki = 0.04 and Kd = 18 which resulting in better stability and the response is not too fast; even though sometimes the quadcopter still drifting in the roll or pitch angle movement.

D. Stabilize Mode Test

The stability mode test of the quadcopter is used to observe the time of the quadcopter from stable condition until the drifting occurs. This experiment will be conducted five times so that approximate time of the system to start drifting can be obtained.

TABLE I. *THE STABILITY TESTING RESULT*

Testing Number	The Maximum Time the quadcopter can fly stable (sec)
1	26.2
2	28.5
3	30.8
4	27.5
5	25.3
Average	27.7
STD	**2.1**

From the table 1, it can be summed up that the drifting period from the stable condition of quadcopter is approximately 27.7 ± 2.1 seconds. The drift is common problem when the fusion algorithm or the IMU filter is not really good enough to estimate the drifting on the gyro and it also part of problem when the PID gain is not really correct so the control system can give fast respond to the recent condition of the system.

E. Human Follower Test

The test will be conducted into two movements: in the pitch angle rotation and movement in the yaw angle rotation. Due to safety reason, quadcopter will be placed in the testing bed during the human follower test. This testing bed can also be used for observing the human follower respond and performance.The other way to improve the result by placing the ultrasonics recieivers above the propellers as shown in Fig. 11.

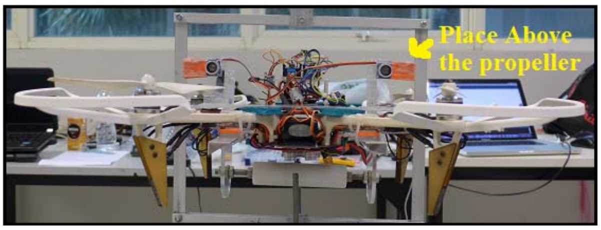

Fig. 11. The New Position Improvement of Ultrasonic Receiver

TABLE II. HUMAN FOLLOWER RESULT IN PITCH ANGLE MOVEMENT AFTER IMPROVEMENT

Human Follower After Modification Result in Pitch Angle Movement										
Distance Setpoint (in cm)	< 50	> 50	< 100	> 100	< 150	> 150	< 200	> 200	<250	>250
Distance result (in cm)	47	53	97	103	147	153	197	203	-	-
Respond Movement	Backward	Forward	Backward	Forward	Backward	Forward	Backward	Forward	No Move	No Move

Table 2 shows the result of the pitch angle movement after the improvement was made. It can be concluded that the distance measurement of the ultrasonic receiver is increasing compare to the previous model. The measurement distance can reach up to 200 cm, even though in the testing of the ultrasonic modification it can reach up to 250 cm.

The result of the yaw angle movement is conducted in the distance of 1.5m between the quadcopter and the human. Stopwatch is used to capture how fast the respond time between the human follower to the changes of movement from the human. Respond is measured based on the first movement of the quadcopter to follow the human until it reached the human position.

TABLE III. HUMAN FOLLOWER RESULT IN YAW ANGLE DISTANCE 1.5M

The Experiment Result of the Transmitter Movement to the Right						
Distance	Human Start(sec)	Human Stop(sec)	Quadcopter Start Moving(sec)	Quadcopter Stop Moving(sec)	Human Moving Time(sec)	Quadcopter Moving Time (sec)
20cm	0	0.5	2.4	6.2	0.5	3.8
40cm	0	0.7	4.1	5.2	0.7	1.1
60cm	0	1.3	3.1	5.2	1.3	2.1
80cm	0	1.7	2.9	6.1	1.7	3.2
The Experiment Result of the Transmitter Movement to the Left						
Distance	Human Start (sec)	Human Stop(sec)	Quadcopter Start Moving(sec)	Quadcopter Stop Moving(sec)	Human Moving Time(sec)	Quadcopter Moving Time(sec)
20cm	0	0.6	1.4	2.4	0.6	1
40cm	0	1	1.6	5.2	1	3.6
60cm	0	1.4	2.1	5.2	1.4	3.1
80cm	0	1.8	2.6	6.7	1.8	4.1

IV. CONCLUSION

The ultrasonic sensor can calculate the estimate distance between the ultrasonic transmitter and receiver. Wireless communication is used in order to synchronize the microcontroller for both transmitter and receiver. The triangulation method is proven capable to estimate the human position and movement respect to the quadcopter and the manual controlled quadcopter is already tested and worked well.

The result shows that in some point of time the gyroscope still drifting. However, the human can simply give a correction in which direction of the drifting. The human follower mode was tested in the testing bed. The reason is to make the human follower integrated to the system; the quadcopter needs to hold the altitude depending on the height of the human.

Empirically, the final result of the PID gain of the pitch and roll angle is $K_p = 1.3$, $K_i = 0.04$ and $K_d = 18$ and PID gain in yaw angle $K_p = 4.0$, $K_i = 0.02$ and $K_d = 0.0$ is with those values, quadcopter can fly in stable position. However, at a certain point there is a possibility that the quadcopter will drift from stable position.

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