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AUTO LEVEL CONTROL SYSTEMS OF V-TAIL QUADCOPTER

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Abstract- This work proposes the auto level control system development of V-tail quadcopter. Orientation control is implemented by PID control technique which used feedback data from the nine d.o.f MARG (Magnetic, Angular Rate, and Gravity) sensors. These sensors are used to estimate the orientation angle by using quaternion algorithm represented Kalman based on fusion sensor. The experimental results shows that the optimum control system in x axis is achieved by determining Kp, Ki, KD and KDd are 8.0, 2.2, 0.316 and 10, respectively. Whereas for y axis: Kp, Ki, KD and KDd are 7.04, 1.72, 0.340 and 10, respectively. The steady state error of controll system is less than one degree for x axis as well as y axis.

Keywords - V-tail Quadcopter, PID control system, MARG, quaternion algorithm

Nomenclature:

Kp	: proportional constantan	AHRS	: *Attitude and Heading Reference System*
Ki	: integral constantan	ESC	: *Electronic Speed Control*
Kd	: derivative constantan	Ω	: motor rotation speed
KDd	: derivative constantan of angle velocity	*MARG*	: Magnetic, Angular Rate, and Gravity
P	: proportional control	α	: projection angle of tail motor
I	: integral control	β	: rotor angle
D	: derivative control	GUI	: graphical user interface
U_B	: output value of controller	PWM	: Pulse width Modulation
L	: motor lift	Z_m	: zero point lift
D	: reaction force caused by propeller rotation	W	: total weight of quadcopter
Z	: control offset value	Windup	: a saturator to avoid integral wind-up
K	: kinematic constantan	d.o.f	: degree of freedom
C	: motion control	G_B	: *gain control*
O	: motor control input	o_m	: offset motor
EB	: Matrix of movement constantan		

I. INTRODUCTION

Development of Unmanned Aerial Vehicle (UAV) continuously performed to obtain the ease of operation characteristic, reliability and the maximum performance. Development of aerial vehicle which uses propeller as the thrust force generator gives the capability of Vertical Take-Off and Landing (VTOL). These characteristics make the UAVs could be potentially developed as a vehicle for the rescue, surveillance and image data collection in difficult conditions.

To observe the object, UAV should be stabilized although disturbance signal comes simultantly and randomly. For this reason, development of the control system to support the stability is important performed. Auto level control is the important control system which can be implemented by applying Attitude and Heading Reference System (AHRS), which is navigation system which capable to give orientation information of the platform.

The control technology development supports a decrease the aerial vehicle size and increase the flying capability.
Significant progress has been made, recent examples include aggressive flight maneuvers [1,2], ping-pong [3] and collaborative construction tasks [4]. To achieve the performance, besides it is easy operated, the UAV should have the capability to correct autonomously itself if the disturbance alters the position as well as the orientation.

Various studies have been carried out to improve the quadcopter performance, i.e. Eresen et al developed Automatic detection of obstacles and junctions by using optical flow velocities. In this technique the optical flow is used to determine the reference yaw angle. The path following process is achieved by the PID controller operating as the low level control scheme. Proposed method is tested in the Google Earth_ virtual environment. The test result shows that proper thresholding of the variance of the gradient of optical flow difference have a critical effect on the detectability of roads having different widths [5]. Liu et al developed fault detection filter or residual generation system. Sufficient conditions are established in the form of linear matrix inequalities (LMIs). System faults can be effectively detected by generating the residues and comparing them with the dynamic fault thresholds. A quadrotor vehicle with faults on angles and angular rates illustrates and verifies the effectiveness of the proposed algorithm [6]. While, Engel et al proposed an approach that enables a low-cost quadrocopter to accurately fly various Figures using vision as main sensor

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modality. This approach consists of three components: a monocular SLAM system, an extended Kalman filter for data fusion and state estimation and a PID controller to generate steering commands. The experimental result show that the Quadrocopter capable to navigate in previously unknown indoor and outdoor environments at absolute scale without requiring artificial markers or external sensors [7].

Development of UAV copter was also performed by varying configuration of propeller number. Tricopter is the UAV which uses three propeller systems, while quadcopter and also pentacopter are the UAV copter which uses four and five propellers systems, respectively. The use of number propeller determines the control characteristic and vehicle stability. Consider this reason, this work proposes the development of V-tail quadcopter in which this is a modified configuration of quadcopter to obtain an increase capability of yaw motion. Besides the frame configuration is modified, the orientation of tail propellers is changed to gives the roll and yaw effects.

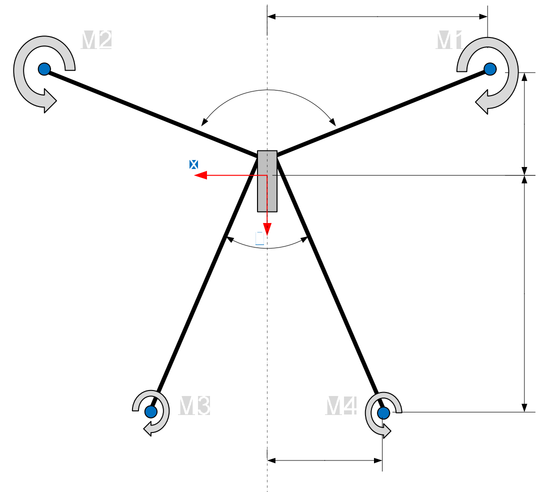
To control quadcopter, orientation of the platform must be initially detected. Thus, the orientation will be used as feedback signal of the controller. Various methods can be used to present the orientation such as Euler Angle, Quaternion, and Rotation Matrix. Quarternion is a four dimensional complex number which represents a frame coordinate in three dimensional space. Orientation of B-frame toward A-frame is achieved by axis which is defined in A-frame [8]. A quaternion based on Kalman filter fusion algorithm and gradient descent will be implemented in this work. In the application, the developed control system uses feedback data obtained from nine d.o.f MARG sensors (Magnetic, Angular Rate, and Gravity) [9].

II. DESIGN OF V-TAIL QUADCOPTER

Mechanical Frame Design

Frame of the quadcopter is built by using aluminium pipe of 10 mm diameter. Frame design is a form of V- tail which has the different angle between the front and the rear arms. The front and rear angles are 135^o and 45^o, respectively. Two tail motors are positioned in angle of 20^o from the vertical direction. V-tail frame is depicted in Fig. 1.

(a)



(b)

Fig. 1 a. CAD design of V-tail quadcopter, b. General dimension of V-tail quadcopter (total weight is 1350 g).

Design And Specification of Electronic Hardware

Design of the V-tail quadcopter used two pairs brushless DC motor as the propellers driver. Each motor is controlled by Standard Electronic Speed Control (ESC). The feedback data to monitor the level and the heading are generated by MARG sensor included three d.o.f of accelerometer, gyroscope and magnetometer. The system is a wireless, while data is real time monitored. The controlled signal flow and the specification of the hardware components are presented in Fig. 2.

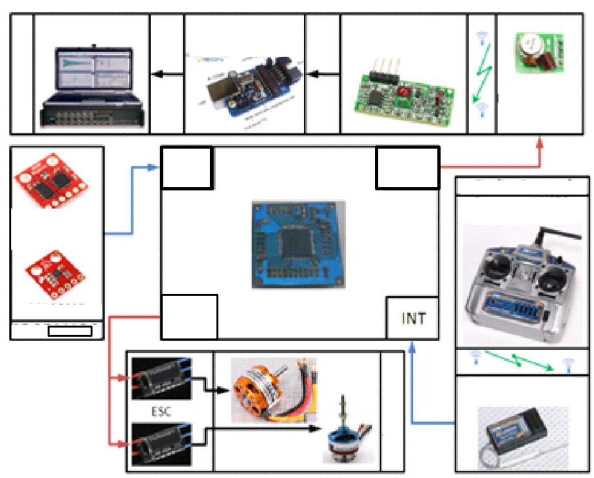


Fig. 2 Design and specification of quadcopter hardware.

Embedded Control System

The post controller of developed V-tail quadrotor is an ATmega1281 microcontroller unit. Algorithm of the control system is implemented into the embedded system using C language, while software is written by using Code Vision AVR comparator.

User Interface For Calibration

To calibrate PID parameters, GUI was developed which can display stability analysis and also orientation angle which is resulted by MARG sensors. Fig. 3 shows the developed Stink Bug interface which was used to support the control system development.

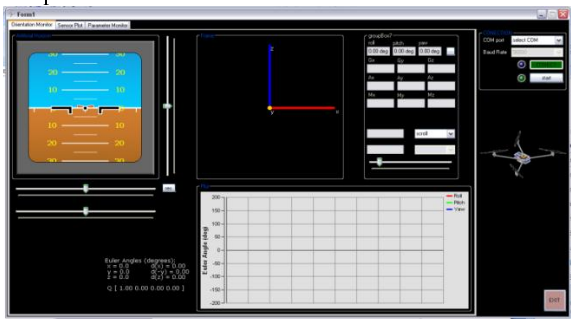


Fig. 3 The developed stink bug interface.

III. IMPLEMENTATION OF THE CONTROL SYSTEM

The developed control system of V-tail quadrotor applies two level control system included orientation and angular velocity controllers. The control system uses the output of orientation control system as the set point of the angular velocity control system. The applied control system is implemented into PID control system, where determining *Kp*, *Ki* and *Kd* is based on experimental respond analysis [10]. Fig. 4 shows the multi level control system of orientation and angular velocity. Explaining each control system is described in the following section.

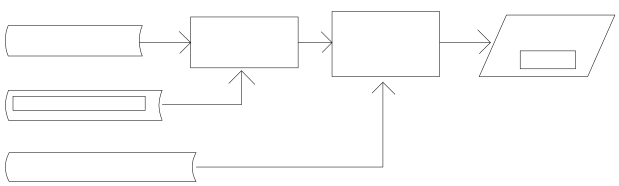


Fig. 4 Multi level control system.

Orientation Control System

Block diagram of the basic orientation control system is depicted in Fig. 5, in which the error signal of orientation input is processed by integral and proportional controls. The output will be compared to the angular orientation measured by MARG sensors.

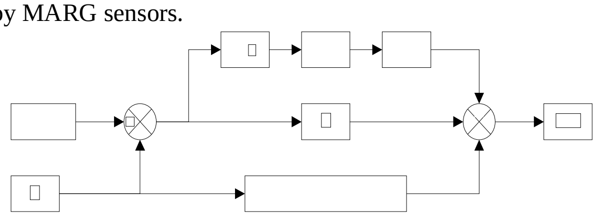


Fig. 5 Basic orientation control system.

For controlling aerial vehicle, the work coordinate must be changed from earth frame (E-frame) to body frame (B-frame), before processed as control input of P and I and error signal must be added with T_θ block. As the consequences, the differential of angular velocity must also be changed into B-frame, in which it is a form of the angular velocity controller. Therefore, this part is not used and then it must be changed into angular velocity controller with set point of 0 rad/s. Based on this reason, block diagram in Fig 5 should be modified into the block diagram in Fig 6.

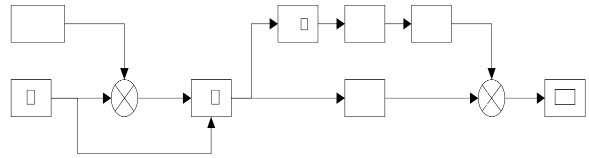


Fig. 6 Modified orientation control system.

Angular Velocity Control System

Angular velocity control is also implemented in PID control system. Compared to the orientation control system, angular velocity control has a *set point* of 0 rad/s. This controller is aimed to maintain the angular velocity and arrange the angular acceleration to be zero. The basic of angular velocity control system is depicted in Fig 7.

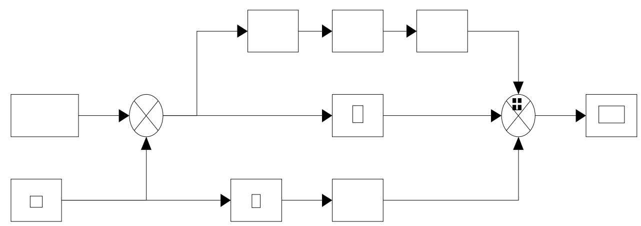


Fig. 7 Basic of angular velocity control system.

In the application, error signal of P can be changed by applying input of angular velocity and change the sign of the final summing. In order to stabilize the orientation controller, I controller is not used. The modified angular velocity control system is depicted in Fig 8.

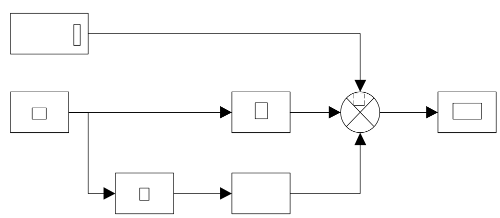


Fig. 8 The modified the angular velocity control system.

Implemented Control System

If the orientation and the angular velocity control systems are combined, two proportional constantans will be obtained. These affect to another control system. Based on this reason, P of angular velocity controller is used as differential orientation controller, while D angular velocity controller is employed as new orientation controller. It will change the controller order into the second order differential controller. It affects on the angular acceleration with Dd constantan. Complete block diagram of multi level PID control system applicable to V-tail quadcopter is depicted in Fig 9, in which it has three inputs including E-frame orientation set point, E-frame orientation measurement and B-frame angular acceleration measurement.

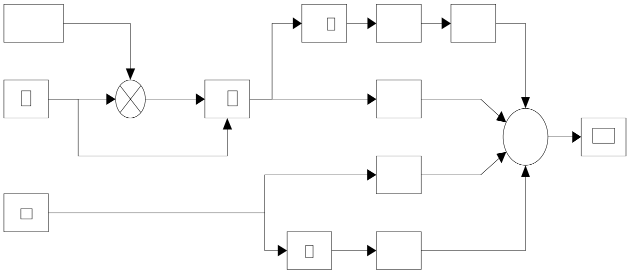


Fig. 9 Complete block diagram of multi level PID control system which is applied in V-tail quadcopter.

Kinematic Inverse

Kinematic Inverse is used to formulate correlation between the output value of the controller U_B and the rotation speed of the propeller driver motor, Ω^2. In the control system, rotation of motor is controlled by arranging PWM signal of each motor. Determination of PWM signal closely correlates with constantan of lift force parameter which is obtained by experiment and calibration, in which this constantan is the specific value which depends on the frame configuration and also the propeller driver motors.

Based on the design specification of V-tail quadcopter, in matrix configuration, output variables of the controller can be expressed in $U_B^T = [U_1\ U_2\ U_3\ U_4]$. While, the basis motion equation of quadcopter based on PWM signal is described in the following section:

$$U_B = [E_B \times O] + Z \qquad (1)$$

$$O = E_B^{-1} \times [U_B - Z] \qquad (2)$$

$$O = [O_1 \quad O_2 \quad O_3 \quad O_4]^T \qquad (3)$$

$$E_B = \begin{bmatrix} l_1 & l_2 & l_3 cos(\beta) & l_4 cos(\beta) \\ l_1 a & l_2 a & -l_3 bcos(\beta) & -l_4 bcos(\beta) \\ -l_1 c & l_2 c & l_3 dcos(\beta) & -l_4 dcos(\beta) \\ D_1 & -D_2 & l_3 C_r + D_3 & -(l_4 C_r + D_4) \end{bmatrix} \qquad (4)$$

$$Z = \begin{bmatrix} zf_1 + zf_2 + zf_3 cos(\beta) + zf_4 cos(\beta) \\ azf_1 + azf_2 - bzf_3 cos(\beta) - bzf_4 cos(\beta) \\ -czf_1 + czf_2 + dzf_3 cos(\beta) - dzf_4 cos(\beta) \\ zm_1 - zm_2 + zm_3 - zm_4 + zf_3 C_r - zf_4 C_r \end{bmatrix} \qquad (5)$$

$$C_r = \left(dsin(\alpha) + bcos(\alpha)\right) sin(\beta) \qquad (6)$$

where: $Z = [Z_1\ Z_2\ Z_3\ Z_4]^T$ is the controller offset. Matrix can be derived from dynamical equation of quadrotor motion which is designed according to the analysis of free body diagram of V-tail quadcopter. Fig. 10 shows the free body diagram of V-tail quadcopter in B-frame.

Based on Fig. 10, in hover condition the angular acceleration of x and y axis equal to zero, so that the total lift should be able to support the total weight of V-tail quadcopter, W. This uses an equation which is derived from free body diagram in yz plane. This equation must insert the total weight, while the average momen in hover condition is zero.

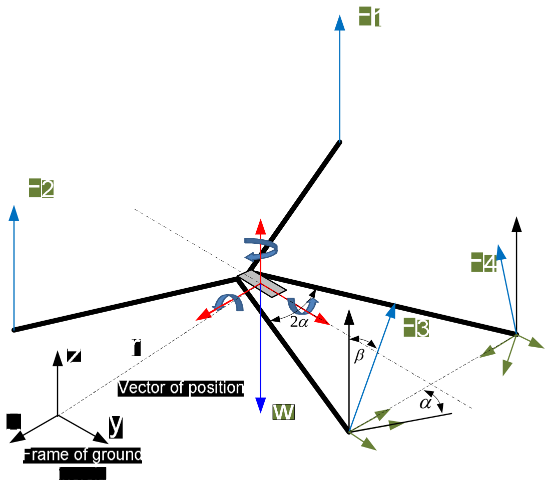


Fig. 10 Free body diagram of V-tail quadcopter.

The total weight can be expressed by using Equation 7.

$$W = F_1 + F_2 + F_3 cos(\beta) + F_4 cos(\beta)$$

$$0 = aF_1 + aF_2 - bF_3 cos(\beta) - bF_4 cos(\beta) \qquad (7)$$

If $F_1 + F_2 = F_f$ and $F_3 + F_4 = F_r$, the Equation 7 can be expressed:

$$W = F_f + F_r cos(\beta)$$

$$0 = aF_f - bF_r cos(\beta) \qquad (8)$$

By substituting this equation, F_f in hover condition can be calculated and the result of maximum rotor orientation is $\beta max = 55^o$.

Motion Inverse Matrix

Correlation between output and input of the motor controller is shown in the following Equation 9.

$$O = E_B^{-1} \times [U_B - Z]$$

$$O = \left(E_B^{-1} \times U_B\right) - \left(E_B^{-1} \times Z\right)$$

$$= \begin{bmatrix} 0{,}0206 & 0{,}0922 & -0{,}1160 & 0{,}0690 \\ 0{,}0304 & 0{,}0980 & 0{,}1241 & -0{,}0733 \\ 0{,}0232 & -0{,}1449 & 0{,}0528 & 0{,}2201 \\ 0{,}0229 & -0{,}1432 & -0{,}0522 & -0{,}2174 \end{bmatrix}$$

$$\times \begin{bmatrix} U_1 - 3125 \\ U_2 - 384 \\ U_3 \\ U_4 \end{bmatrix} \qquad (9)$$

Inverse matrix of this equation is simplified by defining new variables called as motor offset (o_m) constantan, kinematic constantan (K), gain control (G_B) and motion control (C) which is expressed as the following:

$$o_m = E_B^{-1} \times Z = \begin{bmatrix} -103{,}986 \\ -110{,}497 \\ -49{,}383 \\ -48{,}780 \end{bmatrix}$$

$$E_B^{-1} = K \times G$$

$$K = \begin{bmatrix} 0,941 & 0,636 & -0,941 & 0,313 \\ 1,0 & 0,676 & 1,0 & -0,333 \\ 0,764 & -1,0 & 0,426 & 1,0 \\ 0,754 & -0,988 & -0,420 & -0,988 \end{bmatrix}$$

$$G = \begin{bmatrix} G_1 & 0 & 0 & 0 \\ 0 & G_2 & 0 & 0 \\ 0 & 0 & G_3 & 0 \\ 0 & 0 & 0 & G_4 \end{bmatrix}$$

$$= \begin{bmatrix} 0,0304 & 0 & 0 & 0 \\ 0 & 0,1449 & 0 & 0 \\ 0 & 0 & 0,1241 & 0 \\ 0 & 0 & 0 & 0,2201 \end{bmatrix}$$

$$C = G \times U_B = \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} = \begin{bmatrix} 0,0304U_1 \\ 0,1449U_2 \\ 0,1241U_3 \\ 0,2201U_4 \end{bmatrix}$$

Equation 9 can be transformed into Equation 10 and also Equation 11.

$$O = (K \times C) - o_m$$

$$= \begin{bmatrix} 0,941 & 0,636 & -0,941 & 0,313 \\ 1,0 & 0,676 & 1,0 & -0,333 \\ 0,764 & -1,0 & 0,426 & 1,0 \\ 0,754 & -0,988 & -0,420 & -0,988 \end{bmatrix} \times \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} - \begin{bmatrix} -103,986 \\ -110,497 \\ -49,383 \\ -48,780 \end{bmatrix} \qquad (10)$$

$$O_1 = 0,941C_1 + 0,636C_2 - 0,941C_3 + 0,313C_4 + 103,986$$

$$O_2 = 1,0C_1 + 0,676C_2 + 1,0C_3 - 0,333C_4 + 110,497$$

$$O_3 = 0,764C_1 - 1,0C_2 + 0,426C_3 + 1,0C_4 + 49,383$$

$$O_4 = 0,754C_1 - 0,988C_2 - 0,420C_3 - 0,988C_4 + 48,780 \qquad (11)$$

Equation 11 is the implemented equation of embedded control system.

IV. PERFORMANCE TESTING

Thrust Force Testing

The testing result shows that the initial thrust force which is needed to lift the V-tail quadcopter is available at PWM of 1050 millisecond. Although the quadrotor uses two pair identical motors, the performance of each motor is different. Fig. 11 shows the comparison of lift characteristic for four motors (propeller driver) as a function of PWM signal activation.

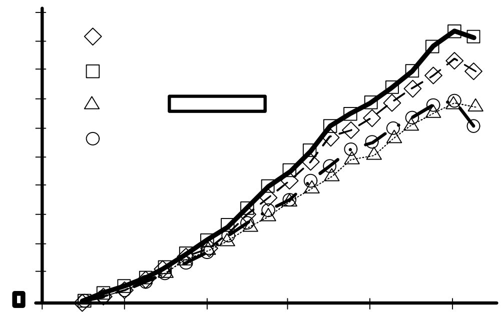


Fig. 11 Comparison of lift characteristic of four motors as a function of PWM signals activation.

According to Fig. 7, by assuming the initial range (before it achieves the maximum lift) is a linear function, lift constantan of each motor can be determined. Testing the effect of motor rotation (*D*) as well as zero point lift (*Zm*) is carried out on the maximum lift force. The results are shown in Table 1.

TABLE 1. LIFT FORCE TESTING RESULTS

	Motor 1	Motor 2	Motor 3	Motor 4
Lift	11,5 N	10,9 N	8,1 N	8,2 N
Zf	-1200 N	-1200 N	-400 N	-400 N
D	0,9 N.m	0,85 N.m	0,8 N.m	0,81 N.m
Zm	-90 N.m	-90 N.m	-40 N.m	-40 N.m

Testing Orientation of Estimation Filter

Before the sensor is applied into the V-tail quadcopter, every sensor is tested the performance to determine the operation constantan such as *Kp* and *Ki*. By using GUI, the optimum constantan of each motor is presented in Table 2.

TABLE 2. Kp AND Ki OF AM SENSORS

Sensor	Sampling time of 12,9 ms	
	Kp	Ki
Accelerometer	0,2	0,0005
Magnetometer	0,5	0,0005

Application of the constantan in each sensor yields the angle performance as shown in Fig. 12. In the static condition (zero calibration), the average difference between reference signal and estimation signal is less than 0.5^0, while in dynamic condition the average error is less than 4^0.

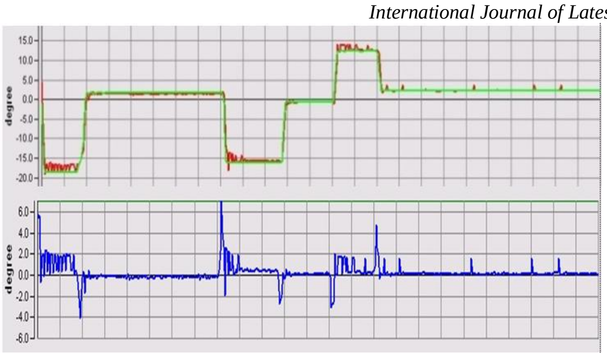


Fig. 12 Comparison between estimation of orientation and the actual orientation using GUI. Green: reference signal (set point), red: the result of estimation filter, blue: the difference between the estimation and the actual orientation.

Control Respond

Operation constantans of the sensors are needed to calibrate the feedback signal. While for controlling vehicle, controlling the motor rotation should be performed, so that the control constantan must be initially determined. According to Fig. 12, control respond testing is carried out experimentally by setting control constantan.

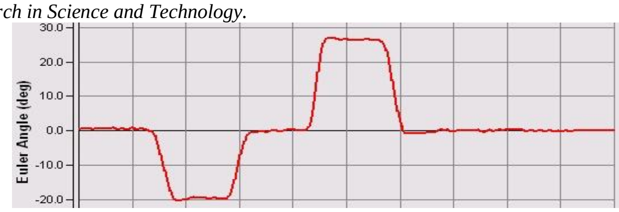
The normal respond, actuator fails to set itself to the initial position. It proves that the integral action combined with actuator saturation can provide a non linear effect which can decrease the performance of the control system. When the integral value is large and the error changes sign it is necessary to wait a lot of time before the system restores its linear behavior. This phenomenon is called integral wind-up. To avoid it, a saturator is added after the integral to limit its maximum and minimum values [11].

The test results using GUI analysis is obtained the PID constantans which are presented in Table 3. By implementing these PID constants in embedded control system, the performance of V-tail quadcopter in pitch and roll motion can approximate the set orientation in X and Y axis as shown in Fig. 13a and 13b, respectively. These show that the steady state error approximates to zero, while error of pitch and roll angles are less than 1^o. The difference of pitch and roll angles causes drift or longitudinal acceleration so the V-tail quadcopter difficulty keep the position.

TABLE 3. PARAMETERS OF ORIENTATION CONTROL SYSTEM

	Kp	Ki	*windup*	Kd	Dd
X axis	8,00	2, 20	10^0	0,316	10,00
Y axis	7,04	1,72	10^0	0,340	10,00
Z axis	10,04	1,00	20^0	0,512	20,00

(a)



(b)

Fig. 13 Orientation control respond of PIDd for: a. Pitch motion (x axis), b. Roll motion (y axis).

V. CONCLUSIONS

Quaternion algorithm of Proposed Filter for processing MARG sensor data successfully gives the orientation data including roll and pitch. The use of the data as feedback signal yields the orientation control error is less than 0.5^o. While the use of PID controller gives the good performance in controlling orientation of V-tail quadcopter. The experimental result shows that the error is less than 1^o.

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