

Stability Augmentation of Attitude Control System for Quadrotor

*Gilar B. Raharja, Gyoubeom Kim, Idris E. Putro and K.J.Yoon
Konkuk University, Gwangjin-Gu, Seoul 143-701, South Korea

ABSTRACT

Autonomous quadrotor is one of the challenging research area in aerospace and control technology, and it is one of the most reliable. This paper presents an MAV we have developed, a mini quadrotor vehicle completed by the stability augmentation system (SAS) system for indoor flight application. Regarding the role of the control parameter and observing the performance by the developed quadrotor dynamic model and simulator, the SAS determined to be used as the control system for attitude hold combined with rate damping system of roll (ϕ), pitch (θ) and yaw (ψ). The autonomous system supported by simple hardware configuration and sophisticated software as a ground control system for monitoring and telecommand. This results a quadrotor vehicle that reliable to hover and able to implement the next level of control and navigation for indoor application.

Keywords: quadrotor, autonomous system.

1 INTRODUCTION

Quadrotor vehicle is one of the most reliable MAV for flying robot application. The mechanical structure, the flight dynamic and the required control system are simpler than a helicopter and it is more robust indeed. Based on these considerations, we designed this autonomous vehicle to implement as flying robot that able to do some mission in indoor environment.

The quadrotor shown in figure 1 used as a platform for implementing control system designed based on theoretical approach. A quadrotor is an unstable vehicle, it is required at least a rate damping system as a minimum control application. Without installing any control system, the pilot cannot fly the vehicle manually. So, the very basic controller should be implemented to acquire the flight data for validation and simulation.

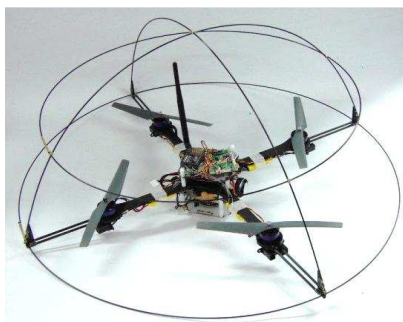


Figure 1. Quadrotor vehicle

*email: agie@konkuk.ac.kr

We implement multi-loop control system for stability augmentation system for the attitude control system [4]. It is consist of inner-loop control system that the control parameter set up satisfied by tuning and a modeling and simulation based control as the outer-loop control system. This paper will discuss about the optimization result of the combined closed-loop control system. We propose this stability augmentation system can be reliable for the basic quadrotor control system.

In [1], the attitude position controller was well developed, in this project; we try to use the stability augmentation system as the first and basic control system that should be implemented in a MAV before other control or guidance system. The quality of SAS will be determined the whole performance of the vehicle.

2 QUADROTOR DYNAMICS MODEL

The simple concept of quadrotor dynamics motion is one of the reason we choose it for studying of control implementation in MAV. The main motion factor is the four cross configuration rotor's speed; the motion can be varied by changing it. The equations of quadrotor motion are described by the equation (1) – (6). [2],[5],[7],[12]

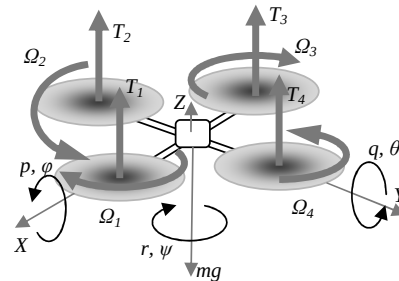


Figure 2. Quadrotor Dynamics [6],[8],[10]

Figure 2 represents the dynamics involved in the quadrotor. By increasing all rotors' speed ($\Omega_1, \Omega_2, \Omega_3, \Omega_4$) together may add more lift forces of all motors (T_1, T_2, T_3, T_4) and vertical dynamics translation ($\ddot{z}$). In other words generate the same thrust from the all propellers.

$$\ddot{z} = \frac{(-mg + (\cos\phi * \cos\theta)(T_{total}) - k_z)}{m} \quad (1)$$

Two rotors (Ω_1 and Ω_3) are rotated clockwise and the others (Ω_2 and Ω_4) are counter-clockwise. Based on this configuration the yawing motion (r, ψ) can be produced by making all the counter-clockwise rotors greater than the clockwise. With the assumption that the each four thrust are

equal, then the yawing motion can be assumed as stable even though the whole dynamics of quadrotor are an unstable system.

$$\ddot{\psi} = \frac{L(-T_1 + T_2 - T_3 + T_4 - k_{\psi})}{I_{zz}} \quad (2)$$

Generate variation of thrust T_1 and T_3 oppositely by varying (Ω_1 and Ω_3) can produce pitching motion (q, θ). The same way is applicable for horizontal translation for forward and backward motion ($\dot{x}$).

$$\ddot{\theta} = \frac{L(-T_1 - T_2 - T_3 + T_4 - k_{\theta})}{I_{yy}} \quad (3)$$

$$\ddot{x} = \frac{(\cos\varphi * \sin\theta * \cos\psi + \sin\varphi * \sin\psi)(T_{total}) - k_{\dot{x}}}{m} \quad (4)$$

The rolling motion (p, φ) can be created by generate variation of thrust T_2 and T_4 oppositely by varying (Ω_2 and Ω_4). This is also applicable for horizontal translation or shifting to the left and to the right ($\dot{y}$).

$$\ddot{\varphi} = \frac{L(-T_1 - T_2 + T_3 - T_4 - k_{\varphi})}{I_{xx}} \quad (5)$$

$$\ddot{y} = \frac{(\cos\varphi * \sin\theta * \sin\psi - \cos\varphi * \cos\psi)(T_{total}) - k_{\dot{y}}}{m} \quad (6)$$

Where:

- m : total mass
- L : distance of propeller to the center
- I_{ii} : moments of inertia
- k_i : drag coefficient

3 CONTROL SYSTEM

A. Main Control Block

Implementing the control input using standard helicopter joystick radio control which are at least consist of four control parameter that apply as vertical control (δ_{col}), longitudinal cyclic (δ_{long}), lateral cyclic (δ_{lat}) and directional control (δ_{ped}) is the first step. The input sensitivity regulated by: $K_{\delta_{col}}$, $K_{\delta_{ped}}$, $K_{\delta_{long}}$ and $K_{\delta_{lat}}$ for satisfy a certain maneuverability.

Thus, the system inputs are:

$$u_1 = K_{\delta_{col}} * \delta_{col} + (\psi_{\kappa} + K_{\delta_{ped}} * \delta_{ped}) + (\varphi_{\kappa} - K_{\delta_{long}} * \delta_{long}) \quad (7)$$

$$u_2 = K_{\delta_{col}} * \delta_{col} - (\psi_{\kappa} + K_{\delta_{ped}} * \delta_{ped}) + (\theta_{\kappa} + K_{\delta_{lat}} * \delta_{lat}) \quad (8)$$

$$u_3 = K_{\delta_{col}} * \delta_{col} + (\psi_{\kappa} + K_{\delta_{ped}} * \delta_{ped}) - (\varphi_{\kappa} - K_{\delta_{long}} * \delta_{long}) \quad (9)$$

$$u_4 = K_{\delta_{col}} * \delta_{col} - (\psi_{\kappa} + K_{\delta_{ped}} * \delta_{ped}) - (\theta_{\kappa} + K_{\delta_{lat}} * \delta_{lat}) \quad (10)$$

where:

$\psi_{\kappa}, \varphi_{\kappa}, \theta_{\kappa}$: the outputs of attitude control loop.

B. Inner-loop Control System

The first control algorithm that we implement is shown in the figure 3, the system consist of damper and attitude holding for the roll, pitch and yaw. The control linkage is representing the devices that linking the control output to the dynamics or the vehicle in certain of constants [4]. In this very base controller, the reference is zero or the equilibrium due to the hovering mode of the quadrotor. Experiment to determine the control parameter is done one by one for the all member of SISO from the inner loop to the outer.

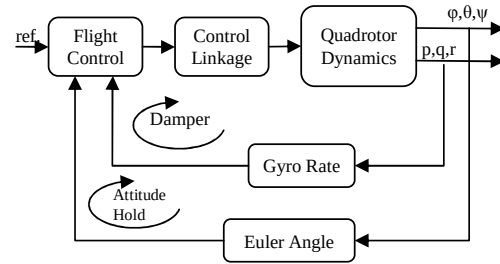


Figure 3. Inner-loop Control System

Firstly we implement the proportional control simply described by equation (11) for the damper, that utilizing the rate gyro sensor data to stabilize the angular rate in each three axis.

$$C_D(s) = g_r * k_p \quad (11)$$

It is implemented in each angular rate (p, q, r), in this term we are dealing with the maneuverability of the vehicle. The low damping ratio will keep the vehicle in frisky unstable system otherwise the vehicle will be sluggish.

The next step is implementing the PID controller for the attitude holding described by equation (12), for the roll, pitch and yaw.

$$C_{AH}(s) = (\theta_{ref}(s) - \theta(s)) (k_p + k_i/s + k_d s) \quad (12)$$

Combining as simple summation of equation (11) and (12), results the total inner-loop control (13).

$$C(s) = C_{AH}(s) + C_D(s) \quad (13)$$

Where:

- $C_D(s)$: rate damping controller
- g_r : rate gyro
- k_p : proportional gain for rate damping
- $C_{AH}(s)$: attitude holding controller
- $\theta_{ref}(s)$: input reference
- $\theta(s)$: current position

$k_p + \frac{k_i}{s} + k_d s$: PID gain for attitude holding
 $c(s)$: total control output

C. Outer-loop Control System

We use another control loop to improve the performance of the attitude control system rather than add more tuning to avoid any mismatch units of parameter's value after the modeling. The figure 4 shows the implemented design of SAS in the modeling of quadrotor, which also represents the integrated on board controller.

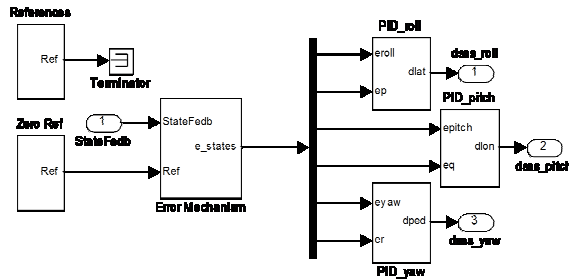


Figure 4. SAS on Quadrotor Modeling

To prevent the sideslip, incidental position changes and oscillating during the hover, we implement the acceleration damping system using the acceleration data from the three axes of accelerometer ($\ddot{x}, \ddot{y}, \ddot{z}$). Some angle adjustments described in equation (14)-(16) are necessary to make a correction to the sensor value due to the gravity effect.

$$\ddot{x} = \ddot{x} - \sin(\theta) \quad (14)$$

$$\ddot{y} = \ddot{y} + \sin(\varphi) \quad (15)$$

$$\ddot{z} = \ddot{z} - (\cos(\theta) * \cos(\varphi)) \quad (16)$$

The whole control loop is presented by the figure 5, the quadrotor dynamics is now an integration of the inner-loop control and the natural dynamics itself.

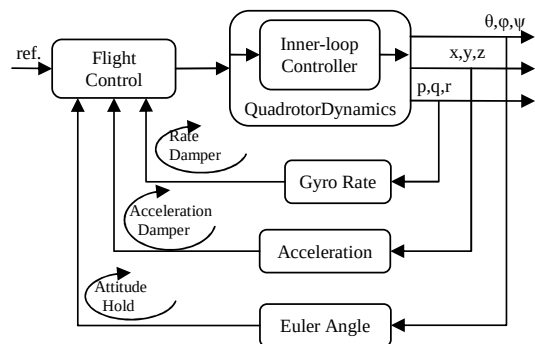


Figure 5. Outer-loop Control System

4 HARDWARE CONFIGURATION

The propulsion system is using the X-UFO blade propellers and brushless DC motors assembled on its very stiff design of the mainly carbon-fiber airframe. The flight

control system is driven by an AVR 32-bit MCU that operates in 16MHz of system clock. We make data acquisition system for acquiring six degree of freedom sensor data from XA3300 AHRS at 60-70Hz of average sampling rate and flight controller system (FCS) process the control algorithm and generating PWM through the four channels for the four electronic speed controllers.

Figure 6 represents the configuration of experimental test for quadrotor system. The control mode configured to be able to control by manually and autonomously by the ground control system through the 2.4GHz of RF modem to avoid risk of damage due to crash or disordered motion.

The wireless data communication make easier to do the experiment for set up the control gain parameter. Easy connect the vehicle to the PC that running the simulator controller without complicated cabling. This configuration reduces the limitation of the vehicle's motion during the experimental test rather than using wire connection. The two ways communication between the data RF modem enabled. The vehicle sending the flight data continuously and the PC sending the command due to the parameter set up changes.

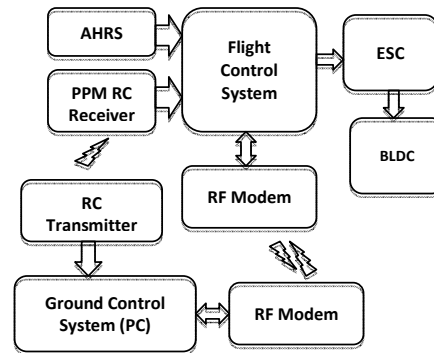


Figure 6. Schematic of Hardware

The FCS also has ability to auto lock the command input in the standby mode as a safety system, then already to receive some special command input as a password to unlock.

A 1500mAh 11.1V Li-Po battery used to drive all the electronics and the four 2500rpm/V DC-brushless motors, proper for seven minutes of flight time. The battery health system in the FCS can prevent the uncontrolled situation when the power goes down or exhausts during the flight and will make the quad-rotor automatically landing.

5 EXPERIMENT RESULT AND ANALYSIS

Experimental test using the base control done in a quadrotor test-setup in indoor environment for satisfying the requirements to collect the flight data for modeling and simulation. The modeling and simulation built in a Simulink/MATLAB platform to observe the performance of quadrotor and to determine the reference models and the role of each control parameter.

A. Flight Data

Figure 7 to 9 we present the gyro rate data that perform the rate damping response, figure 10 to 12 represent the performance of the SAS in the attitude control response of roll, pitch and yaw-axis with SAS implemented.

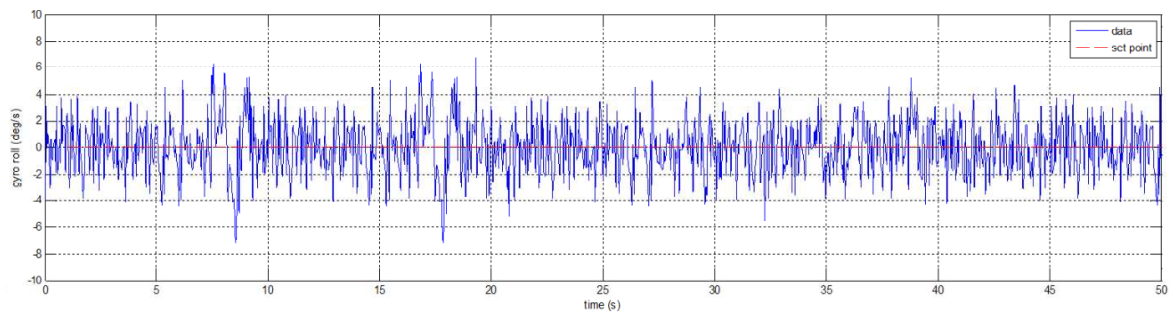


Figure 7. flight data of roll damper response

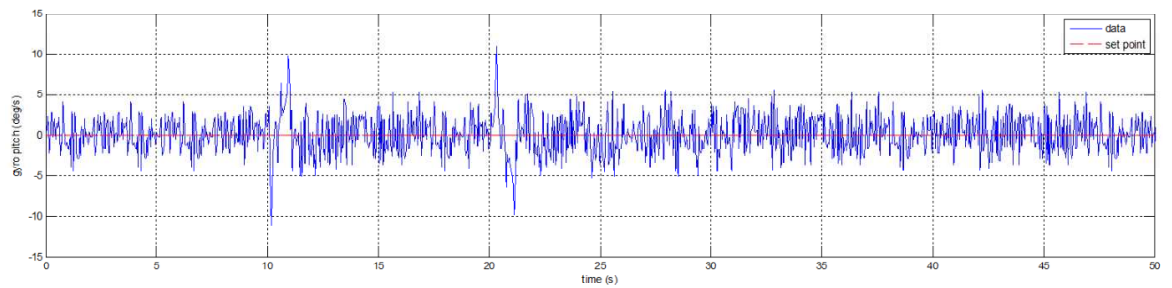


Figure 8. flight data of pitch damper response

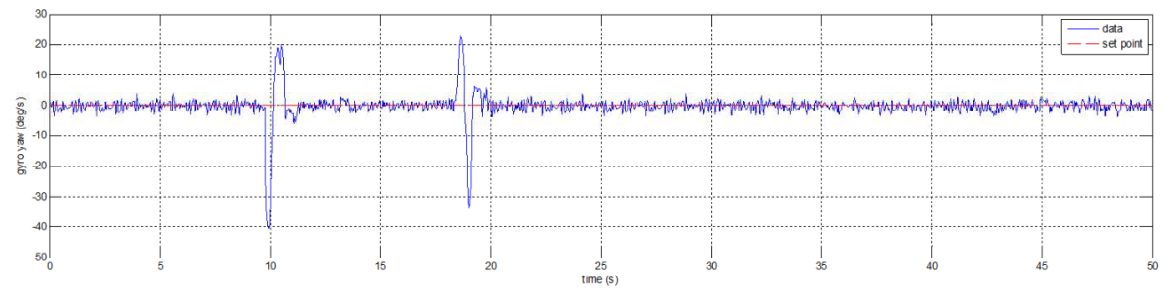


Figure 9. flight data of yaw damper response

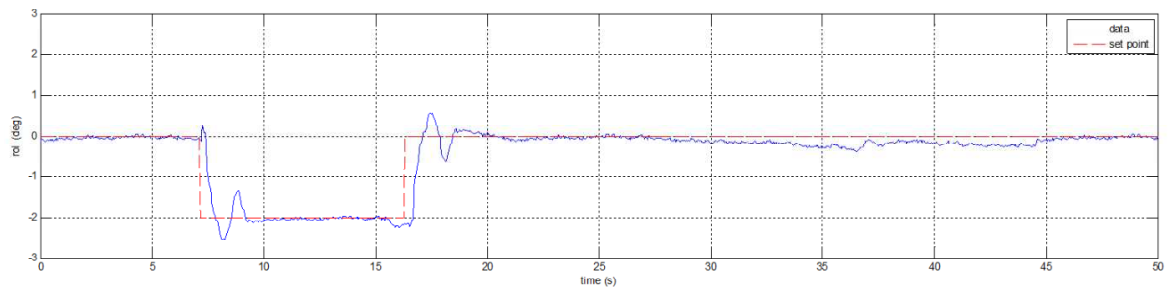


Figure 10 flight data of roll attitude hold response

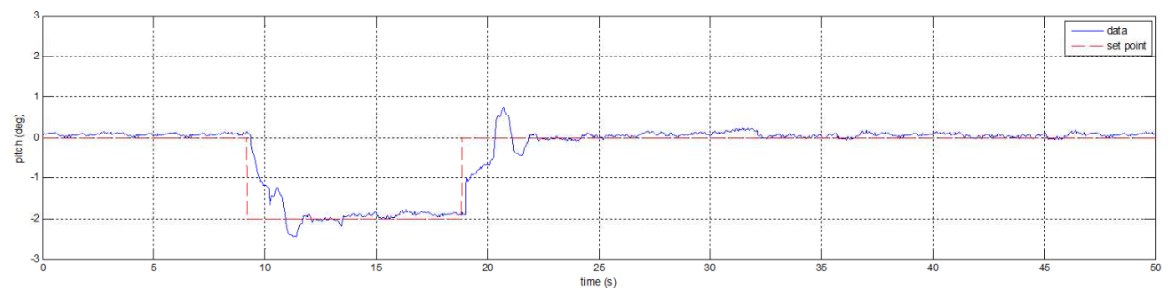


Figure 11 flight data of pitch attitude hold response

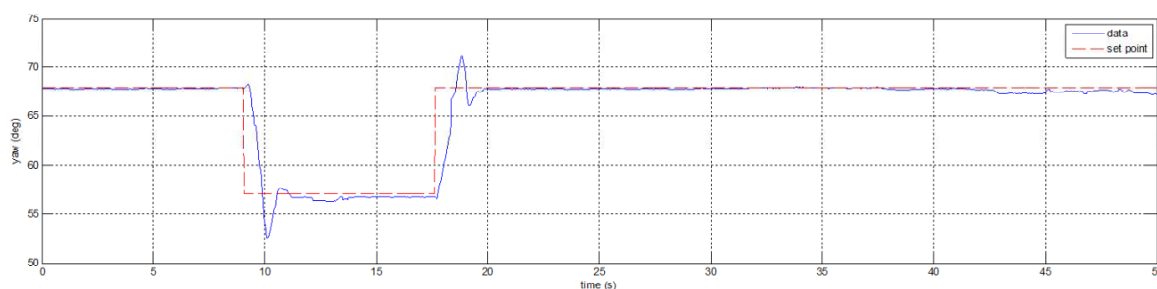


Figure 12 flight data of yaw attitude hold response

B. Analysis

The rate damping work properly in general in the roll and the pitch rate due to the set point change in 2 degrees. The yaw flight data shows the different amplitude with the same trend of response in general due to the set point change until 11 degrees. Due to the vibration occurred during the motor running, a measurement device should have high frequency and large bandwidth to overcome the effect.

The attitude parameter control is success after some additional tuning. To see the performance in the attitude control, we made changes of the set point in 2 degrees seconds in roll and pitch-axis to analyze the response of the control. The small changing value is considering the limitation of the vehicle to be tilted that will caused it move in fast. Some oscillation occurred in the 2 seconds after changing, but in the end, the closed-loop control makes the output follow the set point. During the hover, some small oscillation also occurred caused by bad sensor data package and some unexpected environment disturbance. It makes the quadrotor remains the sideslip motion that drive the vehicle to any arbitrary direction.

In the yaw-axis we changes in 11 degrees of heading reference. In the graph, it shows almost the same response trend as the other attitude control response. The amplitude of oscillation is more significant rather than the roll and pitch, because according to the dynamics the yaw-axis is slower than the others are. Nevertheless, in case the roll or pitch-axis has unstable behavior, sometime it makes some motion in the yaw-axis.

6 CONCLUSION

The quadrotor is already built and available with the experimental set up in the hardware and the software platform, including quadrotor dynamic model. These all things are necessary to observe the performance of the quadrotor and determine the control roll and technique. The SAS is very important part before implement other control or navigation for develop an unmanned quadrotor aerial vehicle. In this paper, the implemented stability augmentation system satisfied by the experimental test in an indoor environment and it makes the quadrotor possibly to use in any indoor application. Some improvements are necessary to do before the next level of control proposed, considering some factors including the sampling rate of the measurement device, speed of flight control processor, gain scheduling based on the flight mode and the additional control technique.

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