공학석사 학위논문

Design of Low Cost Flight Control System for Multirotor UAV using MEMS Sensor

MEMS 센서를 활용한 멀티로터형 무인항공기의
저비용 비행제어시스템의 설계에 관한 연구

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서울대학교 대학원

기계항공공학부

정 성 욱

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이 논문을 공학석사 학위논문으로 제출함

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정성욱의 석사 학위논문을 인준함

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ABSTRACT

Multirotor UAV, so-called "Drone", are widely used in commercial, military field because it has advantages for simple structure, cheap, easy to control and vertical take-off capability. It can measure its attitude using Inertial Measurement Unit(IMU) which is consist of accelerometer sensor, gyroscope sensor. Also, it contains magnetometer sensor to get the heading of vehicle and barometer sensor for altitude estimation. Flight Control Unit(FCU) calculate control amount of each motor using attitude, heading, control command and altitude data from sensors.

To calculate various data from sensors, wireless control system, and motor control system, existing flight control system should use 32-bit micro processor so it is pretty complex, expensive and needs many time to make software development environment for developing flight control firmware and designing PCB circuit and patterns. Also, small and cheap flight control unit usually cannot upload custom software or has limit for extension and only can apply only one or limited number of vehicle model. To solve this limit, the flight control system is constructed by using 8-bit AVR processor, MEMS sensors, C/C++ language which can be quickly and easily programmed, and cheap, easy to buy.

The lacking in performance of 8-bit AVR processor could be solved by a parallel computing method that increased the number of processors. Due to simple structure of the complementary filter technique, designed flight control system could have performance of 250hz of control period despite of low computing performance of the 8-bit processor. By choosing Cascade PID controller as attitude control algorithm, it was able to obtain fast and robust control performance. As a result, stable flight performance could be achieved even in a palm-sized quadrotor UAV with a relatively large vibration.

Keywords Complementary Filter, MEMS Sensor, Quaternion, Cascade PID Control, Bluetooth, AVR

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1. Introduction

After first powered human flight, aircraft has become more faster, more safe and more cost-effective vehicles. Over the past 120 years, aerospace technology has grown exponentially and we are enjoying many benefits, such as flying intercontinental or exploring space But the conventional aircraft is commonly very expensive to buy it for personal purpose, so almost people cannot buy or use aircraft and aerospace service or not easy to buy its services such as aerial photography.

Fig 1. Micro Hexarotor using Low-cost FCU

But after Unmaned Aerial Vehicles(UAV) has been appeared, the peoples can buy their's own aircraft so they can do anything in the air such as aerial photography using this small aerial robots. So we can find the UAVs, called as "Drones", in anywhere and any countries. One of the reason of popularity of drones are low-cost. For example, if you want to get aerial photography or videos from air, you have to use helicopters or fixed-wing aircraft. As you know, we have to pay about rental fee, payroll for pilots and gas for operation. But the UAVs, which is called as drones, are no need to pay about gas, expensive payroll and rental fee because price of aircraft and operation costs are very low compared to conventional aircraft. Actually, it is not easy to make cheap UAVs because it needs various sensors and computing system to calculate its attitude, direction, velocity and so on to operate without pilot. So, all the UAVs need flight control computer or flight control system which is great part of UAV price. Flight control system contains various sensor such as Inertial Measurement Unit(IMU) for attitude, barometer for altitude and magnetometer for heading to obtain stable flight performance.

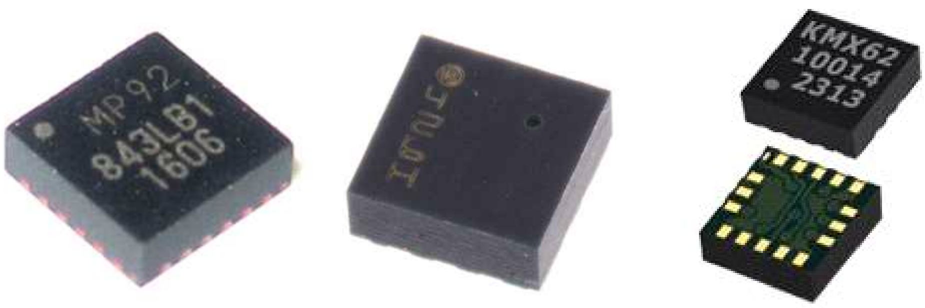

Fig 2. IMU, Barometer, Magnetometer Sensor for Multirotor UAV

Flight control system contains these sensors to get the basic flight data such as altitude, location, heading and attitude from ground and these data are used to calculate control value of each motor. Software is also very important components because vehicle must get data from each sensors and calculate basic flight data to get control values using digital signal process algorithm like Kalma n Filter or Complementary filter. The flight control system is completed by combining these hardware and software so it is usually one of expensive part in drones.

Usability and expandability are also important things for flight control system to use drones for various usage. Existing control system has limitation of expandability and expensive because of price of software and hardware components. To overcome these problems, MEMS sensors and low-cost Micro Control Unit(MCU) are helpful solution to reduce price and to secure usabilities.

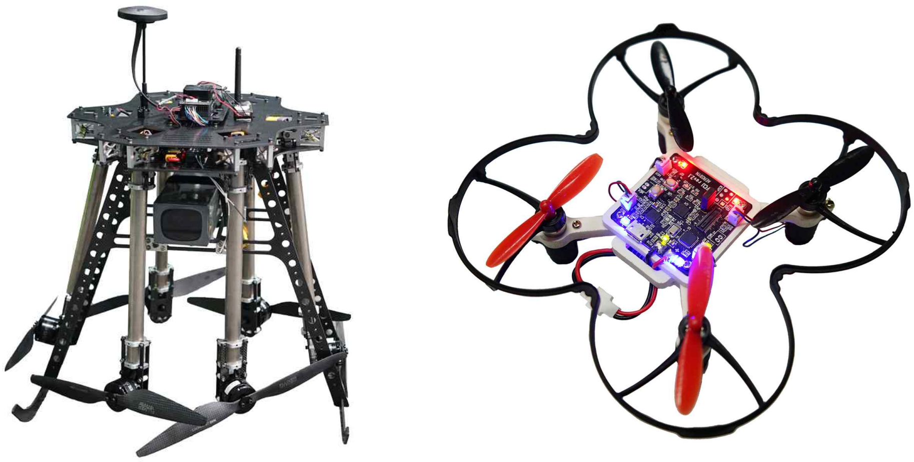

Fig 3. Quad/Hexarotor UAV to estimate flight control system

In this research, hardware and software of flight control system are designed using low-cost MCU and MEMS sensors and small-sized multirotor UAVs are designed using DC motor and BLDC motor to estimate flight performance.

1. 1. About Research

The key point of this research is the flight control system. This small, light-weighted computer system controls all the parts of multirotor UAV and manage entire flight status of vehicles to inform to pilot through wireless communication. This important basic systems are consist of five main parts.
The five main parts are as follow :

1) Power Management Unit(PMU)
2) Main Computing Unit(MCU)
3) Flight Sensor Unit(FSU)
4) Wireless Module
5) Motor Driver Unit(MDU)

These five components are essential to fly the drones in the air. First, Power Management Unit(PMU) controls battery power to produce proper power to propulsion system and computer system on the vehicle. Seconds, Main Computing Unit(MCU) handles sensor data and control data. Using these data, micro control unit(MCU) or micro processing unit(MPU) calculate attitude, direction, velocity, latitude, longitude and so on. Also, it can produce motor control signal to control attitude. It is connected to flight sensor, motor driver unit, wireless module to get data and send data. Third, Flight Sensor Unit(FSU) gather inertial data or altitude data to calculate attitude and navigation information. This sensor system is consist of Inertial Measurement Unit(IMU), barometer sensor, GNSS Module. After gathering these data, sensor unit sends it all to main processor. Fourth, Wireless Module comm unicate with Ground Control System(GCS) or UAV Traffic Management(UTM) System server. There are many wireless technologies using in drones. Typically used wireless networks are Wi-Fi, Bluetooth, Zigbee and LTE.

	Wi-Fi	Bluetooth	Zigbee	LTE
Range	> 1Km	> 100m	> 2Km	∞
Frequency	2.4GHz, 5.8GHz	2.4GHz	2.4GHz	1700/2100/2400
Power Consumption	High	Low	High	High
Latency	Middle	Low	Low	Middle
Speed	Over 50Mbps	Under 3Mbps	Over 1Mbps	Over 1Gbps
Costs	Middle	Low	Low	High

Table 1. Wireless Technology for Multirotor UAV

Fifth, Motor Driver Unit(MDU) controls rotation speed of each motors. There are two types of motor driver unit which is used to multirotor UAVs. One is brushed DC motor driver, the other is Brushless DC motor(BLDC) driver. In this research, DC motor is chosen because of research costs and simplified system.

There are various kinds of Inertial Measurement Unit(IMU) commonly using for Attitude Reference System(ARS) and there are many MEMS sensors which can apply in small-sized UAVs. Commonly using MEMS sensor is MPU series of TDK Invensense such as MPU-9250 or MPU-6050. Difference of these sensors are communication method and built-in magnetometer.

In this research, MPU-9250 sensor has adopted because of built-in magnetometer and size.

1. 2. Basic Theory

The most important things to design Flight Control System is digital signal processing algorithm and PID control algorithm to control attitude accurately. Digital signal processing algorithm is used for Attitude & Heading Reference System(AHRS) which calculate Roll, Pitch and Yaw angle relative to ground. Low Pass Filter and weighted-moving average filter are also commonly used to reduce vibration or error from MEMS sensors because of its simplicity. To get the Roll and Pitch angle from 6-DOF IMU sensor, Complementary Filter(CF) and Kalman Filter(KF) are used for attitude estimator. Each filter has different advantages and disadvantages in amount of calculation, accuracy, linearity and many other, but in this research complementary filter has chosen because of low amount of calculation.

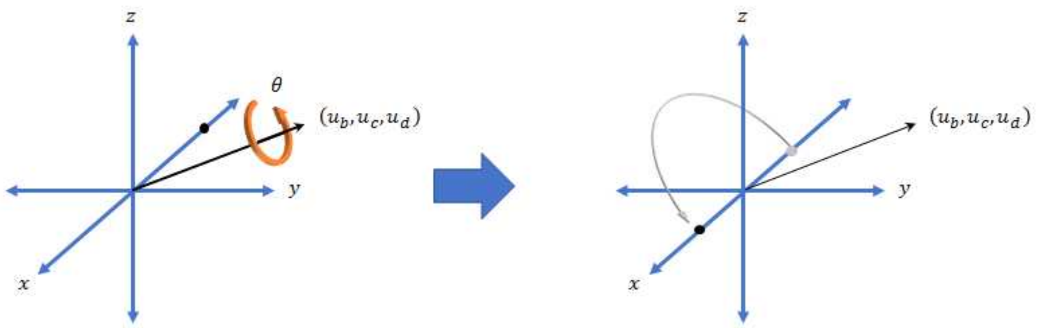

Fig 4. Quaternion in 3-D Space

The quaternion, which used to represent 3-D space with complex number, are used to rotate gravity vector and to get the Roll, Pitch, Yaw angles. This is key point of AHRS algorithm for low-cost flight control system because of advantages of amount of calculation and gimbal lock phenomena. There are many ways to rotate vector in 3-D space, Euler rotation, DCM and quaternion are commonly used. Euler rotation is easy to understand and calculate because of simple rotation principle. However, Euler rotation has fatal flaw called as "Gimbal lock" in which the rotational axes are overlap

Fig 5. Gimbal Lock Phenomena

ped and the Degree of Freedom(DoM) disappears. High computational complexity is another problem of Euler rotation because it needs to calculate 3×3 matrix three times. Quaternion is excellent tools to solve these problems. It represents 3-D coordinates using complex number and real number which is called as imaginary part and real part. It has advantages for low computational complexity and no gimbal lock phenomena but it is not intuitive.

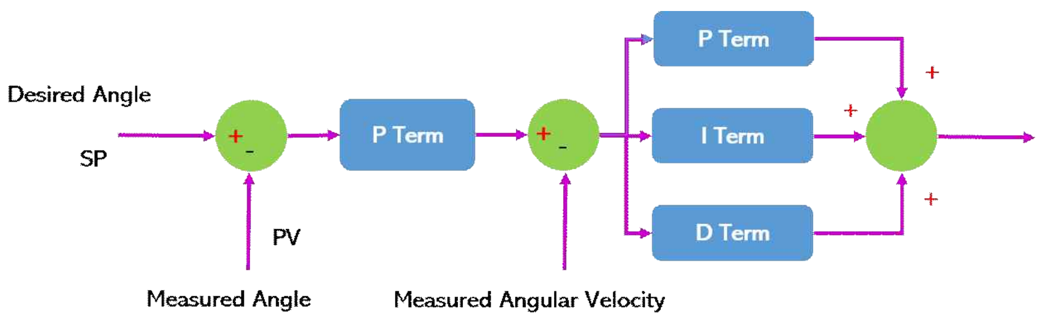

Fig 6. Block Diagram of Basic Cascade PID Controller

PID control algorithm is very widely used in various field of industry such as robots, elevators and car because of its simplicity, good control performance. Multirotor UAV also can use this algorithm to control attitude, altitude and heading. Especially, attit ude control system of multirotor UAV are use cascade PID control algorithm to get better control performance such as fast response, low overshoot. The cascade PID control algorithm uses more input control values than the existing PID algorithm, so it is more effective for systems with many disturbances, such as multi-rotor UAVs, which have many vibrations and fluctuations caused by multiple motors and propellers.

Fig 7. Propellers and motors in Hexacopter

1. 2. 1. Attitude Estimation

Attitude Estimation System is key components of Attitude Reference System(ARS) and it estimates direction of gravity vector from IMU sensor. Using accelerometer and gyroscope sensor data which is integrated in MEMS IMU Sensor, Roll and Pitch angle in global frame can be calculated thanks to sensor fusing algorithm and quaternion. Extented Kalman Filter(EKF) algorithm is commonly used because of its performance, but it needs more computing power than Complementary Filter(CF) algorithm. In a non-linear system, the complementary filter is somewhat lacking i n performance but has sufficient performance for most small UAVs.

Because of these reason, Attitude Estimation System in this research used quaternion and 1^{st} order complementary filter due to low computing power of MCU.

■ Basic of Quaternion

Quaternions are widely used to calculate 3D computer graphics or attitude of aircraft/satellite thanks to the convenience of vector rotation. To rotate vector without quaternion, “Rotation Matrix(RO)” which has information about rotation are needed. To get the rotation matrix, Euler rotation can be used but it is not commonly used in aerospace field because it causes “Gimbal lock” phenomena. Although gimbal lock phenomena is not appeared in “Straped-down system”, computation complexity and rotation sequence are another problems of Euler rotation.

Quaternion can help to solve these problem. Quaternion is consist of two components. One is real part representing rotation magnitude, the other is imaginary part representing direction of the rotation axes.

Quaternion basically can be expressed as follow:

$$q = q_w + q_x i + q_y j + q_z k$$

The quaternions is very similar to normal vector, but it has more component. Addition, subtraction, and multiplication are similar to ordinary vector algebra.

Let's start from two quaternions, p and q.

$$p = p_0 + p_1 i + p_2 j + p_3 k, \ \ q = q_0 + q_1 i + q_2 j + q_3 k$$

The addiction of two quaternions as follow:

$$p + q = (p_0 + q_0) + (p_1 + q_{1)} i + (p_2 + q_2) j + (p_3 + q_3) k$$

The subtraction of two quaternions as follow:

$$p - q = (p_0 - q_{0)} + (p_1 - q_{1)} i + (p_2 - q_{2)j} + (p_3 - q_3) k$$

The multiplication of two quaternions as follow:

$$p \bullet q = p_1 q_1 + p_2 q_2 + p_3 q_3 + p_4 q_4$$
$$p \otimes q = p_1 q_1 - p \bullet q + q_1 \vec{p} + p_1 \vec{q} + \vec{p} \times \vec{q}$$

Complex number also can be calculated.

$$ij = k, \ \ ji = -k$$
$$jk = i, \ \ kj = -i$$
$$ki = j, \ \ ik = -j$$
$$i^2 = j^2 = k^2 = -1$$

Because quaternion is a kind of complex number, conjugate can be calculated.

$$q^* = q_0 - q_1 i - q_2 j - q_3 k$$

Using this quaternion conjugate, magnitude of quaternion and u nit quaternion can be calculated.

$$qq^{*} = |q|^2 = q_0^2 + q_1^2 + q_2^2 + q_3^2$$

$$norm(q) = \frac{q}{|q|} = \frac{q_1}{|q|} + \frac{q_2}{|q|}i + \frac{q_3}{|q|}j + \frac{q_4}{|q|}k$$

The quaternions can be expressed in trigonometric form.

$$q = \sin\frac{\theta}{2} + \cos\frac{\theta}{2}\vec{v}$$

Vector rotation can be performed by multiplication.

$$\overrightarrow{v_g} = q_b \overrightarrow{v_b} q_b^{*}$$

This can be replaced by rotation matrix.

$$\overrightarrow{v_g} = R_b^g \overrightarrow{v_b}$$

$$R_b^g = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_1 q_2 - q_0 q_3) & 2(q_1 q_3 + q_0 q_2) \\ 2(q_1 q_2 + q_0 q_3) & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2(q_2 q_3 - q_0 q_1) \\ 2(q_1 q_2 - q_0 q_3) & 2(q_1 q_3 - q_0 q_2) & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix}$$

■ Complementary Filter

The complementary filter is a type of signal processing filter that is complementary to each other and used to obtain better output by fusing two or more sensor data having the same output. Generally, accelerometer and gyroscope sensors used in multi rotor UAVs are complementary in frequency characteristics. Therefore, when using these two sensors to estimate attitude, complementary filter gives better results than using one sensor have. In the IMU system, the complementary filter is used to compensate the high-frequency noise of the accelerometer and the low-frequency noise of the gyroscope sensor and to suppress the drift caused by integration of the gyroscope sensor.

Complementary Filter has cut-off frequency(α) which usually has value of 0.02 to 0.08 and it is very important because it determine accuracy and time-constant of filter.

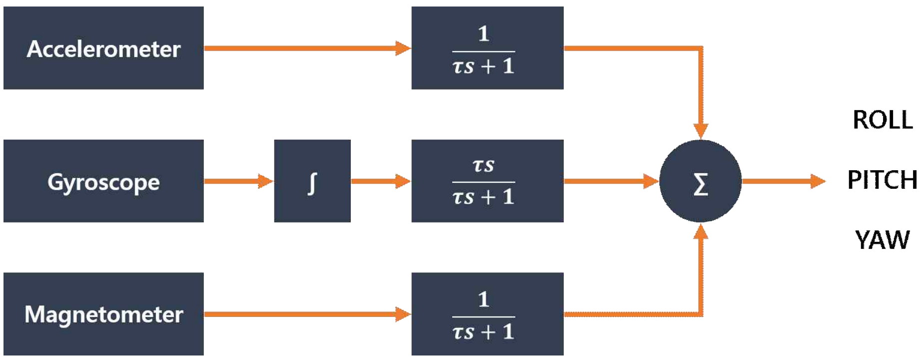

Fig 8. Block Diagram of 1st-order Complementary Filter

Fig 8 is block diagram of complementary filter of attitude reference system. Magnetometer has similar characteristic with accelerometer so it can be applied complementary filter with same transfer function.

The complementary filter consists of three steps of prediction, modification and interpolation. In prediction step, it rotates previous estimated gravity quaternion by integrating gyroscope sensor data and apply the High Pass Filter(HPF). The gravity quaternions from accelerometer also calculated and apply the Low Pass Filter(LPF) to result. After that, two results are combined and c orrect these results using Linear-Interpolation(LERP) or Spheric al Linear Interpolation(SLERP) algorithm.

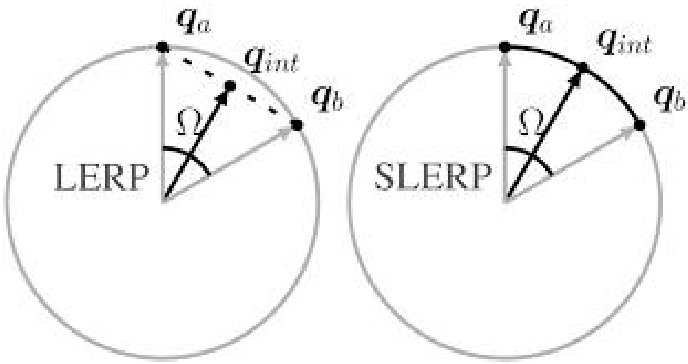

Fig 9. Conceptual Diagram LERP and SLERP

Linear interpolation (LERP) is not a good model for 3-D rotation because the magnitude of the interpolation result is not the same as the original two quaternions. However, calculations are so simple that if you sacrifice accuracy, it can be used it in low-performance computer systems such as 8-bit AVR computing system. Basic LERP algorithm is as follow.

$$q_{cor} = (1-\alpha)\, q_{gyro} + \alpha\, q_{acc}$$

This is very simple and easy to calculate, so MCU has less load compare to using SLERP algorithm.

Finally, estimated gravity quaternion can be convert Euler angle using following formula.

$$ROLL = \phi = \tan^{-1}\frac{2(q_0 q_1 + q_2 q_3)}{1-2(q_1^2+q_2^2)}$$

$$PITCH = \theta = \sin^{-1} 2(q_0 q_2 - q_3 q_1)$$

1. 2. 2. Cascade PID Controller

PID control algorithms are very powerful tools for almost auto matic control systems, and they are used in various fields becau se they are easy to design and have a simple structure. The PI D control algorithm consists of proportional term, integral term, and derivative term, and calculates the control amount using the current error the cumulative error, and the predicted error, resp ectively. Proportional term is basic component of PID controlle r, and it is essential because it corrects current error. Proportio nal gain determines control value of proportional term and basic form is as follow.

$$P = K_p e(t)$$

K_p is proportional gain and it affects rise time, overshoot, settli ng time and stability. If K_p is higher than the appropriate value, the rise time is shortened, the overshoot is increased, and the s teady-state error is reduced.

Integral term of PID controller corrects steady-state error by i ntegrating error. Basic form is as follow.

$$I = K_i \int^t e(t)dt$$

K_i is integral gain and higher K_p eliminate steady-state error. But it increases overshoot and settling time and reduce rise tim e so vehicle can be controlled more accurately.

Derivative term predict error and reduce disturbance like wind shear. This term is also important to reduce overshoot which is caused by higher K_p. However, it may not be used because it c an amplify the vibration of the vehicle.

Basic form of derivative term is as follow.

$$D = K_d \frac{de(t)}{dt}$$

K_d is derivative gain and higher K_p reduces overshoot and settling time but no effect to steady-state error.

	Rise Time	Overshoot	Settling Time	Steady-State Error
K_p	Decrease	Increase	Small Change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Small Change	Decrease	Decrease	Small Change

Table 2. Change of Behavior According to Gain

PID Control is completed by summing all terms, so it can be expressed as follow.

$$u(t) = K_p e(t) + K_i \int^t e(t)dt + K_d \frac{de(t)}{dt}$$

$u(t)$ is control value for each axis such as roll, pitch and yaw. This is pretty simple and easy to program, but not enough for multirotor UAV because large error of MEMS IMU.

■ Cascade PID Control Algorithm

A typical PID controller works well in most situations, but there are some cases where a PID controller is added inside to obtain better control performance. Cascade PID controller adds more processing value(PV) to reduce disturbance and to obtain fast response. Attitude angle and angular velocity are used as processing value for PID controller of multirotor UAVs, outer loop uses attitude angle as processing value and inner loop uses angular velocity as processing value.

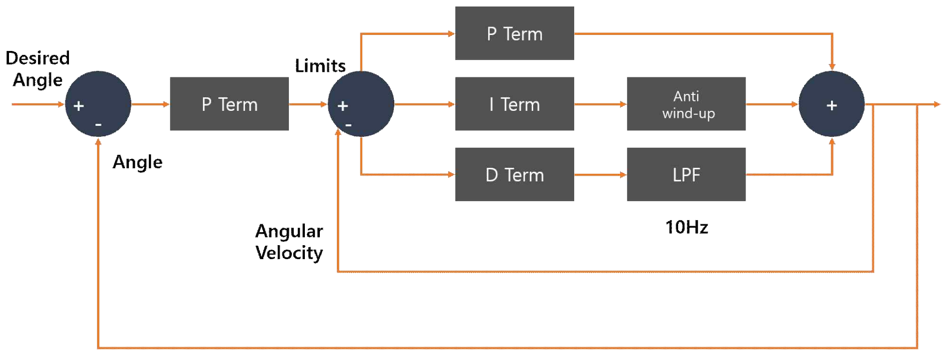

Fig 10. Cascade PID controller for Multirotor UAV

Outer PID controller using attitude angle can use proportional term, integral term, and differential term, but usually it can control performance even with proportional term. Results of outer PID controller is desired angular velocity and it enters to inner PID controller as Set Point. Inner PID controller calculate final control value using angular velocity, and it consists of proportional term, integral term and derivative term. Since the internal PID controller includes the integral term and the derivative term, it is necessary to apply the anti-windup technique to prevent the saturation of the integral term and the Low Pass Filter to prevent the vibration amplification caused by the differential term.

After that, control value goes to motor control algorithm and it will be used as parameter of formula of multirotor dynamics.

1. 3. Research Goal

The design of hardware and software for low-cost flight control system is a key goal, and the performance and cost are estimated by comparing to existing flight control system. Flight computer(FC) will be designed using 8-bit micro control unit and MEMS sensors for low-cost and applying Arduino platform to reduce cost and time. ARS and PID controller is programmed using C/C++ language because multirotor UAV is time-significant system. Entire block diagram of low-cost flight control system can be seen in Fig 11.

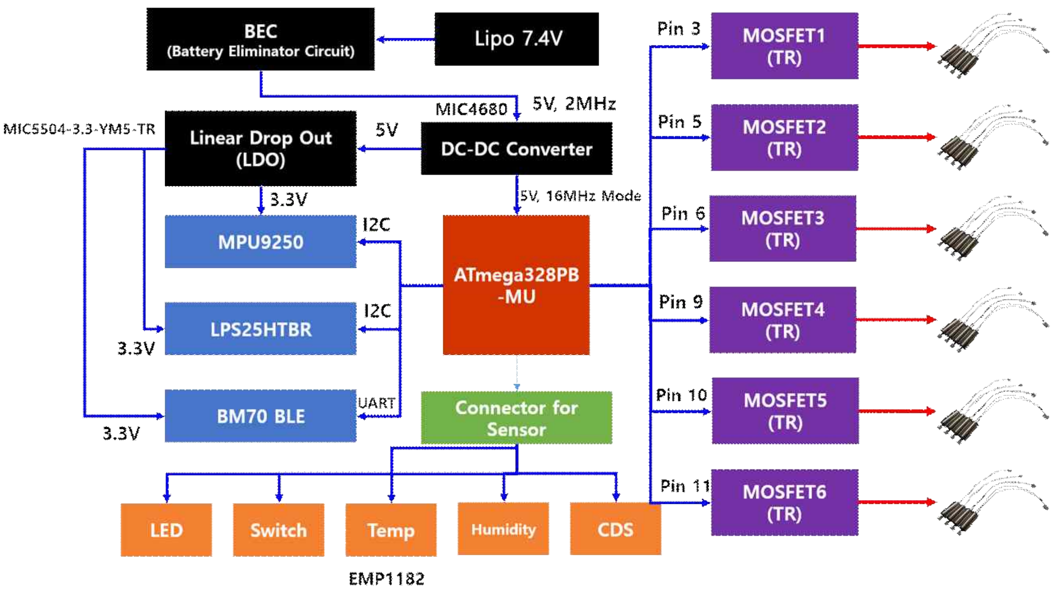

Fig 11. System Diagram of Low-cost Flight Control System

2. Hardware Design

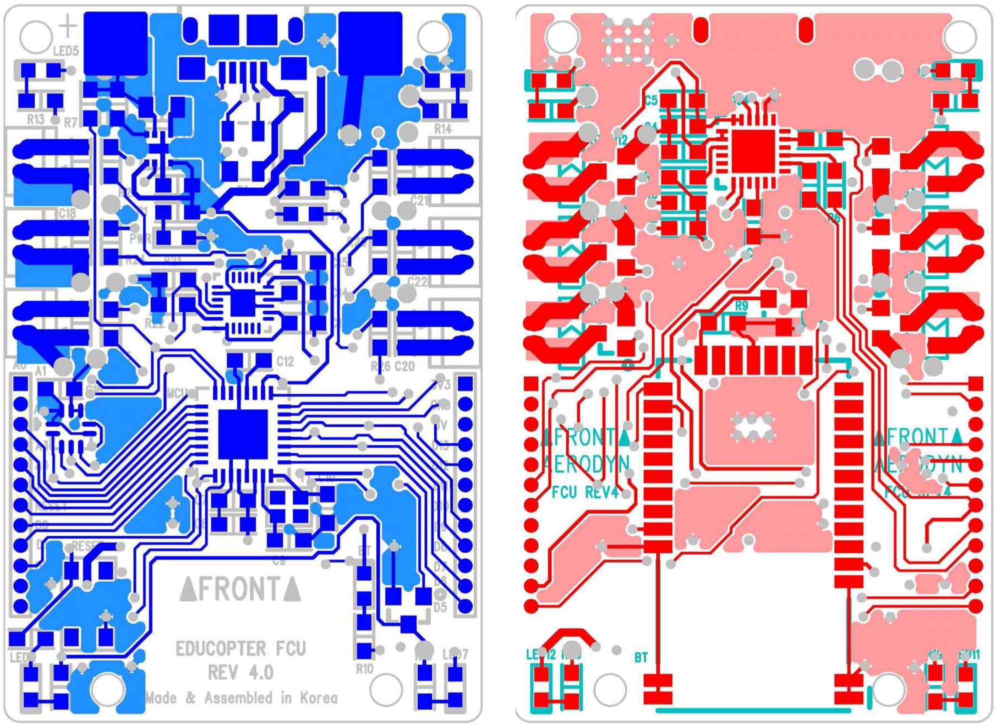

Fig 12. Pattern Design of Flight Control Computer and Motor Driver

In order to design low-cost flight control system, it is necessary to design power management board that manages and distributes power and mainboard which controls the motor and attitude of the vehicle. The mainboard includes an MCU for performing various mathematical calculations, managing and controlling peripherals. It contains IMU for measuring attitude, a digital barometer for measuring altitude and a wireless communication module for sending and receiving commands from the pilot. Arduino platform is also applied to create, modify and test flight control software easily and conveniently. Attitude Reference System(ARS) bas ed on quaternion and 1st order Complementary Filter which is the most important components to multirotor UAVs are also integrated. 6-channel of DC motor driver has been integrated due to convenience for designing micro-sized quadrotor UAV. Also, there are expansion port is located on side of flight control computer, it is easy to add more components and to use BLDC motor driver which is called as Electric Speed Controller(ESC).

Palm-sized qua using coreless dc motor and mid-sized hexacoptor using BLDC motor has been designed and fabricated to estimate flight performance and sensor accuracy. These vehicles are made using plate of Carbon Fiber Reinforced Plastic(CFRP) and ABS resin because of strength and price.

Fig 13. Plate of 3K Plane CFRP (Thickness : 2mm)

2. 1. PCB Design

Low-cost flight control system in this research is consist of two difference Printed Circuit Board(PCB). One is the main control module, the other is Power Management Unit for power conditioning and distribution. Main PCB module has Micro Control Unit (MCU), USB to UART Bridge, Bluetooth Module, MEMS IMU Sensor, digital Barometer and Motor Drive Circuit for DC motor. Power Management Unit(PMU) has DC-DC Converter for Flight Control Unit and sensor system, also distribute power to Electric Speed Controller(ESC) for Brushless DC Motor(BLDC Motor). It utilizes a Schottky diode to design the circuit to supply a wide range of voltages from 14V to 50V.

2. 1. 1. Design of Flight Controller

Low-cost flight control computers have more advantages for compact, light enough to make palm-sized drones with low power consumption in addition to price. Usually the palm-sized drones are less than 150 mm diagonal spacing of the motor, so the flight control computer and power management unit should be designed to be smaller than this size. However, when the DC motor drivers are embedded, line width of circuit must be increased in order to prevent the stable power supply and the overheat. But the most important things are electric components such as resistor, capacitor, MCU, sensor IC and so on because it determine power consumption and voltage level. In order to choose key components, main function and specification of flight control compu ter should be determined. After that, power consumption should be estimated from datasheet of chosen components.

Main purpose of flight control computer is controlling attitude of vehicles using attitude and altitude data. To achieve this goal, main processor and sensors should be chosen after considering cost, dimensions and performance. However, because there are not many low-cost processors that supports the Arduino platform, ATmega328P-MU is chosen as main processor because of price, soldering difficulty and easy to use design reference. Specification of ATmega328P-MU is as follow.

Part Name	ATmega328P-MU
Clock Speed	4 - 20MHz
Operating Voltage	1.8V - 5.5V
Package	MLF32
RAM	2KBytes SRAM
EEPROM	1KByte
Flash Memory	32KBytes
Timer/Counter	8-bit × 2 & 16-bit × 1
Pin Count	32
Pwm Channel	6
ADC	10-bit × 8
Communication	USART, I2C, SPI

Table 3. Specification of Flight Control Computer

This is not powerful processor, but small, cheap and easy to use 8-bit RISC processor, so it is used various embedded system for simple application.

IMU sensor is also very important thing because flight compute r can estimate attitude of vehicle using this sensor. Since IMU consists of an accelerometer and a gyroscope sensor, each sensor can be individually selected, but integrated IMU sensor is better choice because dimension of PCB is limited. The IMU sensor, usually used in small drones, uses MPU series due to low price and lots of design reference. MPU6500 sensor and MPU9250 can be chosen because it contains both accelerometer and gyroscope sensor. Difference of two sensor is as follow.

	MPU6500	MPU9250
Dimension	3mm × 3mm × 0.9mm	3mm × 3mm × 1.0mm
Operating Voltage	1.71V - 3.45V	2.4V - 3.6V
Accelerometer	±2g, ±4g, ±8g, ±16g	
Gyroscope	±250DPS, ±500DPS, ±1000DPS, ±2000DPS	
Magnetometer	No	0.15uT, 0.6uT
Communication	I2C, SPI	
Package	QFN-32	

Table 4. Comparison of MPU6500/9250 sensor series

Barometer is not important sensor, but it is necessary when controls altitude. LPS25HBTR digital barometer is good enough to apply low-cost flight control system because of small-size and supporting I2C communication. Specification of LPS25HBTR is as follow.

Part Name	LPS25HBTR
Resolution	0.01hPa(RMS)
Operating Voltage	1.7V - 3.6V
Range	260 to 1260hPa
Communication	SPI, I2C
Data Rate	1Hz to 25Hz

Table 5. Specification of LPS25HBTR Barometer

The remaining components are the USB interface which support Arduino platform for debugging and programming the software, and the SiliconLabs CP2104 is chosen as the USB to UART Bridge IC. CP2104 can be used as Linear Drop Out(LDO) to get the 3.3V power because it has built-in LDO circuit.

The last component of the flight control unit is a wireless communication module that exchanges data with pilots who is on the ground. Typically, a PPM or SBUS transceiver is used, Bluetooth Low Energy(BLE) is used as wireless communication system because of size and price in this time.

Now, entire power consumption of flight control computer can be estimated from datasheet of each components.

Part Name	Supply Voltages	Peak Current	Power Consumption
ATmega328P-MU	5.0V	950.0mA	4.75W
MPU9250	3.3V	3.7mA	0.01221W
LPS25HBTR	3.3V	0.025mA	0.0000825W
CP2104-F03-GMR	5.0V	18.5mA	0.0925W
RN4870	3.3V	26mA	0.0858W
		Total	**4.94W**

Table 6. Power Consumption of each Components

Next step is circuit design. All the sensors and processor should be connected with each other to gather data for essential flight data such as roll, pitch, yaw.

The first circuit is power supply circuit of flight computer. A power circuit was constructed using a Schottky diode to support battery power and USB power simultaneously.

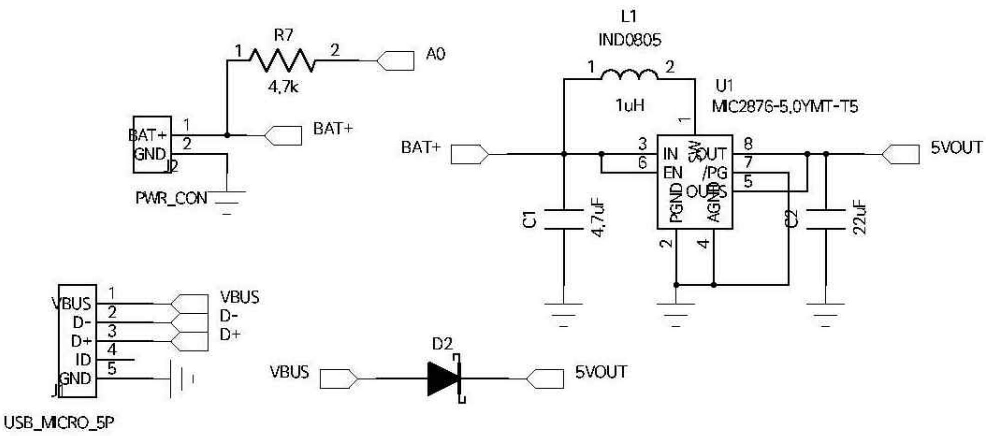

Fig 14. Power Supply Circuit Diagram for Flight Computer

To provide a stable supply of power, Microchip MIC2876-5.0YMT-T5 DC to DC Switching Converter has been used which can supply power 5V output and an average load current of about 2.8A. The Schottky diode, MBR0530T1, was used to protect the USB port when both battery power and USB power were used.

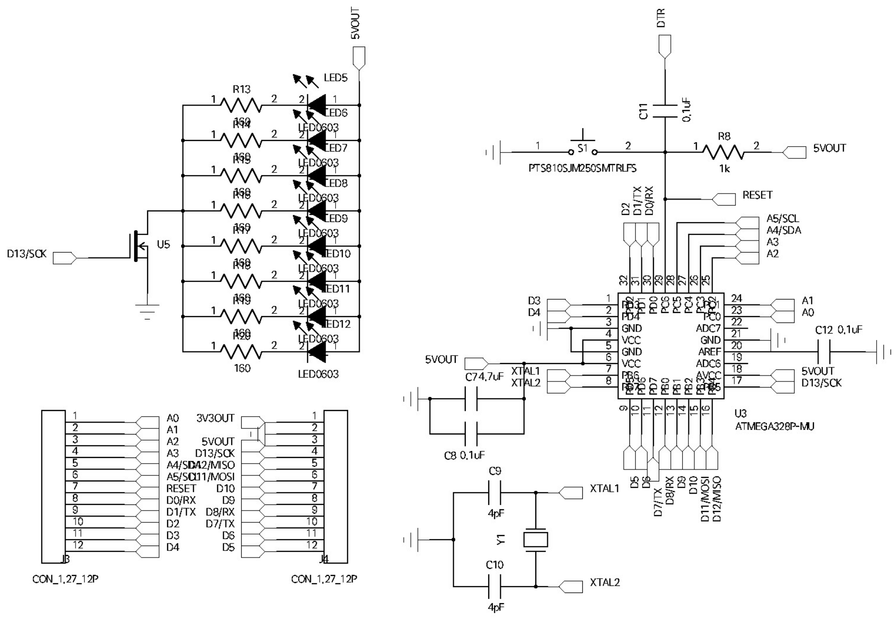

Fig 15. Circuit Diagram of MCU and Extension Port

Next step is circuit for Micro Control Unit(MCU). Due to space constraints, the size of the MCU should be as small as possible and therefore ATmega328P-MU of Micrichip Technology in the MLF-32 package was chosen. To support the Arduino platform, the ATmega328P-Mu chip must be powered from 5V and operate at 16MHz, thus requiring an external oscillator circuit. It also requires an expansion port for feature expansion and chip programming.

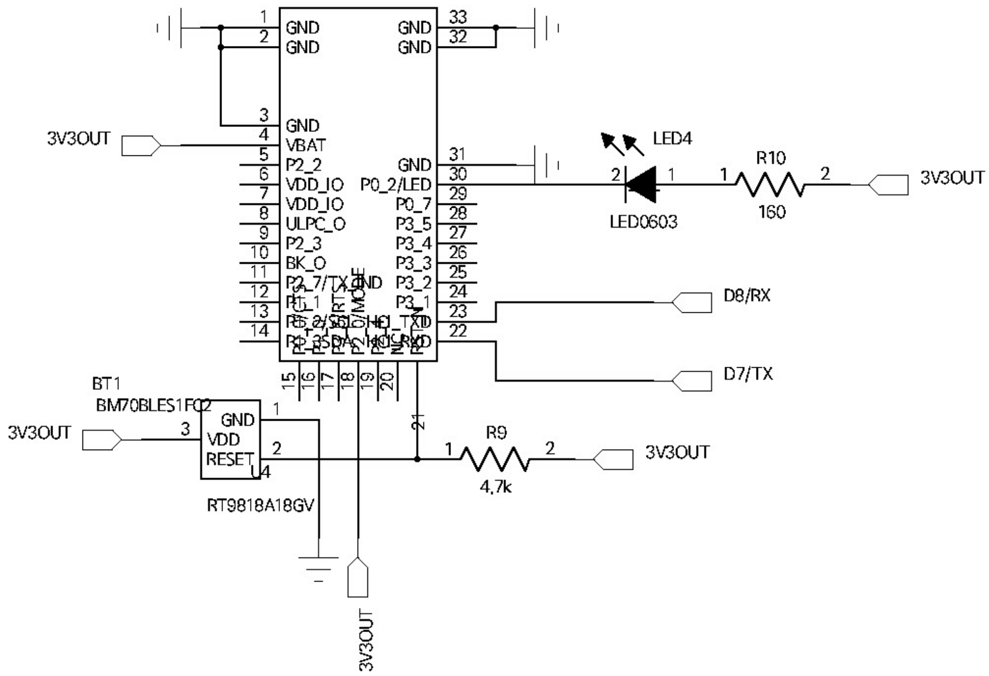

Fig 16. Circuit Diagram of RN4870 Bluetooth Module

Bluetooth is a wireless communication technology that can be useful when controlling or configuring a drones using a smartphone or tablets. There are many ways to add this feature, but Microchip Techonology's RN4870 Bluetooth module has been integrated to reduce reliability, design time and cost.

Next step is circuit of IMU sensor and digital barometer. In order to design low-cost flight control system, MPU9250 9-axis MEMS IMU sensor and LPS25HBTR digital pressure sensor circuit are required. Unlike MCUs, these sensors require a 3.3V power supply and communicate with the MCU using the I2C serial protocol. I2C communication should supply power separately to the data line and the clock line, and it must operate at TTL level. In this design, TTL Level is 3.3V because of reference voltage of sensor.

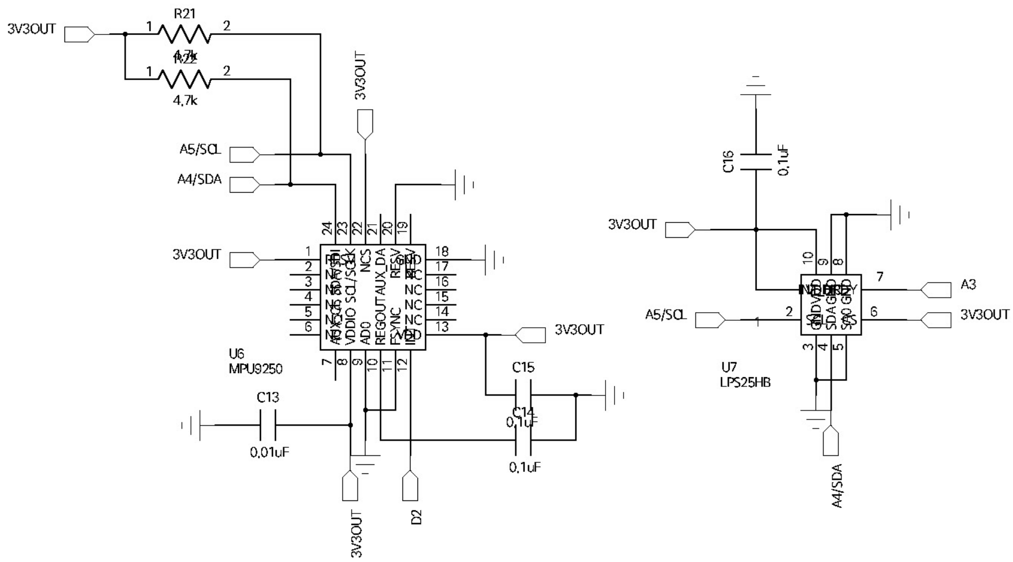

Fig 17. Circuit Diagram of MPU9250 and LPS25HBTR Sensor

The final step is to integrate the motor driver circuit for DC motor drive in the Flight Control Unit. The DC motor uses a transistor to control the voltage input because the rotation speed varies depending on the voltage value. The Pulse Width Modulation(PWM) technique can be used to control the voltage input using transistors. The PWM signal controls the amount of voltag e that is connected to the gate line of the MOSFET. Now, rotation speed of motor can be controlled, but there are several problems on this circuit. The biggest problem in electronically controlling DC motors is the back-EMF phenomenon. This phenomenon can damage the power supply circuitry and diodes and capacitors can prevent this.

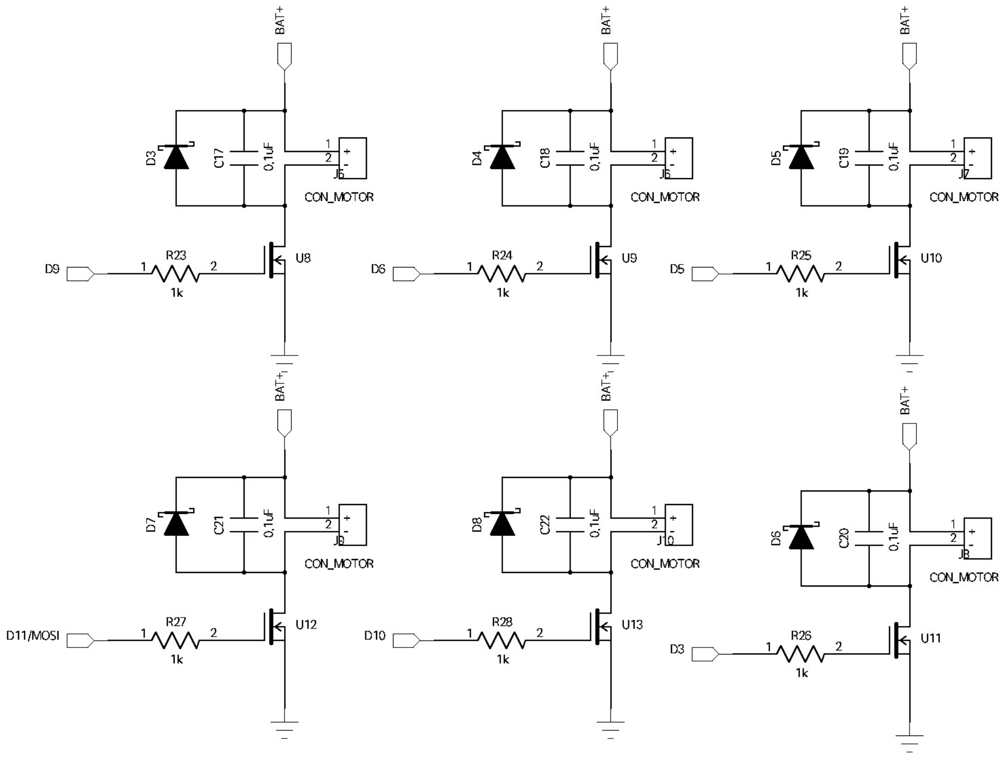

Fig 18. Circuit Diagram of DC Motor Driver Unit.

From this circuit design, circuit pattern of flight control system that includes DC motor drive circuit can be designed. The flight control computer is designed to have a small size of about 40mm(L) × 32mm(W) × 11.8mm(H) including connector that can use with a palm-sized multicopter.

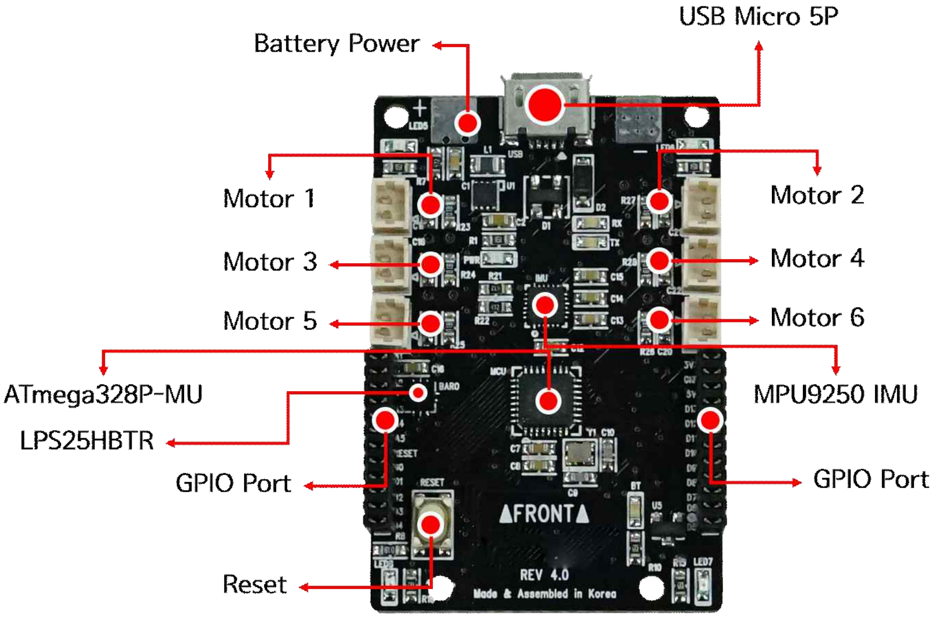

Fig 19. Schematic Diagram of Top of Flight Control Computer

Top of the flight control computer consists of the main processor, sensor, and DC motor connector. DC motor connector uses the Molex Picoblade 0530470210, which is mainly used as the motor connector of the palm-sized multicopter.

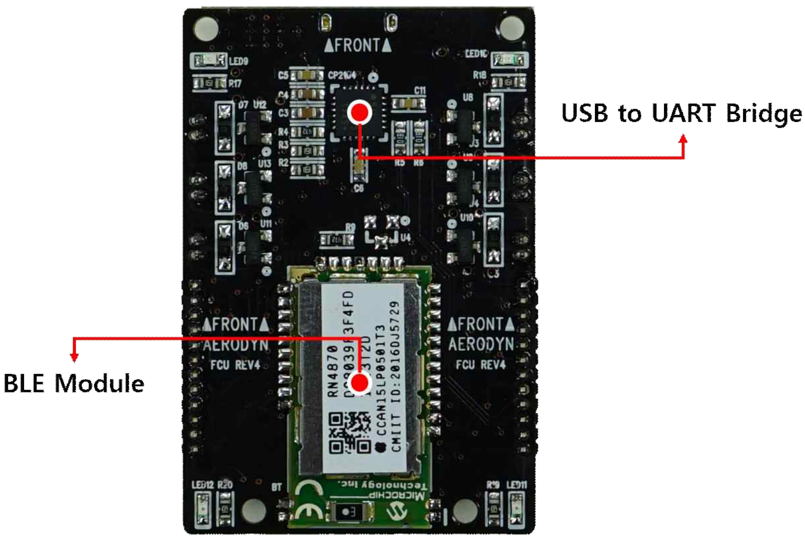

Fig 20. Schematic Diagram of Bottom of Flight Control Computer

2. 1. 2. Design of Power Management Unit for BLDC System

Brush causes friction inside the normal DC motor, which causes various problems such as deterioration of life, heat generation, low output, and noise. Unlike normal DC motor, Brushless DC(BLDC) motor do not have brushes to convert the current flow, so they have a variety of advantages.

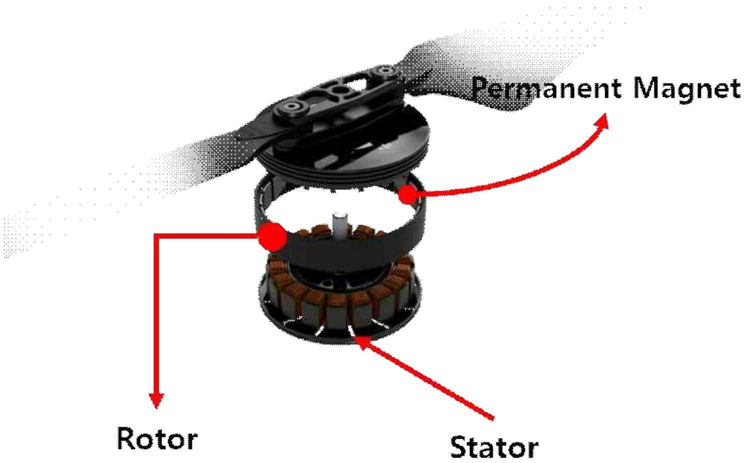

Fig 21. Internal Structure of BLDC Motor

However, BLDC motors require an inverter circuit that convert DC power to 3-phase power because it can not use DC power directly. This inverter is called as Electric Speed Controller(ESC) and it can control rotation speed of BLDC motor. ESC can be controlled by using the PWM signal of a certain period outputted from the MCU and the rotation speed is changed according to the duty cycle of the PWM signal. In general, BLDC motors are driven at a relatively high voltage compared to DC motors because of their high output. Most of BLDC motors are designed according to the number of cells of a lithium polymer bat tery and require a voltage from at least 2 cells (7.4V) to 12 cells (44.4V). However, if such a high voltage is supplied directly to the flight control system, the circuit will be destroyed by the overvoltage. Therefore, the voltage supplied from the battery should be lowered to be supplied to the flight control system, and the motor must be supplied with the battery voltage as it is. Power Management Unit(PMU) can do this. To support most drones systems, PMUs are designed with the following specifications:

Dimension			130mm(L) × 100mm(W) × 25mm(H)
Weight			76.8
Input Voltages			4S(16.8V) to 12S(44.4V)
Output Power			3.3V × 3
			5V × 3
			12V × 3
Operating Current			Max 480A
No. of PWM Channel			8-Channel
Input Connector			XT-90 / AS-150
Output Connector	Under 6S(22.2V)		XT-60 × 1
			XT-90 × 1
	Over 6S(22.2V)		XT-60 × 1
			XT-90 × 1

Table 7. Specification of Power Management Unit

The first step is to design the battery power input circuit. It is needed to support a wide range of voltage inputs from 4 to 12 cells, power diode can be used to increase the voltage input range. When it needs more than 6 cells input, it is possible to supply the power of 12 cells through the circuit containing the diode. Therefore, it is very important to select the power diode appropriately. To support over 480A output current, FSV106

0V(On semiconductor) is proper because of low voltage drop and high Non-Repetitive Peak Forward Surge Current.

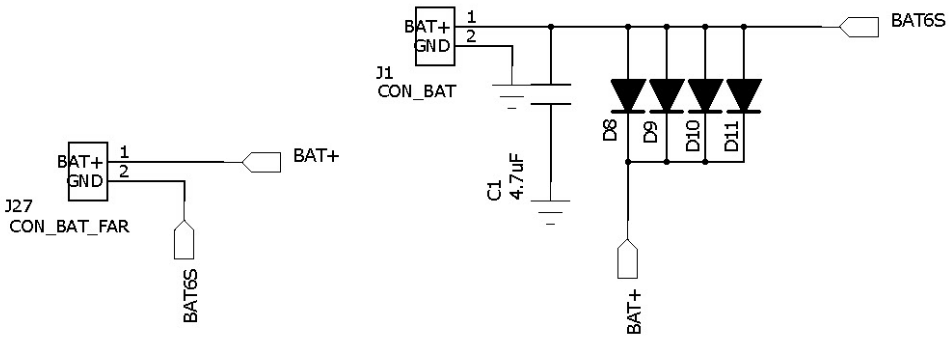

Fig 22. Circuit Diagram of High Voltage Battery Input

Four FSV1060V Diodes were used to support high currents.

The next step is the design of a low-voltage power supply system for Flight Control Computers and peripherals. Flight control system usually uses a voltage of 5V or less, but the 12V circuit is added because the most LED control system or servo system uses 12V. This system supports 12V, 5V, 3.3V voltage output and 1.3A output current through MCP16301H DC to DC Buck Converter.

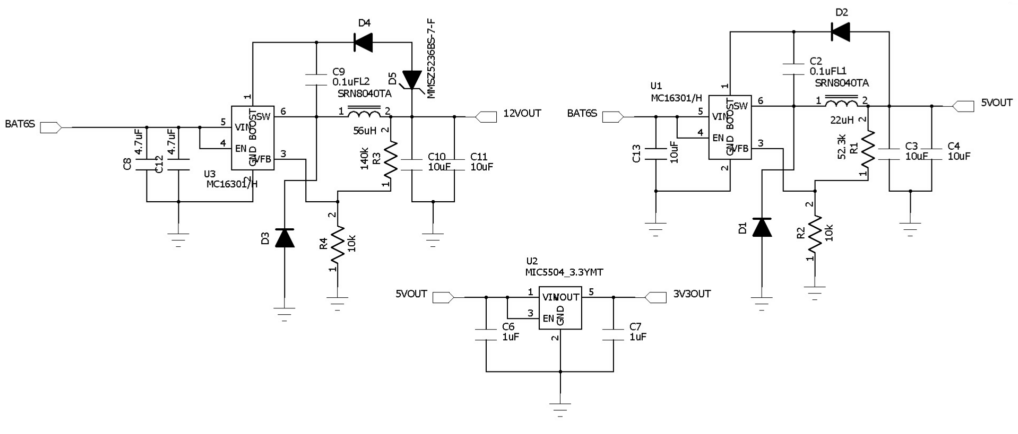

Fig 23. Circuit Diagram of Low Voltage Output

The circuitry that supplies ESC power is simple but very important because of the high voltage and high current. Especially, circuit pattern is very important to supply high current.

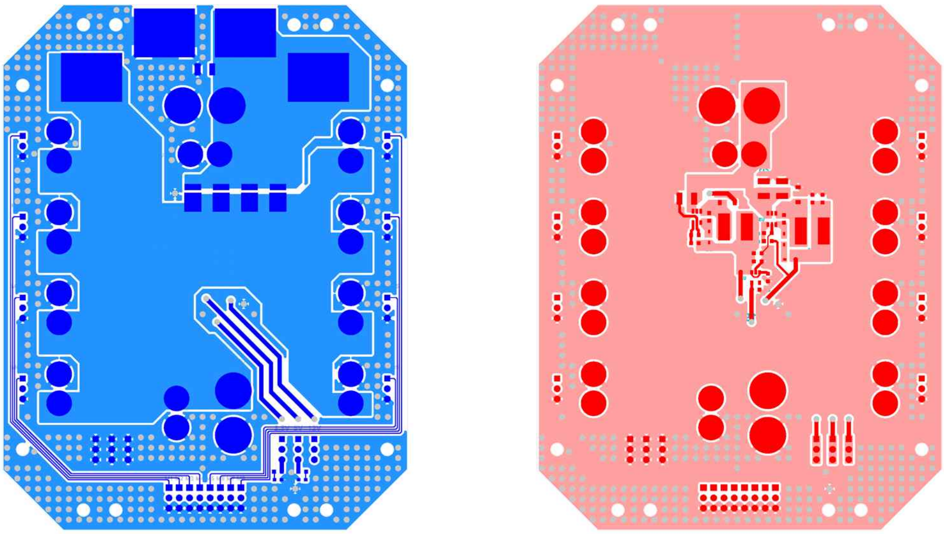

Fig 24. PCB Pattern of Power Management Board

Fig 25. Power Distribution Board for BLDC Motor System

2. 2. Body Frame Design

Body frame is also important thing for multirotor UAV system because MEMS sensors are very vulnerable to vibration. Becau se the most vibration is caused by propulsion system, fuselag e should absorb these mechanical vibration using damper or an ti-vibration design. There are many ways to reduce mechanical vibration that caused by propellers and motors, but it is better to design a fuselage with elastic material such as silicone or ru bber. However, when using only ductile materials, it is not pos sible to cope with the bending stress caused by the thrust gen erated by the motor and the propeller. Therefore, it is better t o apply a ductile material to the area where the motor and the propeller are fixed or the landing gear.

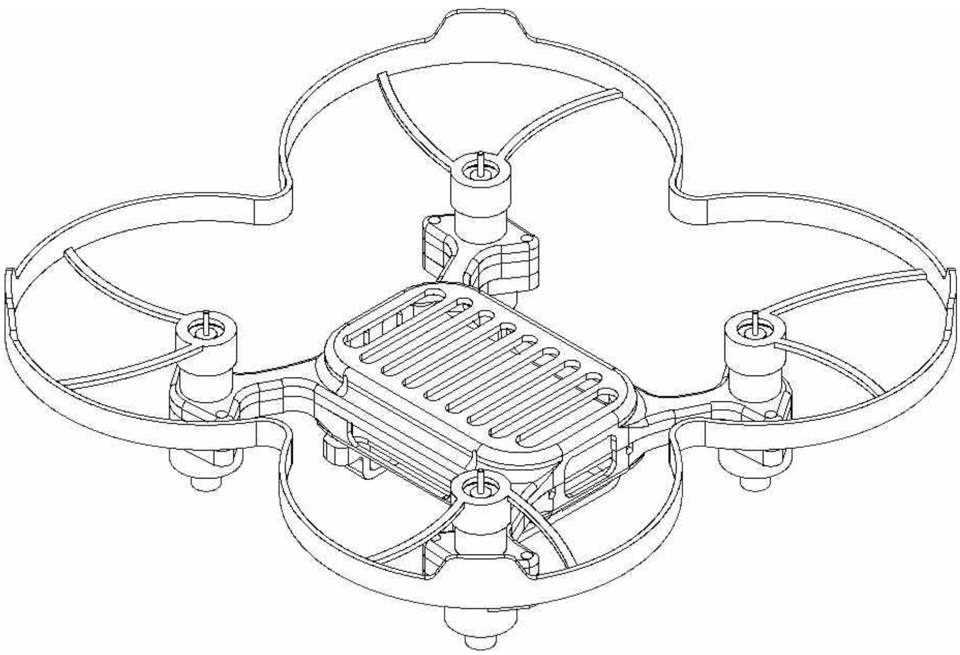

Fig 26. Conceptual Design of DC Motor Powered Quadcopter

In order to reduce the production cost in the case of small-sized production, it is better to use the CNC manufacturing using plate material rather than plastic mold. If the required quantity is 10 or less, a process for producing a mock-up like a vacuum mold may be considered.

2. 2. 1. DC Motor Powered Quadcopter

When DC motor rotates its shaft, there are friction on internal brush and it causes mechanical vibration when the surface of the rotating shaft is not uniform. To reduce such vibration, it is necessary to apply vibration damping pad made of silicon to motor mount or the landing gear.

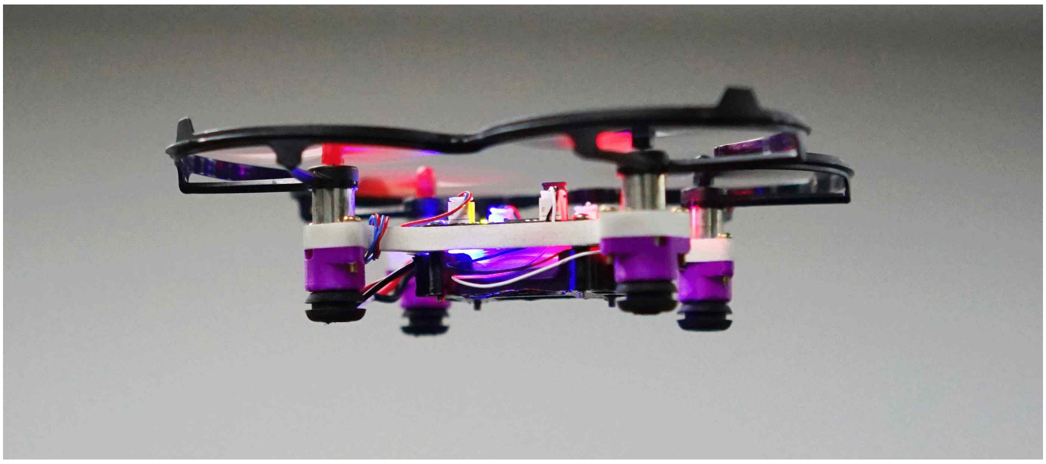

Fig 27. A Lower Body with Vibration Damping Pad

To reduce production costs, propellers and protective cover were made of commercial off-the-shelf products and main body is made by 3-D printing. Specification of DC motor powered quadcopter is as follow:

Dimension	136mm(W) × 136mm(L) × 48mm(H)
Weight(Body Only)	16.8g
Material	ABS
Propulsion System	0825 Coreless DC Motor × 55mm Props
Battery	Lithium-polymer 3.7v 500mAh 25C
Battery Bay	42mm(L) × 25mm(W) × 8.4mm(H)

Table 8. Specification of Palm-sized Quadcopter

The material of the fuselage is ABS resin, which is mainly used in 3D printers, and is relatively shock-resistant and inexpensive. It also has a structure that is firmly fastened with M2× 6 mm screw, so that vibration generated by motor and propeller is suppressed to the utmost.

Fig 28. 3D Rendering Image of Palm-sized Quadcopter

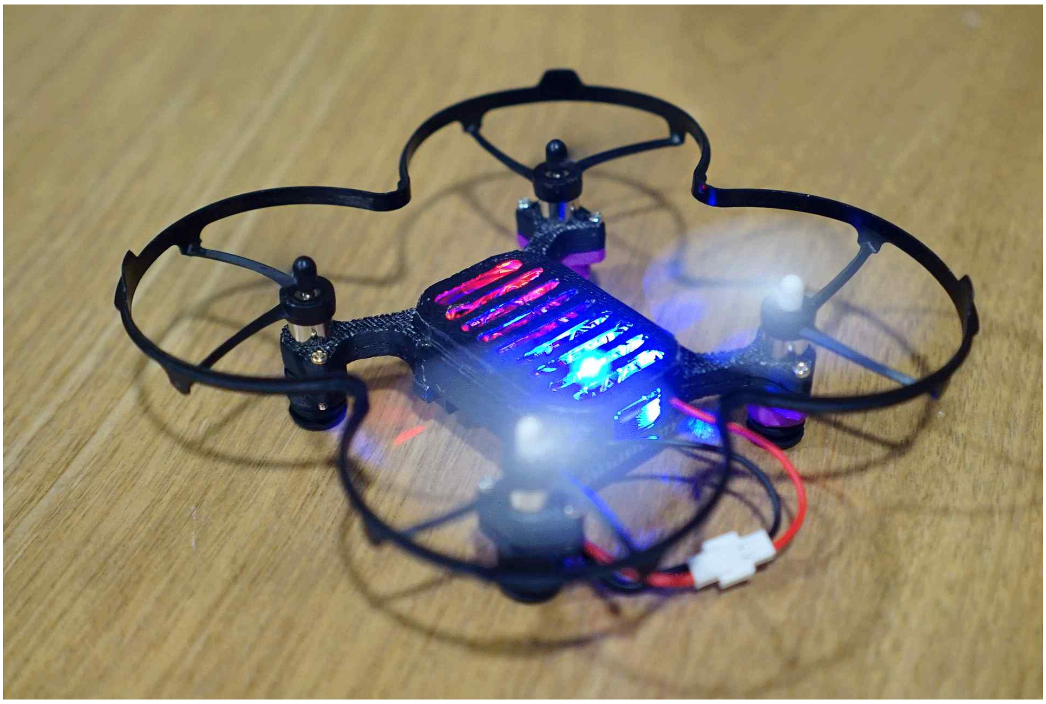

Fig 29. Fully Assembled and Manufactured Body

2. 2. 2. BLDC Motor Powered Hexacopter

Unlike multicopter that use DC motors, drones that use BLDC motors usually have more power and should be designed to be more robust. Also, compared to DC motors, BLDC motors consume enormous energy as strong output, so the batteries that have more capacity and high voltages are needed. Therefore, drones using BLDC motors need to be bigger and they are made of light and durable materials such as CFRP or aluminum to reduce the empty weight.

The CFRP, which is abbreviated word of Carbon Fiber Reinforced Plastic, is light-weighted, high tensile strength material but it is relatively expensive than plastics or aluminium and have bad machinability. Therefore, it is usually designed using aluminum or plastic together without using only CFRP materials.

Fig 30. 3D Rendering Image of BLDC Motor Powered Hexacopter

Empty Weight	3.7Kg
Battery Weight	1.72Kg
Maximum Take-Off Weight	12.0Kg
Payload	약 5.1kg
Cruised Speed	10 m/s (36km/h)
Maximum Speed	15 m/s (54km/h)
Flight Time	20min (12,000mAh 5.42Kg)
Maximum Control Range	1Km ~ 2km

Table 9. Specification of BLDC Motor Powered Hexacopter

3. Software Design

3. 1. Flight Software Design

Flight control systems used in multi-rotor type UAVs vary greatly in flight performance depending on software algorithms and optimization rather than hardware. In particular, the Attitude Reference System(ARS), which uses the MEMS IMU sensor data and Kalman filter or complementary filter to measure the attitude of a vehicle, is a key technology element in designing and manufacturing a multi-rotor UAV. The attitude data obtained from the MEMS IMU sensor is used as the reference data of the PID control system which calculates the control amount of each motor. The PID control system calculates the control amount of each motor using attitude data to maintain the required roll, pitch, yaw angle that desired from the pilot. The PID control algorithms used in most multi-rotor type UAVs are implemented by software and the flight performance can be greatly changed according to the algorithm implementing the PID controller.

Finally, in order to control an multirotor UAVs, wireless communication is indispensable. In order to control multirotor UAVs using wireless communication system, data communication protocol between the object and the pilot is required. The MAVLink protocol is commonly used which is optimized for small UAV, including multi-rotor type UAV, but this system uses stand-alone protocol because of low computing power of flight control system. This protocol optimized to control vehicles through Bluetooth or Wi-Fi to send or receive control/status data.

2. 3. 1. Attitude Reference System

Attitude Reference System is key component of low-cost flight control system to control attitude of drones. Extended Kalman Filter(EKF) algorithm is commonly used for Attitude Reference System and Navigation & Guidance System in drones, but it is not proper to low-cost flight control system because EKF requires a lot of computing power. On the other hand, Complementary Filter algorithm is simpler, faster, and requires less computational complexity than the EKF algorithm. Because of these advantages, the Complementary Filter algorithm is suitable as an attitude estimation algorithm for a low-cost flight control system. To reduce more computation complexity when calculate estimated gravity vector, the quaternion can be useful solution.

To get Roll and Pitch angle and angular velocity using quaternion and 1^{st} order complementary filter, it requires raw sensor data from accelerometer and gyroscope sensor. MPU-9250 sensor can provide these data from integrated 3-axis accelerometer and 3-axis gyroscope sensor, and it send data to MCU through I2C communication line. I2C communication has a 7-bit address system, and I2C address of MPU9250 sensor is 0x68 or 0x69 depending on status of AD0 pin. If AD0 pin is connected to ground, I2C address of MPU9250 is 0x68. When designing PCB of flight control unit, AD0 pin has been connected to ground, so I2C address of MPU9250 is 0x68.

MPU9250 has internal register sets that can control sensor and can store measured data. For example, the register address 0x3B stores the MSB data of the X-axis data of the acceleration sensor. The register addresses that are required to use the

MPU9250 sensor are as follows.

Hex Address	Name	Usage
0x1A	CONFIG	Set Internal Digital LPF
0x1B	GYRO_CONFIG	Gyro Data Range(250~2000DPS)
0x1C	ACCEL_CONFIG	Accelerometer Data Range(2g~16g)
0x1D	ACCEL_CONFIG2	Set Accelerometer DLPF
0x3B	ACCEL_XOUT_H	MSB of X axis Accelerometer Data
0x3C	ACCEL_XOUT_L	LSB of X axis Accelerometer Data
0x3D	ACCEL_YOUT_H	MSB of Y axis Accelerometer Data
0x3E	ACCEL_YOUT_L	LSB of Y axis Accelerometer Data
0x3F	ACCEL_ZOUT_H	MSB of Z axis Accelerometer Data
0x40	ACCEL_ZOUT_L	LSB of Z axis Accelerometer Data
0x43	GYRO_XOUT_H	MSB of X axis Gyroscope Data
0x44	GYRO_XOUT_L	LSB of X axis Gyroscope Data
0x45	GYRO_YOUT_H	MSB of Y axis Gyroscope Data
0x46	GYRO_YOUT_L	LSB of Y axis Gyroscope Data
0x47	GYRO_ZOUT_H	MSB of Z axis Gyroscope Data
0x48	GYRO_ZOUT_L	LSB of Z axis Gyroscope Data
0x6B	PWR_MGMT_1	Sleep/Wake up, Clock Select
0x6C	PWR_MGMT_2	Disable/Enable Gyro/Accelerometer

Table 10. Register Map of MPU9250

These registers allow basic sensor configuration and power management, as well as read raw data from gyroscopes and accelerometers.

To get attitude data from this sensor, initial estimated gravity quaternion should be calculated. Initial estimated gravity vector could calculate from accelerometer data, using following formula which is convert from measured gravity vector to quaternion notation.

$$q_{est,0} = \left[\sqrt{\frac{a_z+1}{2}} \quad -\frac{a_y}{\sqrt{2(a_z+1)}} \quad \frac{a_x}{\sqrt{2(a_z+1)}} \quad 0 \right], \quad a_z \geqq 0$$

$$q_{est,0} = \left[-\frac{a_y}{\sqrt{2(a_z+1)}} \quad \sqrt{\frac{1-a_z}{2}} \quad 0 \quad \frac{a_x}{\sqrt{2(1-a_z)}} \right], \quad a_z < 0$$

Since the quaternion calculated from the accelerometer have b oth size and direction, it should be converted to unit quaternion in order to leave only the direction. When calculating the initial quaternion, vehicles usually start at flat site, so the value of a_z is greater than 0. So, unit quaternion could calculate as follow.

$$|q_{est,0}| = \sqrt{\frac{a_z+1}{2} - \frac{a_y^2}{2(a_z+1)} + \frac{a_x^2}{2(a_z+1)}}$$

$$norm(q_{est,0}) = \frac{q_{est,0}}{|q_{est,0}|}$$

After then, normalized estimated gravity quaternion should be rotated using rotation angle that measured from gyroscope dat a.

$$w = w_x i + w_y j + w_z k$$

Before rotate estimated gravity quaternion, measured gyroscop e data should be converted from Degree(°) to Radian(rad) unit. Dot quaternion($\dot{q}$) can be calculated using gyroscope data and l ast measured estimated gravity quaternion using quaternion mul tiplication.

$$\dot{q}_w = -\frac{1}{2} w \otimes q_{est,0}$$

The rotated estimated gravity quaternion can be obtained directly through integration process.

$$q_w = q_{est,t_0} + \dot{q}_w \triangle t$$

q_{est,t_1} should be normalized because of gyroscope data is not normalized data.

$$|q_w| = \sqrt{q_0^2 + q_1^2 + q_2^2 + q_3^2}$$

$$norm(q_w) = \frac{q_w}{|q_w|}$$

This data should be fused with measured gravity quaternion from accelerometer data using complementary filter. Before fusing process, gravity quaternion from accelerometer should be normalized and minimize effects of external forces.

$$q_{acc} = \left[\sqrt{\frac{a_z+1}{2}} \quad -\frac{a_y}{\sqrt{2(a_z+1)}} \quad \frac{a_x}{\sqrt{2(a_z+1)}} \quad 0 \right], \; a_z \geqq 0$$

$$q_{acc} = \left[-\frac{a_y}{\sqrt{2(a_z+1)}} \quad \sqrt{\frac{1-a_z}{2}} \quad 0 \quad \frac{a_x}{\sqrt{2(1-a_z)}} \right], \; a_z < 0$$

In order to minimize the influence of external force, when a certain level of acceleration is detected, the complementary filter using the acceleration sensor data is not applied.

Threshold acceleration is calculated as follow.

$$norm(q_{acc,t_1}) - norm(q_{acc,t_0}) < 1638 \text{ (Threshold : 0.1g)}$$

After that, apply complementary filter using estimated gravity quaternion from gyroscope and gravity quaternion from acceler ometer.

$$q_{est} = (1-\alpha)q_w + \alpha q_{acc}$$

To convert estimated gravity quaternion to Euler angles, use t he following formula:

$$Roll = \phi = \tan^{-1}\frac{2(q_0q_1 + q_2q_3)}{1-2(q_1^2 + q_2^2)} * \frac{180}{\pi}$$

$$Pitch = \theta = asin(2(q_0q_2 - q_3q_1)) * \frac{180}{\pi}$$

In order to use the Cascade PID controller, angular velocity is required in addition to the angles. Using gyroscope data and de finition of dot quaternion, angular velocity can be directly calcu lated.

$$w_g = R_b^g \overrightarrow{w_b}$$

$$\begin{bmatrix} w_x^g \\ w_y^g \\ w_z^g \end{bmatrix} = \begin{bmatrix} w_x(q_0^2 - q_1^2 - q_2^2 - q_3^2) & 2w_y(q_1q_2 - q_0q_3) & 2w_z(q_1q_3 + q_0q_2) \\ 2w_x(q_1q_2 + q_0q_3) & w_x(q_0^2 - q_1^2 + q_2^2 - q_3^2) & 2w_z(q_2q_3 - q_0q_1) \\ 2w_z(q_1q_3 - q_0q_2) & 2w_y(q_2q_3 + q_0q_1) & w_x(q_0^2 - q_1^2 - q_2^2 + q_3^2) \end{bmatrix}$$

2. 3. 2. Cascade PID Controller

The cascade PID controller is used to minimize disturbance and improve drones attitude control performance such as fast response and minimized steady-state error. The cascade PID controller used in the drone calculates the control amount of each motor using the angle and angular velocity of Roll and Pitch.

First of all, the cascade PID controller calculates the error of the attitude angle that measured from ARS and control input from Ground Control System.

$$e_o(t) = SP - PV$$

SP : Set Point from Ground Control System
PV : Processing Value from ARS

The result obtained by multiplying the error value by the proportional gain is used as the setpoint of the internal PID loop. This result means desired angular velocity of inner loop PID controller.

$$u_o(t) = KP_o * e_o(t)$$

Using this value, inner-loop error can be calculated.

$$e_i(t) = u_o(t) - w(t)$$

($w(t)$: Measured Angular Velocity)

Now, proportional term, integral term and derivative term of inner-loop PID controller can be calculated.

$$P = KP_i * e_i(t)$$

$$I = KI_i \int_{t_0}^{t_1} e_i(t) dt$$

$$D = KD_i * \frac{de_i(t)}{dt}$$

The anti-windup technique should be applied in order to prevent the control failure that caused by the saturation of the actuator because of the excessive control value of the integral term. There are various anti-windup techniques, but it is reasonable to limit the amount of control when considering the computational complexity of the MCU.

```
errorInt[i] += error[i] * dt;
errorInt[i] = constrain(errorInt[i], -10000, 10000);
if(ctrl[0] <= 50){errorInt[i] = 0;}
```

The differential term can be amplified by the motor and the propeller, so it is suppressed by using a low-pass filter. When referring to various papers and experiments, it is recommended to use an Low Pass Filter(LPF) with a cut-off frequency range of 10 Hz to 20 Hz.

```
// Calculate Derivative Term
DELTA[i] = (error[i] - _error[i]) / dt;

// Apply Digital LPF
D[i] = D_FILTER * DELTA[i] + ((1. - D_FILTER) * _DELTA[i]);
D[i] = ((float)D[i]) * KD[i];
```

2. 3. 3. Bluetooth-based Control System

In order to control the drone using wireless communication technology, it is necessary to send and receive not only control signals for attitude values such as roll, pitch, and yaw but also various data for setting the air vehicle. Low-cost flight control system is basically designed to send and receive data wirelessly using RN4870 Bluetooth communication module. Therefore, communication protocol to be exchanged between control application and flight control system should be well defined for stable flight control. Although there is a excellent system called the MAVLink protocol for unmanned vehicles including drone, this protocol also takes up a significant amount of computation when using 8-bit MCUs. Therefore, it requires own protocol that contains only necessary control functions.

Bytes	D0	D1	D2	D3	D4	D5	D6	D7	D8
Value	Start	Mode	Thr	Yaw	Roll	Pitch	R.Trim	P.Trim	203

Using UART service of Bluetooth Low Enegry(BLE) with above simple protocol, application of smartphone or table can easily control vehicles. When using the RN4870 BLE module, create a controller application for the smartphone or smart tablet using own characteristic UUID and own service UUID.

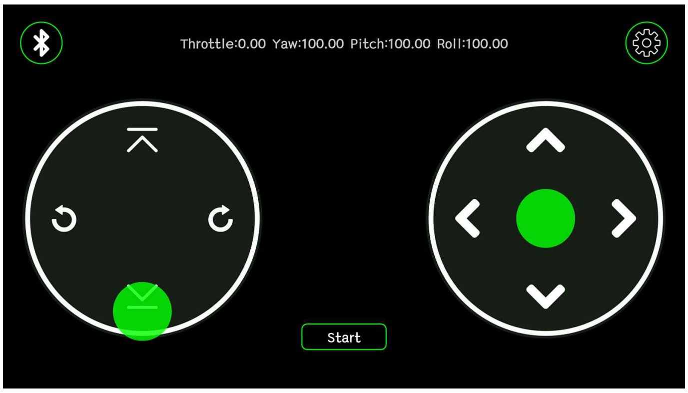

Fig 31. BLE Control App of Smartphone

202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203
202	210	0	100	100	100	50	50	203

Fig 32. Datagram of BLE Controller

First byte of the Bluetooth control protocol indicates whether it is started or not. It indicates standby status when first value is 201, and ready for flight status if it is 202. The second byte can control the flight mode. Third to sixth byte is data for basic flight control. Seventh to eighth is byte for roll and pitch trim, which can fine-tune the attitude. The last byte indicates the end of the data.

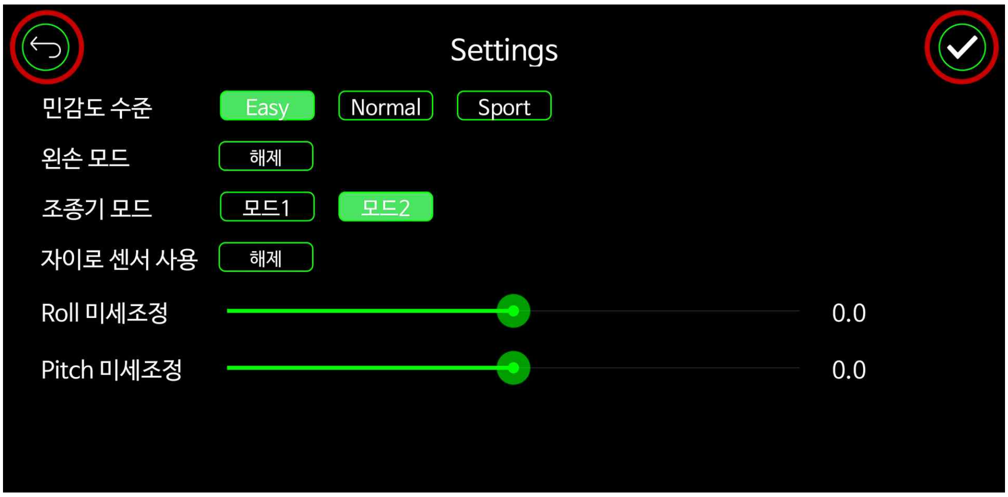

Fig 33. Setting Panel of BLE Control Application

3. 1. IMU & Attitude Reference System

Palm-sized quadcopter body with a DC motor is used to quickly and easily test the performance of the IMU and ARS. The performance of the attitude estimation system was tested in flat plane, 5 degree, 20 degree tilted plane. Before the performance evaluation, the attitude were measured on the flat surface without correcting the initial offset.

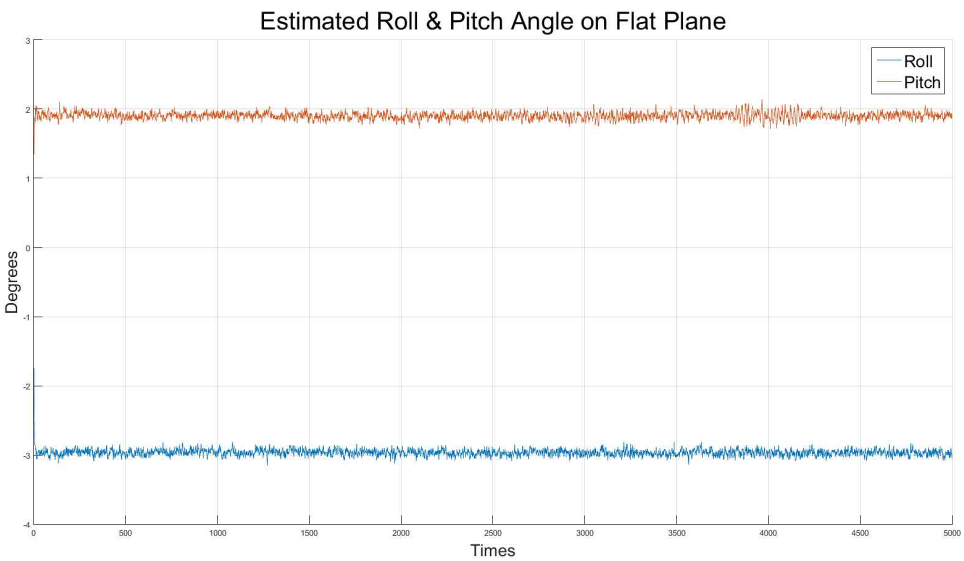

Fig 34. Estimated Roll & Pitch Angles without offset calibration

The offset of the accelerometer and the gyroscope sensor was calibrated by calculating the average value of the error, resulting in an acceleration error of about ±0.01g and a gyroscope sensor error of less than ±0.5DPS.

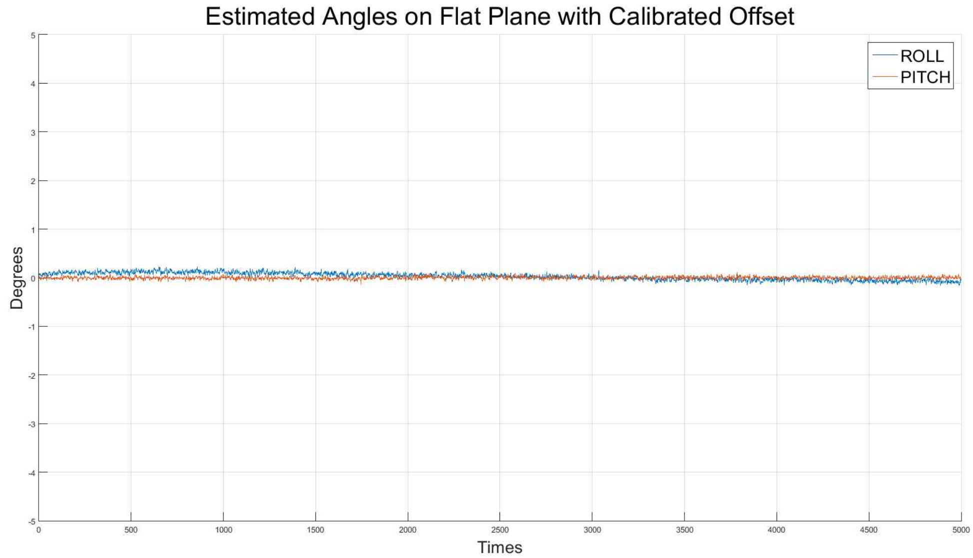

Fig 35. Estimated Roll & Pitch Angles with offset calibration

The angle data corrected for the offset has an error of about ±0.2 degrees at maximum, and it can be seen that the comple mentary filter effectively suppresses the drift that caused by gyroscope sensor.

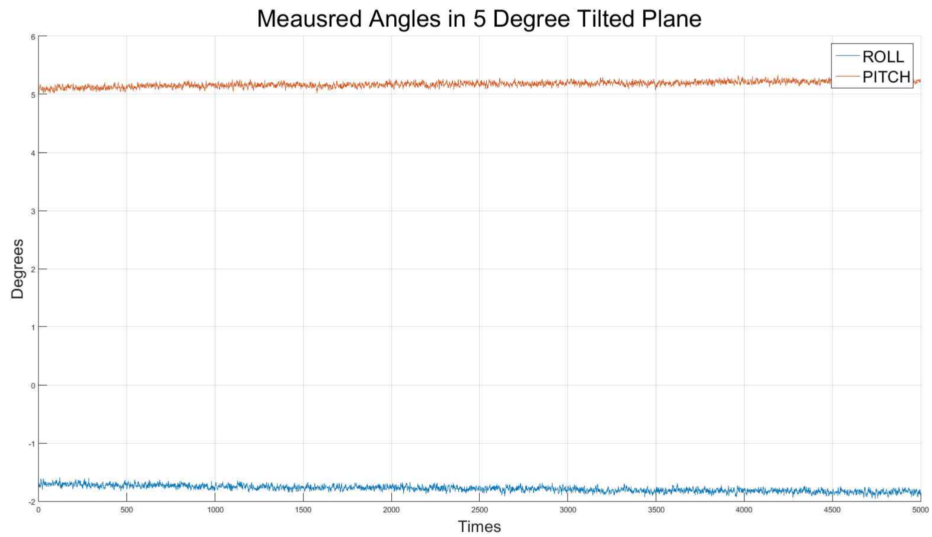

Fig 36. Measured Angles in 5 Degree Tilted Plane

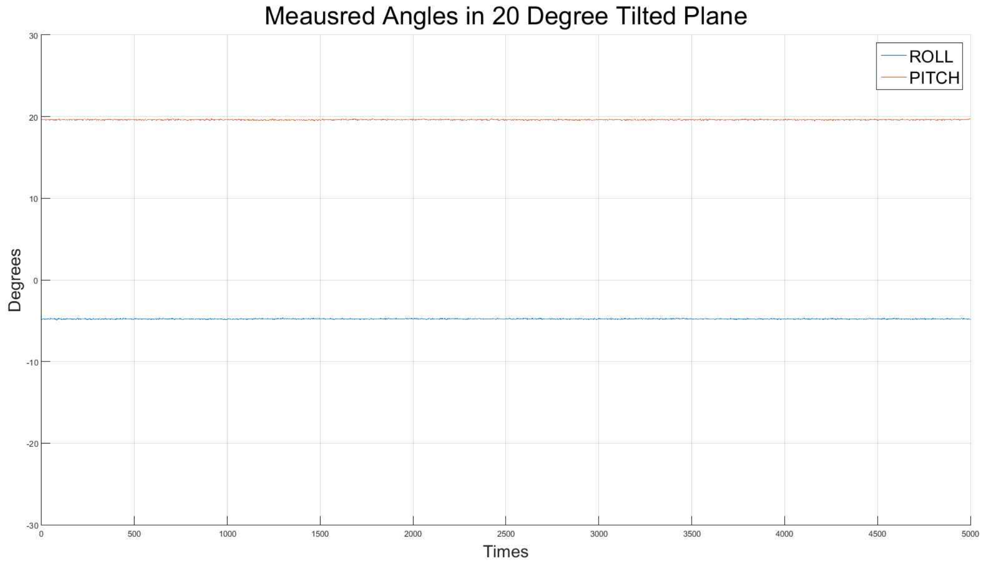

Fig 37. Measured Angles in 20 Degree Tilted Plane

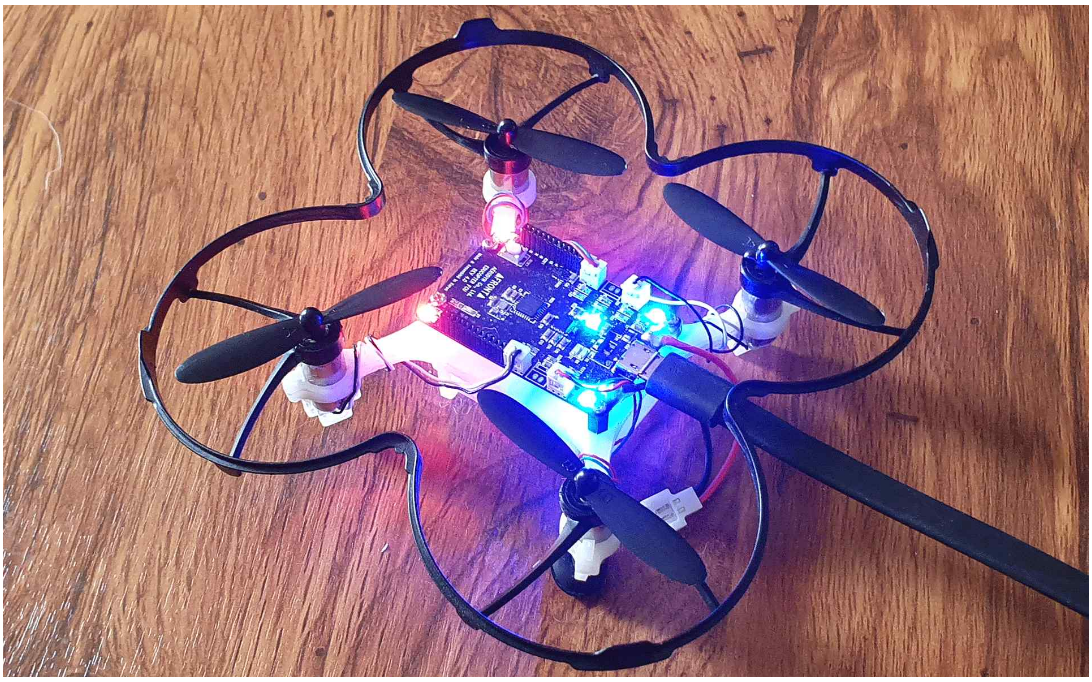

Fig 38. ARS Performance Evaluation on Flat Plane

3. 2. Attitude Control Performance

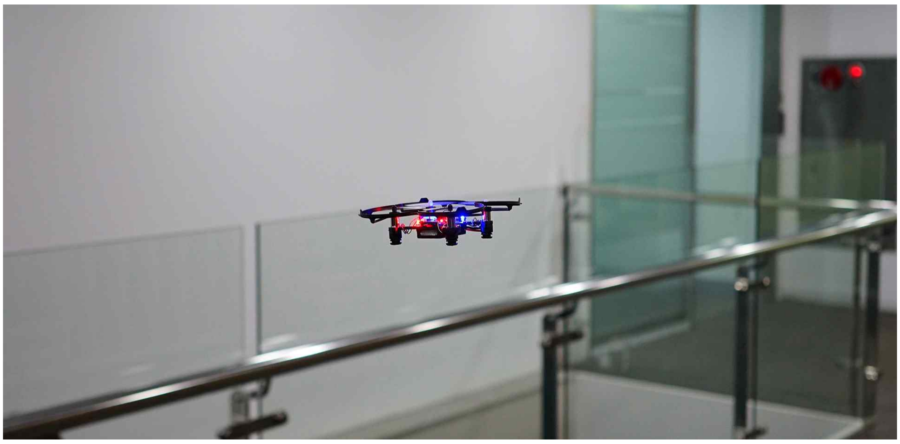

Fig 39. Indoor Flight Test of Low-cost Flight Control System

Through the above process, the designed flight control system, algorithm and body were assembled and flight test was performed indoors. Palm-sized quadcopter is used to measure the flight performance of the aircraft safely and quickly.

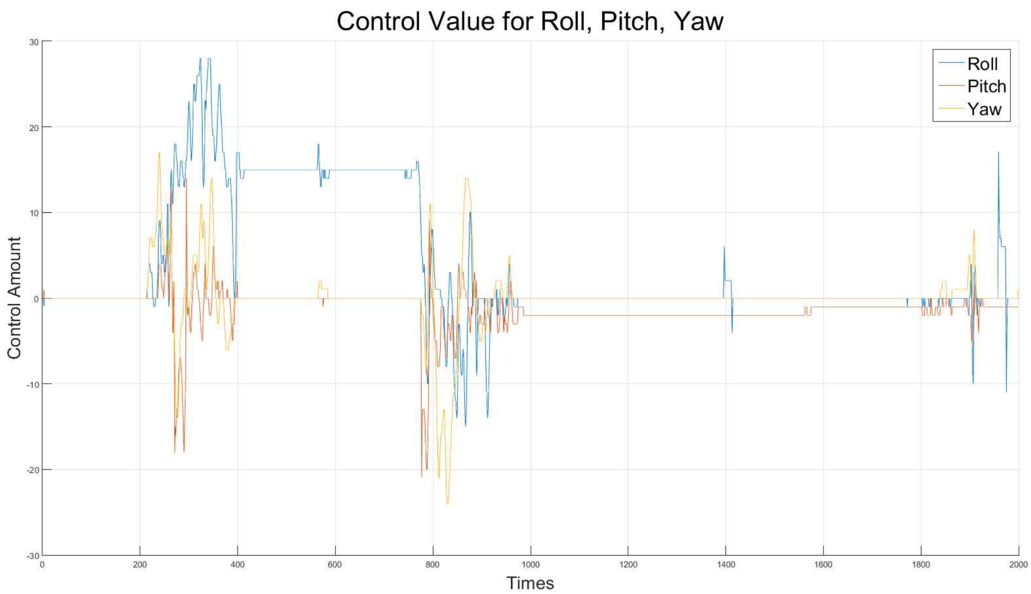

Fig 40. Control Value of each Axis in Flight Test.

Figure 38 shows the control amount of the PID controller for roll, pitch, and yaw. When the set point of the roll angle is 0, i t can be seen that the roll control value increases or decrease s to maintain the attitude.

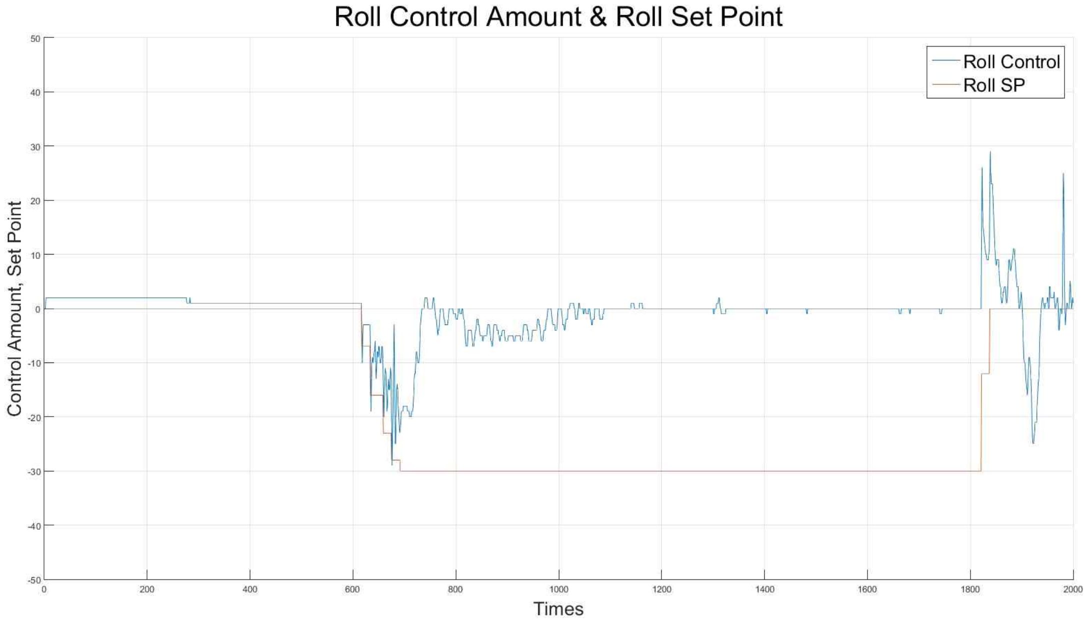

Fig 41. Roll Set Point & Control Amount from PID Controller

Figure 39 shows the control amount of Roll PID controller wit h respect to the roll control value transmitted in the Bluetooth communication. A small vibration of control value is seen by th e effect of the ventilator working in the room.

4. Conclusion

In this study, hardware and software algorithms of the cost-effective flight control systems using MEMS sensors and low-cost, low-performance processors is designed. The existing attitude estimation system of the commonly used multirotor UAV is composed of algorithms which require much computational performance because of Extended Kalman Filter (EKF), so it was necessary to use a processor with a Floating Point Unit(FPU). However, it is possible to design the low-cost flight control system having a control period of about 200 Hz by using MEMS sensor and an 8-bit processor without FPU. The attitude estimation system, which is one of the subsystems of the flight control system, was able to suppress the drift phenomenon and have angle errors of less than ±0.5 degrees using the quaternion and the complementary filter algorithm. By applying the offset calibration algorithm based on the average of error, the error of the MEMS sensor can be minimized. By using attitude angle and angular velocity from attitude estimation system, Cascade PID controller was built that can improve control performance than single PID controller. This attitude control system has rise time(τ) of about 0.4 seconds and has an overshoot of less than 5%.

In order to reduce the buildling cost and time of the Ground Control System(GCS), Bluetooth-based control system has built and can control the multi-rotor UAV within maximum 50m using the ap plication of smartphone and tablet PC. Because of the characteristics of Bluetooth and low-performance processor, a simple and lightweight separate protocol is designed without using the MAVLink protocol. In addition, the environment of designing multirotor UAVs can be simplified by applying the Arduino platform to easily create and modify control software. Arduino Nano platform has been applied because of its simplicity and easy to use.

Finally, test flight has conducted using 3D-printed quadcopter UAV and flight control computer with control software indoor. In this flight test, relatively stable flight performance was obtained compared to other quadcopter UAV. Since this system is only applied attitude control system, additional research is needed to ensure more stable flight performance by adding an altitude control system using integrated barometer.

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초 록

흔히 드론(Drone)이라고 불리는 멀티로터형 무인항공기는 저렴하고 조종하기 쉬우며 간단한 구조와 수직 이착륙이 가능하여 군사적인 용도를 비롯하여 상업적인 용도로 널리 쓰이고 있다. 멀티로터형 무인항공기는 가속도 센서, 자이로스코프 센서를 포함하는 관성 측정 유닛(IMU)을 이용하여 지표면에 대한 자세를 측정하여 각 모터의 회전속도를 제어하는 방식으로 비행하며, 비행 방향을 추정할 수 있는 지자기 센서와 고도를 측정할 수 있는 기압계를 내장한다. 비행체에 탑재되는 비행제어유닛(Flight Control Unit, FCU)은 이러한 센서 데이터와 조종명령을 이용하여 각 모터를 제어한다.

이러한 계산을 수행하기 위해서 기존의 비행 제어 시스템은 하나 이상의 32-bit 마이크로프로세서를 사용하며 이에 따라 비행제어를 위한 펌웨어를 개발하는데 있어 회로 및 패턴 설계 및 소프트웨어 개발 환경(SDK)을 구성하는데 있어 많은 시간과 인력, 비용을 필요로 하여 전체 시스템의 가격이 저렴하지 않다. 또한 작은 크기의 멀티로터에 사용되는 저렴한 비행제어유닛은 프로그래밍이 불가능하거나 확장성에 제약이 있어 하나의 제어 시스템으로 하나의 비행체 모델에만 적용하는 한계가 있다. 따라서 빠르고 간편하게 프로그래밍이 가능하며 저렴하고 구하기 쉬운 8-bit AVR 프로세서와 MEMS 센서, C/C++언어를 이용하여 비행제어시스템을 구성하였으며 그 결과 확장성을

갖추면서 가격이 저렴하면서 효율적인 비행 제어 시스템을 구성할 수 있었다. 부족한 8-bit 프로세서의 성능은 프로세서의 수량을 늘리는 병렬 컴퓨팅 방법으로 해결할 수 있었으며 상보 필터의 간결한 구조로 인해 8-bit 프로세서의 낮은 컴퓨팅 성능으로도 초당 약 250Hz의 제어 주기를 가질 수 있었다. 자세 제어 알고리즘으로 Cascade controller를 선택하여 외란에 강하며 빠른 제어 속도를 얻을 수 있었다. 결과적으로 진동이 상대적으로 큰 팜 사이즈의 쿼드로터 UAV에서도 안정적인 비행 성능을 구현할 수 있었다.

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