Flapping Wing Micro Air Vehicle (FW-MAV) State Estimation and Control with Heading and Altitude Hold

S. Aurecianus[1], H.V. Phan[2], S. L. Nam[1], T. Kang[1]*, and H.C. Park[2]
[1]Department of Aerospace Information Engineering, Konkuk University, Seoul, South Korea
[2]Department of Smart Vehicle Engineering, Konkuk University, Seoul, South Korea

ABSTRACT

In this work, small control board is specifically designed to control the flapping-wing micro air vehicle (FW-MAV) called KUBeetle. In addition, remote control is also custom-built to transmit control command and receive flight data in real time. Then, a method to estimate the attitude and altitude is developed and used to control the behaviour of KUBeetle. The attitude estimation is obtained by combining gyroscope, accelerometer, and magnetometer measurement. While the altitude estimation is obtained by using ranging sensor combined with z-axis accelerometer. FW-MAV is a system with very high vibration noise which are generated by flapping motion and its body. Without using any mechanical damping, the sensors signals are filtered using low pass and Kalman filter. The altitude estimation is evaluated using ball screw driven linear motion guide system. Proportional-Derivative (PD) and proportional-integral-derivative (PID) control with feedback are implemented for attitude and altitude control, respectively. The KUBeetle can demonstrate hover flight and control its attitude and altitude.

1 INTRODUCTION

Since the past few years, flapping-wing micro air vehicle (FW-MAV) has been studied and developed from several aspects [1, 2], such as aerodynamic model, fluid structure interaction, flapping-wing motion mechanism, small and light control board design and navigation and control. In this paper, mainly two aspects of FW-MAV called KUBeetle [3, 4, 5], control board design and control system, are studied. KUBeetle design is inspired from hummingbirds [6] and some insects [7] which have nearly horizontal flapping stroke plane. Its attitude is controlled by changing flapping properties, such as trailing edges at the wing roots and stroke plane, instead of relying on control surface.

Small control board is designed to estimate onboard state and to control KUBeetle. It is equipped with inertial measurement unit (IMU) containing gyroscopes, accelerometers, and magnetometers, and a ranging sensor. Other FW-MAVs, such as nano hummingbird [8], Robobee [9], Delfly [10], and robotic hummingbird [11], also utilize some of these sensors on their control board. Some researches require the use of external equipment [3, 12], such as high-speed camera, to obtain flight information. Or in some other researches the flight data need to be saved on the on-board memory first. Taking this into account, a remote control is specifically designed which not only transmit control commands to the control board, but also receive flight data from the control board during flight. Thus, the response of the FW-MAV can be observed in real time.

Controlling FW-MAV is a challenging task as the system produces high vibration noise, mainly due to the flapping motion, which could disrupt the sensor measurement. The noise could be reduced by attaching mechanical damping on the control

*contact email: tskang@konkuk.ac.kr

board or through filter in the control program [3, 13]. In order to obtain estimation of pitch, roll, yaw angle, and altitude, low pass filters (LPF) and Kalman filters (KF) [14, 15] are used to filter out noises and combine the sensor signals. The altitude estimation is examined using a ball screw driven linear motion guide system which could provide accurate and precise displacement.

On the previous work [3], KUBeetle can demonstrate stable take off and hover flight through proportional-derivative (PD) control with angular rate feedback from gyroscope. In this work, PD control with angle feedback is implemented for attitude control and proportional-integral-derivative (PID) control with altitude feedback is implemented for altitude control. The addition of magnetometer and ranging sensor helps improving KUBeetle heading and altitude control.

The main contributions of this paper are: (1) design of control board and remote control which allows on board control and access to flight data in real time, (2) developing method to filter and estimate attitude and altitude sufficiently without any mechanical damping, specifically for KUBeetle, and (3) developing control method which improves the performance of KUBeetle, especially for heading and altitude control. The rest of the paper is arranged as follows: in Section 2 the brief introduction to the KUBeetle. Then followed by the control board and remote control design in Section 3. The filters and control method used are described in Section 4 and 5, respectively. The experiment setup and result are shown in Section 6 and the last section presents concluding remarks.

2 KUBEETLE

The KUBeetle model has been updated multiple times during development process. The model that is used in this study implements stroke plane change mechanism, while the previous model [3] implements trailing edge change at the wing roots mechanism. Figure 1 shows the KUBeetle model and its main parts. The attitude control is performed through three servos and the altitude control is performed through coreless DC motor. More detailed information regarding KUBeetle model used in this study can be found in [16].

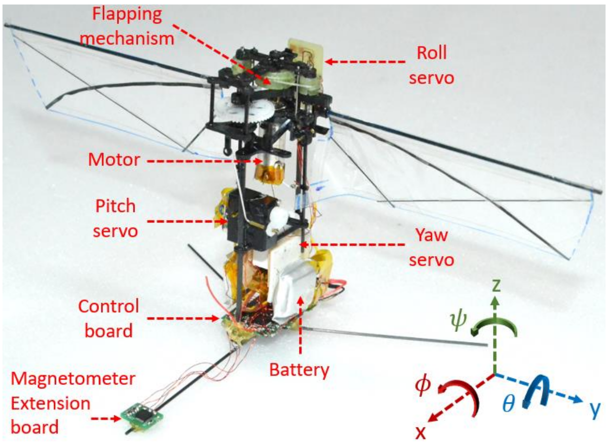

Figure 1 - KUBeetle

3 CONTROL BOARD AND REMOTE DESIGN

The control board is designed so that micro-processor, sensors, and transceiver can be placed in one board to reduce the total weight of the FW-MAV. It consists of a micro-processor STM32L432KC, an inertial measurement unit (IMU) MPU-9250, a ranging sensor VL53L0X, a transceiver nRF24L01+, a motor driver, power regulators, and supporting components, such as resistors and capacitors. The IMU consists of three-axes gyroscope, accelerometer, and magnetometer (AK8963C). Figure 2 shows top and bottom view of the control board. It is made as small and light as possible with some design limitation and restriction. The weight without components is 0.3 g and with components is around 0.9 g. It has maximum width 17 mm and length 23 mm. The board consist of 4 layers with total thickness around 0.4 mm. The IMU is placed at the centre of the board and perpendicular to centre of gravity (CG) of KUBeetle. The ranging sensor is placed at the bottom side, so it shall face the ground after being attached to KUBeetle.

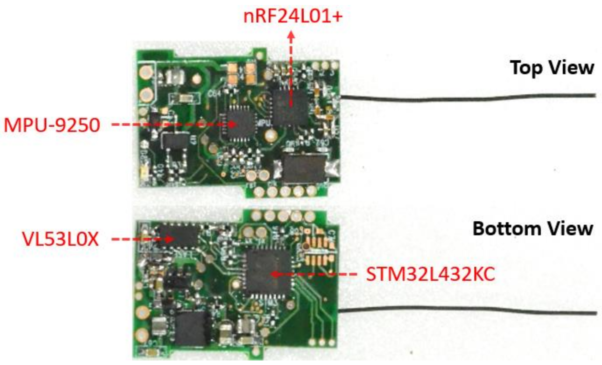

Figure 2 - Control board

The selected micro-processor enables main control loop to have 400 Hz frequency. This frequency still can be increased further with high frequency external oscillator. Currently, the magnetometer on the control board is not used due to magnetic field interference produced by the surrounding high current lines, servos, and motor. Alternatively, an extension board is made specifically for magnetometer so that it can be placed apart from the interference sources. This serve as temporary solution to ensure stable measurement until better solution is found. The ranging sensor uses laser to obtain accurate range measurement. The sensors sampling rate and specification are shown in Table 1. The magnetometer and ranging sensor have slower sampling rates than other sensors but are sufficient enough to control the KUBeetle.

Sensor	Sampling Rate	Output Range	Sensitivity
Gyroscope	400 Hz	± 1000 °/s	32.8 LSB/(°/s)
Accelerometer	400 Hz	± 8g	4096 LSB/g
Magnetometer	100 Hz	± 4800 μT	0.6 μT/LSB
Ranging sensor	25 Hz	0 - 2 m	1 mm/LSB

Table 1 – Sensors sampling rate and specification

Remote control is custom-built with the same transceiver as the control board. It has similar parts as conventional remote control, such as joysticks, potentiometers, and buttons. In addition, IMU is added to allow control by motion when selected. Figure 3 shows the designed remote control. The remote control works as control command transmitter and flight data receiver at the same time. The flight data is sent to computer in real time for observation and recorded. The data rate depends on RF signal stability and data size which can be modified accordingly. With 14 Byte payload data transmission and 115200 baud rates UART/USART communication to the computer, the data rate is around 40 to 50 Hz.

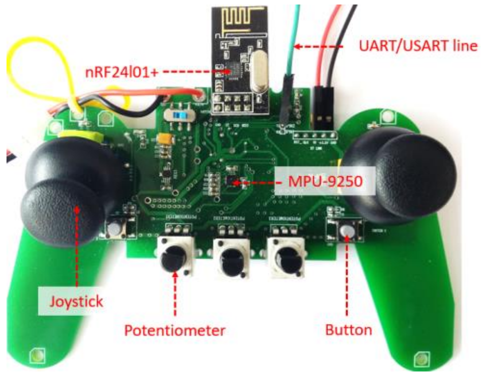

Figure 3 – Remote control

4 FILTERS AND STATE ESTIMATION

The control board is attached firmly at the bottom part of the KUBeetle without any damping material. Consequently, all the noise should be filtered by software in the control board.

4.1 Low pass filter

Infinite impulse response (IIR) LPF is used multiple times throughout the calculation process until the estimation of angle and altitude is obtained. It is used to filter out high frequency noises. The IIR LPF equation can be written as:

$$\hat{\delta}[k] = \alpha\delta[k] + (1-\alpha)\hat{\delta}[k-1] \qquad (1)$$

where $\hat{\delta}$ is filtered signal, δ is unfiltered signal, α is coefficient between 0 to 1, and k is time index. The coefficient value will determine the cut off frequency of the filter and affect time and phase delays of the signal. Firstly, LPF is used to filter the angular rate, acceleration, and magnetic field vector measurement from sensors. Secondly, it is used to filter accelerometer tilt angle signal for pitch and roll which is obtained by inputting filtered acceleration signal to tilt angle equation computed according to the rotation sequence x-y-z (roll-pitch-yaw) [17, 18]. Even though the use of low pass filter creates delay, its effect is mitigated by increasing the control loop frequency.

4.2 Kalman filter

Standard discrete Kalman filter (KF) [13, 14] is used to obtain pitch, roll, and altitude estimation. For angle estimation, the state matrix, x_k, state transition model, A, control input model, B, and observation model, H, are defined as:

$$x_k = \begin{bmatrix} \theta \\ \dot{\theta}_b \end{bmatrix}_k \quad (2)$$

$$A = \begin{bmatrix} 1 & -\Delta t \\ 0 & 1 \end{bmatrix} \quad (3)$$

$$B = \begin{bmatrix} \Delta t \\ 0 \end{bmatrix} \quad (4)$$

$$H = \begin{bmatrix} 1 & 0 \end{bmatrix} \quad (5)$$

where θ is estimated angle, $\dot{\theta}_b$ is estimated bias, and Δt is loop period or time interval. The control input of the KF is the filtered gyroscope signal and the measurement of the KF is the accelerometer tilt angle signal. Similar iterative process of KF is used for both pitch and roll. While the estimated yaw angle is obtained using equation derived from inverted rotation matrix of magnetometer with rotation sequence x-y-z (roll-pitch-yaw) and tilt compensation [19].

For altitude estimation, the model is derived from z-axis velocity and distance equation by integrating z-axis acceleration. The state matrix, x_{2k}, state transition model, A_2, control input model, B_2, and observation model, H_2, are defined as:

$$x_{2k} = \begin{bmatrix} V_z \\ h_z \end{bmatrix}_k \quad (6)$$

$$A_2 = \begin{bmatrix} 1 & 0 \\ \Delta t & 1 \end{bmatrix} \quad (7)$$

$$B_2 = \begin{bmatrix} \Delta t \\ \frac{\Delta t^2}{2} \end{bmatrix} \quad (8)$$

$$H_2 = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad (9)$$

where V_z is estimated velocity and h_z is estimated distance on z-axis or altitude. The control input of the system is the gravity compensated filtered z-axis acceleration signal and the measurement of the system is the ranging sensor altitude measurement.

5 CONTROL METHOD

KUBeetle is an inherently unstable system. As preliminary study of KUBeetle attitude control, PD control with angle feedback is implemented to control KUBeetle attitude. The rotation angle is maintained as the initial condition. The control maintains the pitch and roll angle close to zero degree rotation. Furthermore, it maintains the yaw or heading angle close to initial heading, holding the initial heading direction. To hold the altitude of KUBeetle during flight, PID control with altitude feedback is implemented. As it is much easier for KUBeetle to go down than go up, the control output is made much smaller when the altitude error is negative. It can be done by limiting the range of control output or gain scheduling. The altitude control only works when altitude hold command is received. All the control gains are tuned by experiment. Figure 4 and 5 show the control loop diagram for attitude and altitude control, respectively. The set point and offset can be adjusted through remote control.

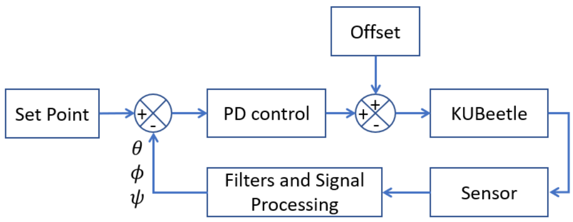

Figure 4 – Attitude control loop

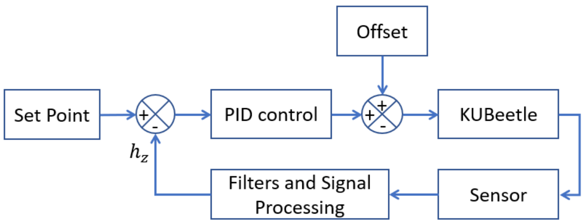

Figure 5 – Altitude control loop

6 EXPERIMENT AND RESULT

6.1 Altitude estimation

The altitude estimation evaluation is conducted using the ball screw driven linear motion system shown in Figure 6. It can change KUBeetle position, higher and lower, at known distance. For convenience, the experiment is conducted using sensors modules and MBED LPC1768 which attached to the moving platform. The displacement distance and ultrasonic sensor measurement are used as comparison. The data is sent to the computer and recorded to be used for data processing and simulation.

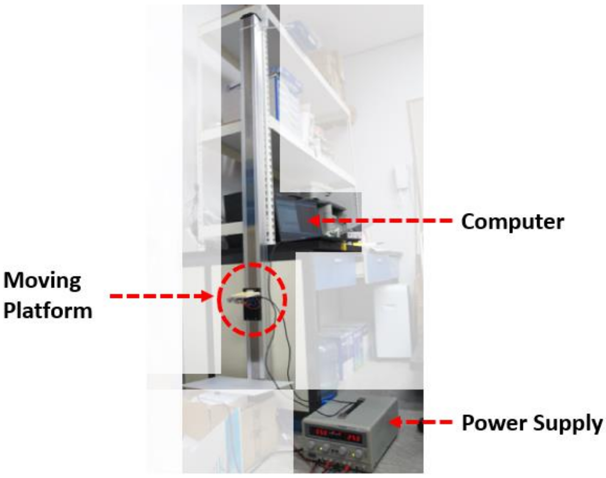

Figure 6 – Linear motion guide system

Figure 7 shows the experiment result for altitude estimation using laser ranging sensor compared with ultrasonic sensor. In this experiment the position of the system is increased by 10 cm every 3s. The laser ranging sensor is quite stable and close to the real height compared to ultrasonic sensor which has a lot more noise as the height increased which caused by echo. While this experiment is conducted without any vibration from flapping motion, the mechanical vibration from the linear motion guide system is much larger than flapping vibration. It can be concluded that the laser ranging sensor is not much affected by the mechanical vibration.

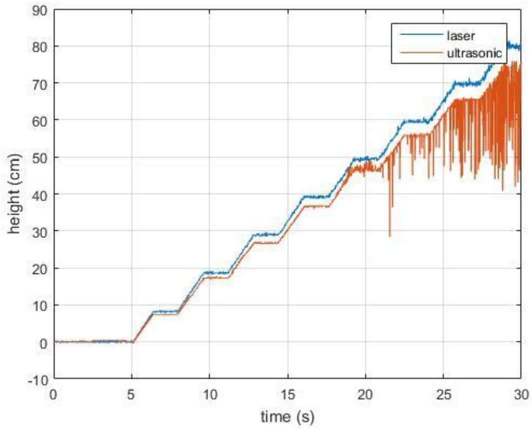

Figure 7 – Altitude estimation

6.2 Flight test

The flight test is conducted in the closed room with no wind. Figure 8 shows the altitude and altitude estimation during hover flight. The attitude estimation values are close to zero with around 10 degree variation which shows that the control is working well and able to maintain the attitude. The red line indicates when the altitude hold is activated. There are some larger altitude oscillation or instability after some time which require more tuning to PID gains to improve the altitude hold performance. This is also affected by the response time of the motor. The altitude graph also shows that the flapping motion and mechanical vibration do not much affect the altitude estimation.

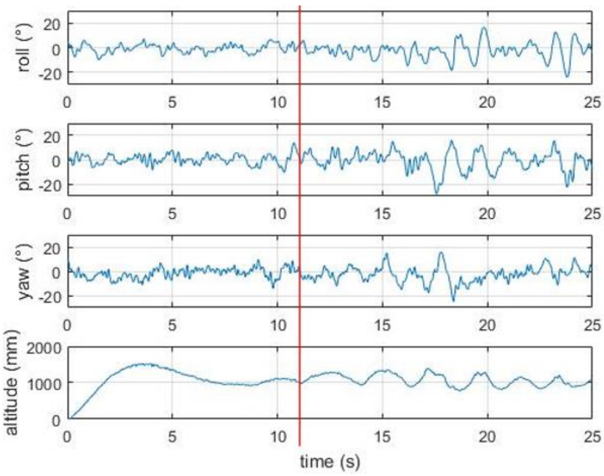

Figure 8 – Attitude and altitude estimation during flight

The snapshot image during flight is shown in figure 9. KUBeetle able to maintain its attitude and altitude with some position changes in x and y axis direction.

Figure 9 – Snapshot image of the KUBeetle during flight

7 CONCLUSIONS

Control board and remote control have been made to control KUBeetle and obtain real time flight data. The data rate is around 40 Hz for 14 Byte transmission payload with 115200 baud rates UART/USART communication. The attitude and altitude of KUBeetle are estimated sufficiently with low pass and Kalman filter without any external mechanical damping. KUBeetle able to demonstrate attitude control, especially heading, with good stability using PD control. The attitude can be maintained within 10 degree in hover flight. While the altitude estimation is quite stable and accurate, the altitude control needs to be improved to have stable altitude.

REFERENCES

[1] J.H. Han, J.S. Lee, and D.K. Kim. Bio-inspired flapping UAV design: a university perspective. Proceedings Volume 7295, Health Monitoring of Structural and Biological Systems, 2009.

[2] M.F.B. Abas, A.S.B.M. Rafie, H.B. Yusoff, and K.A.B. Ahmad. Flapping wing micro-aerial-vehicle: Kinematics, membranes, and flapping mechanisms of ornithopter and insect flight. Chinese Journal of Aeronautics, 29(5):1159-1177, 2016.

[3] H.V. Phan, T.S. Kang, and H.C. Park. Design and stable flight of a 21g insect-like tailless flapping wing micro air vehicle with angular rates feedback control. Journal of Bioinspiration & Biomimetics, 12(3):036006, 2017.

[4] H.V. Phan, T.N. Truong, and H.C. Park. Stable controlled flight of an insect-like tailless flapping-wing MAV. In Korean Society for Aeronautical and Space Sciences Fall Conference, 2016.

[5] H.V. Phan and H.C. Park. Remotely controlled flight of an insect-like tailless flapping-wing micro air vehicle. The 12th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI), 2015.

[6] S. Healy and T.A. Hurly. Hummingbirds. Current Biology, 16(11):R392-R393, 2006.

[7] R. Dudley. The biomechanics of insect flight: form, function, evolution. Princeton University Press, Princeton, NJ, 2002.

[8] M. Keennon, K. Klingebiel, H. Won, and A. Andriukov. Development of the Nano Hummingbirds: a tailless flapping wing micro air vehicle. 50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 2012.

[9] S.B. Fuller, E.F. Helbling, P. Chirattananon, and R.J. Wood. Using a MEMS gyroscope to stabilize the attitude of a fly-sized hovering robot. International Micro Air Vehicle Conference and Competition, 2014.

[10] S. Tijmons, M. Karasek, and G. de Croon. Attitude control system for a lightweight flapping wing MAV. Bioinspiration & Biomimetics, 13(5), 2018.

[11] D. Coleman, M. Benedict, V. Hrishikeshavan, and I. Chopra. Design, development and flight-testing of a robotic hummingbird. In American Helicopter Society 71st Annual Forum, 2015.

[12] F.Y. Hsiao, H.K. Hsu, C.L. Chen, L.J. Yang, and J.F. Shen. Using stereo vision to acquire the flight information of flapping-wing MAVs. Journal of Applied Science and Engineering, 15(3):213-226, 2012.

[13] J.L. Verboom, S. Tijmons, C.D. Wagter, B. Remes, R. Babuska, and G.C.H.E. de Croon. Attitude and altitude estimation and control on board flapping wing micro air vehicle. IEEE International Conference on Robotics and Automation (ICRA), 2015.

[14] G.M. Siouris. An engineering approach to optimal control and estimation theory, John Wiley & Sons, Inc, New York, NY, 1996.

[15] F.L. Lewis. Applied optimal control and estimation. Prentice Hall International, New Jersey, NJ, 1992.

[16] H.V. Phan, S. Aurecianus, T.S Kang, and H. C. Park. Attitude control mechanism in an insect-like tailless two-winged flying robot by simultaneous modulation of stroke plane and wing twist. International Micro Air Vehicle Conference and Competition, 2018.

[17] M. Pedley. Tilt sensing using a three-axis accelerometer, application note AN3461. Freescale Semiconductor, 2007.

[18] AN3182 application note, tilt measurement using a low-g 3-axis accelerometer. STMicroelectronics, 2014.

[19] V. Grygorenko. Sensing – magnetic compass with tilt compensation – AN2272. Cypress, 2014.