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Arduino-based Altitude and Heading Control of A Flapping Wing Micro-Air-Vehicle

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Abstract— This paper presents the development of hardware module to perform versatile flight controls of flapping wing micro air vehicles (FWMAVs) or ornithopters. Firstly the authors survey the developed avionics, including the configurations of full integration and with discrete components, respectively for flight and control of FWMAVs in the literature. MEMS micro-barometers and micro-compass are frequently interfaced with a microcontroller to determine the altitude and orientation of FWMAVs. Herein a custom-developed printed-circuit-board (PCB) is also integrated with an inertial-measurement-unit (IMU) and a barometer to obtain constant altitude of the air vehicle. The heading of the FWMAV is controlled using a micro-compass with reference to magnetometer direction in the IMU. Simulation and hardware testing were carried out using an ATmega-328P micro-controller onboard. The result confirms that the proposed control system can be adopted to control the FWMAVs efficiently some comments on the necessity of integration about the control avionics are also addressed.

Keywords— Altitude hold, barometer, directional flight, inertial measurement unit (IMU), flapping wing micro air vehicle (FWMAV).

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I. INTRODUCTION

NATURE of flapping flight for human beings is a source of inspiration from the birds. Mankind has been trying to create a flying machine from humble bird flight across the sky. There are tremendous technological advancements can be seen in aerospace sector. From propeller aircrafts to modern jet aircrafts it travels more than the speed of sound, lightweight and with diverse applications and functions. However, today's aircrafts are large and the majority of them need landing space. Small aircrafts like micro-air-vehicles (MAVs) have high privacy. MAVs can be carried easily and used on the battlefield for detection of enemies [1]. It can also be used for the people's livelihood purposes, such as environmental monitoring, traffic exploration and deploying in harsh environments. In the last decade, small MAV has stimulated many research interests. Controlling of flapping wing vehicle system is considered to be technically more challenging because of its flight feature. Their non-linear dynamic and vibration phenomena are difficult to predict.

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At present, wide range of sensors and controllers has been used in rotary and fixed wing UAVs. They may not be suitable for MAVs because of weight factor. The development of motion transmission elements and controllers with inertial measurement units (IMUs) are of prime importance to design a MAV. Especially, flapping wing micro air vehicles (FWMAVs) are light weight with capability to simulate flight movements of birds [2]-[3]. For example the FWMAV developed by the Tamkang University has mass of about 13g, wing span 20cm and flapping frequency about 10-15 Hz, of a 0.2m-span MAV (b = 0.2) [4]-[7].The body mass m cannot surpass 0.011 Kg and the wingbeat frequency f must be faster than 15 Hz. Hence designing and fabricating the key mechanism component of a light flapping MAV is not easy. In other words, the gear transmission mechanism for flapping motion should be as tiny and light as possible in design; the corresponding wingbeat frequency should be also fast enough at the same time; most important of all, the flapping gesture ought to mimic the natural flyers accordingly. In comparison with the fixed wing and multirotor vehicles, FWMAVs possess superior maneuvering abilities. In general, the application spectrums of the FWMAVs are superior for indoor missions [8] due to its very low speed and agile maneuver. In further, the development of autonomous system with limited sensors units is another challenging problem that has to be encountered for deployments in versatile environments. So in order to have a better and versatile control on the FWMAVs the control components should be as small as possible.

Some existing autopilot boards which have been developed and tested worldwide are shown below in the Table 1. A Paparazzi autopilot22 uses previous experience with this autopilot's integration into micro air vehicles. The autopilot includes a Phillips ARM7 microprocessor, a built-in U-Blox GPS receiver with an 18-mm patch antenna mounted on the autopilot board, and an infrared sensor board to determine the attitude of the vehicle [9].

In remote controlled planes, an elevator and a rudder are used for the control of the flight direction. Likewise, an elevator and a rudder are attached for the control of the ornithopter in the tail wing. Two servo motors are required for control of the tail wing. A lightweight receiver and speed controller are also required for the radio control. Therefore, an integrated component, which includes two servo motors, a receiver and a speed controller are used. The Mx-0104ARX-LBL integration receiver weighs 2.9 g [10].

The newest DelFly can carry sufficient payload to carry a 0.98-gram autopilot and a 4.0 gram stereo vision system (cameras and processor). Although the payload makes the DelFly heavier, it also allows the autonomous exploration of unknown spaces. Since this sets this DelFly apart from all previous versions. It has a wing span of 28 cm and a weight of 20 grams. The flight time of the DelFly Explorer is typically around 10 minutes. Furthermore, it features two-way telemetry and rpm-monitoring. The autopilot is not necessary to achieve stable flight, as the tail of the DelFly passively stabilizes it during flight. However, the autopilot can serve other purposes, such as performing height control, disturbance rejection or more precise attitude control [11].

The control system used on the successful flights so far is written in C and runs on the Gumstix computer at 40Hz, which is the target update rate because it is the maximum that the servos can take commands since the frequency of their variable duty cycle pulses is 40Hz. The pitch and derivative of the pitch come directly from the IMU and do not undergo further filtering. In tests so for the desired pitch has been set to a constant value approximating what has been seen in manual fights but this can easily be changed as progress is made [12].

The modified robot, though, weights 13.6g and this result in a dampening out of the slow climb/stall oscillations because the ornithopter, unable to climb, essentially performs a smooth landing on its body. Thus, the only significant source of unsteadiness in these experiments comes from the flapping. Note that the 13.6g weight includes the 7g airframe, 2.5g of boards, a 2.6g battery, and 1.5g of wiring and mounting hardware [13].

Table 1 Several types of control avionics for ornithopters and their module mass

Which are	Autopilot board	Module mass (grams)
Integrated	Paparazzi Tiny[9]	22
Integrated	Mx-0104ARX-LBL integration receiver [10]	2.9
Discrete	Delfly with camera [11]	4.98
Integrated	Elektra and Gumstix [12]	43.5
Discrete	Microchip dsPIC33FJ128MC706 (custom) [13]	2.5
Discrete	Arduino Tinylily processor with sensors and drivers in this work	2.44
Integrated	M1AP[21]	1.26

In present scenario, the emerging research scope for the FWMAVs are in aerodynamic performance [2]-[3], vision systems [14]-[16], autonomous control [17]-[20] and development of light weight sensors modules. In such an extensive domain, the present study considers controlling of altitude and heading direction of FWMAV with limited sensor modules. Here in the direction control of ornithopters is performed by using a magnetometer which is presented on-board, paired with the microcontroller to obtain compass heading. The altitude of FWMAV is measured using a MEMS-based barometer sensor. These two sensors are able to measure the flight features like altitude hold and navigational flight of the ornithopter in real time to control the vehicle [21].

II. RESEARCH FRAMEWORK

The schematic representation of control strategy is depicted in Figure 1. MEMS based barometers are predominantly used in MAVs to measure the atmospheric pressure which results in altitude of vehicle. In this work, a 1.18gram discrete barometer will be initially utilized to provide the altitude of FWMAV.A typical MEMS discrete magnetometer weighs 0.95gram is considered for measuring the direction of FWMAV. The vehicle heading is obtained with reference to the earth magnetic field.

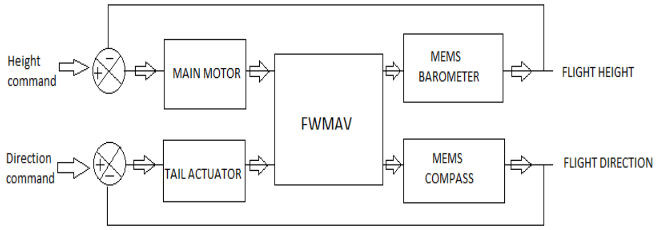


Figure 1 Control schematic for the FWMAV

The barometer and magnetometer are embedded with two digital wires i.e. SCL (serial clock line) and SDA (serial data), with I2C wiring communication protocol. Both the sensors are connected to the Arduino compatible microcontroller parallel to each other. As they are MEMS based sensors, power consumed by these sensors is less and high resolution data is obtained. The Arduino integrated development environment (IDE) microcontroller is used as programming module. Interfaced sensors are calibrated with the pre-defined parameters and are tested [16]. In order to reduce the weight of the FWMAV, connectors which are used to input the program in microcontroller are replaced by future technology devices international (FTDI) connector which is a type of adapter to upload program in ATmega microcontrollers. A receiver is connected to the microcontroller to obtain pulse width modulated (PWM) signals from transmitter.

A. *Interfacing of barometer*

Barometer (BMP180) is interfaced with Arduino microcontroller with I2C protocol. BMP180 is 5V operated, 3.3V regulator and I2C level shifter is included in the circuit board. The sensor is coupled with Arduino through connecting 3.3V pin to 3.3V, GND to ground, SCL (serial clock line) to I2C clock (A5) pin and SDA (serial data) to I2C data (A4) pin. The respective connections are shown in Figure 2.

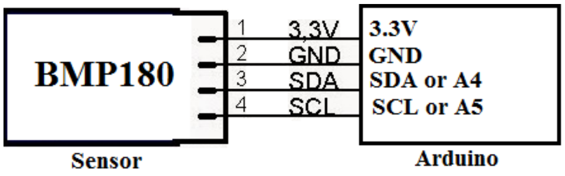


Figure 2 Interfacing of the barometer BMP180

In this work, ATmega 328p is used as a microcontroller which is scaled down version of Arduino-Uno to the small size, and it weighs about 0.3g. It is powered through Lithium polymer battery. In order to control the altitude of the FWMAV, it is important to have good control over the throttle of the ornithopter. Since the ornithopter is driven by DC motor, the motor driving circuit is essential to control rotation per minute (RPM) based on the PWM from the input transmitter. The PWM can be generated from the range of (0-255) where 0 is the minimum throttle and 255 is the maximum throttle. According to the need, the altitude of the ornithopter can be maintained by the sensor BMP180. Based on these arrangements, an important flight feature of altitude hold flight to achieve hovering characteristics of ornithopter is attained. Microcontroller can be programmed to hold the altitude of the vehicle to a fixed height. Altitude readings from the sensors are fed into the microcontroller which in turn actuates the motor drive circuit according to the predefined altitude.

B. Interfacing of magnetometer or MEMS compass

Magnetometer is connected to the ATmega microcontroller with I2C protocol for data transfer. Connection for interface is as follows: connect VIN to 5V pin, GND to ground, SDA to A4 pin and SCL to A5 pin on the microcontroller respectively. Since, HMC5883L has a fixed I2C address library, at a time single magnetometer can be connected to microcontroller. The Figure 3 shows the connectivity of magnetometer to the microcontroller unit.

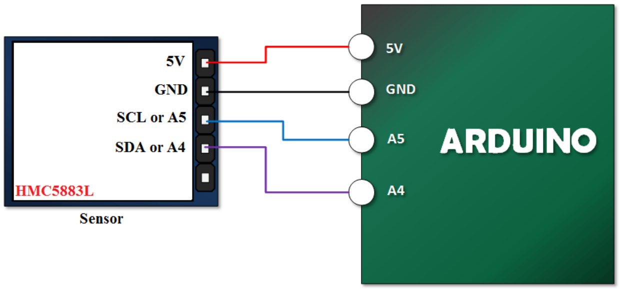


Figure 3 Interfacing of the megnatometer or MEMS compass HMC5883L

The interfacing in Figure 3 provides data to the ATmega microcontroller in the form of stream of data X Y Z in micro Tesla (µT) and then overall calculated heading is fed into the microcontroller. If sensor is installed parallel to the ground it will show reading relative to the magnetic north. One example reading which is given to the microcontroller is as follows, X: 24.82 µT, Y: -98.51 µT, Z: 34.14 µT. These data can determine the heading of the FWMAV while in flight. The heading information will exemplify later on.

C. PCB of ornithopters

In the printed circuit board (PCB), sensors are housed and mounted in specific pattern, distance between motor drive circuit and magnetometer sensor is maintained so that magnetic interference is avoided as possible as we can.

Various components such as IMU, motor drive circuit, and motor are connected to the ATmega 328p. Motor is connected to the motor drive circuit. The basic connection of the control circuit is shown in Figure 4.

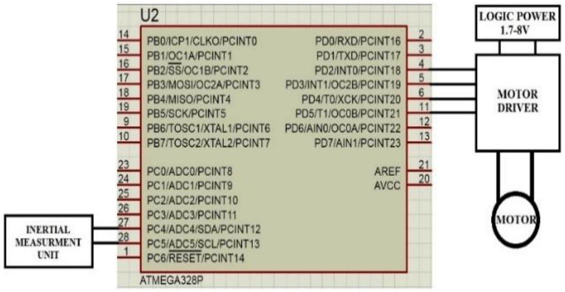


Figure 4 Motor driver interfacing with ATmega 328P

D. Testing data from MEMS devices

The directivity of the FWMAV is achieved through controlling the tail motor. The motor drive circuit is connected through an ATmega328p microcontroller powered by lithium polymer battery as depicted in Figure 5. By passing high output signal on one terminal and low signal on the other, the motor is made to rotate. Changing the terminal into high and low, the direction of the rotation is altered.

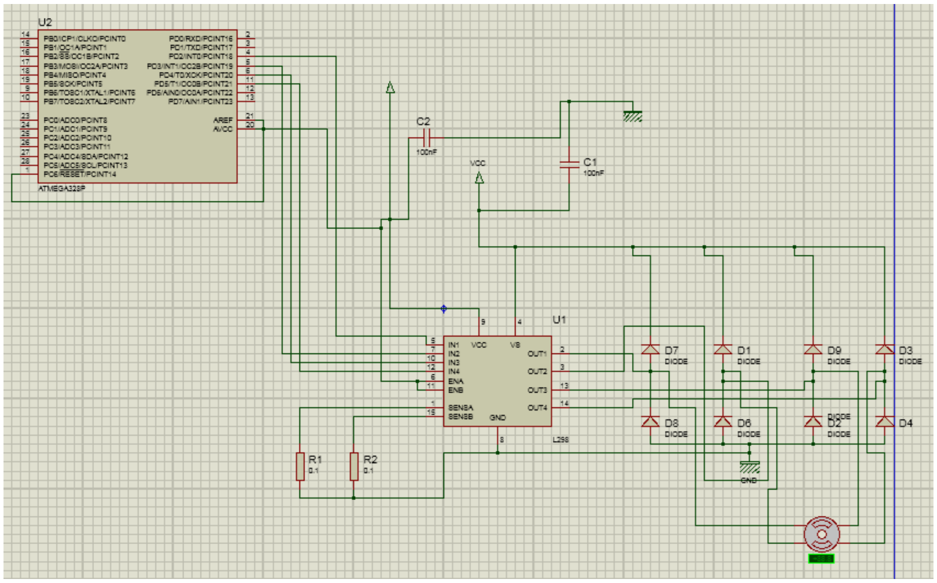
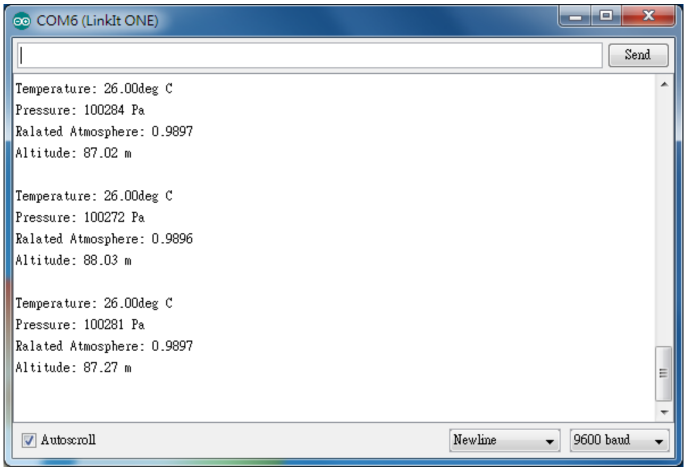


Figure 5 Motor drive and ATmega 328P interfacing

III. CONTROL

A. *Altitude measurement*

A digital barometer is added to the sensor unit to measure the altitude of the MAV. BMP180 has a resolution of 10cm and is used with I2C protocol. The parallel connection enabling the microcontroller may not necessitate any additional pin for connecting other sensors. The sensor is successfully tested and one example is shown in Figure 6. BMP180 is capable of delivering pressure, altitude and temperature but here we are more concentrated in the pressure and altitude data. Example serial monitor data like pressure, altitude and temperature are as follow: 100284 Pa, 87.02 m and 26 degree Celsius.



```
Temperature: 26.00deg C
Pressure: 100284 Pa
Ralated Atmosphere: 0.9897
Altitude: 87.02 m

Temperature: 26.00deg C
Pressure: 100272 Pa
Ralated Atmosphere: 0.9896
Altitude: 88.03 m

Temperature: 26.00deg C
Pressure: 100281 Pa
Ralated Atmosphere: 0.9897
Altitude: 87.27 m
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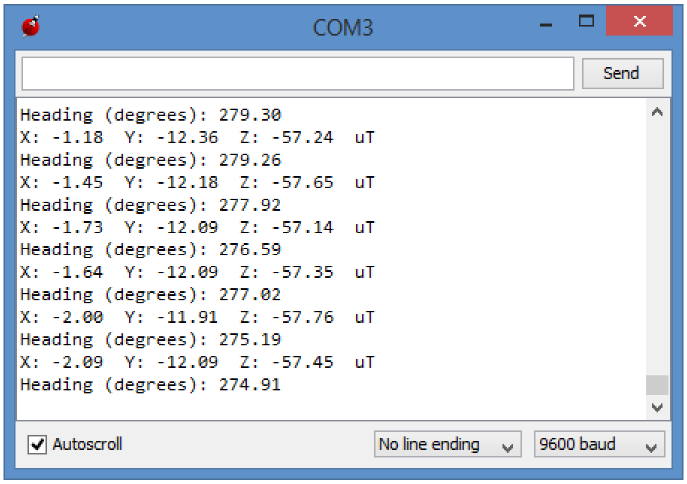
Figure 6 Measurement of altitude using the Barometer BMP180



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Heading (degrees): 279.30
X: -1.18  Y: -12.36  Z: -57.24  uT
Heading (degrees): 279.26
X: -1.45  Y: -12.18  Z: -57.65  uT
Heading (degrees): 277.92
X: -1.73  Y: -12.09  Z: -57.14  uT
Heading (degrees): 276.59
X: -1.64  Y: -12.09  Z: -57.35  uT
Heading (degrees): 277.02
X: -2.00  Y: -11.91  Z: -57.76  uT
Heading (degrees): 275.19
X: -2.09  Y: -12.09  Z: -57.45  uT
Heading (degrees): 274.91
```

Figure 7 Heading direction using the magnetometer HMC5883L

B. *Heading control*

Magnetometer sensitive to earth's magnetic field provides three axis of measurement. With these axes, dimensional vector pointing to the direction of maximum magnetic strength is determined corresponding to earth's magnetic field. The measured field direction is used to provide the direction of heading and it plays a vital role in autonomy of flight navigation. The sample coordinate values are given to the controller which in turn provided the heading of FWMAV and one example is shown in Figure 7. The connected sensor is HMC5883L. The sensor provides heading data 279.30 as a true heading or also called the direction of the FWMAV. The X, Y and Z readings, i.e. -1.18 µT, -12.36 µT, and Z -57.24 µRespectively maps the FWMAV in the 3-dimensional space.

IV. RESULT DISCUSSIONS

A. *Output signals from the on-board discrete MEMS devices.*

Three axis readings are used for tracking ornithopter in 3D space. In this study, HMC5883L magnetometer sensor is used which has 0.2 tesla of resolution with a sample output at 15 Hz. DRDY pins on the sensors are connected to the microcontroller and sampling rate is increased. Figure 8 shows the discrete components of BMP180, PWM motor driver and Arduino Tinylilly Atmega 328p.

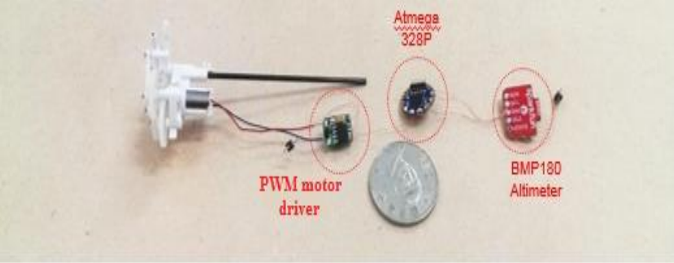


Figure 8 PWM motor driver, Atmega 328p MCU, BMP180, and a flapping mechanism (left side)

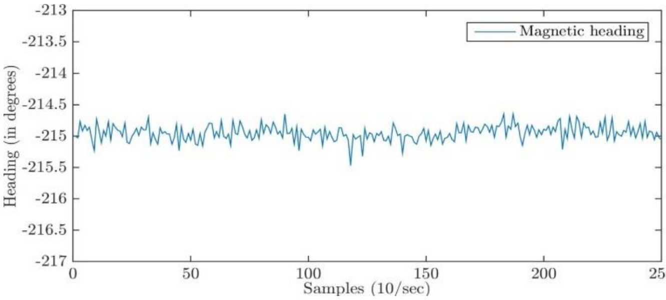


Figure 9 Magnetic heading signal; heading fluctuation is ± 0.4 deg

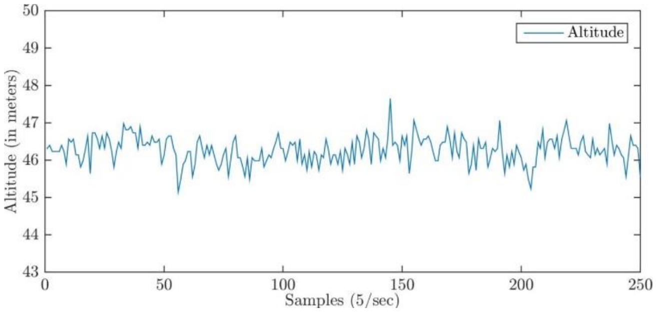


Figure 10 Altitude signal; altitude fluctuation is ± 0.9m

The accuracy of integrated sensors is evaluated and it is observed from Figure 9 and Figure 10. In this discrete configuration, all the sensors and microcontroller are connected to each other by means of connecting wire and this leads to extra weight which occupies more space also. A typical microcontroller with various sensor module weights is estimated in Table 2.

It can be seen from Table 2 that, the total weight of 2.44gram added to FWMAV causing decrease in endurance and lifting of the vehicle is also tedious. It also occupies more space and power requirement is a major concern. Even though the discrete avionics weight of 2.44 gram is the lightest one in Table 1. this weight is still a big payload to our 20 cm-span FWMAV. Hence, a printed circuit board (PCB) integrated with all the necessary sensors is necessary.

Table 2
Weight distribution of microcontroller and sensors for FWMAVs

No.	MCU and MEMS chips	Weight (gram)
1	Microcontroller ATmega 328P	0.36
2	Magnetometer HMC 5883L	0.58
3	PWM motor driver	0.32
4	Barometer BMP 180	1.18
Total		2.44

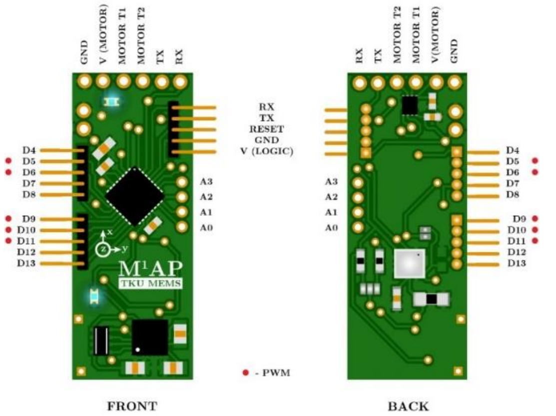


Figure 11 M1AP designed by Tamkang University [21]

B. Integration module M1AP by Tamkang University

The "M1AP" PCB integrated with all sensor modules is indigenously designed and fabricated at Tamkang University and shown in Figure 11 [21]. The barometer and magnetometer are assembled with necessary wires and pins. The total weight of the PCB is reduced to 1.26 grams which can make significant effect in the performance of the FWMAV. From the chip, the data acquisition and a test flight utilizing the obtained data has been successfully demonstrated.

The array of data made available to lightweight MAVs through this autopilot board has a large scope in terms of development and implementation of control algorithms, attachment of additional sensors, and interpretation of obtained data. It is vital for the PCB to be compact and light weighted. To address this need, the Universal Serial Bus (USB) interface that connects the ATmega microcontroller to a host computer for the purpose of programming is conceived as an extra attachment that is not on-board. The proposed light weight control module can be utilized in FWMAV applications to control the vehicle effectively.

C. Constant-heading flight by discrete MEMS devices

A program to seek magnetic north was written to the microcontroller and a flight test was performed. The FWMAV equipped with discrete avionics in Table 2 was launched facing north, south, east and west. The results are presented in Figure 12. The results from the flight test proved that the microcontroller based control system was working and illustrated that the data from on-board IMU can be used to make control decisions on the on-board microcontroller. The deviation for north, south, west and east launch as are 30.6º, 28º, 26.6 and 20.9º, evaluated from the flight paths of Figure 12.

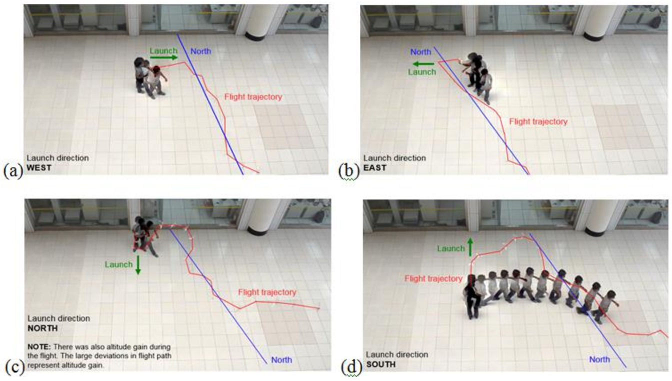
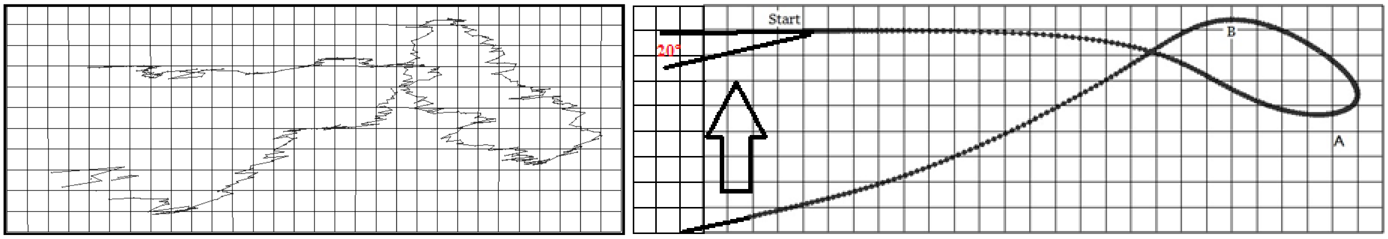


Figure 12 Constant-heading flight test (toward to north) on "E-Bird": Launch from (a) West; (b) East; (c) North; (d) South

D. Constant-heading flight by the integration module M1AP

Equipping with M1AP in Figure 11, the FWMAV performed a better constant-heading flight (Figure 13) than the case with discrete sensors in Figure 12. The authors also used two cameras on ground to do the stereo photography of the flight path. The trajectory of the FWMAV was obtained by software Kwon3D processing the capture images. The details for calibrating the standard grid for the image processing is using software Kwon CC to input the coordinates of many floor tile grids with the interval of 50 cm on site. The main program capturing the characteristic points outputs the raw 3D trajectory as Figure 13(a). With proper filtering technique, the corresponding trajectories with smooth curves are shown in Figure 13(b). The FWMAV loitered and started to deviate its heading at the 5m place away from the starting point. Point A in Figure 13(b) denotes the moment for taking a turn of 180 degrees. Point B denotes starting the return flight. The heading deviation per to-and-fro flight is evaluated as 20 degree. This heading deviation may be due to the integration error of flight navigation and the intrinsic magnetic interference from the electrical motor of FWMAV on the MEMS-compass.



(a) (b)

Figure 13 Constant-heading flight control:
(a) the raw data of the 3D trajectory of a to-and-fro flight test; (b) the smoothened data of the 3D trajectory of a to-and-fro flight test

E. Constant-height flight by discrete MEMS devices

In addition to the direction test, an altitude test was devised to utilize the altitude data coming from the barometer. The altitude is calculated based on the pressure readings and it is important to note that the reading can vary depending on the weather, temperature and even the architecture of the building, if the MAV is flown indoors. In this test, the MAV was designated to reach a target altitude from the ground level and land by slowing down and yawing downward. The result of the test is as Figure 14 Constant-height flight by discrete MEMS devices. The ground level was noted from the sensor data as 53m above sea level (as the university is located atop a mountain), and the target altitude was set as 60m. The test was only a partial success as the MAV tried to yaw as it reached 58m, which close to the target altitude of 60m. It then spiraled sideward and crashed. To successfully control the altitude, a tail rotor or an aileron structure is recommended for further works. In a true test for altitude control, the MAV must be able to hold the altitude, as demonstrated by Hsiao et al [7]. It is suggested that PID control be used in further works for controlling the altitude of the MAV.

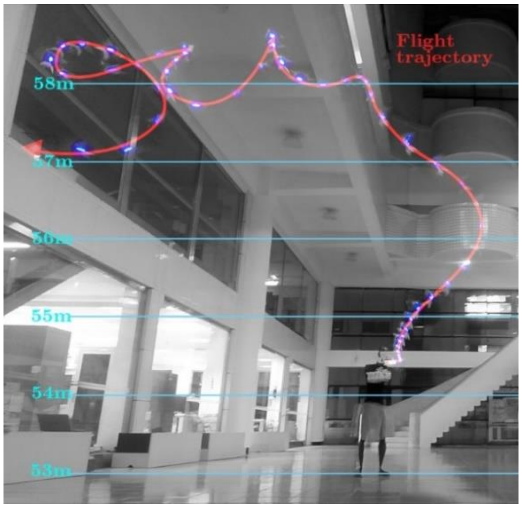


Figure 14 Constant-height flight by discrete MEMS devices

F. Constant-height flight by the integration module M1AP

In the previous work done by Hsiao et al. [7] the authors gave up checking the real height during the flight, but only put a height benchmark on wall for comparison. Take the example of the red line (which is calibrated and presumed as 50 m height above the horizon) in Figure 15. The MEMS-compass on the FWMAV just finds out the real height and do the comparison with the presumed 50 m high. If the real height is less than the red line (Figure 15(a), then increasing the flapping frequency, vice versa, decreasing the flapping frequency as the real height is larger than the red line with 1m over (e.g. 51m) Figure 15(b). The goal is to moderately adjust the flapping frequency as to maintain the flight height between 50m and 51m in Figure 15(c).

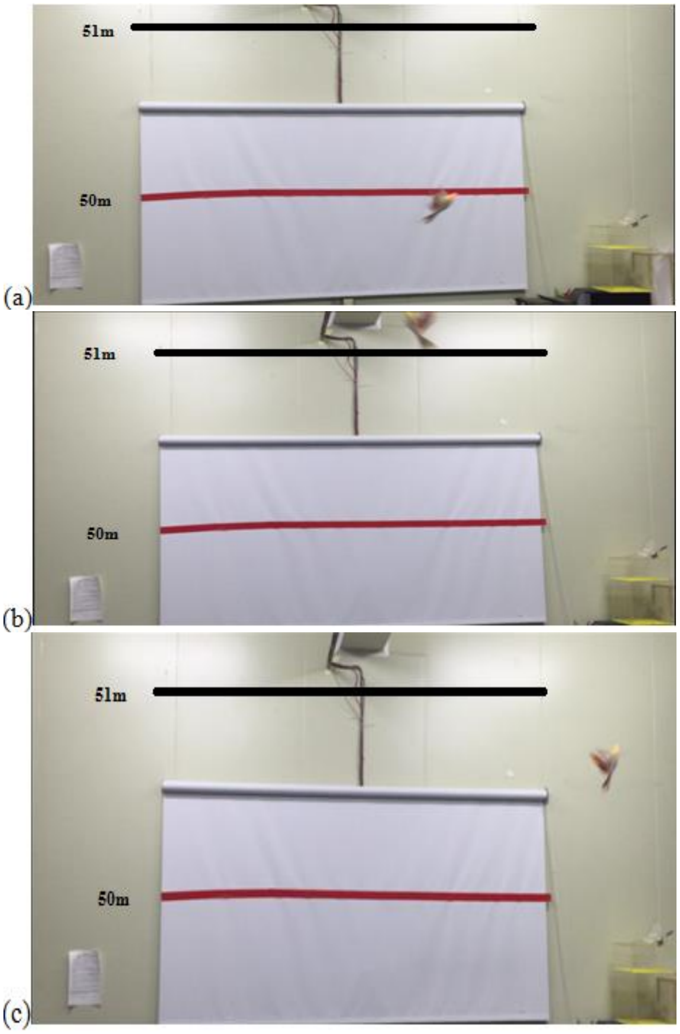


Figure 15 Flight-height control of a FWMAV:
(a) increasing the flapping frequency while below the red line;
(b) decreasing the flapping frequency while above the red line;
(c) keeping the flight-height between 50m and 51m

V. CONCLUSIONS

The measurement of FWMAV's altitude using barometer and directivity with an aid of magnetometer sensors is performed through integrating ATmega microcontroller and embedding these sensors into an indigenously fabricated PCB. The developed hardware module has achieved a weight reduction of in comparison with the existing PCB based controller that would significantly improve the endurance of MAV and increasing the payload capacity. Simulation and hardware test shows promising results to implement the constructed control module in FWMAVs to achieve heading and altitude control. Semi-autonomous flight test and altitude hold test flights was also performed in this research both the results were promising, in the semi-autonomous flight test the FWMAV was programmed to fly in a preprogrammed direction no matter in what direction it is launched. The FWMAV was able to detect the direction and was able to correct the position according the program. In the altitude hold program the FWMAV was able to hold the programmed altitude near to the assigned value. So, the integrated sensor PCB control board or M1AP results were excellent and due to the weight reduction in total weight of the FWMAV.

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