Altitude Estimation for a Micro Aerial Vehicle in a Complex Environment

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***Abstract*—Development done in Mechatronics has allowed Aerial Vehicles to be scaled down and be used for indoor and outdoor environments. Those Micro Aerial Vehicles (MAV) provide small size and great flying ability allowing professionals to use them for a wide range of applications. Flying micro aerial vehicles in complex environments such as indoors requires a semi-autonomous system able to adjust to surrounding objects. Therefore to address the issue a network of sensors is implemented to monitor and control the altitude of the system regardless of the environment. The research done through the summer helped analyze the readings that is obtained when using certain sensors for a flying system. The data obtained helped quantify the maximum range, data rate, and type of noise for each sensor.**

***Index Terms*— Altimeter, Altitude Estimation, Micro-Controller, MAV, Micro Aerial Vehicle**

I. INTRODUCTION

The recent research done in the field of robotics has given aerial vehicles the ability to have a significant impact across several disciplines. The advantage of flying has allowed professionals to complete several tasks too demanding for man. Current aerial vehicles have had great success in the area of search and rescue. A recent research by Alessandro Renzaglia et al. [1] explains how a group of unmanned aerial vehicles navigate in a convex environment can be used used for search and rescue. The General Robotics, Automation, Sensing and Perception (GRASP) Laboratory at the University of Pennsylvania has researched scaling the size of helicopters down, while avoiding the complex mechanical components of the real- size aerial vehicles. The swash-plate is one of the complex components which is made of several moving parts. The swash-plate is used to transfer the lift of the rotors into pitch using several moving components, and is very difficult to implement when aerial vehicles are scaled down. Obviously the cyclic pitch control (cyclic control) created by the swash-plate is a very important concept to helicopters therefore, the Modlab has researched a method to scale the MAV down without the complexity of the swash-plate but still capable to produce the same cyclic control as the swash-plate. With the mechanical aspects of the MAV improved, an intelligent control system is still to be implemented. When flying, it is very important to include feedback such as altitude, pressure, attitude and even surrounding objects. Most aerial vehicles make use of an attitude controller to achieve stable flight. Designing the adequate attitude controller involves modeling the MAV as a system dependent, not only on inputs from the operator, but on external disturbances [2].

This paper describes the methods toward an altitude estimation for a MAV in a complex area. Estimating the altitude is necessary to implement the appropriate altitude controller. The altitude controller is a crucial component for the MAV and is used for properly adjusting the position of the MAV with respect to its vertical degree of motion. Estimating the altitude will enable us to hover at a designated height and use the sensors to assist the operator during flight. There are several methods used for implementing altitude controllers based on control theory. Where the study of control theory involves two main categories, linear control theory and nonlinear control theory. As an example, the article [3] describes a nonlinear controller, using dynamic surface control implemented on a quad-rotor. However non-linear controllers are very difficult to implement, typical controllers are instead attained using linear control theory. Those controllers consist of Linear- Quadratic- Regulators (LQR) [4], or Proportional Integral and Derivative controllers (PID) [3]. The Proportional Integral and Derivative controller is commonly used in the industry; the PID controller is based on the desired output of the system (specified value) and the actual output (actual value.) Subtracting the desired output from the actual output indicates the error needed to be corrected. By monitoring the error, the error's rate of change and the accumulated error, PID controllers are used in very wide range applications. Essentially controllers are built around a system using control theory so the response of the system due to certain inputs and disturbance can be optimized. Therefore it is necessary to model the plant with its mathematical description to know the plant's response to disturbances and input controls.

Designing the controller requires using the adequate sensors for data acquisition where the choice of sensors is constrained by the MAV's weight and the need to keep the cost affordable. Most altitude controllers rely heavily on the inertial measurement unit [3] even though they operate using Deduced Reckoning (Dead Reckon.) Cunxiao Miao and Jiancheng Fang, from Beihang University, Beijing China, implemented an altitude controller using just an IMU and a dual GPS module to provide feedbacks. Similarly, using the appropriate sensor, a PID controller can be implemented using a micro-controller (μC) and a Digital Signal Processor (DSP.) The μC is used to interface with the sensors, acquiring the input signals, while the DSP extracts intelligence out of the signals, and processes the signals. The DSP is also used to implement the mathematics involved in the altitude controller, which implies that a digital controller is needed.

Altitude controllers are designed using sensors like IMUs [3], barometric sensors [4], ranging sensors [5], magnetometers, cameras [6], GPSs [3], or radar altimeters. IMUs, barometric sensors, and ranging sensors are more commonly used for MAVs since the sensors can be physically scaled down. Ideally, the altitude controller will use ranging sensors, (which could be either an ultrasonic or an infrared sensor) and a sensor that measures altitude with reference to the initial position. The ranging sensors will be used to provide a direct reference to the ground or objects below the MAV while a barometric sensor can be used to indicate any change in the real altitude with reference to true ground. Interfacing with the sensors allows the MAV to be semi-autonomous. To estimate the altitude, the system is required to complete a series of data acquisition and then go through a step of data processing. Our system is designed on the STM32F373 Arm Cortex M4F (M4) which is essentially a Digital Signal Controller (DSC); this allows the M4 to be robust and be used for a wide range of applications. Fig. 1 illustrates a mapping of the DSC and the sensors. The μC provides digital and analog communications such as USART, I2C or ADC/ DAC which allows us to use a wide range of external hardware.

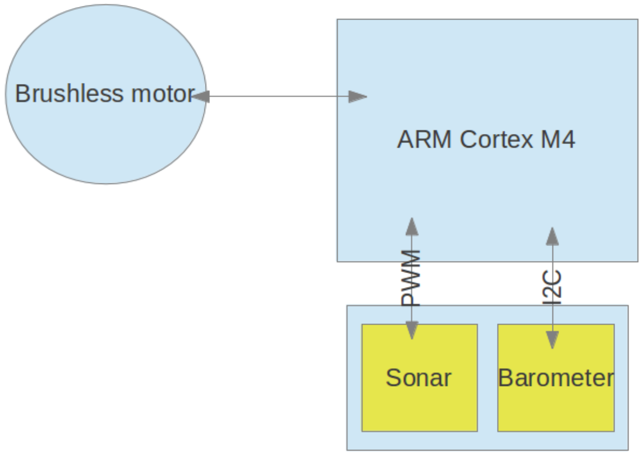

Fig. 1: Basic computation layout of the DSC

Fig. 1 illustrates the M4 with its basic input and output peripherals

The paper is organized as follow: **Section 3,** *Method of Design*, covers the methods used to for building the testbed for the altitude controller. **Section 4** of the report, *Altitude Estimation & Results*, focuses on the algorithm for estimating the position of the MAV. **Section 5** *Altitude Controller & Future Work* describes the potential methods for implementing the digital controller on the MAV and future work to be done. Finally, the paper concludes with **Section 6**, the Conclusion & *Discussion* which observes and discusses the *Analog Controller & Future Work* section and the research project as a whole.

II. BACKGROUND

A. Digital control theory

Digital control theory is a subset category of control theory where computers are used to control a system. The computer, also known as the micro-controller (μC,) is able to convert analog signals into digital signals and to process the desired output by computing in the digital domain. To process the signals, Digital Signal Processors (DSPs) are commonly used to carry the computation. A typical Digital Controller consist of both a DSP and a μC on a single chip, such hybrids are referred to as Digital Signal Controller (DSC).

B. PID Controller:

In control theory a Proportional, Integral and Derivative controller is a system which analyzes the difference between the desired output against the obtained output. The PID can be expressed as a function in the time domain as illustrated in Equation 1. The proportional term of the PID is a multiplier to the error referred to as “K_P” which simply scales the error with respect to the value of “K_p”. The integral term is related to the previously occurred error or the “past,” as the error is summed by the integral, it is then scaled by the factor “K_i.” At last, the derivative term evaluates the rate at which the error changes or the “future,” and multiplying with the term “K_d.” PID controllers are widely used in the industry and are very efficient for adapting to different inputs.

$$G(t) = K_p * e(t) + K_i * \int e(t)\,dt + K_d \, {}^{de(t)}/_{dt} \qquad (1)$$

C. STM32F373 Arm Cortex M4F (M4):

To analyze our sensors, our system makes use of the M4 a very powerful digital signal controller provided by ST Microelectronics. The M4 is designed to have a low- power consumption while still meeting the needs of most applications. The M4 is a DSP/ µC hybrid hence it consists of Input/ Output (IO) peripherals to communicate to external sensors and DSP instructions to process the signals.

III. METHOD OF DESIGN

To test the altitude controller, a testbed comprised of rails was designed to constrain our system to one degree of freedom, the Z-axis. Constraining the system to one degree of freedom allows us to isolate the system from the other degrees of motion (yaw, roll and pitch.) The testbed is made from an aluminum frame from the company 80/20 Inc, who provides easy and quick to assemble frames. The frame which stands at a height of 60inches (150cm,) is designed to allow a cart with a propeller to fly along the testbed to the rail. With a height of five feet, the system gives enough clearance to simulate flight for an indoor environment.

The rolling system (cart) is designed to contain the sensors used to monitor the height at which the system moves along the testbed. An optical encoder is used to precisely measure the displacement of the system. The optical encoder reads a quadrature pattern printed on the testbed to generate an analog signal using an infrared (IR) sensor. Using an IR transmitter paired with a receiver, the quadrature signals printed on the testbed are sent to the M4 using the ADC peripherals. With the testbed, we are able to decode the displacement with an accuracy of 0.5 inches and direction of the system during testing.

To fly indoors, the system would need sensors that are able to detect surrounding objects, estimate altitude with reference to objects below the MAV and estimate the altitude with reference to the ground level. Ranging sensors are commonly used to detect objects or measure the distance with reference to the object, therefore an ultra-sonic sensor (MB1010 LV MaxSonar EZ1) and an IR sensor (Sharp GP2YOA2YK) were observed using the testbed. On the other hand, the ranging sensors are not able to provide altitude with reference to the true ground, therefore we tested a barometric sensor on the testbed. The barometric sensor is monitoring the changes in pressure as the altitude changes therefore it will inform us of true displacement.

A common problem that occurs when analyzing data captured using a µC is the lack of a communication scheme to analyze the data through a computer. Our USB communication protocol takes advantage of the M4's USB peripheral to efficiently encode packets that are "pushed" through the USB port of the computer, using a Python script; we are able to "grab" the packets in real time for later use such as plotting or even processing. Using the peripheral, we are able to generate plots and compute the data using Matlab. Fig. 2 illustrates a schematic for the setup of our configuration between the PC and the µC.

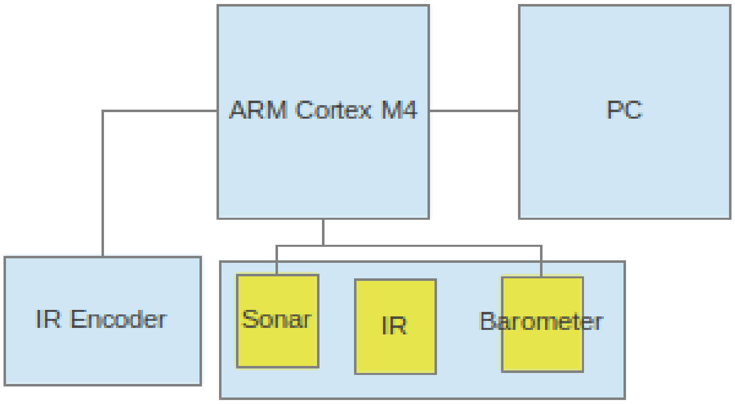

Fig. 2 illustrates the how the µC interfaces with the sensors and the computer. The external peripherals are communicating using the following digital and analog communications: I2C, PWM, USB and Analog

IV. ALTITUDE ESTIMATION & RESULTS

In this section we tested the sensors using our testbed, our objective was to test and evaluate the data rate, precision and range of data for each sensors using the testbed. Using our USB communication protocol between the testbed and the computer, we generated data plots for each sensors as we manually moved the system along the track.

A. Infrared Sensor

The first sensor to be tested was the IR sensor from Sharp Electronics. The sensor operates with an input voltage up to 7V; we found it convenient to use a supply voltage of 3.3V which is the same as that of the M4, our µC. The IR sensor outputs an analog voltage inversely proportional to the distance of the closest object found. The analog input read by the µC was converted into distance (inches) by using Matlab's Curve Fitting Tool to obtain a relation between the voltage and distance. By taking several measurements within a range of six feet, the relation between the voltage outputted by the sensor and the actual distance was calculated. As illustrated in Fig. 3, Equation 2 characterized the voltage to distance relationship.

$$Distance = \frac{313.436}{Volts^2 + 3.543 * Volts + 4.712} \quad (2)$$

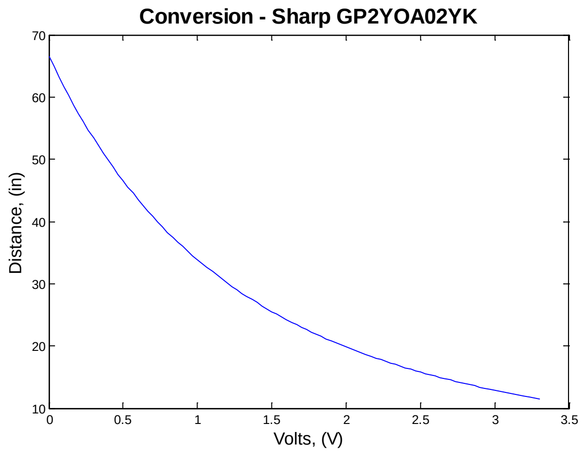

Fig. 3: The Sharp IR analog output converted into inches

The output of the sensor is between 0- 3.3V and is able to detect object from 7.87- 66 inches

Fig. 3 and Equation 2 are the conversion for the voltage read by the controller into the appropriate distance in inches. The IR uses an array of Charged Coupled Devices (CCD) and using those CCDs the sensor is able to measure the angle of the triangle created between the sensor and the object detected. The CCDs give the sensor the ability to be indifferent of the surface's color; such feature has made the Sharp's IR sensor superior to other IR sensors which are known to be unreliable with surfaces of reflective colors. As illustrated in Fig. 3 the IR sensor provide of a range of 9–65inches. To evaluate the IR sensor, our linear encoder implemented on the testbed was used to assess the accuracy of the sensor. Fig. 4 illustrates the results obtained after abruptly moving the rolling system on up and down the testbed.

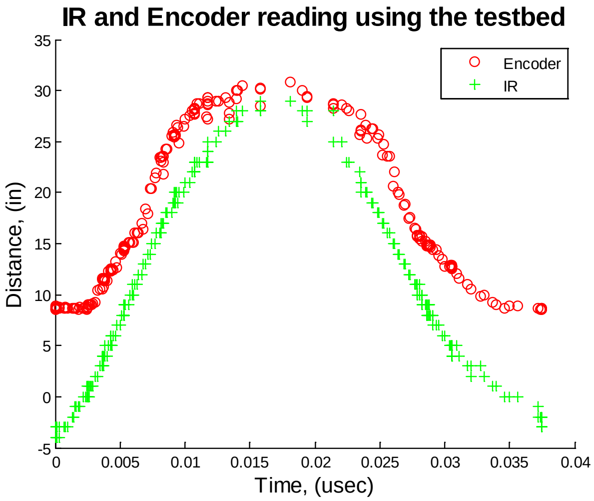

Fig. 4: The displacement of the system along the testbed read by the encoder and the IR

As previously stated, the IR is unable to read values below a certain height (9 inches).

The results illustrated in Fig. 3 show that the sensor is very precise starting from 10inches. The explanation for the offset is because of the nature of most ranging sensors which cannot measure the distance of objects that are too close sensor's emitter and receiver side. At a certain distance, the signal reflects on the object with an angle too wide to be received by the receiver side of the sensor. Hence, the IR sensor has a minimum range of 10 inches as illustrated in the Fig. 4.

B. Ultrasonic Sensor

The other ranging sensor tested was the MB1010, an ultra-sonic range finder which has seen several of its applications in the area of robotics. The MB1010's ability to communicate through several methods of communication makes it a very reliable sensor to use. In cases where a µC may not be able to communicate through some mean of communication, the MB1010 has a total of three different methods of communication. To receive the data from the sensor, we chose to use a Pulse Width Modulated (PWM) signal to send data to the µC. Using PWM, the data is less susceptible to be distorted compared to an analog signal and has a very fast data rate. Unlike the IR sensor, the Ultra-sonic sensor provides us with a large range of operation (15–254inches) and a resolution equal to an inch. Our analysis of the ultra-sonic sensor consists in verifying the range of the sensor, and its resolution. The linear encoder attached on the testbed is used as a reference to the displacement of the system.

Using Matlab, the signal acquired using the PWM peripheral of the M4 was plotted after sliding the system along the testbed. Fig.5 illustrates the plot of the ultra-sonic sensor with the true displacement of the system obtained using the encoder.

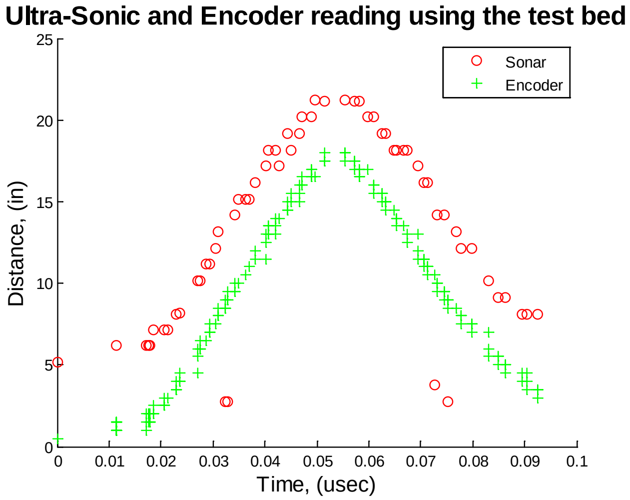

Fig. 5: The displacement of the system along the testbed read by the encoder and ultra-sonic sensor

C. Barometric Sensor

The other sensor tested was a barometric sensor (barometer.) The barometer is a Micro-Electro-Mechanical Sensor MEMS able to convert pressure (Pascal) to height (inches) using its embedded micro-controller it communicates using a digital signal. The barometer is needed to have altitude values with reference to the true ground level or the initial altitude of the system. However when using the barometer indoor, the signal tends to be very noisy and drifting over time. To observe the signal, we read a very large sample of data to categorize the noise corrupting the signal. Fig. 6 illustrates the noisy waveform for a total of 1,000 points of the barometer.

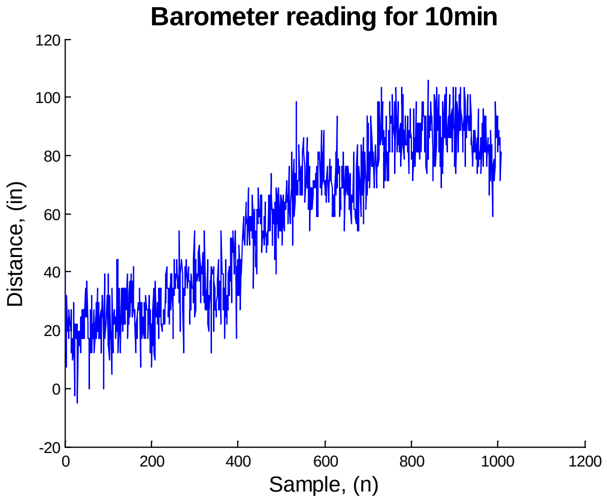

Fig. 6: Reading the barometer for a total of ten minutes. To classify the type of noise that we have we decided to read from the barometer for a long time

As Fig.6 illustrates, the barometer starts with an offset of 20in and starts drifting. The barometer converts its pressure readings to altitude with reference to pressure at sea-level. Therefore, a DC offset is obtained related to the difference in altitude between sea-level and our position at the time of testing. To remove the offset, we subtracted an average of the first readings obtained from the barometer, hence our barometer was calibrated with reference to our initial position instead of sea level. Further testing was done to observe the behavior of the barometer as the system is going up and down the testbed. Using the encoder, we are again able to verify the readings of the sensor as illustrated in Fig. 7.

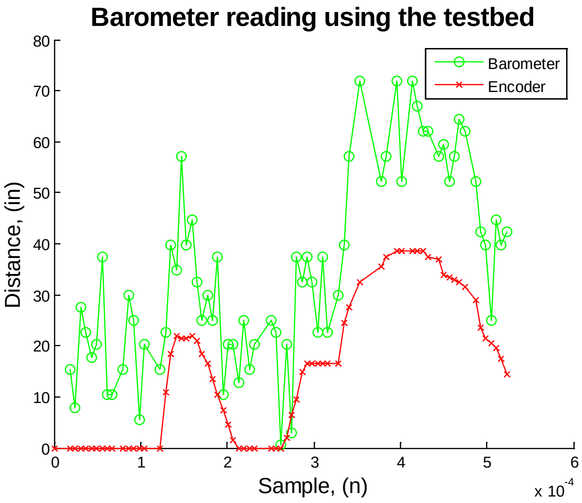

Fig. 7: The displacement of the system read by the barometer and the encoder

As illustrated, the barometer senses changes in altitude as we move the system up and down however the signal is clearly noisy.

V. Altitude Controller and Future Work

For future work, we intend to redesign the system to include a brushless motor with propellers. Mounting the brushless motor would complete the flying system and allow us to implement the digital controller based on the outputs of the sensors. The testbed will make sure that only altitude is a factor in our controller and will also assist in analyzing the controller in terms of percent overshoot, rise time and settling time.

To implement the controller, the PID controller was considered because of its simplicity to implement and tuning techniques. Several methods for tuning PID controllers have been used for several applications. One of those methods is the Ziegler-Nichols approach for tuning PID controllers. The Ziegler-Nichols method involves slowly altering the multipliers of the PID coefficients (K_P, K_I, K_D) until the ideal behavior is obtained from the controller. Article [7] explains how a PID controller for a DC motor was implemented using the Ziegler-Nichols approach.

VI. CONCLUSION & DISCUSSION

At the conclusion of the research, the data acquired and illustrated show the properties to expect from the sensors and how they can be integrated on a flying vehicle. While conducting the research my observations were that successfully estimating the altitude depends on the sensors' data rate. The data rate of the sensor determines how reliable the sensor can be when integrated on a MAV which is expected to change position quickly. As we observed, a sensor such as the MPL3115A2 will not be able to register quick changes in altitude because of its slow data rate.

The data obtained illustrates the behavior of each sensor and helps us to apply changes unto our system so that the sensor can be used effectively on an aerial vehicle. Fig. 4, Fig. 5, and Fig. 7 each illustrates that the sensors have a slight offset compared to the displacement obtained from the encoder. Such DC component is very difficult to remove with a filter. The DC offset are usually removed using both a high-pass filter and low-pass filter to reduce signal.

In the case of the barometer, implementing a low-pass filter is necessary to extract intelligence from the signal. As illustrated in Fig. 7 the signal is severely distorted, by what seems to be high-frequency noise. It is clear to see that the barometer behaves similarly to the encoder; however the signal contains noise and an offset. W. Tang from Ching Yun University and Y.H. Tsai from the National Taiwan University discuss the behavior of barometers tested on flight the Boeing 727[8]. The two authors concluded from their experiments that the barometer was incapable of providing accurate measurements for low frequencies, where the altitude is constant. However, the barometer is great at detecting quick changes in altitude as illustrated in Fig. 7. As our results illustrate, the measurements obtained using the barometric sensor contains several spikes in the graph where the system is at a constant altitude but the barometer is still able to follow the shape of the true position as illustrated by Fig. 7. We believe that the signal is distorted with high-frequency noise due to changes of pressure indoors and air-conditioning vents.

With the plots acquired from analyzing the data, we will be able to confidently place the sensors onto the MAV where each one of the sensors will have a specific purpose. Although the IR sensor has a short range of operation, its accuracy would help with vertical take-off and landing and objects detection. In the case of the sonar sensor, we have the ability to achieve several tasks. The sonar's accurate and long range of operation allows us to use it for ground detection and even for vertical landing or take-off. Finally, the barometer will also be a great addition on a MAV since it is indifferent of physical objects. The barometer will then serve to provide measurements of the altitude with reference to ground which will be adequate in a complex environment.

ACKNOWLEDGMENT

I would like to acknowledge the support of the National Science Foundation, through NSF REU grant no. 1062672 and I greatly appreciate the opportunity that I had to conduct the research.

I would also like to acknowledge the University of Pennsylvania, which through Dr. Mark Yim I was able to complete my research using the resources available at the Modlab and finally I would like to thank his two Phd. students who guided me through the research, Jimmy Paulos and Matthew Picolli.

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