Altitude Control of an Unmanned Aerial Vehicle Using a Binaural Bat Echolocation System

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ABSTRACT

By using a binaural bat echolocation system, we designed and built a testbed to control the altitude of a small unmanned aerial vehicle (UAV). The sonar system consists of a speaker and two microphones that resemble the mouth and ears of a bat. This system emits ultrasonic pulses (40kHz) toward the ground, and then detects, amplifies and rectifies the returning echoes. The echo duration and interaural level difference (ILD) are incorporated into a proportional-derivative (PD) control algorithm to calculate the necessary tail-flap angle for altitude control. Using custom hardware and PIC microcontrollers, we simulated and tested the aircraft's ability to maintain a fixed elevation using a bat echolocation system.

1. INTRODUCTION

Bats use echolocation as a technique for navigating through various environments and to forage for food. Bats emit ultrasonic pulses and listen for returning echoes. They are able to extract acoustic localization cues encoded in the echoes, namely the echo's time-of-flight and interaural level difference (ILD) [1]. Because of their highly effective acoustic perceptual system, bats are practical models to use in designing a sonar system for controlling the altitude of a small UAV.

A bat-inspired aircraft is built with a binaural sonar system that comprises of a speaker and two microphones, similar to the mouth and ears of a bat, respectively. These artificial auditory features are capable of sensing targets through sound localization. The sonar system emits sound pulses through a speaker ("mouth"), directed toward the ground. Two microphones ("ears"), positioned on either side of the speaker, receive echoes reflected from the ground. Before decoding the aircraft's altitude and pitch angle, the sonar system first filters and rectifies the echoes. Once the aircraft altitude and pitch angle are computed, the altitude control algorithm generates a signal to control the aircraft's tail-flap and guide it to the desired altitude.

1.1 BAT ECHOLOCATION SYSTEM

Echolocation is a method of sensory perception by which sound instead of light is used to map the surrounding environment. Most animals use conventional visual perception, yet some animals, like bats, cannot see well and rely upon aural perception.

Contrary to popular belief, bats are not "blind"; in fact, bats can see but with poor vision [2]. Because their sense of hearing is much more sensitive than their vision, they rely heavily upon acoustic mechanisms to navigate through dark environments.

Bats generally emit a series of ultrasonic pulses through an open mouth, usually sweeping over several modulated and constant frequencies, depending on the species of bat [1]. The emitted pulses become shorter and faster as a target is approached. The returning echoes are detected by the ears of the bat and processed to extract the information about the target. The shape of the target surface and its location determine the amplitude, duration and delay of the echo.

Bats are known to estimate a target's distance by measuring the time it takes for an outgoing pulse to reach the target's surface and return [1]. Analytically, the altitude is computed by multiplying half of the time-of-flight by the speed of sound.

Bats have a typical mammalian binaural auditory system and like many small mammals, their perception of azimuth appears to be dominated by interaural level differences (ILD), however, some species have been shown to use interaural time differences (ITD) [1]. Because bat ears are very close to one another, the ITD is generally too small to provide much accuracy.

With the ILD approach, the ear that is closest to the object hears a louder echo than the other ear because the bat's head attenuates the returning sound and creates a "shadowing" effect. By comparing echo amplitudes between their left and right ears, bats can effectively determine the azimuth angle to the object. As a result, the bat can move its head to detect the angular position of any target, such as its pitch angle.

The aircraft's binaural sonar system is designed and built to mimic a bat echolocation system. The speaker, as the ultrasonic pulse emitter, is comparable to the mouth of the bat while the two microphones are analogous to its ears. These three transducers form a sonar "head". The sonar head (in our application) is configured such that it is facing the ground with one microphone at the front end and the other at the rear end. The binaural sonar system uses the bat's target range and azimuth estimation technique to compute its altitude and pitch angle with respect to the ground.

2. THE SONAR-BASED ALTITUDE CONTROL SYSTEM

The sonar-based altitude control system for the aircraft is organized into four subsystems:

(1) The sonar/sensory system consists of the ultrasonic speaker, which emits a 40kHz ping, and the two ultrasonic microphones, which receive returning echoes. The microphones are positioned 45° away from the aim of the speaker, as shown in Fig. 1. The front-end sonar board processes the echoes by detecting, amplifying and rectifying the signals.

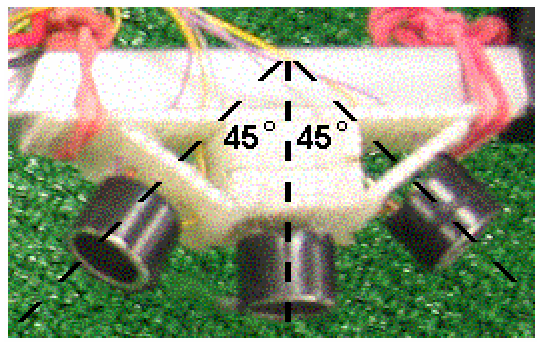

Fig. 1: The 40kHz ultrasonic microphones are positioned to point 45° away from the aim of the 40kHz ultrasonic speaker

(2) Altitude and pitch angle computations are performed by one of the PIC microcontrollers. The microcontroller measures the time difference between the emitted ping and the incoming echoes to calculate the altitude of the aircraft.

(3) The altitude control algorithm is executed in another PIC microcontroller which uses the calculated altitude and pitch angle to compute a control response, which is sent as a pulse to the tail-flap servo.

(4) The tail servo control system uses a servo to move the tail-flap to the desired angle, thus controlling the pitch change-rate.

Fig. 2 below illustrates the sequence in which the four systems perform their tasks.

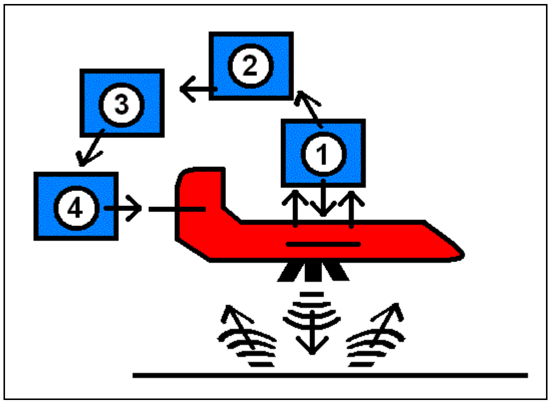

Fig. 2: Sequence for performing system tasks: (1) sonar/sensory system, (2) altitude/pitch angle computations, (3) altitude control algorithm, (4) tail servo control system

Fig. 3: Low-altitude test setup with the aircraft suspended at the nose and tail for adjustable pitch and altitude

2.1 ALTITUDE AND PITCH ANGLE COMPUTATIONS

In order to compute both the ILD and altitude of the aircraft, we collected echo amplitude data and analyzed them to find the best fit function. We were able to build a controlled test apparatus that acquires data and performs computations for altitude and pitch estimations. The apparatus comprises of a pulley system, a wireless transmitter and receiver, a PC and oscilloscope, a binaural sonar system, and the aircraft. The aircraft is suspended with ropes at an initial altitude of 5 feet. With pulleys attached to the ropes at both ends of the aircraft, we were able to adjust and measure the altitude and pitch angle. With the apparatus, we recorded and analyzed waveforms of the echoes on the oscilloscope to derive appropriate mathematical functions for the altitude and pitch angle. The data from different mapping functions were streamed wirelessly into a PC for further analysis to determine which equation best characterizes the actual altitude and pitch angle. Fig. 3 shows the test setup in the laboratory.

2.1.1 ALTITUDE

The altitude of the aircraft is computed by measuring the time difference between the outgoing pulse and the first returning echo that crosses a fixed voltage threshold. Fig. 4 shows an example of a detected echo trace.

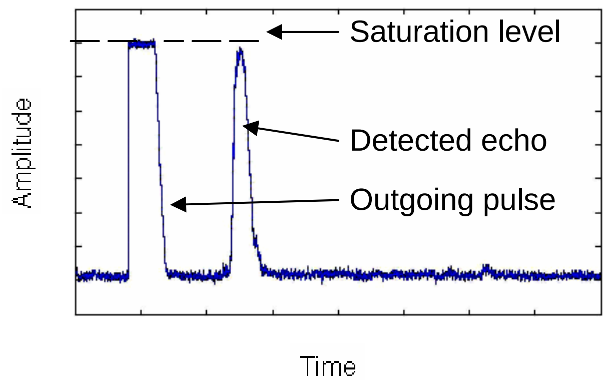

Fig. 4: A typical echo trace received by a microphone, showing an echo resulting from the outgoing pulse followed by an echo returning from the ground

The fixed voltage threshold allows us to distinguish the actual detected echoes from other ultrasonic noise. By averaging the echoes' time-of-flight over multiple noisy measurements, we were able to accurately compute the altitude:

$$\text{altitude} = \frac{1}{2} \cdot (\text{SoundSpeed}) \cdot \frac{\sum \text{TimeDelay}}{\text{N}} \quad (1)$$

2.1.2 PITCH ANGLE

Because ILD is dependent on the angular attenuations received by the two microphones, it can be easily incorporated into the binaural sonar system to measure the pitch angle of the aircraft. By analyzing the waveforms of the returning echoes, we were able to formulate four possible ILD mapping functions:

$$ILD = \ln(PeakEchoRear) - \ln(PeakEchoFront) \tag{2}$$

$$ILD = \ln(AvgPeakEchoRear) - \ln(AvgPeakEchoFront) \tag{3}$$

$$ILD = \ln(\sum RearEcho) - \ln(\sum FrontEcho) \tag{4}$$

$$ILD = \ln(\sum(\int RearEcho)) - \ln(\sum(\int FrontEcho)) \tag{5}$$

With the data processed by the binaural sonar system, we applied a set of detected echo data to each of the above equations and only the logarithmic integral ratio (5) yielded desirable results necessary to compute the ILD.

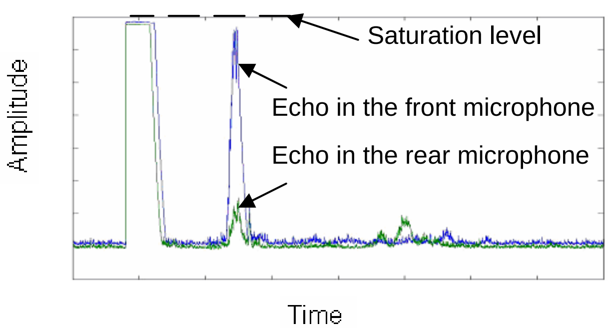

Fig. 5: Examples of echo traces received by the front and rear microphones

As shown in Fig. 5, for each microphone, the area under each echo "bump" is computed (integrated) to estimate the received amplitude for a given ping and then these estimates are averaged for five consecutive pings. The pitch angle of the aircraft is then estimated using a linear function:

$$\text{pitch} = \alpha\left(\frac{ILD - MinILD}{MaxILD - MinILD}\right) + \theta \tag{6}$$

2.2 ALTITUDE CONTROL ALGORITHM

To control the altitude of our aircraft, we devised an algorithm based on proportional-derivative (PD) control theory. When controlling the altitude of the aircraft, proportional control computes a correction term that is proportional to the error in altitude, whereas derivative control generates a correction term that is proportional to the time derivative of the error term.

Proportional control with a proportionality constant between 0 and 1 would theoretically guide the aircraft to its desired altitude, yet there is always the possibility of overshooting the target altitude when testing the aircraft under realistic conditions. Overshooting can create problems where the aircraft oscillates up and down before settling at the desired altitude. By combining a derivative control term with the proportional term, we could dampen oscillatory movements of the aircraft, which led us to choosing a PD control algorithm. Our PD control algorithm is characterized by the following equation, where $u_{pd}(t)$ is the correction term, h_t is the desired altitude of the aircraft, and k_p and k_d are proportionality constants for P and D control, respectively:

$$u_{pd}(t) = k_p(h_t - h(t)) + k_d \cdot \frac{d}{dt}(h_t - h(t)) \tag{7}$$

Furthermore, our algorithm uses the PD control response to determine the necessary tail-flap angle to change the pitch and altitude of the aircraft. The following equation gives the relationship between the PD correction term and the desired tail-flap angle (γ), where dh/dt is the time derivative of the altitude, q is a constant dependent on the tail-flap angle and the rate-of-change of the pitch-angle, v is the speed of the aircraft, and θ is the pitch-angle of the aircraft:

$$\gamma = \frac{dh}{dt} \cdot \frac{1}{q} \cdot \frac{1}{\cos\theta} = \frac{u_{pd}(t)}{dt} \cdot \frac{1}{q} \cdot \frac{1}{\cos\theta} \tag{8}$$

The computed tail-flap angle, γ, is mapped into a pulse-width and sent to a servo to drive the tail-flap.

In addition, we ran MATLAB simulations to determine appropriate values for k_p, k_d, and other control parameters. After observing data from several simulations, we were able to find reasonable parameter values for controlling the aircraft. Fig. 6 shows the aircraft's altitude, pitch-angle, and tail-flap angle as a function of time, respectively. The aircraft is initially released with a downward pitch at an altitude of 5.5 feet with $k_d = -0.15$ and $k_p = 0.1$.

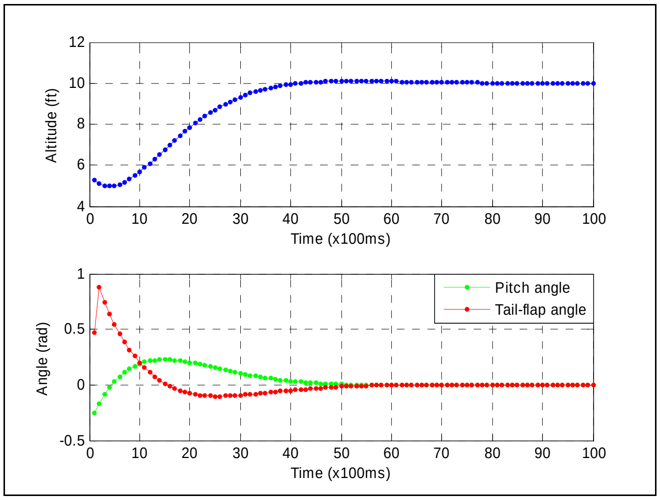

Fig. 6: Results of a MATLAB simulation showing the aircraft altitude, pitch angle, and tail-flap angle as a function of time

2.2.1 TAIL-FLAP CONTROL

The tail-flap of the aircraft is driven to a specific angle by sending a series of 3.4V pulse signals with a set pulse-width. Fig. 7 below shows pulse signals for setting the tail-flap to its maximum angle (approximately +30°), its zero angle, and its minimum angle (approximately -30°). A linear function was used to compute the necessary pulse-widths for tail-flap angles between the minimum and maximum values.

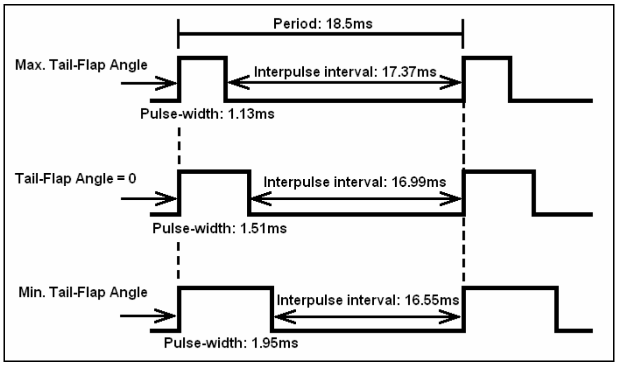

Fig. 7: Pulse-width characteristics for setting the tail-flap to its maximum, zero, and minimum angle (not drawn to scale)

3. HARDWARE IMPLEMENTATION

The hardware components of our altitude control system include a custom-built sonar board, a 40kHz ultrasonic speaker, two 40kHz ultrasonic microphones, two PIC microcontrollers, and a servo. The sonar board and the microcontrollers were mounted onto a punchboard and attached to the body of the aircraft.

The tail-flap servo was detached from the original receiver of the R/C airplane and attached directly to one of the PIC microcontrollers.

The implemented hardware board and the tail-flap servo are shown in the figure below.

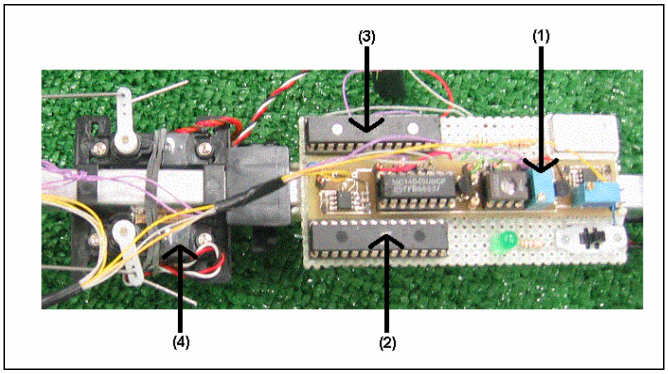

Fig. 8: Implemented hardware: (1) front-end sonar board, (2) microcontroller that handles altitude/pitch angle computations, (3) microcontroller that executes the altitude control algorithm, (4) servo that drives the tail-flap

4. RESULTS

We tested the aircraft over a flat, tiled surface and a textured grass-like surface. We recorded the altitude and pitch angle results from the binaural sonar system on a PC and manipulated the data to determine its accuracy. For the altitude, we positioned the aircraft at 9 different altitudes, starting at 4 feet with 0.5-foot incremental intervals up to 8 feet. Shown in Table 1 are altitude test results over a flat, tiled surface and a textured grass-like surface.

Table 1: Actual and measured altitude over a tiled surface and a grass-like surfaces

Actual (ft)	Measured (ft) [tiled surface]	Measured (ft) [grass-like surface]
4.0	4.0	4.1
4.5	4.5	4.4
5.0	5.0	5.2
5.5	5.5	5.5
6.0	6.0	6.1
6.5	6.5	6.6
7.0	7.0	6.9
7.5	7.5	7.4
8.0	8.0	8.0

The aircraft was capable of measuring the altitude to within ± 1 inch accuracy over the textured grass-like surface and with 99% accuracy over the flat, tiled surface.

Since the ILD turned out to be inconsistent from time to time, it was difficult to accurately measure the ILD from a single echo reading. However, we were able to measure the average ILD from a collection of 100 detected echoes for each measured pitch angle range. Table 2 shows the ILD results of six ranges of pitch angles and at zero pitch. The aircraft was pitched upward and downward at three different angles each when the aircraft was tested at 4.5 feet over the textured grass-like surface. The data for the zero pitch angle was measured at four different altitudes, from 4.5 to 6 feet at 0.5-foot increments.

After integrating all systems, the aircraft was able to control its tail-flap in response to its altitude and pitch angle.

Table 2: Average ILD and pitch-angle measured for different pitch angle ranges over the grass-like surface

Pitch-angle range (actual)	Average ILD	Average pitch-angle (measured)
(+) 20-30°	0.5698	(+) 15.1947°
(+) 10-20°	0.3493	(+) 9.3147°
(+) 0-10°	0.1302	(+) 3.4720°
0°	-0.0113	(-) 0.3013°
(-) 0-10°	-0.1902	(-) 5.0720°
(-) 10-20°	-0.3878	(-) 10.3413°
(-) 20-30°	-0.8955	(-) 23.8800°

5. FUTURE WORK

This summer, we have been able to construct a small UAV that was capable of detecting its altitude to within 1 inch of accuracy, and its pitch to within 10° of accuracy. Even though our aircraft may be able to take flight in realistic conditions (e.g. flying over grass and rough terrain in breezy conditions) for a brief period of time, there are a few things we would like to refine before attempting a test flight outside.

To date, we have only been able to test the echolocation system over a hard floor and a surface that simulates very short grass. Although the latter gave us a good idea of how difficult it is to detect scattered sound waves from rough surfaces, we were not able to pinpoint the exact pitch of the aircraft at any given moment. We would like to improve upon our ILD algorithm and make it more robust so that the plane can fly over a greater variety of surfaces.

Furthermore, we did not get a chance to measure the ultrasonic noise that is generated by the propeller of the aircraft. We have noticed that the propeller introduces a significant amount of ultrasonic noise that interferes with the returning echo signals. Eventually, we want to design a filter to separate the propeller noise from the echo that is needed for computing the altitude and pitch of the aircraft.

Lastly, we would like to experiment with our sonar/sensory system by implementing an algorithm similar to the bat's ability to use FM/CM frequency sweeps to detect altitude and pitch. When navigating and hunting prey, bats echolocate with a range of frequencies to acquire more information (size, shape) about the objects around it. We believe that applying such a concept to our project may have given the aircraft a better sense of its position and orientation in the air.

6. CONCLUSION

The sonar system was able to successfully sense the aircraft's altitude and pitch angle over a flat, tiled surface and a grass-like surface. Furthermore, the altitude control algorithm, in conjunction with the servo control system, responded accordingly and steered the tail-flap to an angle necessary to reach the desired altitude.

The binaural sonar-based altitude control model can potentially be adapted to any UAV or autonomous robot. However, its application can have a significant impact on highly-developed military UAVs that fly at low altitudes. These vehicles, with limited visibility, need to fly over mountains and forests without crashing. Rugged terrains pose a challenge for the UAV to maintain a steady altitude because the reference ground level is frequently changing. In these cases, a binaural sonar-based altitude control mechanism can solve the problem.

7. ACKNOWLEDGEMENTS

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