Bat News Travels Fast

Final Report

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3 Introduction

As the sun sets into dusk on a June evening over a cave in New Mexico, a feat of nature commences. Around half of a million Brazilian free-tailed bats emerge from the cave in a dense, undulating stream at speeds of 25 mph. Each produces ultrasonic, frequency modulated, downswept calls of 60 to 20 kHz at intense levels of 100 to 120 dB, for around 10 milliseconds in duration. Though their only goal is to forage for food, how they meet that goal is much more remarkable; they demonstrate refined swarming behavior and echolocation techniques in navigating towards food sources. The level of communication required to guide the swarm is maintained while traveling in tightly packed clusters, without colliding or jamming each other's biosonar chirps. Understanding how bats modify their echolocation strategies to avoid interference has far-reaching implications for signal processing and Naval technology, such as missile swarms. For this reason, Dr. Robert Stevenson of the Notre Dame Electrical Engineering Department and Dr. Laura Kloepper, an expert on bat bioacoustics, received a grant from the Office of Naval Research to explore the Brazilian free-tailed bats' swarming and biosonar behavior.

Under the guidance and at the request of Dr. Stevenson, this project was developed to improve upon current techniques used to monitor bat communication in these swarms. Previous iterations mounted electronics with omnidirectional microphones on a trained hawk, meant to fly directly into the swarm to collect data as close as possible to the source. However, this method of data collection created significant design restrictions in weight and size of the equipment, and there was no way to isolate where the signals were coming from. This year, those constraints were lifted in order to seek out higher performance and better directionality of the incoming signals. The monitoring equipment was designed to be stationed at the mouth of the cave rather than being mounted on the hawk. In this location, it will be positioned to listen into the heart of the bat swarm.

The project started with a few specific goals. The first was to add directionality to the microphone board so that it would catch only the signals in its direct boresight, reducing noise and making it easier for Professor Stevenson to discern individual bat chirps. An array of sixteen microphones was designed to enable the beam-forming required for this directionality. After modeling the beam forming capabilities of various sizes and shapes of arrays, a circular format of two rings and an outer diameter of six inches was adopted. The second goal was to allow the user of the device to operate it from a distance. An ESP8266 was chosen to fulfill this goal, as it could act as a WiFi access point on the device, enabling the user to remotely pull up a web server and communicate. This web server would have options to start and stop recording, change the gain on the microphone amplifier, and download the data file of the recording. The PIC32 microcontroller was chosen to sample and process the data at a high enough rate to fully capture the desired signal and to manage the ESP, SD card, and amplifier via SPI protocols.

After six months, four board designs, 255 square inches of PCB, and six soldering renditions, the final product successfully met both of the main goals, albeit not exactly how it was originally envisioned. Directionality was achieved, as signals outside of the board's boresight of 30 degrees were diminished, while those in front of it were strongly recorded. A web server was developed, which provides the user with a method of remotely starting and stopping the recording, as well as changing the variable gain on the amplifier. Lastly, the PIC was successfully configured to read and write from the SD card, sample and process data at a necessary rate, and interface with the ESP and amplifier.

It was discovered that, contrary to the initial simulations we ran, better directionality was achieved with just the inner ring of the microphone array. Since the microphones of the outer ring were destructively interfering with each other, they were removed from the final implementation. To preserve space and enable fast enough read and write operations to the SD card, an intricate bit shifting operation had to be implemented on the sampled data. Additionally, due to unexpected limitations of the ESP's Wifi data rate, downloading large amounts of data from the web server became impractical. Instead, the SD card was made accessible on the board such that the user can take it out to read the data files.

Overall, the project proved a success in meeting the system requirements and can be leveraged in the field for the enhanced collection of bat biosonar data. As with any endeavor, further improvements can be made to the system to make it even more efficient in isolating data points, capable of WiFi downloading, and durable against unforeseen circumstances. Detailed suggestions for these improvements are proposed at the end of this document.

4 Detailed System Requirements

Design Requirements:

The main requirement of the system is to record ultrasonic (around 20kHz to 100kHz) signals from a bat swarm, store the data as it’s being collected, and later transfer it to a laptop for analysis and signal processing. The device must be able to record signals at about 100 dB from ten to fifteen feet away, and store over 1 GB of data for each recording which will last up to an hour. The recordings must also achieve a high level of directionality, thus filtering out the majority of the signals from other directions. This requires a significant amount of storage on the board and a large enough rechargeable battery to keep the device active for multiple runs.

The microcontroller must be able to sample and process the data at a high enough rate to preserve the full signal and to prevent aliasing. It also must be able to write the data to an SD card or other storage component at this rate. The system must have an interface that allows the user to start and stop recording from the device, as well as adjust the gain setting of the variable gain amplifier. Since it would drastically improve the device to be able to control it remotely, the user should be able to access this interface on his or her phone far away from the actual cave. This requires a WiFi access point on the board and a web server through which the user can make changes to the device’s state.

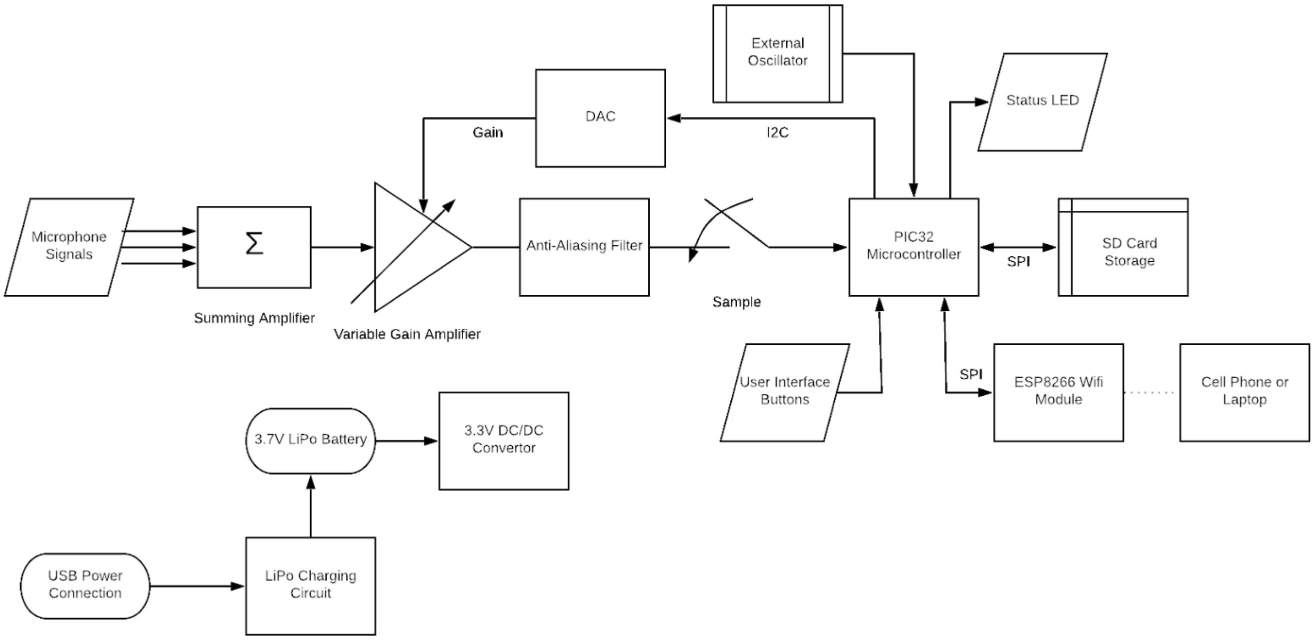
5 Detailed project description

5.1 System theory of operation

The device consists of two circuit boards - a main board with the majority of the components, and a microphone board that contains a microphone array and an amplifier. The device is controlled by a PIC32 microcontroller that communicates with the other components of the device. The PIC samples the signal coming from microphone board at 250 kHz, and writes the samples to a MicroSD card in real time. It communicates periodically with an ESP12 module, which provides a WiFi connection to the device and hosts a web server. The PIC also controls other peripherals, including a status LED, buttons on the device, and a digital to analog converter. The device is powered by a 3.7V LiPo battery or by a USB connection. It is also equipped with a charging circuit to recharge the battery once it’s depleted.

The microphone board contains sixteen microphones placed in an array of concentric circles. The output of each microphone is then summed together using a summing amplifier before going into a variable gain amp. The summation of sixteen signals located at different points on the board creates destructive interference when a signal source is not equidistant from each mic. By designing the physical distance between each microphone to be a function of the ultrasonic wavelength in which we’re interested, the destructive interference can be utilized to attenuate signals coming from certain directions. This limits the number of bat signals the device hears at a time, and allows for easier processing of the data.

5.2 System Block diagram



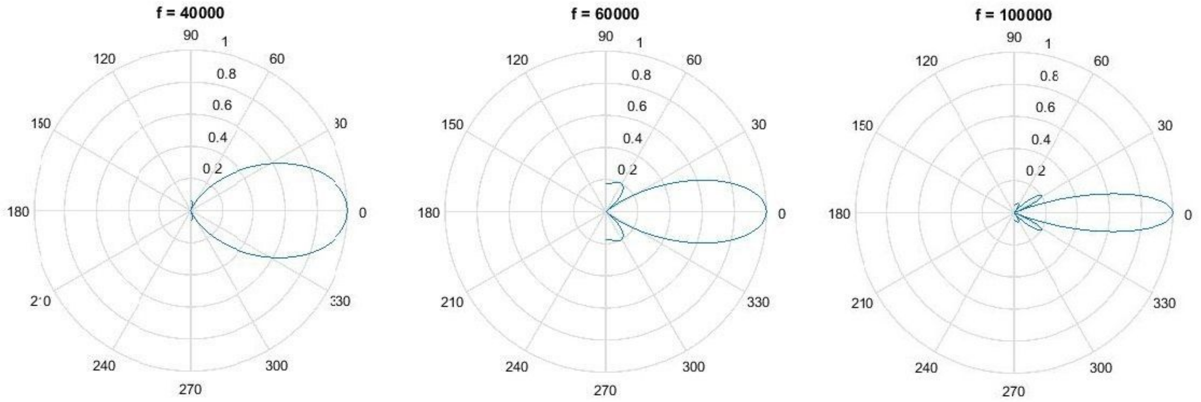
Block Diagram of the Entire System

5.3 Detailed design/operation of microphone board

The microphone board is designed to suppress as much environmental noise outside of the signal of interest as possible. In this case, the signal of interest is the calls of one or a few bats at a time. The primary source of noise in the environment is the calls of the other tens to hundreds of bats within range of the microphones.

The theory behind the design of the microphone array is that sound waves from the same source will reach each microphone at different times if the point of origin of the sound arrives at an angle that is not normal to the plane of the board. The electrical signals from each microphone will be out of phase from one another according to the time at which the sound arrived. The signals are added together by an operational amplifier, so signals originating normal to the plane of the microphone array (on boresight) will constructively interfere, while signals originating at an angle should destructively interfere.

This time-arrival-interference approach is sensitive to how far apart the microphones are spaced (since wider spacing results in larger phase-differences for a given angle of incidence) and the frequency (proportional to wavelength, hence, phase differential) of the arriving sound wave. So, a given design pattern will be constrained to a small range of sizes for optimum performance across the desired frequency range of 20-100 kHz. The array can not be too small, or else there will not be enough sensitivity. The array can not be too large, or else the main lobe will be too acute. Large arrays, if significantly larger than necessary, are also at risk of developing large sidelobes. The design pattern chosen for this project is that of sixteen microphones, spaced at approximately three and a half centimeters apart, and positioned in concentric circles, which outperformed star-shaped and rectangular grids of the same number of microphones and similar spacing in simulations.



Polar Plot of the Microphone Array Expected Angular Sensitivity at Different Frequencies

5.4 Detailed operation of web server

The ESP12 chip on the device is equipped with a built-in WiFi interface and antenna. It is used as a WiFi access point, and users of the device can connect to the network BAT_NEWS_TRAVELS_FAST when it is powered. The ESP12 memory is used to store the HTML for a webpage, which can be accessed from any device connected to the network. This webpage allows the user to start and stop recording, and to change the gain of the microphone board amplifier. We decided to use WiFi over Bluetooth because of the ease of using the ESP chip and the ability to communicate with the device using a web page rather than a cell phone app.

When the user changes a setting from the web server, the ESP12 stores this change in its internal memory to be sent to the PIC. The two devices communicate using an SPI interface, with the PIC acting as the master and the ESP as the slave. The PIC requests an update from the ESP approximately ten times per second, which is faster than a user can request actions from the server. The ESP sends any commands it receives from the server to the PIC, which responds to them appropriately.

The ESP12 is programmed using the Arduino IDE with built in libraries for WiFi connectivity and SPI interfacing. The device is equipped with a serial connection pin header that the user can use to reprogram the ESP if desired.

5.5 Detailed operation of PIC interface

The PIC32 microcontroller is the central component of the device and controls each peripheral. In addition to the SPI interface used to receive updates from the ESP12, it uses an SPI interface to read and write to a MicroSD card, an I2C interface to control a digital to analog convertor, an internal analog to digital convertor to sample the analog microphone signal, and various GPIO pins to control other peripherals. The PIC is programmed using Microchip’s MPLABX IDE and a PicKit3 connection, which is included on the board. We selected the PIC as our main microcontroller because of its versatility and the large amount of documentation available.

The PIC uses an external 20 MHz ceramic resonator and operates at a clock frequency of 105 MHz and a peripheral bus clock of 52.5 MHz. While recording, it samples at 250 kHz using its internal analog to digital converter. The frequency range of interest is between 20 and 100 kHz, so this sampling rate is more than enough to prevent aliasing. The ADC has 10 bit resolution, and uses ground and Vdd (3.3V) as its reference voltages. The sampling rate is controlled by Timer 3, which is set using the peripheral bus clock. The ADC is equipped with an interrupt that triggers when 8 samples have been collected and copies them to a larger buffer as another 8 samples are being collected. This interrupt is set to the highest priority, since sampling is the most critical operation of the device. The ADC uses 16 bit words to store the 10 bit samples, so the ISR (interrupt service routine) performs bit shifting to store the samples more compactly in the larger buffer.

When the buffer reaches 16000 bytes it begins writing data to a MicroSD card, while continuing to sample at the same rate. The SD card also communicates using an SPI interface, with a clock frequency of 5.25 MHz. This write speed enables the device to send the entire 16000 byte buffer before another one is filled. We chose a MicroSD card to store data because of the large amount of data being collected, possibly over 1 GB per recording session.

As mentioned in section 5.4, the PIC communicates with the ESP12 to receive web server updates. It uses Timer 2 to control this, and updates approximately 10 times per second. The PIC writes 0x04, which is the get status command, and then sends four empty bytes. The ESP responds with the current status in the first byte, and any relevant data (e.g. gain value) in the next three. A status of 0x00 means nothing has changed, 0x11 means start recording, 0x12 means stop recording, and 0x13 is a change in gain. As soon as the PIC receives a command, it updates the other peripherals accordingly.

The PIC also receives input from a record button located on the board, which triggers a change notification interrupt when pushed and either starts or stops recording, depending on the current status. While the user will generally use the web server to control the device, physical buttons provide a backup in the event that the web server stops functioning or the user does not have a WiFi enabled device. The recording status is shown using an LED on the board, which turns on when the device is recording and blinks if the device is in an error state.

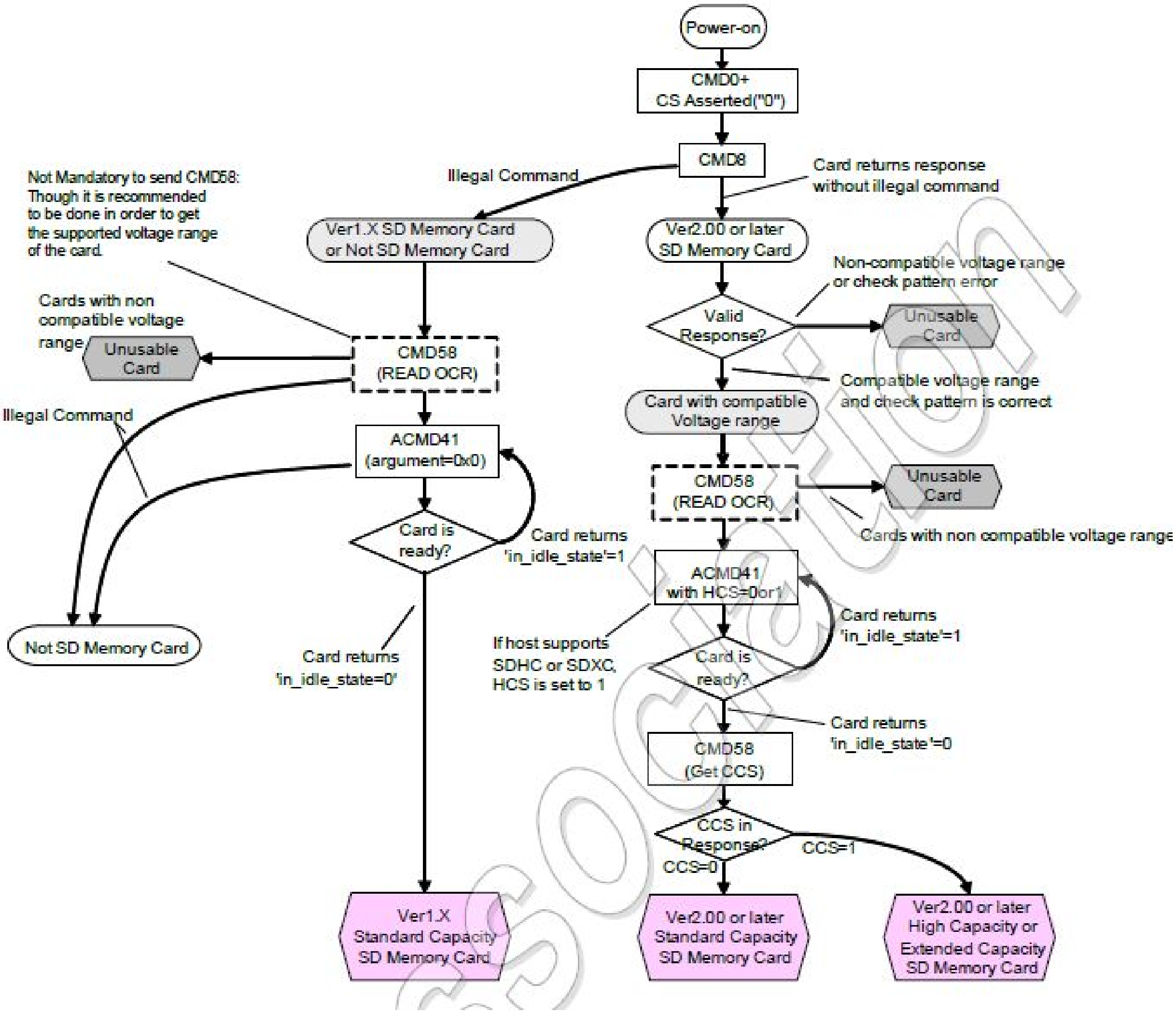
When the device gain is changed using the web server, the PIC sends an update to an MCP4716 DAC over an I2C interface. The device address is 0xC0 and the command to change the output voltage is 0x40. The new gain is then sent, on a scale from 0 to 1023, with the 8 most significant bits first. The DAC output voltage ranges from ground to Vdd (3.3V). The output of the DAC is connected to the variable gain amplifier on the microphone board, which changes the gain of the amp based on the input voltage it receives.

5.6 Detailed operation of MicroSD card

Reading and writing to the SD card is accomplished using ChaN’s library, which can be found online and is free to use and modify. The library has a relatively simple set of functions to mount a file system on the card, create a file, and then read and write to it. When the device starts recording, it mounts a file system and reads the card to see how many data files already exist. It then creates a new file, naming it appropriately, and begins writing data when the first 16000 byte buffer is full. After each write operation, the card syncs, which flashes the data to memory and prevents it from being lost if the device were to suddenly power down. The SPI commands and responses from the SD card are mostly abstracted away in the ChaN library.

The most challenging aspect of the SD card interface is timing. Since the card takes a certain amount of time to flash data to memory, writing another block of data too soon will interrupt the process and create a loss of data. The PIC uses Timer 3 to ensure enough time is spent between operations. Some SD cards also require a periodic break in writing data that can last up to several hundred milliseconds, so the choice of SD card is essential to preserving all the data collected. The SanDisk Extreme Plus V30 has been tested and verified to work in the device.

When testing a new card, it is useful to understand the initialization sequence the SD protocol requires and the ChaN library uses. A flow chart of this command sequence is shown below. Using a logic analyzer to decode the SPI transmission allows the user to verify the SD version, acceptable voltage range, etc. and debug problems with the card.

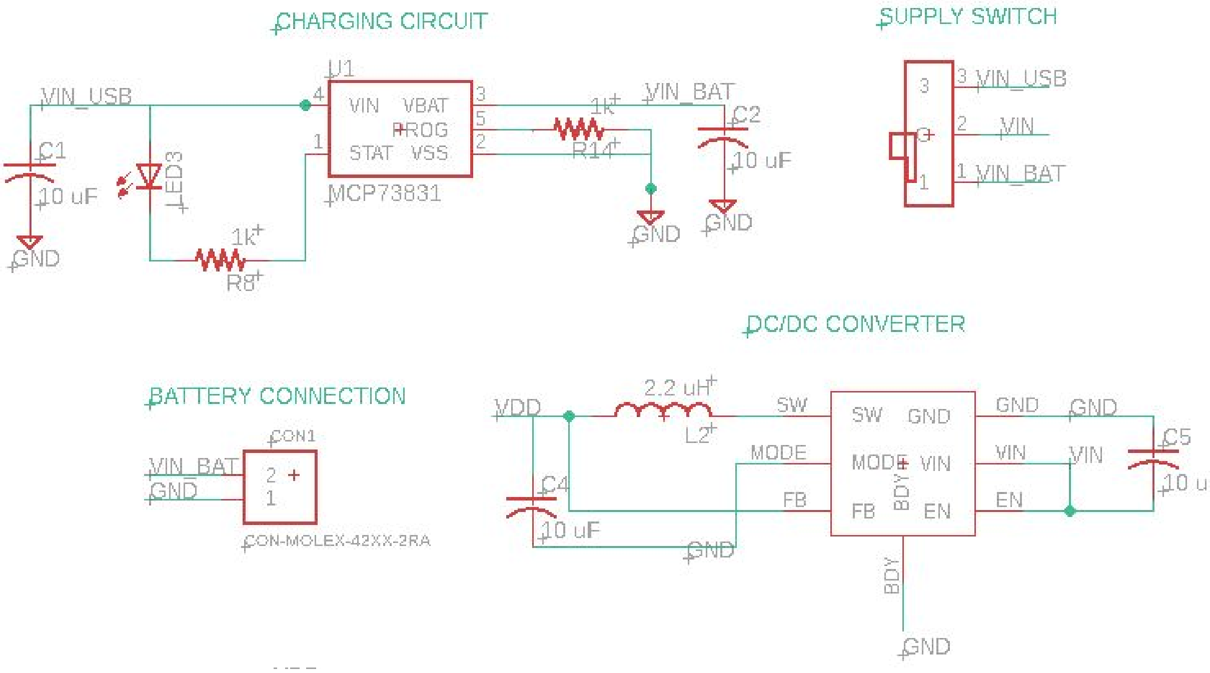


SD Card Initialization Flow Chart

5.7 Detailed operation of power/charging circuit

The device is powered using either a 3.7V LiPo battery or a standard 5V USB connection. When powered by USB, the device uses a Microchip MCP73831 charging IC to recharge a connected battery. The device draws about 240mA of current when recording, so a sizeable LiPo battery will last several hours before requiring a charge.

The voltage on the device is stepped down to 3.3V using a TPS62291 DC/DC converter. This converter is capable source up to 1A of current, which is far more than required for the device. The remainder of the components on the board run off of 3.3V.



Power Supply and Charging Circuits

6 System Integration Testing

6.1 Describe how the integrated set of subsystems were tested.

Microphone Array

The microphone array was tested using an ultrasonic emitter at 40kHz. The emitter was used to verify that the microphone array was collecting the summation of the 16 microphone signals, as well as, testing for directionality of the whole array system. To test the summation of the signals, we started with a one microphone board and two microphone board and connected the output the boards to a multi-channeled oscilloscope. The purpose of this initial test was to see if the voltage signal collected from the two microphone board was double that of the single microphone board. Once we determined that it was, we moved onto the 16 microphone board. The signal was not 16 times as large, but we expected this. The goal of the 16 microphone board was not solely amplification of the signals (we have an amplifier for that) but rather directionality. To test this, the microphone board was placed 6, 12, and 18 feet away from the ultrasonic emitter. At each incremental step, we measured the strength of the signal head on, and 30 & 60 degrees to either side, The goal of this testing was to verify that the signal would be the strongest in front of the board, and be attenuated in any other direction. The strongest signal was indeed directly in front of the board, and all other angles were attenuated due to destructive interference from the precisely placed microphones.

Power Supply/Battery

The battery was verified during some of the recording test runs. It sufficiently powered the board during these tests. The current consumed by the board was tested, around 240 mA, and proved that a 2000 mAh battery could run for about 8 hours of testing.

ESP12 (WiFi Module)/Web Server

The web server was tested using both cellular and laptop devices. We connected to the network, and entered the correct password. We then changed the parameters on the web server interface to ensure that when start and stop recording were submitted, the device responded appropriately. When the output of the microphone board was connected to an oscilloscope, we changed the gain on the web server interface and saw on the oscilloscope that the amplitude of the signal was magnified or decreased accordingly.

SD Card

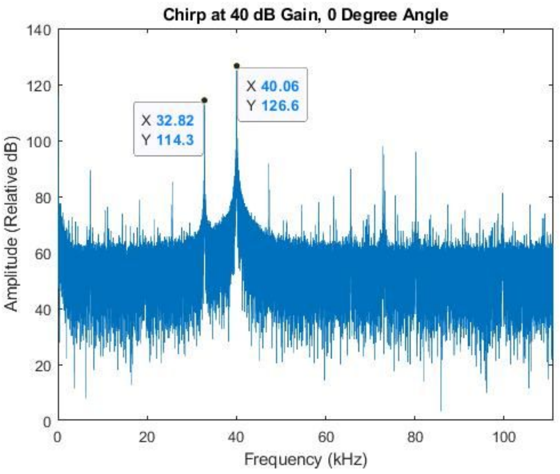
Reading and writing from the SD card was verified using both a logic analyzer and observable results on the card. The logic analyzer demonstrated that data was being written at the appropriate speeds, and that it was fast enough to finish one write cycle before another began. When a signal of known frequency was sampled by the PIC and written to the card, we looked at the data in MATLAB in both the time and frequency domains to verify that nothing was lost.

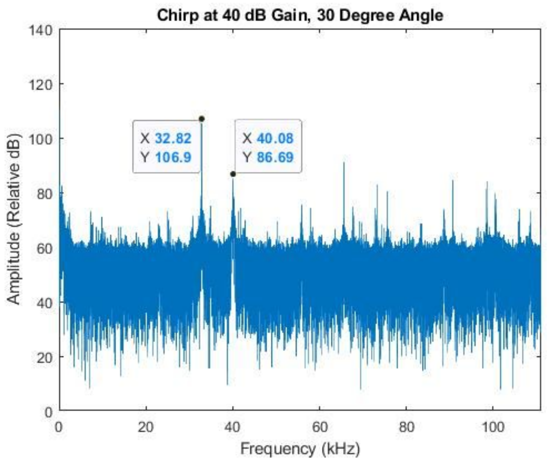
PIC32 Interface

One of the most challenging parts of the project was getting everything to interface together, using the PIC microcontroller. A particular challenge, and point of testing, was the timing of events that occured. Because several different devices were communicating with the PIC simultaneously using interrupts, it was critical that they did not interfere with each other, particularly with the sampling rate and SD card communication. We ran several tests with different combinations of peripherals working simultaneously, and the device was able to maintain its critical functionality in each case.

6.2 Show how the testing demonstrates that the overall system meets the design requirements

Having a high level of directionality was one of the design requirements set at the beginning of the project. The testing proved that directionality was achieved without having to mechanically move our device. As evident in the plots below, the signals that were in the boresight of the array were much stronger than those that were not. For, when the 40 kHz signal hit the array at a 30 degree angle, the amplitude of the signal was attenuated by 40 dB, which is quite significant, while the amplitude of a second 32 kHz peak stayed relatively constant.


Chirp at 40 dB Gain, 0 Degree Angle


Chirp at 40 dB Gain, 30 Degree Angle

The SD card read/write speed is sufficient for our purposes and fulfills the design requirement of collecting data as the microphones are recording. We tested it at the appropriate data rate speeds, and it is enough for the recording speeds we need for bat chirps.

7 Users Manual/Installation manual

7.1 How to install your product

Step 1: Locate a bat cave (or desired bat recording site).

Step 2: Place the device with the microphone board facing the direction of the oncoming bats. You would need to place the device so that the heart of the bat swarms would be about 10-15 feet from the device.

Step 3: Confirm that the device is on. Turn on the device and then screw on the back covering. Verify that the microphone board is still pointed in the proper direction.

Step 4: Record when ready. To start recording, connect to the device's WiFi and click 'start recording'. Verify that the red LED that also says 'record' turns on. You can turn off the recording through the same process.

Step 5: Sit back and enjoy as your ultrasonic microphone array device captures the calls of the bats flying overhead.

Step 6: After the bats have returned to the cave, turn off recording of the device via WiFi, and then waiting for the next day's recording. During non-bats hours, you should visually check to see that nothing has obstructed the microphone array.

7.2 How to setup and use your product

The device can be powered on by first moving the switch at the bottom of the board near the ESP12 to the ‘PROG’ position and then providing power to the device. Once the device is powered, move the switch back to ‘RUN’ to let the device function properly. Without this step, the ESP will not boot properly and portions of the device will not function. Once the device is powered, everything will be functional and the user can begin recording immediately.

If at any time the user needs to reprogram the PIC32 or the ESP12, this is possible using pins already on the board. The PIC can easily be reprogrammed with a PicKit3 and the MPLABX IDE. The existing code for the device can be found on the team website, linked in the Appendix.

The ESP12 requires a few more steps to program. To boot it into programming mode, move the switch near the ESP to ‘PROG’, press and hold the ‘RST LOW’ button, press and hold the ‘GPIO0 LOW’ button, release ‘RST LOW’, then release ‘GPIO0 LOW’. With the device in this mode, connecting a USB to Serial FTDI cable to the pins near the ESP will allow an Arduino programming environment to communicate with the chip. The existing ESP code is also located on the team website.

Once data has been collected and the user wants to remove it from the SD card, it first needs to be decompressed. The device compresses the data to save space and to maximize write speeds to the SD card. The device comes with a piece of software called parse_data.exe that will decompress the data from the card and output a csv file. It can be run from a command line using

```
$ ./parse_data NBII000.DAT 1
```

where the first argument (NBII000.DAT) is the filename and the second argument is the recording number. The command above will produce a file called data1.csv. This file can then be read into MATLAB or some other signal processing software.

7.3 How the user can tell if the product is working

If installed properly, a red LED on the main board will turn on once the device is connected to power. When recording, another red LED will turn on, and will turn off when the recording is stopped. If the product is working, there will be proper data collection sent to the SD card. Before placement of the device into the recording environment, verifying that a test recording sends data to the SD card is recommended.

7.4 How the user can troubleshoot the product

<u>SD Card:</u> Verify that there is no dust in the SD card slot inside the case, and that the SD card has been fully inserted.

<u>Microphone Array:</u> Verify that the microphone board is placed in the correct orientation. The board should be placed “face down” because the holes are on the bottom of the board. Also, make sure that the microphone holes are clear of any dust, dirt, etc.

Power Supply/Battery: Verify that the positive terminal of the battery is connected to the positive terminal of the device. Also verify that the battery itself is charged. If the battery is not charged, utilize the charging circuit on the board.

ESP8266 (WiFi Module): Verify that you are accessing the device with something that is able to access WiFi.

Web Server: Verify that the correct network, password, and browser window are being used. Also, make sure to press “submit” after each individual parameter is changed. For example, if you wish to change the gain and start recording, enter the value for gain, click “submit”, click start recording, and click “submit” again.

8 To-Market Design Changes

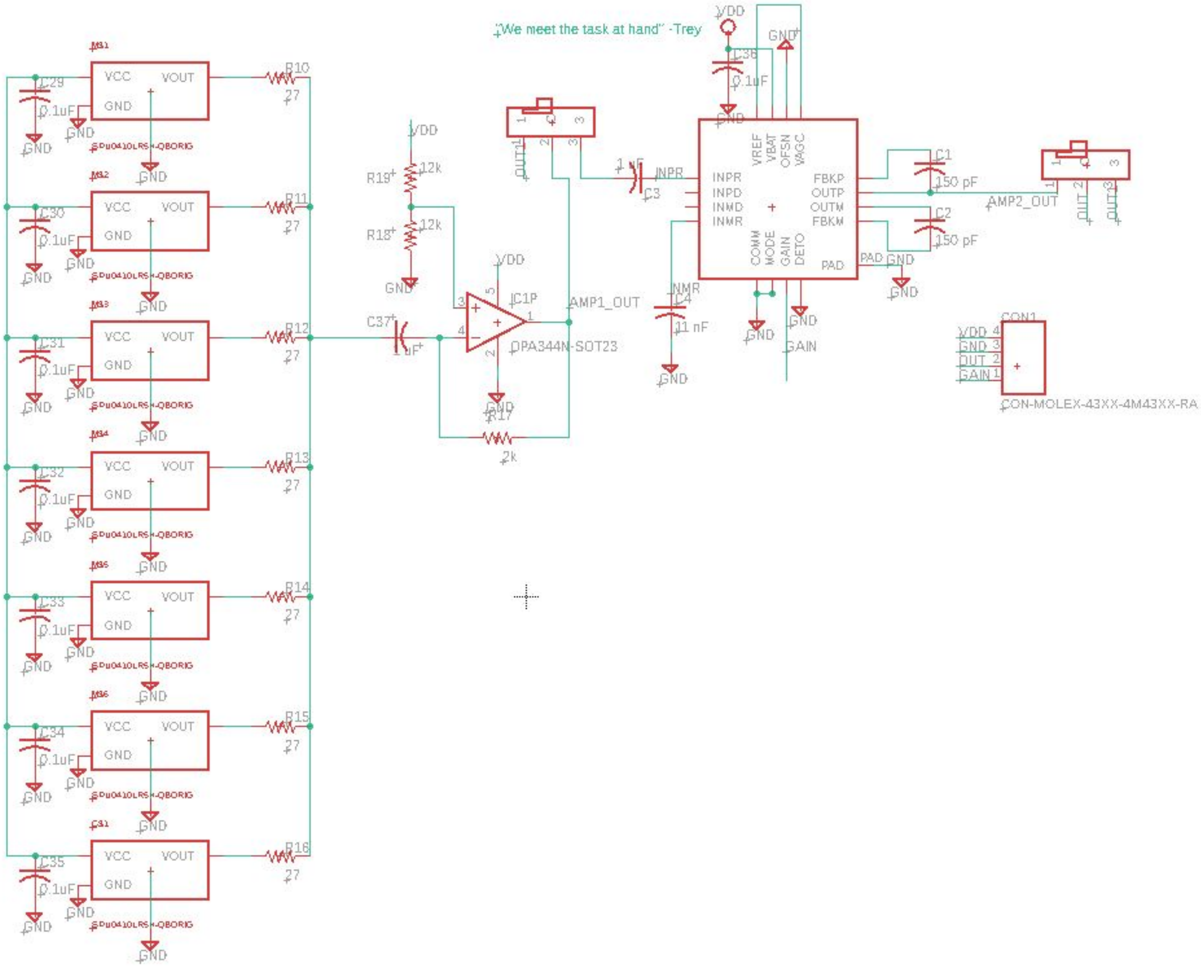
Before this device can be sold commercially (or in this case, used for Dr. Stevenson’s research), a few changes have to be made. Namely, the microphone array needs to be adapted. After thorough testing, the team realized that the sixteen microphones were not all adding constructively in boresight in the way they were designed, which was a result of the spacing between the microphones. This is not to say that directionality was not achieved, however. After the outer circle of microphones was removed, the array proved to be successful in attenuating signals that were not in boresight, and amplifying those that were. Regardless, it will only make the design stronger if all sixteen microphones can be utilized in the array as originally intended.

Another improvement that needs to be made to the device is “dust-proofing”. Since this device will be utilized in an outdoor environment, additional protection is needed. A container used to house the two boards was designed and 3D printed, however, it was a bit too small to fit the boards properly (due to the board schematics being a different size than the microphone board itself by a couple millimeters). A second iteration of this kind container could successfully protect the boards from the elements. Additionally, some kind of filter or screen will be used to protect the microphones from being clogged with dust. The team was unable to experiment with different materials that could be used to cover the microphones without attenuating the signals. Thus, some research and development is still needed in this area.

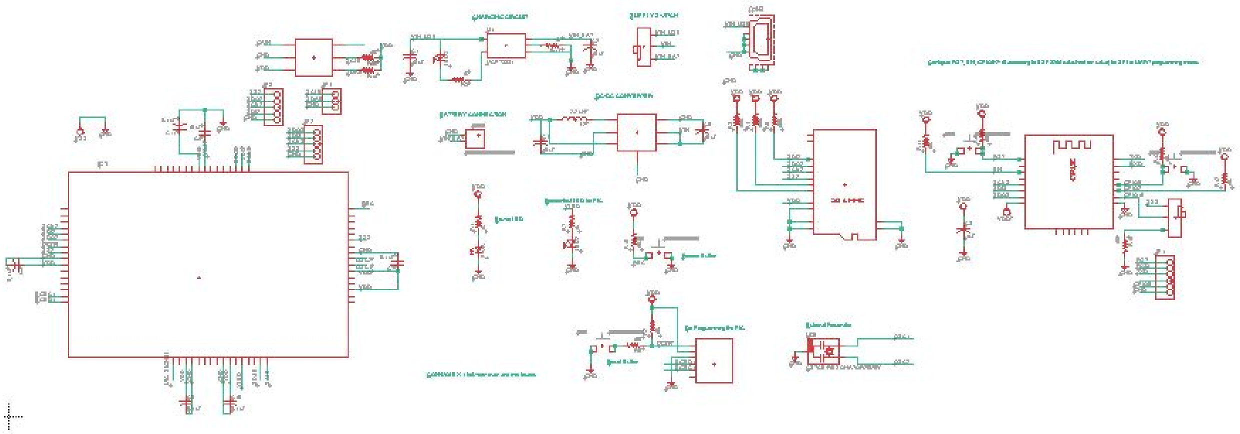
7 Conclusions

This iteration of bat recording device delivers several significant enhancements to Dr. Stevenson and Dr. Kloepper. A substantial level of directionality is achieved with the circular array of seven microphones. This will allow the professors to isolate portions of the bat swarm’s biosonar pulses, make sense of the data they collect, and draw meaningful conclusions in their signal analysis. Lessons learned about the concept of beam forming in models as compared to outcomes of beamforming in real life and the recommendations for future array shapes will crucially inform Dr. Stevenson in future iterations of the project. The obstacles overcome in reading and writing to the SD card from the PIC, as well as the bit shifting program created to resolve these problems, will greatly help Dr. Stevenson in future, as well as any upcoming senior design classes who require this functionality. Because of this project, Dr. Stevenson will be able to start and stop his recordings and change the variable gain from a comfortable distance from the bat cave, avoiding flying bat feces, rabies, and tarantula bites. The group is happy to deliver the professors with a device that has met the requirements so successfully and solid, detailed recommendations for further improvements.

8 Appendices



Microphone Board



Main Board

Link to Team Website (includes board design and code):
http://seniordesign.ee.nd.edu/2019/Design%20Teams/bat/index.html

Component Data Sheets

PIC32MX795
http://ww1.microchip.com/downloads/en/DeviceDoc/60001156J.pdf
ESP12S
https://www.digikey.com/products/en/rf-if-and-rfid/rf-transceiver-modules/872?k=esp-12
Knowles SPU0410LR5H-QB Microphones
https://media.digikey.com/pdf/Data%20Sheets/Knowles%20Acoustics%20PDFs/SPU0410LR5H-QB_RevH_3-27-13.pdf
https://media.digikey.com/pdf/Data%20Sheets/Knowles%20Acoustics%20PDFs/SiSonic_Design_Guide.pdf
TI OPA344 Operational Amplifier
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Microchip MCP4716 Digital to Analog Converter
http://ww1.microchip.com/downloads/en/DeviceDoc/22272C.pdf
TI TPS62293 DC/DC Converter
http://www.ti.com/lit/ds/symlink/tps62293.pdf
Murata CSTCE20M0V53C-R0 20MHz Ceramic Resonator

https://www.murata.com/~/media/webrenewal/support/library/catalog/products/timingdevice/ceralock/p16e.ashx
Microchip MCP73831 LiPo Charger
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Analog Devices AD8338 Variable Gain Amplifier
https://www.analog.com/media/en/technical-documentation/data-sheets/AD8338.pdf