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Authors

Bergren, Steven
Latino, Carl D
Varnon, Christopher A
[et al.](#)

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A Portable System for Detecting Infrasound Using a Microcontroller

Steven Bergren ¹, Carl D. Latino ¹, Christopher A. Varnon ², and Charles I. Abramson ³

¹ Department of Electrical Engineering, Oklahoma State University, Stillwater, OK, USA

² Department of Psychology, Converse College, Spartanburg, SC, USA

³ Department of Psychology, Oklahoma State University, Stillwater, OK, USA

The purpose of this project was to create a device to detect infrasound communication from elephants. The device was designed and prototyped to be capable of monitoring an input signal for infrasound. If infrasound is detected, an audible alarm and a visual stimulus are presented. This device can record audio signals for long periods of time to a digital storage device. It can be utilized for other areas of study with some modification. For example, by selecting appropriate sensors, the device can be used for studying vibrations in structures, such as bee hives and buildings. The device is low-cost, so it would be able to be procured more easily and in higher quantities than more expensive and cumbersome laboratory monitoring equipment. This device could also be used as an educational and research device for students studying animal behavior in the field and laboratory. Infrasound is not limited to only elephants; hippopotamuses, rhinoceroses, and giraffes also communicate with infrasound. Environmental infrasound from sources such as wind turbines, sonic booms, explosions, tornadoes, and earthquakes can also be monitored.

Keywords: infrasound detection, microcontroller, elephants, fast Fourier transform, seismometer, geophone

The purpose of this article is to show how the Propeller Experiment Controller (PEC) can be used to record infrasound and, in general, serve as another example for how the PEC is a low cost solution for controlling behavioral experiments. In several previous articles, we advocated that comparative psychologists need to learn how to use microcontrollers and that the PEC is a good choice (Varnon & Abramson, 2013; Varnon & Abramson, 2018; Varnon, Lang, & Abramson, 2018).

We illustrate the use of the PEC by developing a low-cost device to measure infrasound. Infrasound is below the threshold of audible human hearing, generally defined as below 20 Hz. Our rationale was to develop a device that can serve as a tool to record infrasound at zoos and in other locations. We also had interest in developing the device as a means of increasing interest in comparative psychology. There are not many teaching exercises available for a course on comparative psychology, and we believe that this can be one of them (Abramson, 1990; Abramson, Curb, Barber, & Sokolowski, 2011; Abramson, Hilker, Becker, Barber, & Miskovsky, 2011). In addition,

we wanted to continue our development of the PEC as a general, low-cost laboratory controller that can be used by both students and professionals. We have found only two other published accounts on how to use a device for detecting infrasound (Chilo & Lindblad, 2007; De Silva & De Zoysa, 2009).

Method

The Propeller Experiment Control (PEC)

The PEC is free, open-source software for a microcontroller designed to meet the basic needs of automated behavioral research. First, the PEC detects behavioral and environmental variables, such as the lever-pressing behavior of a rat in an operant chamber or the ambient temperature. Second, it affects the environment, in turn, often indirectly affecting a subject's behavior. For example, the PEC may control a pellet dispenser, shock grid, stimulus light, or heater. Third, the PEC records detailed data about any event of interest in an experiment. In addition to producing its own standard data spreadsheet, the PEC also supports MED-PC formatted data (a common standard) and user-customized data output. Finally, the PEC implements the above needs (detect, affect, and record) at very precise intervals of time, while also allowing the user to execute events at specific times and record temporal variables. The PEC also goes beyond the basic needs of behavioral research in that the PEC is both uniquely portable, not requiring a connection to a computer, and is very affordable compared to commercial alternatives, costing under \$100 for the basic experiment controller.

The PEC has been used in a variety of contexts, both for teaching and research. We used the PEC to develop a low-cost learning laboratory course (Varnon & Abramson, 2013, 2018). In experimental research, the PEC has been used with a variety of species including honey bees, horses, human infants, pigeons, and wild squirrels (Black, Fofah, Giray, Wells, & Abramson, 2018; Colaizzi, 2016; Craig, Varnon, Pollock, & Abramson, 2015; Dinges, Varnon, Cota, Slykerman, & Abramson, 2017; Phelps & Varnon, 2015).

The adaptable design of the PEC provides behavioral scientists with an inexpensive yet powerful automation system that can be used in many behavioral fields such as comparative psychology, behavior analysis, behavioral ecology, and behavioral neuroscience. The PEC is designed to remove reliance on expensive commercial equipment and return control of research to those who conduct it, and this is uniquely positioned to encourage new research in the study of behavior. Prior to this article, there were only two complete accounts of recording infrasound (Chilo & Lindblad, 2007; De Silva & De Zoysa, 2009).

The Infrasound Detection System (IDS)

The IDS is a portable, self-contained unit, consisting of a detector and a processing unit. The detector was an off-the-shelf unit, but the processing unit was designed, constructed, and tested as part of a joint research effort between the psychology and electrical engineering departments at Oklahoma State University. The detector senses the vibrations produced by the elephant or other test subject, converts them to electronic signals, and sends the signals to the processing unit. The processing unit amplifies, samples, conditions, and records the incoming signal. Concurrently, the signals are processed once per second to detect critical infrasound frequency content. If infrasound signals are detected, the processing unit issues audible and visual alarms informing the handler of imminent danger.

The IDS Components

The IDS needs a sensor for detecting low frequency vibrations and converting them to electrical signals. The sensor is an external component and will vary depending on the operating conditions. The purpose of the sensor is to provide reliable input, and it was not considered an integral part of the IDS. Transfer characteristics of the sensor can be handled in various means, but the sensor was not the focus of this effort. Depending on the particular environment, the sensor may vary. For the current application, we utilized a seismometer, which is a device that detects low-amplitude and low-frequency ground vibrations. The sensor detects the vibrations and produces low-amplitude electrical signals that must be amplified, sampled, and digitally stored. The sensor is connected to the processing unit via cable.

The processing unit is a small portable enclosure that houses the amplifier, filter, display, LED array, batteries, memory, programming buttons, and embedded processor. The propeller microcontroller is the embedded processor. The processor was chosen to be compatible with other custom laboratory equipment in our laboratory. It operates all functions, including software that performs real time, continuous spectral analysis of the received signals. There are 5 LED's that display signal strength, while the 2 line by 16 character display provides frequency information. The data is collected and stored in memory for both immediate analysis and future laboratory research. Figure 1 shows the unit, Figure 2 identifies the parts, and Figure 3 is an internal view.

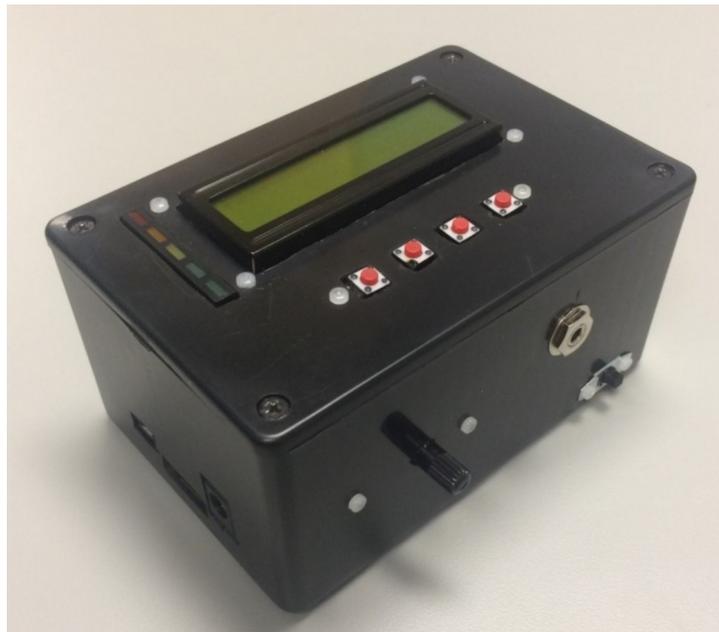


Figure 1. Infrasound Detection System

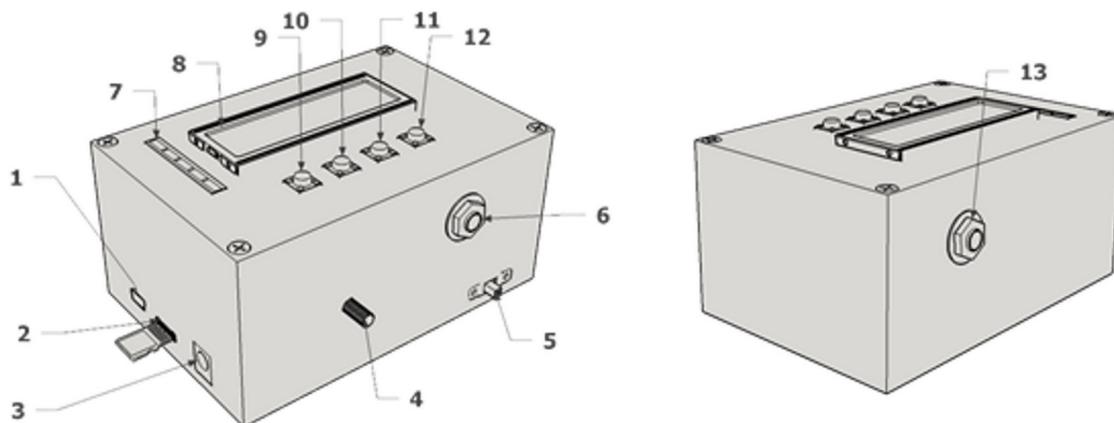


Figure 2. Infrasound Detection System - Identification of parts. (1) Mini USB Connector - Used to program and/or power the device (2) Micro SD Card Slot - Cards are inserted face down (metal contacts face up) (3) 2.1 mm Power Jack - Used to power device (6-9 VDC) (4) Gain knob - Controls amplifier gain (2-229x) (5) Power Switch (6) Output Jack - 3.5 mm mono output (7) LED Strip - Displays input amplitude (8) Display - 2-line interface displays device instructions and status (9) Back button - Interface control - displayed as < (10) Up Button - Interface control - displayed as ^ (11) Down Button - Interface control - displayed as v (12) Select Button - Interface control - displayed as OK (13) Input Jack - 3.5 mm mono input (0-2.5 VAC).

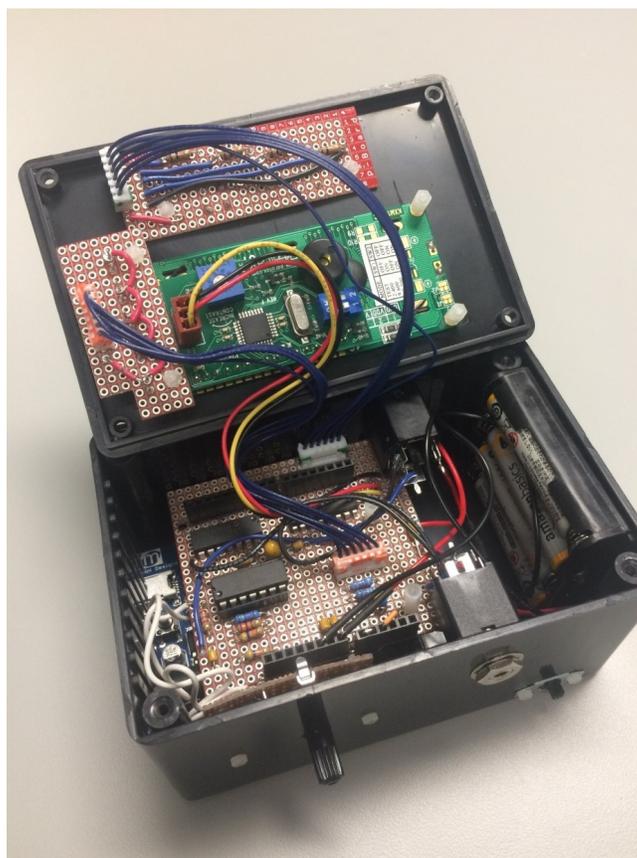


Figure 3. Interior View of the IDS

Protocol

1. Infrasound Detection System Device Setup

- 1.1. Slide the power switch to the ON position. The display will illuminate showing “Starting...” and play a startup tone. The LED block will flash on and off. The menu options will show. The display has two lines. The top line will show information and status. The bottom line will show what button options are available.
- 1.2. Press the **UP** and **DOWN** buttons to switch between the options. Press **BACK** in any menu to return to a higher-level menu. Press **OK** to select the option shown.
- 1.3. Monitor with Alarm
 - 1.3.1. Press **OK** to select. This will put the device in *Monitor* mode. If the signal from the input is a frequency below 40 Hz that exceeds the alarm threshold level, the alarm will sound, and display lights will flash. Pressing **BACK** will return the user to the main menu and disable the *Monitor with Alarm*.
- 1.4. Recording
 - 1.4.1. Press **OK** to enter the *Recording* menu. Recordings are made in WAV format. Filenames are autogenerated. The default filename is 000_OKC.WAV. Subsequent files will increment the three-digit number at the front of the filename. Two options are available.
 - 1.4.2. *Timed Recording*: Press **OK** to select. This option allows the user to record the input signal for a specified amount of time. Pressing **UP** or **DOWN** in this menu switches the predefined time options ranging from 1 min to 24 hr. When the desired duration is displayed, press **OK** to start the recording. The device will record until the time has elapsed or the maximum file size has been reached, whichever is earlier.
 - 1.4.3. *Rec Until Stop*: Press **OK** to select. The display will show “Rec Continuous”. This option can start a recording that will continue until either the **OK** button is pressed or the maximum file size is reached, whichever is earlier. Press **OK** to start and stop the recording.
- 1.5. Playback
 - 1.5.1. Press **OK** to enter the *Playback* menu. Valid WAV file names will be shown on the display. Press **DOWN** to step through the files on the SD card. Press **OK** to start playback of the selected file.
 - 1.5.2. While the file is playing, press **DOWN** to toggle between 1x and 10x playback speeds. Press **OK** to stop playback.
- 1.6. Settings: Press **OK** to enter the *Settings* menu.
 - 1.6.1. *Sampling Frequency*: Press **OK** to select. This option allows setting the sampling frequency between 1,000 Hz and 20,000 Hz in 1,000 Hz increments. Press **UP** and **DOWN** to switch between frequency settings. Press **OK** to set the frequency. This value is only used while the device is powered on. On reset, the sampling frequency reverts to default (1,000 Hz.).
 - 1.6.2. *Alarm Threshold*: Press **OK** to select. This option allows setting the amplitude threshold that will trigger the alarm for frequencies below 40 Hz. The valid range is between 10%

and 90% of maximum amplitude. Press **UP** and **DOWN** to switch between threshold percentages in increments of 10%. Press **OK** to set the threshold level. This value is only used while the device is powered on. On reset, the alarm threshold value reverts to default (10%).

2. Setting Input Levels

*NOTE: When monitoring or recording, the gain of the amplifier must be adjusted to account for different input levels and different input devices.

- 2.1. Put the device in either *Monitoring with Alarm* or *Recording* mode. While in these modes, the 5-light LED bar will show the input signal level.
- 2.2. Provide an input signal of a type similar to the expected volume level of the recording. For example, if the device is a microphone and the expected volume level is similar to human speech, speak into the microphone at the approximate volume level. Speak continuously for several seconds while raising and lowering the voice level while monitoring the LED bars. If the seismometer is to be used as the input device, connecting a vibrating motor to it will cause signals to be generated. These signals can be observed on an oscilloscope, and, simultaneously, frequency information can be seen on the 16 by 2 line display. The frequency of the vibration is controlled by varying the input voltage to the motor. Using an oscilloscope, the signal magnitude can be observed and allows the user to properly adjust the gain. In order to receive the best results, the gain adjust knob should be adjusted so that on average the third or fourth LED is illuminated. If the fifth LED illuminates, it is possible that the input signal is saturating, so the gain might need to be reduced. If most of the time the 2nd LED is on, the input signal is low, and the gain should be increased. It is up to the operator to select a suitable gain level. Including an automatic gain control capability might help, but this was not a part of this effort.

*NOTE: Having performed the above steps, the input gain level is now set.

3. Operating the Infrasound Detection System (IDS)

- 3.1. Before using the IDS, it must be set up to receive the proper signals. For best operation, the desired signals must be large enough to process but not so large as to saturate the input. A gain control knob on the processing unit allows the operator to make the proper setting prior to actual operation.
- 3.2. Turn on the processing unit and using the programming buttons, select *Monitor Mode*. *Monitor Mode* causes the system to run continuously until stopped. The IDS, once programmed and started, operates automatically.
- 3.3. Firmly stake a seismometer to the ground so that it detects even small vibrations. The seismometer consists of a magnet suspended in a coil of wire by a spring. If a different sensor is used, then it should be mounted to best provide the desired input. The sensor was a necessary component but not a main focus of this effort.
- 3.4. To simulate an input while using a seismometer, a small electric motor with an offset weight is attached and the combination suspended with an elastic band. By using a variable voltage power supply, the speed of the motor could be controlled and hence provide a variable frequency input. Monitoring the input waveform on an Oscilloscope and observing that the readout on the IDS provides similar results, the proper operation of the IDS is verified.

*NOTE: Vibrations cause the magnet to move, generating an electric signal which is sent to the processing unit via cable. The processing unit amplifies, filters, samples, and stores the data. This data is then processed by the processing unit in real time to determine the frequency spectrum. If the spectrum includes frequencies in the infrasound range, an alarm will sound.

3.5. The data is automatically stored on an SD memory card for later possible analysis.

4. Signal Processing

*NOTE: The raw signal sensed by the detector contains vibrations from various sources. The received signal consists of many frequencies. Since most of the frequencies are unwanted, they must either be removed with analog filters or identified with signal processing techniques. The high frequencies of the incoming signal are removed with an analog low pass filter. The remaining signal may contain the frequencies that we are trying to detect. Well-known digital signal processing techniques exist that allow the spectrum analysis of the incoming signals.

- 4.1. Remove unwanted high frequency signals with a low pass filter. Frequencies above approximately 30 Hz are unwanted and may be considered "noise". We utilized a third order Butterworth filter with 30 Hz cutoff, which proved to be effective. Higher order filters could have been used if sharper cutoff characteristics were desired.
- 4.2. Amplify the filtered signal and subject to a fast Fourier transform (FFT). The FFT is a widely known algorithm that was created in 1965 based on a principle known in 1805. The authors neither created nor modified this algorithm. They merely used it in order to expose the frequency spectrum of the input signal. In our application, the FFT is performed on every 1,000 sample points. The FFT is automatically performed once per second.
- 4.3. Analyze the spectrum for frequencies of interest exceeding the prescribed threshold. When infrasound frequencies with energy exceeding threshold are detected, the processing unit generates the audible and visible warnings.

5. Sensing an Elephant

Generating signals that can be used for simulating actual elephant sounds can be accomplished by adding signals of different amplitudes and frequencies together. Many tools exist to allow the generation of complex signals. We used MATLAB (Natick, MA) to both generate signals and analyze them. Signal generation techniques were not a part of this effort. Signals were generated so that the frequency content was known. Applying signals with known frequencies were how we verified that the IDS in fact extracted the correct frequency information from the input signal. Since the frequencies of interest were below 30 Hz, various test signals were created with combinations of sinusoids of frequencies such as 5, 12, and 24 Hz. These signals were created, fed to the IDS, and used as tests to verify that the frequencies were in fact detected.

Because being in close proximity to an elephant may be potentially dangerous, being there when he or she is agitated makes collecting live data very difficult. So, to test the device on real elephants, sound recordings were used, available online as .WAV files. Unfortunately, although these data are real, they are played directly to the processing unit, bypassing the seismometer. It was verified experimentally that when vibrations of known frequencies are artificially imposed on the sensor, the sensor produced detectable signals. Within these signals, the IDS was able to identify low frequencies, including infrasound when present. Also, with real data to work with, waveforms can be simulated that accurately mimic elephant sounds with and without infrasound. Work is currently underway on a system where the elephant "wears" a sensor and transmits the waveform wirelessly. This proposed method has many advantages including the ability to monitor an elephant continuously for hours or even days.

Representative Results

To verify the correct operation of the Infrasound Detection System (IDS), waveforms with known frequency and amplitude content were computer generated. These signals were generated by combining frequency f1 at amplitude A1 with

frequency f_2 at amplitude A_2 , etc. This complex generated signal was played into the IDS and checked for correct detection of frequency and amplitude against the known values. For computer generated waveforms, the results were accurate. Detecting real data obtained from the sensor was more difficult to verify. These difficulties were primarily due to the inherent characteristics of the sensor. The primary sensors that were tried were speakers and seismometers. They both introduced difficulties due in part to internal resonances and other characteristics. Selection of the sensor is a critical part of the system.

To obtain good results, some knowledge of the frequency and amplitude of the incoming signal should be known. This helps the user select input devices and set proper input gain. If the signal is too low, the samples do not provide a suitable dynamic range. If the signal is too high, it will clip and saturate. Future improvements to the system might include Automatic Gain Control (AGC) and wireless communications. These issues were not considered during this effort.

The end result of utilizing the protocol is an audio recording stored as a .WAV file on an SD card. To verify the results of the recording, the file can be played back on the device itself or the SD card can be transferred to a computer for playback. An infrasound recording is generally below human-hearing threshold, so the file would need to be played back at an increased speed for the frequency to be in the audible range. The IDS has a 10x capability available during playback. This feature serves two purposes: It allows the user to detect if usable data has been recorded and speeds up the playback, reducing time to find usable portions of collected data. Speed increase on a computer is dependent on the software used to listen to the file.

If the IDS is in *Monitor with Alarm* mode, then detecting frequencies of interest above the amplitude threshold would result in flashing of the display backlight and LEDs. An audible alarm is played, and the screen would display the amplitude and frequency of the detected signal.

To test the device's ability to properly record low frequencies, a 30 Hz signal was generated in software and recorded by the device. Figure 4 shows that the device accurately detected the 30 Hz signal.

Audio files of African elephant low-frequency calls, or rumbles, were played on a computer connected to the input of the IDS and recorded to test the infrasound detection capabilities of the device. The original source recording was then run through a spectral analysis tool in MATLAB to determine the amplitude of the frequencies. Software on the IDS then output the spectral analysis using a FFT. Figure 5 shows the original audio recording. The sampling rate was far higher than needed to obtain the desired frequency information. Figure 6 is the same information in Figure 5 but sampled at lower rate and still much higher than the Nyquist rate, which, in this case, would be 60 Hz. To detect frequencies accurately, sampling rates must exceed the Nyquist rate for the highest frequency contained in the signal. Since the IDS samples the waveform at orders of magnitude higher than the Nyquist frequency, the spectrum of the signal is accurately known even if fewer samples are taken.

Figure 7 shows a small seismometer-like device called a geophone. We used this to determine if it could detect infrasound travelling through the ground. It was connected to the IDS input and affixed to a holding device. A small vibrating motor was placed on a table approximately 1 m from the geophone. The motor was turned on with the IDS in monitoring mode. The movement of the motor was detected and returned a frequency of 29 Hz, which was the natural frequency of the geophone. It proved to not be an ideal device for recording infrasound due to the frequency response of the geophone being strongly influenced by its natural frequency.

The sensor is still the most critical component of the entire system. An ideal sensor is sensitive and omnidirectional, with a resonance far from the frequencies of interest.

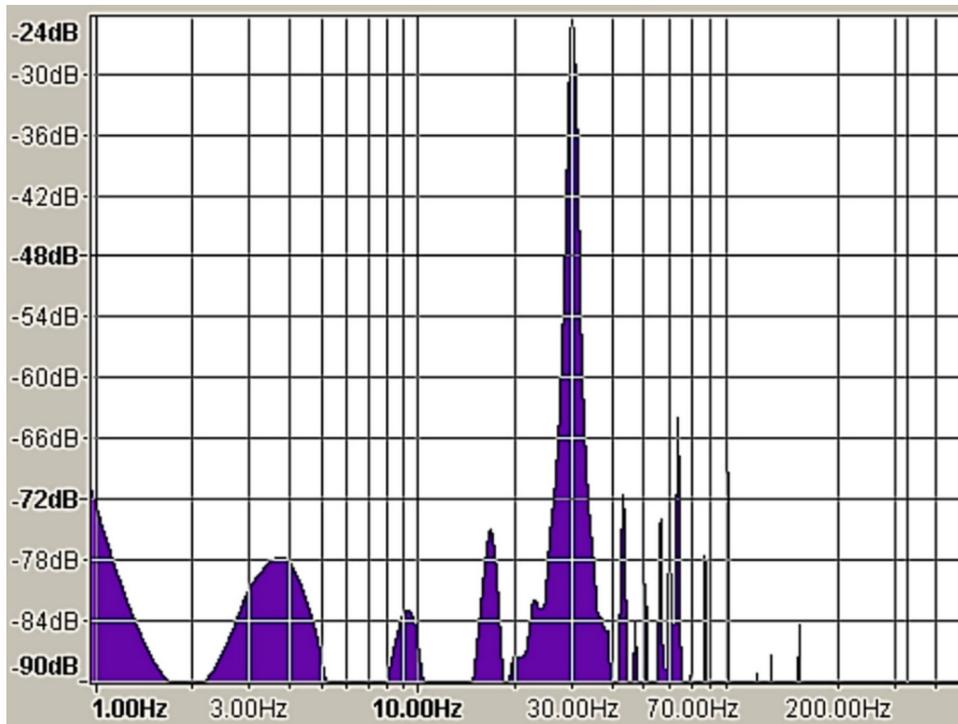


Figure 4. **Spectrum graph of recorded audio.** Spectral analysis shows that the device properly recorded the 30-Hz input signal.

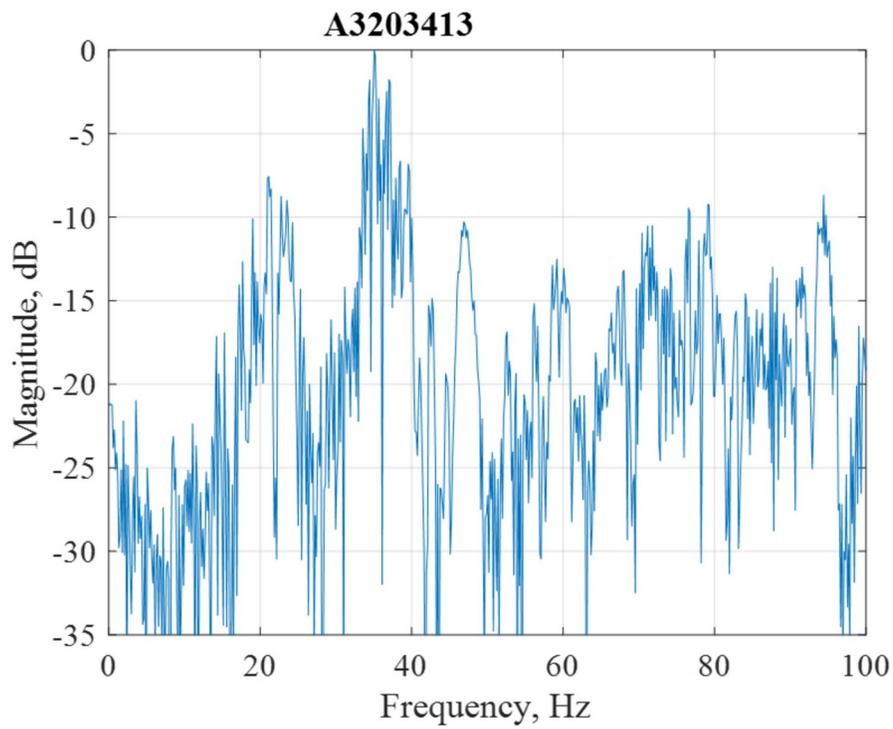


Figure 5. **Raw data of an original elephant call recording using MATLAB**

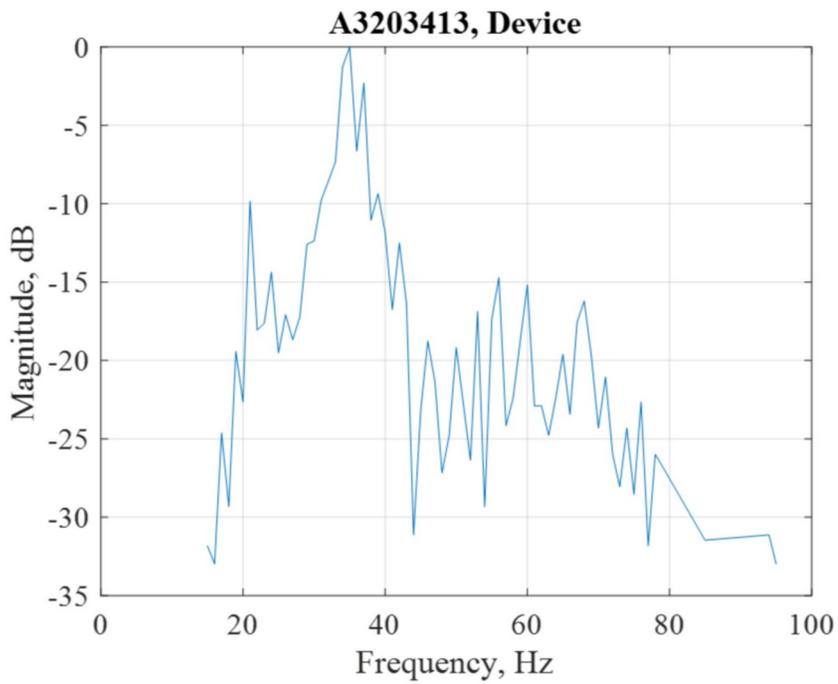


Figure 6. **Raw data of an original elephant call recording.** A reduced number of data points contributed to the relative smoothness of the graph.



Figure 7. **Geophone.** The geophone was used as a sensor to determine the capability of the IDS to detect infrasound.

Discussion

This work describes the design of a device used to record infrasound. If the incoming signal spectrum is of the proper amplitude and in the frequency range of interest, it is processed in real time and provides an audible and visual signal when infrasound is detected. To be effective, the sensor must provide a good signal, therefore making the sensor a critical part of the system. The analog signal is filtered, digitized, and processed to provide a spectrum of the incoming signal. This processing occurs approximately once every second. If the spectrum includes frequencies in excess of a specified threshold, then the cues will be presented. To select an appropriate input gain, approximate signal amplitude should be known. The gain can then be manually adjusted. In practice, this could be problematic. However, as a prototype, it demonstrated a proof of concept.

The device is small (4.5" wide, 3" high, and 2.25" deep), light, and portable. Construction cost was less than \$120, a cost that would be greatly reduced if made in quantities. Features to make the device more usable would be an automatic gain control (AGC) and a wireless communications system to allow the remote monitoring and safer data collection of elephants.

This device was only a prototype and not intended for mass production. More work could be done to enhance some features of the device. Using a printed circuit

board to build the circuitry would enhance the look, clean operation, and reliability of the device. Additional circuitry may need to be added and/or software changed to enhance playback to remove the noise that was present in this device. A slightly larger enclosure to better accommodate the internal components would make the device easier to build and maintain. That larger enclosure may also allow room for larger batteries, potentially allowing the device to be powered internally for longer periods of time.

Just simply switching to AA batteries may increase powered-on time to over 15 hr. Likewise, an external battery source could be plugged in using the DC power jack for a much longer usability period. The device can take an input of up to 9 VDC. This would also allow the device to stay in place without the external battery pack needing to be changed in and out.

The ability to identify and eliminate constant background noise, such as an air conditioner, would be helping in preventing false alarms when infrasound from those sources would be able to surpass the alarm threshold. This noise cancelling feature would make the device more accurate, but this was not part of the original objective.

The most important future work would be on the input sensor. The experimentation with the geophone showed that it was able to detect vibration; however, that particular device does not seem to be the most efficient sensor for infrasound due to its natural frequency being close to the desired frequencies. Without a sensor that can consistently and accurately detect infrasound, the safety capability of this device would be in question. Finding a microphone or other input sensor for a low cost would be an important objective of the continuing work.

With the addition of a remote communications capability, the device would have the ability to transmit data live and in real time to an operator at a remote location. This would allow for 24-hr monitoring of elephants.

We selected the Propeller over other microcontrollers, such as the Arduino, for several reasons. We based our selection upon estimating the microcontroller speed needed, the core bit size, and the amount of input/output (I/O) pins required. As this device is intended to be low cost and small, a microcontroller would be the most likely solution to meet those requirements. The clock frequency required is tied to the highest sampling speed desired. The goal of this device is to sample infrasound, which is 20 Hz or less, so a slow microcontroller would be sufficient. However, the additional objective of making this device usable in many applications requires a much higher sampling rate, such as the CD-quality sampling rate of 44,100 Hz. Each sample will take dozens of clocks for the operations, not to mention the additional processes of storing the data to an external storage device and any other device functions occurring simultaneously, such as human interface monitoring. A “safe” clock rate would be at least 1,000 clocks per sample, therefore a microcontroller clock greater than 44 MHz would be the best option in order to meet the required sampling speed.

The core size of the microcontroller would need to be sufficient to handle the bit

depth of the analog to digital converter. An 8-bit core could only handle a -128/127 value from the analog to digital converter (ADC), which would only provide a signal to quantization noise ratio of 48.16 dB. A greater bit depth is desired, so the core of the microcontroller should be more than 8 bits.

The microcontroller also requires enough IO pins to interface with all peripherals. Connections need to be made to at least the ADC, digital to analog converter (DAC), display, interface buttons, and external storage device. This does not even include any spare pins that should be made available to future uses or expansion. These requirements allow for no less than 16 IO pins to be available on the microcontroller.

There is a wide range of microcontrollers that meet these requirements. Any one of them would be sufficient for the purposes of this device. An additional factor that would help the choice of microcontroller is the programming language. As these devices are intended to be used by individuals who are not necessarily frequent programmers, utilizing a programming language and interface that is easier to understand would make the device more usable by a wider range of individuals. Though some functions may reside in assembly-level instructions, the portions of the code that may need to be changed by future users in order to meet their application should be in a higher-level language that is much easier to access.

To that end, the Parallax Propeller microcontroller (Rocklin, CA) meets the desired requirements. In addition to meeting all of the technical requirements stated above, the company has its own programming language called Spin made just for this controller. There is also the Propeller Assembly (PASM) language, which allows for more detailed control of the microcontroller. This microcontroller has already been used in the Comparative Psychology and Behavioral Biology Laboratory at Oklahoma State University and is gaining in popularity as a versatile low-cost laboratory controller for behavioral experiments (Varnon & Abramson, 2018; Varnon et al., 2018). Psychology students are not focused on programming yet have successfully used the microcontroller to control experiments in their laboratories. Utilizing a Propeller microcontroller for this device increases the likelihood of maintainability and easier modification by individuals who are not strong programmers.

In conclusion, we illustrate that the Propeller microcontroller is a low cost device that can be used to detect infrasound. The device can be used as part of a general comparative psychology “teaching laboratory” or as a research tool. The use of microcontrollers for research and teaching in comparative psychology is opening up new opportunities for comparative psychologists and illustrates the benefits of comparative psychologists collaborating with computer scientists.

Acknowledgments

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References

- Abramson, C. I. (1990). *Invertebrate learning: A laboratory manual and source book*. Washington, D.C.: American Psychological Association.
- Abramson, C. I., Curb, L. A., Barber, K. R., & Sokolowski, M. B. C. (2011). The use of invertebrates and other animals to demonstrate principles of learning: Activities developed by the laboratory of Comparative Psychology and Behavioral Biology. *Journal of Behavioral and Neuroscience Research, 9*, 1-6.
- Abramson, C. I., Hilker, A. C., Becker, B., Barber, K. R., & Miskovsky, C. (2011). Cost-effective laboratory exercises to teach principles in the Comparative Analysis of Behavior. *Journal of Behavioral and Neuroscience Research, 9*, 7-15.
- Black, T. E., Fofah, O., Giray, T., Wells, H., & Abramson, C. I. (2018). Influence of environmental experience on aversive conditioning of honey bees (*Apis mellifera* L.). *Apidologie, 49*, 647-659. doi: 10.1007/s13592-018-0592-0
- Chilo, J., & Lindblad, T. (2007, September). A low cost digital data acquisition system for infrasonic records. In *4th IEEE Workshop on intelligent data acquisition and advanced computing systems: Technology and Applications*, Dortmund, Germany.
- Colaizzi, J. M. (2016). *Empathy and prosocial behaviors in infancy*. (Unpublished doctoral dissertation). Oklahoma State University, Stillwater, OK.
- Craig, D. P. A., Varnon, C. A., Pollock, K. L., & Abramson, C. I. (2015). An assessment of horse (*Equus ferus caballus*) responding on fixed interval schedules of reinforcement: An individual analysis. *Behavioural Processes, 120*, 1-13.
- De Silva, G. D., & Zoysa, K. A. (2009, September). A low cost infrasound recording system. In *27th National Information Technology Conference of The Computer Society of Sri Lanka Colombo, Sri Lanka*.
- Dinges, C. W., Varnon, C. A., Cota, L. D., Slykerman, S., & Abramson, C. I. (2017). Studies of learned helplessness in honey bees (*Apis mellifera ligustica*). *Journal of Experimental Psychology: Animal Learning and Cognition, 43*, 147-158.

- Phelps, B. J., & Varnon, C. A. (2015, May). *Using a microprocessor -controller for measures of foraging behavior by free roaming eastern fox squirrels Sciurus niger*. Poster presented at the annual meeting of the Association for Behavior Analysis International, San Antonio, TX.
- Varnon, C. A., & Abramson, C. I. (2013). The propeller experiment controller: Low-cost automation for classroom experiments in learning and behavior. *Innovative Teaching*, 2(2), 1-18. doi: 10.2466/07.08.IT.2.2
- Varnon, C. A., & Abramson, C. I. (2018). *The propeller experiment controller: Automation for the comparative analysis of behavior in research and teaching* [Monograph]. *The Journal of Mind & Behavior*, 39, 1- 153.
- Varnon, C. A, Lang, H., & Abramson, C. I. (2018). Automated research in comparative psychology: Limitations and new directions. *International Journal of Comparative Psychology*, 31. Retrieved from <https://escholarship.org/uc/item/8gf4d5tx>

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