



AudioMoth: A low-cost acoustic device for monitoring biodiversity and the environment



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ABSTRACT

Environmental sound is a powerful data source for investigating ecosystem health. To capture it, scientists commonly use ruggedized, but expensive acoustic monitoring equipment. In this paper we fully describe the hardware build of a low-cost, small, full-spectrum alternative, called AudioMoth. The credit-card sized device consists of a printed circuit board, micro-controller and a micro-electro-mechanical systems microphone. This simple to construct device facilitates: (1) deployments in remote locations, with a small size and a simple mechanism that allows it to be retrofitted into numerous low-cost ruggedized enclosures; (2) long-term monitoring, with low-power operation; (3) modular expansion, with easy to access general purpose input and output pins; and (4) acoustic detection, with onboard processing power.

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Specifications table:

Hardware name	AudioMoth
Subject area	Conservation biology, environmental, educational tools
Hardware type	Acoustic sensor
Open source license	Creative Commons Attribution 4.0 International
Cost of hardware	53 USD for 1 unit, 25 USD for 1000 units
Source file repository	Available with the article

1. Hardware in context

The analysis of environmental sound is a rapidly developing branch of ecological research, often referred to as ecoacoustics [1]. The science relies on analyzing stored datasets of captured sound. Datasets are often collated from audio recordings generally taken either on mains powered acoustic setups, or more often by battery powered passive acoustic monitoring (PAM) devices. A full list of current acoustic hardware and software can be found in the WWF guidelines for passive acoustic monitoring in ecology and conservation [2]. Traditionally PAM is performed using commercial devices, such as the SongMeter

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series from Wildlife Acoustics (www.wildlifeacoustics.com) and the BAR series from Frontier Labs (www.frontierlabs.com.au). These portable commercial devices are valued for their excellent recording quality, making them well suited to bioacoustics research. Although the cost of these devices is considerably cheaper than complex mains powered setups, they are still an expensive research tool for conservation uses, at a starting price of approximately 800 USD. For many applications requiring coverage of large areas, this cost presents a restriction on usage. In certain projects, such as the use of acoustics to monitor biodiversity or poaching, cheaper units that enable researchers to cover larger areas could have utility even if some sound quality is lost in minimizing unit price [3]. To this end, custom designed, fit-for-purpose solutions have seen a rapid increase over the last 3 years, often facilitated by new low-cost technologies [4]. Accessible and affordable single-board computers, such as the Raspberry Pi, have disrupted the acoustic monitoring market, with many new releases of open-source modular forms of PAM [5–8]. Despite reducing the unit cost to less than 100 USD, modular build-yourself devices are restricted by their high power consumption, sometimes requiring a car battery to sustain longer deployments, and the time required to build each device, often needing hobbyist software and electronics knowledge.

Here, we describe AudioMoth¹: an environmental and wildlife acoustic monitoring tool that addresses many of the barriers associated with pre-existing acoustic monitoring tools. The small size and low power consumption of the device make it amendable to long-term and large-scale scientific research [9]. It provides a manyfold lower cost alternative to pre-existing equipment, and lowers the technical barrier to entry into open-source hardware. This is the first paper to fully describe the AudioMoth hardware build and two types of enclosure to house it.

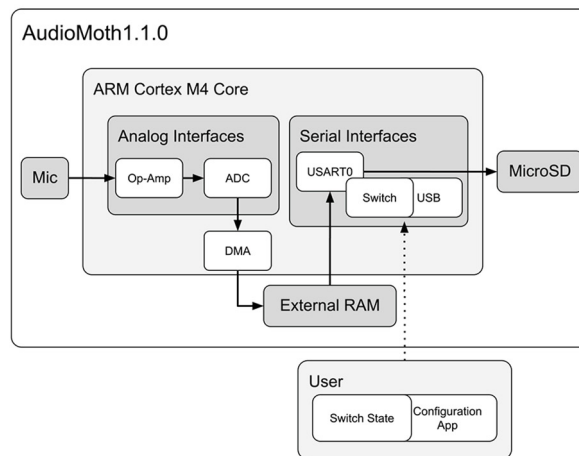
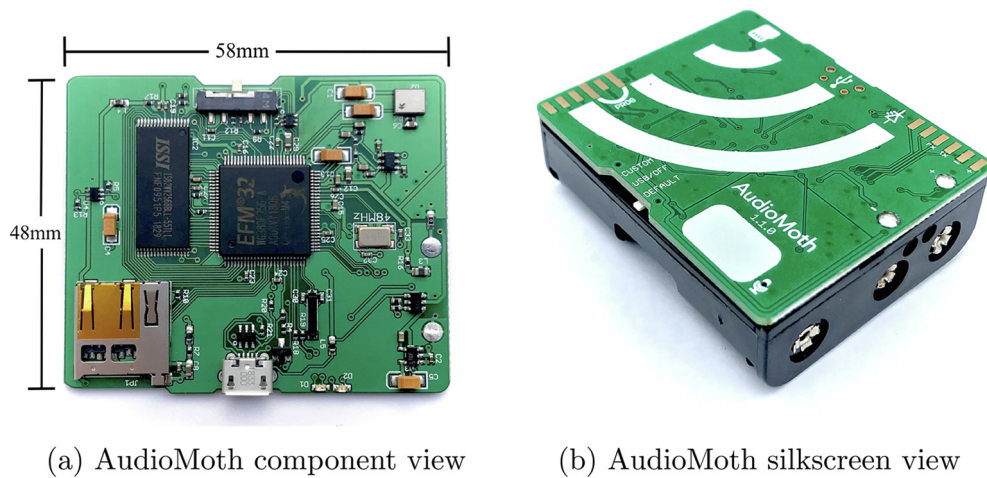
2. Hardware description

AudioMoth consists of a single credit-card sized ($58 \times 48 \times 15$ mm) printed circuit board (PCB), which includes a side-mounted switch, universal serial bus (USB) port, red & green light emitting diode (LED), and microSD card port. The single board design doubles as an enclosure, with components placed between the board and the battery holder on the top layer of the two-layer PCB (Fig. 1a). The hidden component placement together with an indented switch and SD card connector means the device is robust to knocks that usually occur during general use. Sound is captured through a drill hole, which is located inside the silkscreened microphone symbol on the bottom PCB layer (Fig. 1b). Behind the drill hole sits a bottom ported MEMS microphone. Programming pins (PROG) and four general purpose input/output (GPIO) pins are located on this bottom layer for easy access. The GPIO pins create the option to plug in external modules that interface with the device, allowing users to add hardware modules that extend the device's functionality. The PROG pins enable the device to enter programming mode, which enables users to upload and update device firmware by USB.

AudioMoth's main advantages over pre-existing tools is its lower cost, lower power usage, small size and ease of use. Its cost, approximately 50 USD for a single unit, is at about 10 times cheaper than pre-existing commercial equivalents. Its size enables easy deployments, with numerous devices able to fit in one field backpack. Its easy-to-use supporting software makes it possible for users at any skill level to configure a device for multiple applications. It can handle both audible and ultrasonic sound capture from one microphone and can be deployed in application specific enclosures. These improvements are achieved through a combination of low-level audio processing that can be optimized for low-power applications, simple single board construction, and a user-centered software/hardware interface. Instead of using a Linux based processor that is harder to optimize for power usage, AudioMoth is built around a power efficient ARM Cortex M4 micro-controller. This micro-controller benefits from floating point functionality, which when combined with low-power operation makes it possible to achieve on-board detection for real-time sound filtering [10].

Fig. 1c shows the hardware overview and the typical flow of operation when running the basic firmware. Users can interface with the device using the three-position hardware switch, and software running on a Windows, Mac or Linux computer via the USB connector. The software provides a graphical user interface (GUI) configuration application, which allows custom parameters within hardware to be changed without needing to modify the firmware. Parameters can be adjusted in the application for multiple deployment scenarios. The switch allows the user to shift between three firmware states, which can be customized using the open-source code. Typically, the default switch position enables the device to start recording immediately with default (if not previously configured) or selected (if previously configured) parameters, the middle switch position enables the device to be configured by USB using the configuration application, and the custom switch position enables the configured parameters to be applied for time scheduled recordings. The analog peripherals and the microphone switch on when the device is ready to record. The analog microphone signal is amplified by the internal firmware-controlled op-amp circuitry. The output of which is then converted to digital samples by the 12-bit analog to digital converter (ADC), which automatically fills a buffer located in the external static random access memory (SRAM) using direct memory access (DMA). Over-sampling can be applied to generate 16-bit samples if required. DMA allows samples to be routed to the external memory in low energy modes without needing to wake up the processor. Using DMA saves substantial battery power during deployments. When the buffer is sufficiently full, it is saved to the microSD card via the serial peripheral interface (SPI) bus. A more detailed description of how the hardware works will be covered in Section 3.1.

¹ The device is a revision on a previous model of acoustic logger, AudioMoth1.0.0 (www.openacousticdevices.info). The revision, AudioMoth1.1.0 has improved power management and robustness for outdoor field deployments, using custom built or off-the-shelf enclosures.



(c) Hardware Overview

Fig. 1. AudioMoth.

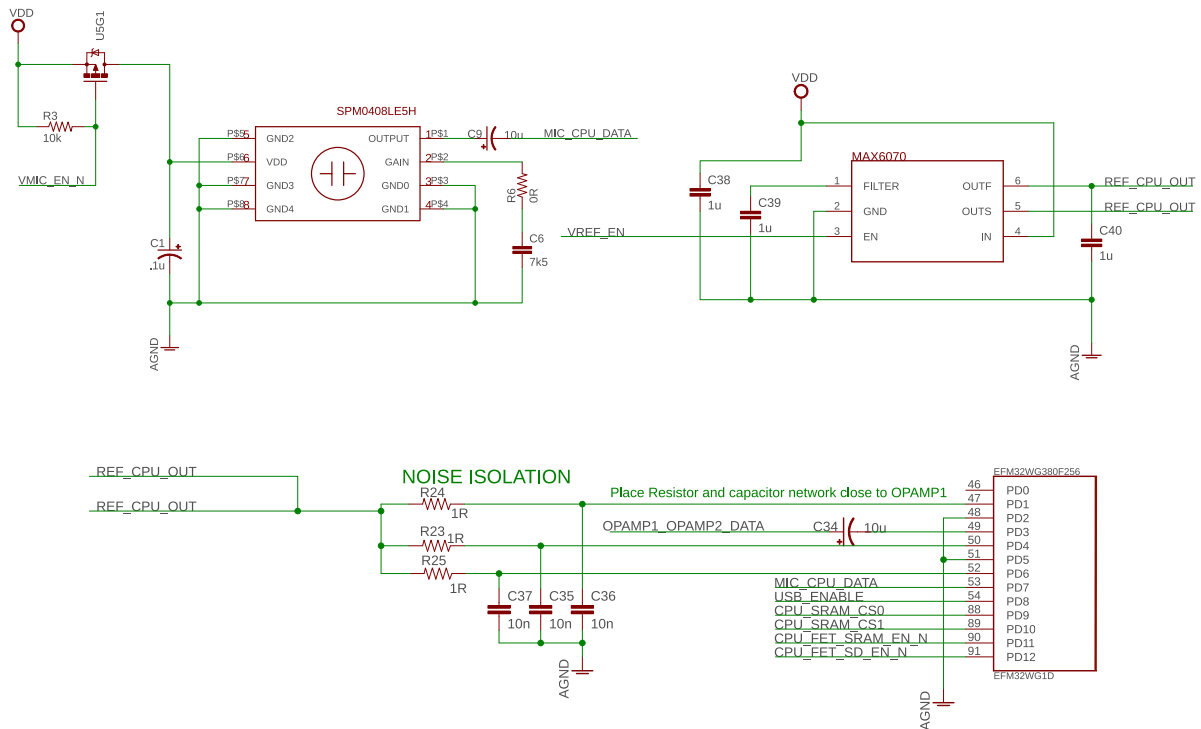
AudioMoth can be configured to record at many sample rates, making it suitable for monitoring sounds from different source types. These include: anthropogenic noise, such as gunshots, chainsaws or engine noise (8 kHz sample rate); audible wildlife, such as bird, insect or frog vocalization (48 kHz sample rate); and ultrasonic wildlife, such as bat or amphibian calls (384 kHz sample rate). The device can be used in multiple deployment scenarios, such as scheduled or triggered acoustic monitoring in remote areas, handheld acoustic monitoring, large-scale acoustic monitoring projects, long-term acoustic monitoring projects, environmental monitoring for education, and large scale citizen science projects.

3. Design files

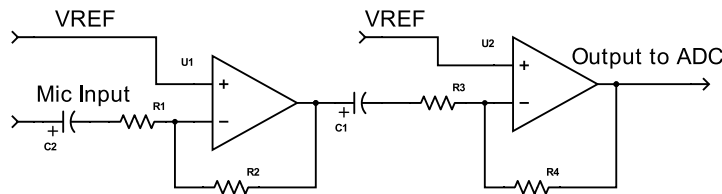
The design files consist of all the needed content to manufacture, assemble and deploy AudioMoth in two variations of weather proof enclosure (Table 1).

3.1. Hardware

'Hardware' is a folder containing an Eagle schematic (AudioMoth1-1-0.sch) and Eagle PCB layout (AudioMoth1-1-0.brd). The schematic is split into labelled functional groups: power, audio, memory and debug. The device can be powered from any 3.6 V–20 V DC supply. This power supply connects to a regulator that converts the DC supply to a stable 3.3 V, or alternately the device can be supplied by 5 V USB power, which connects to the internal voltage regulator inside the micro-controller. To reduce the load on the DC supply when USB power is used, a N-channel and P-channel MOSFET array



(a) Audio circuitry schematics



(b) Microphone cascaded inverting operational amplifier

Fig. 3. Microphone and analog amplification circuitry.

3.2. Software

Software is split into two sections: (i) 'Firmware', the software that runs on the device; and ii) 'Applications', the software that supports the device. All source code for these two sections can be accessed on the device GitHub page (www.github.com/OpenAcousticDevices). 'Firmware' is a binary file that can be used to program AudioMoth by USB. A full description of the firmware project, library and example code can be found on the GitHub Wiki page (www.github.com/OpenAcousticDevices/AudioMoth-Project/wiki). 'Applications' contains the downloadable Flash application, the Electron based Configuration App and Time App. Three downloadable variations of each application are included for Unix, Mac and Windows desktop operating systems. The Flash application allows AudioMoth to be programmed over USB using a compiled firmware binary through the onboard boot-loader. The Flash application is run from the command line.

The Configuration App enables AudioMoth to be configured by USB. When connected to AudioMoth, the Configuration App displays the device's onboard time, identification number (ID), firmware version and battery voltage. The Configuration App allows users to set the audio parameters and recording schedules for various deployment scenarios (Fig. 6). Four separate recording periods can be set during a 24hr period, with the option between eight different sample rates (8 kHz, 16 kHz, 32 kHz, 48 kHz, 96 kHz, 192 kHz, 256 kHz, 384 kHz), five different gain levels (low = 27.2 dB, medium-low = 28.7 dB, medium = 30.6 dB, medium-high = 31.6 dB, high = 32.0 dB), any sleep duration less than 12 h, any recording duration less than 12 h, and LED's can be enabled or disabled. After configuration, the application calculates and displays the daily memory and battery consumption. The Time App enables AudioMoth to be configured by USB. When connected to AudioMoth, the Time App displays the device's onboard time, identification number (ID), firmware version and battery voltage. The Time App only allows the time to be set, and is useful to use with customized firmware. Table 2 presents the software source locations.

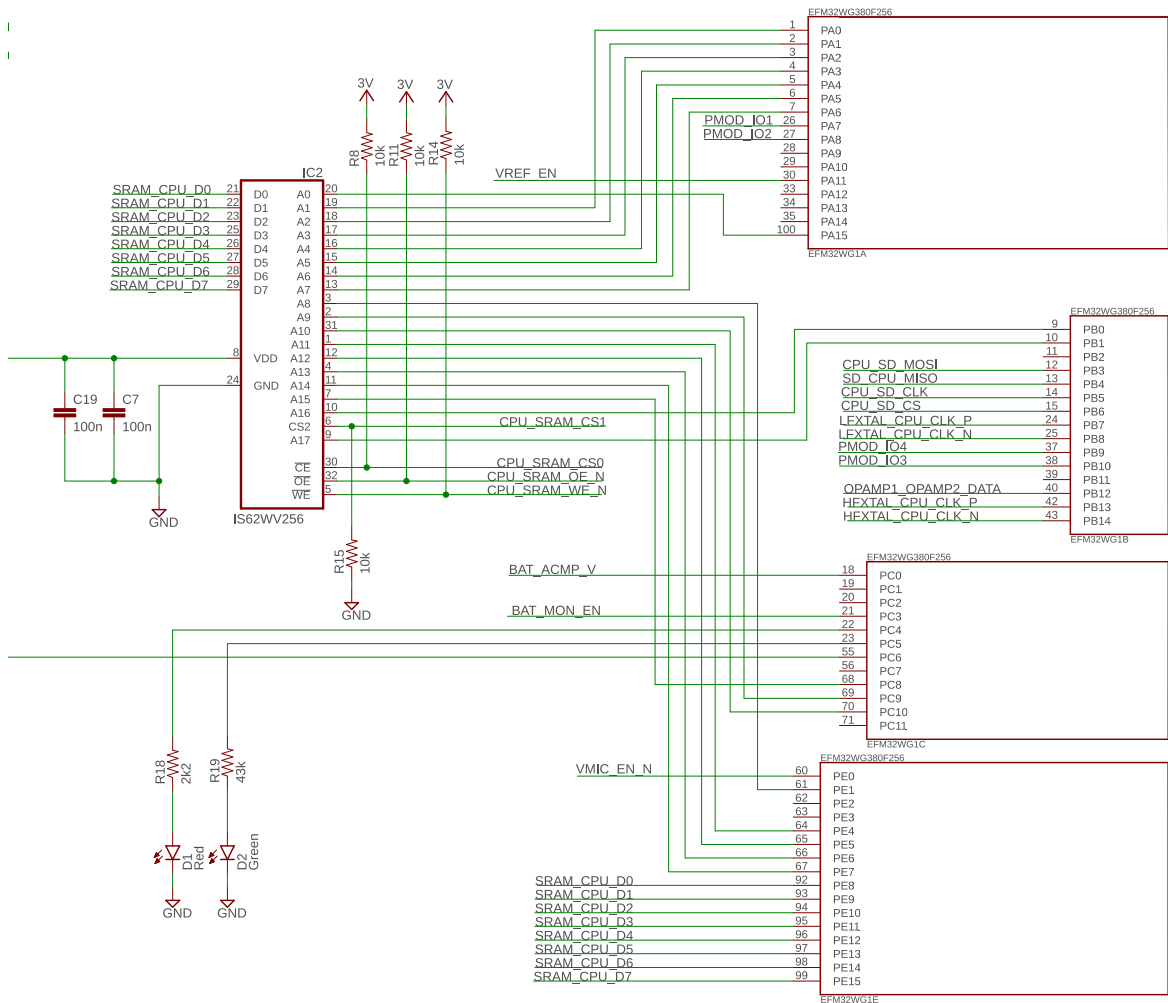


Fig. 4. SRAM schematic.

3.3. Enclosures

We will illustrate two simple laser cut versions of AudioMoth enclosure. The first case design is located in the 'AA enclosure' zip file, which contains three CAD design files. These files are used to laser cut acrylic and neoprene gasket sandwich layers. They can be assembled to form a waterproof case for AudioMoth when using a through hole AA battery connector. The top and bottom acrylic layers (Fig. 7a) use 5 mm acrylic and the two middle layers (Fig. 7b) use 10 mm acrylic. Neoprene gaskets (Fig. 7c) are used between the layers to prevent water ingress. Many off-the-shelf enclosures can also be used to protect AudioMoth too. Examples of these can be found at www.openacousticdevices.info/support/enclosures.

The second case design is located in the '6 V enclosure' file, which contains three CAD design files and a hardware schematic and layout file. The hardware files form a base PCB assembly to hold AudioMoth onto a connector for the 6 V battery. The CAD design files are used for laser cutting acrylic sandwich layers to form an internal structure to hold the PCB assembly against a 6 V battery. Most of the internal structure uses 3 mm acrylic (Fig. 8a) held together by cable ties. The internal structure is designed to fit within common industrial 110 mm diameter coupling drain pipes. One 5 mm piece of acrylic is used to hold AudioMoth flush against the internal drain pipe plug end (Fig. 8b). Fig. 8c shows a jig paper cutout that can be used as a guide for the microphone drill hole and the placement of the rectangular key in Fig. 8a. The small semi circle structure in this figure is the rain hood, which should be used on the outside of the drain pipe plug to prevent moisture pooling.

Fig. 6. Configuration App.

Table 2
Source code location.

Software	Description	Location
Flash AudioMoth-Firmware-Basic	A command line tool to program AudioMoth Standard firmware for AudioMoth	www.github.com/OpenAcousticDevices/Flash www.github.com/OpenAcousticDevices/AudioMoth-Firmware-Basic
AudioMoth-Project	A minimal project on which all AudioMoth firmware can be built	www.github.com/OpenAcousticDevices/AudioMoth-Project
AudioMoth-Time-App	Application capable of setting the on-board clock on AudioMoth	www.github.com/OpenAcousticDevices/AudioMoth-Time-App
AudioMoth-Configuration-App	Application capable of configuring the functionality of AudioMoth	www.github.com/OpenAcousticDevices/AudioMoth-Configuration-App

5.2. AA battery enclosure

The AA battery enclosure uses the default AA battery holder to power the device. Once the battery holder is attached, the unit can be placed inside an enclosure. This acrylic enclosure can be laser cut using the design files or ordered from any laser cutting service. The enclosure can be built using the following instructions:

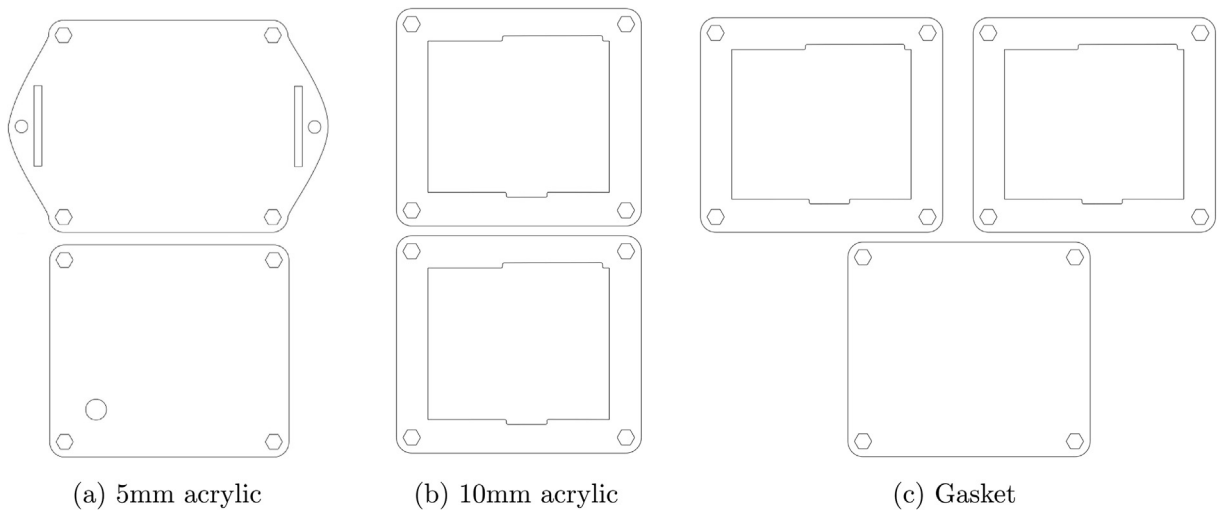


Fig. 7. AA battery enclosure design files.

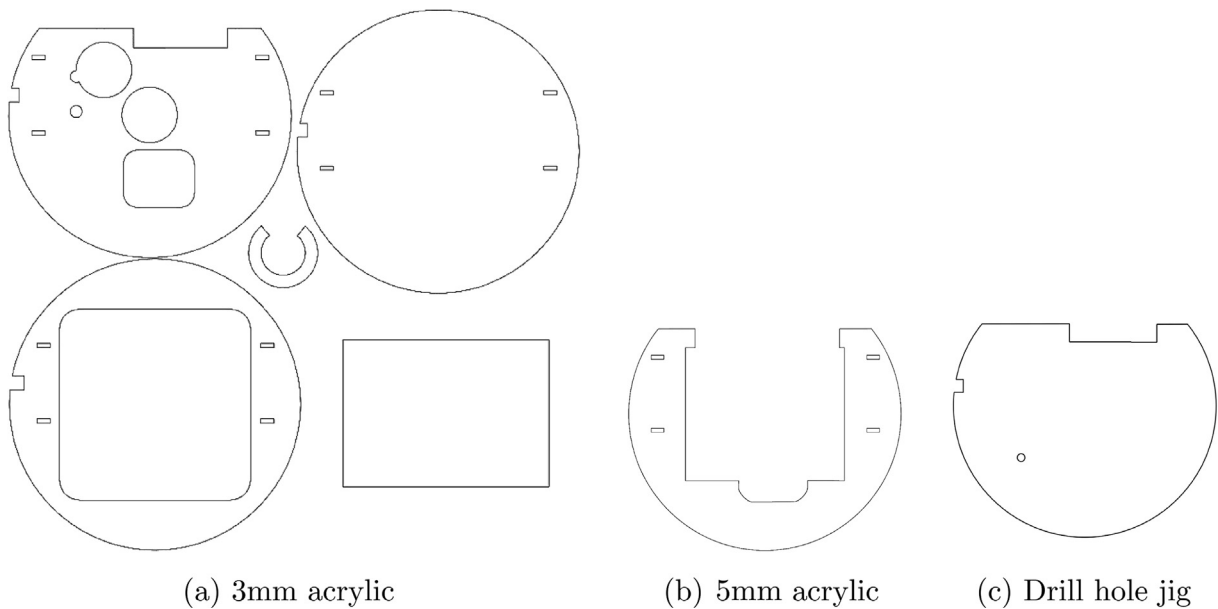


Fig. 8. 6 V lantern battery enclosure design files.

1. Place two small dabs of hot glue on the top layer PCB as shown in [Fig. 9a](#), make sure not to glue on top of any components.
2. Keeping the PCB parallel with the battery connector, hold the PCB in place.
3. Once the glue has cooled, solder the through hole battery connector (Keystone 2464, [Table 4](#)) to the PCB.
4. Once soldered and solder is cool, trim the battery connector legs flush with the PCB using wire cutters.
5. Lay out all of the components to make the acrylic enclosure ([Fig. 9c](#)).
6. Place the first 5 mm acrylic cutout flat on a surface, with the four hex spaces inserted into each hex slot.
7. Place the first expanded neoprene gasket through the four hex spaces so it sits flush against the first acrylic layer.
8. Place the first 10 mm acrylic cutout through the four hex spaces, with the SD and USB protrusion located in the top left corner.
9. Place the second expanded neoprene gasket through the four hex spaces so it sits flush against the second acrylic layer, with the SD and USB protrusion located in the top left corner.
10. Place the second 10 mm acrylic cutout through the four hex spaces, with the SD and USB protrusion located in the top left corner.

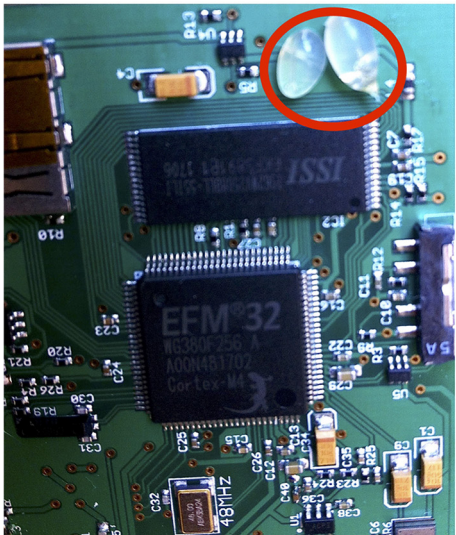
Table 3
AudioMoth bill of materials.

Designator	Component	Qty/ unit	Batch of 1 (USD)	Batch of 1000 (USD)	Source	Material
Y2	ABM3B-48.000MHZ-B2-T	1	1.09	0.57	digikey.com	Electronics
C10 C11 C16 C2 C22 C38 C39 C40 C6	04026D105KAT2A	9	2.88	0.5	digikey.com	Electronics
C13 C15 C3 C35 C36 C37	0402YC103KAT2A	1	0.1	0.01	digikey.com	Electronics
Y1	ECS-.327-7-38-TR	1	0.73	0.43	digikey.com	Electronics
IC2	IS62WV2568BLL-55TLI	1	2.21	1.68	digikey.com	Electronics
U2	SPM0408LE5H-TB	1	2.74	1.44	digikey.com	Electronics
C1	T491A104M035AT	1	0.52	0.15	digikey.com	Electronics
C34 C4 C5 C9	T491A106K010AT	4	1.76	0.34	digikey.com	Electronics
U3	LT1761ES5-3.3#TRMPBF	1	2.44	1.20	digikey.com	Electronics
D1	150060RS75000	1	0.33	0.06	digikey.com	Electronics
U1	MAX6070BAUT18 + T	1	2.16	0.99	digikey.com	Electronics
J1	1050170001	1	0.91	0.50	digikey.com	Electronics
L2 L4	BLM18HG601SN1D	2	0.38	0.11	digikey.com	Electronics
L5	BLM18SG221TN1D	1	0.14	0.04	digikey.com	Electronics
L3	BLM21BD102SN1D	1	0.17	0.05	digikey.com	Electronics
C30 C31	GRM1555C1H7R5CA01D	2	0.2	0.02	digikey.com	Electronics
C14	GRM155R60J475ME87D	1	0.19	0.03	digikey.com	Electronics
SW1	CSS-1310 TB	1	0.63	0.42	digikey.com	Electronics
U11	IP4220CZ6F	1	0.44	0.13	digikey.com	Electronics
Q1	BSS123LT1G	1	0.31	0.06	digikey.com	Electronics
T1	FDC6420C	1	0.68	0.25	digikey.com	Electronics
R18	ERJ-2GEJ222X	1	0.1	0.01	digikey.com	Electronics
R9	ERJ-2GEJ274X	1	0.1	0.01	digikey.com	Electronics
R12	ERJ-2RKF1003X	1	0.1	0.01	digikey.com	Electronics
R1	ERJ-2RKF4701X	1	0.1	0.01	digikey.com	Electronics
R26 R4	ERJ-2RKF5102X	2	0.2	0.02	digikey.com	Electronics
R2	ERJ-2RKF6801X	1	0.1	0.01	digikey.com	Electronics
R22	ERJ-3GEY0R00V	1	0.1	0.01	digikey.com	Electronics
C32 C33	CL05C180JB5NNNC	2	0.01	0.2	digikey.com	Electronics
C12 C29 C8	CL10A106KP8NNNC	3	1.08	0.21	digikey.com	Electronics
IC1	EFM32WG380F256-QFP100	1	5.48	4.63	digikey.com	Electronics
R6	CRG0402ZR	1	0.1	0.003	digikey.com	Electronics
R10 R11 R13 R14 R15 R3 R5 R8	CRCW040210K0FKED	8	0.8	0.04	digikey.com	Electronics
U4 U5	SI1967DH-T1-E3	2	0.96	0.35	digikey.com	Electronics
D2	150060GS75000	1	0.14	0.10	digikey.com	Electronics
JP1	693071010811	1	2.92	2.06	digikey.com	Electronics
C19 C20 C23 C24 C25 C26 C27 C7	CC0402KRX7R6BB104	8	0.8	0.06	digikey.com	Electronics
R19	RC0402FR-077K5L	1	0.1	0.003	digikey.com	Electronics
R20 R21	RC0402JR-0715RL	2	0.2	0.01	digikey.com	Electronics
R16 R17 R23 R24 R25 R7	RC0402JR-071RL	6	0.6	0.02	digikey.com	Electronics
VENT	SEL-3391-14/9	1	0.1	0.1	selectronix.co.uk	Fabric
MAINPCB	AudioMoth PCB	1	8.69	0.39	pcbcart.com	PCB
MICROSD	Sandisk Extreme 32 GB	1	9.55	8.50	bulkmemorycards.com	Memory
Total for 1 unit			53.34	25.74		

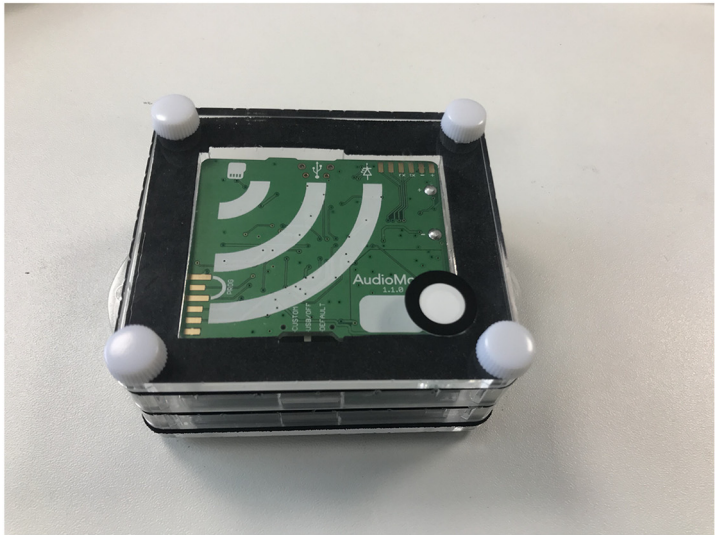
- Place the third expanded neoprene gasket through the four hex spaces so it sits flush against the third acrylic layer with the SD and USB protrusion located in the top left corner.
- Place the configured AudioMoth inside the acrylic case so the SD card lines up with the protrusion in the 10 mm acrylic cutouts.
- Place the final 5 mm acrylic sheet on top of the enclosure and make sure the drill hole lines up with the microphone.
- Screw up the four top thumb screws (Fig. 9I).
- Turn over and screw the last four thumb screws into the bottom of the enclosure.
- Firmly screw up all thumb screws and stick the acoustic vent over the microphone hole.
- Thread the cable ties through the drill holes on the back acrylic layer.

List of equipment

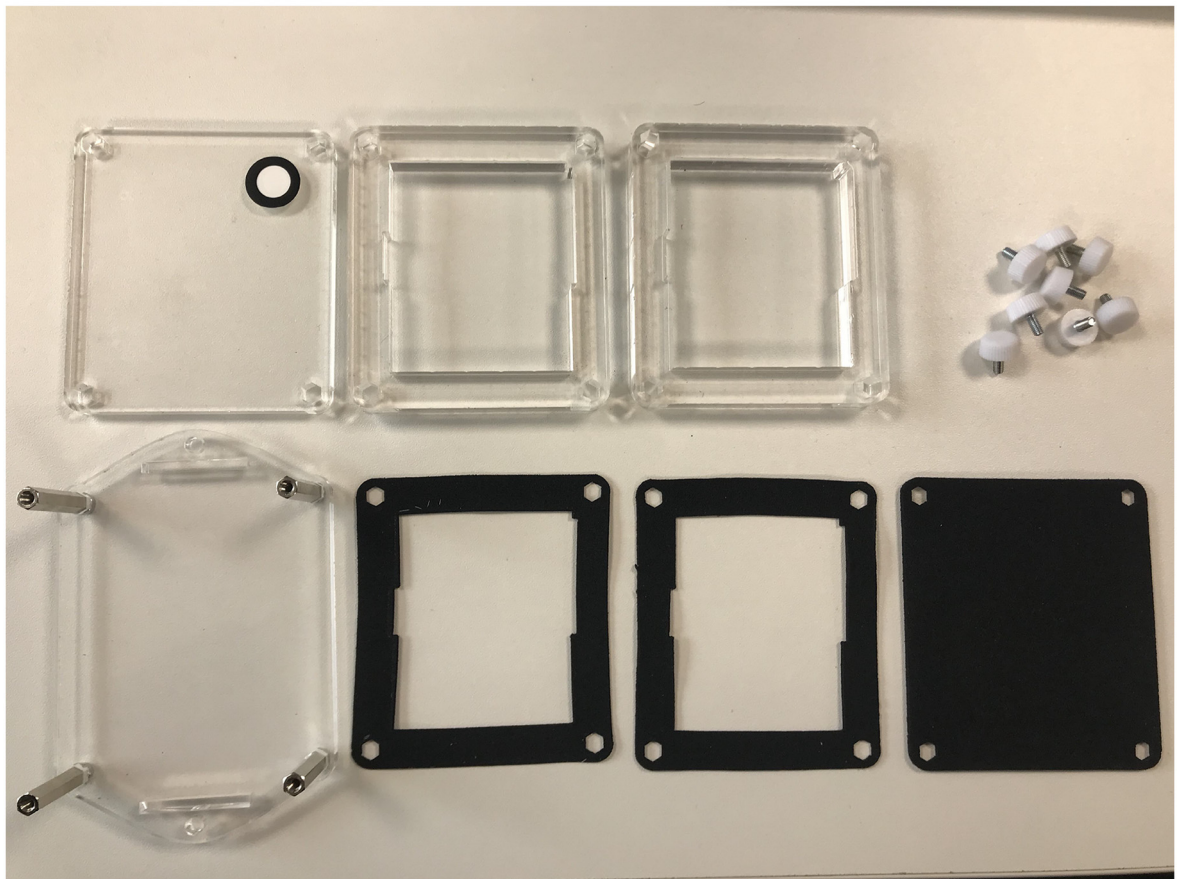
- For enclosure build
 - Laser cutter
 - Hot glue gun



(a) Glue from hot glue gun to hold AudioMoth against the AA battery holder



(b) Constructed AA enclosure



(c) Components of AA enclosure

Fig. 9. AA enclosure build steps.

Table 4

AA enclosure bill of materials.

Designator	Component	Qty	Unit	Total (USD)	Source of materials	Material
U1	Keystone 2464	1	1.58	1.58	digikey.com	Electronics
Hex Spacer	HTSB-M3-30-5-1	4	0.38	1.52	uk.rs-online.com	Casing
Thumb Screw	KSUH NO.1 M3X6 White	8	0.14	1.12	uk.rs-online.com	Casing
5 mm Acrylic 300 mm x 200 mm	AC.CLR0000.05.3020	1	3.77	3.77	hobarts.com	Casing
10 mm Acrylic 300 mm x 200 mm	AC.CLR0000.10.3020	1	6.88	6.88	hobarts.com	Casing
AABattery	Energizer L91	3	1.71	5.14	amazon.com	Battery
Cable Tie	111-05260	2	0.12	0.24	uk.rs-online.com	Casing
Total				20.25		

Table 5

6 V lantern enclosure bill of materials.

Designator	Component	Qty	Unit	Total (USD)	Source of materials	Material
6VPCB	6 V battery holder PCB	1	7.20	7.20	pcbcart.com	PCB
110 mm Socket Clip	SP83B	1	2.56	2.56	drainagepipe.co.uk	Casing
110 mm Coupling Socket	RS4	1	2.38	2.38	drainagepipe.co.uk	Casing
110 mm Plug	D296	2	2.99	5.98	drainagepipe.co.uk	Casing
3 mm Acrylic 300 mm x 200 mm	AC.CLR0000.03.3020	1	2.10	2.10	hobarts.com	Casing
5 mm Acrylic 300 mm x 200 mm	AC.CLR0000.05.3020	1	3.77	3.77	hobarts.com	Casing
6VBattery	Energizer 529	1	13.0	13.0	amazon.com	Battery
Cable Tie	111-05260	4	0.12	0.48	uk.rs-online.com	Casing
Total				37.47		

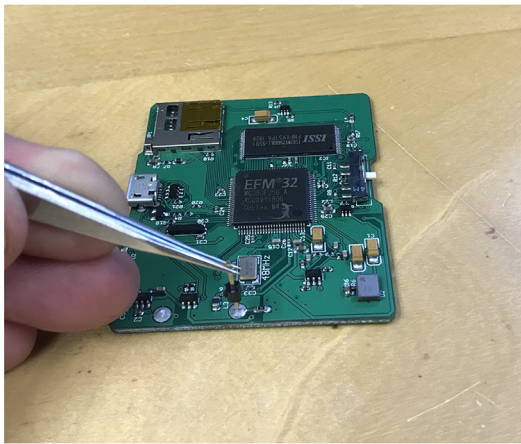
*Hot glue sticks**Wire cutters**Expanded neoprene gaskets from recommended distributor**5 mm and 10 mm acrylic sheets from distributor, pre-cut or in sheets*

5.3. 6 V battery enclosure

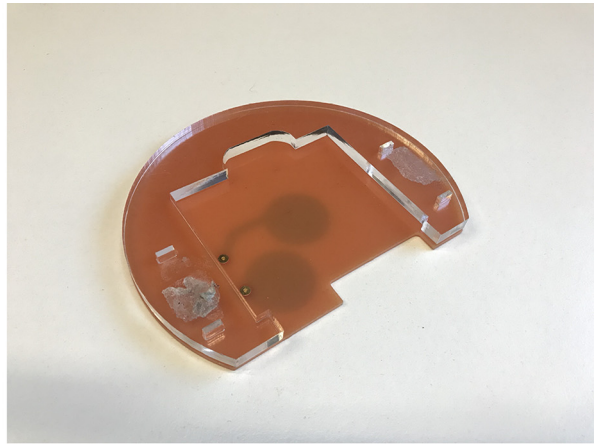
The 6 V battery enclosure uses two PCBs in its construction: the main AudioMoth PCB and a separate additional PCB that acts as a power connector to support the larger 6 V battery to power the device. The additional PCB can be acquired by uploading the '6 V enclosure' design files, or generated Gerbers to any PCB assembler. This enclosure uses cable ties to hold the acrylic layers in position. The acrylic layers can be laser cut using the design files or ordered from any laser cutting service. This case is useful as it extends the operation life of AudioMoth, with some 6 V batteries having a capacity of 24Ah (<http://data.energizer.com/pdfs/529.pdf>). The 6 V battery must have two-spring connectors and not the screw post terminals. (Table 5).

The enclosure is ruggedized and waterproof for hostile deployments. The 110 mm drain enclosure can be purchased at local hardware stores worldwide. This availability means the enclosure does not have to be shipped to the deployment country. The enclosure can be built using the following instructions:

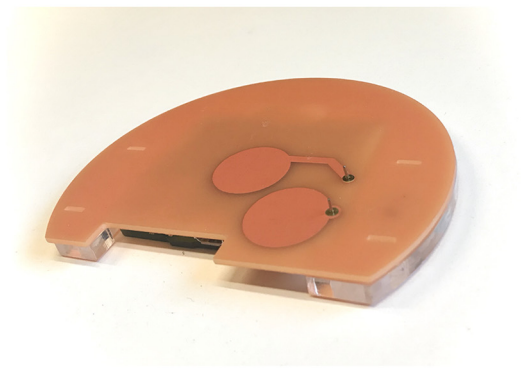
1. Solder the two small single pin connectors to the AudioMoth battery connector pins and cut flush with the bottom layer of the PCB (Fig. 10a).
2. Place and lineup the 5 mm acrylic cutout over the 6 V enclosure PCB (Fig. 10b).
3. Place two small dabs of hot glue on the top layer PCB as shown previously in Fig. 9a, making sure not to glue on top of any components
4. While the glue is still hot, place the AudioMoth PCB onto the 6 V enclosure PCB and flip the assembly over so the AudioMoth PCB sits flush with the workshop surface (Fig. 10c).
5. Once the glue has cooled, solder the AudioMoths power pins to the 6 V enclosure PCB keeping the AudioMoth PCB bottom layer flush with the top of the 5 mm acrylic cutout (Fig. 10d).
6. Once solder is cool, trim the battery connector legs flush with the PCB using wire cutters.
7. Lay out all of the internal acrylic structural components (Fig. 11a).
8. Thread the cable ties through the first 3 mm acrylic cutout (Fig. 11b).
9. Line up the square notch cutouts, place the second 3 mm acrylic layer over the battery, and thread the cable ties through (Fig. 11c).
10. Line up the square notch cutouts, place the third 3 mm acrylic layer with PCB assembly over the battery, and thread the cable ties through (Fig. 11d).



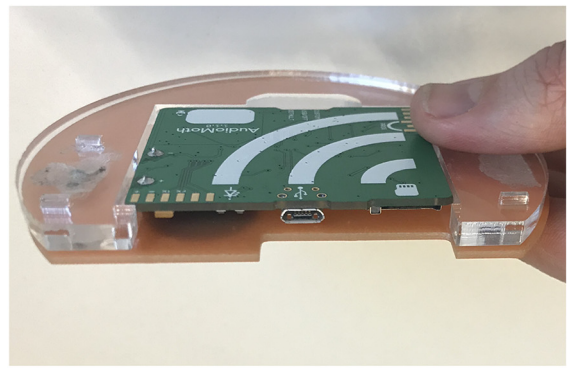
(a) Single pin connector



(b) 5mm acrylic sitting on top of 6V enclosure PCB



(c) Flipped AudioMoth PCB resting on workshop surface while glue is setting



(d) Complete PCB assembly used in the internal structure of the 6V enclosure

Fig. 10. Build steps for the PCB assembly of the internal structure.

11. Insert the battery while cable ties are loose and push the complete PCB assembly firmly over the battery and tighten the cable ties (Fig. 11d). Make sure to line up the battery connector pads and battery springs correctly.
12. To prepare the external enclosure to hold the internal structure place the printed drill jig into one end of the plugs (Fig. 12b).
13. Using the hot glue gun, glue the rectangle key into position (Fig. 12b). This is used to lock the internal structure into position.
14. Drill a 5 mm diameter microphone hole using the same printed jig as a guide (Fig. 12b).
15. Place double sided tape or hot glue onto the underside of the 3 mm acrylic rain hood and place over drill hole (Fig. 12c).
16. Insert and lock the internal structure into position making sure the microphone lines up with the drill hole. Place the acoustic vent on the outside of the enclosure over the drill hole.

6. Operation instructions

Fully illustrated operation instructions are available with this article. Maintained operation instructions can be found on the AudioMoth website (www.openacousticdevices.info). For up to date instructions visit (www.openacousticdevices.info/getting-started).

6.1. User instructions for firmware development

AudioMoth firmware is written in C and can be edited and compiled using the free Silicon Labs IDE, Simplicity Studio (www.silabs.com/products/development-tools/software/simplicity-studio). For detailed instructions on how to setup Simplicity Studio and create an AudioMoth project, visit the AudioMoth wiki at www.github.com/OpenAcousticDevices/



(a) Components of the internal structure for the 6V enclosure



(b) First 3mm acrylic layer showing how to thread the first cable tie



(c) Second 3mm acrylic layer showing how to thread the second cable tie



(d) Third 3mm acrylic layer combined with PCB assembly



(e) Push force on top of PCB assembly to thread cable ties



(f) Cable ties can be tightened during push force

Fig. 11. Build steps for the internal structure.



Fig. 12. Build steps for the outer enclosure.

[AudioMoth-Project/wiki/AudioMoth](https://github.com/audiomoth-project/wiki/AudioMoth). Firmware can be uploaded to the device by building the project and using the compiled '.bin' file via USB.

7. Validation and characterizations

In this section, we specify how to validate the correct build of the AudioMoth hardware and measure its performance. Since the hardware is built around a micro-controller, validation simply involves checking the functionality of the peripherals used. The peripherals include, the USB boot-loader, the USART SPI interface that communicates with the microSD card, the EBI, the op-amps and the ADC.

7.1. Boot-loader validation

To test the boot-loader, the Flash application (Section 3.2) can be used. Validation of the boot-loader is achieved through the following steps:

Table 6
Online operation instructions.

Operation instructions	Description	Location
Initial set-up	Instructions to use AudioMoth with Configuration App	www.openacousticdevices.info/setup-guide
Configuration App	Instructions to use just the Configuration App	www.openacousticdevices.info/config-app-guide
Flashing by USB	Instructions for programming AudioMoth via USB	www.openacousticdevices.info/flashing
Batteries	Instructions for purchasing batteries	www.openacousticdevices.info/batteries
SD cards	Instructions for purchasing microSD cards	www.openacousticdevices.info/sd-card-guide
LEDs	Description of LED flash meanings	www.openacousticdevices.info/led-guide

1. AudioMoth's micro-controller has a boot-loader pre-programmed at factory. When put into programming mode, a fully assembled AudioMoth will be recognized by a PC when plugged in via USB.
2. To put the device in programming mode the PROG pins must be shorted as the device is powered on. A metal paper clip can be used to do this.
3. While the PROG pins are shorted, the USB connector can be plugged into the device. The short on initial power up puts AudioMoth in boot-loader mode.
4. The Flash application (Section 3.2) can then be run to validate boot-loader functionality. For this test, start the 'Flashing by USB' instructions (Table 6) at step 6.
5. The device port number should return on the command line Flash application. Follow the rest of the 'Flashing by USB' instructions from step 6 to program the hardware with the 'AudioMoth-Firmware-Basic' firmware. If boot-loader has failed the flash application will return NULL, meaning either the PROG pins were not shorted correctly at start-up, or there is another hardware fault.

7.2. Peripheral validation

Validation of all other peripherals can be achieved by using a programmed AudioMoth to make a WAV file voice recording to microSD card. Voice recordings can help quickly identify hardware issues. For example, skips heard in the recorded voice indicate a slow SD card, or incorrect voice pitch indicate problems with sample rate. For validation, it is useful to download the free open-source, cross-platform audio software, Audacity (www.audacityteam.org/download) to view AudioMoth recordings. Validation of the peripherals is achieved through the following steps:

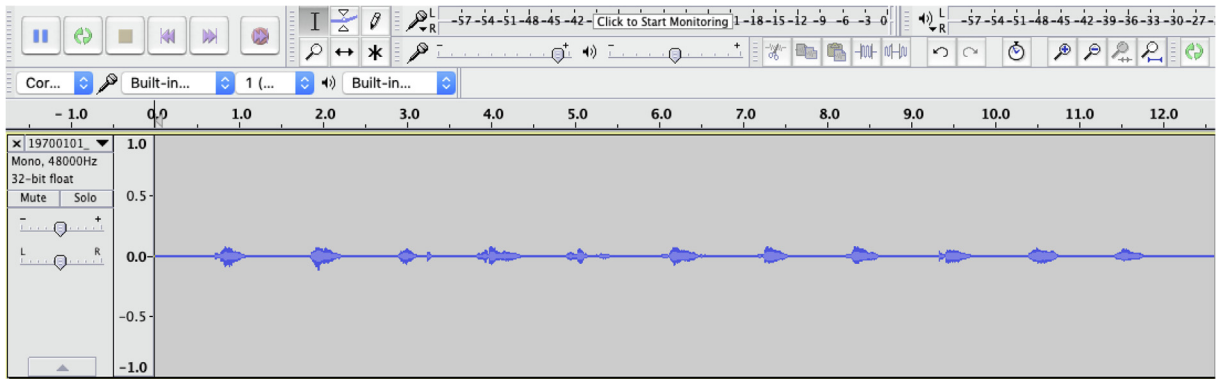
1. To record, insert batteries and set the switch to DEFAULT. The red LEDs should immediately start flashing to represent a recording is taking place. If both green and red LED flash together an SD card error has occurred.
2. Quietly count down from ten about 1 m from the AudioMoth device during the red LED flashes.
3. After the count down, the switch should be set back to USB to stop the recording.
4. The microSD card can now be taken out and inserted into the PC.
5. If the USART SPI peripheral is functioning correctly a WAV file should have been created, named '19700101_xxxx.WAV'.
6. To validate the functionality of the EBI, op-amps and ADC peripherals the playback of the counting sequence needs to be analyzed. The recording can be opened in Audacity.
7. Voice should be clearly heard without distortion during playback. Recordings can be viewed as a waveform showing amplitude against time (Fig. 13a), and also as a spectrogram, showing the spectrum of frequencies against time (Fig. 13c).

7.3. Measuring power

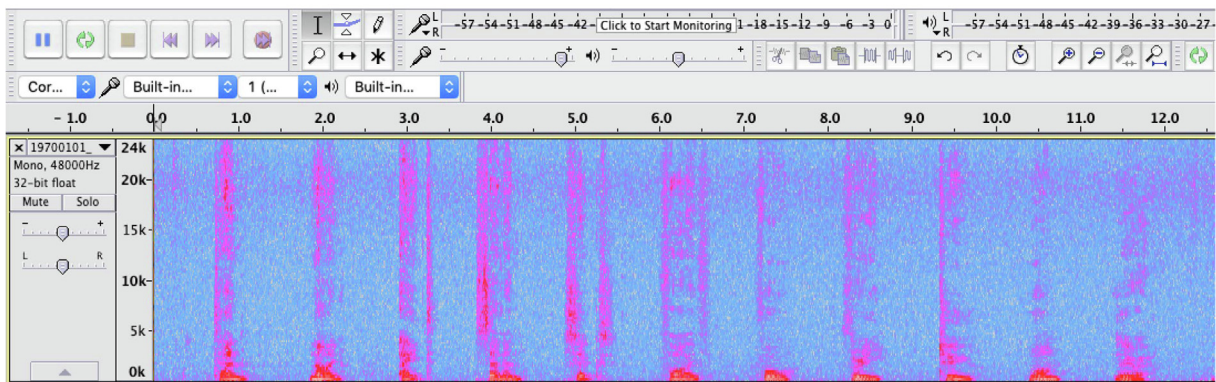
Keeping power consumption low is critical for long-term acoustic monitoring applications in remote areas. To measure the current consumption on AudioMoth, a Silicon Labs starter kit can be used (www.silabs.com/products/development-tools/mcu/32-bit/efm32-giant-gecko-starter-kit). Using the energy profiler application within the Simplicity Studio IDE, the starter kits VMCU pins on the external header can be used to power AudioMoth. For detailed instructions on how to use the Starter Kit for power measurements visit the following forum post: www.silabs.com/community/mcu/32-bit/knownledge-base.entry.html/2014/05/21/using_aem_to_measure-BdWl. AudioMoth consumes approximately 30uA while sleeping and draws 10 mA to 40 mA during recording, depending on sample rate. Table 7 shows how current changes with sample rate using the SanDisk Extreme 32 GB microSD card. These are guideline numbers as each model of micro SD card may draw different overall current during a recording.

8. Typical applications and deployments

Acoustic monitoring has multiple applications, including the monitoring of specific species [11–14], soundscape analysis [15–17], environmental surveillance [18,19], and as a hobby for wildlife enthusiasts [20]. Each application can change the requirements for hardware configuration. The most important sound characteristic to capture is the range of sound frequencies emitted by the target. To record the source frequency the sample rate must be at least twice the top end frequency pro-



(a) Audacity waveform view of voice countdown sequence



(b) Audacity spectrogram view of voice countdown sequence

Fig. 13. Validation of peripherals using Audacity.**Table 7**

Power consumption at varying sample rates during a recording to Sandisk Extreme PLUS 32 GB micro SD card.

Sample rate (Hz)	Recording current (mA)
8,000	10
16,000	12
32,000	13
48,000	14
96,000	17
192,000	25
256,000	30
384,000	40

duced by the target. Half the sample rate is called the Nyquist frequency, any sound above the Nyquist frequency will not be recorded. Sample rates must therefore be set to correspond to at least double the sound source in question. Hardware configuration guidelines for different applications and the corresponding source frequencies are shown in [Table 8](#).

The speed of SD card required depends on the sample rate used, with higher sample rates requiring higher SD card speeds. The speeds required for each application can be found in the last column of [Table 8](#). As well as source frequency, other device parameters can be adjusted for certain applications. The duty cycle routine and timed recording schedules can be matched for specific target activities. For example, bat echolocation calls are active at sunset. The duration of sound can be used to set a duty cycle routine, which saves the amount of power and memory required for each deployment. Sounds that are known to be frequently emitted, or to last longer can have larger sleep periods between each recording event. Short duration sounds, or sounds less frequently emitted will need smaller sleep periods. For night deployments or deployments prone to theft, indication LEDs can be turned off to prevent unwanted attention. Gain can be changed to adjust for different background noise levels during recordings. Generally, gain can be left at the default medium setting unless a high noise environment is known.

Table 8

Example configuration parameters for acoustic monitoring applications using AudioMoth with 3Ah capacity AA-cell lithium batteries and a Sandisk Extreme 32 GB microSD card.

Application	Source	Sample rate	Schedule	Sleep time	Record time	LEDs	Gain	Battery life	Total data captured	Swap SD every:	SD speed
Soundscape	20–20 kHz	48 kHz	00:00 to 24:00	0s	3600s	On	Med	9 days	64 GB	4 days	Class 10
Bird	1 kHz–10 kHz	32 kHz	06:00 to 09:00	0s	3600s	On	Med	75 days	49 GB	48 days	Class 10
LF Bat	20 kHz–50 kHz	192 kHz	18:00 to 22:00	2s	10s	Off	Med	35 days	153 GB	7 days	U3
HF Bat	50 kHz–120 kHz	384 kHz	18:00 to 22:00	2s	10s	Off	Med	22 days	193 GB	3 days	U3
Chainsaw	100 Hz–1 kHz	8 kHz	00:00 to 24:00	300s	30s	Off	Med	115 days	14 GB	none	Class 4

If this is the case gain should be lowered accordingly to prevent audio clipping or distorting. Sample rates, time schedules, duty cycle routines, LED function and gain can all be set using the Configuration App. Battery life often outperforms memory capacity when using a 32 GB SD card; the penultimate column shows how often the memory card should be swapped during the life cycle of one set of 3Ah batteries.

9. Deployment instructions

The deployment of battery powered devices is an important, and often problematic, part of acoustic monitoring in remote locations. Before deploying AudioMoth, first it must be configured with the appropriate recording schedules and acoustic parameters to perform its task. The battery and memory consumption predictions should be recorded to estimate battery life, this can be used to plan a collection schedule to replace batteries and memory cards. Before placing devices in the pre-built enclosures the switch must be put into CUSTOM mode.

9.1. AA Enclosure

1. Thread cable ties through the drill holes on the back acrylic layer of the enclosure.
2. Attach the cable ties around a 200–400 mm wide tree trunk, branch or pole.
3. Deploy above head height to avoid the reach from grazing animals.
4. Return to device at the collection schedules given to you by the Configuration App. Replace batteries and SD cards as necessary,
5. It is important to recycle old batteries at your nearest recycling center and not to leave old batteries in the field.

9.2. 6 V Enclosure

1. The 6 V battery enclosure requires two people to deploy a single device. The device can be deployed using a hammer and nails, or with cable ties to prevent damage.
2. Thread one cable tie or nail through the top drill hole on the 110 mm socket clip.
3. Attach the cable tie around a large tree trunk and tighten the socket clip into position or hammer the first nail into position. Place above head height to avoid visual detection for long deployments.
4. Get a second person to hold the 6 V enclosure inside the socket clip.
5. Thread the second cable tie or nail through the bottom drill hole on the 110 mm socket clip.
6. While the 6 V enclosure is held in position by person two, person one should tighten the second cable tie around the tree trunk, or hammer the second nail to keep the enclosure in place (Fig. 12d).
7. Return to device at the collection schedules given to you by the Configuration App. Replace batteries and SD cards as necessary,
8. It is important to recycle old batteries at your nearest recycling center and not to leave old batteries in the field.

10. Conclusion

In this paper we have described the hardware design of the AudioMoth acoustic logger. We have given instructions on the location of its open-source design files, the construction of two enclosures to house the PCB, validation processes required after hardware assembly and guidelines on how to deploy the final working product. AudioMoth can be used for many different acoustic monitoring applications, such as monitoring ultrasonic bat calls, and audible wildlife vocalizations. AudioMoth's low cost, small size, low power operation and simple construction increases the scalability of deployments in remote areas. This enables bigger conservation research questions to be answered than has been possible up to now with conventional acoustic technology.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.ohx.2019.e00073>.

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