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

Andrew P. Hill, Peter Prince, Jake L. Snaddon, C. Patrick Doncaster, Alex Rogers

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Authors: Andrew P. Hill, Peter Prince, Jake L. Snaddon, C. Patrick Doncaster, Alex Rogers

Affiliations: University of Southampton, Oxford University

Contact email: ah1u14@soton.ac.uk

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 (PCB), micro-controller and a micro-electro-mechanical systems (MEMS) 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.

Keywords: Acoustic monitoring, audible and ultrasonic capability, conservation technology, soundscape monitoring, wildlife monitoring

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]. Traditionaly PAM is performed using commercial devices, such as the SongMeter 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, 6, 7, 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 AudioMoth[1]: 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 x 48 x 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 (Figure 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 (Figure 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].

Figure 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

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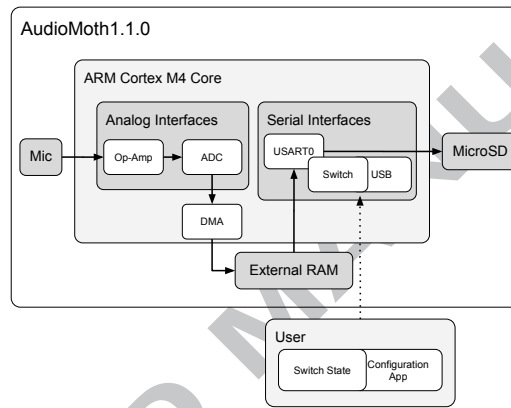[1]The device is a revision on a previous model of acoustic logger, AudioMoth1.0.0 (`www.openacousticdevices.info`). The revision, AudioMoth1.1.0 has improved power management and robustness for outdoor field deployments, using custom built or off-the-shelf enclosures.
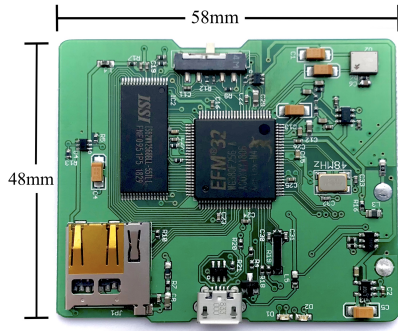
(a) AudioMoth component view

(b) AudioMoth silkscreen view

(c) Hardware Overview

Figure 1: AudioMoth

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.

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 (8kHz sample rate); audible wildlife, such as bird, insect or frog vocalization

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(48kHz sample rate); and ultrasonic wildlife, such as bat or amphibian calls (384kHz 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 2).

Table 2: List of design files available

Design filename	File type	Open source license	Location of the file
Hardware	PCB design zip file	CC BY 4.0	Available with the article
Firmware	Binary file	CC BY 4.0	Available with the article
Applications	Downloads in zip file	CC BY 4.0	Available with the article
AA enclosure	CAD zip file	CC BY 4.0	Available with the article
6V enclosure	CAD zip file	CC BY 4.0	Available with the article

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 3.6V - 20V DC supply. This power supply connects to a regulator that converts the DC supply to a stable 3.3V, or alternately the device can be supplied by 5V 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 disconnects the supply power when the USB is connected. The power circuitry also has digital noise isolation that uses a series resistor and ferrite bead to isolate the analog audio circuitry from the digital transmission lines (Figure 2).
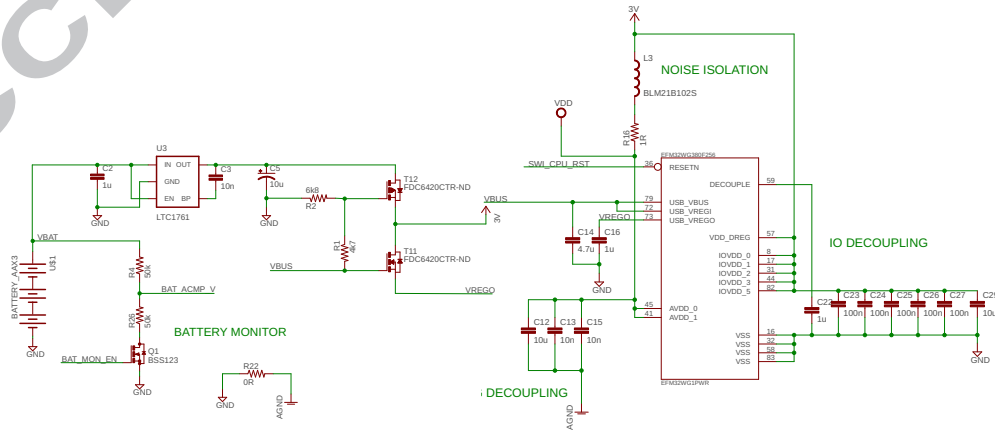

Figure 2: Power schematics

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(a) Audio circuitry schematics

(b) Microphone cascaded inverting operational amplifier

Figure 3: Microphone and analog amplification circuitry

The audio circuitry begins at the microphone input, which is routed directly to the micro-controllers analog peripherals (Figure 3a). Inside the pre-amp block, two on-board op-amps create a cascaded inverting amplifier that can be controlled by the supporting software for gain setting adjustments (Figure 3b). A low noise DC voltage is generated from an external voltage reference chip to create a stable bias voltage that feeds into the positive inputs of both op-amps.

The micro-controller links to an external SRAM chip, which expands on the internal RAM resources. The external SRAM interfaces with the micro-controller using an external bus interface (EBI) (Figure 4). Direct memory access (DMA) allows the device to sleep in low energy modes while data is sampled and routed between the analog interface and the external SRAM chip. The SRAM chip is split into an eight element circular buffer in firmware. This buffer structure allows acoustic data to fill in contiguous elements. When a set of elements have filled with a sufficient number of acoustic samples, the micro-controller wakes up to store those elements to microSD card. This is done while simultaneously filling the next element, thus allowing a continuous stream of audio to be recorded to storage. Only secure digital high-capacity (SDHC) microSD cards, formatted to FAT32, are compatible with AudioMoth. SD cards over 32GB in capacity may require explicit reformatting to FAT32 to function correctly.
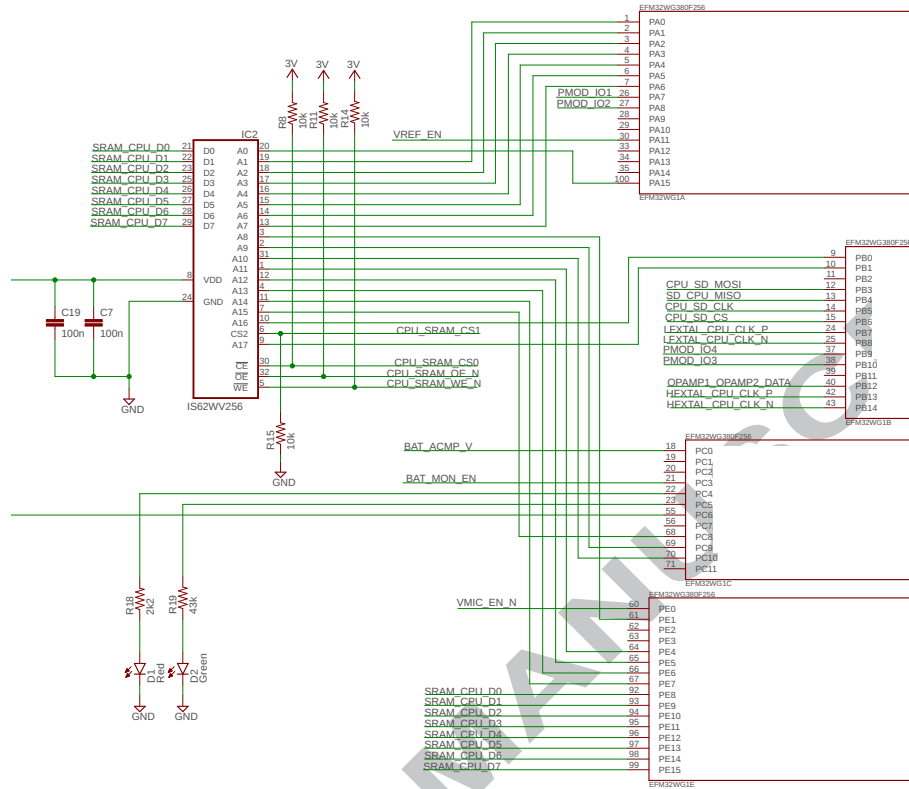
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Figure 4: SRAM schematic

The user interface is arranged on the bottom layer of the PCB layout (AudioMoth1-1-0.brd), with all external peripherals marked with clear silkscreen annotations (Figure 5a). These annotations include switch positions, USB port, microSD card port, LED locations, expansion header pin functions and programming header locations. Users interface with the physical hardware via the switch, which is used to define different operation modes. The USB port is used to upload configuration settings from a cross-platform configuration application, where recording schedules and audio requirements can be set from an intuitive GUI. The LED's, which can be viewed from the side of the device, provide feedback to the user as to what state the device is in (www. openacousticdevices.info/led-guide), the microSD card port allows the user to save and transfer audio recordings. The expansion port provides an interface for the potential development of external modules. Figure 5a displays the micro-controller pin numbers associated with the header pins. These numbers can be used to create expansion firmware for AudioMoth. The GPIO pins, tx and rx, connect to the micro-controller's universal asynchronous receiver/transmitter (UART) peripheral on pins B9 and B10. Example modules for potential expansion using UART include GPS (www.adafruit.com/product/746) and wireless commutation transmitter/receiver modules (www.pycom.io/product/lopy4/) for internet of things (IoT) applications.
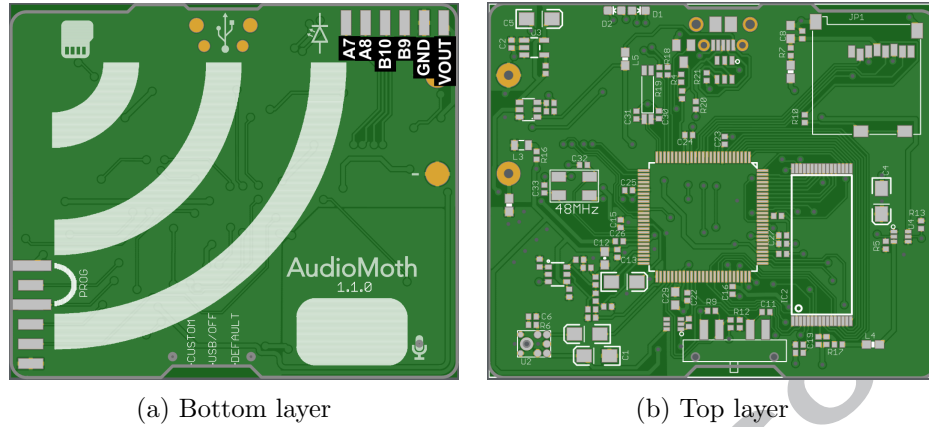
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(a) Bottom layer   (b) Top layer

Figure 5: AudioMoth PCB Layout

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 (Figure 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 hrs, any recording duration less than 12 hrs, and LED's can be enabled or disabled. After configuration, the application calculates and displays the daily memory and battery consumption. The Time App enable 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 3 presents the software source locations.
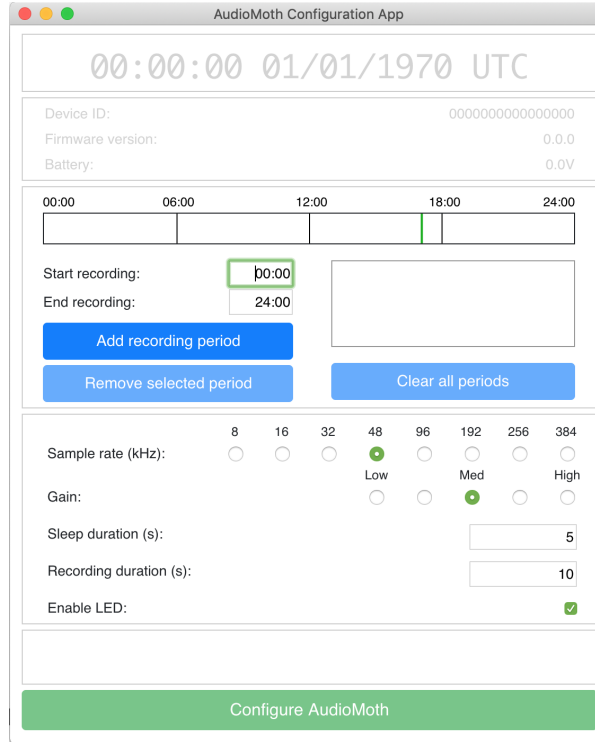
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Figure 6: Configuration App

Table 3: Source code location

Software	Description	Location
Flash	A command line tool to program AudioMoth	www.github.com/OpenAcousticDevices/ Flash
AudioMoth-Firmware-Basic	Standard firmware for AudioMoth	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

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 (Figure 7a) use 5mm acrylic and the two middle layers (Figure 7b) use 10mm acrylic. Neoprene gaskets (Figure 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 can be found at www.openacousticdevices.info/support/enclosures.

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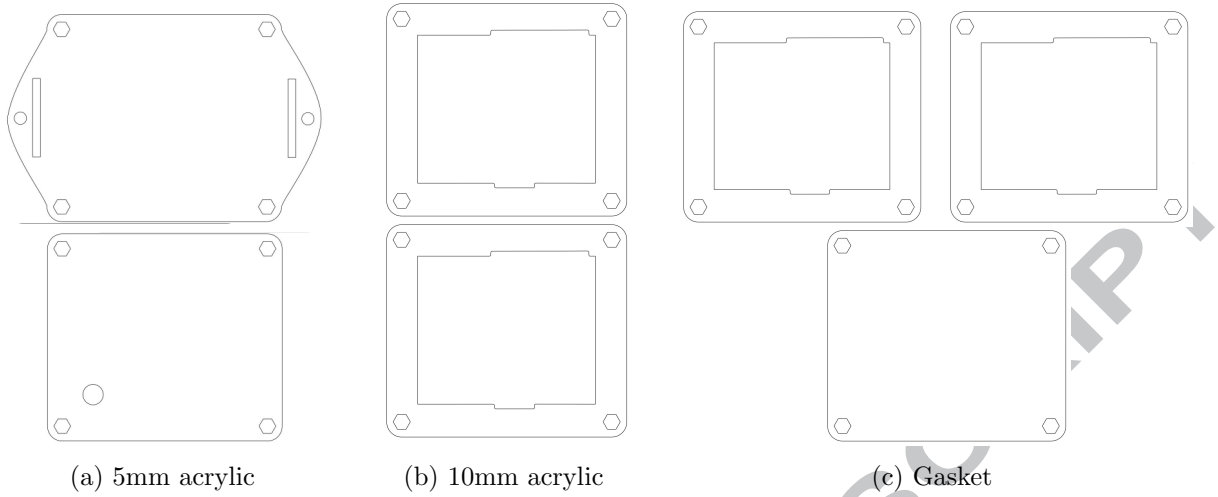(a) 5mm acrylic   (b) 10mm acrylic   (c) Gasket

Figure 7: AA battery enclosure design files

The second case design is located in the '6V enclosure' zip 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 6V 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 6V battery. Most of the internal structure uses 3mm acrylic (Figure 8a) held together by cable ties. The internal structure is designed to fit within common industrial 110mm diameter coupling drain pipes. One 5mm piece of acrylic is used to hold AudioMoth flush against the internal drain pipe plug end (Figure 8b). Figure 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 figure 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.
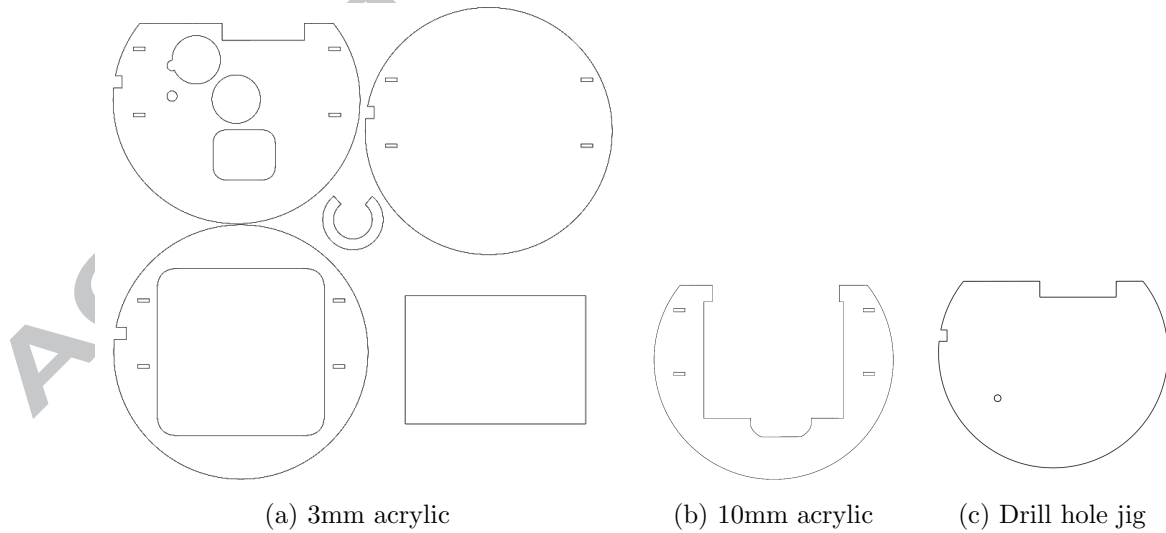

(a) 3mm acrylic   (b) 10mm acrylic   (c) Drill hole jig

Figure 8: 6V lantern battery enclosure design files

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4. Bill of materials

The bill of materials are split into the AudioMoth hardware and two version of custom enclosure, the AA battery operated version and the 6V battery operated version. Table 4 includes unit pricing to purchase components sufficient to build a single device or a batch of 1000. Batch ordering components and PCBs in this way results in a larger cost saving per device.

Table 4: AudioMoth bill of materials

Designator	Component	Qty/unit	Batch of 1 (USD)	Batch of 1k (USD)	Source	Material
Y2	ABM3B-48.000MHZ	1	1.09	0.57	Digi-Key	Electronics
C10 C11 C16 C2 C22 C38 C39 C40 C6	04026D105KAT2A	9	2.88	0.5	Digi-Key	Electronics
C13 C15 C3 C35 C36 C37	0402YC103KAT2A	1	0.1	0.01	Digi-Key	Electronics
Y1	ECS-.327-7-38-TR	1	0.73	0.43	Digi-Key	Electronics
IC2	IS62WV2568BLL	1	2.21	1.68	Digi-Key	Electronics
U2	SPM0408LE5H-TB	1	2.74	1.44	Digi-Key	Electronics
C1	T491A104M035AT	1	0.52	0.15	Digi-Key	Electronics
C34 C4 C5 C9	T491A106K010AT	4	1.76	0.34	Digi-Key	Electronics
U3	LT1761ES5-3.3	1	2.44	1.20	Digi-Key	Electronics
D1	LTST-C190CKT	1	0.33	0.06	Digi-Key	Electronics
U1	MAX6070BAUT18+T	1	2.16	0.99	Digi-Key	Electronics
J1	1050170001	1	0.91	0.50	Digi-Key	Electronics
L2 L4	BLM18HG601SN1D	2	0.38	0.11	Digi-Key	Electronics
L5	BLM18SG221TN1D	1	0.14	0.04	Digi-Key	Electronics
L3	BLM21BD102SN1D	1	0.17	0.05	Digi-Key	Electronics
C30 C31	GRM1555C1H7R5CA01D	2	0.2	0.02	Digi-Key	Electronics
C14	GRM155R60J475ME87D	1	0.19	0.03	Digi-Key	Electronics
SW1	CSS-1310TB	1	0.63	0.42	Digi-Key	Electronics
U11	IP4220CZ6F	1	0.44	0.13	Digi-Key	Electronics
Q1	BSS123LT1G	1	0.31	0.06	Digi-Key	Electronics
T1	FDC6420C	1	0.68	0.25	Digi-Key	Electronics
R18	ERJ-2GEJ222X	1	0.1	0.01	Digi-Key	Electronics
R9	ERJ-2GEJ274X	1	0.1	0.01	Digi-Key	Electronics
R12	ERJ-2RKF1003X	1	0.1	0.01	Digi-Key	Electronics
R1	ERJ-2RKF4701X	1	0.1	0.01	Digi-Key	Electronics
R26 R4	ERJ-2RKF5102X	2	0.2	0.02	Digi-Key	Electronics
R2	ERJ-2RKF6801X	1	0.1	0.01	Digi-Key	Electronics
R22	ERJ-3GEY0R00V	1	0.1	0.01	Digi-Key	Electronics
C32 C33	CL05C180JB5NNNC	2	0.01	0.2	Digi-Key	Electronics
C12 C29 C8	CL10A106KP8NNNC	3	1.08	0.21	Digi-Key	Electronics
IC1	EFM32WG380F256	1	5.48	4.63	Digi-Key	Electronics
R6	CRG0402ZR	1	0.1	0.003	Digi-Key	Electronics
R10 R11 R13 R14 R15 R3 R5 R8	CRCW040210K0FKED	8	0.8	0.04	Digi-Key	Electronics
U4 U5	SI1967DH-T1-E3	2	0.96	0.35	Digi-Key	Electronics
D2	150060GS75000	1	0.14	0.10	Digi-Key	Electronics
JP1	693071010811	1	2.92	2.06	Digi-Key	Electronics
C19 C20 C23 C24 C25 C26 C27 C7	CC0402KRX7R6BB104	8	0.8	0.06	Digi-Key	Electronics
R19	RC0402FR-0743KL	1	0.1	0.003	Digi-Key	Electronics
R20 R21	RC0402JR-071RL	2	0.2	0.01	Digi-Key	Electronics
R16 R17 R23 R24 R25 R7	RC0402JR-071RL	6	0.6	0.02	Digi-Key	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 32GB	1	9.55	8.50	bulkmemory cards.com	Memory
	Total for 1 unit		53.34	25.74		

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Table 5: AA enclosure bill of materials

Designator	Component	Qty	Unit	Total (USD)	Source of materials	Material
U1	Keystone 2464	1	1.58	1.58	Digi-Key	Electronics
Hex Spacer	HTSB-M3-30-5-1	4	0.38	1.52	RS 280-8913	Casing
Thumb Screw	KSUH NO.1 M3X6 White	8	0.14	1.12	RS 280-8913	Casing
5mm Acrylic 300mm x 200mm	AC.CLR0000.05.3020	1	3.77	3.77	Hobarts	Casing
10mm Acrylic 300mm x 200mm	AC.CLR0000.10.3020	1	6.88	6.88	Hobarts	Casing
AABattery	Energizer L91	3	1.71	5.14	Amazon	Battery
Cable Tie	111-05260	2	0.12	0.24	RS online	Casing
			Total	20.25		

Table 6: 6V lantern enclosure bill of materials

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

5. Build instructions

This section describes the build instruction for the PCB and two waterproof enclosures for outdoor deployments. The AA battery enclosure is to be used for deployments requiring less battery capacity and the 6V battery enclosure is to be used for deployments requiring large battery capacity.

5.1 AudioMoth PCB

The bare PCB or the assembled PCB can be acquired by uploading the bill of materials (Table 4) and the 'Hardware' design files, or generated Gerbers to any PCB assembler. PCB assemblers usually charge a tooling setup cost, ranging from 200 USD to 1000 USD to place components. Ordering small batches of assembled devices from PCB assemblers is not recommended due to this high setup cost. Manually assembly from the bare board would be more cost effective. However, the components would need to be soldered by hand. Manually soldering components takes approximately 4 hours per board. In terms of both cost and time, the most effective route to acquire an AudioMoth is through group purchase websites, such as www.groupgets.com/manufacturers/open-acoustic-devices/products/audiomoth. This acquisition route delivers assembled and

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programmed AudioMoths for a fixed unit cost of 49.99 USD. If not assembled, the components can be placed using the following instructions:

1. Sort the AudioMoth bill-of-materials into labelled component bins (Table 4).

2. Solder components to their silkscreen designator locations, which are displayed on the PCB bottom layer (Figure 5b). Most components can be soldered using a soldering iron. For components smaller than '0402' sized passives such as Y2 and U2, a heat gun, or oven should be used. Solder paste and a stencil can help with manual assembly using an oven.

List of equipment

- For soldering PCB (if not pre-assembled)
  Soldering iron or oven/heat gun
  Solder/solder paste
  Tweezers
  Flux pen
  Flux off
  Alcohol PCB cleaner

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:

1. Place two small dabs of hot glue on the top layer PCB as shown in Figure 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 5) 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 (Figure 9c).

6. Place the first 5mm 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 10mm 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 10mm acrylic cutout through the four hex spaces, with the SD and USB protrusion located in the top left corner.

11. 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.

12. Place the configured AudioMoth inside the acrylic case so the SD card lines up with the protrusion in the 10mm acrylic cutouts.

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

(b) Constructed AA enclosure

(c) Components of AA enclosure

Figure 9: AA enclosure build steps

13. Place the final 5mm acrylic sheet on top of the enclosure and make sure the drill hole lines up with the microphone.

14. Screw up the four top thumb screws (Figure 9b).

15. Turn over and screw the last four thumb screws into the bottom of the enclosure.

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16. Firmly screw up all thumb screws and stick the acoustic vent over the microphone hole.

17. Thread the cable ties through the drill holes on the back acrylic layer.

List of equipment

- For enclosure build

    Laser cutter

    Hot glue gun

    Hot glue sticks

    Wire cutters

    Expanded neoprene gaskets from recommended distributor

   *5mm and 10mm acrylic sheets from distributor, pre-cut or in sheets*

5.3 6V battery enclosure

The 6V 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 6V battery to power the device. The additional PCB can be acquired by uploading the '6V 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 6V batteries having a capacity of 24Ah (`http://data.energizer.com/pdfs/529.pdf`). The 6V battery must have two-spring connectors and not the screw post terminals.

The enclosure is ruggedized and waterproof for hostile deployments. The 110mm 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 (Figure 10a).

2. Place and lineup the 5mm acyclic cutout over the 6V enclosure PCB (Figure 10b).

3. Place two small dabs of hot glue on the top layer PCB as shown previously in Figure 9a, making sure not to glue on top of any components

4. While the glue is still hot, place the AudioMoth PCB onto the 6V enclosure PCB and flip the assembly over so the AudioMoth PCB sits flush with the workshop surface (Figure 10c).

5. Once the glue has cooled, solder the AudioMoths power pins to the 6V enclosure PCB keeping the AudioMoth PCB bottom layer flush with the top of the 5mm acrylic cutout (Figure 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 (Figure 11a).

8. Thread the cable ties through the first 3mm acrylic cutout (Figure 11b).

9. Line up the square notch cutouts, place the second 3mm acrylic layer over the battery, and thread the cable ties through (Figure 11c).
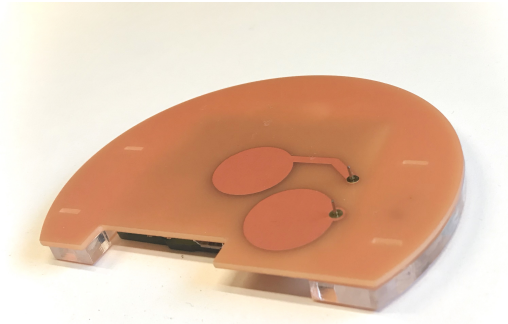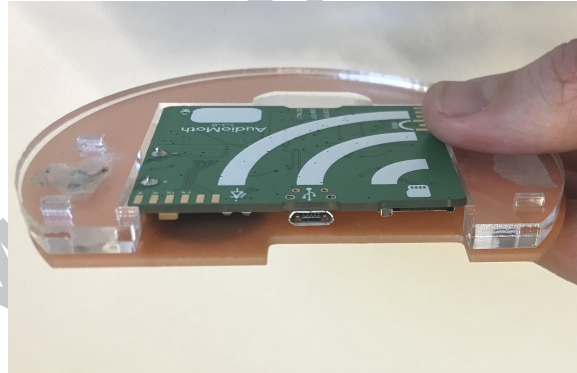
14
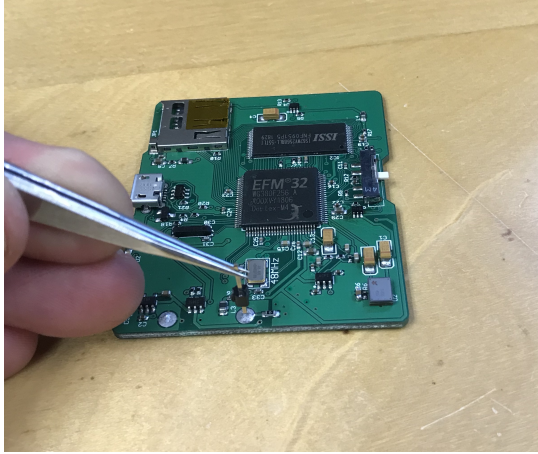
(a) Single pin connector
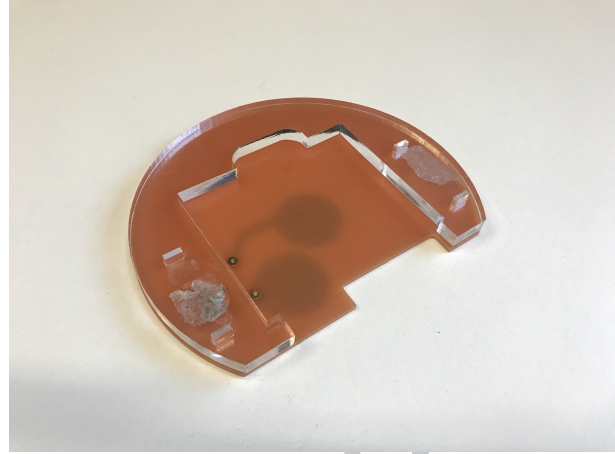
(b) 5mm acrylic sitting on top of 6V enclosure PCB

(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

Figure 10: Build steps for the PCB assembly of the internal structure

10. Line up the square notch cutouts, place the third 3mm acrylic layer with PCB assembly over the battery, and thread the cable ties through (Figure 11d).

11. Insert the battery while cable ties are loose and push the complete PCB assembly firmly over the battery and tighten the cable ties (Figure 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 (Figure 12b).

13. Using the hot glue gun, glue the rectangle key into position (Figure 12b). This is used to lock the internal structure into position.

14. Drill a 5mm diameter microphone hole using the same printed jig as a guide (Figure 12b).

15. Place double sided tape or hot glue onto the underside of the 3mm acrylic rain hood and place over drill hole (Figure 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.

(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

Figure 11: Build steps for the internal structure

(a) Components of the outer 6V enclosure

(b) Aligning drill hole and acrylic locking rectangle with printed jig

(c) Rain hood over drill hole

(d) Deployed 6V enclosure

Figure 12: Build steps for the outer enclosure

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`).

Table 7: 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

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/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:

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 7) 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.
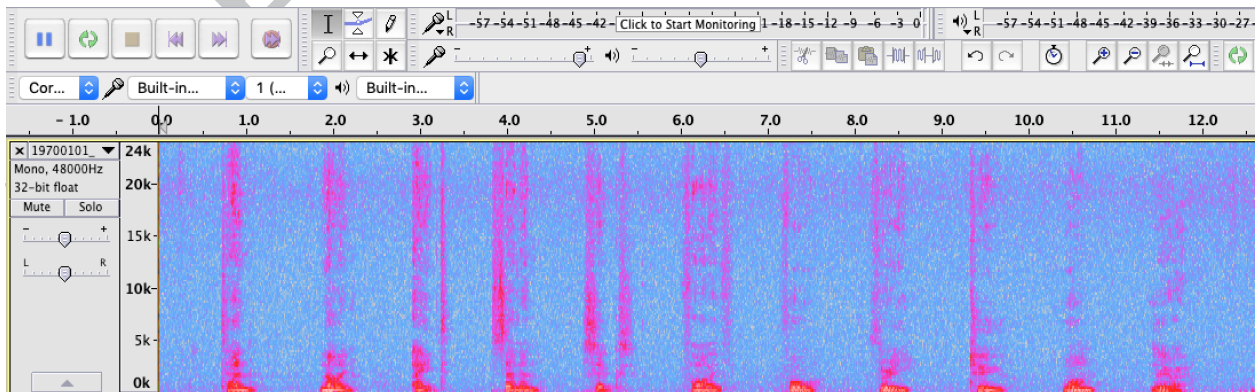
7.2 Peripheral validation

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 1m from the AudioMoth device during the red LED flashes.
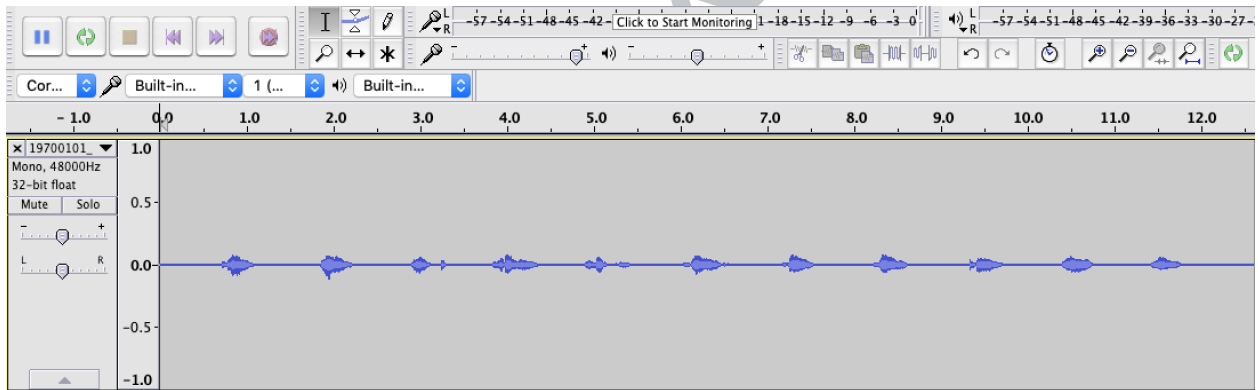
(a) Audacity waveform view of voice countdown sequence

(b) Audacity spectrogram view of voice countdown sequence

Figure 13: Validation of peripherals using Audacity

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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 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 (Figure 13a), and also as a spectrogram, showing the spectrum of frequencies against time (Figure 13b).

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/knowledge-base.entry.html/2014/05/21/using_aem_to_measure-BdWl`. AudioMoth consumes approximately 30uA while sleeping and draws 10mA to 40mA during recording, depending on sample rate. Table 8 shows how current changes with sample rate using the SanDisk Extreme 32GB microSD card. These are guideline numbers as each model of micro SD card may draw different overall current during a recording.

Table 8: Power consumption at varying sample rates during a recording to Sandisk Extreme PLUS 32GB 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

8. Typical applications and deployments

Acoustic monitoring has multiple applications, including the monitoring of specific species [11, 12, 13, 14], soundscape analysis [15, 16, 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 produced 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 9.

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 9. 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. 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 32GB SD card; the penultimate column shows how often the memory card should be swapped during the life cycle of one set of 3Ah batteries.

Table 9: Example configuration parameters for acoustic monitoring applications using AudioMoth with 3Ah capacity AA-cell lithium batteries and a Sandisk Extreme 32GB microSD card

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

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 200-400mm 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 6V Enclosure

1. The 6V 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 110mm 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 6V enclosure inside the socket clip.

5. Thread the second cable tie or nail through the bottom drill hole on the 110mm socket clip.

6. While the 6V 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 (Figure 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.

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Declaration of interest: none

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192kHz- 96kHz- 48kHz- 24kHz- 0Hz-

Hardware description

Hardware build instructions

Validation tests

Enclosure build instructions

Low-cost acoustic monitoring