UNIVERSITY OF SOUTHAMPTON

FACULTY OF PHYSICAL SCIENCES AND ENGINEERING

Electronics and Computer Science

Low-cost, open source acoustic sensors for conservation

by

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ABSTRACT

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Biodiversity data-gaps must be better understood to inform conservation policy. Scalable technology, such as camera traps and satellite imaging, have been shown to increase coverage. This research explores the field of acoustic monitoring, which although long-established, has struggled to scale effectively due to cost, usability and power inefficiency of existing equipment. This research aims to investigate whether creating an advanced, power-efficient and low-cost acoustic hardware solution can expand coverage.

User-centred design principles and aspects of the collaborative economy are adopted in order to design a fit-for-purpose solution to scalability. The hardware design takes inspiration from the utilitarian construction of single-board computers and exploits the recent availability of advanced smartphone and *Internet of Things* technology. The resulting open source device, *AudioMoth*, is described, in which the baseline levels of performance improve on existing tools, with better power efficiency, miniature overall dimensions, reduced material cost, and the ability to capture audible and ultrasonic sound simultaneously.

Open source hardware, however, imposes barriers to entry for non-technical users such as conservation practitioners. To improve access, it is necessary to remove the do-it-yourself nature of construction while remaining low-cost and flexible to adapt. Barriers can be overcome using new collaborative methods of consumption, where crowds can accumulate funds to bulk manufacture and automate hardware assembly with an economy of scale.

A collaborative management framework is proposed, in which guidelines enable users to acquire fully assembled open source hardware from crowdfunding opportunities. The framework is applied to *AudioMoth*, permitting individual devices to be acquired ready-to-use for $49.99 with approximately 8,000 delivered to date. This general system has provided conservation practitioners with access to an adaptable hardware solution, thus expanding the coverage of monitored biodiversity. Conservation policy should consider user-centred design in all new technical innovations and further explore the work outlined in this thesis, thereby allowing those communities outside of the pockets of wealth and high opportunity to monitor biodiversity at low cost.

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Nomenclature

A	Amp
ADC	analog to digital converter
Ahr	amp hours
CAD	computer aided design
CPU	central processing unit
CSS	cascading style sheets
DAC	digital to analog conversion
dB	decibel
dBA	A-weighted decibel
dBV	decibel volt
DC	direct current
DIY	do-it-yourself
DMA	direct memory access
EBI	external bus interface
exFAT	extended file allocation table
FOV	field-of-view
g	gram
GPIO	general purpose input and output
GPS	global positioning system
GUI	graphical user interface
HCI	human-computer interaction

hr hour

HTML hypertext markup language

Hz Hertz

IC integrated circuit

ID identification number

IDE integrated development environment

IoT Internet of Things

IP intellectual property

IR infra-red

ISO International Standards Organisation

LCD liquid-crystal display

LED light emitting diode

MEMS microelectromechanical systems

mm millimetre

MOSFET metal-oxide-semiconductor field-effect transisitor

NGOs non-government organisations

NOCMIG nocturnal migration

OSH open source hardware

PCB printed circuit board

PDM pulse density modulated

PIR passive infra-red

PROG Programming pins

PWM pulse width modulation

RAM random access memory

RTC real time counter

rx receive

SD secure digital

SDIO secure digital input output

SNR signal to noise ratio

SPI serial peripheral interface

SPL sound pressure level

SRAM static random access memory

tx transmit

UART universal asynchronous receive and transmit

UCD user-centred design

ULP ultra-low-power

USB universal serial bus

USD US dollar

V volt

VMCU micro-controller voltage

WEEE waste electric and electronic equipment

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Many thanks go to my fiancée Ruby for her enthusiasm and willingness to support my work, some of which saw her trek the rainforest, become a documentary filmmaker, manually assemble devices in the field and sacrifice her *Ford Fiesta* for yearly off-road deployments in the New Forest. I thank Ruby and my family for their patience and support throughout this PhD.

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"Operational efficiency in association with the conservation of energy"

Gregory Francis Hill (1949 - 2015)

Declaration of Authorship

I, Andrew Peter Hill, declare that the thesis entitled *Low-cost, open source acoustic sensors for conservation* and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- parts of this work have been published as specified in Section 1.4

Signed:l

Date:

Chapter 1

Expanding the coverage of monitored biodiversity

Over the last century, a combination of climate change, anthropogenic land use and wildlife overexploitation have profoundly damaged the complex environmental factors that shape global environmental health (Newbold et al. 2015, Garcia et al. 2014). Subsequently, a declining wildlife population (Barrett et al. 2018, Díaz et al. 2019) and an escalating global warming effect have been observed (Hansen et al. 2005). Environmental trends such as these are observed by capturing environmental data points at regular intervals over time. The data points are often collected by experts, using automated scientific equipment, which combine to create global datasets that can be modelled to provide reliable diagnostic evidence. For negative environmental impacts, evidence-informed policy can be implemented to prevent further damage. In 2016 for instance, the Paris Agreement enforced new climate policies to prevent a future predicted temperature rise of more than 2 ℃, which was supported by captured historical global temperature and CO_2 trends (Schleussner et al. 2016).

An environmental factor now of critical priority to the global economy and international food security is biodiversity (Mace et al. 2018, Chaplin-Kramer et al. 2019). Biodiversity generally refers to the variety and abundance of species in the world. Its richness is shown to positively correlate with a stable climate and its recent unprecedented rates of decline are having major impacts on climate regulation, pollination, agriculture, air and water quality (Hooper et al. 2012). Since 1970, an unprecedented 60% fall in species abundance was observed from the monitoring of 4,005 species (Grooten and Almond, 2018). However, monitoring biodiversity is complex and unlike climate data, is severely underrepresented. There are over 7 million species worldwide and each species requires varied methodologies for their measurement. The majority are monitored at local scale, often by individuals devoted to just a single species. Generally, it is the bigger terrestrial mammals that are recorded, meaning the other species, such as marine life, rodents, insects, amphibians, birds, reptiles and plants are neglected. Hence, it is suggested that a radical 86% of global terrestrial species and 91% of global marine species are undiscovered, with a further 99.99% still unmonitored (Mora et al. 2011).

Traditional biodiversity monitoring is manually performed by experts, typically using specialist bio-monitoring techniques to physically collect data from the ground. These techniques can be intrusive to wildlife, expensive to execute and slow to perform (Artiola et al. 2004). Increasingly, more surveys are adopting new technology to address these issues. Examples include commercial automated equipment, such as camera traps that take snapshots of animals with infra-red triggers; bio-telemetry devices that attach to animals and record their behaviour or monitor their health (Cooke et al. 2004); aerial satellites that take birds-eye-view snapshots of large habitats over time (Morgan et al. 2010); and acoustic monitoring devices that lay static in an ecosystem for several days recording animal vocalisations (Browning et al. 2017). All of these tools are beneficial, as they reduce the human capacity needed to record biodiversity at larger scales, while also improving the scientific rigour and reducing human bias compared to traditional monitoring methodologies. Despite the benefits, however, commercial scientific measuring equipment is expensive. For individual researchers studying at local scale, cost is often the limiting factor for monitoring projects (James et al. 1999), especially for those in developing countries, which are often located in regions most affected by biodiversity loss.

To achieve broader participation in large-scale and long-term ground-level field surveys, developing alternatives to commercial tools is critical (Rose et al. 2018). Thus, technology for monitoring the environment has seen a shift towards the *do-it-yourself* (DIY) culture thanks to the *physical computing* – the study of how humans physically interact with electronic systems – and *open source* movements over the last decade (Kling, 2018). Originally aimed at reducing the barriers to entry when designing or programming interactive electronics, physical computing started its life using open source embedded micro-controller development boards, such as *Arduino*. These computationally restricted boards implement simplified programming languages to enable scientists with basic electronics knowledge to rapidly develop affordable specialist sensors for themselves (Pearce, 2014, Kwok, 2017). The open source aspects of these boards refer to their intellectual property, design principles, and legality of the freely available software and hardware design files. Design files consist of circuit board schematics, circuit board layout files, and the software source code that together permit construction and programming of a piece of electronic hardware. The open source initiative makes it possible to generate a community of collaborative users, it also provides transparency, allowing full public scrutiny of designs to the benefit of their scientific integrity. These benefits enable open source single-board computers to colonise niches in technology markets previously unreachable by models based on the protection of intellectual property (Hsing, 2018). In 2012 the combination of these movements prompted the development of *Raspberry Pi* (Richardson and Wallace, 2012), which further simplified user interaction by moving away from micro-controller technology towards computing on a full *Linux* operating system. Due to the speed and simplicity of prototyping with *Raspberry Pi*, they have become the go-to platform for electronic product development and even commercial products themselves[1].

In conservation biology – a broad field of biodiversity management, aiming to protect species, habitats, and ecosystems (referred to hereon in as "conservation") – *Raspberry Pi* computers are commonly adapted to create low-cost alternatives to commercially available scientific measuring equipment. A commonly applied use of Raspberry Pi is in the monitoring of animal vocalisations and anthropogenic noise. In these applications low-cost plug-in external microphones are added to create prototype acoustic logging devices (Caldas-Morgan et al., 2015, Sankupellay et al., 2016, Noriega-Linares and Navarro Ruiz, 2016, Whytock and Christie, 2017, Beason et al., 2018, Segura-Garcia et al., 2014, Sethi et al., 2018, Bello et al., 2018). Although the prototypes are relatively cheap compared to the commercial equivalents, certain constraints limit their utility in large-scale and long-term deployments where many devices are required. The scaling issues are as a consequence of: (i) power constraints caused by the lack of low-level power optimisation, and (ii) the need to build and program deployable prototypes individually by the user. Fundamentally, the DIY aspect of single-board computers reduce their accessibility to less technically skilled individuals, while also making it less viable to bulk manufacture final prototypes at scale. Although global monitoring coverage can be increased by improving the access to scientific equipment in terms of reducing cost (Pocock et al. 2018), prototypes built on single-board computers have shown that adopting existing easy-to-program technology is not always appropriate for acoustic monitoring applications. Largely, this comes down to *Raspberry Pi* being designed as an educational tool, rather than a device tailored for remote ground-level sensing.

To this extent, the present work applies two broad approaches in computer science to deliver a scalable acoustic monitoring tool to conservation practitioners. The first approach is *user-centred design*, which considers good product design as iterative, serving a communities needs and the tasks they want to perform, rather than trying to design a tool around a specific technology (Gulliksen and Göransson, 2001). User-centred design aims to iteratively develop a usable system, achieved through the involvement of potential users during system development (Karat, 1997). The second approach is the *collaborative economy*, which focuses on the economic benefits of a shared community. Specifically, this area investigates the advantages of open source designs, fabrication using crowdfunding, deployments using citizen science and crowdsourcing analysis (Hamari et al. 2016). Overall, this work adopts these principles to design and sustain an improved

[1] `https://guide.openenergymonitor.org`

acoustic monitoring device, which expands the coverage of monitored biodiversity to better inform policy. (Geijzendorffer et al. 2016, Schmeller et al. 2017, Girardello et al. 2019, Adams et al. 2019, Lessa et al. 2019, Coad et al. 2019, Xing et al. 2019).

1.1 The problem

Less than 0.01% of the ∼1.3 million known species are currently monitored. A global response is now urgently required, with more than one million species threatened with extinction[2]. Conservation needs accessible, affordable, fit-for-purpose tools to better understand global biodiversity and prevent illegal wildlife trade[3]. The currently available commercial acoustic tools used to monitor biodiversity are too expensive to deploy at large scale. Despite the recent growth and cost benefits of using DIY equipment built around single-board computers, power constraints and user know-how force acoustic technology away from the majority of conservation practitioners.

1.2 Research aims

To enable the long-term observation of audible biodiversity, further research is required to advance the scientific equipment used to monitor it. This work aims to develop a fit-for-purpose hardware solution that will expand the coverage of ground-level acoustic monitoring for conservation. To achieve this overall goal, three main contributions are identified:

1. The design, implementation and description of an acoustic monitoring device that fulfils the research problem.
2. The proposal of a general system to facilitate sustained community support, distribution and manufacture at scale.
3. The description of real-world deployments as an evaluation of the whole system and evidence of its use by the conservation community.

Each contribution presents considerable challenges to overcome.

1.3 Challenges

The challenges posed in the first contribution apply to the electronic design of a novel acoustic monitoring device and the user-centred design principles employed to develop

[2] `https://www.ipbes.net/news/Media-Release-Global-Assessment`
[3] `https://royalsociety.org/topics-policy/projects/illegal-wildlife-trade/`

it. Although the acoustic performance of the device takes up an important proportion of the design, one of the biggest constraints to overcome is understanding the user. The user is defined as *conservation practitioner*; however, many variations of this particular profile exist. They include, but are not limited to: *university/institution level students/researchers*; *government institutions and council* volunteers assisting in citizen science programs; *employees and volunteers of conservation organisations* surveying species; *nature reserve managers* monitoring habitats for protected species; and *local and indigenous communities* protecting local forests from illegal human activity. The differences observed in each of these profiles demands carefully designed hardware and supporting applications that allow flexibility to suit users' requirements, as well as their level of technical ability. Evaluating the latest technologies and choosing appropriate components and software to fulfil these requirements is necessary. However, the technology must also be designed with the conservation application in mind. It must withstand deployments in areas of biodiversity, which are often isolated, inaccessible and have extreme weather conditions. It must be able to endure these adverse conditions for long periods of time without mains power or digital communications. Long lasting deployments require appropriate power management and where vehicle access is minimal, large-scale projects need smaller and lighter devices. These requirements provide major challenges for electronics design, power optimisation and continued maintenance in the field. Furthermore, the hardware must match or improve on the performance and usability of existing technology, whilst also significantly reducing cost. Designing an electronic device, from concept to manufacture, presents numerous technical challenges, including circuit simulation, schematic capture, printed circuit board (PCB) layout, assembly, firmware development, testing, developing supporting software and evaluating performance against existing technology.

The second challenge arises when supporting a community using open source technology. Models built around open source hardware (OSH) have traditionally targeted the more technically savvy user, often requiring them to build their own products from open source design files (Pearce 2017); however, for less technically skilled users, such as the conservation practitioner, this presents a barrier that restricts adoption. To address this barrier, a general system is required to help conservation communities build and receive their own ready-to-use OSH. A general system would need a complex combination of manufacturing processes, distribution logistics, community support and funding. The system is essentially a management framework that provides guidelines for others to create new conservation technology. The system requires online platforms for the community to acquire the device. It requires a platform to manufacture the device, or someone with knowledge to set this up. After manufacture, the system requires funding for logistical operations and distribution. Then, after the community receive their devices, the system requires a platform to facilitate online support. Lastly, if another tool were to adopt such a system, they would then require funding to get off the ground.

These requirements provide conceptual management challenges, collaboration with logistical and manufacturing partners, the need for online platforms to support each stage of the system life-cycle, and a real-world case study to validate the concept within the conservation community.

The last challenge focuses on supporting the community that use the novel acoustic monitoring device in real-world deployments. The majority of which are satisfied by the default firmware and the key aspects developed as part of the second challenge, such as annotated online instructions and online support. However, the default firmware available with the general system is not always suitable, with some users requiring firmware modification and technical support to achieve their research aims. These users need much closer assistance, involving adjusting firmware for detection, experimental design and assisted execution in the field. Custom algorithms may need to be developed in collaboration with the conservation practitioners and third party algorithm developers, thus provoking technical constraints on the hardware when developing beyond the basic functionality provided by the general system. In the wider system, low-level optimisation problems then need to be overcome, requiring low-level firmware techniques to improve deployment time, and power usage. Feasibility studies in experimental conditions need to be developed to test the effectiveness of the firmware and deployments must be designed to reflect accurate conservation outcomes. Finally, executing deployments requires overcoming logistical problems, especially in vehicle restricted inhospitable habitats.

1.4 Contributions

This work advances the field of conservation and bioacoustics in three main contributions:

1. The first is the hardware design description of a novel acoustic monitoring device. The appellation *AudioMoth* is used to describe this contribution, conveying the unassuming appearance, yet extreme hearing ability of the nocturnal flying insect, "the moth". *AudioMoth* is shown to advance the field of bioacoustics in terms cost, size, weight, longevity and usability. Capable of recording the audible (20 Hz - 20 kHz) and ultrasonic (20 kHz - 192 kHz) frequencies simultaneously with a single microphone, *AudioMoth* creates a powerful, minimalist, utilitarian and ultimately lower cost tool, which can be enclosed in simple re-purposed enclosures to improve durability. The *AudioMoth* unit material outlay is low, costing $25.74 USD (October, 2019). This is approximately seven times lower compared to sensors made from single-board computers and approximately 40 times lower than commercial devices with the equivalent features. *AudioMoth* utilises an ultra-low power (ULP) embedded system and microelectromechanical systems (MEMS) microphone, which reduces energy consumption and size of the device considerably compared to existing tools. *AudioMoth* makes a substantial step towards the future of acoustic

technology, in providing an affordable tool to help cover large areas of inhospitable habitats with a network of devices, as acknowledged in the 2018 *WWF*, *Conservation Technology: Acoustic Monitoring guidelines* (Browning et al. 2017).

This work has been published in:

- **A P Hill**, Prince P, Snaddon J L, Doncaster C P, and Rogers A. Audiomoth: A low cost acoustic device for monitoring biodiversity and the environment. HardwareX, 2019; e00073. `https://doi.org/10.1016/j.ohx.2019.e00073`

  Contribution to manuscript: I led the writing of this manuscript, designed the *AudioMoth* device, and led the user-centred development of the hardware and enclosures. I also led the development and contributed to the default firmware running on the device, together with A, Rogers and P, Prince, until its public release on *Github*.

2. A generalised framework is discussed, which facilitates the bulk distribution and manufacture of analogous OSH. The *AudioMoth* devices were used in a case study to develop a novel system to support both community and creators of open source conservation hardware. The system embraced existing online platforms to facilitate logistics, manufacture and distribution. For community acquisition, an online crowdfunding platform was adopted to consolidate community funds for the organised bulk manufacture and distribution of the final product. For support, an online forum and online tutorial website were created to enable the community to configure their *AudioMoth*, share their experiences and support one another. During the case study the general system distributed 7,820 *AudioMoths* to every continent of the global conservation community.

   This work has been published in:

   - **A P Hill**, A Davies, Prince P, Snaddon J L, Doncaster C P and Rogers A. Leveraging conservation action with open-source hardware. Conservation Letters, 2019; e12661. `https://doi.org/10.1111/conl.12661`

     Contribution to manuscript: I led the writing of this manuscript, as well as the conception and development of the framework to support OSH for conservation. I led the introduction to and management of overseas partners, organising sourcing parts to fullfill large global batch orders of *AudioMoth* hardware. I led the evaluation of the manufacturers build quality and managed user support to the community. Lastly, I led the design and development of the *Open Acoustic Devices* supporting website, including user instructions and the support forum, together with A, Rogers and P, Prince.

3. *AudioMoth* and the distribution system have made a large global impact on conservation and ecological research, we will separate this significance into two parts. The first is the evaluation of the general system and evidence of its use by the conservation community, and the second is the evaluation of the wider system, which to achieve full functionality, modification of the default firmware is required to implement tailored deployments:

   (a) The general system enabled *AudioMoth* to be used in numerous conservation projects around the world. In August 2019 *AudioMoth* made a clear impact on expanding the coverage of biodiversity, being used as a scientific tool to recognise the call and subsequent discovery of two new species of bush cricket: (i) *Anisophya una* and (ii) *Xenicola xukrixi* (Fianco et al. 2019). Over 900 projects are now using the device to enable a multitude of different conservation practitioners to collect biodiversity data. *AudioMoth* has enabled many different genera of animal to be monitored, including numerous species within each genus. These ranged from monitoring insects in the UK to monitoring Manatees in Florida. The wider system combined with the *AudioMoth* technical benefits, enabled others to expand on previously infeasible research questions, including a method to optimise large-scale acoustic deployments. As well as making a significant contribution to the field of acoustics, *AudioMoth* has contributed to important public engagements and thus raised the profile of national and international conservation. These included being used as a teaching tool for environmental monitoring (*Kings College London & The University of Southampton*), appearing in two conservation technology awards (Winner of the 2019 *IWT WILDLABS TechHub Prize* UK, Finalist of the *Con X Tech Prize* US) and appearing with Prince William at the *Illegal Wildlife Trade* conference in 2018.

   This work has been published in:

   - E Pina-Covarrubias, **A P Hill**, P Prince, J L Snaddon, A Rogers, and C P Don- caster. Optimization of sensor deployment for acoustic detection and localization in terrestrial environments. Remote Sensing in Ecology and Conservation, 2018. `https://doi.org/10.1002/rse2.97`

     Contribution to manuscript: I contributed to the gunshot study leading its conception, design and execution in Central America together with all authors. I also contributed to revisions of this manuscript.

   (b) The default open source firmware was successfully adapted during a collaborative software implementation during two different real-world deployments: (i) working with UK conservation organisation, *BugLife*, to detect an insect species in The New Forest National Park; and (ii) working with the *Belize*

Forestry Department and ecologists at the *University of Southampton* to record poaching events in a protected nature reserve in Central America. The experimental methodologies of this wider system were used to evaluate *AudioMoth* as a versatile conservation tool. This was published in the ecology Journal, *Methods in Ecology and Evolution.* This paper is currently the go-to publication for references of acoustic advancements in the field, receiving 79 citations to date. The same manuscript is in the top 1% of most highly cited papers for its age since publication, within the subject area of ecology, given by its *Highly Cited* classification in *Web of Science*[4].

This work has been published in:

- **A P Hill**, P Prince, E Pina-Covarrubias, C P Doncaster, J L Snaddon, and A Rogers. Audiomoth: Evaluation of a smart open acoustic device for monitoring biodiversity and the environment. Methods in Ecology and Evolution, 2017. `https://doi.org/10.1111/2041-210X.12955`

  Contribution to manuscript: I led the writing of this manuscript and contributed to the cicada case study, leading its conception, design and execution together with A, Rogers and P, Prince. I contributed to the gunshot case study leading its conception, design and execution together with all authors. Lastly, I contributed to trialling, testing and implementing the developed algorithms on the *AudioMoth* hardware.

- P Prince, **A P Hill**, E Pina-Covarrubias, P Doncaster, J L Snaddon, and A Rogers. Deploying acoustic detection algorithms on low-cost, open-source acoustic sensors for environmental monitoring. Sensors, 19(3):553, 2019. `https://doi.org/10.3390/s19030553`

  Contribution to manuscript: I contributed to the cicada trials, leading their conception, design and execution together with A, Rogers and P, Prince. I contributed to the bat case study, leading its conception, design and execution together with P, Prince. I contributed to the gunshot study leading its conception, design and execution together with all authors. I contributed to the testing and implementation of the developed algorithms on the *AudioMoth* hardware and lastly, contributed to the revisions of this manuscript.

1.5 Thesis structure

The remainder of the thesis is structured as follows:

[4] `www.webofknowledge.com`

Chapter 2 presents the background behind the *AudioMoth* concept, of which the overarching principles are based upon user-centred design (Section 2.1), the context-of-use when applied to ground-level conservation technology (Section 2.2) and the benefits of a collaborative economy. Section 2.3 describes the field of acoustic monitoring, focusing on the baseline levels of performance, issues, deficiencies and difficulties of monitoring biodiversity on existing commercial hardware. Section 2.4 introduces the collaborative economy, first covering the baseline levels of performance on existing open source DIY acoustic systems (Section 2.4.1). Together with the underlying theme of *open source*, Section 2.4.1.3 introduces two recent technological developments that provide potential improvements to existing acoustic hardware, thus motivating the creation of *AudioMoth*. Lastly, Section 2.4.2 introduces the economic advantages of crowdfunding, which provokes the formation of a general system to support OSH for conservation.

Chapter 3 presents a full description of the device, including the hardware design, the enclosures to house it and the locations of the corresponding design files. It details the materials, build instructions and operation instructions, as well as outlining the validation process, characteristics of a fully built *AudioMoth* device and the conservation applications it can be deployed in.

For conservation practitioners unable to build the device themselves, Chapter 4 discusses a generalised framework to support the use of OSH for less technically skilled users. In this framework, manufacturing procedures, distribution logistics and community support are covered using *AudioMoth* as a case study. The results observed in Section 4.3 indicate the significance of this contribution, with a globally distributed community of over 900 users.

Chapter 5 gives evidence of the general system, describing implementations by the conservation community with key examples. It then describes the real-world deployments of two projects run by two different conservation practitioners. This description gives a detailed evaluation of the wider *AudioMoth* functionality, which relates to running real-time algorithms on the device.

Finally, Chapter 6 concludes and suggests future work.

Chapter 2

An approach to advance acoustic conservation technology

In this chapter we put the research aims and challenges into context, in which the current state of technology used for conservation and acoustics are summarised. Motivations behind the design of *AudioMoth* – a scalable acoustic conservation tool – are defined by bringing together the computing fields of *user-centred design* and the *collaborative economy*. First, we introduce the field of user-centred design, which is the underlying method guiding the creation of *AudioMoth*.

2.1 User-centred design

User-centred design (UCD) is the process of designing usable products and is recognised by the *International Standards Organisation* (ISO) as an effective design framework for producing interactive products (*ISO 9241-210:2019*[1]). The UCD concept grew from the area of human-computer interaction (HCI), and was driven by the need to observe user-software interactions in their context of use (Norman, 1988, Abras et al., 2004). The *ISO* definition aims to make products useful and usable by focusing on user requirements. The definition states that for a design to be user-centred: (i) it should be based upon the clear understanding of users and the tasks they perform; (ii) users should be involved throughout the development; (iii) it should be directed by user evaluation; (iv) it should be iterative; (v) it should address the whole user experience, which is needed to effectively allocate product functions based on prior experiences, perception, skills and habits; and (vi) the design team should be multidisciplinary to effectively collaborate and become aware of the realities between the team member's disciplines. The main focus of UCD is to discover early in the design stage as to what the users require and how the requirements change within different contexts of use (Byrd et al. 1992). To design a conservation

[1]`https://www.iso.org/standard/52075.html`

monitoring tool, it is crucial to understand the specific characteristics within different conservation groups.

2.1.1 The conservation practitioner

Conservation practitioners are a diverse group of individuals, including university level students, researchers, employees or volunteers of conservation organisations, volunteers at local councils, managers of nature reserves, and local communities. Each group has specific needs and their own individual constraints. This section defines five groups of typical conservation user, aiming to specify their user requirements.

The first group are *university/institution level students/researchers*. This group practise conservation research as part of their university program or with the support from government research councils. They generally have a broad level of educational backgrounds. This could be, but is not limited to, further education in biological sciences, environmental sciences, mathematics or geography, as well as higher education in anthropology, economics, history or sustainable development. They are computer literate, generally using the *Windows* operating system for their research. They also hold basic coding knowledge, with higher educational users typically having experience in the *R* programming language for statistical computing. Their knowledge of electronics and interactive computing is generally low; however, their research may drive them to pick this skill up, thus allowing them to adapt hardware/software to address particular questions of interest. In the UK, a typical postgraduate student would often receive a *research training and support grant* as part of their funding, allowing them to purchase equipment for their research. This is typically $3,700 USD per year[2]. Researchers are some of the most affluent in conservation, therefore, commercial scientific equipment – which we describe in the context of acoustics in Section 2.3.1.1 and 2.3.1.5 – are conventionally utilised in their projects. This group perform the majority of published research in the area of conservation. Researchers who work for research institutes, such as the *Centre for Ecology & Hydrology*[3] and *Rothamsted Research*[4], often bridge from conservation theory to practice much more effectively than university researchers. Their research contributes to establishing the frameworks on which conservation is carried out by other groups.

The second group are *government institutions and councils*, such as the *Joint Nature Conservation Committee (JNCC)*[5] and *Natural England*[6] in the UK, and internationally, *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)*[7] and *United Nations Environment Program (UNEP)*[8]. They are often office

[2] https://www.ukri.org/skills/funding-for-research-training/
[3] https://www.ceh.ac.uk/
[4] https://www.rothamsted.ac.uk
[5] https://jncc.gov.uk
[6] https://www.gov.uk/government/organisations/natural-england
[7] https://www.ipbes.net/
[8] https://www.unenvironment.org/

based, with advisory roles towards governmental conservation policy. They act as a focal point of contact and advice for all stakeholders in conservation. They also actively manage some types of conservation area.

The third group are *employees and volunteers of conservation organisations*, such as the *Zoological Society of London* (ZSL)[9] and the *World Wildlife Fund (WWF)*[10]. They run mission-oriented and time-limited projects with goals that demonstrate tangible improvements in the functioning or state of ecosystems, habitats or the status of species. Individuals in this group tend to be wildlife enthusiasts, with employees tending to be from higher educational backgrounds (Adomavičiūtė et al. 2012). The volunteers educational levels are harder to define. This group would typically have a low to zero wage, and no available expenses to spend on technology themselves. This group therefore rely on the conservation organisation supplying equipment for their monitoring projects. In many projects located in wealthier regions of the world, volunteers often utilise their smartphones to facilitate crowdsourced citizen science projects. Examples of these projects include, *iNaturalist*[11], *Instant Wild*[12], *iBats*[13], *Cicada Hunt App*[14] and *Leafsnap*[15].

The fourth group are *nature reserve managers*. This group actively sustains and restores habitat, often in conjunction with a government institution or conservation organisation. They include the managers of government run national parks, individual farmers who are incentivised by governments to protect environmental services on their land and for-profit companies owning adjoining natural habitats (Porras, 2010). This groups educational backgrounds are harder to define, but can vary from the highly educated remote managers of forests, who use sophisticated satellite imaging techniques, to ground-level management, that monitor and patrol areas by foot. Ground-level management may have basic-level desktop computing skills, but would often lack programming knowledge. This group would typically have an average to low living wage and little available extra expenses to spend on conservation technology that might support their work.

The final group are *local and indigenous communities*. This group are generally located inside important conservation areas or located in close proximity to them. They are typically in remote locations with little to no electrical or communication infrastructure. This group are the least affluent, they may not own mobile phones and are generally computer illiterate. Technology is often donated to enable this group to participate (Sabogal, 2015).

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[9] `https://www.zsl.org`
[10] `http://wwf.org/`
[11] `https://www.inaturalist.org/`
[12] `https://instantwild.zsl.org/intro`
[13] `https://www.bats.org.uk/our-work/national-bat-monitoring-programme/past-projects/ibats`
[14] `http://newforestcicada.info/app/`
[15] `https://www.nhm.ac.uk/take-part/identify-nature/leafsnap-uk-app.html`

The start of this chapter derives product requirements by evaluating the context of use in conservation. This includes: reviewing the field of conservation technology, the standard levels of operation, issues and deficiencies of existing acoustic tools, and the tasks bioacousticians typically perform.

2.2 Conservation technology

Conservation technology is an extensive field of research aiming to improve the management and protection of biodiversity with technology (Pearce, 2012, Greenville and Emery, 2016, Marvin et al., 2016, Iacona et al., 2019, Lahoz-Monfort et al., 2019). Just like the technological advances that revolutionise industries, such as the bulk manufacturing of goods, food production, mining and travel, emerging technologies have been predicted to drive future conservation efforts (Pimm et al. 2015). However, technology alone is not a miraculous fix and barriers have surfaced that stagnate its use for global conservation (Lahoz-Monfort et al. 2019).

Innovative technology has always been at the forefront of conservation, from biotelemetry devices that attach to organisms and document their interactions in real-time (Cooke et al. 2004), to quadcopter drones that catch respiratory vapour, exhaled by free-swimming humpback whales (Pirotta et al. 2017). Although many small conservation research projects have addressed important challenges with these new technologies, few have yet to involve the global community to drive large-scale conservation problems.

Satellite imaging and camera trapping are unique examples that have gone someway to achieve this. Their features create non-invasive deployments and easy to access data, which is often freely available online. Satellite imaging enables large-scale ecosystem monitoring and has been available since the launch of the first specialised imaging satellite in 1972 (Giri, 2012). This monitoring technique accurately captures both temporal and spatial data, covering huge areas of an ecosystem from a birds-eye perspective. It is useful for identifying broader changes over time, especially those relating to flora species, such as clear cutting or forest fires (Fuller, 2006). Increasingly, satellite images are open access (Kalyvas et al. 2017). Hence, this free availability has increased its use amongst the conservation community, helping generate huge databases and community websites such as *Global Forest Watch*, which track land-use change and deforestation over time[16]. However, the coarse image resolution, which is about 30 m per pixel, means satellite imaging cannot usually be used for monitoring animal biodiversity at species level (Reiche et al. 2016). Events which are hidden by tree cover, or those that are too fine-scale for image resolution, remain unaccounted for without ground-level monitoring (Peres et al. 2006).

[16] https://www.globalforestwatch.org/

Camera traps achieve ground-level coverage using low-cost, portable, battery powered and semi-automated cameras that trigger photos or videos with passive infra-red (PIR) sensors (Rowcliffe and Carbone 2008). Camera traps originally emerged as a tool for game hunting. This mass market enabled economies of scale, reducing the cost per device and allowing them to proliferate into ecology. When applied to conservation, camera traps make versatile monitoring tools, being used to monitor wildlife populations, or as surveillance tools to protect nature reserves. They are often used to give reliable samples in terms of vertebrate observations and can be implemented to clearly state health, abundance and distribution of each particular group of animal over time (Rovero et al. 2010). Camera traps have been used to increase public engagement through online image sharing and like satellite imaging, have enabled citizen science projects to crowdsource analysis through freely available platforms, such as *Instant Wild*[17] (Wearn and Glover-Kapfer, 2019). The issues with camera trapping are around the design and optimisation of trapping grids, and whether to maximise captures, which frequently give positive bias issues with elusive animals, or to sample randomly, which will likely reduce capture rate (Tobler and Powell, 2013). Camera trap images are limited to the field-of-view (FOV) and resolution of the camera. As a consequence, insects and elusive biodiversity that lay outside of the FOV or smaller than a pixel remain unaccounted for. It is also difficult to detect amphibians and cold blooded wildlife because the PIR sensors used to trigger recordings only detect differences in temperature. Lastly, camera traps are often prone to theft (Glover-Kapfer et al. 2019).

An increasingly common approach to avoiding these issues is to use acoustic monitoring.

2.3 Acoustic monitoring for conservation

Whether it be from the isolated calls of bats navigating around a city, invertebrate chirps across the savannah, or the disturbances caused by illegal poachers under the forest canopy, hidden events broadcast identifiable sounds into the environment. For conservation, this can offer a rich source of information about the health of an ecosystem and the threats posed to it by human occupancy.

Acoustic monitoring is the process of recording acoustic data from an environmental soundscape. There are three main forms of sound within a soundscape: sound made by the weather or geology, sound made by humans or machinery and sound made by animals. Every sound within each form has a unique characteristic, which can be described using the pattern of its dominant frequency components over time. Sounds are defined as audible if between 20 Hz - 20 kHz (e.g. anthropogenic noise, birds, amphibians and insects) and ultrasonic if between 20 kHz - 192 kHz (e.g. bats, amphibians,

[17] `https://instantwild.zsl.org/intro`

insects and marine mammals). Individual sounds can be identified from listening, viewing them as spectrograms or classifying them with software. This identification process allows information, such as identity, location and behaviour to be extrapolated. This analysis process results in the field of acoustic monitoring facilitating a broad range of applications.

The study of species, population and behaviour is a key area of research in conservation, particularly around indicator species, endangered species, or species that have a lack of data. Acoustic monitoring can be used to detect their occurrence by recording their vocalisations to detect and identify them rather than their visual presence. This means smaller elusive species, such as marine life, birds, amphibians and insects can be recorded (Borker et al. 2015, Zilli et al. 2014). Capturing sound can improve coverage as well as resolution compared to visual techniques. This is important in detecting the occurrence of species concealed by obstructions. For example, the Indian forest elephant, whose sound can propagate through forested areas for hundreds of metres (Thompson et al. 2010, Wrege et al. 2017). As well as occupancy, animal vocalisations can be used to estimate population density (Dawson and Efford 2009, McDonald and Fox 1999, Efford et al. 2009, Marques et al. 2013, Sueur et al. 2008). This is the measurement of population per area and is typically counted by invasive capture-recapture techniques. Unlike these traditional techniques, acoustic monitoring is non-invasive and does not impact the ecosystem, this is particularly important for monitoring elusive species that are more vulnerable to human presence. Acoustic monitoring carried out at large-scale and over long periods of time can identify important spatiotemporal behaviours in animals that signify larger conservation outcomes. These include highlighting foraging hotspots (Johnson et al. 2009), breeding behaviours (Hawkins and Amorim 2000) and even climate change from the monitoring of indicator species (Pettorelli et al. 2013). Another key area in acoustic monitoring is the surveillance and protection of natural resources by monitoring human activity. This can be achieved through detecting anthropogenic sounds in the environment, such as gunshots (Astaras et al. 2017), chainsaws (Papán et al. 2012), mining (Alvarez-Berríos et al. 2016) and road noise (Bee and Swanson 2007).

Stored datasets are required in all acoustic monitoring projects. These are often collated from audio recordings taken on battery powered acoustic monitoring devices. The next section looks at the commercially available acoustic technology, summarising their features and limitations for addressing large-scale terrestrial conservation problems.

2.3.1 Commercial hardware

To date, conservation publications on terrestrial acoustic monitoring overwhelmingly report data capture using commercially available battery-operated devices. Each device has specifications for memory capacity, bandwidth, microphone sensitivity, signal to noise ratio (SNR), weight, memory capacity and battery life.

Since sound represents fluctuations in air pressure, one of the most important features to understand is that of bandwidth, which gives the speed of fluctuations per second (frequency) that the microphone is specified for. For a bandwidth to be captured correctly the sound pressure level (SPL) at the transducer must be sampled at a theoretical minimum rate. The *Nyquist Theorem* states that the sample rate must be double the specified peak frequency emitted by the target in order to capture that sound. If no filtering is present on the output of the microphone, any sound above half of the sample rate will be aliased to a lower frequency, appearing as artifacts or noise. Sample rates must therefore be set to correspond to at least double the sound source frequency in question.

SNR indicates the quality of a microphone by specifying the ratio of a reference signal to the microphone output noise level, it is defined as:

$$SNR = 20 \times \log_{10}\left(\frac{V_s}{V_n}\right) \tag{2.1}$$

where V_s is the signal voltage and V_n is the noise voltage. This noise voltage or *noise floor* includes the low-level electronic background noise produced by the microphone system and also that emitted by the transducer itself. Higher SNR indicates a cleaner recording and better audio quality. SNR ratio is normally given as an A-weighted decibel value. The decibel (dB) is a logarithmic scale used to describe the intensity level of a sound wave. The correction factor, dBA, relates to the sensitivity level of human hearing. This corrects for the psychological sensation of loudness perceived by humans, which is not directly related with sound intensity.

Traditionally, terrestrial devices have been defined as working in either the audible or ultrasonic frequencies, with different microphone technologies required for each application. Audible microphones usually lose their sensitivity in higher frequencies, due to the microphone transducer being unable to physically vibrate in the ultrasonics. The same is true for ultrasonic transducers which lose their sensitivity in lower frequencies. Analog microphone sensitivity is defined as:

$$Sensitivity_{dBV} = 20 \times \log_{10}\left(\frac{Sensitivity_{mV/Pa}}{Output_{AREF}}\right) \tag{2.2}$$

where $Output_{AREF}$ is the $1V/Pa$ output reference ratio. Sensitivity gives a logarithmic ratio of the output voltage to the input SPL of a given signal and determines the magnitude of the microphone output signal given a known input (Lewis, 2012). Sensitivity is specified in decibels with respect to 1 Volt (dBV) when capturing a 1kHz tone at one pascal (94 dBA SPL). This results in a negative dBV value, with a dBV value closer to zero being the most sensitive. Due to the measurement tone being at 1kHz, sensitivity level is only applicable for devices that record in the audible frequencies. Sensitivity is often used to assess the ability of the microphone to detect sound at a distance, where higher sensitivity reduces the amount of sensors needed to cover a larger area.

Another important feature to define is operation life, measured in hours of operation. Since each device may have a different power consumption or battery capacity, operation life is measured with respect to recording continuously at a 44.1kHz sample rate. For ultrasonic devices it is measured as hours of operation with respect to bat triggering functionality.

2.3.1.1 Best-in-class audible

The leading device for audible terrestrial acoustic monitoring is the *Song Meter* (*SM*) from *Wildlife Acoustics*[18]. The latest version 4 (*SM4*) costs $849 USD and has the capability to record audible sounds from 20 Hz - 48 kHz (96 kHz sample rate) (Figure 2.1a). The *SM4* is designed to record avian, terrestrial and marine data in a ruggedised casing. Acoustic specification wise, the *Song Meter* series are the benchmark acoustic monitoring devices for conservation applications and the versions, from *SM2 to SM4*, have been used in hundreds of published projects around the world, from the earliest species population estimation application, which analysed soundscapes by calculating metrics of biodiversity using acoustic indices, to the latest study collecting acoustic data for a rare species of night parrot (Sueur et al. 2012, Zwart et al. 2014, Towsey et al. 2014, Da Silva et al. 2015, Alquezar and Machado 2015, Celis-Murillo et al. 2016, Murphy et al. 2017, Towsey et al. 2018, Mennill et al. 2019). The *Bioacoustics Audio Recorder* (*BAR*) from *Frontier Labs* is another leading acoustic monitoring device[19] (Figure 2.1b). The *BAR* costs $750 USD with built-in microphone and again, capable of recording audible sounds from 20 Hz - 48 kHz (96 kHz sample rate). Like the *SM4*, the *BAR* device is designed to record avian, terrestrial and marine data in a ruggedised casing. The *BAR* device is a recent arrival on the market and in the last few years has started to appear in acoustic monitoring studies around the world (Burivalova et al. 2018, Sugai and Llusia 2019, Hines and Rowland 2017). The *BAR* has one of the most sensitive microphones available and arguably the best recording quality, with a -14 dBV sensitivity and an 80 dBA SNR. Both devices record continuous streams of audio and feature supporting configuration software that can be used to set recording schedules and duty cycle routines to preserve battery by reducing recordings in unwanted periods of the day. From hereon-in the *BAR* and *SM* devices will be described as "best-in-class audible". As demonstrated in Figure 2.1, best-in-class audible devices show value in their rugged construction and enduring operation life for long-term conservation applications. They also have the capacity to swap or add external microphones, this is useful to improve sensitivity and SNR for better quality recordings.

[18] https://www.wildlifeacoustics.com/
[19] https://frontierlabs.com.au/

image from https://www.wildcare.co.uk

Cost	$849
Bandwidth	20 Hz – 48 kHz
Sensitivity	-28 dBV
SNR	80 dBA
Battery	400 hr
Weight	1.2 kg
Memory	1 TB

(a) Wildlife Acoustics SM4

image from https://frontierlabs.com.au

Cost	$750
Bandwidth	20 Hz – 48 kHz
Sensitivity	-14 dBV
SNR	80 dBA
Battery	600 hr
Weight	900 g
Memory	2 TB

(b) Frontier Labs BAR

Figure 2.1: Commerical best-in-class audible acoustic recording units, including the Wildlife Acoustics SM4 and the Frontier Labs BAR

These benefits come at the cost of large size and high purchase price. The subsequent aesthetic nature of the devices also promote unwanted theft and vandalism (Clarin et al. 2014). These properties are particularly disadvantageous for projects requiring a greater number of devices to improve coverage. As a result their use in large-scale assessment has been relatively sparse over the last decade.

2.3.1.2 Dictaphones

For large-scale projects, many low-cost and less capable units often yield more data than fewer units with better performance (Gold et al. 2008). Therefore, new developments in lightweight handheld dictaphones have established a low-cost alternative for larger deployments in certain scenarios. Out of the huge range of dictaphones on the market, three have become commonly used in conservation research: the *Zoom H2* series, the *Tascam DR* series and the *Olympus WS* series (Gryllus 2017, Tan et al. 2018, Fristrup and Mennitt 2012, Rempel et al. 2013, Borie et al. 2019, Braulik et al. 2017, Penone et al. 2013). Figure 2.2 shows the latest versions of these devices with clear drops in performance relating to battery life, ruggedisation and SNR compared to the best-in-class devices. However, dictaphones present many advantages for applications where the observer is present. This was seen with a study using the *Tascam DR* device to estimate Orthoptera diversity and abundance (i.e. cicada, bush crickets and grasshoppers) (Gryllus, 2017) (Figure 2.2b). For this study the benefits of acoustic monitoring was highlighted against traditional invasive physical trapping techniques. In addition to not harming the wildlife, dictaphones were not susceptible to theft, of which 27 of the 50 physical traps were (Merchant et al. 2015). Dictaphones also feature voice activation modes that can be used to trigger from external microphones (Braulik et al. 2017). This function has been applied in one study to assess anthropogenic pressures on insect populations, with the help of citizen scientists (Penone et al. 2013). In this study, play-back

image from https://www.thomann.de/gb/zoom_h2n.htm

Cost	$187
Bandwidth	20 Hz – 48 kHz
Sensitivity	-23 dBV
SNR	68 dBA
Battery	20 hr
Weight	190 g
Memory	32 GB

(a) Zoom H2n

image from https://tascam.com

Cost	$173
Bandwidth	20 Hz – 96 kHz
Sensitivity	-20 dBV
SNR	>60 dBA
Battery	17 hr
Weight	176 g
Memory	128 GB

(b) Tascam DR-05X

image from https://https://olympus.co.uk

Cost	$100
Bandwidth	20 Hz – 22 kHz
Sensitivity	-35 dBV
SNR	>60 dBA
Battery	110 hr
Weight	100 g
Memory	32 GB

(c) Olympus WS-854

Figure 2.2: Commerical light-weight audible acoustic recording units, including the Zoom H2n, the Tascam DR-05X and Olympus WS-853

detectors were attached to *Zoom H2n* dictaphones to trigger recording of the insects while masking out traffic noise (Figure 2.2a). It was found that large temporal and spatial changes in their abundance were successfully observed from multiple numbers of devices attached to the side of observers cars. Despite the organisers having to purchase the equipment to appropriately tool each citizen, the results showed that when suitably supplied, citizens can achieve large-scale conservation outcomes.

2.3.1.3 Smartphones

The New Forest Cicada Project demonstrated that a suitable tool for audible research is actually in the hands of almost every citizen: the *smartphone* (Zilli et al. 2014). Smartphones are ubiquitous, powerful handheld computers with high-quality sensors that make ideal tools for acoustic surveying. Intuitive software applications enable the implementation of real-time acoustic detection to be performed on the device. After the on-board analysis, the findings can be immediately uploaded to a server for the researchers to review. This same process was performed during *The New Forest Cicada Project*, in which visitors to the New Forest National Park used the *Cicada Hunt App*[20] to search for the call of the rare *New Forest cicada* (*Cicadetta montana*) during its emergence period (Zilli et al. 2014). The application enabled many trained and amateur naturalists to re-discover the rare species. The success of the project highlighted limitations around smartphone based mass participation projects. The first being that the habitat becomes at risk from over exposure to footfall if too many citizens participate (Moran et al. 2014). The second limitation is that most of the spatial and temporal positioning recorded during the survey were biased towards periods of common visiting hours and locations close to maintained trials, with many suitable emergence hotspots and times of day missing from the stored data. A project that addresses some of these issues is *Rainforest Connection*, which aims to remove the human in the loop biases by statically deploying re-purposed smartphones throughout a conservation area. In this case, the overall goal of the project was to create a real-time surveillance system to detect and alert rangers of illegal logging activity within a 3G connected nature reserve[21]. The individual system: *Guardian*, intended to stream compressed audio through 3G mobile networks, allowing detection classifiers to run near-instantaneously on cloud servers. However, when running continuously smartphones have high power consumption, with some models having a runtime of as little as four hours (Malik 2012). Hence, to generate enough power, expensive power banks and solar panels are required. Besides cost, the smartphones rely on 3G networks and with many high-risk conservation areas not having 3G coverage, bigger communication infrastructure problems arise. Although the *Guardian* is not yet on the market, the *ARBIMON* recorder ($4,000 USD) – a statically deployed acoustic

[20] `http://newforestcicada.info/app/`
[21] `https://rfcx.org/`

station including a ruggedised enclosure, data transmission app and a solar panel – gives a sense of cost required to implement a very similar concept[22].

2.3.1.4 USB microphones

The disadvantage of using smartphones and all of the monitoring technologies we have looked at so far, is that their microphones are designed for the audible range, meaning organisms that vocalise in the ultrasonic frequency range cannot be recorded. One of the most widespread conservation applications in acoustic monitoring is bat surveying. Bats are elusive, nocturnal and almost impossible to survey by eye. Nevertheless, they broadcast their identity and location almost continuously with ultrasonic navigation and communication vocalisations. Thereupon, the technology used to monitor them offers a more extensive range than those available in the conservation space for audible applications. These vary from universal serial bus (USB) microphones that enable smartphones to pick up ultrasonics; such as the *Wildlife Acoustics EchoMeter Touch* ($349 USD)[23], the *Petterson M500-384* ($360 USD)[24] and the *Dodotronic Ultramic UM250K* ($278 USD)[25] (Brizio, 2015); to hand-held playback detectors that allow surveyors to count bat passes manually by ear. Although allowing convenience and sharing the deployment characteristics of dictaphones, hand-held tools are less useful for long-term coverage.

2.3.1.5 Best-in-class ultrasonic

To this extent, the largest range of devices are the *best-in-class ultrasonic* units (Figure 2.3), with automatic triggering functionality (Stahlschmidt and Brühl, 2012). Like the best-in-class audile range, the ultrasonic range are built to endure long-term deployments in remote locations. The top acoustic performance is that of the *Wildlife Acoustics SM4BAT*, which costs $1,099 USD and features a broad bandwidth from 10 kHz to 250 kHz (Figure 2.3a). The SMBAT series are the go-to system for bat monitoring worldwide (Britzke et al., 2013, Mirzaei et al., 2015, Appel et al., 2017, Krauel et al., 2018, Kemp et al., 2019). *Pettersson D500X MKII* is another top of the range device, costing $2,551 USD and features the lowest bandwidth range from 5 kHz to 190 kHz (Figure 2.3d). This device is often used for bat behaviour surveys (Slough et al. 2014, Fernandez et al. 2014, Cox et al. 2016). The *Titley Scientific Anabat Swift* is the newest device available and the most versatile, with a weight of 648 g and battery life of 530 hr (Figure 2.3c). As well as having ultrasonic microphone capabilities, the best-in-class ultrasonic range differ to the audible range with a compelling feature that allows them to trigger recordings in response to frequency. The triggering functionality

[22] `https://www.sieve-analytics.com/products`
[23] `https://www.wildlifeacoustics.com/products/echo-meter-touch-2`
[24] `https://batsound.com/product/m500-384-usb-ultrasound-microphone/`
[25] `https://www.dodotronic.com/product/ultramic-um250k/?v=79cba1185463`

image from https://www.wildcare.co.uk

Cost	$1,099
Bandwidth	10 kHz – 250 kHz
Sensitivity	Not applicable
SNR	Not applicable
Battery	450 hr
Weight	1.3 kg
Memory	1 TB

(a) Wildlife Acoustics SM4BAT

image from https://batlogger.com

Cost	$1,180
Bandwidth	10 kHz - 150 kHz
Sensitivity	Not applicable
SNR	Not applicable
Battery	50 hr
Weight	695 g
Memory	128 GB

(b) Elekon Batlogger A+

image from https://titley-scientific.com

Cost	$1,194
Bandwidth	10 kHz - 125 kHz
Sensitivity	Not applicable
SNR	Not applicable
Battery	530 hr
Weight	648 g
Memory	1 TB

(c) Titley Scientific Anabat Swift

image from https://wildcare.co.uk

Cost	$2,551
Bandwidth	5kHz - 190kHz
Sensitivity	Not applicable
SNR	Not applicable
Battery	140h
Weight	1.3 kg
Memory	128GB

(d) Pettersson D500X MKII

Figure 2.3: Commercial best-in-class ultrasonic acoustic recording units, including the Wildlife Acoustics SM4BAT, the Elekon Batlogger A+, the Titley Scientific Anabat Swift and the Petterson D500X MKII

is implemented with high-pass filtering techniques, which prevent continuous audio files by triggering recordings in response to ultrasonic sounds above a threshold amplitude. This technique can be achieved, as the spectrum above 16 kHz is generally very quiet, with only bats, Orthoptera, and amphibians broadcasting their calls within it. Despite their higher sample rates, these devices have equivalent battery life to the best-in-class audible range. This is because recording to SD card is one of the most energy consuming tasks in a modern portable electronic system (Abdelmotalib and Wu, 2012), therefore, even though ultrasonic devices are sampling at a much higher rate and consume more power during operation, filtering in this manner results in less overall recordings to SD card and a reduced average energy consumption. However, as seen with the best-in-class audible range, these devices restrict large-scale conservation work due to: (i) their cost (ii) their tendency to be stolen, and (iii) their large dimensions/weight.

The cost of acoustic hardware presents a huge barrier to entry for the majority of conservation practitioners. Consequently, few if any available commercial acoustic monitoring devices can feasibly be deployed for large-scale conservation work, resulting in many fragmented small-scale studies. In recent years, however, a disruptive form of hardware hacking has gone some way to address the cost issues in particular. The approach behind this philosophy is that of the collaborative economy, where users co-create, develop and deploy technology as a community.

2.4 The collaborative economy

Over the last 30 years, science has seen a shift towards data transparency with the growth of open science and the internet. This has included open-access journals, websites hosting open data, community forums and sharing through social media (Hampton et al., 2015). From this openness has emerged a broad computing and business field known as the *collaborative economy*. In business terms it is defined as a socio-economic system, which commits to the sharing of human and physical resources. Sharing these resources is made accessible by the computing aspect, which utilises online distributed platforms or decentralised networks aiming to create a sense of mutual benefit by empowering anyone to consume, trade, create, produce or distribute. Collaborative economies often have transparency and a value-driven mission that inform long-term strategies, giving the community an overall collective accountability (Botsman, 2015). The collaborative economy is now one of the most prosperous economies in the world, including software platforms such as *Github*[26], *Airbnb*[27], *Uber*[28] *and Kickstarter*[29]. It has generated a profound change in the way that technology is now developed, leading to non-technical

[26] `https://github.com/`
[27] `https://www.airbnb.co.uk/`
[28] `https://www.uber.com`
[29] `https://www.kickstarter.com/`

scientists collaborating with engineers to create bespoke tools for their specific applications (Kwok, 2017, Lahoz-Monfort et al., 2019).

In this section we will look at a few subcategories within this field, focusing on the outcomes of community collaboration, including the benefits of open source DIY hardware and maker communities. After describing the base technology and the types of acoustic tools that can be built on OSH, this section will then focus on collaborative methods for product accessibility and how a collaborative community can enable large-scale deployments.

2.4.1 The open source movement

The open source movement originated from the hacker culture, where several thousand globally spread part-time developers connected to the internet to create the *Linux* operating system (Raymond, 1999). In general, *open source* relates to the licensing of free and unrestricted source code. There are about 97 different licences approved by the *Open Source Initiative*[30], with the 10 most popular being *Creative Commons*, *Apache 2.0*, *MIT, GPLv3*, *AGPL*, *Simplified BSD, GPLv2*, *Mozilla Public 2.0, LGPL*, and *Artistic 2.0.* The licenses are used to define how the source files can be shared, attributed, modified and commercialised. Open source does not just relate to the licensing of the software source code, but also the development processes behind its creation (O'Reilly, 1999). The open source development process is typically run by a de-centralised community of users that innovate and develop for their own consumption without a manufacturer to act as agent. The development cycle is rapid, where committed changes feed back into public repositories and put back into projects so that they can be released and tested iteratively. Due to the unrestricted access to source code, high-quality, quick results can be achieved. Consequently, open source software has become ubiquitous in all aspects of computing.

The advantages observed in open source software has slowly diverged into the development of hardware (Davidson, 2004). The reason for the slower uptake is not due the licensing itself, but the fact that the open source development process is heavily restrained by electronics know-how and the physical prototyping systems that users require to participate (Waddington and Taylor, 2007).

2.4.1.1 The DIY community

The insurgence of OSH was first facilitated by *physical computing*. This concept aims to create a link between the physical world and the computer using electronic sensors and actuators. Traditional hardware examples include the desktop monitor, mouse and keyboard. The design of physical computers depends on prototyping complex physically

[30] `https://opensource.org/`

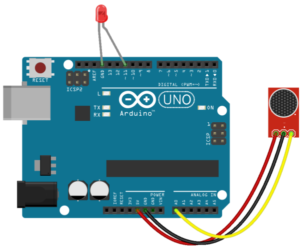


image from http://johnny-five.io

Cost	$30
Bandwidth	5 Hz - 5 kHz
Sensitivity	Not applicable
SNR	48 dBA
Battery (1000mAhr)	20 hr
Weight	30 g
Memory	3 kB

Figure 2.4: Arduino with external microphone: the first open source physical computer and catalyst for the DIY community

interactive systems (O'Sullivan and Igoe, 2004), with recent research driven by art-based interaction design students. The development of a tool that simplified the physical prototyping process was pushed by this non-technical community. Subsequently, an intuitive prototyping system emerged (*Wiring* by Barragán, 2004), which was designed to facilitate the non-technical students to build their own physical computers. The open source prototyping board was originally developed for the *Interaction Design Institute Ivrea*, and became known as *Arduino*[31]. The board was designed to simplify the implementation of adding physical sensors and actuators with easy-to-use software architecture. *Arduino* uses low-cost readily available plugin components to reduce the cost of the device ($22 USD) and computes on an 8-bit *ATmega328* micro-controller running at 16 MHz (Figure 2.4). The device is a bare prototyping board designed for mains/USB power with easy to access plugin input and output peripherals, including a serial peripheral interface (SPI), six analog 8-bit pulse width modulation (PWM) buses and a universal asynchronous receive and transmit (UART) bus. *Arduino* was one of the first minimalist and utilitarian electronic products designed for the general public. What made *Arduino* compelling was that the original hardware commit had no concerns for quality or aesthetics. However, due to its open source nature and the large community of students involved in using the product, its iterative development rapidly improved its quality and usability. *Arduino* soon matured, moving away from the physical computing space, finding itself at the forefront of a new OSH hacking culture.

The DIY community is another name for the physical form of commons-based peer production, which began soon after the release of *Arduino* with the educational *Makerspace* and *Hackerspace* culture (Raasch and Von Hippel 2012, Jackson 2014, Kostakis et al. 2015). Unlike commons-based online communities, such as those observed in open source software, the DIY community relies on individuals meeting in physical places to share ideas, knowledge and equipment (Ferretti, 2019, Cressey, 2017). This started with after school social clubs that used these boards to teach and educate (Buechley 2009, Niaros

[31] `https://www.arduino.cc/`

et al. 2017). Open source prototyping boards, such as *Arduino,* were key to the electronics DIY community, allowing individuals to innovate and create products for themselves, without the need for computing experts or a centralised manufacturer (Von Hippel, 2001). As well as educational makerspaces, the DIY community soon realised the benefits of *Arduino* for creating low-cost scientific equipment (Pearce 2012). The unrestricted access of creators to user needs, and users to developer designs, facilitated rapid community prototyping of fit-for-purpose tools, either by centrally managed revisions based on user feedback or by user modifications on original designs (O'Mahony, 2007). The resulting self-made equipment soon enabled replicable data to be gathered at a lower cost than could be achieved with commercial hardware of equivalent utility (Drack et al. 2018). These benefits enabled systems based on OSH to colonise niches in technology markets previously unreachable by models based on intellectual property (IP) (Hsing 2018). The first scientific tools built using the open source *Arduino* included lab kits for learning embedded electronics at home (Sarik and Kymissis 2010), adding radar and infra red (IR) cameras to them for off-shore wind farm monitoring (Jamali et al. 2011), monitoring forest activity (Shafiril et al., 2016) and as a general environmental monitoring tool (Gertz and Di Justo 2012). *Arduino* was even applied to acoustic monitoring applications for rainfall sensors (Trono et al. 2012) and acoustic event localisation (Perez and Carrera, 2014). However, the original *Arduino* was not quite equipped to record high quality audio, with a slow analog to digital converter (ADC) that limited the sample rate to 10 kHz (Figure 2.4). For both these studies *Arduino* captured acoustic data at very slow sample rates (i.e. 10 Hz for the rain fall study).

2.4.1.2 Single-board computers

One technology that has radically improved the specifications, usefulness and speed of producing DIY scientific equipment, is that of the *Raspberry Pi* single-board computer[32]. Although the hardware is not open source, *Raspberry Pi* creates a community feeling of commons-based peer production, running the open source *Linux* operating system and having exposed general purpose input and output (GPIO) pins (Brock et al. 2013). The hackable single-board computer creates a freedom to extend for specific applications (Kling, 2018). *Raspberry Pi* is based on the *Cortex-A72 BCM2711* processor, which has an equivalent processing power to that of a laptop from 2010. The device measures just 56 mm by 86 mm and like *Arduino,* it has a utilitarian and minimalist philosophy, costing $35 USD. The system was designed to get young people interested in technology and programming; however, the low-cost, small size, and huge number of GPIO pins quickly saw *Raspberry Pi* become the global standard in hardware prototyping (Severance, 2013). *Raspberry Pi* has allowed researchers to look beyond high-quality commercially available options, enabling them to replace their specialist scientific equipment with hand-built sensors.

[32] `https://www.raspberrypi.org/`

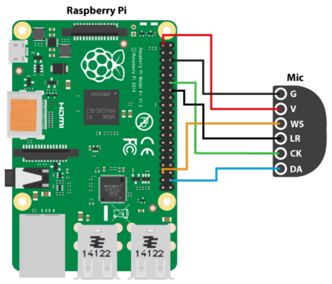


image from https://www.audiophonics.fr/

Cost	$432
Bandwidth	60 Hz to 192 kHz
Sensitivity (audible only)	-28 dBV
SNR	80 dBA
Battery (1000mAhr)	13 hr
Weight (including case)	700 g
Memory	64 GB

Figure 2.5: Raspberry Pi with external microphone: a powerful educational micro-computer designed to teach users about the workings of a computer. The specs are taken from the latest acoustic monitoring device, AURITA

To this end, hand-built, fit-for-purpose solutions have seen a rapid increase in the last few years, often facilitated by new additions to the low-cost single-board computer space (i.e. *BeagleBone*[33] and *PCDuino*[34]). In the fields of conservation, ecology, and environmental sciences alone, there has been a staggering uptake, with over a hundred publications reporting on scientific tools created using just *Raspberry Pi*. Recent examples include tools created to monitor pedestrian behaviour at festivals (Biedermann et al. 2015), environmental humidity, air quality and earthquakes (Ibrahim et al., 2015, Kumar and Jasuja, 2017, Saha et al., 2018), plant growth (Grindstaff et al. 2019), water quality (Vijayakumar and Ramya, 2015), animal tracking (Chen and Wong, 2015, Ahmad et al., 2018), and one of the most most popular: acoustic monitoring (Travaglione et al. 2014, Mydlarz et al. 2017, Haro et al. 2014, Küçükbay et al. 2017, wa Maina et al. 2016, Eliseev et al. 2014, DelPreto et al. 2015, Whytock and Christie 2017, Aravinda et al. 2016, Gyulyustan and Enkov 2017, Noriega-Linares and Navarro Ruiz 2016).

The latest acoustic monitoring tool based on *Raspberry Pi* is *AURITA* (Beason et al. 2018), consisting of an audible microphone (*Primo EM172*[35]) and a commercial *Peersonic RPA2* bat recorder[36]. The *AURITA* is compelling as it can record both audible and ultrasonic frequencies simultaneously. As seen in Figure 2.5, the *AURITA* outperforms many of the commercial best-in-class devices with a bandwidth from 60 Hz to 192 kHz, sensitivity of -28 dBV and a SNR of 80 dBA (Figure 2.1 & 2.2).

Despite the advantages seen in DIY tools, many barriers still lie in the way of implementing them for conservation purposes. Firstly, they are restricted by their high power consumption (Figure 2.4 & 2.5). The devices based on *Raspberry Pi* for instance, have inefficient power optimisation and consequently require large batteries to sustain power over long periods. Solo, a well known *Raspberry Pi* based platform (Whytock and

[33] `https://beagleboard.org/bone`
[34] `http://www.linksprite.com/pcduino-family/`
[35] `https://micbooster.com/primo-microphone-capsules/8-primo-em172.html`
[36] `https://peersonic.co.uk/`

Christie, 2017), uses a 12 V car battery to compensate for its high power consumption in long-term deployments. As with commercial acoustic monitoring devices, the need for larger battery capacity often makes monitoring tools based on single-board computers too bulky for field deployments in remote areas where sensors must be transported manually. Although the open source single-board computers are usually less than $40 USD to purchase, the external sensors and batteries required for them to function usually makes a complete system well over $100 USD. Most studies using single-board computers require a considerable investment in terms of time to configure each unit. To fabricate more than one, a considerable amount of human resource is required, with numerous steps that can incur human error. In addition, all hardware modules require hobbyist electronics or programming skills to initially configure. These are skills the average conservation practitioner is unlikely to possess. Therefore, even though so many studies are utilising them for small-scale research, they are still infeasible to use for large-scale deployments. For this reason, researchers are now looking beyond off-the-shelf options, towards completely tailored open source systems engineered for specific tasks (Kwok, 2017).

2.4.1.3 Tailored open source hardware

The open source movement is now at a stage where anyone with electronics know-how can become a hardware engineer at home. Circuit board development is easy and cheap to perform, with numerous computer aided design (CAD) programs available to download for free. These include *Eagle*[37], *Upverter*[38], *Kicad*[39] and *CircuitMaker*[40]. Electronics components are getting easier to access online, with websites such as *Octopart*[41] providing global availability, with associated vendors and delivery to order. OSH is generally dependant on advancements in technology (Gibb et al. 2019). Advancements push demand and usage of components with high volume manufacture, thus making usually expensive components more accessible online and lowering costs. Together with the rapid developments, cost/size reductions and accessibility of new advanced technology, these open access software resources are allowing researchers to miniaturise and improve on commercial and single-board computer designs with their own fit-for-purpose scientific equipment (Wang et al. 2009, Martinez et al. 2017, Mickley et al. 2019). One recent technological advancement is that of new low-cost miniature microphones.

[37] https://www.autodesk.com/products/eagle/overview
[38] https://upverter.com/
[39] http://www.kicad-pcb.org/
[40] https://circuitmaker.com/
[41] https://octopart.com/

Low-cost miniature microphones

Low-cost microphones first started appearing with the development of the piezoelectric type, also known as ceramic or crystal microphones (Sawyer, 1931). These microphones use the interactions between electromagnetic fields and mechanical stresses on piezoelectric materials (e.g. crystals) to produce an electrical charge. Ions on the solid structure are displaced when the structural surface is strained by fluctuations in sound pressure, known as the electromechanical effect (Muralt, 2001). Originally, these types of microphone were made of naturally occurring minerals, such as quartz and Rochelle salt. Although prone to depletion in humid environments, their cost made them suitable for applications where sound quality was not a priority, such as public address systems and two way radios during the 1930s. Piezoelectric microphones are now made from synthetic material (e.g. barium titanate and potassium niobate) and have improved in performance considerably over the last few years. The *muRata 7BB-35-3* is a typical example of a low-cost ceramic piezoelectric diaphragm, costing $0.90 USD[42]. Having high sensitivity in air, this type of microphone are prone to handling noise and have poor performance in the audible range. Subsequently, they are more often used as contact microphones, hydrophones or ultrasonic transducers.

The miniaturisation and cost of microphones improved considerably since the invention of the electret condenser microphone (Sessler and West, 1964). Electret condenser microphones function in a similar manner to traditional condenser microphones, using the change in capacitance between a membrane plate and fixed backplate to produce an electrical charge. Conventional condenser microphones require a maintained charge across the membrane and the backplate from an external power source. In electret microphones, one of the capacitor plates is made from a ferro-electric material with a prepolarized charge, eliminating the need for an external power source. Without the need for external power, these microphones can be miniaturised. This makes them cheaper to produce without loosing the sensitivity and SNR performance of the expensive condenser microphones. They are now the most readily used microphones, with over two billion produced each year. A typical electret microphone is the *CUI CMC-4015025T,* which is circular shaped, costing $2.09 USD and measuring 4 mm in diameter[43]. This microphone is comparable in quality to the best-in-class audible range, with -25 dBV sensitivity and a 62 dBA SNR.

One of the largest uses of low-cost electret sensors is that of the smartphone industry, utilising approximately 900 million a year (Nielsen and Fürst, 2007). The rapid push for reducing microphone size, improving performance and lowering cost, influenced the development of the latest microphone type, the microelectromechanical systems (MEMS) microphone. These tiny surface mounted integrated silicon circuits (IC) can measure 2

[42] `https://www.murata.com/~/media/webrenewal/support/library/catalog/products/sound/p37e.ashx?la=en-us`

[43] `https://www.cuidevices.com/product/resource/cmc-4015-25t.pdf`

mm by 3 mm in size (Figure 2.6). MEMS microphones act in a similar manner to condenser microphones. The transducers in these ICs are created by etching away layers of material that lie on top of a base silicon wafer to form: a moveable membrane, a layer of free moving air, and a fixed backplate. The membrane is designed to vibrate with changes in air pressure, which form a capacitance between the fixed backplate. The microscopic size of the membrane enables high sensitivity in both the ultrasonics and the audible frequencies. MEMS microphones are therefore able to outperform the majority of larger traditional microphones in terms of bandwidth. As a result, they have compelling full-spectrum performance at an extremely low cost. MEMS microphones come in two forms: digital and analog. Digital MEMS microphones process the analog signal as part of the MEMS IC, using a clock input from the processor. The output of digital MEMS microphones can either be a single bit pulse density modulated (PDM) or inter IC sound (I^2S) stream of data. The advantage of digital microphones is that they output amplified digital signals that are relatively immune to noise and do not require any ADC or amplification circuitry. This results in a very simple hardware implementation. The disadvantages of digital MEMS microphones, however, is that they are limited to the audible frequency bandwidth and have higher current consumption than analog MEMS microphones. In comparison, analog MEMS microphones are relatively simple in their construction, with only three pins, including power, analog output and ground. They are advantageous because of their broad bandwidth, which is controlled by the ADC peripheral on the processor rather than the input clock frequency. The disadvantage with analog microphones, however, is that they require more complex circuitry that requires meticulous PCB layout to avoid noise. In addition to this, other hardware design stages are required, including amplification and ADC oversampling techniques.

MEMS microphones are approximately 50 times cheaper than those available in the best-in-class ranges. From the cheapest *Knowles SPU0410LR5H*, costing $0.30 USD, to the most expensive *TDK InvenSense INMP404ACEZ,* costing $4.30 USD. MEMS microphones have very low current consumption, with some having as little as 52 µA during operation. They also have excellent durability, with temperature operating ranges between -40 to 100 ℃. MEMS microphones are now moving from electret condenser techniques to piezoelectric, with the first piezoelectric MEMS microphone released in 2017, the *Vesper VM1000.* The *VM1000* differs to larger piezoelectric types with a stable performance in all conditions, high SNR of 64 dBA and a sensitivity of -38 dBV. Table 2.1 compares the features of some of the smallest, most sensitive and cost effective microphones available.

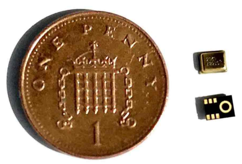


Figure 2.6: Illustrative figure demonstrating the size of MEMS microphones

Microphone	Type	Sensitivity	SNR	Bandwidth	Current	Cost
Vesper VM1000	Piezo Analog	-38 dBV	64 dBA	20Hz - 190kHz	165 µA	$1.20
CUI CMC-4015025T	Electret Analog	-25 dBV	62 dBA	20Hz - 48kHz	500 µA	$2.09
Knowles SPU0410LR5H	MEMS Analog	-38 dBV	63 dBA	20Hz - 190kHz	120 µA	$0.30
Knowles SPV1840LR5H	MEMS Analog	-38 dBV	62.5 dBA	20Hz - 80kHz	52 µA	$0.35
Vesper VM1000	MEMS Analog	-38 dBV	62 dBA	20Hz - 80kHz	165 µA	$0.57
Knowles SPM1423HM4H	MEMS Digital	-22 dBFS	61.5 dBA	20Hz - 48kHz	500 µA	$0.64
Knowles SPM0408LE5H	MEMS Analog	-18 dBV	63 dBA	20Hz - 190kHz	350 µA	$1.39
InvenSense INMP404ACEZ	MEMS Analog	-38 dBV	62.5 dBA	20Hz - 48kHz	250 µA	$4.30

Table 2.1: Comparisons of available MEMS microphones

For comparability to the best-in-class audible performance, the *Knowles SPM0408LE5H* stands out with a -18 dBV sensitivity. Neglecting SNR, the sensitivity and bandwidth of this microphone demonstrate improvements to those highlighted in the best-in-class products, except for that of the *Frontier Labs BAR* (Figure 2.1 and 2.3).

Ultra-low-power embedded systems

New micro-controller technology is enabling the use of evermore powerful ultra-low power on-board processing, which can be utilised to create algorithmic decisions as whether to store data. Unlike smartphone and *Raspberry Pi* based tools, the energy consumption on ultra-low-power (ULP) embedded systems can be optimised. As power usage can be lowered when not in full operation, static deployments can be performed over years rather than hours. With the recent growth of small battery powered devices connected to the internet, known as the *Internet of Things* (IoT), the performance of ULP embedded systems have rapidly improved. ULP embedded systems are generally built from low-power micro-controllers, which come in a variety of classes. They are characterised by their memory architecture, instruction set, peripherals, clock speed and register size. Generally, register size, clock speed and peripherals are the main characteristics that describe the functionality of a micro-controller for a specific application. Register size comes in three different types: 8-bit, 16-bit and 32-bit. Bits refer to the arithmetic register limit that can be reached, with higher bit depth resulting in increased speed of mathematical operations (i.e. 8-bit register is limited to 0-255, 16-bit register is limited to 0-65535 and 32-bit register is limited to 0-4294967295). High precision is imperative for acoustic monitoring devices, with typical audio sampled at 12 or 16 bits. Therefore, the micro-controllers of concern are the 32-bit class, which are also much faster than typical 8-bit systems.

The micro-controller peripherals describe whether the input or output pins have hardware enabled protocols, which are predefined on-chip. These functions may include integrated regulators, digital chip-to-chip communications (i.e. SDIO, UART, I^2C), direct memory access (DMA), ADC, digital to analog conversion (DAC), timers, counters, and liquid crystal display (LCD) controllers.

Power is important to understand in ULP embedded systems. When describing the energy consumption of a micro-controller, it is often normal to see it as a measure of

Manufacturer	Micro-controller	Active energy	Architecture	Peripherals
Silicon Labs	Giant Gecko	80µA/MHz	32-bit M4F	EBI, I²C, SPI, UART/USART, USB, DMA, I²S
Silicon Labs	Tiny Gecko	37µA/MHz	32-bit M0+	I²C, SPI, UART/USART, DMA, I²S
Ambiq	Apollo2	10µA/MHz	32-bit M4F	I²C, SPI, UART/USART
ST	STM32L5	60µA/MHz	32-bit M4F	I²C, IrDA, SPI, UART/USART, DMA
NXP	LPC1768FBD100	500 µA/MHz	32-bit M3	I²C SPI, UART/USART, USB, DMA, I²S

Table 2.2: Specification comparisons of available ultra-low power (ULP) micro-controllers

continuous current at a specific clock frequency (e.g. 500µA/MHz). This is because power is directly proportional to the clock frequency of the processor. As a comparison, Table 2.2 shows the power consumption of some of the most energy efficient micro-controllers on the market.

2.4.1.4 Barriers to entry

Despite the technological advancements now available to DIY projects, OSH products are far from usable when considering the conservation practitioner. As with the majority of tailored OSH, the processes involved in purchasing, fabricating, testing, configuring and deploying bespoke systems presents many technical barriers that limit their uptake and the systems usability. Device purchase requires users to interact with manufacturers to fabricate PCBs from design files. This requires users to have electronics fabrication knowledge to place the order. To build each device, users need to manually assemble them by hand. This involves the soldering of surface mount components, which depending on size and number of components, can take several hours per board for even an expert to complete. To test the device, users require development boards and an integrated development environment (IDE) to get the board up and running. To configure the device, users need to hardcode application specific functions, requiring a deep understanding of the low level source code and the micro-controller specific compilation process. Experience from users of devices such as Mataki[44] suggests that conservation technology puts a premium on ease of configuration in the field. *Raspberry Pi* and *Arduino* differ in this respect with a large global outreach, meaning device purchase, fabrication and testing is achieved using a commercialised central manufacturer.

Overlooking the success of *Arduino*, it is normal for organisations formed around OSH to find difficulties in obtaining financial resources to continue development after the first prototype is published. Hence, OSH projects soon terminate after initial funds are spent. Generally, this is due to lack of a consumer market (Li et al., 2018). New creators inadvertently reinvent tools when the design files of previously created equipment lapse or become lost. Commercial hardware retains an advantage in this respect with the higher financial outlay paying for product delivery, guarantees and after-sales care.

[44] `https://www.mataki.org`

In recent years, however, the collaborative economy has expanded from simply sharing knowledge – as seen in the open source movement – towards the sharing of personal monetary resources to achieve a mutual benefit for the community. The collaborative economy therefore shows promise for community driven OSH consumption.

2.4.2 Crowdfunding

Crowdfunding is a computer facilitated method of collecting funds from a group to finance the delivery of a resource (Ward and Ramachandran, 2010). A resource could be anything from information, money, goods or services (Foa and Foa, 2012). Delivery is achieved through models of shared access and distribution, with many companies now providing this as efficient online services (Greenberg et al. 2013). Although not the first, *Kickstarter* is one of the most well known services, with over 146,000 funded projects to date. *Kickstarter* works by hosting products or services, creating an efficient online platform where capital can be donated by the general public (*backers*) to kickstart a business (Steinberg, 2012). The backers in *Kickstarter* are incentivised by tangible rewards based on their donations (Mitra and Gilbert, 2014). Since *Kickstarter*, numerous variations of crowdfunding services have appeared. Some dedicate themselves to real-world issues and worthy causes such as *MightyCause*[45] and *Crowdrise*[46]. In the last few years some have found their niche within the hardware manufacturing realm. *CrowdSupply*[47] is one online platform, similar to *Kickstarter*, that specialises in hardware startups, enabling creators and engineers to fund electronic product developments for interested backers.

Traditional OSH is aimed at users who enjoy manual assembly by hand, generally with no support other than online build instructions. The *build-yourself* nature therefore requires electronics development skills, with tailored tools, needing soldering and validation procedures. However, OSH does not always have to be soldered manually, as seen with *Arduino,* which is assembled by a central manufacturer. To achieve this, *Arduino* incurs a high tooling cost to place the components, this is fixed no matter the size of the order. Thus, using a manufacturer to build low quantity orders is always very costly. For conservation practitioners who lack electronics DIY knowledge and take up a very small commercial market, OSH presents barriers to entry.

One crowd funder that addresses this issue is *GroupGets*[48]. *GroupGets* is a hardware-based crowd funder that unlocks economies of scale by supporting like-minded communities to unite in a bulk order.

This type of crowdfunding motivates my work in Chapter 4, where I investigate how it can improve the accessibility of OSH for conservation practitioners.

[45] `https://www.mightycause.com/`
[46] `https://www.crowdrise.com/`
[47] `https://www.crowdsupply.com`
[48] `https://groupgets.com/`

2.5 Summary

In summary, environmental sound is a powerful data source for investigating ecosystem health. To capture it, scientists commonly use ruggedised, but expensive acoustic monitoring equipment. OSH can be used to build lower cost, full-spectrum alternatives, presenting benefits by enabling rapid reuse of new technological advances to improve on commercial tools. However, knowledgeable user communities are often required to make use of them. Instead of relying on experts to apply existing open source tools to specific conservation problems – as seen in *Raspberry Pi* and *Arduino* projects – one reputable approach would be to design a usable open source tool around the conservation practitioners themselves (i.e. UCD, Abras et al. 2004). Hence, to design an acoustic monitoring conservation tool, it is crucial to understand the specific characteristics of the user-groups within the conservation technology system.

User requirements can be derived from the evaluation of the existing acoustic monitoring tools (Table 2.3) together with the characteristics of the conservation practitioners defined in Section 2.1.1.

Device class	Model	Battery	Sensitivity	SNR	Bandwidth	Weight	Memory	Cost
Smartphone	ARBIMON	10 yr	-45 dBV	n/a	50Hz-20kHz	1.7 kg	n/a	$4000
Best-in-class	D500X	140 hr	n/a	n/a	5kHz-190kHz	1.3 kg	128 GB	$2,551
ultrasonic	Batlogger	50 hr	n/a	n/a	10kHz-150kHz	695 g	128 GB	$1,180
	Anabat	530 hr	n/a	n/a	10kHz-125kHz	648 g	1 TB	$1,194
	SM4BAT	450 hr	n/a	n/a	10kHz-250kHz	1.3 kg	1TB	$1,099
Best-in-class	SM4	400 hr	-28 dBV	80dBA	20Hz-48kHz	1.2 kg	1 TB	$849
audible	BAR	600 hr	-14 dBV	80 dBA	20Hz-48kHz	900 g	2 TB	$750
Single-board	AURITA	13 hr	-28 dBV	80dBA	20Hz-192kHz	700 g	64 GB	$432
Dictaphone	H2n	20 hr	-23 dBV	68 dBA	20Hz-48kHz	190 g	32 GB	$187
	DR-05X	17 hr	-20 dBV	>60 dBA	20Hz-96kHz	176 g	128 GB	$173
	WS-853	110 hr	-35 dBV	>60 dBA	20Hz-22kHz	100 g	32 GB	$100

Table 2.3: Comparisons of existing acoustic monitoring devices

The following user requirements have been established from this literature review:

1. The acoustic monitoring tool should be able to function in the same context as all devices reviewed. These include, statically deployed best-in-class devices (e.g. the *Song Meter* series described in Section 2.3.1.1 and 2.3.1.5), handheld dictaphones (e.g. *Zoom H2n* in Section 2.3.1.2) and customisable/extendable single-board devices (e.g. *Raspberry Pi* in Section 2.4.1.2).

2. The most important baseline feature to match is that of bandwidth. The user therefore requires a tool with high quality ultrasonic and audible sound capture capabilities, enabling them to record all vocalising animals. Table 2.3 defines the baseline range from the lowest frequency: 20Hz (*SM4*), to the highest frequency: 250kHz (*SMBAT*).

3. The majority of acoustic monitoring projects are performed outside, therefore, users require a device that must perform measurements outdoors in remote locations. This means hardware must be able to power itself away from the mains grid, while also protecting itself from harsh weather conditions. The baseline casings for outdoor deployments are illustrated in the best-in-class ranges in Figure 2.1 and 2.3.

4. The user should be able to leave the monitoring equipment for extended periods of time with minimal maintenance visits. The device should be power efficient to enable batteries to last over long periods of time. The maximum baseline operation life is 600 hrs, which is achieved by *Frontier Labs BAR* (Figure 2.1b). Single-board computers display deficiencies in this area, running full Linux operating systems.

5. Conservation areas are remote and in locations hard to access. The user should be able to transport many units by foot. This means hardware must be lightweight and small.

6. Conservation technology is renowned to attract theft, the hardware must be designed in a way that prevents this.

7. Each group of user must be able to acquire the hardware globally, whether it be bought by themselves, donated or funded through research. The device must therefore have low material costs, the baseline is that of the *Olympus WS-854* dictaphone at $100 USD.

8. The majority of conservation practitioners have little knowledge on electronics assembly methods, therefore, the device must have an option to be acquired fully assembled.

9. The users requires device support, whether it be for device setup, software help or deployment planning.

10. An important user, which is often overlooked in open source conservation technology, is that of the *OSH creator*. As part of the overall system, their monetary requirements must be considered to allow continued utility beyond device creation.

11. The *university level students/researchers* should be able to perform on-board analysis on the hardware, such as that seen on best-in-class ultrasonic devices (Section 2.3.1.5). This would allow researchers to perform triggering functionality to address specific research questions.

12. The system should be configurable, relevant to the users ergonomic and user interface experience. Multiple configuration options should be available to both the computer literate, those unfamiliar with modern computing interfaces and also experienced open source developers that can improve on the design.

In the next chapter (Chapter 3) we fully describe the hardware development and build of a low-cost, small, full-spectrum acoustic monitoring device, which was designed against these requirements using UCD principles.

Chapter 3

AudioMoth: A low-cost, open source acoustic sensor for conservation

The shortcomings of existing acoustic technology outlined in Chapter 2 motivated the development of *AudioMoth*, an open source acoustic monitoring tool for conservation. The credit-card sized device consists of a printed circuit board, ULP micro-controller and a MEMS microphone. This simple to construct hardware facilitates: (i) large-scale deployments in remote locations, with a small size and a simple mechanism that allows it to be retrofitted into numerous low-cost ruggedised enclosures; (ii) long-term monitoring, with low-power operation; (iii) acoustic detection, with onboard processing power; and (iv) modular expansion, with easy to access general purpose input and output pins. This chapter summarises its UCD development (Section 3.1), then fully describes its hardware build (Section 3.2, 3.3 and 3.4) and user-instructions (Section 3.5, 3.6 and 3.9). For users wishing to manually assemble the hardware, the validation process is described in Section 3.7. In Section 3.3.3 two types of enclosure to house *AudioMoth* are described and instructions are outlined for how these enclosures can be deployed in typical conservation applications (Section 3.8). Chapter contents from Section 3.2 are taken from the peer-reviewed *Hardware X* journal publication (Hill et al. 2019b).

3.1 Summary of the user-centred design process

AudioMoth development was guided by the UCD *ISO 9241-210:2019* definition, as stated in Section 2.1. This section briefly details the development process, with subsection headings elaborating on each part of the *ISO* definition, including: (i) the multidisciplinary design team, (ii) the whole user experience, (iii) the users and the tasks they perform, (iv) the iterative design, (v) the user involvement, and (vi) the user evaluation.

3.1.1 Multidisciplinary design team

The *AudioMoth* design team is a research group known as *Open Acoustic Devices (OAD)*[1]. The team consists of myself and five other multidisciplinary members, including:

Andrew Hill (author): An electronics engineer and computer science PhD student with skills in electronics hardware design, programming, human-computer interaction, accessibility, hardware manufacture, product design, maintenance, multimedia production, technical writing, user support, branding and service management.

Peter Prince: A software engineer and computer science PhD student with skills in software design, programming, human-computer interaction, usability, user research, technical writing, user support and data analysis.

Alex Rogers: Professor of computer science at the University of Oxford with skills in human factors, ergonomics, branding, user interface, product design, training, technical writing, software design, programming, human-computer interaction, usability, user research, systems engineering, software engineering, hardware design, production and manufacturing.

Patrick Doncaster: Professor of ecology at the University of Southampton with skills in technical writing, statistics, health and safety, programming, training, application domain expertise and subject matter expertise in conservation and ecology. He is a conservation practitioner and has an advisory role in product design representing user perspectives.

Jake Snaddon: Environmental scientist at the University of Southampton with skills in technical writing, statistics, sustainability, multimedia production, photography, training, application domain expertise and subject matter expertise in ecology and environmental sciences. He is a conservation practitioner and has an advisory role in product design representing user perspectives.

Evelyn Piňa-Covarrubias: Conservation scientist at the University of Southampton with skills in technical writing, statistics, user-research, application domain expertise and subject matter expertise in ecology and conservation. She is a conservation practitioner and has an advisory role in product design representing user perspectives.

[1]`https://www.openacousticdevices.info/`

3.1.2 Users and tasks

The conservation practitioners that will use *AudioMoth* as well as those that might be affected by its use are split between five groups, each with specific tasks:

1. ***University or institution level students/researchers*** tasks:
   (a) Overall their goal is establish frameworks for others to carry out conservation work.
   (b) They aim to publish findings in journals or conferences.
   (c) Publications are based on the analysis of data to identify species, location and behaviour, thus answering very specific research questions.
   (d) Analysis relies on the collection of audio data to analyse.
   (e) The larger the spatiotemporal scale of data collection the higher the impact.
2. ***Government institutions and councils*** tasks:
   (a) Overall their goal is to advise government conservation policy.
   (b) They use published findings to influence decisions.
   (c) They actively manage conservation areas in partnership with volunteers.
   (d) Volunteers take part in surveys to assess biodiversity.
   (e) Surveys are often visual counting exercises.
3. ***Conservation organisation employees and volunteers*** tasks:
   (a) Overall their goal is to run mission-oriented and time-limited projects demonstrating tangible improvements in the functioning or state of ecosystems, habitats or the status of species.
   (b) Volunteers take part in surveys to assess biodiversity by collecting data with donated, free or loaned tools.
4. ***Nature reserve managers*** tasks:
   (a) Organise research locations throughout the reserve and report incidents.
   (b) Manage the collection of audio data or species samples.
   (c) Make sure governance is complied with and hunting regulations are enforced.
   (d) Manage the protection of all natural resources.
   (e) Manage public engagement and education.
5. ***Local rural communities*** tasks:
   (a) Report incidents.
   (b) Protection of their own natural resources.

These groups are described in more detail in Section 2.1.1.

3.1.3 The whole user experience

Each aspect of the whole system requires careful design decisions to justify the overall user experience. These decisions are based on the context of use, starting at product discovery all the way to data analysis. The design decisions take into account the users' and stakeholders' prior experiences, skills and habits. Design choices are based on the relative capabilities and limitations of technology, as well as the methods available for purchase and distribution. The human activities outlined in Figure 3.1 were developed throughout the UCD design process. They form the set of tasks that are meaningful as a whole to the conservation practitioner, OSH creator and manufacturer. This Chapter focuses on the physical hardware aspects of the human activities, with purchase and distribution covered later in Chapter 4.

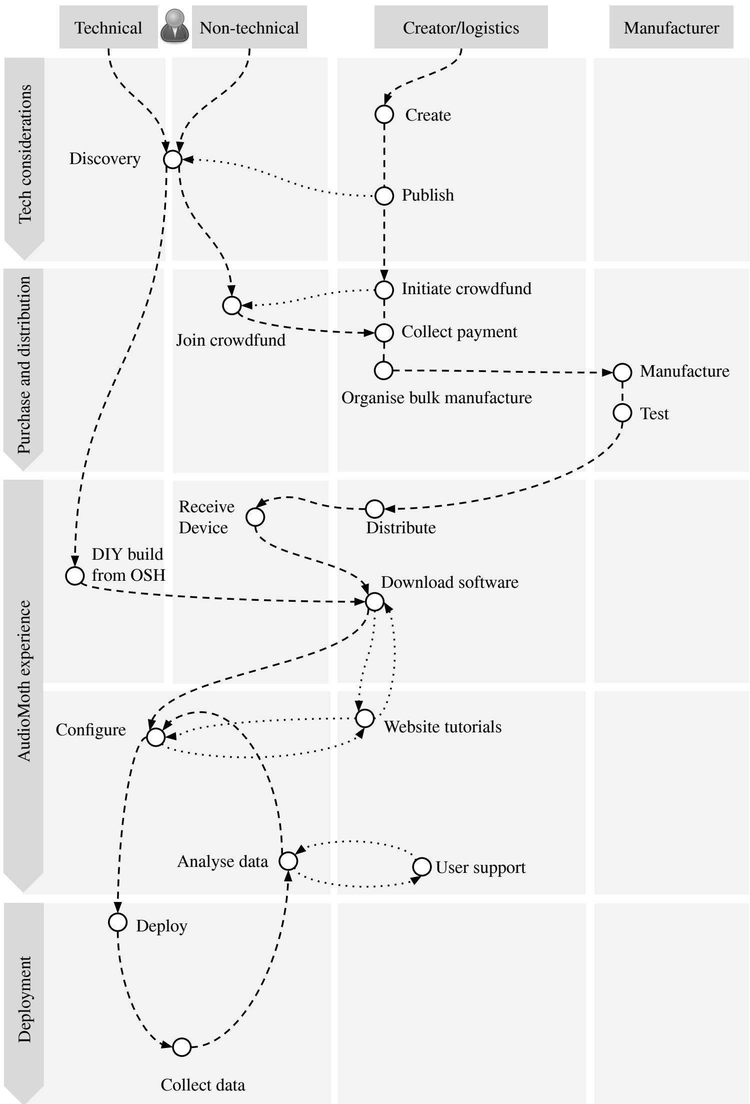


Figure 3.1: The whole AudioMoth system and user flow of operation

3.1.4 Iterative hardware design

Table 3.1 shows each hardware prototype, with column two displaying the related user-deployments and timeline, column three shows the main design differences for that prototype. Prototypes starting from Prototype 3 represent iterations based on user feedback and deployments. Each user deployment will be introduced and each design change per iteration will then be listed, relating back to specific user's comments. This chapter

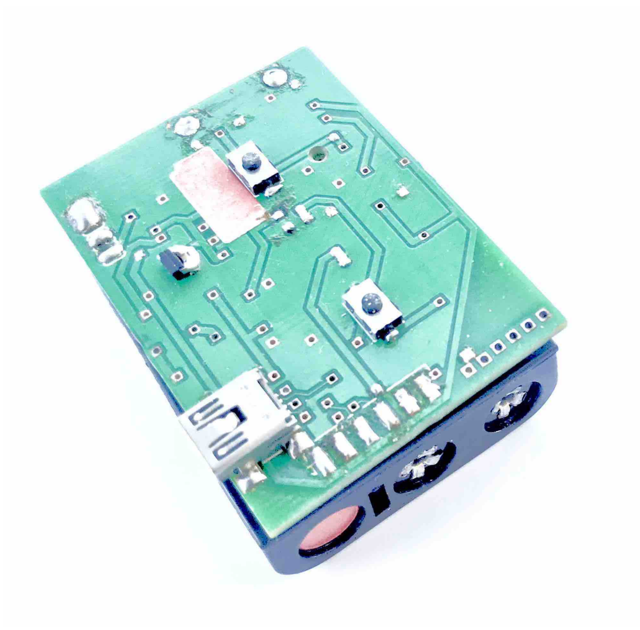
Prototype	Deployments	Design modifications
1	The New Forest Cicada Project, 2015	Single-board PCB with M3 LPC1768FBD100
		Digital microphone
		Outward facing components
2	Lab-based microphone evaluation, 2016	Removed digital microphone
		Added two analog microphones
		Moved some components to face inwards
		Switched to a ULP M3 EFM32GG980F512
3	Belize anti-poaching project, April 2016	Kept best performing analog microphone
	The New Forest Cicada Project, April 2016	Removed worst performing analog microphone
	BBC Garden Bat project, July 2016	Single push-button
	Recording bats by drone, January 2017	Removed USB mini connector on outward facing layer
		Added USB micro connector to inward facing layer
4	Belize anti-poaching project, April 2017	Removed push-button
	The New Forest Cicada Project, March 2017	Moved all components to face inwards
	The Southampton bat project, 2017-2018	Added 3-way switch
	The Madeira bat project, June 2017	Reduced distance between PCB and microSD card connector
	The Cuban bat project, July 2017	Modified firmware to indicate configuration
		Modified firmware to indicate battery life
		Modified PCB layout to remove electronic noise in ultrasonics
		Modified firmware to standardised .WAV format
		Switched to a ULP M4 EFM32WG380F256
		Added external SRAM to increase sample rate
5	Belize anti-poaching project, April 2018	Changed PCB size to support AA batteries
	The New Forest Cicada Project, April 2018	Added AA battery connector
	The Cuban bat project, July 2018	Modified firmware to turn LEDs off during operation
	User community deployments, 2018 - 2019	Modified firmware to remove hardware enabled oversampling
		Modified firmware to add software enabled oversampling
		Created custom enclosure to house AudioMoth from weather
		Added external GPIO header on outward facing layer
6	All user community deployments, 2019	Indented switch
		Tented vias
		Modified firmware to support exFAT microSD cards

Table 3.1: User deployments and the modifications for each AudioMoth prototype

is intended solely to outline the UCD process and design decisions. Full deployment descriptions will be discussed in Chapter 5.

Prototype 1 and 2 are early designs that exploit the new technologies described in Section 2.4.1.3. They are intended for lab-based preliminary tests, with the first prototype (Figure 3.2a) designed specifically for audible applications running on the ULP *NXP*

(a) Prototype 1

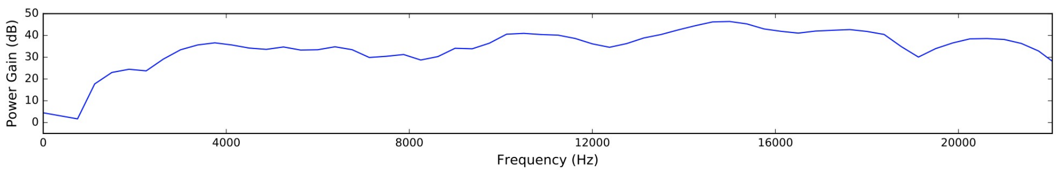


(b) Prototype 2

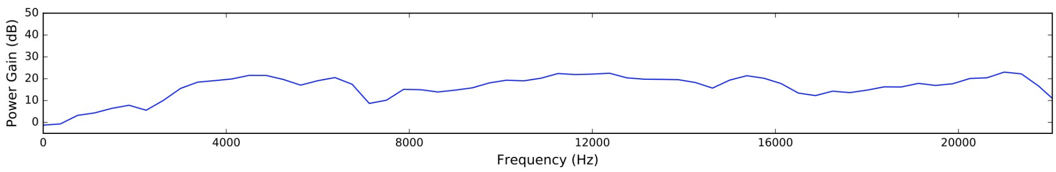
Figure 3.2: AudioMoth design iterations 1 and 2

LPC1768FBD100 (Table 2.2). Prototype 1 has a sensitivity level equivalent to the best-in-class audible range (-22 dBV), a low cost of $25 USD and a miniature size, measuring 35 mm by 50 mm. It was developed to address the issues observed in citizen science smartphone applications (as described in Section 2.3.1.3), particularly looking at continuous environmental monitoring to record the *New Forest cicada* as part of *The New Forest Cicada Project*. Like the smartphone running the *Cicada Hunt App*, Prototype 1 uses a digital MEMS microphone.

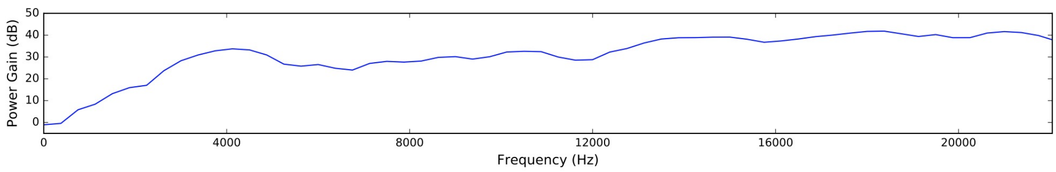
OAD used Prototype 1 as the starting point in the development of *AudioMoth*, implementing it as a baseline to evaluate available analog MEMS microphones, to increase the bandwidth to the ultrasonics (Table 3.1). *Prototype 2* was designed to support two analog MEMS microphones with improved energy efficiency, running on the ULP *ARM Cortex-M3 Silicon Labs EFM32GG980F512*. The analog microphones were used to compare the audio quality in comparison to Prototype 1 (Figure 3.2b). Figure 3.3 shows the results from microphone sensitivity tests. The graphs show sensitivity represented as power gain across the audible bandwidth. The graphs are generated by taking two recordings within an anechoic chamber: one of white noise and the other of silence. The ratio of white noise to silence for each microphone gives an indication of the microphones sensitivity across the bandwidth 0 - 24 kHz. For an ideal frequency response white noise should be at an equal amplitude across all frequencies. A lower power gain shows a reduced sensitivity. Figure 3.3 shows SPV1840LR5H-B to have the least sensitivity across all of the frequency ranges. SPM1423HM4H-B and SPM0408LE5H-TB show a comparable



(a) Prototype 1, using the Knowles SPM1423HM4H-B digital microphone



(b) Prototype 2 using the Knowles SPV1840LR5H-B analog microphone



(c) Prototype 2 using the Knowles SPM0408LE5H-TB analog microphone

Figure 3.3: MEMS microphone frequency response results

sensitivity (Figure 3.3a & 3.3c) and it can be seen that they have an evenly distributed sensitivity across the majority of frequencies, with the SPM1423HM4H-B having a better power gain in the mid frequency range from 5kHz to 12kHz. The analog microphone SPM0408LE5H-TB has a flatter frequency response across the higher frequency ranges indicating its potential for ultrasonic sounds capture.

3.1.4.1 User involvement and evaluation

The next iterations of hardware are built from *Prototype 3*, implementing the improved SPM0408LE5H-TB microphone for ultrasonic performance (Figure 3.4a). *Prototype 3* is the first iteration where the conservation practitioner's involvement and evaluation influence the *AudioMoth* design decisions.

Prototype 3: Capturing gunshot sounds

In April 2016 *Prototype 3* devices were deployed by Patrick Doncaster and Evelyn Piňa-Covarrubias, with the aim to capture gunshot and chainsaw disturbances for a comparative usability study using the commercial *SM3+* and Prototype 1 devices. The deployment was located at Pook's Hill lodge, located in Belize. The deployments were performed over a two day period, in which the data was collected and later analysed at the University of Southampton. The devices were set to record and left running while shotgun and chainsaw sounds were triggered at various distances from the devices. Below are Patrick's comments about *Prototype 3*:

> **Professor Patrick Doncaster, The University of Southampton** - *"Need to replace push-buttons with switches for start/stop and reset (to prevent inadvertent start/stop/reset). MicroSD can get caught between board and batteries if inserted carelessly. Would be useful to have a light to show that the logger has the time, or even LEDs that show the time if they don't consume much power. Would be useful to have LEDs or equivalent to show remaining battery life. It would be useful to allow recordings without time tag. Will need to filter out penetrating sound of cicadas (in Cockscomb)."*

Prototype 3: The BBC Garden Bat Project

In July 2016 several *Prototype 3* devices were deployed by Rory Gibb in residential gardens around Bishop's Stortford (UK). This was an initiative to get the public involved in crowd sourcing bat data. In this study the devices were compared against the popular *SM2+*. Rory Gibb was the field ecologist using the device at the time. Below are Rory's comments about *Prototype 3*:

> **Rory Gibb, University College London** - *"On one device the clock seemed to reset to 1970 at some point during each night's recording, and as a result it collected a lot less data than others. From manually inspecting and also running our detector/classifier algorithms on data from most of the loggers, it suggests that most of the best data (in terms of retaining bat call information and not being so noisy that it excessively confuses the classifier) was recorded by logger AudioMoth_P3. In these there was still background/-processing noise, but it was low enough to enable the bat passes to be recorded with enough clarity to detect/classify. On some devices the background noise (which looks like onboard processor noise) is mostly very loud, meaning that lots of the shape detail of the bat calls tends to be drowned out. The detector can still pick them up, because it was trained on very noisy data, but this makes it harder for classification/manual verification of species ID."*

Prototype 3: Recording Bats from Drones

Over January 2017 a project known as *EREBUS*[2] used *Prototype 3* to try and find out whether you can record bats by strapping the device to a small automated plane or boat. Tom August was the field ecologist using the device. Below are his feedback comments.

> **Tom August, Centre of Ecology and Hydrology** - *"Firstly, the device looks fantastic, the size is brilliant for our application! One of the major benefits of this detector is the size - it's tiny! This is a big help as the less weight we carry when flying the better; although, when using a detector on the boat this is less important. When testing the AudioMoth I pressed the button to set recording going, waited a few seconds, then pressed the button again to stop the recording. This created a short wav file which I was able to listen back to on my PC. However the file information suggested it was 1 minute long which it wasn't. Presumably this is because you have set it up to record one minute files. This appears to cause a problem with batsound as I was not able to open these short files with that program (which is our standard for opening and reviewing bat detector files). Figuring this was the cause I let it record for a few minutes and this time the files opened in batsound without a problem."*

Implemented decisions based on user feedback:

- Replaced push-button with switch (Patrick).
- Reduced distance between PCB and microSD card connector (Patrick).

[2] `www.projecterebus.weebly.com`

- Firmware changed to flash LEDs to indicate an error if time is not set (Patrick).
- Battery level is fed-back to user as various flash patterns on LEDs and also fed-back to display on the Configuration App (Patrick).
- Changed PCB layout to remove noise in ultrasonics (Rory).
- Changed audio *.WAV* format to allow integration with *Batsound* software (Tom).
- Changed processor to an M4F for improved mathematical precision and speed (Rory).
- Added external SRAM using EBI for higher sample rates beyond 250 kHz (Rory).

Prototype 4 is the next iteration based on user evaluation (Figure 3.4b).

Prototype 4: The Southampton Bat Project

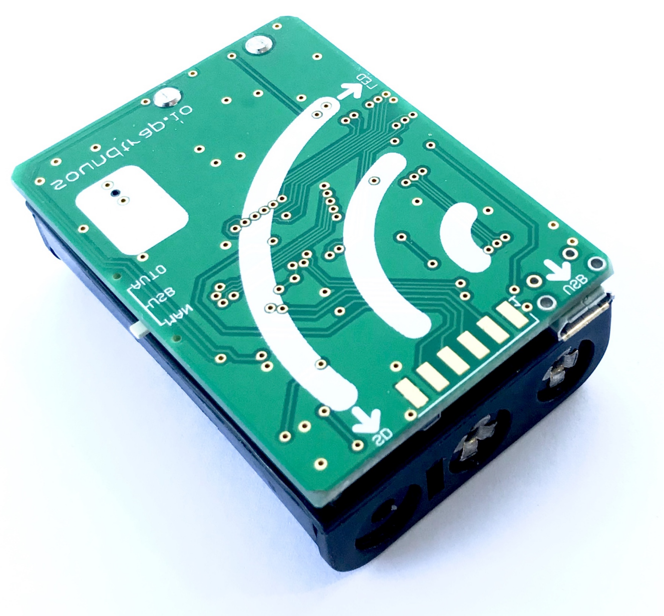
Jack Merrifield monitored bats around Southampton City through 2017 to 2018 using *Prototype 4* as part of his PhD project at the University of Southampton (Figure 3.4b). His research looked at establishing the impact that artificial light and ultrasonic sound can have on the foraging behaviour of bat species native to Southampton. Below are his feedback comments.

> **Jack Merrifield, The University of Southampton** - *"I'm enjoying using the loggers. Really excellent signal-to-noise ratio. For some reason they frequently seem to record for a short period rather than from sunset to sunrise. For example, one of them recorded until 9.30pm last night but the other didn't even get to sunset so only a few hours of useable data between them. The batteries are long life and aren't dislodged and I replace them between each sampling night. The card isn't full as it is also cleared between sampling nights. Yesterday I went to collect the devices only to find two of them had been stolen despite being inconspicuously placed. They were out of reach but I found a cut cable tie where one had been and a torn bag and damaged branch where the other had been so someone had clearly gone to some trouble to get to them."*

Prototype 4: The Madeira Bat Project

The Madeira bat monitoring trial was performed by Diogo Ferreira, aiming to compare *Prototype 4* to commercial bat monitoring devices, such as the *SM2+*, in a long-term

(a) Prototype 3



(b) Prototype 4

Figure 3.4: AudioMoth design iterations 3 and 4

monitoring project. Madeira may be populated by three bat species, including the vulnerable Madeira pipistrelle. However, not much is known about the bats on the island. Diogo deployed *Prototype 4* in randomised locations across the island. Below are Diogo's feedback comments.

Diogo Ferreira - *"Some suggestions and comments regarding my experience* *with AudioMoth. The detectors are quite easy to use and things are going as planned right now. I had a problem in the beginning with the detectors (except with one of them) that had the new SD cards. They stopped recording at the beginning/middle of the night and after the red light appeared. I still don't know why. The other thing was the rain. It rained during one day and in the top of the mountains the humidity was really high. The plastic bags are not a good option when you need to use them during a long period. It would be nice if the detectors had a transparent plastic case (like a small water proof box) with a ring where you could attached a pole (just some thoughts). Finally, I think that the overwrite data thing is not that useful (probably you can program the device to not do that) because if I can't go to the field one day I can lose the data that I have already saved. It would be nice to have an android app to set the clock, this way I could set the clock while I was in the field. The device shouldn't overwrite the data, in the case that you can't pick up the detector after the three nights you will lose the data recorded in the previous nights. I think a case/box for the detector is something that you should focus on. Sometimes the conditions in the field are not that good and this would allow the detector to be protected from the environmental conditions. This would also protect it during transportation, which is important when you have to walk kilometres in the middle of vegetation or climbing mountains. If one battery is displaced during the transportation (box would also mitigate this problem) an app would allow to reset the clock. This happened to me a couple of times and I wasn't able to reset the clock because I didn't have a laptop with me. I have 6 AudioMoths where the red light is always flashing (I stopped using them) and I have some AudioMoths that from time to time stopped recording during the night (maybe a problem with the SD cards). On the SM2 the files names contain the location, date and time. I don't know if it is possible to do it on the AudioMoth but it would be much more intuitive. On the SM2 you can set the location manually."*

Prototype 4: The Cuban greater funnel-eared bat

A field expedition run by Ollie Wearn in 2017 used *Prototype 4* with a detection algorithm to record the IUCN Red-Listed Cuban greater funnel-eared bat (Natalus primus), currently known to inhabit only one 20-km^2 area of the *Guanahacabibes National Park* in Cuba (Wearn, 2017). *Prototype 4* captured calls of free-flying individuals in recordings at a sample rate of 250 kHz.

Ollie Wearn, ***ZSL*** - *"Had quite a lot of battery problems - I was using some dodgy Ni-Mh rechargeables that failed on me. Think four devices worked in the end, but haven't had time to check the recordings since pulling them from the*

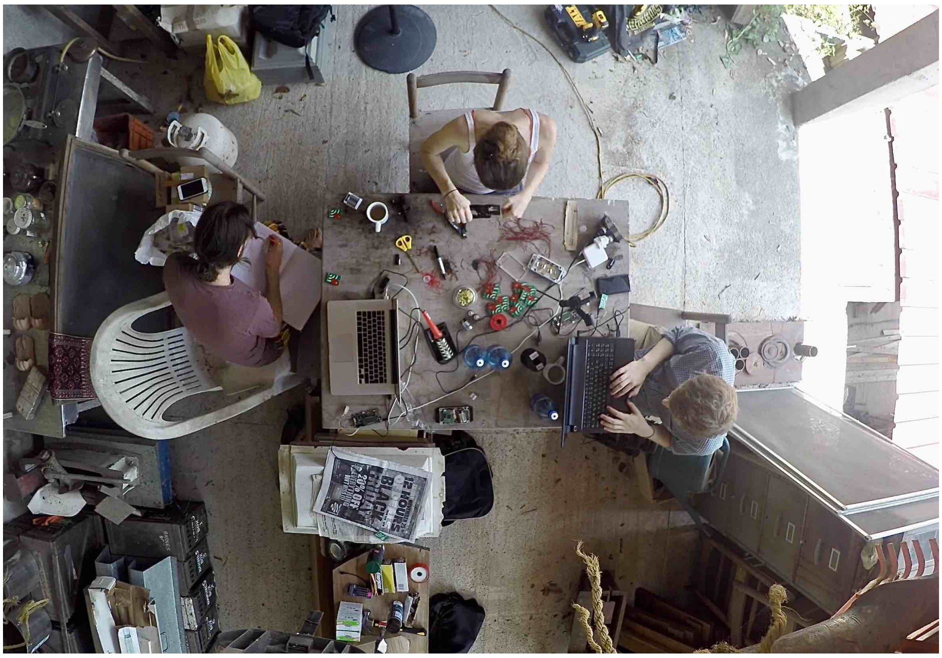


Figure 3.5: Assembling AudioMoth prototype 4 in Belize

field. Will let you know in the NY! An example sonogram recorded from one of four captured Cuban greater funnel-eared bats (Natalus primus) in Cueva la Barca. The species has a broad-band frequency-modulated (FM) call typical of Natalidae, usually with a double harmonic (although this is not always present, as for the last call in this sequence). Each pulse lasts $<$ 3 ms, with a frequency range of ~35-70 kHz for the lower harmonic, and peak frequency of ~50-60 kHz. The faint grid pattern in the background is the noise of the AudioMoth recording data to the SD card."

Prototype 4: Belize anti-poaching project

As part of this thesis the *OAD* team travelled to Belize to build and deploy several *Prototype 4* devices for gunshot detection trials in a remote tropical rainforest. Part of the trials involved building 40 deployable units from pre-assembled *Prototype 4* devices and enclosure parts imported from the UK, batteries were sourced at location. The enclosure parts consisted of C-cell battery holders, wires to connect all electronic parts and the IP68 waterproof enclosures with acoustic vent. Figure 3.5 shows the assembly process, which was carried out in an outdoor shelter inside the forest. Soldering tools and laptops were powered from a petrol generator. The import and assembly process exposed several practical issues when using DIY conservation tools in remote areas. Problems included baggage costs when importing empty enclosures, personal discomfort when building the deployable units in extreme temperatures/humidity, difficulties in sourcing C-cell batteries, and issues in debugging software without internet connectivity.

Implemented decisions based on user feedback:

- Implemented configuration option to turn LED off in software to prevent theft (Jack).
- Created acrylic AA enclosure (Section 3.5.2) to replace deployments inside grip sealed bags (Diogo and Jack).
- Created easy to build rugged enclosure without any in-field soldering requirements (Section 3.5.3). The bulk of the parts could also be sourced from local drainage suppliers to reduce import costs when deploying in remote and overseas locations.
- Implemented new oversampling technique to reduce noise when using low voltage batteries (Ollie).
- Changed battery size from AAA to AA for accessibility in remote regions of the world (i.e. Cuba) while increasing capacity to for long term deployments (Ollie).
- Changed silkscreen switch annotations to give more intuitive labels (Ollie).
- Added external GPIO header to allow for modular expansion (Context of use - *Raspberry Pi*).

Prototype 5 is the next iteration based on user evaluation (Figure 3.6). This is the first public release of the AudioMoth hardware and the foundation for the open source community to develop on.

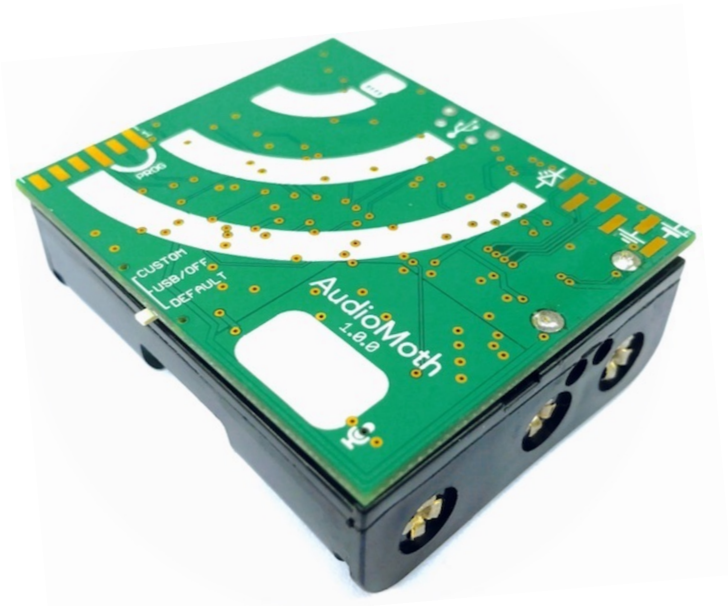


Figure 3.6: Prototype 5: AudioMoth 1.0.0

Prototype 5: User community forum suggestions

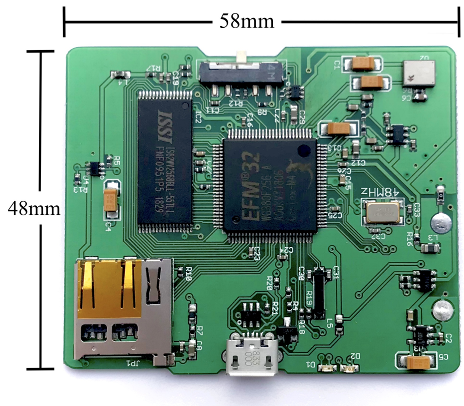
In 2017 the *OAD* support forum opened, thus allowing users to feedback issues and suggestions based on user experience.

> **David Martin** - *"Would it be possible to adjust the position of the switch so that the sticking out bit is within the bounds of the board? Potentially by a 1mm cutout and shifting it inboard, so that it is within the rectangular bounds of the board. "*
>
> **Martin** - *"This is a necessary modification ! After testing 1 of my two new Audiomoth units I unwrapped the second to deploy them and found that the "sticking out bit" was broken off !! I don't know when or how it got broken but I think this mod would help in preventing this sort of problem !"*
>
> **Jenna Griffiths** - *"I'm having a lot of problems with SD cards. I started with 3 audiomoths and 3 kingston SDHC 1 cards 32GB, all three worked and I got data back after my field work days. The second trial of 4 days, one produced no audio recordings and the other recorded for one day and then stopped after that. One worked fine and I have data, this SD card is still working well in the devices. Both these SD cards, the one that produced no data and one day worth of data have data on them but I just cannot delete anything from them, it takes minutes to delete one file and they now do not record anything when I put them in the audio moths, they flash red for a minute as if they are recording then stop for about 20 seconds and when you put them in to check the data there is nothing on them. I have a sandisk ultra 64GB SDXC1 that refuses to be recognised by the devices, it just flashes green and red and I just brought a Toshiba SDHC 10, this is even stranger, it flashes and records for one minute each time for put it in and set it on custom or default and then just stops recording, although the red light flashes faintly still. Its not the audio moth as im getting the same results what ever device I put them in, its the cards. What am I doing wrong, I formatted them first and Im only recording at 48 khz. Help me what am I doing wrong!"*
>
> **Implemented decisions based on user feedback:**
>
> - Indented switch position to reduce unnecessary damage (David).
> - Tented vias to reduce metal corrosion.
> - Changed SD card format to exFAT so higher capacity microSD cards can be used (Jenna).

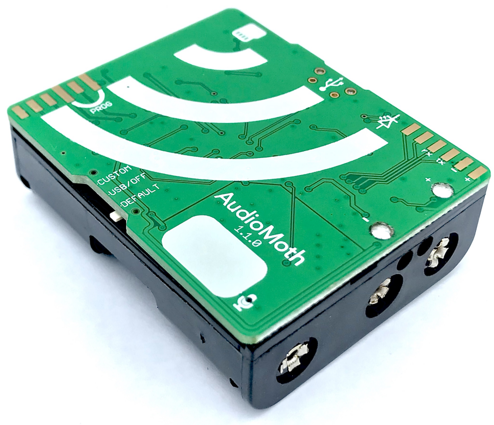
AudioMoth1.1.0 is the latest iteration based on user evaluation, referred to hereon in as *AudioMoth*. This is the iteration that will be described in detail for the remainder of this chapter.

3.2 Hardware overview

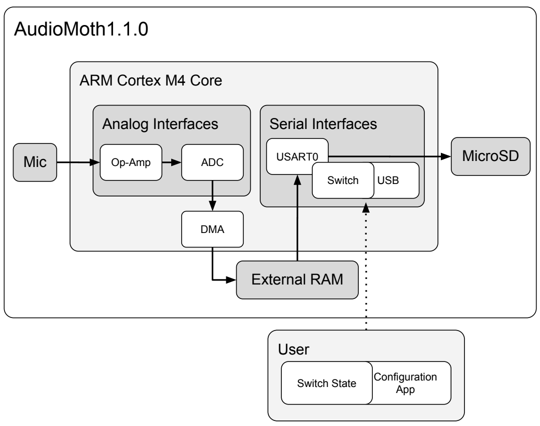
AudioMoth consists of a single credit-card sized (58 x 48 x 15 mm) PCB, which includes a side-mounted switch, USB port, red & green light emitting diode (LED), and microSD card port. The single-board design doubles as an enclosure, with components placed between the board and the battery holder on the top layer of the two-layer PCB (Figure 3.7a). 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. The acoustic sensor is located inside the silkscreened microphone symbol on the bottom PCB layer (Figure 3.7b). Behind the drill hole sits a bottom ported *Knowles SPM0408LE5H* MEMS microphone with a -18 dBV sensitivity and 63 dBA SNR (see Table 2.1). In addition to device protection, the look and construction of *AudioMoth* is inspired by the minimalist and utilitarian philosophy described in Section 2.4.1.1 to lower manufacturing overheads. Programming pins (PROG) and four GPIO pins are exposed to replicate the DIY nature of the single-board computers described in Section



(a) AudioMoth component view



(b) AudioMoth silkscreen view



(c) Hardware Overview

Figure 3.7: AudioMoth

2.4.1.2. The GPIO pins create an easy to access option to plug in external modules that interface with the device, allowing users to add DIY hardware modules that extend the devices functionality. The PROG pins allow the device to enter programming mode, which enables users to upload and update device firmware by USB. *AudioMoth* is powered by a ULP *Silicon Labs EFM32WG380F256*[3] *ARM* Cortex-M4F 32-bit micro-controller, chosen for its large number of in-built features and ULP consumption (211 μA/MHz in run mode and 20 nA/MHz in shutoff mode). The overall hardware utilises features such as cascaded operational amplifiers for microphone pre-amplification, 12-bit ADC with 16-bit oversampling, DMA for data routing in low energy modes, SPI for high-speed microSD card communications and USB for device configuration (Figure 3.7c). DMA routing uses the additional feature of the external bus interface (EBI) to synchronise with an external *IS61LV25616AL*[4] 4-Mbit static random access memory (SRAM) IC to improve on the internal 32-kB RAM for audio buffering.

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 vocalisation (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 (see Chapter 5).

3.3 Elements of design

The design of *AudioMoth* is made up of three main elements: (i) the hardware design, consisting of schematics and PCB layout files, (ii) the software source code, and (iii) the enclosure CAD design files. Each part of the design uses a supporting IDE or framework, which is selected for free and easy user access.

3.3.1 Hardware

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 voltage range allows many battery types to be used, such as rechargeable 3.7 V lithium polymer batteries, series connected 1.5 V alkaline batteries or large 12 V car batteries. The DC battery power source connects directly to the *LT1761*[5] power regulator, which converts the

[3] `https://www.silabs.com/documents/public/data-sheets/efm32wg-datasheet.pdf`
[4] `http://www.issi.com/WW/pdf/61LV25616AL.pdf`
[5] `https://www.analog.com/media/en/technical-documentation/data-sheets/1761sff.pdf`

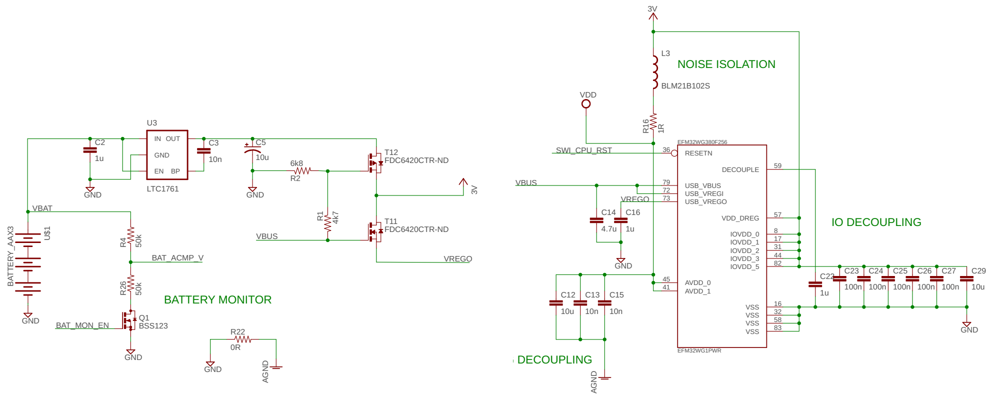
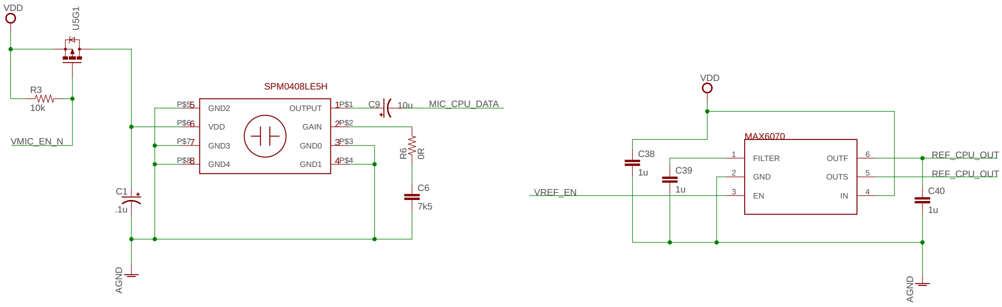


Figure 3.8: Power Schematics

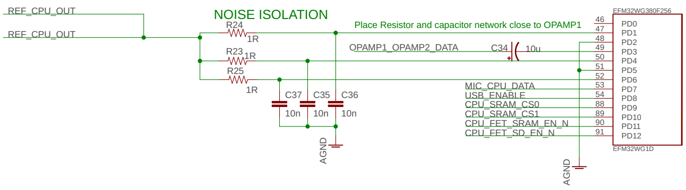
DC supply to a stable and low-noise 3.3 V. Or alternately the device can be supplied by 5 V USB power, which connects to the internal voltage regulator inside the micro-controller. To reduce the load on the DC supply when USB power is used, a N-channel and P-channel MOSFET array disconnects the supply power when the USB is connected. This is designed to extend the battery life during current consuming USB configuration operations (Figure 3.8). High speed digital noise can often spill over onto analog data lines, therefore, the power circuitry on *AudioMoth* is designed to separate potential digital noise. This is achieved using a series resistor and ferrite bead to isolate the analog audio circuitry from the digital transmission lines.

The audio circuitry begins at the microphone data output, which is routed directly to the micro-controllers analog peripherals (Figure 3.9a). The analog peripherals consist of a software enabled pre-amp block, with two on-board op-amps creating a cascaded inverting amplifier. The op-amp design allows for flexible control of gain using the supporting software. The feedback resistor values on the inverting amplifiers can then be adjusted by the user at configuration stage (Figure 3.9c). To prevent errors on the non-inverting bias voltage from amplifying through the op-amp as noise, *AudioMoth* is designed to use an external voltage reference chip to create a stable 1.5 V bias voltage with a small 4.8µ$V^{P\text{-}P}$ noise floor. This stable voltage feeds into the non-inverting inputs of both op-amps to create a clean bias voltage. The op-amps then feed internally through the micro-controller to the ADC. Here, software oversampling and averaging in firmware is applied to increase: the resolution of audio samples from 12-bits to 16-bits, filter anti-aliasing artifacts, and increase the SNR of the audio signal. Oversampling and averaging increase the resolution without the cost and complexity of using expensive off-chip ADCs. Although hardware enabled oversampling is available on the *EFM32* micro-controller, software oversampling, which is emulated using explicit *C* code[6], allows dynamic sample rate changes using the supporting software.

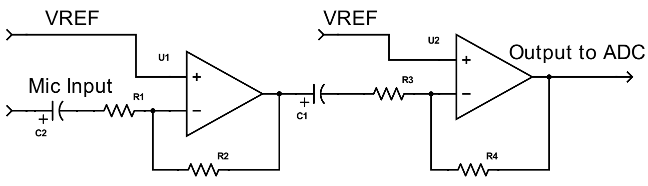
[6]https://www.silabs.com/documents/public/application-notes/an118.pdf



(a) Audio circuitry schematics



(b) Internal operational amplifier schematic



(c) Microphone cascaded inverting operational amplifier

Figure 3.9: Microphone and analog circuitry

In real-time audio processing, there is often a trade-off between maximum sample rate and size of RAM, where RAM represents the amount of buffer space available to process or write audio while other parallel processes are taking place. To expand on the audio buffering space, 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 EBI (Figure 3.10). EBI enables the external SRAM IC to automatically memory map into the address bus of the micro-controller, without manually manipulating the input or output settings. Together with DMA the Cortex-M4 can 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. The increased size of 4-Mbits enables *AudioMoth* to sample continuously at rates of up to 384 kHz. *AudioMoth* supports extended file allocation table (exFAT) microSD cards, which have no realistic file-size or partition-size limits. This means any size microSD card formatted to exFAT is compatible with *AudioMoth*.

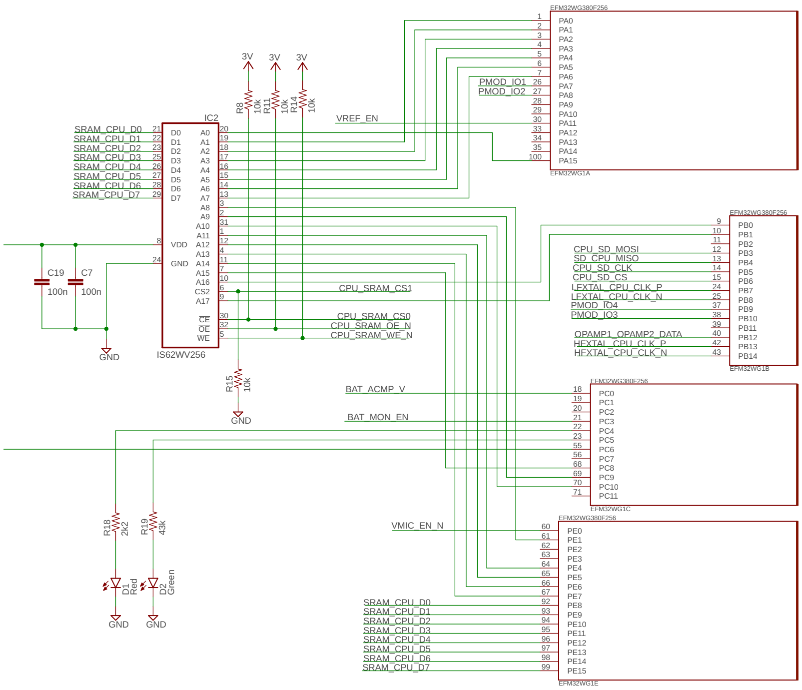
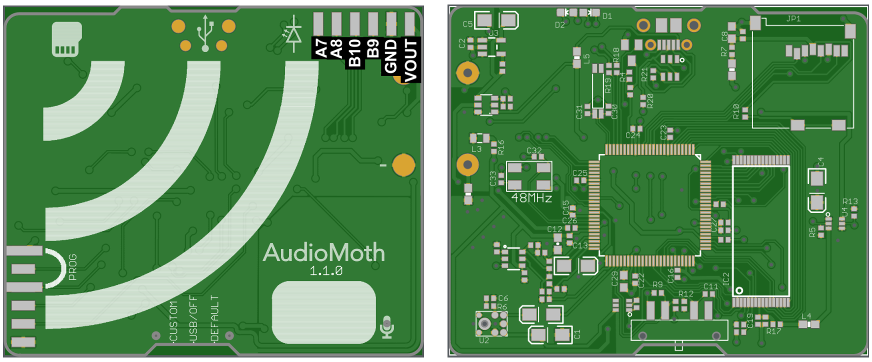


Figure 3.10: SRAM schematic

The user interface is arranged on the bottom layer of the PCB layout, with all external peripherals marked with clear silkscreen annotations (Figure 3.11a). 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 graphical user interfaces (GUI). The LEDs, which can be viewed from the side of the device, provide feedback to the user as to what state the device is in[7], 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 3.11a 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 UART peripherals on pins B9 and B10. Example modules for potential expansion using UART include GPS[8] and wireless commutation transmitter/receiver modules[9] for IoT applications.

[7] www.openacousticdevices.info/led-guide
[8] www.adafruit.com/product/746
[9] www.pycom.io/product/lopy4/



(a) Bottom layer **(b)** Top layer

Figure 3.11: AudioMoth PCB layout

The free *Eagle* CAD desktop IDE is chosen for the electronic hardware design of *AudioMoth*. Although one of many available free platforms for hardware design (see Section 2.4.1.3 on page 29), *Eagle* is chosen because it is easy to use, has a large online community and is known amongst the OSH commercial providers (i.e. *Sparkfun*[10] and *Adafruit*[11]) as the standard OSH CAD tool. The *AudioMoth* hardware design files consist of an *Eagle* schematic (AudioMoth1-1-0.sch) and *Eagle* PCB layout (AudioMoth1-1-0.brd)[12].

3.3.2 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. Firmware consists of the software source code, which is developed in *C* using a simple control loop with interrupt-controlled subtasks. Applications consist of two *Electron*[13] based GUIs: the Configuration App and the Time App. *Electron* is a free open source framework for creating cross platform desktop applications with web languages, such as JavaScript, HTML, and CSS. An additional tool, called *AudioMoth Flash* App, enables compiled firmware binary files to be flashed onto the micro-controller using the USB boot-loader.

The Configuration App enables *AudioMoth* to be configured by USB. When connected to *AudioMoth*, the Configuration App displays its 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 3.12). Four separate recording periods can be set during a 24 hr 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

[10] https://www.sparkfun.com/
[11] https://www.adafruit.com/
[12] https://circuithub.com/projects/OpenAcoustics/AudioMoth.
[13] https://electronjs.org/

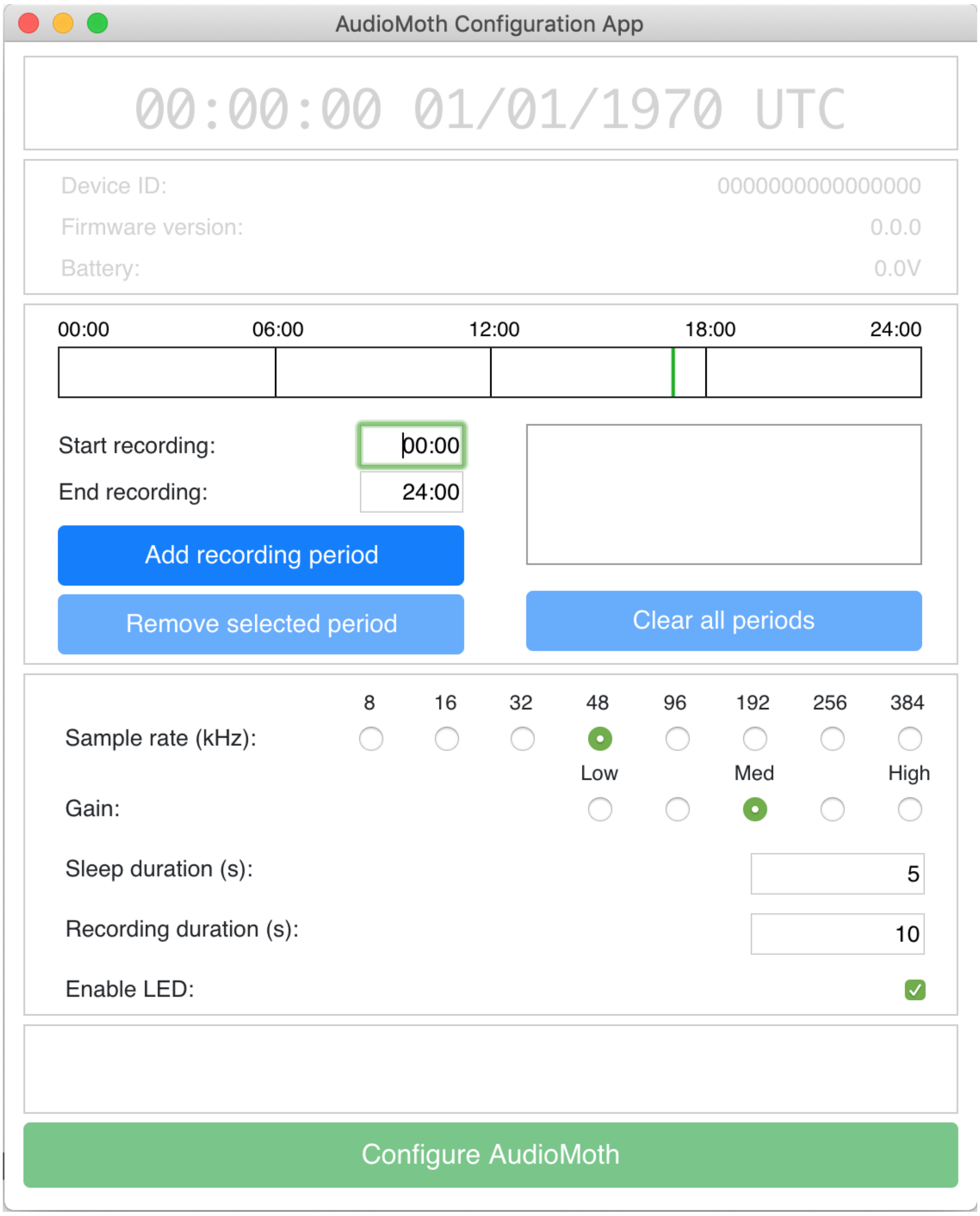


Figure 3.12: Configuration App

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 LEDs 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 onboard time, ID, firmware version and battery voltage. The Time App only allows the time to be set, and is useful to use with customised firmware. Two deployments using the Time App are described in Section 5.2 on page 101.

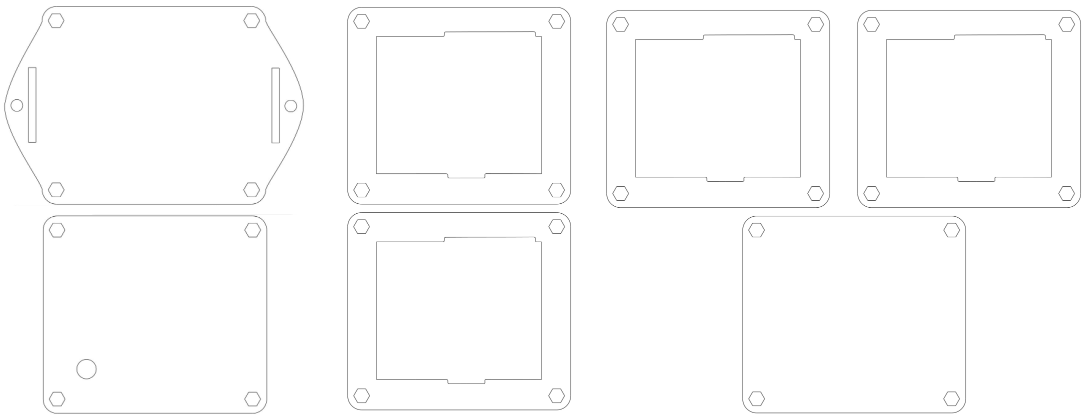
Software	Description	Location
Flash	A command line tool to program AudioMoth	https://github.com/OpenAcousticDevices/AudioMoth-Firmware-Basic
AudioMoth-Firmware-Basic	Standard firmware for AudioMoth	https://github.com/OpenAcousticDevices/AudioMoth-Firmware-Basic
AudioMoth-Project	A minimal project on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

Table 3.2: Source code location

All source code can be accessed on the device *GitHub* page[14]. Table 3.2 presents the software source locations.

3.3.3 Enclosures

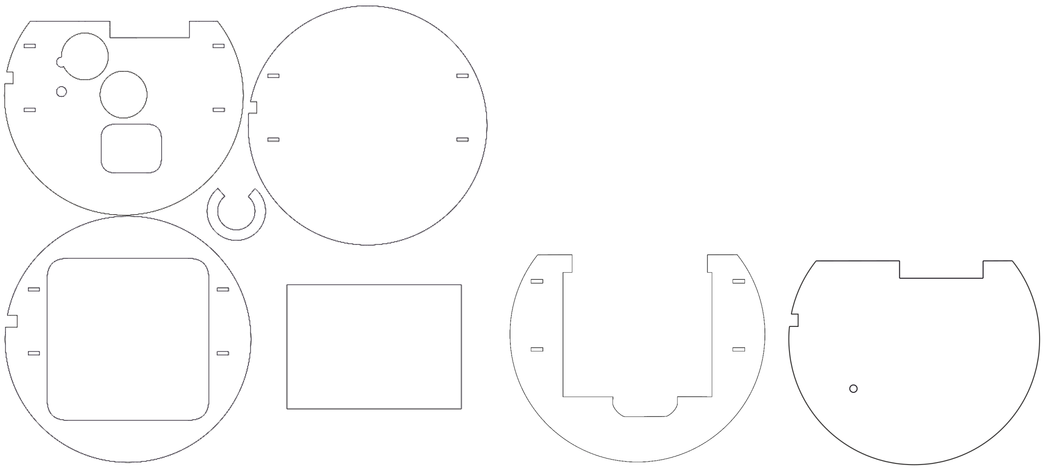
This section illustrates two simple laser cut versions of *AudioMoth* enclosure. The AA enclosure consists of three CAD design files (AudioMothCoupling_3mm.dxf, AudioMoth-Coupling_5mm). These files are used to laser cut acrylic and neoprene gasket sandwich layers. They can be assembled to form a waterproof case for *AudioMoth* when using a through hole AA battery connector. The top and bottom acrylic layers (Figure 3.13a) use 5 mm acrylic and the two middle layers (Figure 3.13b) use 10 mm acrylic. Neoprene gaskets (Figure 3.13c) 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`.



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

Figure 3.13: AA battery enclosure design files

[14] `www.github.com/OpenAcousticDevices`



(a) 3 mm acrylic **(b)** 5 mm acrylic **(c)** Drill hole jig

Figure 3.14: 6 V lantern battery enclosure design files

The second case design is the 6V enclosure, which consists of three CAD design files (AudioMothCoupling_3mm.dxf, AudioMothCoupling_5mm.dxf and AudioMothCoupling_Drill_Jig.dxf), a hardware schematic (bottom_Lantern_holder.sch) and layout file (bottom_Lantern_holder.brd). 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 (Figure 3.14a) 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 (Figure 3.14b). Figure 3.14c shows the jig paper cutout that can be used as a guide for the microphone drill hole and the placement of the rectangular key in Figure 3.14a. The small semicircle structure in this figure is the rain hood, which should be used on the outside of the drain pipe plug to prevent moisture pooling. All enclosure design files are located in the supplementary material with the *Hardware X* journal publication, *AudioMoth: A low-cost acoustic device for monitoring biodiversity and the environment* (Hill et al., 2019b).

3.4 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 6 V battery operated version. Table 3.3 includes unit pricing to purchase components sufficient to build a single device or a batch of 1,000. Batch ordering components and PCBs in this way results in a larger cost saving per device.

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	0.02	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	0.2	0.021	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		53.34	25.74		

Table 3.3: AudioMoth bill of materials

Designator	Component	Qty /unit	Cost /unit	Toal (USD)	Source	Material
U1	Keystone 2464	1	1.58	1.58	digikey.com	Electronic
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 3.4: AA enclosure bill of materials

Designator	Component	Qty /unit	Cost /unit	Toal (USD)	Source	Material
6VPCB	6 V battery holder PCB	1	7.20	7.20	pcbcart.com	Electronic
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	Battery
6VBattery	Energizer 529	1	13.0	13.0	amazon.com	
Cable Tie	111-05260	4	0.12	0.48	uk.rs-online.com	Casing
			Total	37.47		

Table 3.5: 6V enclosure bill of materials

3.5 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 6 V battery enclosure is to be used for deployments requiring large battery capacity.

3.5.1 AudioMoth PCB

The bare PCB or the assembled PCB can be acquired by uploading the bill of materials (Table 3.3) 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 $1,000 USD to manufacture PCBs and 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 hr per board. In terms of both cost and time, the most effective route to acquire an *AudioMoth* is through group purchase websites, such as *GroupGets* [15]. This acquisition

[15] `www.groupgets.com/manufacturers/open-acoustic-devices/products/audiomoth`

route delivers assembled and 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 3.3).
2. Solder components to their silkscreen designator locations, which are displayed on the PCB bottom layer (Figure 3.11b). 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

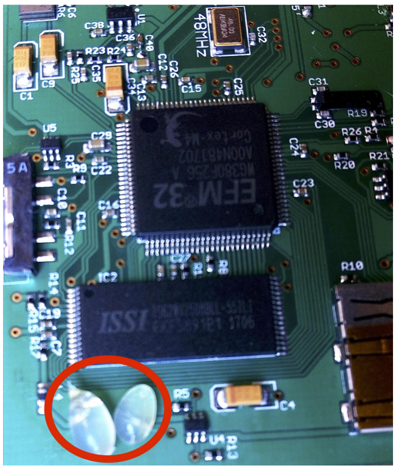
  Flux off

  Alcohol PCB cleaner

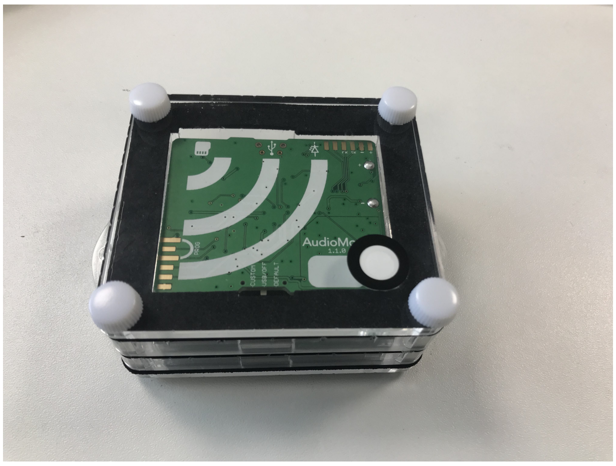
3.5.2 AA battery enclosure

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:

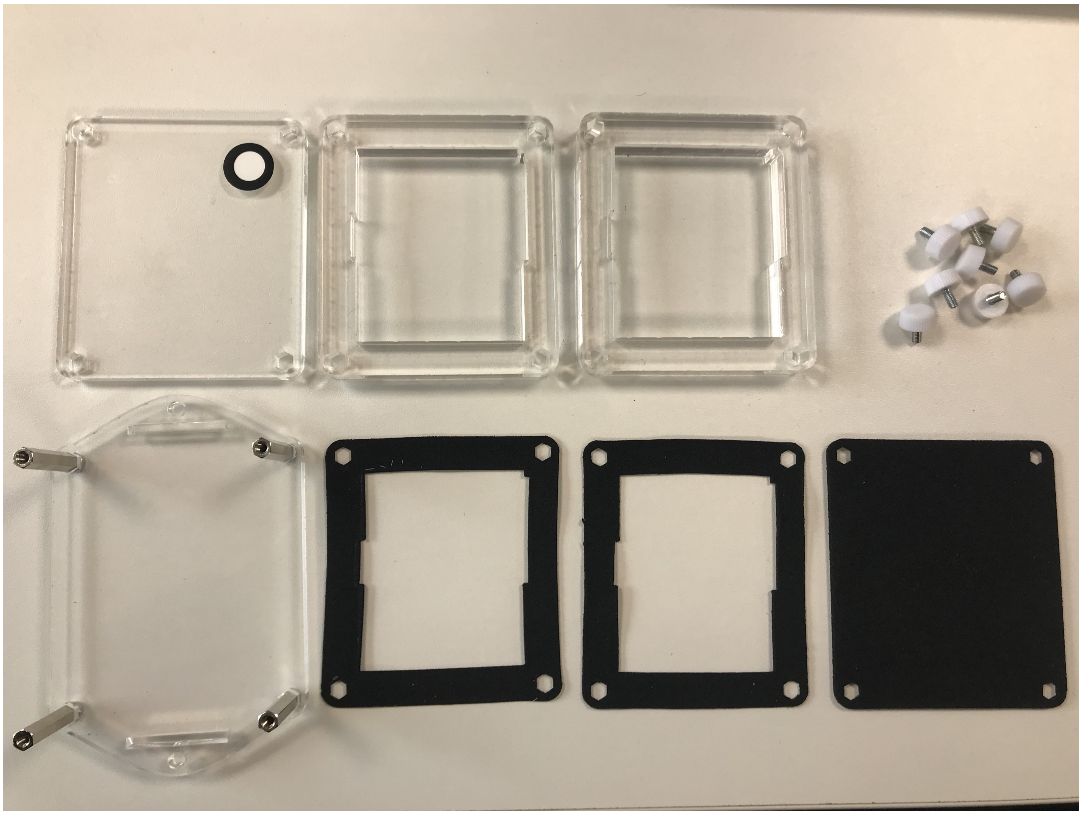
1. Place two small dabs of hot glue on the top layer PCB as shown in Figure 3.15a, make sure not to glue on top of any components.
2. Keeping the PCB parallel with the battery connector, hold the PCB in place.
3. Once the glue has cooled, solder the through hole battery connector (Keystone 2464, Table 3.3) 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 3.15c).
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.



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



(b) Constructed AA enclosure



(c) Components of AA enclosure

Figure 3.15: AA enclosure build steps

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.
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 10 mm acrylic cutouts.
13. Place the final 5 mm 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 3.15c).
15. Turn over and screw the last four thumb screws into the bottom of the enclosure.
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

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

3.5.3 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 *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. In Section 5.2.2 on page 107 we describe a deployment using the 6 V enclosure. This enclosure is useful as it extends the operation life of *AudioMoth*, with some 6 V batteries having a capacity of 24 Ahr[16]. The 6 V battery must have two-spring connectors and not the screw post terminals.

The enclosure is ruggedised and waterproof for hostile deployments. The 110 mm drain enclosure can be purchased at local hardware stores worldwide. This availability means the 6 V enclosure does not have to be shipped to the deployment country. The enclosure can be built using the following instructions:

[16] `http://data.energizer.com/pdfs/529.pdf`

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 3.16a).

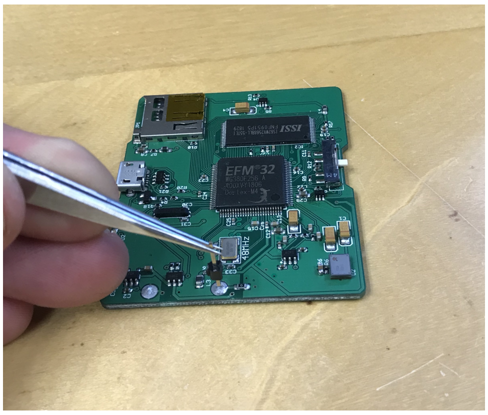
2. Place and lineup the 5 mm acyclic cutout over the 6 V enclosure PCB (Figure 3.16b).

3. Place two small dabs of hot glue on the top layer PCB as shown previously in Figure 3.15a, making sure not to glue on top of any components.

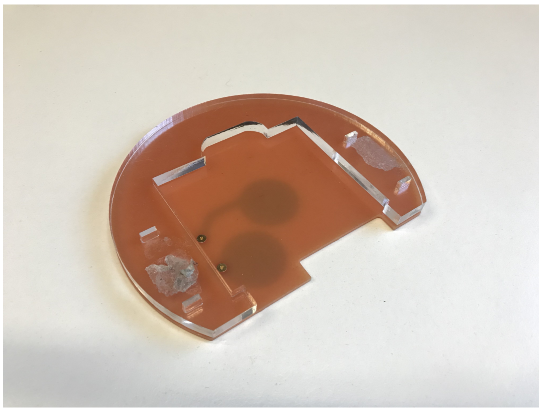
4. While the glue is still hot, place the *AudioMoth* PCB onto the 6 V enclosure PCB and flip the assembly over so the *AudioMoth* PCB sits flush with the workshop surface (Figure 3.16c).

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 (Figure 3.16d).

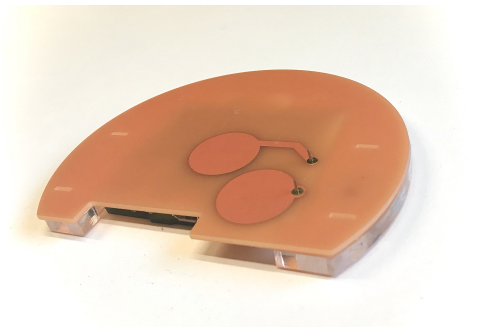
6. Once solder is cool, trim the battery connector legs flush with the PCB using wire cutters.



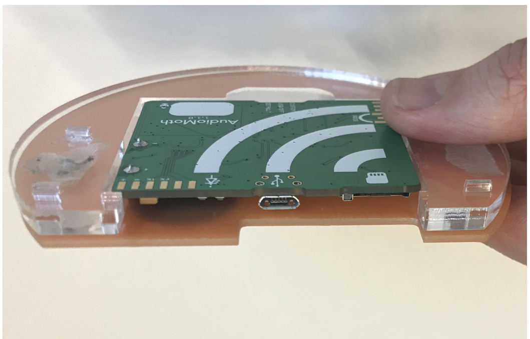
(a) Single pin connector



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

Figure 3.16: Build steps for the PCB assembly of the internal structure

7. Lay out all of the internal acrylic structural components (Figure 3.17a).

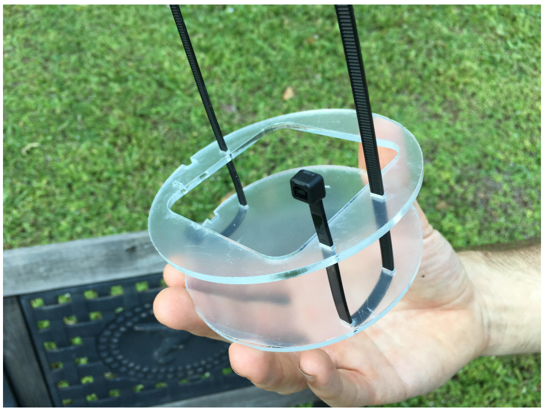
8. Thread the cable ties through the first 3 mm acrylic cutout (Figure 3.17b).

9. Line up the square notch cutouts, place the second 3 mm acrylic layer over the battery, and thread the cable ties through (Figure 3.17c).

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 (Figure 3.17d).

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

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



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

(d) Third 3 mm 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 3.17: Build steps for 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 (Figure 3.17e). 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 3.18a).
13. Using the hot glue gun, glue the rectangle key into position (Figure 3.18b). 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 (Figure 3.18b).
15. Place double sided tape or hot glue onto the underside of the 3 mm acrylic rain hood and place over drill hole (Figure 3.18c).

(a) Components of the outer 6 V enclosure

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

(c) Rain hood over drill hole

(d) Deployed 6 V enclosure

Figure 3.18: Build steps for the outer enclosure

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.

3.6 Operation Instructions

Maintained operation instructions can be found on the *AudioMoth* website[17]. Table 3.6 lists the different instructions available and locations where they can be found.

Operation instructions	**Description**	**Location**
Initial set-up	Instructions to use AudioMoth with Configuration App	`www.openacousticdevices.info/setup-guide`
Configuration	Instructions to use just the Configuration App	`www.openacousticdevices.info/config-app-guide`
Flashing	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`

Table 3.6: Online operation instructions

3.6.1 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*[18]. For detailed instructions on how to setup Simplicity Studio and create an *AudioMoth* project, visit the *AudioMoth* wiki[19]. Firmware can be uploaded to the device by building the project and using the compiled *.bin* file via USB.

3.7 Validation and Characterisations

This section specifies 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.

3.7.1 Boot-loader validation

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

[17] `www.openacousticdevices.info/getting-started`
[18] `www.silabs.com/products/development-tools/software/simplicity-studio.`
[19] `www.github.com/OpenAcousticDevices/AudioMoth-Project/wiki/AudioMoth`

1. The micro-controller on *AudioMoth* has a boot-loader pre-programmed at factory. When put into programming mode, a fully assembled *AudioMoth* will be recognised 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 can then be run to validate boot-loader functionality. For this test, start the *Flashing* instructions (Table 3.6).

5. Follow the rest of the *Flashing* instructions to program the hardware with the *AudioMoth-Firmware-Basic* firmware. If boot-loader has failed, either the PROG pins were not shorted correctly at start-up, or there is another hardware fault.

3.7.2 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*[20] 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.

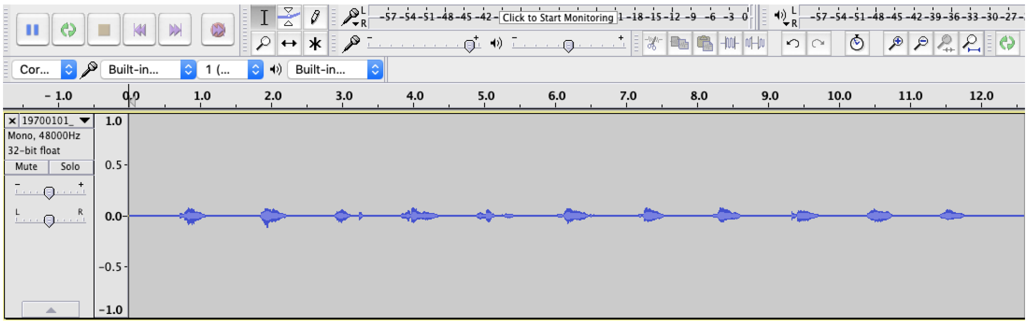
3. After the count down, the switch should be set back to USB to stop the recording.

4. The microSD card can now be taken out and inserted into the PC.

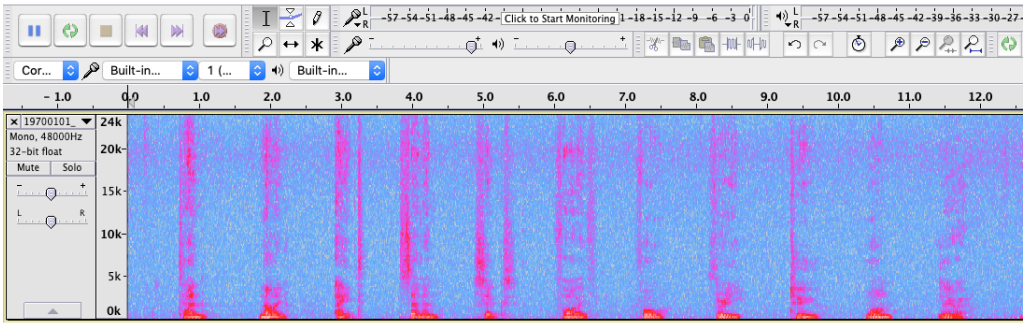
5. If the USART SPI peripheral is functioning correctly a WAV file should have been created, named *19700101_xxxx.WAV*.

6. To validate the functionality of the EBI, op-amps and ADC peripherals the playback of the counting sequence needs to be analysed. The recording can can be opened in Audacity.

[20] `www.audacityteam.org/download`



(a) Audacity waveform view of voice countdown sequence



(b) Audacity spectrogram view of voice countdown sequence

Figure 3.19: Validation of peripherals using Audacity.

7. Voice should be clearly heard without distortion during playback. Recordings can be viewed as a waveform showing amplitude against time (Figure 3.19a), and also as a spectrogram, showing the spectrum of frequencies against time (Figure 3.19b).

3.7.3 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[21]. Using the energy profiler application within the *Simplicity Studio* IDE, the starter kits micro-controller voltage (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[22]. *AudioMoth* consumes approximately 30 µA while sleeping and draws 10 mA to 40 mA during recording, depending on sample rate. Table 3.7 shows how current changes with sample rate using the SanDisk Extreme 32 GB microSD card. These are guideline numbers as each model of microSD card may draw different overall current during a recording.

[21] www.silabs.com/products/development-tools/mcu/32-bit/efm32-giant-gecko-starter-kit

[22] www.silabs.com/community/mcu/32-bit/knowledge-base.entry.html/2014/05/21/using_aem_to_measure-BdWl

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

Table 3.7: Power consumption at varying sample rates during a recording to Sandisk Extreme PLUS 32 GB microSD card.

3.8 Typical applications and deployments

Acoustic monitoring has multiple applications, including the monitoring of specific species (Newson et al. 2017, Roe et al. 2018, Pérez-Granados et al. 2018, Metcalf et al. 2019), soundscape analysis (Deichmann et al. 2018, Burivalova et al. 2019, Sugai and Llusia 2019), environmental surveillance (Alam 2019, Astaras et al. 2017), and as a hobby for wildlife enthusiasts. 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 that frequency. Hardware configuration guidelines for different applications and the corresponding source frequencies are shown in Table 3.8.

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 3.8. 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. 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 3 Ahr batteries.

Application	Source	Sample rate	Schedule	Sleep time	Record time	LED	Gain	Battery life	Total data	Swap SD every:	SD speed
Soundscape	20-20kHz	48kHz	00:00 to 24:00	0s	3600s	On	Med	216 hr	64GB	4 days	Class 10
Bird	1kHz-10kHz	32kHz	06:00 to 09:00	0s	3600s	On	Med	1800 hr	49GB	48 days	Class 10
LF Bat	20kHz-50kHz	192kHz	18:00 to 22:00	2s	10s	Off	Med	840 hr	153GB	7 days	U3
HF Bat	50kHz-120kHz	384kHz	18:00 to 22:00	2s	10s	Off	Med	526 hr	193GB	3 days	U3
Chainsaw	100Hz-1kHz	8kHz	00:00 to 24:00	300s	30s	Off	Med	2760 hr	14GB	none	Class 4

Table 3.8: Example configuration parameters for acoustic monitoring applications using AudioMoth with 3 Ahr capacity AA-cell lithium batteries and a Sandisk Extreme 32 GB microSD card.

3.9 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.

3.9.1 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 centre and not to leave old batteries in the field.

3.9.2 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 (Figure 3.18d).

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 centre and not to leave old batteries in the field.

3.10 Summary

This chapter has described the hardware design of the *AudioMoth* acoustic sensor, providing information for a user with hardware experience to build the device. Descriptions include the location of open source design files, instructions on how to build the hardware and construct two enclosures to house the PCB, validation processes required after hardware assembly, and guidelines on how to deploy the final working product. It gives engineers a starting point to build on the hardware and software design files for *AudioMoth*. This chapter addresses the user requirements (1) to (6), which were previously highlighted in Section 2.5 on page 35. It shows that *AudioMoth*: (1) can be used in the same context as existing devices, including static deployments, handheld deployments using the DEFAULT switch functionality, and single-board extendable deployments with access to external GPIO pins; (2) has a bandwidth from 10 Hz to 192 kHz allowing for the simultaneous capture of ultrasonic bat calls, audible wildlife vocalisations and anthropogenic disturbances; (3) can be deployed in harsh outdoor environments using the enclosures described in Section 3.3.3; (4) can be deployed over long term deployments using its ULP micro-controller to control power consumption, giving it an operating life of 216 hr for the AA-cell case, or 1714 hr for the 6 V lantern case; (5) can be deployed over hard-to-access locations, with a size measuring 58 mm by 48 mm and a weight of 30 g; and (6) can be configured to prevent theft, allowing users to turn off LEDs during deployments.

From addressing these requirements *AudioMoth* presents as a physical tool with properties that show promising characteristics to increase the scalability of monitoring at ground level. Although this chapter has been written for users with more technical experience, it does not provide sufficient information to allow a typical conservation practitioner access to *AudioMoth*. Consequently, the next chapter (Chapter 4) attempts to address the additional requirements: (7) hardware acquisition, (8) hardware assembly, (9) user support and (10) creator support.

Chapter 4

Leveraging conservation action with open source hardware

Chapter 3 described the open source *AudioMoth* hardware, providing sufficient information for a user with hardware experience to purchase components, assemble, test and deploy the device. Although giving engineers a basis to adapt the hardware and software to a specific need, many barriers still lie in the way of implementing OSH for conservation purposes. Models now exist to support adoption of open source software, such as *Canonical*[1] providing commercial services for consumers of *Linux Ubuntu* operating systems. Such frameworks are still lacking, however, to support the not-for-profit uptake and implementation of OSH for conservation. Although profitable businesses are being built around OSH, they meet a demand that comes principally from technically savvy users, capable of building their own hardware from published design files (Pearce, 2017). Conservation practitioners largely fall into a different category of user. They often have limited technical electronics know-how, or have limited resources for technical training. These users typically require others to build the hardware for them. They remain hard to target for OSH business models, due to the complexities that go with hand fabricating hardware from an open design. With appropriate support, conservation practitioners are best placed to apply OSH to conservation actions.

In this chapter, a provisional framework for developing and sustaining the life cycle of not-for-profit OSH for conservationists is introduced. The framework addresses current technical barriers to manufacture and presents simple guidelines for distribution, user accessibility, creator support, and user support. It comprises a set of defined product-development processes that guide a collaborative team through the life cycle of an open source product, from construction and after-sales support, to the reinvestment strategy that sustains the creators and community. An application of the framework is demonstrated with a real-world case study of an OSH product in the form of *AudioMoth* (Hill

[1] `https://www.canonical.com/`

et al. 2019b). The case study serves to illustrate how the framework unlocks useful technology for local communities, researchers funded by government research councils, and individuals funded by non-government organisations (NGOs). In recent years, similar frameworks, such as *Crowd Supply*, have been shown to increase the adoption of proprietary products by consumers (Ilin et al. 2018) and even to improve competitive advantage through crowdsourced tools (Nagle, 2018). We argue for wide adoption of flexible approaches of this sort by conservation NGOs and universities in particular. A framework can facilitate rapid uptake of OSH for conservation activities supported by these organisations, thereby fostering the proliferation of local-scale projects that lead to global-scale action (Arlettaz et al., 2010, Pocock et al., 2018).

All sections of this chapter are taken from the peer-reviewed *Conservation Letters* journal publication (Hill et al. 2019a).

4.1 A framework to support open source hardware for conservation

The framework has six phases, each with formulated guidelines: (i) hardware, (ii) manufacture, (iii) release, (iv) distribution, (v) support, and (vi) sustainability (Figure 4.1). The framework is formed around a management team consisting of a creator group (engineering team), which leads the technical developments of the technology, and a

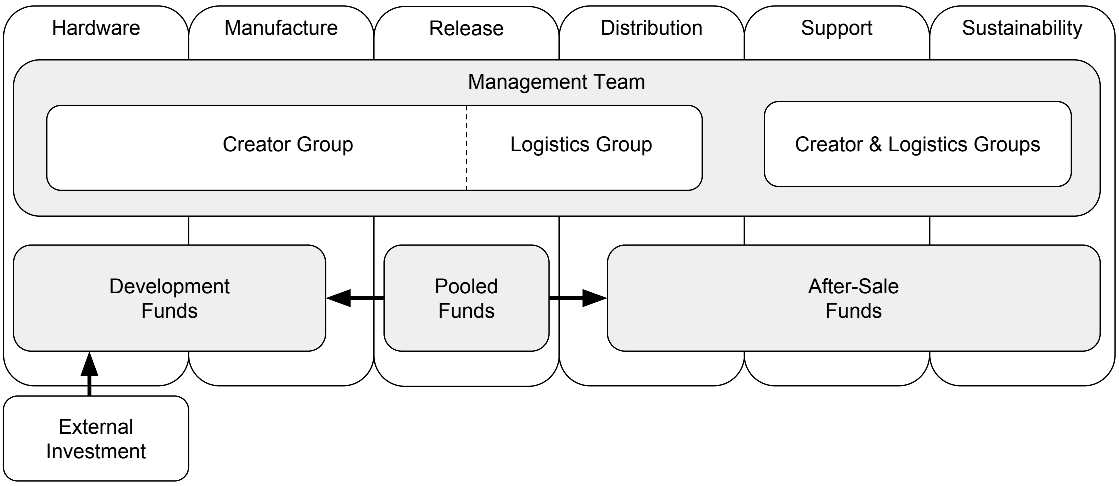


Figure 4.1: An overview of the framework for developing, funding, supporting, and sustaining open source hardware (OSH) for conservation. The framework differs from a traditional business model for a commercial product in having open source licenses, relying on word-of-mouth in lieu of an advertising budget, allowing group-purchase only, explicitly excluding housing for electronic components and guarantees on product performance, and outsourcing after-sales care to web forums

	Responsibility
Creator group	Conception of idea
	Circuit design
	Hardware development
	Software development—website, firmware, supporting software and algorithm design
	Prototyping
	Bench testing
	Field testing
	Choosing appropriate manufacturers
	Testing small-batch build quality of chosen manufacturer
	Testing alternative components if original components become obsolete
	Website maintenance
	Technical community support via website forum
Logistics group	Initiating crowd funded campaign
	Taking payment from crowdfunding organisation
	Co-organising distribution of units
	Assurance-related community support via crowd funders website
	Holding pool of funds
	Distributing pool of funds to support technology development
Shared responsibilities	Social media presence

Table 4.1: Distribution of responsibilities for the management team, between the creator group, which focuses on hardware issues, and the logistics group, which focuses on assurance issues

logistics group (i.e. funder, NGO or university), which leads logistical and financial operations. This unified entity requires an open and collaborative relationship between the two groups, with clear lines of responsibility (detailed in Table 4.1).

The end users are the communities requiring the conservation hardware, such as local conservation activists, research scientists, educators, and wildlife enthusiasts. The framework provides a provisional set of management guidelines for OSH development, and a scalable method for the community to acquire and use the created technology. The framework generates a pool of crowdsourced funds out of unit sales margins obtained in the bulk manufacturing of hardware. Funds can be reinvested back into the hardware project to sustain its lifespan. In addition to providing support for creators and users, the framework minimises the investment in human and financial capacity needed to initiate, manufacture, and distribute OSH. It makes use of new websites for crowdfunding and for turn-key electronics manufacturing to provide tailored and cheap solutions for non-technical conservation organisations. A framework can be viewed as successful if it is able to harness a large community of individuals to acquire low-cost single units from a high volume manufacturing process, while also creating extra funds to continue support. Success will depend on simple hardware construction to reduce overheads when manufacturing at bulk, and the timely orchestration of a large group of buyers to crowdfund industrial manufacture of the hardware (Kohler and Chesbrough, 2019).

The initial *hardware* phase is the design stage, which commences after the creator group has proven the feasibility of using a particular technology for a desired conservation task. The proven hardware needs to be adapted to an open source design, and initial investment is required to fund this development. To open source a technology means to apply an open license to it. Various licenses are commonly used to define how OSH design files can be adapted, shared, or commercialised by the user community (Table 4.2). Each license has its own benefits, depending on the goal. For example, the most open license, CC0, may be useful for community ownership of the design, thus allowing it to be shared, adapted, and commercialised without the need to attribute changes to the original creator(s). Any of the OSH licenses can be used in the framework. Oberloier and Pearce, 2018, detail formal procedures for designers of OSH.

Creative Commons licenses	**Adaptations can be shared**	**Commercial use**
CC0 (No attribution)	Yes	Yes
Attribution (CC BY)	Yes	Yes
ShareAlike (CC BY-SA)	Yes, but must share alike	Yes
NonCommercial (CC BY-NC)	Yes	No
NonCommercial-NoDerivatives (CC BY-NC-ND)	No	No
NoDerivatives (CC BY-ND)	No	Yes
NonCommercial-ShareAlike (CC BY-NC-SA)	Yes, but must share alike	No

Table 4.2: Comparison of the available Creative Commons OSH licenses

The *manufacture* phase involves physical fabrication and testing of the subsequent OSH design. Manufacturing often involves complex fabrication processes, including sourcing parts, assembly of PCBs, programming the PCBs, and developing housing for the product suitable for field deployment. Keeping this sequence as simple as possible minimises manufacturing costs. Web services chosen for PCB manufacture should be trialed by testing the build quality of small batches of the developed hardware units before release. Tests should involve checking the quality of assembled PCBs, assessing the fit-for-purpose functionality of the final product and providing solutions to assembly problems found during manufacture. Issues found at this stage need to be resolved before continuing to the next phase. Spare devices built during this process can be used as trial devices or backup units to support after-sales assurance issues.

The *release* phase consists of the publication, promotion, sales, and large-batch manufacture of the hardware units. Technology design files are first uploaded to a publicly accessible open source hosting website to allow community access. The guiding principle of this phase is to minimise the cost per unit for users while also generating a pool of funds. Large-scale industrial manufacturing processes reduce unit material cost and assembly time; however, they require an initial sum of money to bulk order before making any sales. To this end, minimum quantity batch manufacturing can be crowdsourced to reduce risk and produce an economy of scale (Wheat et al. 2013). A crowdfunding platform is required to collect user's funds during funding campaigns. Campaigns should run at regular intervals and each should end when a maximum order quantity is reached, or a time period is elapsed. The crowdfunding campaign should be publicised on social media and conservation forums, so as to gain traction and reduce the risk of failing to meet the monetary target.

The *distribution* phase consists of the global dissemination of the manufactured units. Depending on the crowdfunding organisation used, the logistics group may need to take on the role of global distributor, or employ a dedicated distribution house to ship and track deliveries.

The *support* phase provides technical and logistical assistance to the community of users. Users may require support with diverse issues, including devices getting lost in transit, out-of-box malfunctions, and difficulties with operating the device. A mechanism should be established for users to send their end-of-life devices back to the creator group, for re-use or disposal according to Waste Electric and Electronic Equipment (WEEE) Regulations.

Sustainability encompasses the reinvestment strategy to facilitate continued functioning of the technology into the future. It involves addressing how pooled funds can be generated and used to continue future development and promote future purchases. To create pooled funds, a margin should be added to each unit sold that generates enough funds from the minimum quantity order to sustain the team until the next group purchase campaign ends. The crowdfunding campaign should set its goal to this minimum batch order. Costs incurred by the logistics group to manage logistical operations, such as employing a part-time member of staff and purchasing packaging for shipping, should be reimbursed from this generated fund. The creator and logistics groups should take a percentage of funds to support their tasks after each group funding campaign. The remaining pool of funds can be held by the logistics group and made accessible to the creator group as needed to pay for further support, bug fixes, and further enhancement or development. It is important to acknowledge the environmental impacts of large scale electronics manufacturing and distribution without a central manufacturer (Kohtala and Hyysalo 2015). Organisers and adopters of the proposed framework must consider sustainable practises and environmental impacts.

4.2 Case study

The framework was developed and formalised for the open source manufacture and distribution of *AudioMoth*. Within the management team, the creator group comprised *OAD*, and the logistics group comprised a small conservation NGO called the *Arribada Initiative*[2].

The *AudioMoth* case study used the *Creative Commons Attribution 4.0 International (CC BY)* open source license (Table 4.2). This attribution allowed full participation by the community in all aspects of design, attributing all changes to the original creators. The license allowed other manufacturers to construct and re-sell the platform independently (e.g. *LabMaker*[3]). This brought mixed benefits: it raised awareness and distribution of devices, while also reducing the funds available for sustaining the devices, although in this case only by about one-tenth.

Hardware was designed to fit a single fixed part, consisting of one single-sided PCB that could be purchased from a single manufacturer. The creator group developed the hardware as part of their research budget from *UK Research Council* grants. Development of the product was funded by grants totalling ∼$13,000 USD per/year over 3 years for two PhD students, excluding stipends and course fees.

The chosen manufacturer was *CircuitHub*[4]. This online web service specialises in assembly of open source PCBs. It enables design files to be uploaded, shared, manufactured, and delivered to order, with transparent batch size, lead time, and pricing. It first built small test batches of prototype PCBs, which were used to evaluate the single-board construction and address any build issues. Test boards had a 20-day lead time and cost $60 USD per unit for a batch of 50.

The finalised *AudioMoth* design files were published on the open source hosting websites *GitHub* and *CircuitHub*. This made them freely available to adapt and share. The *CircuitHub* online quotation tool was used to calculate the unit selling price on a manufactured batch of 200 units. A further 20% was added to this unit price, which was calculated to generate enough funds to support global distribution, after-sales support, and future enhancements. Cost-free promotion of *AudioMoth* was achieved through the *WILDLABS* forum[5], social media, and the *OAD* subscription page. Trial devices were distributed to potential users to proliferate the spread of information throughout the conservation community and to generate feedback to the creator group on *AudioMoth* utility.

[2] https://blog.arribada.org
[3] https://www.labmaker.org/
[4] https://www.circuithub.com/
[5] https://www.wildlabs.net

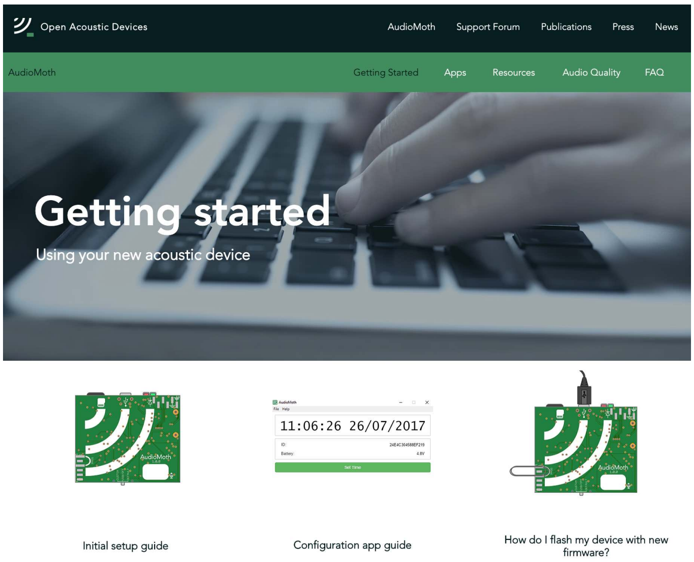
The crowdfunding organisation *GroupGets*[6] coordinated the group purchase campaign for each batch order from *CircuitHub*. *GroupGets* linked back to *OAD's* subscription page to help the creators gauge the level of online interest. To fulfil a cost-effective manufacturing run, each campaign had to gain a minimum of 200 backers.

GroupGets handled postage to users based in the United States. For orders bound elsewhere, *GroupGets* batch posted the ordered units to the UK headquarters of the logistics group. This minimised individual customs declarations, freeing up sufficient funds from the price margin for the logistics group to distribute units to the rest of the world. The logistics group handled all non-U.S. distribution until the rising level of demand necessitated a dedicated distribution house. *Weengs*[7] were then selected to receive devices directly from *GroupGets* and manage the major distribution channels to the UK and EU.

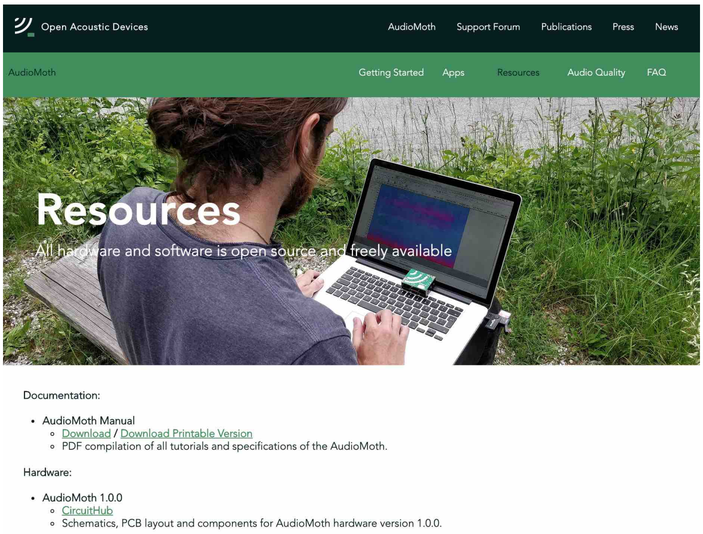
The creator group maintained a website supporting users of *AudioMoth* (Figure 4.2). This was updated on a weekly basis, taking approximately 2 person-hours/week. The website was designed on the *Wix*[8] platform, hosting usage instructions (Figure 4.2a), open source design files (Figure 4.2b), and a support forum (Figure 4.2c). The forum enabled users to discuss ongoing projects, report technical issues, and suggest modifications to the open source design files. Over time, it became partially self-sustaining as the community of users gained expertise in the technology. The creator group was still required to provide solutions to more technical issues.

The case study supported eight rounds of group-purchase campaigns over 2 years from October 2017 to September 2019. These campaigns generated a pool of funds to finance U.S. distribution, hardware improvements, ongoing user support for all purchased devices, and community-based events including workshops for users. The sixth group-funding campaign introduced the first hardware modification to the design files. A lesson learned during this change was the importance of maintaining backwards compatible firmware across hardware versions. The eight campaigns resulted in 7,820 unit sales in total, with 31% purchased by universities, 24% by conservation organisations, 10% by businesses/consultants, 4% by government agencies, and 31% by unspecified individuals. All devices sold for $49.99 USD per unit, creating a net revenue of $390,921.80 USD and a pool of funds after device manufacture and distribution of $96,732.23 USD (discounting the initial external investment). Pooled funds were managed by the logistics group up until round seven, whereby a new logistics group managed funds. The remaining pool will continue to be reinvested back into the framework to pay for ongoing maintenance of the website, to support the community of users, and to further improve the hardware (Table 4.3).

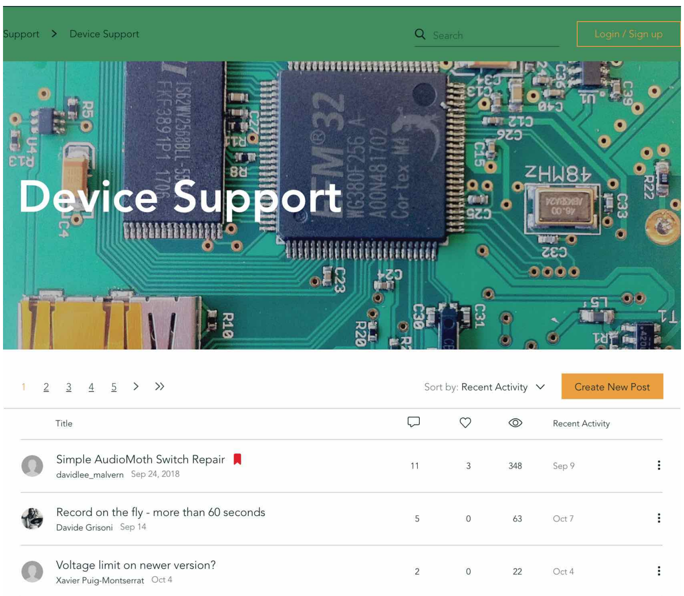
[6] https://groupgets.com/
[7] https://www.weengs.co.uk/
[8] https://www.wix.com/



(a) Usage instructions



(b) Hosted design files



(c) The AudioMoth support forum

Figure 4.2: Website supporting users of AudioMoth

Payments in/out	Amount (USD)
Sale of 7,820 units	$390,921.80
Manufacturing costs	−$209,280.468
Group purchase fees	−$52,214.68
Postage fees	−$11,228.25
Community activity costs	−$11,286.67
Additional hardware improvements	−$10,179.55
Total pool of funds	$96,732.23

Table 4.3: Breakdown of revenue and expenditure throughout the 2-year AudioMoth case study using the framework to support OSH

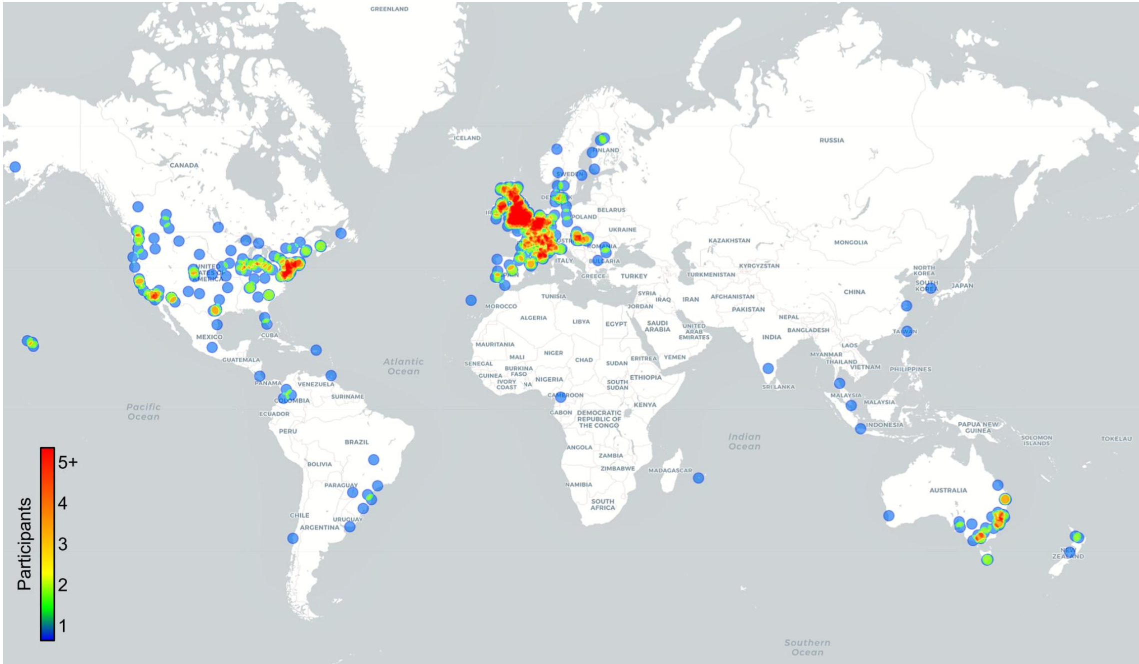
4.3 Leveraging frontline action

The case study demonstrates the capability of the framework for sustaining the lifecycle of an open source conservation tool, while also stimulating global deployment of conservation technology. The framework has to date enabled 932 separate projects to purchase OSH. Purchasers are globally distributed (Figure 4.3a), with clusters around the financial hubs of advanced economies, particularly in Europe (63%), North America (25%), and Australia (6%). Purchases made elsewhere include Central and South America (4%), Asia (2%), and Africa (<1%).

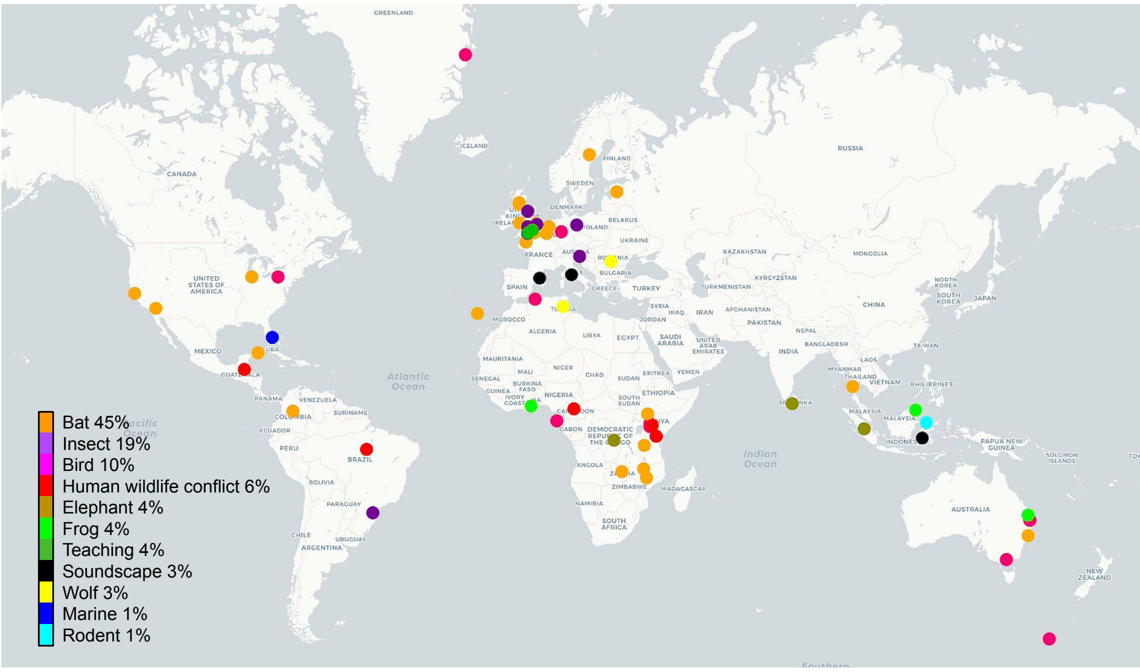
Ten percent of the end-users posted on social media about conservation work using *AudioMoth*s, with conservation action occurring largely away from purchase locations. For example, Africa was the source country for only four sales, but the deployment location for 15% of the end-users. Devices were used for a wide range of applications, including terrestrial monitoring of individual species, general ecosystem soundscape analysis, monitoring of human–wildlife conflicts, experimental marine surveys, and university-level education (Figure 4.3b). Also, by lowering the cost of participating in applied acoustic monitoring research, the application of the framework to *AudioMoth* facilitated public engagement, including citizen science projects for a national bat survey[9], biodiversity mapping surveys[10,11,12], and engagement by the general public in wildlife monitoring[13]. It also led to the development of new methods to address previously untestable research questions. These applications will be explored further in Section 5.1.

Those participating in group purchases of *AudioMoths* actively shared modifications and enhancements, including designs for housing the devices, on independent forum pages as well as on the *OAD* online community forum[14] where changes could be validated by the creator group. Although the framework functions well for *AudioMoth*, more complicated

[9] `https://www.bats.org.uk/our-work/national-bat-monitoring-programme`
[10] `https://www.soundscapes2landscapes.org`
[11] `https://www.wesa.fm/post/pitt-researchers-are-eavesdropping-birds-name-science`
[12] `https://www.cetalingua.com/citizen-science/`
[13] `https://www.nocmig.com/audiomoth`
[14] `https://www.openacousticdevices.info/support/`



(a) Heat map of all OSH purchase locations



(b) Deployment locations and field applications of a 10% sample of purchasers

Figure 4.3: The global impact of the framework to support OSH.

OSH products may need additional manufacturing stages. Incorporating a framework to support OSH into NGO policy still requires substantial work, including further case studies of different conservation monitoring equipment. Without a framework of the type we propose, however, existing OSH will continue to have short life spans, and remain out of reach for the majority of conservation biologists.

4.4 Summary

This chapter discussed a framework to support the use of OSH for less technically skilled users, as well as supporting the system creators. The framework looks at whether purchasing opportunities available to *AudioMoth* or any other simply designed open source conservation tool, can be modelled to reduce the overheads when acquiring and developing conservation monitoring equipment. The discussion looks at manufacturing procedures, distribution logistics and community support. The proposed framework removes the technical barriers to entry into OSH, while providing a manyfold lower cost and simple alternative to traditional small batch electronic manufacture.

This chapter has addressed the user requirements (7) to (10), which were previously highlighted in Section 2.5. The framework provides the following: (7) an opportunity for groups with limited budgets to perform systematic bioacoustics research, for example by benefiting from economies of scale in group purchases. This was observed with the success of the *AudioMoth* case study where the open source device could be acquired by an individual conservation practitioner, ready to use for $49.99 USD. This is half the price of the lowest cost commercial dictaphone, *Olympus WS*, as seen in Section 2.3.1.2, Figure 2.2c; (8) guidelines to acquire a fully assembled piece of OSH. This can be achieved with simple hardware construction and utilising assembly with new online turn-key PCB manufacturers; (9) user support from online community forums; and (10) procedures for creators to receive monetary support to continue development.

The next chapter (Chapter 5) aims to address the remaining user requirements, (11) and (12), giving an overall evaluation of the whole system.

Chapter 5

Evaluation of AudioMoth as a conservation tool

In previous chapters we addressed the majority of the user requirements outlined in Section 2.5, creating a general system to enable open source acoustic monitoring for conservation. In Chapter 3 the system focused on points (1) to (6) of these requirements, defining the technical description of the *AudioMoth* hardware and in Chapter 4 on points (7) to (10), with a framework to improve the accessibility of OSH for conservation.

In this chapter we start by evaluating this general system, giving evidence of its use by the conservation community, of which the majority are satisfied by both the default firmware, described in Section 3.3.2, and the supporting framework, described in Section 4.2. Since the default firmware is not always suitable for every application, this chapter also looks at a wider system. Specifically working with users who require firmware modification and technical support to achieve their conservation aims. In Section 5.2, we look at the remaining user requirements (11) and (12), focusing on expanding the default device functionality. Here we explore the feasibility of modifying the default firmware to attain larger, more complex deployments. For these deployments users require much closer assistance, involving adjusting firmware for detection, experimental design and assisted execution in the field.

Parts of this chapter are taken from the peer-reviewed *Methods in Ecology and Evolution* journal publication (Hill et al. 2018).

5.1 The general system

The development of *AudioMoth* has been driven by demand from the conservation community, with numerous partnerships around the world. During this work, from 2016 to 2019, over 7,000 devices were acquired using the framework described in the last chapter. The combination of the previous chapters create the general system, where all *AudioMoths* can be acquired for $49.99 USD with general or *default* firmware pre-programmed at factory. The default firmware enables deployments for multiple applications, being compatible with the downloadable Configuration App (see Table 3.8 on page 75). This allows the majority of conservation practitioners to deploy *AudioMoth* as a versatile scheduled recorder without any requirements to code or learn a computer programming language.

This section evaluates the general system, using key examples taken from *Twitter* deployment posts (Section 4.3, Figure 4.3a) or relevant journal publications. An updated table (Table 5.1) and illustrative *Twitter* timeline (Figure 5.1 and 5.2) gives an overview of the general system.

Device class	Model	Battery	Sensitivity	SNR	Bandwidth	Weight	Memory	Cost
Smartphone	ARBIMON	10 yr	-45 dBV	n/a	50Hz-20kHz	1.7 kg	n/a	$4000
Best-in-class	D500X	140 hr	n/a	n/a	5kHz-190kHz	1.3 kg	128 GB	$2,551
ultrasonic	Batlogger	50 hr	n/a	n/a	10kHz-150kHz	695 g	128 GB	$1,180
	Anabat	530 hr	n/a	n/a	10kHz-125kHz	648 g	1 TB	$1,194
	SM4BAT	450 hr	n/a	n/a	10kHz-250kHz	1.3 kg	1TB	$1,099
Best-in-class	SM4	400 hr	-28 dBV	80dBA	20Hz-48kHz	1.2 kg	1 TB	$849
audible	BAR	600 hr	-14 dBV	80 dBA	20Hz-48kHz	900 g	2 TB	$750
Single-board	AURITA	13 hr	-28 dBV	80dBA	20Hz-192kHz	700 g	64 GB	$432
Dictaphone	H2n	20 hr	-23 dBV	68 dBA	20Hz-48kHz	190 g	32 GB	$187
	DR-05X	17 hr	-20 dBV	>60 dBA	20Hz-96kHz	176 g	128 GB	$173
	WS-853	110 hr	-35 dBV	>60 dBA	20Hz-22kHz	100 g	32 GB	$100
Tailored OSH	AudioMoth6V	1714 hr	-18 dBV	63 dBA	20Hz-192kHz	800 g	1 TB	$70.24
	AudioMothAA	260 hr	-18 dBV	63 dBA	20Hz-192kHz	30 g	1 TB	$49.99

Table 5.1: AudioMoth compared to existing acoustic monitoring devices

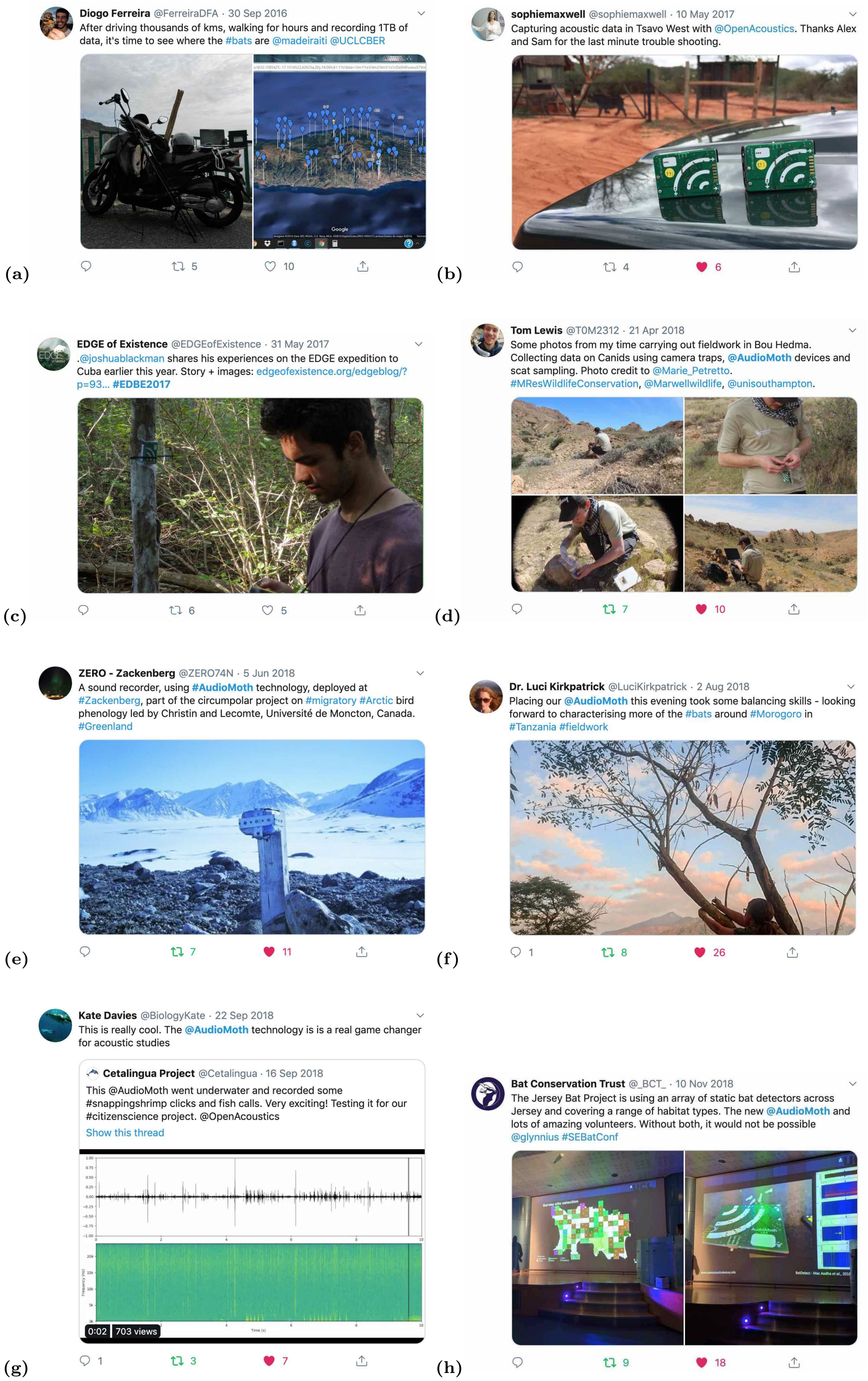


Figure 5.1: Twitter timeline of a small selection of applications using the general system and default firmware, from 2016 to 2018

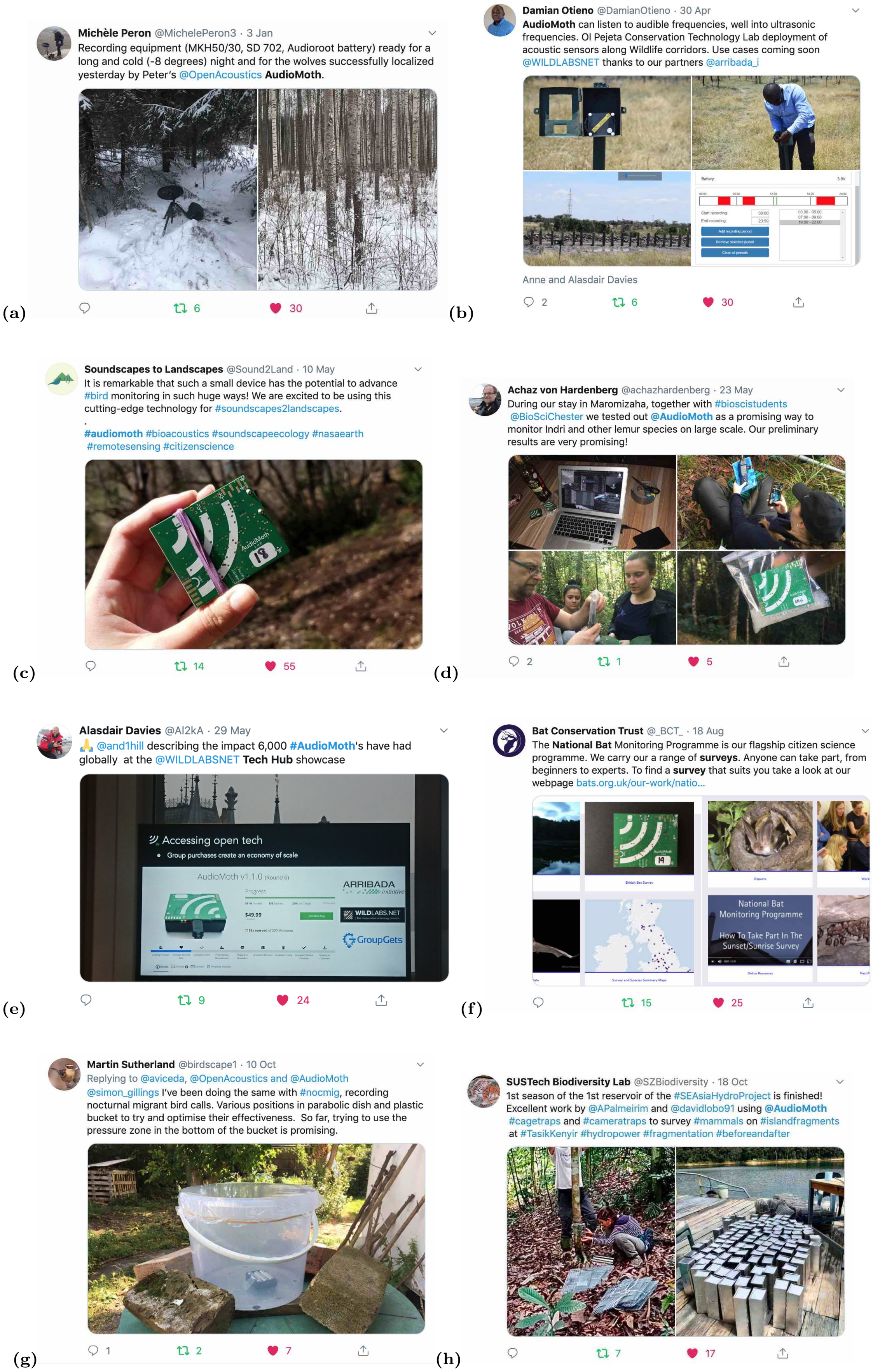


Figure 5.2: Twitter timeline of a small selection of applications using the general system and default firmware, from 2018 to 2019

5.1.1 Traditional bioacoustics applications

Over the course of this work, well over 900 projects have used the general system. The most common uptake has been in traditional bioacoustics research and educational field projects. In these projects individuals typically deploy single devices to perform systematic analysis of one species. Educational projects benefit from the open-source and simply constructed hardware, facilitating cost-effective access to high quality acoustic technology. Many have involved undergraduate field courses, such as that demonstrated by the department of Biological Sciences at The University of Chester (Figure 5.2d). In this project the general system was deployed by teaching staff on a field trip to Madagascar. *AudioMoth* was used as a tool to learn about the *indri* lemur species, being cheap enough to give each student a device to deploy and collect data on.

Masters, PhD, post-doc and institutional researchers have utilised the general system to create large global advances in conservation. Because *AudioMoth* can be acquired at a fraction of the cost compared to commercial equivalents, researchers can purchase single *AudioMoths* as minor expense claims from their research budgets. Examples of projects include wolf howl studies by Masters students (Figure 5.1d) and researchers studying characteristics of bats in Tanzania (Figure 5.1f).

A key study in 2019 led to Masters students in Brazil using the general system to record the discovery of two new species of bush cricket: *Anisophya una* and *Xenicola xukrixi*. The individual species vocalisations were recorded while in a foam cage at a sampling frequency of 192 kHz. The male *Anisophya una* was recorded as having calls in the bandwidth of 10 kHz - 58 kHz and the *Xenicola xukrixi* in the bandwidth of 50 kHz - 90 kHz (Fianco et al. 2019). As a comparison, to record at these samples rates on a commercial device would have required a best-in-class ultrasonic type, requiring a research budget for equipment of more than $1,099 USD (Table 5.1).

5.1.2 Citizen science applications

The general system has enabled the widespread uptake of acoustic citizen science, with numerous projects utilising *AudioMoth* for large-scale biodiversity monitoring. The initial group of studies that applied the early prototypes were ultrasonic bat projects. The earliest of which were acquired by the *Bat Conservation Trust* and installed across the main island of Madeira in 2016. This project was part of a larger survey of bat populations to investigate anthropogenic impacts on native fauna. With the small dimensions and weight of *AudioMoth* – approximately 20 times less than the lightest best-in-class ultrasonic device (Table 5.1) – many devices were able to fit into a standard field backpack. This ability to carry multiple devices greatly facilitated this project, allowing a single user to transport multiple *AudioMoths* around the island by moped. The project captured more than 1TB of data, which is contributing to analyses of long-term population trends to aid in future conservation efforts[1] (Figure 5.1a). Other bat projects gained benefits from using the wide ultrasonic bandwidth of *AudioMoth*. This was required to capture the calls of lesser horseshoe bats during the *Jersey Bat Project* (Figure 5.1h), with this species producing the highest vocalising frequency of any terrestrial animal[2]. In this study the AA enclosure was used (see Section 3.5.2). Although providing substantial waterproofing, user feedback indicated that the case caused increased microphone directionality due to the thickness of the acrylic hole formed around the microphone. The latest bat related citizen science project was the *British Bat Survey* or *National Bat Monitoring Programme* (Figure 5.2f). In 2018, this study was undertaken by 989 volunteers, across 1,907 sites in the UK. Captured data produced population trends for 11 of the 17 breeding bat species in Britain. Findings suggested no declines in any of the 11 species, suggesting current government legislations should continue[3]. Although successful, user feedback in this study indicated that the mechanism to tighten the AA enclosure was laborious.

For audible biodiversity, the *Soundscape to Landscape* citizen science project, used over 100 *AudioMoths* to advance biodiversity monitoring by mapping bird diversity across Sonoma County, California. In this project static *AudioMoth* early prototypes were deployed throughout the habitat inside low-cost grip-sealed bags. Although these bags were very cheap, *AudioMoth*s were vulnerable to water ingress and condensation during deployments, resulting in many devices malfunctioning. Despite the vulnerability, to date, the general system has enabled this project to perform 597 unique site visits, validated 17,218 bird calls and identified 32 bird species[4] (Figure 5.2c). In a similar manner, the *Kitzes Lab* used the general system to deploy 200 *AudioMoths* in 2018[5,6]. Despite making huge savings in cost – approximately $140,000 USD compared to using the same amount of best-in-class devices (Table 5.1) – this project required *AudioMoth* for its low power optimisation ability. The study, located in Sproul Forest, Pennsylvania, is aiming for a multiple year deployment using low run-time duty cycle routines. These routines will create yearly data stores of audio and an opportunity to identify trends in species population over a large spatiotemporal scale (Kitzes and Schricker, 2019). Although single-board computers could have been bought at a relatively low cost too (e.g. Solo at $200, Whytock and Christie, 2017), the fact that they run a full *Linux* operating system during operation means they consume anywhere from 400 mW to 1,000 mW when idle (Figure 5.3), with minimal to no power management available during operation. Even during recording to microSD card at 48 kHz, *AudioMoth* is ∼15 times more energy efficient than the most energy efficient *Raspberry Pi* based device, and

[1] `https://batdetect.wordpress.com/2016/10/19/research-update-road-testing-our-bat-call-detection-software/`
[2] `https://www.bats.org.uk/our-work/national-bat-monitoring-programme`
[3] `https://www.bats.org.uk/our-work/national-bat-monitoring-programme/reports/nbmp-annual-report`
[4] `https://soundscapes2landscapes.org/`
[5] `https://www.wesa.fm/post/pitt-researchers-are-eavesdropping-birds-name-science`
[6] `http://www.kitzeslab.org/`

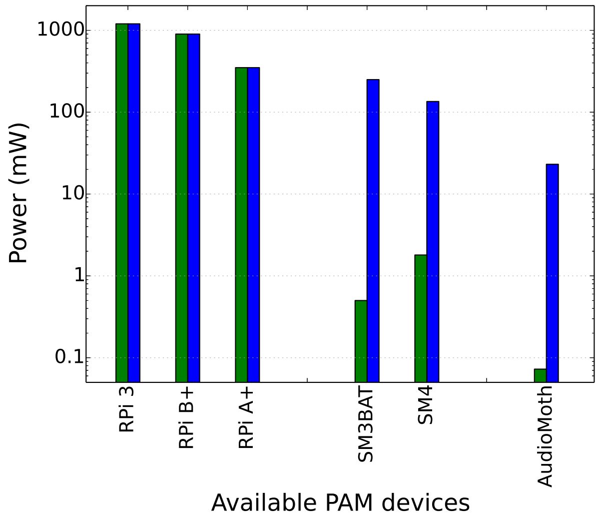


Figure 5.3: Power consumption comparisons of currently available passive acoustic monitoring (PAM) devices, when idle (green) and when recording to microSD card at 48 kHz (blue). RPi devices are all single-board computers constructed on a Raspberry Pi; B+ was used by Razali et al. (2015) for monitoring rainforest health; A+ was used by Caldas-Morgan et al. (2015) for monitoring underwater industrial activities, and Whytock and Christie (2017) for their Solo device. Song Meter (SM) devices are commercially available from Wildlife Acoustics

~4,000 times more energy efficient during its idle state. With a shutdown power of 72 µW when outside a scheduled wake-up period, *AudioMoth* would be able to keep track of time for approximately 6 years, using three AA-cell lithium batteries.

5.1.3 Experimental applications

The accessibility and affordability of *AudioMoth* has allowed for more experimental acoustic deployments compared to using expensive commercial devices. Some users have successfully tested durability of *AudioMoth* in extreme environments, such as hot arid deserts with temperatures well above 40 ℃ (Figure 5.2b), as well as sub-zero environments in Greenland (Figure 5.1e) and Estonia (Figure 5.2a). The *Cetalingua Project* applied *AudioMoth* to aquatic applications[7]. In this citizen science project manatee vocalisations were investigated as a means to identify individuals and their behaviours. This project deployed *AudioMoth* as part of a kit inside a waterproof box, with the intention to deploy them underneath kayaks or paddle boards during exploratory visits around the manatees' habitat (Figure 5.1g). Experimental studies have also applied *AudioMoth* to specialist sensing techniques, such as that of long distance sound capture. This has been demonstrated by users recording the nocturnal migration (NOCMIG) of bird species. NOCMIG studies require highly sensitive microphones, with species normally flying between 200 and 1,500 m above sea level (Dokter et al. 2010). Some users

[7] `https://cetalingua.com/`

have enhanced *AudioMoth,* by experimenting with hardware deployment setups to create there own DIY parabolic microphones for NOCMIG studies [8] (Figure 5.2g).

5.1.4 Public engagement and teaching applications

A key solution to improving biodiversity policy is increasing public engagement to those not necessarily engaged in conservation (Rose et al. 2018). *AudioMoth* has been readily used as a teaching tool in undergraduate biology and environmental science soundscape courses throughout this work. It has been used in workshops at leading universities, such as the *Zoological Society of London*, the *Institute for Conservation Research - San Diego Zoo, Queensland University of Technology* - Australia, *King College London*, and the *University of Southampton* - UK. During these workshops the low cost DIY nature of *AudioMoth* allowed each student to perform their own quick acoustic monitoring study, collecting acoustic data on campus, then returning to the lab to perform soundscape analysis on the captured data in *R*.

AudioMoth has appeared in high profile conservation events. It was invited to the *Illegal Wildlife Trade* conference in 2018, where it appeared with Prince William and the Foreign Secretary Jeremy Hunt. It won the WILDLABS Tech Hub prize in 2019, where it was introduced to the *Foreign & Commonwealth Office, Amazon Web Services, Microsoft, Digital Catapult* and *the Satellite Applications Catapult* (Figure 5.2e), and was selected as a finalist in the Conservation X Labs Tech Prize.

5.1.5 Human-wildlife conflict applications

Lastly, the general system is readily applied to the investigation of human-wildlife conflicts. An initial example of this was carried out by employees at *ZSL*, who explored the feasibility of using engine noise to trigger an early warning system to alert nature reserve managers of potential human threats on wildlife (Figure 5.1b). Accordingly, *AudioMoth* offers users a low-cost opportunity to collect data and assess whether sound can be used to identify anthropogenic disturbances in real-time. In an ideal scenario, additional external modules would be added to the GPIO ports of *AudioMoth* to enable low-cost real-time alerts by low power radio. This possibility has prompted many scientists to collect data in the anticipation to train detection algorithms to trigger alerts from relevant sounds (i.e. car engine noise, poaching by gun, logging by chainsaw, or animal vocalisations).

Next we examine a key example in more detail, in which the general system is implemented by researchers at the *University of Southampton,* in collaboration with the *Belize Forestry Department,* to collect example gunshot audio recordings. First, data is used to

[8] `https://www.nocmig.com/audiomoth`

evaluate the listening range of *AudioMoth* and identify if optimal placements of devices can offer a feasible solution to deploy over large forested areas. Then, in collaboration with an algorithm developer, the procedure to train an algorithm on *AudioMoth* is explored. The algorithm implementation moves us away from the general system discussed in previous chapters, towards a wider system where the default open source code can be adapted by users to expand the devices functionality (Section 5.2).

5.1.5.1 Poaching in tropical forests

This study aimed to test the detection range of *AudioMoth* for capturing gunshot events in mature, deciduous, broadleaf tropical rainforests in *Pook's Hill Reserve*, a private nature reserve in Belize. The study was carried out as part of this thesis, aiming to evaluate the feasibility of using *AudioMoth* as a real-time alert system for illegal poaching.

Acoustic monitoring for gunshot detection currently exists in urban environments. It is used to alert relevant authorities of events in real time (Choi et al. 2014). Such applications require numerous large and mains-powered devices, positioned on the tops of buildings in strategic locations. However, these systems are impractical in the natural environment, away from a power source and in situations where large devices are prone to unwanted discovery and destruction, as commonly occurs with camera trapping (Jumeau et al. 2017). Applications relating to resource exploitation require small-sized, low-energy and low-cost devices, suitable for cryptic deployment of sufficient numbers for a grid that achieves full coverage of large tracts of exploitable habitat, often in remote terrain, over a continuous period of several months. Many of the natural environments most prone to poaching have no Wi-Fi or mobile coverage, ruling out the use of cloud-based acoustic systems (see Section 2.3.1.3). This applies to the *Pook's Hill Reserve* in Belize.

Here 18 *AudioMoths* were deployed to record continuously to identify the minimum number of devices required to cover the 25 km^2 reserve. The devices were configured to record within the typical gunshot bandwidth, between 10 Hz and 3 kHz (see Figure 5.4). An 8 kHz sample rate was chosen to reduce both the file size of each recording and the

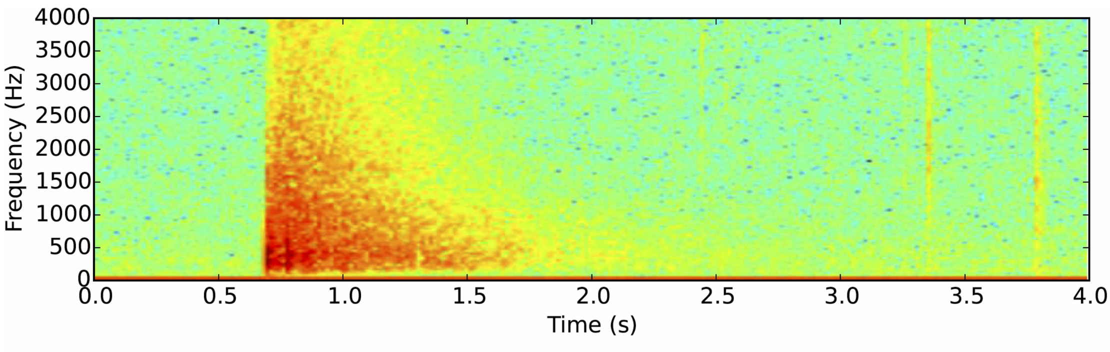


Figure 5.4: Gunshot recording at 400 m

current consumption, whilst still capturing all relevant gunshot frequency information. The devices were positioned at 13 sites on hilly terrain, 60 – 160 m above sea level. Five sites were set along a 1.2 km transect, with a device pinned to both the east and west side of a tree trunk. The remaining eight sites were distributed over a grid north and south of the transect with a device at each site, all with the same (easterly) orientation, representative of a real-world scenario. All sites were separated from each other by 200 m. Sixty-five controlled gunshots were fired in sets at various locations within the grid, aiming either east or west to test detection capabilities of the devices with respect to the orientation and distance of the sound source. Two common gun types for hunting in the area were used: a 12 gauge (Baikal MP-18EM-M) shotgun and a 16 gauge (Rossi single shot) shotgun. Deployments were performed on foot through thick vegetation led by a local woodsman, with all devices carried by one researcher in a single backpack. The deployment of 18 devices at 13 sites took approximately 6 hr.

The initial results are shown in Figure 5.5. They indicate a high chance of detection when gunshots are located within 200 m, no matter the orientation of gunshot or device. However, although showing gunshot amplitude diminishing with distance, as expected, a few unpredicted results were observed. Many of the 420 m gunshots had higher amplitudes than the 400 m gunshots, this can be seen in Figure 5.5a. The cause in disparity was identified as a physical obstruction between the gunshot sound source and the propagation path to the *AudioMoth*. From a topographic map, it was found that the obstruction was caused by a slight hill.

This finding suggested that by taking spatial variations in the sound pressure from a known sound source – relating to topography, vegetation cover and weather – a probabilistic near optimal deployment model could be designed. In 2019 fellow researchers used *AudioMoth* and this suggestion to develop a near-optimal placement methodology, which halved the required number of sensors compared to the 200-m square grid (Pina-Covarrubias et al. 2018). This reduced a potential two week deployment to just one. The cited method proves the feasibility of using *AudioMoth* with the default firmware for cost-effective large-scale deployments.

Although the general system enabled the collection of large quantities of data with minimal technical expertise – allowing new research questions to be answered (Pina-Covarrubias et al. 2018, Kitzes and Schricker 2019) and discovering new species (Fianco et al. 2019) – there exists barriers that restrict the wider potential of *AudioMoth*. For instance, to train an algorithm that can run on the device for real-time alerts would require technical expertise in digital signal processing, machine learning techniques and programming power-optimised low-level *C*.

The next section evaluates the feasibility of implementing such real-time detection on *AudioMoth*, initially focussing on simply filtering relevant sounds to memory.

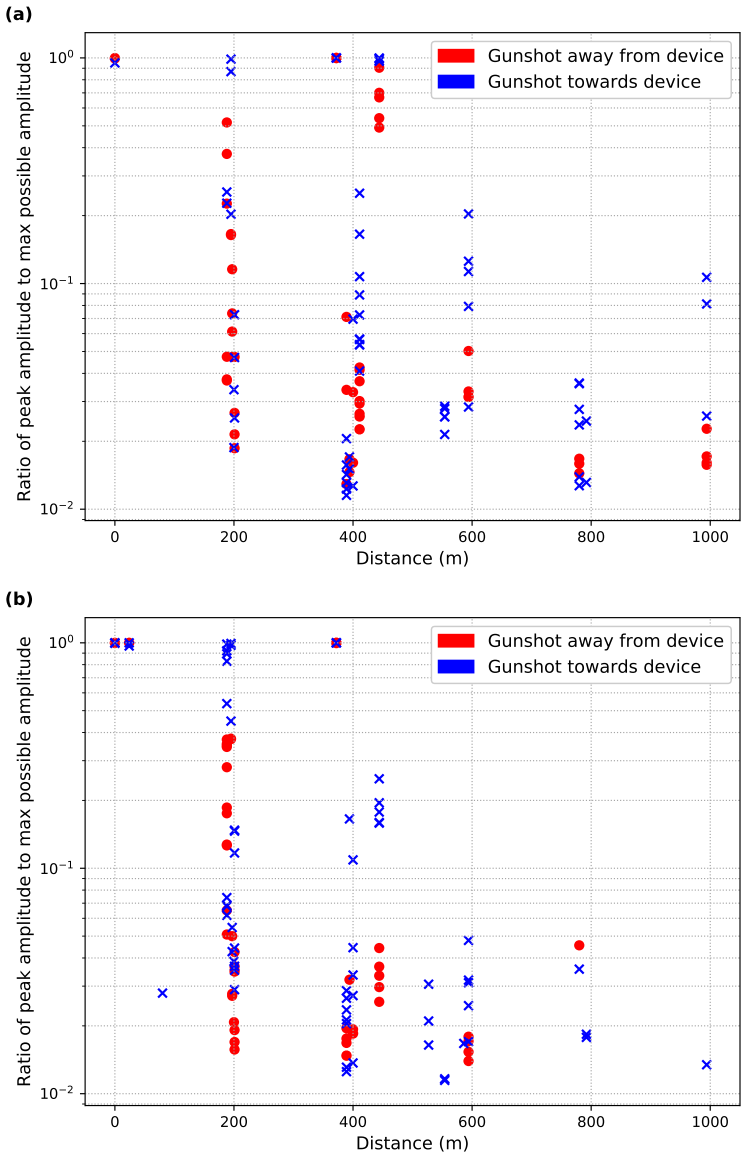


Figure 5.5: Ratio of gunshot peak amplitudes relative to the maximum possible amplitude, from continuously recording AudioMoths. (a) Devices facing towards the gunshot source, demonstrating a higher performance of audio capturing ability; (b) devices facing away from the gunshot source, demonstrating a lower performance of audio capturing ability

5.2 The wider system

To unlock the wider functionality of *AudioMoth*, users are encouraged to customise and design their own on-board software for filtering or classifying sounds as they happen. The user can modify and distribute *AudioMoth* software for specific applications, on the open *MIT* licence[9]. Modifications to the existing code upload easily onto the device without additional development boards, this is described in detail in Section 3.6. Having

[9] `https://opensource.org/licenses/MIT`

the ability to choose what to record introduces several benefits over acoustic methodologies that make use of continuously recording devices, especially in large scale and long-term deployments (Mayer et al., 2019, Sheng et al., 2019). For instance, *AudioMoth* can be programmed to filter relevant sounds such that only those of interest are saved, thus reducing post-processing time, power usage and data storage requirements. In conjunction with its low power consumption while listening, and its full-spectrum frequency response, *AudioMoth* creates a unique opportunity for users to design specific classification algorithms for individual projects. In order to realise its performance capabilities, however, *AudioMoth* employs the low-level programming language, *C*. This coding language requires a greater level of technical expertise than the less efficient high-level programming language *Python*, which is often used on single-board computers. Despite this constraint, *AudioMoth* achieves ultra-efficient power optimisation, high-speed data processing and a wide spectrum acoustic performance through the greater control over low-level processes.

This section evaluates the versatility of *AudioMoth* by implementing real-time audio processing on the device. The subsequent algorithms were developed and deployed in collaboration with Peter Prince, at the *University of Southampton* (Prince et al. 2019). The underlying theory behind them is the *Goertzel* filter (Goertzel, 1958), which evaluates specific terms of a fast Fourier transform on temporarily buffered audio samples without the computational expense of a complete transform.

To apply the *Goertzel* filter to temporarily buffered audio samples, they are first split into N windows of length L given by: $(s_{1,1}, \ldots, s_{1,j}, \ldots, s_{1,L}, \ldots, s_{N,1}, \ldots, s_{N,j}, \ldots, s_{N,L})$ where $1 \leq i \leq N$ and $1 \leq j \leq L$. The *Goertzel* filter then operates on each window, generating a magnitude m_i:

$$m_i = y_{i,L}^2 + y_{i,L-1}^2 - c \cdot y_{i,L} \cdot y_{i,L-1}. \tag{5.1}$$

In this expression, c is determined by the central frequency of the filter, f, and is given by:

$$c = 2\cos\left(\frac{2\pi f}{f_s}\right), \tag{5.2}$$

where f_s is the sample rate of the recording. As the values of f and f_s do not change, the constant c is precomputed. The temporary sequence of values y is obtained from constant c and Hamming windowed data h_j:

$$y_{i,j} = (h_j \cdot s_{i,j}) + (c \cdot y_{i,j-1}) - y_{i,j-2}. \tag{5.3}$$

In order to prevent spectral leakage, a Hamming window is applied to the samples before the *Goertzel* filter in each case. The window itself uses constants α and β, and can also be precomputed for a window of length L with $\alpha = 0.54$ and $\beta = 1 - \alpha = 0.46$:

$$h_j = \alpha - \beta \cos\left(\frac{2\pi j}{L-1}\right). \tag{5.4}$$

Goertzel filters possess a bandwidth dictated by the sample rate and the number of samples used to form the final amplitude. The equation representing this relationship is arranged such that the length of a filter window L can be calculated, given a fixed bandwidth B and known sample rate f_s:

$$L = 4\frac{f_s}{B}. \tag{5.5}$$

This allows the bandwidth of all *Goertzel* filters to be set to cover the range of frequencies used by the target vocalisation or acoustic event. We use the calculated magnitudes over N number of windows to produce a median. The subsequent comparison of this median to a calibrated threshold value identifies whether or not the sound present in the buffered audio samples is appropriate for recording.

For long-term deployments using continuously running algorithms, power consumption often requires optimisation in firmware. Power optimisation essentially falls on refining how *AudioMoth* utilises its static and dynamic power during continuous use. Static power relates to the baseline current consumption of internal and external peripherals that persist over different clock frequencies (e.g. SRAM, MEMS mic power, op-amps, interrupt timers and ADC). The remaining micro-controller peripherals use dynamic power. Dynamic power is directly proportional to micro-controller clock frequency (see Section 2.4.1.3), thus, it can be optimised by reducing the clock frequency of the processor. Static power, on the other hand, can be lowered by optimising code structure to speed up functional processes and implementing different sleep modes when certain peripherals are no longer required. Sleep modes on the *EFM32* micro-controller include: (i) run mode (EM0), where the central processing unit (CPU) of the micro-controller is running; (ii) sleep mode (EM1), where the CPU is sleeping and all peripherals, including DMA are active; (iii) deep sleep mode (EM2), where the high frequency clock is off and low energy peripherals such as the RTC, Op-amps and USB are active; (iv) stop mode (EM3), where the low frequency clock is off and there is full CPU and RAM retention; and (v) shutoff mode (EM4), where all chip functionality is off, except for the backup real time counter (RTC) and retention RAM. Using trade-offs in dynamic and static power, *AudioMoth* can be optimised for a variety of long-term algorithmic deployment scenarios.

AudioMoth is first evaluated with a simple implementation of the formerly described *Goertzel* filter, which is optimised using the *finish fast sleep longer* methodology. This power optimisation technique maintains battery life using the highest clock frequency of 48 MHz to enable classification to complete as fast as possible and increase the percentage of time in EM4. This implementation is designed in the context of an ongoing monitoring study aiming to achieve large-scale and long-term coverage with a large number of smart devices. The overall goal in this study is to test for presence of the New Forest cicada (*Cicadetta montana*, Scopoli, 1772), an elusive species last sighted in the UK over 22 years ago (Pinchen and Ward, 2002). Later, we move back to the Belize gunshot study, exploring a more complex implementation of the *Goertzel* filter using a machine learning technique.

5.2.1 The New Forest cicada

This study aimed to locate an extant population of cicada species, known to be the only native species to the UK (Figure 5.6). The New Forest National Park being the last known area of occupancy outside continental Europe. New Forest cicadas spend most of their lives underground as nymphs, emerging as adults in ∼7-year cycles. The high-pitched call of the adult, at 14 kHz, is out of the hearing range of most humans other than children. This life history and behaviour has made it difficult to search for the species in manual surveys. Until now, listening devices have been too expensive, energy-hungry and intrusive to deploy in long-term systematic surveys over the large scale of the cicada's potential range. In a first such systematic survey, 87 *AudioMoths* were deployed in four locations for the 2- to 3-month emergence periods from spring to early-summer of 2016 and 2017. Devices were deployed in low-cost grip-sealed bags. Deployments were performed together with *Buglife*[10], a conservation organisation in Europe devoted to the conservation of all invertebrates. *Buglife* assisted in device positioning, with locations chosen in habitats considered most likely to support the species, based on previous entomological surveys and historical records of occurrence.

Figure 5.6: *Cicadetta montana* caught in Slovenia measuring 20 mm

[10] `https://www.buglife.org.uk/`

Recordings of the species made in Slovenia were used to characterise the song of the male cicada, as an extended buzz lasting 30 s with a call bandwidth from 12 kHz to 21 kHz. To capture the whole call a 48 kHz sample rate was used. Because the mid frequencies of this call are rarely present in the calls of other insect species found in the New Forest, the 14 kHz component of the New Forest cicada song was used to inform the detection algorithm (Figure 5.7a). The ratio of the 14 kHz component to an 8 kHz component of each sample produced an identifier robust to broad spectrum noise. This ratio overcame an issue with algorithms simply using 14 kHz, which were prone to false positives from white noise interference caused by strong wind or by movement in close proximity to the microphone. A recording was triggered by a high ratio, resulting from a high 14 kHz value and a low 8 kHz value (Figure 5.7b). A low ratio that might result from high values at both 14 and 8 kHz was more likely to be wind than a cicada call (Figure 5.7d).

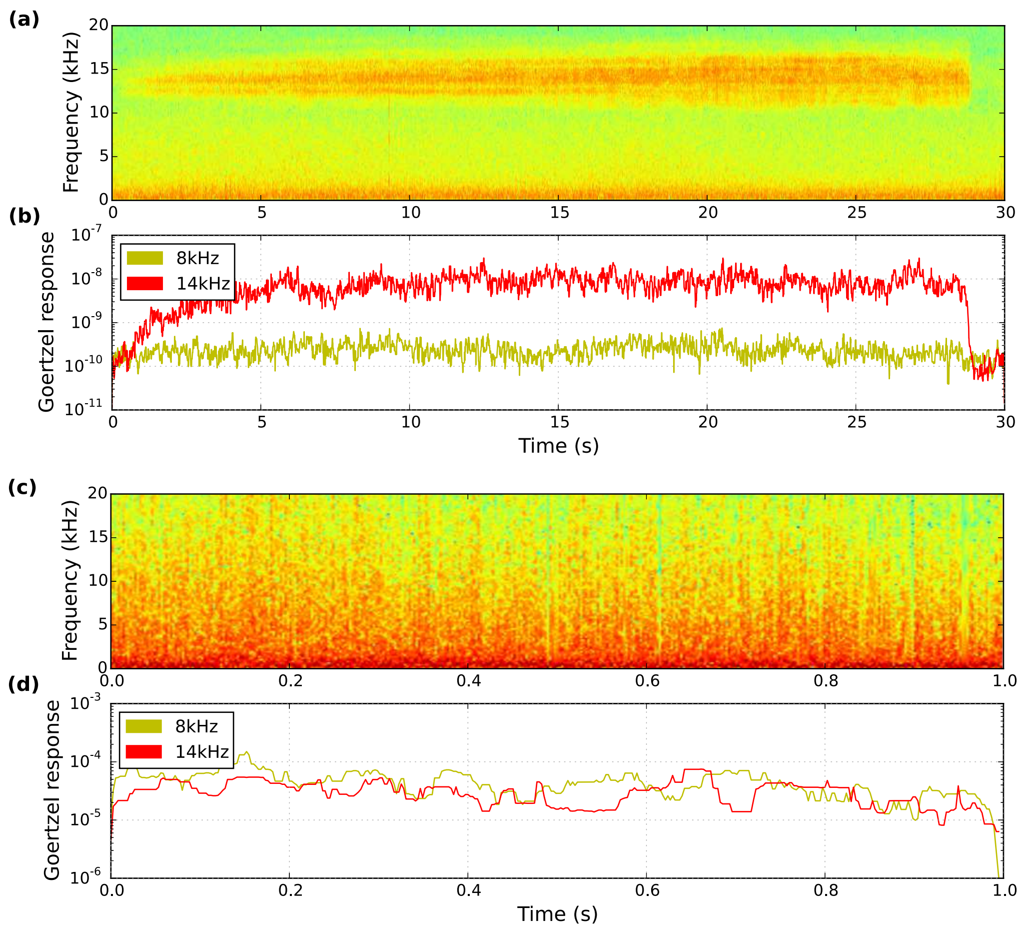


Figure 5.7: Spectrogram and Goertzel responses used to classify the cicada song: (a) the New Forest cicada recording taken in Slovenia; (b) the Goertzel filter response to this same recording, with the species detected and distinguished from wind interference by the presence of a 14 kHz component and an absence of the 8 kHz component; (c) wind noise spectrogram of a recording taken in the New Forest; (d) the Goertzel filter value in response to the wind noise recording taken in the New Forest, with the species not detected because the 14 kHz component and the 8 kHz are both high

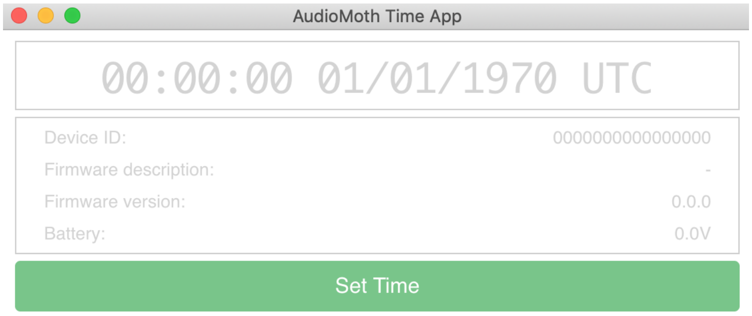


Figure 5.8: Illustrative figure of the Time App, which was designed to simplify the configuration process for users with less user interface experience.

The implementation of the New Forest cicada firmware was based on the standard code structure used in the default firmware; however, sample rate, recording schedules and duty cycles were hardcoded in the *C* firmware. Configuration before deployment could then be simplified using the single-button Time App (Figure 5.8). For full autonomy over the 3 month emergence period, *AudioMoth* operated on a duty cycle routine, waking every 5 s to listen over one buffer lasting 171 ms. Duty cycles only ran in the cicada's emergence hours during daytime. Otherwise *AudioMoth* slept, consuming 72 µW in EM4. This allowed a full set of batteries to last the whole deployment, while giving the algorithm an opportunity to repeat multiple times over a 30-second call. When awake and listening, the detection algorithm cycled through 8,192 instantly buffered samples in the external SRAM. *Goertzel* filtering, using a bandwidth B of 1.5 kHz and filter length L of 128 (Equation 5.5), was applied sequentially to sections of the buffer using a moving window. This produced 64 magnitudes for each of the 14 kHz and 8 kHz bands in the window. The 14:8 kHz ratio of magnitudes for each window then produced 64 values, from which was derived a median ratio.

$$C = \begin{cases} 1, & \textbf{if } \text{Median} \left\{ \frac{m_i^{14}}{m_i^{8}} \mid 1 \leq i \leq N \right\} > T \\ 0, & \textbf{otherwise} \end{cases} \tag{5.6}$$

If this median exceeded a calibrated threshold T, it informed the classification C to trigger a 30-s recording; otherwise the device returned to its shutdown power mode until the next wakeup period in 5 s (Equation 5.6).

The detection capabilities of *AudioMoth* were tested by playing the cicada recordings captured from Slovenia inside an anechoic chamber. When the cicada recording was played in conjunction with a collection of 5-s recordings of background noise captured in the New Forest, the algorithm achieved a true positive rate of 0.998 and a false positive rate of 0.01. These tests verified its ability to react to low amplitude cicada recordings. The devices responded to a 14 kHz ~60 dB SPL test tone within a range of 10 m in a forest environment. The test tone was played from a smartphone with the volume measured from a sound level meter 200 mm away from the smart phone speaker. After deployment in the field, devices were collected and all of the triggered recordings were consolidated into a grid of spectrograms. The total field deployment resulted in 129 hr of audio triggered by positive algorithm responses. These were identified as false positives from a number of sources, including dog whistles, leaf noise during strong winds, and bird songs. In comparison, recording continuously for 12 hr per day over the same period would have created 156,600 hr of audio data for analyses. Potential true positive recordings were identified by visual inspection of this grid over periods when local weather data indicated suitable conditions for emergence. Playback of these candidate recordings, however, revealed no calls of the New Forest cicada over the two-year study. During this deployment, 23% of devices suffered some level of water damage, due to heavy rain and failure of the grip-sealed bag. Despite not finding the species, the New Forest cicada case study showed the effectiveness of running real-time algorithms on the restricted 256 kB of *AudioMoth* flash storage. Only 50 kB of flash was occupied by the cicada algorithm code, leaving 80 % available to further improve performance.

In the next section we return to the Belizean gunshot study (Section 5.1.5.1) and use the *Goertzel* filter as the foundation of a more complex detection algorithm.

5.2.2 Gunshot detection

When recorded at close range, a gunshot is heard as an initial muzzle blast. This consists of a loud impulse covering a wide range of frequencies. As the sound propagates from the gunshot, the high frequency components start to decay as they are absorbed into the air and the surrounding environment. The gunshot detection algorithm for *AudioMoth* bases its detection on the characteristic rate at which select frequencies peak and then decay from the initial muzzle blast. These characteristics were determined by the ground truth trials performed in Section 5.1.5.1.

To characterise the gunshot features, we developed a five state hidden Markov model, which used the *Viterbi* algorithm (Forney, 1973) to establish the most likely path through the five states taken by the recording. These states are as follows: silence (S), noise (N), initial impulse (I), decay (D) and tail (T), each representing a distinct stage of a shotgun blast. Each state is represented by three frequency components, extracted using *Goertzel* filtering around 2,000, 1,200 and 400 Hz (Figure 5.9). These states were modelled from recordings of gunshots taken at the field site, by manually classifying blocks of samples within each recording as one of the five states and then fitting log-normal distributions to each (Figure 5.10). These probability distributions then formed the hidden Markov model, on which an implementation of the Viterbi algorithm was run. The vast majority of windows returned a series of silence or noise states, with the distributions representing these states being robust enough to contain likely false positives such as branches snapping. The algorithm deemed the window to contain a shot only when the selection of states returned by the Viterbi algorithm included all three states that represent a gunshot, in their expected sequence.

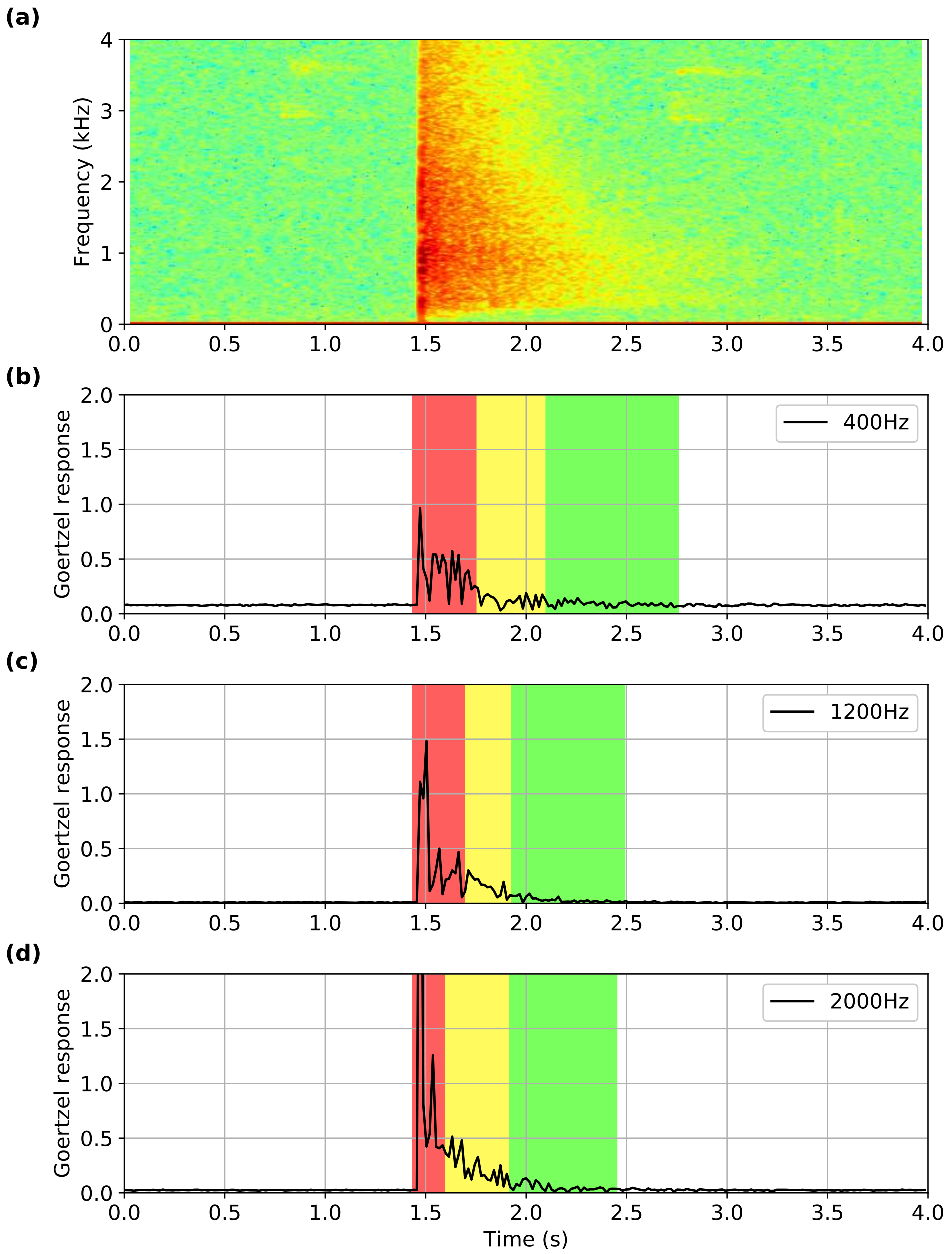


Figure 5.9: Spectrogram and Goertzel responses used to classify gunshots: (a) spectrogram of a gunshot recording taken in Belize at 255-m distance from the source, (b)–(d) the 400, 1,200 and 2,000 Hz Goertzel filter values in response to the gunshot recording, at 2,000 Hz showing high frequency sound decay. Response periods are colour-coded according to the selected states used to build the classification model: initial impulse (red), decay (yellow), tail (green)

The captured data were run through the detection algorithm on a desktop machine after deployment, which identified 100% of gunshots up to 300 m, 94% at 400 m and 54% at 500 m. The compiled algorithm had a flash size of 60 kB, which was an extra 10 kB compared to the cicada detection firmware. The precision and code size demonstrate that it would be feasible to deploy an effective gunshot algorithm on *AudioMoth*.

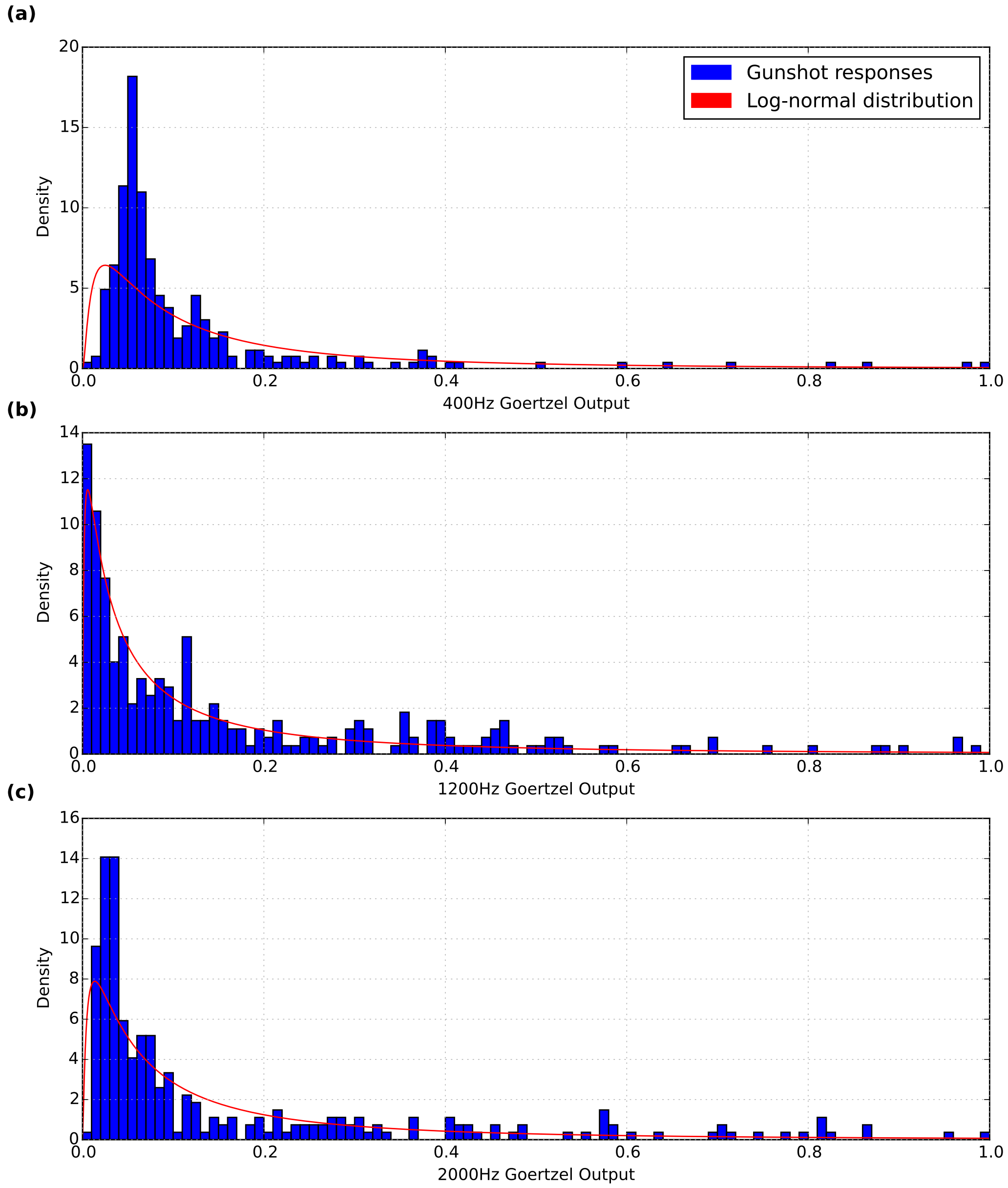


Figure 5.10: Response densities of the three Goertzel filter outputs for gunshots collected at various distances in Belize. Each histogram shows a fitted log-normal distribution used for gunshot detection at the impulse state. The Goertzel filters were centred at (a) 400 Hz, (b) 1,200 Hz and (c) 2,000 Hz

In April 2018, 20 *AudioMoths* were deployed at 10 locations for one year. The deployment placements were optimised using the methodology described by Pina-Covarrubias et al. 2018. For this deployment, the firmware was adapted in a slightly different way compared to that of the cicada deployment. The ground-truth dataset revealed that gunshots in the tropical forest environment last ~1 s before decaying beyond detection. Unlike for the 30-s cicada call, a duty cycle hoping to catch the event in one of the listening periods would result in a high number of false negative responses. Accordingly, the firmware was adjusted to listen constantly, using a three element circular buffer to collect audio

	Listen		Write	
	EM0	**EM1**	**EM0**	**EM1**
11 MHz	6.8 mA	4.8 mA	29.9 mA	5.7 mA
14 MHz	7.8 mA	5.1 mA	30.9 mA	6.0 mA
21 MHz	10.1 mA	5.6 mA	33.2 mA	6.7 mA
28 MHz	12.4 mA	6.4 mA	35.5 mA	7.4 mA
48 MHz	19.9 mA	8.3 mA	42.1 mA	9.2 mA

Table 5.2: Current consumptions when processing and writing to SD card in run mode (EM0) and sleep mode (EM1)

samples in one 2-s buffer while performing analysis on the two previous consecutively filled buffers. This resulted in an implementation with no breaks in listening, whilst limiting all analysis to calculations that could be performed in the time it took to fill one of the buffers (i.e. 2 s). Unfortunately, with no breaks in capturing data, EM4 could never be reached. This was because the audio data had to continuously transfer between the microphone, micro-controller and SRAM IC. Instead, EM1 could be entered to reduce power consumption after each classification had been completed.

Dynamic power was reduced by dividing the clock frequency in firmware. To achieve the current consumption to that measured at the lowest 11 MHz (Table 5.2), the code structure was optimised to allow enough time to complete a classification in the 2-s window. Instead of using software oversampling, emulated using explicit *C* code (see Section 3.3.1), the ADC sampling implementation was changed to take advantage of the available on-board hardware oversampling protocol. Although less flexible for software sample rate changes, this implementation removed several clock cycles during the initial

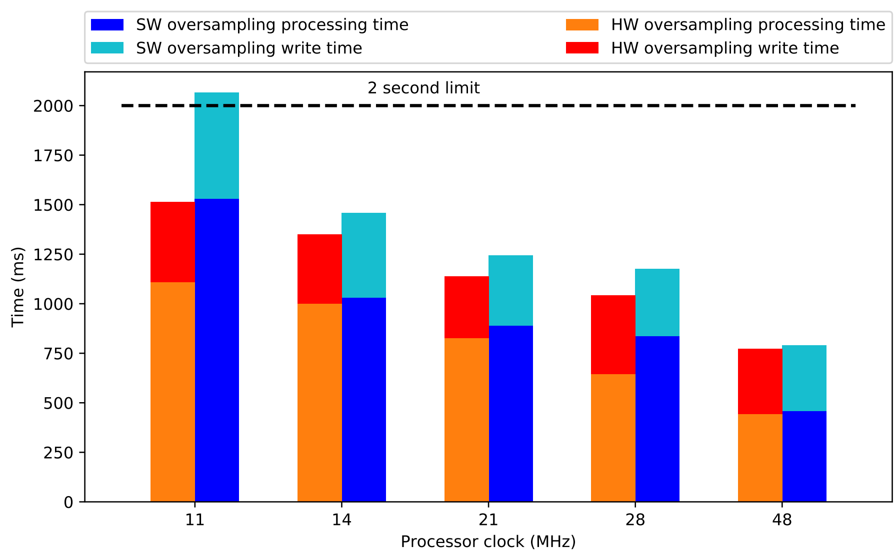


Figure 5.11: Trade-offs in time to process/write at various clock frequencies, with either ADC software oversampling or hardware enabled oversampling

Figure 5.12: The 2018 AudioMoth gunshot algorithm deployment inside the 6 V enclosure

ADC sampling stage of the classification. Thus, enabling processing and writing to microSD card within 1.5 s. This reduced current consumption by 13.1 mA in EM0 and 3.5 mA in EM1, compared to the 48 MHz CPU clock frequency implementation (Figure 5.11).

To keep *AudioMoth* listening for a whole year, the 11 MHz algorithm implementation was deployed in tandem with the 6 V enclosure (see Section 3.14). Two devices were stationed at each location, one configured to record during the day and the other configured to record during the night (Figure 5.12). The 6 V enclosure increased battery capacity to 24 Ahr, meaning both devices could listen at each location for ∼8,328 hr (∼347 days). Devices were collected the following year in April 2019. The algorithm triggered on average, 111,000 recordings per device, with the majority being false positives. The average false positive rate was calculated as 0.08, producing an average of 145 false positives an hour. With such a high rate of recordings, four devices lost power before the year had completed. One after 7 months, two after 11 months and one just before collection on 9th April 2019. 13 *AudioMoths* remained powered for the whole year and in these devices there were nearly half as many triggered recordings. Two devices failed due to the membrane being penetrated by insects, resulting in water ingress and electronic damage. One after two months and one after four months. The remaining device survived the whole year; however, it had no files recorded due to loosing configuration on the day of deployment. Overall, approximately 70 true gunshots were verified by manually listening to the captured recordings. These could be located roughly to the closest 400 m circumference of each *AudioMoth* location, however, due to a lag on the *AudioMoth* RTC, which has an accuracy of ±20 parts per million, a definitive number of gunshot events and specific locations could not be concluded. Although the algorithm responded to recorded gunshots in an anechoic test environment, not enough background recordings were collected to predict the false positive performance of the algorithm. This meant that any sound source producing a similar gunshot frequency sequence, produced a false positive response. False positives analysed by listening to the data included snapping branches, bird calls, human speech and insect calls.

Areas for improvement were highlighted by the findings of this study. These included: (i) the collection of yearly background noise to test and design the algorithm around false positive performance, (ii) better synchronisation of clocks for gunshot localisation and (iii) insect deterrents to prevent them penetrating the membrane used on the 6 V enclosure. Further suggestions will be covered in Section 6.1.

5.3 Summary

This chapter demonstrated that a variety of monitoring projects become feasible with access to open, smart, small and power-efficient devices. *AudioMoth* enables researchers to flood large areas with these devices for improved coverage of obscured, remote and inhospitable ecosystems. Section 5.1 addressed the user requirement (11), suggesting a method to perform on-board analysis and detection on *AudioMoth* in two studies looking at insect detection and gunshot detection. The capacity to perform real-time detection with a programmable algorithm vastly reduces on-board memory requirements, and post-deployment data analyses. Although detection capability is also available on commercial devices, such as the *Peersonic RPA3* and *SM4BAT* bat detectors, users have limited ability to customise or verify the accuracy of the in-built classification algorithms. *AudioMoth* software allows users to have complete control over their on-board detection algorithms for their specific application, thereby greatly improving the flexibility of the tool and reducing the need for post-processing software to analyse data after deployment. User requirement (12) was partly addressed with a simple version of configuring the device using the Time App. This requirement will be be addressed further in the next future work chapter.

The last chapter (Chapter 6) concludes this thesis and suggests further work.

Chapter 6

Conclusion and future work

The conservation of biodiversity is described as humanity's most pressing policy concern, with predicted rates of species extinction suggested to have devastating impacts on the environment and human life (Chaplin-Kramer et al. 2019). Recent ecology and conservation literature – reviewed in Chapter 1 – concluded that to inform conservation policy we must better understand biodiversity data-gaps (Geijzendorffer et al. 2016, Schmeller et al. 2017, Girardello et al. 2019, Adams et al. 2019, Lessa et al. 2019, Coad et al. 2019, Xing et al. 2019). The scarcity of monitored biodiversity has prompted conservation institutes and government councils to push towards improving conservation technology. My research has taken a lead on this push, exploring the field of acoustic monitoring to develop the first scalable, financially self-sustaining and fit-for-purpose open source conservation monitoring system.

Chapter 2 has defined an ideal acoustic monitoring device in terms of conservation user-requirements. These have been specified from the baseline performance of existing commercial and open source equipment, especially those based on single-board computers. Typical single-board computers have a utilitarian open source design philosophy, reducing hardware costs and enabling DIY hacking for unique scientific research. Previous literature promoted the cost and community benefits of *Arduino* and *Raspberry Pi* (Buechley 2009, Brock et al. 2013); however, concerns have been raised around their high power consumption for long term deployments and poor usability for non-technical users. The computer science literature has long described the involvement of users in product design as the most effective process to achieve usable systems (Norman, 1988, Abras et al., 2004). Hence, instead of adopting existing single-board computers as the foundation of a new tool, which is often standard practice in conservation, it can be concluded that although inspiration can be taken from their construction, better and novel technology can be designed through user-centred developments. The user-requirements outlined in this chapter contribute to the field conservation technology.

Chapter 3 documents the first contribution of this work, describing the *AudioMoth* design and construction, in which two key technological advancements have been engineered to address the cost and power issues defined in the user-requirements. The advancements have emerged from the increased global production of the smartphone and IoT industry, bearing low-cost MEMS and ULP micro-controller technology, respectively. Exploiting these technologies, *AudioMoth* has matched and even improved on the baseline levels of performance of existing best-in-class commercial devices. These have included: simultaneous audible and ultrasonic sound capture, increased long-term performance, miniaturised overall dimensions, and reduced material cost. The instructions and *Github* pages defined give engineers a basis to improve and adapt the design for their specific needs. Thus, similar to that seen with *Arduino* and *Raspberry Pi*, this research has created an adaptable tool, in which a larger DIY community can be built around. Although this chapter clearly defines the hardware for users with technical experience wishing to manually assemble *AudioMoth*, it raises the question of accessibility for less technically skilled conservation practitioners unable to build the device.

To this end, Chapter 4 has proposed a generalised framework to improve access, not just to *AudioMoth*, but any OSH designed for conservation. The framework attempted to challenge the OSH business model literature (Pearce 2017) and address the many barriers that block conservation practitioners from adopting DIY hardware. A collaborative approach has been established in this chapter, in which proposed guidelines have been case-studied using *AudioMoth.* The framework has provided guidelines to acquire fully assembled OSH and an opportunity for groups with limited budgets to benefit from economies of scale in crowdfunding. The case study used these methods to sustain the life-cycle of *AudioMoth,* which to date, has achieved a reach of 923 globally-spread users. Although deployment locations were located in areas of high biodiversity, the purchase locations of *AudioMoth* indicate the limitations of the framework at reaching beyond the geographic regions of wealth. Despite the limitations, it can be concluded that a framework based on crowdfunding can provide new insights into how OSH conservation technology can be accessed at scale.

While Chapter 3 and 4 have focused on the improved accessibility and initial design of the *AudioMoth* hardware, the usage of the system by the conservation community has confirmed the overall research aim by provoking important contributions to ecology. Chapter 5 has demonstrated with real-world examples that a variety of projects become feasible with access to the *AudioMoth* general system. These have included: (i) several projects collecting previously hidden anthropogenic disturbance data, (ii) hundreds of projects collecting numerous vocalisations of previously unmonitored species, (iii) the discovery of two new bush cricket species in Brazil, (iv) the catalyst behind the first large-scale spatiotemporal citizen science acoustic monitoring project, (v) a novel optimisation method of sensor deployments, and (vi) increased public engagement in conservation. Additional projects have become feasible with the wider system, in which the default firmware of *AudioMoth* has been modified to change its functionality, allowing for detection on the device. From previous literature, the benefits of filtering have shown to increase the scalability of monitoring projects by increasing battery life, reducing storage requirements, and simplifying analysis after data collection (Mayer et al., 2019, Sheng et al., 2019). Although conservation users were unable to create algorithms on *AudioMoth* themselves, by collaborating with a software developer, implementations have been successfully deployed in two studies. The New Forest cicada study used the simple *Goertzel* filter for audio classification on the insects 14 kHz call. Deployed devices were shown to trigger to cicada calls in Slovenia. The gunshot detection study used the more complex hidden Markov model machine learning classifier. *AudioMoths* deployed over both studies endured the entire study period without maintenance visits. Both of the algorithms took up a very similar, but small proportion of the *AudioMoth* flash storage size, leaving approximately 190 kB available for improvements. Each deployment clearly illustrated the effectiveness of running real-time algorithms on restricted hardware – in which filtered recordings increase the longevity of the device – whilst demonstrating ecological outcomes. The first outcome identified no cicada occurrences for at least two years. However, with an emergence period of seven years, the findings suggested that the species emergence might have been missed, or that a larger deployment grid may be required to accurately state the species status in the UK. The second outcome detected 70 illegal gunshot events over all devices deployed. Although this provided an indication of which month poaching activity occurred in, due to the inaccuracy of device time, it could not be used to count or localise each gunshot event.

Overall, the work presented in this thesis has provided conservation practitioners access to a fit-for-purpose hardware solution to monitor all vocalising terrestrial wildlife. With further developments in the new technologies described here, we are getting closer to achieving a basic requirement of sustainable development, that local communities can afford to monitor their own natural resources and expand the coverage of monitored biodiversity.

6.1 Future work

The positive uptake and its impact on conservation has encouraged this research to continue beyond this thesis. This section groups the continued development into five parts: hardware add-ons, hardware modifications, usability, software and conservation policy.

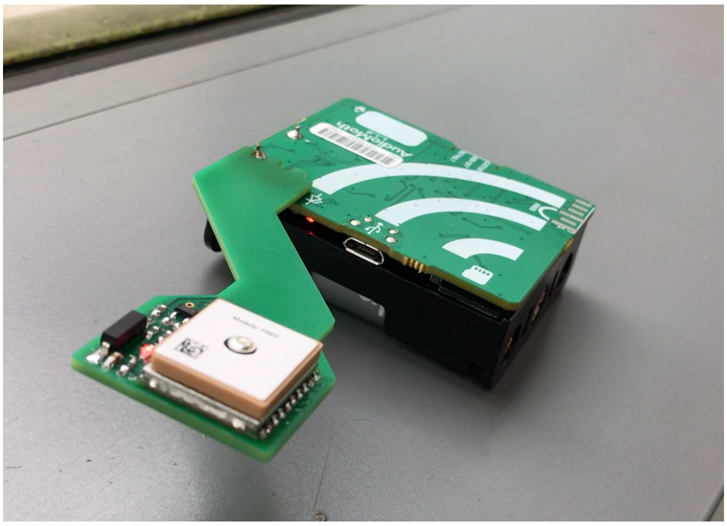
6.1.1 Hardware add-ons

Add-ons represent external pieces of hardware that, when combined with *AudioMoth*, complement performance. Based on the conclusions drawn from the evaluation chapter (Chapter 5), the following optional hardware add-ons have been recommended for future work:

- The most regular issues fed-back by users have been enclosure related. These are split between enclosure usability and the adverse effects caused by them to microphone performance. These issues have been discussed in Section 5.1.2. Figure 6.1 presents the first suggested add-on, which is recommended to improve the original acrylic enclosure design described in Section 3.3.3. The enclosure aims to have improved omni-directionality by reducing the depth of material around the microphone and improved usability using a *GroPro*[1] style clasp to simplify the closing mechanism. This enclosure costs approximately $35 USD.

Figure 6.1: GoPro style enclosure to improve usability, durability and omni-directionality during outdoor deployments

[1]`https://gopro.com/en/us/shop/mounts-accessories/protective-housing/AJDIV-001.html`



(a) Custom GPS extension to improve timestamp metadata on recordings

(b) LoPy extension module attached to AudioMoth GPIO ports, with a custom acrylic enclosure for LoRa gunshot alerts

Figure 6.2: GPIO extension modules

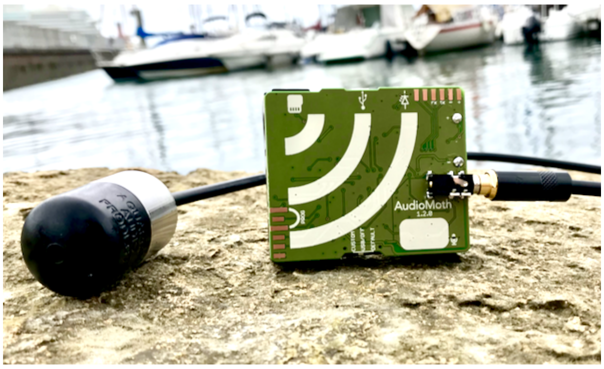
- Given the limitations of the *AudioMoth* RTC observed in Section 5.2.2, the second suggested add-on is an alternative time keeping mechanism. This is recommended to achieve better clock accuracy for localisation applications. One method to achieve this has been to design an external module that connects to the *AudioMoth* GPIO pins, enabling the RTC to synchronise to 1-ms accurate GPS time. Figure 6.2a presents a prototype GPS external module currently being trialled to address the time lag issue. The GPS prototype is due to be trialled with the Belize gunshot detection in early 2020 to identify precise locations of poaching events.

- On success of GPS time synchronisation, the gunshot detection applications should push towards a complete early warning alert system, as encouraged in Section 5.1.5. Therefore, the suggested third add-on is an additional method to send these alerts wirelessly. With many low-cost off-the-shelf modules now available, long range radio (LoRa) has been initially identified as an effective method to send alerts in non-connected regions of the world (Vangelista et al., 2015). Figure 6.2b presents an early LoRa enabled *AudioMoth* prototype using the easy to program *LoPy*[2] module.

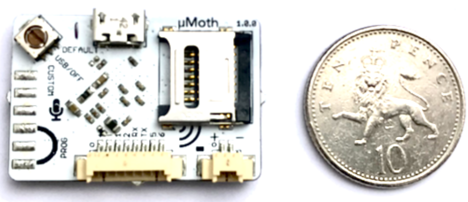
6.1.2 Hardware modifications

Modifications represent hardware changes to improve the original open source design files. These would be publicly published as updated versions of *AudioMoth*. Guided by demand from the community, the following hardware modification have been recommended for future work:

- With commercial aquatic acoustic technology costing far more than commercial terrestrial acoustic devices, there is an immediate need for low-cost options to increase the coverage of monitored marine and fresh water biodiversity. This has been observed in Section 5.1.3 with the manatee citizen science project. To extend *AudioMoth* to underwater applications, one method is to add plugin capabilities



(a) AudioMoth 1.2.0: the next version of AudioMoth designed to accept external microphones or hydrophones



(b) µMoth: the first version of AudioMoth developed by the open source community

Figure 6.3: New hardware developments

[2] `https://pycom.io/product/lopy4/`

for use with existing low-cost external hydrophones. Figure 6.3a is a prototype version of *AudioMoth* with an external 3.5 mm connector to allow the use of off-the-shelf hydrophones. This version of *AudioMoth* has been elected as a finalists in the *Conservation X Labs Tech Prize*[3] *2019.*

- Being an open source technology, users outside of this research have been able adapt the hardware design files to suit their requirements. This has been observed in a project run by conservation organisations, *ZSL* and the *Arribada Initiative*, who have taken the original *AudioMoth* design and adapted it to suit their needs. Figure 6.3b shows their first concept, in which the components and PCB layout have been changed to reduce the weight of *AudioMoth* from 30 g to 5 g. This device, renamed as *μMoth*, has been designed for animal-borne monitoring, specifically for listening to in-flight vocalisations of bird species.

6.1.3 Usability

A limiting factor in the development of *AudioMoth* has been the lack of rural, local and indigenous communities taking part in the UCD process. Hence, *AudioMoth* usage has been biased towards those with access to modern computing equipment and software. Based on this, further research with rural conservation practitioners is considered necessary to develop a complete tool for conservation.

Despite the lack of collaboration with this group, two possibilities have been suggested to configure *AudioMoth* without a computer. The first uses the *AudioMoth* microphone to decode audible configuration signals from a mobile phone speaker (Jewell et al., 2015). As well as removing the requirement for a personal computer, this method allows multiple devices to be configured simultaneously, resulting in a substantial time savings for large-scale deployments. Configuring *AudioMoth* by audio was trialled in Summer 2018 and 2019, in the *British Bat Survey*[4], previously described in Section 5.1.2 on page 95.

Another possibility is to use GPS to automatically configure *AudioMoth* time when a satellite signal is received. This removes all ergonomic considerations around the configuration process, with users only needing to physically deploy and collect the device after the study.

6.1.4 Software

Further research is needed to reduce the false positive response of the gunshot detection algorithm discussed in Section 5.2.2. Algorithms should make use of the remaining 500

[3] `https://conservationxlabs.com/con-x-tech-prize`

[4] `https://www.bats.org.uk/our-work/national-bat-monitoring-programme/british-bat-survey/configure-your-audiomoth`

ms of computational time and 190 kB of flash storage to take into account variations in acoustic structure due to orientations of the device and sound source. To enable conservation practitioners to implement their own classifiers there could be future possibilities to create a compiler that generates C code or configuration parameters from implementations using GUIs to simplify the digital signal processing techniques.

One of the biggest challenges ahead is in data management, to store, sort, filter, and analyse the massive amounts of data produced by acoustic sensors. Issues for open-source acoustic data include: storage costs, data labelling and curation, data flows between creators and users, needs, values, ethics and technical support.

6.1.5 Conservation policy

It was concluded that OSH has the potential to improve the monitoring coverage of biodiversity. However, with such few species monitored and sound only produced by certain species, further policy support should be considered to enable the creation of new OSH technologies to further increase coverage. Since this PhD, national governments have started to commit to the conservation-technology sector, in which open science plays a vital role. The UK government, for instance, are funding initiatives to tackle illegal wildlife trade using innovative open data standards[5]. Practitioners and these new initiatives should always consider UCD in new conservation technology developments.

The final recommendations are based on the conclusions drawn from the framework proposed in Chapter 4. They indicate that creating legacy value for OSH and proprietary projects used for conservation should be considered the first principle of action for conservation organisations, institutes and universities wanting to invest in further technology. Online community platforms for conservation technology such as *WILDLABS* or *Conservation X Labs*[6] could take a lead in policy adoption, creating official platforms for recording long-term OSH findings for the community to share and learn from. It is important to push access to OSH toward communities outside of the pockets of wealth and high opportunity that the framework has initially served. Future developments should consider investigating the benefits and costs of completely transitioning the framework to the conservation community, ways of making it more accessible to those communities typically underserved by citizen science, and methods of community-led support for conservation tools.

Nonetheless, the framework, at present, will be the funding foundation to continue further support for existing users and to develop *AudioMoth* into the future.

[5] https://gov.uk/government/news/digital-revolution-to-use-the-power-of-data-to-combat-illegal-wildlife-trade-and-reduce-food-waste
[6] https://conservationxlabs.com/

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