Solo: an open source, customisable and inexpensive audio recorder for bioacoustic research

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(1) **Solo website** https://solo-system.github.io/
(2) **Video tutorial** https://youtu.be/2Fq05JlEKjw

Summary

1. Audio recorders are widely used in terrestrial and marine ecology, and are essential for studying many cryptic or elusive taxa. Although several commercial systems are available they are often expensive and are rarely user-serviceable or easily customised.
2. Here, we present the Solo audio recorder. Units are constructed from the Raspberry Pi single board computer and run easy-to-install and freely available software. We provide an example configuration costing £167 (£83 excluding suggested memory card and battery), which records audible sound continuously for approximately 40 days. We also provide a video tutorial showing hardware assembly and documentation is available via a supporting website.
3. The Solo recorder has been extensively field tested in temperate and tropical regions, with over 50,000 hours of audio collected to date. This highly customisable and inexpensive system could greatly increase the scale and ease of conducting bioacoustic studies.

Introduction

Bioacoustics has improved our understanding of evolution, taxonomy, wildlife conservation and animal physiology (Blumstein et al. 2011). Many birds (Aves) and invertebrates produce territorial song, bats (Chiroptera: Microchiroptera) use ultrasound to detect prey, and elephants *Loxodonta* sp. use infrasound to communicate. Calls and songs are often unique to a species, and in many instances convey the biological, behavioural and ecological characteristics of the source. Acoustic recordings can therefore reveal a wealth of information about individuals, populations and the environment.

Outside the laboratory, ecological sounds are typically recorded using remotely operated or handheld devices (Efford et al. 2009; Bardeli et al. 2010; Blumstein et al. 2011; Marques et al. 2013; Cerquiera & Aide 2016). Automated systems that record continuously or in response to acoustic triggers have become increasingly popular, and can be deployed in isolation or complex spatial arrays (e.g. Mennill et al. 2012). These are suitable for a variety of ecological applications ranging from simple species presence/absence surveys to tracking acoustically active animals in three-dimensional space, and identifying individuals from their unique vocalisations. Such systems are indispensable for studying cryptic taxa such as bats, and for detecting elusive, nocturnal or rare species. However, although deploying small numbers of commercially available recording units (e.g. Wildlife Acoustics' Song Meter) can be affordable (Mennill et al. 2012), deploying large numbers (e.g. for landscape-scale studies) can be costly. Relatively inexpensive systems based on tablet computers have become available more recently (Aide et al. 2013; Cerquiera & Aide 2016). However, the core components of these systems are rarely user-serviceable and they often contain unnecessary hardware and software that becomes redundant when used for bioacoustic research.

Inexpensive single board computers have become widely available in the past decade. For example, the Raspberry Pi single board computer (*c.* £20 at time of writing), which was originally developed as an educational tool, has been adapted for a broad variety of applications. These and similar devices, such as the BeagleBone Black development board consume minimal power and use high-specification hardware relative to their small size and low cost. Furthermore, they are operated using freely distributed and readily available open source, Unix-based operating systems, and can be powered by any DC battery, such as USB charging devices or vehicle batteries. These features make single board computers like the Raspberry Pi highly customisable, and they have many potential applications in ecology.

Here, we introduce the Solo audio recorder. The system records audible sound up to 22.05 kHz for long periods (> one month) without user intervention, and can also record audio up to a Nyquist frequency of 96 kHz (i.e. sampling rate of 192 kHz). The Solo is straightforward to build and operate, and is constructed from inexpensive hardware and freely available software. Solos have proven to be robust during extensive field testing in temperate and tropical environments, and users can customise the software or hardware configuration to suit research needs.

System overview

Solos (Figure 1) are operated using custom-written software and the current version is available online from https://solo-system.github.io/. The core system comprises a Raspberry Pi single board computer (Farnell element14, Leeds, UK), PiFace clock module (OpenLX SP Ltd, London, UK) and Cirrus Logic audio card (Cirrus Logic, Austin, Texas, USA; CLAC). Although other suitable single-board computers are available, we chose the Raspberry Pi as the foundation of the Solo, since it was the first single-board computer to be generally available, it was rapidly successful and the software is now widely supported and debugged. It also supports the CLAC high definition audio card, which has a sampling rate of up to 192 kHz.

The Solo is compatible with a wide range of external microphones, and accepts microSD cards and any 5 V power supply (Box 1). Using the default software configuration, the Solo records audio continuously at a sampling rate of 16 kHz (8 kHz Nyquist) in .wav format (saved as individual ten minute, time stamped sections) until the power supply is removed or the memory card reaches storage capacity. However, the audio file section length, time zone, sampling rate and microphone gain can be configured to suit research requirements. Source code is also available via the supporting website for advanced users who wish to customise the software.

Field testing

Audible sound

Approximately 52,381 hours of audible sound have been recorded to date by 40 Solos using a variety of hardware and software configurations. Five systems (*n* = 600 hours recorded) were deployed in the Ebo forest, southwest Cameroon during the wet season in 2015, where annual rainfall is approximately 3,500 mm. A further ten systems (*n* = 10,383 hours recorded) were deployed between February and June 2015 in Central Scotland and Central England as part of a pilot study of long-eared owl *Asio otus* and tawny owl *Strix aluco* ecology in association with the British Trust for Ornithology. Finally, approximately 41,398 hours of audio (*n* = 35 systems) were recorded in 2015 and 2016 in Central Scotland and Central England as part of the Woodland Creation and Ecological Networks (WrEN) project (Watts et al. 2016). Four spectrograms of bird song recorded using the example configuration presented here are shown in Figure 2.

Ultrasound

The ultrasound capabilities of the Solo have not been tested extensively, nonetheless there is considerable scope for development given the maximum sampling rate of 192 kHz. During a small scale field test in Central Scotland (*n* = 240 hours from five systems), foraging calls of soprano pipistrelle *Pipistrellus pygmaeus* were recorded (Figure 3). This was achieved using the example hardware configuration given below and setting the sampling rate to 192 kHz. The Solo was positioned on the ground beneath a known roost, and bats emerged and foraged approximately 3 - 4 m above the microphone.

There is considerable scope for developing the ultrasound capabilities of the Solo. We recommend that anyone interested in recording ultrasound should experiment with alternative microphones, such as the Knowles FG series (Knowles, Itasca, Illinois, USA).

Example hardware configuration

The example hardware configuration (Table 2) described here was designed to record breeding woodland birds in temperate broadleaved woodland as part of the WrEN project, and it was found to be the most cost-effective configuration relative to battery life and audio quality. Using the default software settings, this configuration will record at a sampling rate of 16 kHz continuously (i.e. 24/7) for approximately 40 days during deployment (mean = 39.8, SE = 0.9 days, *n* = 24 systems with available data). See the supporting website https://solo-system.github.io/ and video tutorial https://youtu.be/2Fq05JlEKjw for a full description of how to build, operate and customise a Solo recorder.

Data retrieval

Using the default configuration, audio is stored in a folder-per-day hierarchy as 10 minute sections. The data are stored on a dedicated partition on the microSD card and are accessed by using a computer and SD card reader. Free software may be required by non-Linux users to access the partition (see supporting website).

Discussion

The Solo is a reliable, inexpensive, highly customisable audio recorder that can operate in remote locations for long time periods without user intervention. Example applications include landscape-scale studies (e.g. Watts et al. 2016) where dozens of systems might be required to achieve sufficient sample sizes, or deployment in situations where there is a high risk of the device being destroyed (e.g. by vandalism). Citizen science data are also increasingly used in ecological and conservation research (e.g. Newson et al. 2015; Kobori et al. 2016), and the Solo could increase participation in large-scale bioacoustic studies where the expense of commercial systems potentially limits participation.

Another advantage of the Solo over several existing systems is that it is predominantly built from open source hardware and software, and it can accept a wide variety of off-the-shelf microphones and power supplies. These features not only future-proof the system, but also make it user-serviceable, thus encouraging modification and development by the end user to suit specific research needs. Although commercial systems are likely to remain popular with those who require the additional benefits of warranties, customer services and out-of-the-box usability, the Solo recorder offers unprecedented flexibility at a fraction of the cost, which itself is likely to reduce over time given price trends in technology.

Directions for future development

At present, the Solo does not have a scheduling function, which would allow audio to be recorded only during predetermined time periods rather than continuously. In some audio recorders this can increase battery life. However, the Raspberry Pi does not have an efficient low-power mode, and a scheduling function would not therefore reduce power consumption significantly. Nonetheless, scheduling would improve storage capacity, which is of particular concern when recording at high sampling rates. In particular, scheduling is likely to be essential for recording taxa that are only active during short periods of the day and emit ultrasound, such as many bats and invertebrates. Furthermore, advanced scheduling could be used to improve the scope of field studies. For example, sampling rates could be changed according to prescheduled times, perhaps recording audible sound during daylight and ultrasound at night.

Audio is currently recorded in raw uncompressed .wav format, which requires approximately double the storage space of a compressed lossless format such as .flac, and future versions of the Solo software image could offer users a range of audio format options to address this. Furthermore, although the Solo can be operated for long time periods unattended, the user must collect the data and refresh the battery periodically, which may be difficult in some circumstances. Other systems are capable of wirelessly transmitting data to a base station (e.g. Aide et al. 2013), which addresses this problem. These capabilities could also be implemented in future Solo versions.

Finally, the processing power and potential functionality of the Raspberry Pi is underused by the Solo system in its current form, and the Raspberry Pi has the capacity to support many other features not discussed here. Examples include the addition of acoustic triggers that only record sounds above a specified amplitude, on-board data processing (e.g. species detection), a digital display, wireless communication in the field (e.g. with a smart phone or tablet) and the addition of peripherals (e.g. temperature loggers).

Conclusion

The Solo is an open source, customisable and inexpensive system for collecting high definition, long-term audio data. It has several advantages over comparable systems, and its introduction here (1) makes high-quality equipment accessible to those with limited resources, (2) improves the feasibility of conducting bioacoustic research across representative spatiotemporal scales, and (3) has the potential to advance the field of bioacoustics through the development of novel hardware and software configurations, leading to improved data collection.

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Author contribution statement

JC developed the software and RW contributed to design. RW led field testing and writing of the manuscript. Both authors contributed critically to drafts and gave final approval for publication.

Data accessibility

This manuscript does not use any data.

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Box 1. Hardware options

Raspberry Pi (essential): The following Raspberry Pi models have been tested: A+, B+, 2B, 3B, Pi Zero (the last model requires soldering). The Raspberry Pi A+ was used during all field testing because it has the lowest power consumption.

Cirrus Logic audio card (essential): Provides a high-fidelity (up to 192 kHz sampling rate) interface between the Raspberry Pi and an external microphone. The CLAC also has an internal stereo microphone, but this is difficult to weatherproof and an external microphone is recommended for field deployment.

External microphone/s (optional): The CLAC supports an external microphone (mono or stereo pair) with a 3.5 mm jack input (converters are widely available, e.g. from XLR to 3.5 mm jack). 2 – 3V of plug-in-power can be supplied to the microphone via the CLAC if required.

PiFace clock module (optional): Used to store the date and time of recordings and is powered by a button cell battery (CR1220). It must be set up prior to deployment using a network connection (see https://solo-system.github.io/).

Power: Any 5 V power supply (micro-USB) providing a minimum of 700 mA is suitable, such as a USB travel charger or 12 V car battery with a 5 V converter and micro-USB adapter. A mains supply can also be used if available. Using a Raspberry Pi A+, the units consume approximately 0.35 W during operation.

Memory: The Raspberry Pi accepts a single microSD card of any size. The Solo software image requires approximately 1.5 GB of memory space and the remainder is used to store audio data. Table 1 shows estimated storage requirements for various sampling rate and memory card size combinations.

Table 1. Approximate storage capacity (hours in .wav format) of different microSD memory card sizes and sampling rate combinations when recording on a single channel. These values should be halved when recording in stereo.

	8 GB	**16 GB**	**32 GB**	**64 GB**	**128 GB**	**256 GB**
8 kHz	112	251	529	1085	2196	4418
16 kHz	56	125	263	524	1098	2209
44.1 kHz	20	45	96	196	398	801
192 kHz	4	10	22	45	91	184

Table 2. Components used to build the example Solo hardware configuration, approximate cost and manufacturer details. Suggested websites for purchasing non-generic components are also given.

Component	Cost (£)	Model	Manufacturer	Website
Raspberry Pi	15	Model A+ (lowest power consumption available)	Farnell element14, Leeds, UK	http://uk.farnell.com
Cirrus Logic Audio Card	24	One model	Cirrus Logic, Austin, Texas, USA	http://uk.farnell.com
PiFace clock	9	Clock module with dedicated button-cell battery (CR1220)	OpenLX SP Ltd, London, UK	http://uk.farnell.com
128 GB microSD memory card	40	SanDisk Ultra SDXC class 10	SanDisk, Milpitas, California, USA	-
Car battery	44	063XD: 12 V, 50 Ah	generic	-
Battery terminal clamp	2	12 V car battery terminal clip	generic	-
12 V to 5 V converter	9	DC-DC 12V To 5V converter module with USB adapter 15 W 3 A	generic	-
Microphone	15	Clippy EM172 model FC049	Primo Microphones, Inc. Mckinney, Texas, USA	http://micbooster.com/
Plastic electronics enclosure	1	Business card box	generic	
DRiBOX	8	FL-1859-200	DRiBOX, Black River Falls, Wisconsin, USA	http://dri-box.com/
Total cost	**£167**			

Figure legends

Figure 1. Illustrative examples of assembled Solo recorders; (a) Raspberry Pi A+ and CLAC, (b) Raspberry Pi A+ and CLAC with attached EM172 microphone and USB travel charger as a power supply, (c) example configuration (see text) deployed in a woodland (driBox lid removed to show contents).

Figure 2. Spectrograms (Hanning window length = 256) of four bird songs recorded using the example Solo configuration. The Solo was deployed in the middle of a small (*c.* 1 ha) broadleaved woodland in Central Scotland. No post processing was performed.

Figure 3. Spectrogram (Hanning window length = 1024) showing foraging calls of a soprano pipistrelle. No post processing was performed.

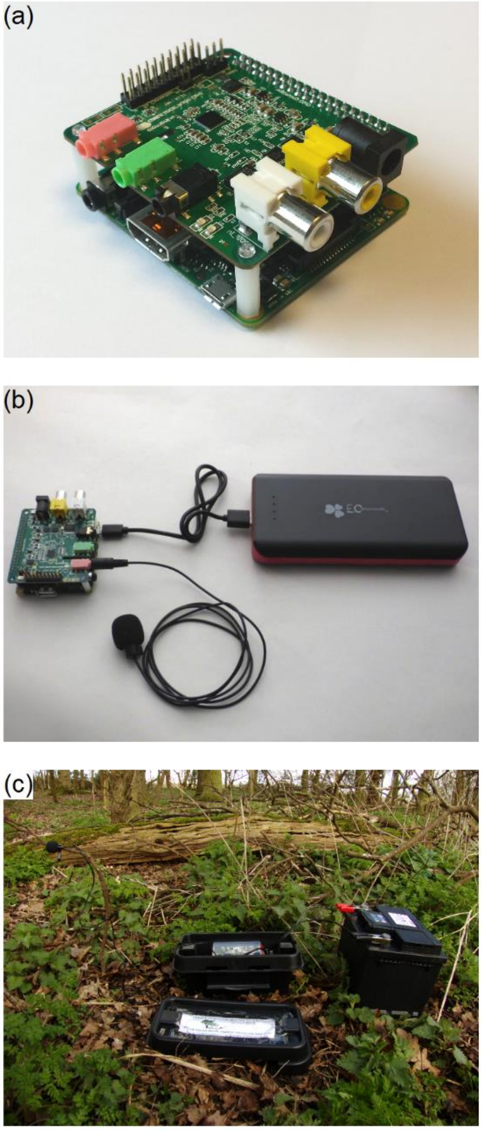

Figure 1

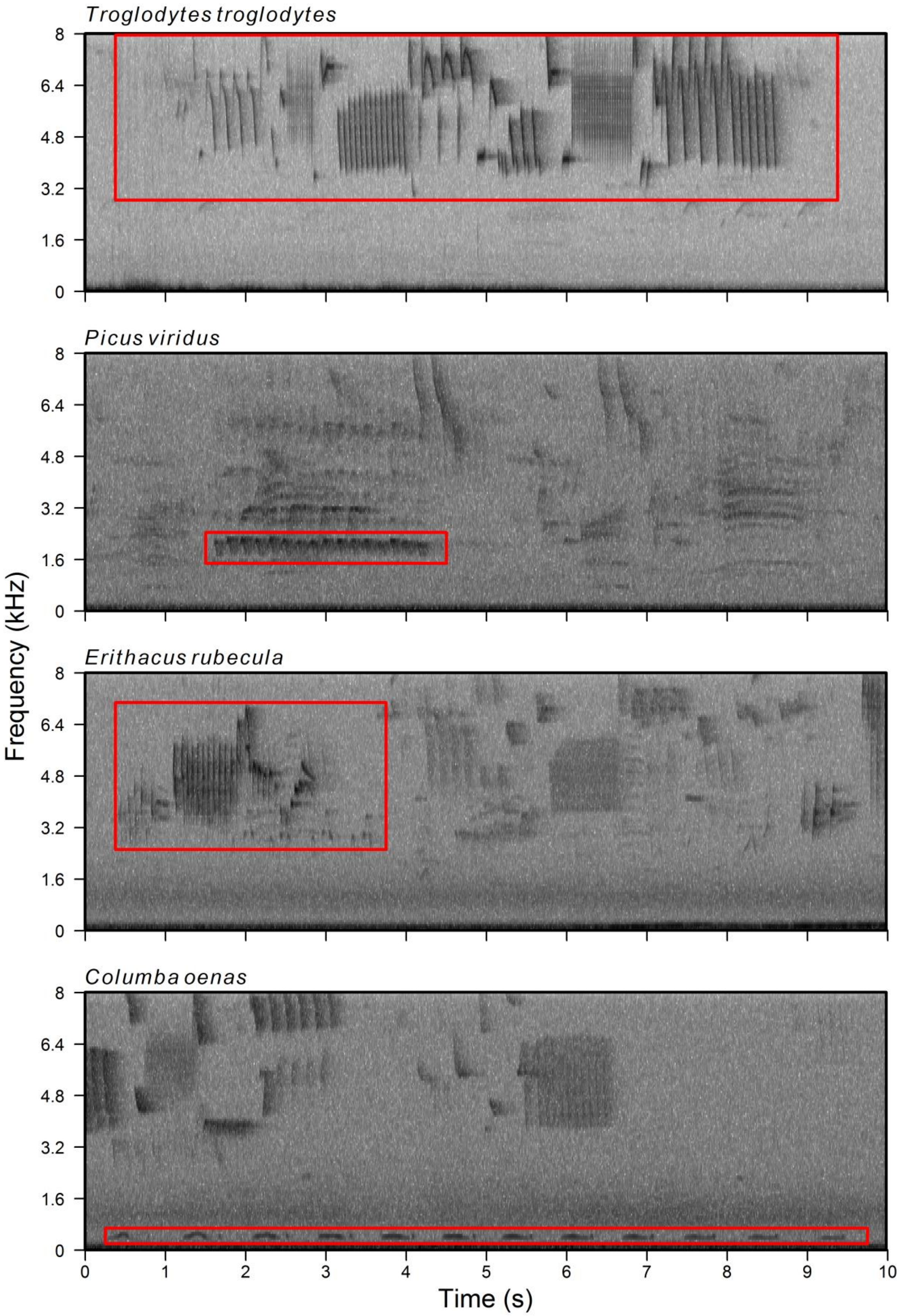
Troglodytes troglodytes
Picus viridus
Erithacus rubecula
Columba oenas
Frequency (kHz)
Time (s)
0
1.6
3.2
4.8
6.4
8
0
1
2
3
4
5
6
7
8
9
10

Figure 2

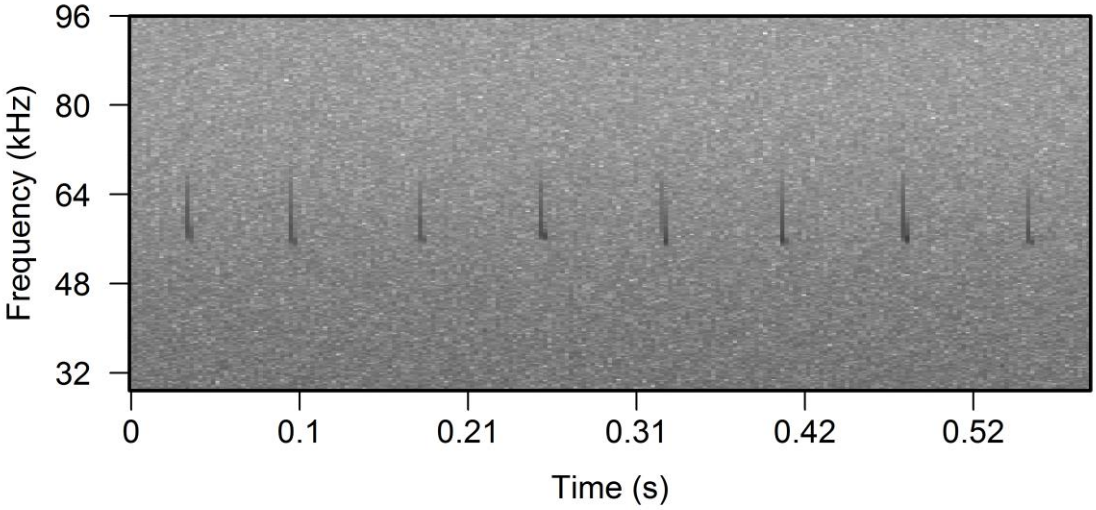

Figure 3