Open source, low cost modular GPS collars for the monitoring and tracking of wildlife

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Running headline: Open Source Telemetry Devices

Summary

1. Monitoring the movements and behaviour of wildlife using radio telemetry or GPS devices has been critical to the fields of ecology and conservation over several decades. For many field projects however, commercially available devices can be expensive and may not always be ideally suited for collecting desired data.
2. We present a low-cost solution of customisable tracking devices based on the open source Arduino system. These devices can be custom designed for specific studies and easily programmed to collect desired data.
3. Custom-built collars with GPS and accelerometer units were trialled on 30 free-ranging domestic dogs in rural Ethiopia. These collars collected high-resolution data at a frequency of 10 fixes per hour and accelerometer data at 10hz over a 10 day period, at a cost of approximately £100 ($130 USD) per collar.
4. These devices can be placed on any species that can handle a weight of 15.4g plus battery and housing. The current configuration weighs approximately 240g which would be suitable for any animal above 8kg living in terrestrial environments.

Key Words: Telemetry, GPS, Open-Source, Modular, GPS-Collar, Wildlife

Introduction

GPS technology, pioneered in the 1990s (Wingenroth, 1993; Rempel, Rodgers and Abraham, 1995), was transformative for wildlife telemetry. These devices give highly accurate location data directly through triangulation by satellites, without need to actively track the individuals on the ground or from the air. Data collected from GPS collars is increasingly becoming a powerful tool for research and monitoring of animals. GPS data can be used to determine animal's home ranges, daily activity patterns, habitat use and has applications in planning for management of species (Morris, 2003). With the rise of big data and machine learning (Goldberg and Holland, 1988; John Walker, 2014), our ability to analyse increasingly large or complex data, obtained during GPS collar studies of wildlife, has dramatically increased.

Modern GPS collar technology can now capture additional information from wildlife that was not previously accessible or utilised in scientific research, by including sensors such as audio recorders, accelerometers or video loggers, which allow identification of behaviours and interactions, or individual state (Moreau *et al.*, 2009). Accelerometers measure forces of accelerations due to the force of gravity and active movements. By correlating to individual behaviours, patterns of acceleration can be validated and extrapolated across the full data. From this, behavioural patterns can be recognised (Ravi *et al.*, 2005) and daily activity patterns and other metrics of collared individuals broken down, in far more detail than previously possible. Accelerometers record data up to hundreds of times per second and constantly throughout the day, which is impossible with direct behavioural observations; allowing an understanding in far more detail of how an animal moves and uses its landscape (Brown *et al.*, 2012)

Significant recent advances in wildlife telemetry have made GPS collars readily available and less expensive due to reduction in prices in the components, mass production and increased competition from newer companies (Hebblewhite and Haydon, 2010; Thomas, Holland and Minot, 2011; Jung *et al.*, 2018). GPS tracking devices are becoming the standard in wildlife research and monitoring work. However, commercial wildlife devices can still cost thousands of dollars each depending on the study species and required features, due to the need for custom-built species-specific devices; companies need to recoup costs for research and development, and typically lack a market to scale up production. This represents a high cost for any field study and can prove to be even more difficult for wildlife projects where GPS collars are a prerequisite and funding is limited and highly competitive. Globally there is an increasing need for wildlife monitoring and lower cost devices provide an opportunity to alleviate some of the financial burden that comes with the requirement to purchase GPS collars. This has implications for any projects working with wildlife, allowing larger projects to monitor many more individuals, or institutions in developing countries and NGOs with limited funding to begin their own monitoring projects.

Until recently, the only options for wildlife telemetry were generally the high cost commercial solutions that often included sensors recording unnecessary data or were missing sensors for recording the specific data a project relies on, requiring further modification. Customisation of commercial devices to allow for collection of specific data types, such as raw formats, or at desired frequency to meet the requirements of a specific study or species is possible with direct consultation with the manufacturers. However, this customisation generally comes at an increased expense while lower cost commercial devices come at the price of heavily reduced features (Jung *et al.*, 2018). To avoid expense or to gain features there has been a rise in recent years of researchers building their own devices (Clark *et al.*, 2006; Fischer *et al.*, 2018). This has generally come with the caveat that researchers have worked with engineers or computer scientists to develop devices that are highly specific and difficult to replicate (Wijers *et al.*, 2018).

Thanks to the development of open source microelectronics platforms such as Arduino, Raspberry pi and Micropython it is now possible to build these devices with little previous knowledge or experience of electronics. Being open source there are numerous manufacturers competing to produce the chips, driving costs down, and a wealth of examples and guides with which to programme devices. These platforms are designed to be modular and have chipsets for almost any purpose. Modular GPS collars based on these can be designed from inception to contain components that collect specialised data, which allows for optimisation of programming and structural design. This provides a low-cost means to develop custom devices for a research project without expert domain knowledge and could help improve and expand wildlife telemetry globally. The objectives of this paper are to describe the construction, testing and usage of one such device based on one of these platforms that is capable of being easily replicated and modified by almost any user.

Description and Implementation

Development of Devices and Housing

Custom-built GPS collars with accelerometers were constructed using the open source electronics and programming platform, Arduino (Fisher and Gould, 2012). The primary component of the device was a MicroController board with an onboard micro SD card storage. There are varieties of such Ardunio boards that are compatible with the devices, depending on the storage, power, shape, species weight or size requirements of the project. The MicroController used in this trial was an Adafruit Feather m0, weighing 5.3g and measuring 47mm x 28mm. Soldered onto the board was a separate GPS board (an Adafruit Feather GPS Breakout) with a GPS chip with 66-band antenna and a backup 3V 250mAh button cell battery, weighing 8.8g and measuring 47mm x 28mm. Wired onto the processor board was an Adafruit LIS3DH 3-axis accelerometer, weighing 1.3g and measuring 25mm x 25mm. The test units were powered by a 4400mAh rechargeable Lithium ion battery pack (weight 98g). It should be noted that any size battery with a JST connector or a micro USB can be used depending on the power or weight requirements of the study or species that the device will be deployed on. The battery will often be the bulkiest and heaviest component of the device. Each component draws a specified power during usage, the lowest being the accelerometer which draws 2mAh during usage, the GPS board had the highest power usage at 20 mAh while active, the microprocessor draws 11mAh while writing to the SD card.

To protect the components from damage they were placed in a plastic housing 3D printed with a Makerbot Replicator 2 printer (build volume of 28.5 x 15.3 x 15.5 cm, https://www.makerbot.com/)(figure 1). The 3D printed housing was then coated in a clear polyester resin that helped increase the weather resistance of the housing and provided added durability; the housing was sealed with a lid around which a rubber seal was glued to ensure water could not get in. The housing for the test units was attached to a conventional durable leather dog collar fastened with a metal buckle. The housing of these devices was specifically designed for use on free-ranging domestic dogs which were highly aggressive to conspecifics wearing collars requiring protection from bites. Depending on the species or environmental requirements, different housing solutions could be applied, and 3D printing allows complete customisation.

The devices were programmed using the Arduino repositories based on the C++ language (Stroustrup, 2000). The programming allows for the frequency of data collection to be easily changed by altering parameters in the setup code for both GPS and accelerometer individually. If desired devices be programmed to sleep if there was no movement detected in the accelerometers over a user defined time period to improve battery life.

The completed test collars were extremely lightweight (240g), with nearly all the weight associated with the strap and battery (Table 1); there is further potential to reduce weight by using different components, smaller batteries, housing or straps. The total weight of these collars was similar to commercially available products for the same species size that vary between 200-300g. Figure 2 provides full step-by-step instructions for construction of the electronics. Code, specifications and construction instructions are available in the supplementary material or online.

Table 1: Cost and weight specifications of each component in the trialled devices.

Part	Cost (£) (USD)	Mass (g)	% Of Total Mass
MicroController board	22.50 ($29.25)	5.3	2.2
GPS board	40 ($52)	8.8	3.6
Accelerometer	9.40 ($12.22)	1.3	0.5
Battery	4 ($5.2)	95	39.5
Micro SD	3 ($3.9)	0.5	0.2
Strap	13.75 ($17.88)	118	49.1
Plastic Housing	4 ($5.2)	11	4.5
Total	**96.65 ($125.65)**	**240**	**100**

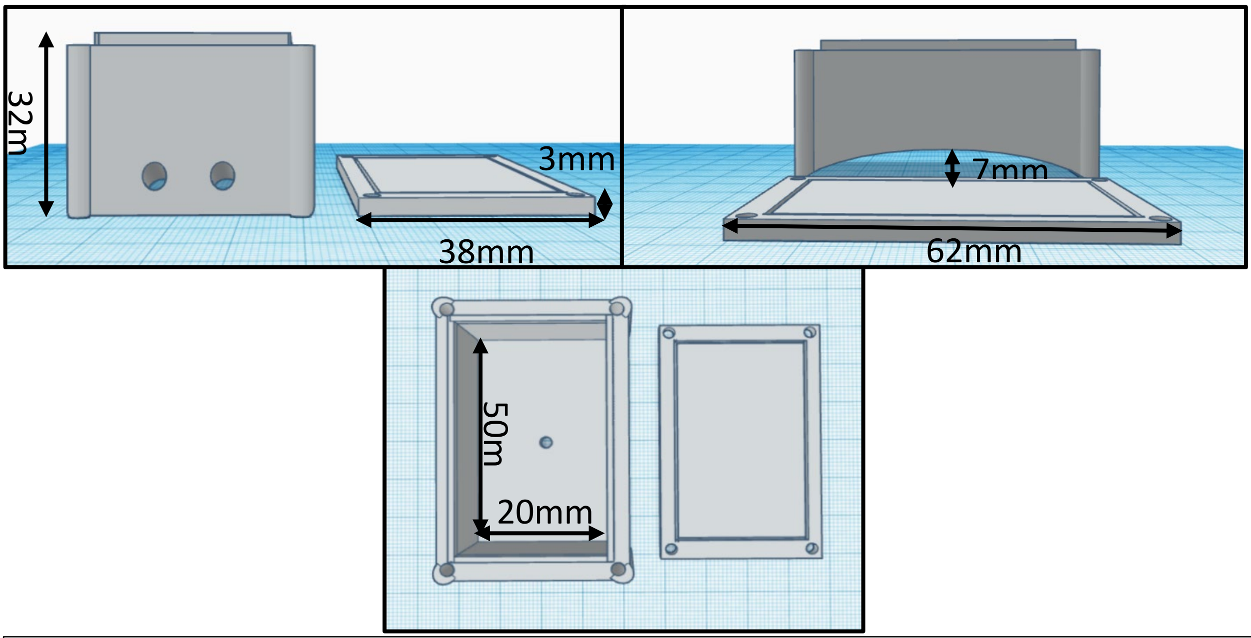

Figure 1: 3D model used for the 3D printed housing. A rounded bottom was used to better fit the housing with the curve of the neck. Four 3mm screws connected the lid to the body of the housing. Two larger 4mm screws on each side went through the leather collar to attach the housing.

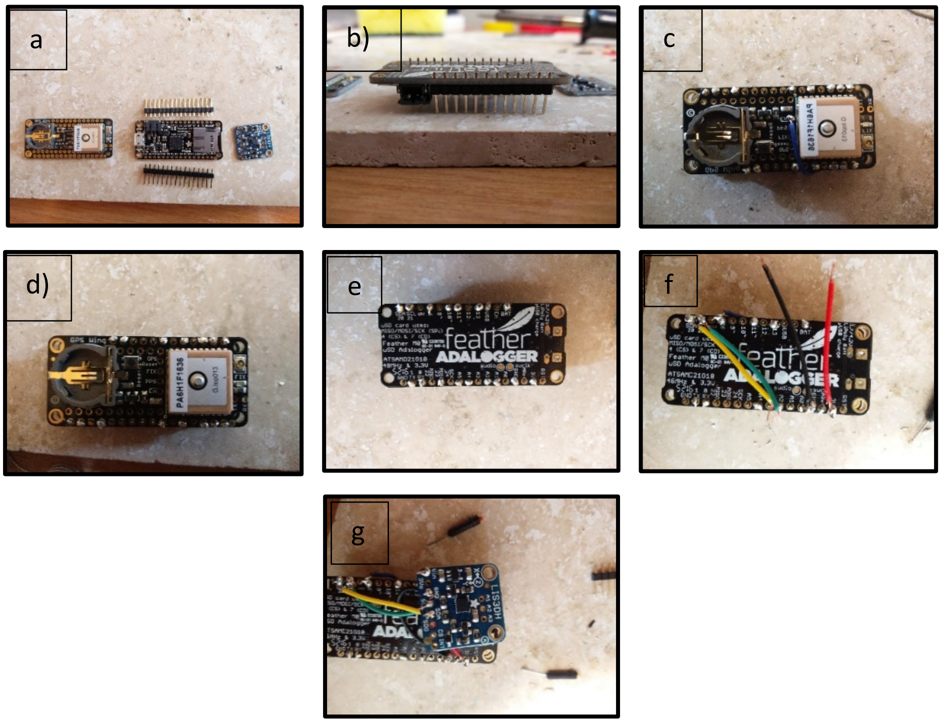

Figure 2: a) Starting components from left: GPS board, MicroController board with header pins, accelerometer. b) First step was to place the header with the smaller pins through the controller board. c) Solder the pins into the board making sure that at least the gnd, 3V TX and RX were securely connected. d) Solder the GPS board onto the longer pins above the controller board. e) Solder a wire that connects a data pin in the controller board to the enable pin in the GPS board. f) Solder wires onto the 3V (red) gnd (black), SCA (green) and SDA (yellow). g) Solder the wires into their corresponding pin on the accelerometer.

Performance Evaluation

The performance of the devices was evaluated using similar measures to Jung *et al.* (2018). Overall performance was taken from deployment success rate, measuring how many devices were working on deployment, and the early failure rate, measuring how many of the devices stopped collecting data earlier than expected. The GPS was evaluated using the fix success rate, determined by the proportion of failed fixes out of the total number of scheduled fixes for each device. A fix was determined to have failed to be acquired if after three minutes the device was not providing a latitude and longitude and this was recorded in the data as "No Fix". The accuracy of fixes of the device, being the error of each fix measured in meters was calculated using the horizontal dilution of precision (Langley and Langley, 1999) (HDOP), a measure of the impact of satellite position on accuracy, as 2 X mean HDOP X device accuracy. HDOP measurements are provided by the chips inbuilt software using the transmitted location, angle and number of satellites. The quality of accelerometer data was examined using a K statistic cut off method based on distance between points and mean amplitude, clustering the differences together to see if there are clusters of data which are extremely different from the mean (Slaven *et al.*, 2006). Accelerometer drift was tested by looking for consistent shifts of measured acceleration over a long recording period.

Performance on Free Ranging Dogs

Twenty-five of these devices were constructed and deployed on 30 domestic dogs (Figure 3) in two separate deployments; 12 in the wet season (March to October) and 18 in the dry season (November to February) in the Bale Mountains National Park of southern Ethiopia. Here dogs are owned, but are free to move in and out of their villages, and thus considered free-roaming, where they act as a vector of disease for the Ethiopian wolf (*Canis simensis*)(Laurenson *et al.*, 1998). At 240g, collars did not exceed 3% of the animal's weight, which is a recommended threshold (Wilson, 1996; Sikes, 2016). In this trial anaesthesia was not required for collaring, the help of the dog owners was recruited to handle them. The collars were programmed to collect high-resolution data, with GPS fixes on a 6-minute interval and accelerometer at 10 Hz over a 10-day period with the devices not programmed with a sleep function. These devices were programmed to collect data over a short period, as the high intensity data was a feature of this study. However, these devices can also be used over longer time periods and collect data at different rates depending on the requirements of the project. The devices themselves are capable at recording data in the GPS at up to 10Hz and 5kHz in the accelerometer and should be adjusted as per the needs of a study.

Across all the deployments only one device did not record data and was deemed to be a failed deployment, a further 6 devices during deployments failed early, providing a total deployment success rate of 77.6% (23/30). This was comparable to many commercial devices (Habib *et al.*, 2014). A comparison of commercially available collars deployed on Australian mammals by Matthews et al. (2013), found that 48.6% of collars deployed failed early, with 30% of collars having intermittent failures during deployment. However, Jung et al (2018) had an 89% overall deployment success rate on over 100 collars of a single brand and type deployed. Collins *et al.* (2014) compared custom devices to commercial devices where their custom devices had a high failure rate (7/8) which suggests that the devices trialled here may be more reliable than other custom devices but does highlight the risk that could occur with custom devices. During deployment there was a mean fix success rate of 99.57% ± 0.15% with a range of 98.4% - 100%, however the study area was in an open high altitude area and acquisition rates may be lower in dense canopy forests (Vance *et al.*, 2017). The devices are capable of a 1.8m accuracy of fix however, with a mean HDOP error of 4.9 ± 4.2 the mean fix accuracy was 14.76m, this HDOP error is slightly higher than the mean of many commercial collars at 3.0 (Matthews *et al.*, 2013). Some 98% of data were clustered together in a K score of < 10 indicating a large proportion of high-quality data. There was no evidence of drift in accelerometer data at the programmed frequency of collection however, any drift that might be occurring would have been removed during analysis as it passed through a high pass filter prior to analysis (Takeda *et al.*, 2014). The frequency of data collection chosen in this study, at 10Hz, is lower than many other accelerometer devices however, with the advent or more advance machine learning methods this is becoming more than sufficient for behavioural classification, with classification now being possible with as low as 1Hz (Studd *et al.*, 2019).

The 3D printed housing was resilient enough to take impact from the dogs including biting by con-specifics, movement through rough terrain and mud, and exposure to varied environmental conditions including high and low temperatures (-8°C to +28°C) and heavy rain. All housing survived the deployment without being pierced or breached by water. Despite the lack of apparent damage to the housing it is possible some of the failures were caused by impact from con-specifics as noted for other species (Jung and Kuba, 2015), but this could not be explicitly tested for. The housing can be used in harsh conditions and could be deployed in a variety of other environments, including both hot and cold areas. However, the device would most likely need to be adjusted if used in aquatic environments or if there is a high likelihood of prolonged submersion. 3D printing allows the user to customise the size, shape and attachments of the housing to be varied, based on what is needed and is a key tool in the modularity of the devices.

Future Considerations

Under the data collection parameters the collars were drawing a total of approximately 7.77 mA, which would allow for a maximum battery life of 23.6 days at this sampling rate. The GPS is the largest power draw accounting for 6.66 mA or 85% of the power draw. If the GPS sampling rate was reduced to 1 fix per hour there is a hypothetical battery life of 103 days under a 1.77 mA draw. There is a possibility that battery life was hampered by the large temperature oscillations in the Ethiopian highlands (varying between -8°C to +28°C over 24 hrs), the batteries performed below estimates made from usage in a stable environment in the United Kingdom however this was not tested. While the estimated battery life is lower than many commercial GPS collars, which often state multi-year battery lives, further improvements and efficiency changes in the programming may bring this up to competitive levels. Magnetometers have become commonly used in conjunction with accelerometers as they can assist with calibration and provide a wealth of added features for behavioural classification (Williams *el al*., 2017); they were not trialled in this device for space, weight and power reasons but would make an excellent complement to other such devices.

The devices trialled had no satellite or radio reporting components, meaning they were required to be collected from the collared animals and data downloaded from the onboard SD card; however, these could be added by attaching further components such as a radio transmitter depending on size limitations. GPS reporting would require a satellite network subscription. An easy addition of a GSM board would be capable of sending the data in a text allows the devices to not require collection or satellite subscription at a low cost if this is required and relevant GSM networks are available. It should be noted that accelerometer data rapidly becomes very large due to the high frequency of data collection and will likely be too large to send via GSM. It may be better to send GPS location data via GSM and then supplement it with the accelerometer data once the device can be recovered. There are also post-processing algorithms that can be part of the device programming which can extract summary statistics or, using pre-calibrated classifiers, even behavioural classifications which can then be sent over GSM instead of the raw data (Cox *et al*., 2018). It is important to note that these algorithms require both memory and processor capacity within the device so must be lightweight and will come with an increase in power draw.

Figure 3: A collared dog during GPS collar deployment in Bale Mountains National Park. January 2018.

Conclusions

The custom-built devices reported here are a simple proof-of-concept of a modular device that can be customised and built from the ground up to fulfil the exact needs of a given study. With the use of 3D printing, customised housing can be as light or resilient as required and be shaped ideally for the species that it is being deployed on. The components used in these devices are relatively inexpensive and readily available from numerous retailers. Little background knowledge is needed to construct and programme a working device and a large deal of support is available online including guides, tutorials and help forums. There is still much scope to improve upon the basic devices presented here and the device concept represents a platform that could be widely used across numerous research areas. The inexpensiveness and high usability of the devices mean that there is an opportunity for a far greater level of wildlife monitoring in many systems without incurring a large cost.

Ethics Approval

All work in this paper was performed under full ethical approval after review from Oxford University and an approved permit from the Ethiopian Wildlife Conservation Authority.

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Author's Contributions

CJF Conceived and designed the devices and methodology with input from CSZ. CJF was responsible for the direct trial of the devices. The CJF and CSZ wrote the manuscript. Both authors contributed critically to the drafts and gave final approval for publication.

Data Availability

Full design instructions and code can be found at 10.5281/zenodo.3631265 and trial data can be found at 10.5281/zenodo.3631277.

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