Camazotz: Multimodal Activity-Based GPS Sampling

Raja Jurdak[1], Philipp Sommer[1], Branislav Kusy[1], Navinda Kottege[1],
Christopher Crossman[1], Adam McKeown[2], David Westcott[2]

[1]Autonomous Systems Lab, CSIRO ICT Centre, Brisbane, QLD, Australia
[2]CSIRO Ecosystem Sciences, Cairns, QLD, Australia
firstname.lastname@csiro.au

ABSTRACT

Long-term outdoor localisation with battery-powered devices remains an unsolved challenge, mainly due to the high energy consumption of GPS modules. The use of inertial sensors and short-range radio can reduce reliance on GPS to prolong the operational lifetime of tracking devices, but they only provide coarse-grained control over GPS activity. In this paper, we introduce our feature-rich lightweight Camazotz platform as an enabler of Multimodal Activity-based Localisation (MAL), which detects activities of interest by combining multiple sensor streams for fine-grained control of GPS sampling times. Using the case study of long-term flying fox tracking, we characterise the tracking, connectivity, energy, and activity recognition performance of our module under both static and 3-D mobile scenarios. We use Camazotz to collect empirical flying fox data and illustrate the utility of individual and composite sensor modalities in classifying activity. We evaluate MAL for flying foxes through simulations based on retrospective empirical data. The results show that multimodal activity-based localisation reduces the power consumption over periodic GPS and single sensor-triggered GPS by up to 77% and 14% respectively, and provides a richer event type dissociation for fine-grained control of GPS sampling.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Wireless Communication

Keywords

Wireless Sensor Networks, Tracking

1. INTRODUCTION

Embedded systems technology has been developing at remarkably fast rates, which has led to heightened expectations for a wide range of applications. End-users now expect platforms to continuously follow intuitive trends, such as shrinking in size and weight while having longer battery lives. In order to deliver on all those expectations concurrently, system developers typically reduce the number of sensing modalities on monitoring platforms and the sensor sampling frequencies. For many mobile sensing applications, including bird tracking at continental scales, the requirement for multiple sensing modalities and durable lightweight platforms are continuously in tension.

Recent work [1] has aimed for lightweight long-distance and long-term tracking of the endangered Whooping Crane in North America, using custom-designed platforms that include GPS, cellular, and weigh just above 100 g. While this work has provided a proof-of-concept of large scale and lightweight wildlife tracking, this technology cannot be used for tracking smaller flying animals, as the sheer weight of the devices would prevent the animals from flying freely. This paper is motivated by the need to track one such species of particular interest, namely flying foxes. Flying foxes, also known as fruit bats, are megabats that spread virulent and deadly diseases such as Ebola, Hendra, and the recently discovered SARS-like Coronavirus [26], at a global scale.

Tracking flying foxes requires platforms and algorithms that can deliver position and activity information from highly mobile individual animals over long-durations. While position monitoring can use GPS as the main sensor modality, behaviour and activity classification require additional sensor modalities, such as inertial, acoustic, and air pressure sensors. For instance, audio signals can be used for detecting previously unknown congregation areas, or roosting camps, for flying fox populations. The introduction of new sensing modalities places a burden on the limited node energy, processing, and memory resources, as well as an indirect cost of more complex system management. The uncontrolled 3-D mobility associated with bird tracking can also have unpredictable effects on the performance of node components, particularly transceivers and solar panels. All of the above challenges highlight the need for holistic design of feature-rich mobile sensing platforms with early prototyping to incorporate these subtle dependencies among system components.

This paper introduces Camazotz[1], a lightweight and feature-rich mobile sensing platform, which aims at long-term wildlife tracking. Camazotz uses a CC430 system on chip (SoC) with a low power GPS, inertial, acoustic, air pressure and temperature sensors, two solar panels, 300 mAh Li-Ion battery, with a total weight just under 30 g targeted at tracking smaller wildlife such as flying foxes. We describe our holistic design

[1]Camazotz was a bat god in Mayan mythology.

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process for the platform that relies on early prototyping and empirical evaluation of three key aspects: (1) the impact of 3-D mobility on radio performance using an unmanned aerial vehicle for controlled mobility experiments; (2) the performance of low power GPS as a function of shutoff time and its implications on node lifetime; and (3) the ability to perform in situ activity recognition using audio and inertial sensors through basic signal processing on Camazotz. Based on the evaluation results, we show how Camazotz can enable Multimodal Activity-based Localisation (MAL) that detects activities of interest by combining multiple sensor streams for fine-grained control of GPS sampling times.

Our evaluation shows that 3-D mobility has limited effect on Camazotz's radio connectivity to a ground base station. We mainly find signal degradation for high angles of alignment between Camazotz and the base. Our GPS evaluations confirm a weak dependence of the time to first fix on GPS off time, and our on-bat experiments show that the GPS design of Camaztoz achieves consistent position accuracies below 10 m. Solar experiments from nodes on bats yield an estimate of 3 mA average solar current during the day, which we use to set duty cycles that deliver energy-neutral operation to Camaztoz. Our activity recognition results from flying fox experiments with Camazotz demonstrate the detection of interaction and waste removal events with audio and inertial sensors respectively, and confirm that air pressure sensors can provide a much more precise estimate of altitude than GPS. Finally, we use these results to demonstrate MAL by considering how simple fusion of audio and inertial sensor events through logical OR and AND operations can dissociate event types, deliver fine-grained activity-based control of GPS samples, and by doing so, save power consumption.

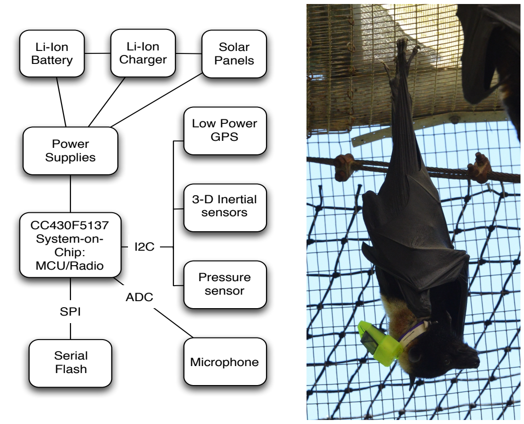
The remainder of the paper is organised as follows. Section 2 motivates the design of Camaztoz. Section 3 presents our empirical validation experiments to evaluate the platform's performance. Section 4 shows how Camazotz can enable multimodal activity-based localisation to accurately detect events and extend node lifetime. Section 5 discusses related work, and Section 6 concludes the paper.

2. CAMAZOTZ PLATFORM

2.1 Motivating Application

Surprisingly little is known about flying-fox ecology behaviour due to difficulties associated with studying animals that are nocturnally active and which roost in large aggregations (often 40-50000 animals at a single site [23]). Recent research shows that the source of our difficulties in studying these animals lies in the extra-ordinary mobility exhibited by individuals and by flying-fox populations. Studies show that individual animals are highly mobile, travelling on average 20 km to their first feeding site in a night and over 100 km during nightly foraging [25]. Over weeks and months individuals can move hundreds or thousands of kilometres [4]. This mobility is also observable at the scale of the population with flying-fox populations moving in and out of regions, often over periods of just days [23].

Flying-foxes are of great interest to wildlife managers in Australia. On the one hand these animals are listed as threatened species, and at the same time, they are recognised as agricultural pests, causing as much as $20 million of damage to fruit crops per year [24]. Most importantly, flying-foxes are effective vectors of a number of virulent emerging infectious diseases that threaten both humans and livestock. Developing effective management responses to these flying-fox impacts requires that assumptions are made about their mobility.



(a) Functional components of Camazotz (b) Flying fox with Camazotz attached

Figure 1: The Camazotz platform couples a SoC with GPS, inertial, acoustic, air pressure and temperature sensors, two solar panels, 300 mAh Li-Ion battery, with a combined weight < 30 g.

Our application requirements are to obtain day roost locations for comparison with surveyed camp locations. Where these locations do not match with known camps, we need to know whether the animal is roosting alone or in a small group, or, whether it is at an unknown camp. This requires visiting each such location – an impossible task given that such events could happen multiple times each day across the range of the species (i.e. 2800 km) and will often be in inaccessible locations. Since flying-foxes in camps are highly vocal animals [19] an alternative would be to use collar node-based microphones to make recordings of flying-fox noise to provide an index of the number of animals at a roost.

Most flying-fox risks, such as crop damage and transmission of disease, are incurred away from camps at the locations where flying-foxes are feeding. Predictive models of how these risks will be distributed within a landscape require an understanding of how flying-foxes respond, in terms of their movement and choice of foraging locations, to the structure of landscapes and the distribution of resources within them, and how this varies across landscapes, seasons and individuals. Developing such an understanding requires high temporal and spatial resolution data on movement during nighttime foraging sessions, with sample frequencies as high as 1 Hz potentially under some circumstances.

The devices that can achieve the goals outlined above must be capable of: (1) collecting regular daytime fixes (with an accuracy of 10 m) at camps to identify new camps; (2) collecting high-frequency nighttime fixes to monitor movement patterns and landscape use, and doing this with an accuracy of 10 m or less using inertial sensors during fine-scale movements; (3) making daytime audio recordings to allow estimation of camp size; (4) operate over long periods, i.e. 12 months, and preferably longer; and (5) provide data download capability.

Such simultaneous goals are clearly at odds with current technology but can be approached through smart power, sensor and data management algorithms and flexible duty-cycling. Available technologies, such as Platform Terminal Transmitter (PTT) and GPS tags [18], cannot hope to achieve these goals because their power demands conspire to make the tags useful for only single aspects of the study described above. That is, they can either collect a handful of daytime fixes at regular intervals over long-periods, or they can collect high-frequency movement data over short periods. No tags are currently capable of collecting audio data. This paper addresses this gap for accurate, flexible and energy-efficient position tracking of flying-foxes. This work is part of a large national project that aims to deploy hundreds of tracking nodes (up to 1000) on individual flying foxes.

2.2 Design Challenges

bioacoustic signals alongside inertial and altitude information for real-time activity classification.

To achieve the above goals, we need to address specific design challenges relating to dimension constraints of tracking nodes and to the mobility dynamics of migratory birds. According to animal ethics regulations in Australia, the *weight* of any objects placed on flying foxes must not exceed 5 % of their body weight, corresponding to target cumulative weights of 30 to 50 g for all the electronics and enclosures for tracking. The range of target weights stems from the weight differences of individual animals between adolescents and larger males. This weight restriction obviously constrains the size and capacity of batteries on the devices.

Size is another issue, where tracking devices cannot exceed a few centimetres in height or length and 2 cm in depth to ensure that the devices do not hinder or affect the animal's ability to fly freely. In addition to placing further constraints on the battery and electronics, this size restriction is likely to affect the size of the recommended GPS antenna which may in turn impact location accuracy.

The *mobility dynamics* of flying foxes represent yet another major challenge. Flying foxes are able to fly up to 100 km in a single night and they are known to visit truly remote areas at continental and transcontinental scale. Because they are likely to spend significant portions of time either in remote areas or across country borders, cellular coverage may not be available. Additionally, cellular modules would add significant weight, size, and energy cost to the overall platform. We choose to transfer position data by installing base stations at known roosting camps and using short-range radio communication opportunistically when the animals are in these camps. However, only a small proportion of the camps where these animals congregate to roost is known, and there is no deterministic mapping of an individual animal to one or more known roosting camps. These dynamics suggest that the design of tracking devices has to account for a high degree of delay tolerance in both hardware, providing enough memory to store position and activity data for periods of disconnectivity, and software, to compress stored data and opportunistically deliver it once connectivity returns.

Device	Size (mm)	RAM (Bytes)	Flash (KB)
TI CC430F5137	7×7	4096	32
Freescale MC12311	8×8	2048	32
Nordic nRF9E5	5×5	256	4
Atmel ATA8743	5×5	256	4

Table 1: Comparison of 900 Mhz SoC devices.

2.3 Hardware

Given such tight constraints on the size and weight of the platform, we select a system on chip (SoC) for the microcontroller and radio transceiver. In particular, we compare the size, RAM, and Flash capacity of existing SoC options, as shown in Table 1. Based on this comparison, we use the Texas Instruments CC430F5137 which includes an MSP430 core and a CC1101 radio. Apart from its favourable physical size/capacity advantage, the MSP430 core supports low power operation and offers high compatibility with popular sensor network operating systems. The CC1101 equivalent radio transceiver provides a GFSK communication in the 915 MHz band.

Figure 1(a) illustrates the functional components of Camazotz. Key to its success in the field is to maximise location accuracy for the available size, weight, and energy resources. We adopt the u-blox MAX-6 GPS module, which optimises for size and power consumption and provides the high performance of the u-blox 6 series positioning engine.

The localisation hardware also includes the GPS antenna, which involves a design choice between antenna size/type on one hand, and the GPS signal directionality and strength on the other. Table 2 shows two considered GPS antenna options: a Taoglas GPS patch antenna with integrated amplifier, which while providing strong signal reception will also have high directionality and take up a reasonable amount of space and weight; and a Fractus small planar monopole GPS antenna [9], which is lighter, less directional, yet provides weaker signal reception. The smaller antenna's omnidirectional radiation pattern maintains consistent GPS reception in any orientation, which is particularly favourable for the 3-D mobility of flying foxes. We therefore select the Fractus antenna and augment it with a 20 dB low noise amplifier (LNA) to boost its signal to comparable levels as the patch antenna, whilst consuming less power.

One disadvantage with our antenna choice is that it requires an adjacent ground plane that is nearly 12 times its size to work efficiently. We opportunistically match the size of the ground plane to the overall Camazotz board footprint, so that the same Camazotz board that includes all the functional components has a dual role as the ground plane for the GPS module. This design choice keeps the overall node's weight and size within their respective targets.

Figure 2 shows the top and bottom views of the Camaztoz platform, while Figure 1(b) shows the node within its enclosure on a bat during one of our field trials. Note the dual solar panels in Figure 1(b) on opposite sides of the enclosure, in order to maximise the chances of energy harvesting when foxes are roosting in a camp (typically in the upside down position, where the node slightly flops down), or flying at the beginning or end of the day, which exposes the top-side panel to the sun.

The energy charging architecture of Camaztoz is yet another design consideration. Since nodes on flying foxes will

Type	Size(mm)	Gain (dB)	Power@1.8 V
Taoglas AP.10F	10×10×4	-10 + 20	9
Fractus Geofind + LNA	10×10×0.9	1.5 + 20	5.61

Table 2: Comparison of small GPS antennas.

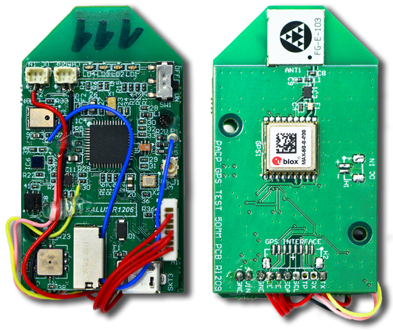


Figure 2: Top (left) and bottom (right) view of Camazotz prototype device without battery and solar panel. Dimensions are 54×30×14 mm.

have unpredictable and intermittent access to solar energy, we need a flexible energy architecture that opportunistically exploits available solar energy. In particular, there will be situations when node batteries are either fully charged or fully flat. In both these cases, it is beneficial to power the node directly through the solar panel to make the most of the node's sun exposure. We therefore incorporate a solar bypass circuit to enable Camazotz to consume energy directly from the solar panels during extreme battery states. The flat battery state occurs when the battery is completely flat and is only trickle charging at a very low current. In this case, the bypass allows the device to power up cleanly, rather than relying on the flat battery to power up, which would risk oscillation around a minimum voltage threshold leading to data loss. During the fully charged state, the bypass circuit on Camazotz can use any excess solar energy (that would otherwise be wasted) for increased sampling or computation.

The design of Camazotz also adopts a low power approach in its selection of sensors and in the integration of these sensors into the board. We select low power sensors for Camazotz to suit its restricted energy budget, with an eye towards Multimodal Activity-based Localisation for fine-tuned GPS sampling control. In particular, we select the Bosch BMP085 pressure sensor, the STMicroelectronics LSM303 3-axis accelerometer/magnetometer and a Knowles microphone. The BMP085 pressure sensor draws only 12 μA, and when combined with a static node's pressure reading, can provide us with a more accurate height measurement (see Figure 11(a)). The LSM303 accelerometer consumes 830 μA of current and allows for detection of different behaviours (see Figure 10). The final sensor is the Knowles microphone, which is connected to the 12-bit ADC on the microcontroller, and consumes less than 1 mA in operation. The microphone can be used in conjunction with other sensors for more robust activity detection.

Integrating these sensors into Camazotz requires a design decision in itself. Having access to a limited energy supply and a goal of long term operation dictates that we duty-cycle the node components. This is a particular focus to ensure that we could minimise the energy consumption in the sleep state. Rather than putting all the peripheral components into their standby modes, which are in the order of 40 μA total, we create a single digital line that can cut power to all peripherals surrounding the SoC prior to entering sleep state for the lowest possible energy consumption of 12 μA on average.

2.4 Software

The Camazotz platform runs the Contiki operating system, which provides a threaded programming environment using the C programming language. We add two key features on top of the Contiki core: remote procedure calls, and a logging abstraction.

As the Camazotz device will be deployed on wild animals, retrieval the node for reconfiguration is not an option. To address this issue we implement remote procedure calls (RPC), allowing us to send a radio command to the device to perform certain actions (e.g. reading memory blocks or status information) or to adjust configuration parameters such as the GPS duty-cycle. Every RPC command is sent as a unicast or broadcast packet containing a unique command identifier and a list of arguments. Our implementation of RPC commands serves as a basic building block to support additional functionality for future use cases. For example, a base station located at a roosting camp can query status information of a mobile node to request sensor data stored in the flash memory to be sent over the radio.

Logging on the Camazotz device is critical to its success, due to the delay-tolerant nature of the flying fox application. Communication outage times may range from hours, days, weeks or even months before there is an opportunity to offload data. Initially, data will be logged at a high sample rate to a Secure Digital (SD) flash card, for board and code verification, and then switch to external flash for final testing. To address this requirement for interchangeable storage, we introduce a data logging abstraction, which provides a consistent application programming interface (API), regardless of the underlying storage mechanism. The advantage of the logging abstraction approach is that we can log high sample rate sensor data to the SD card while in the development and testing phases, then for the final version we reduce the sampling rate, required by our energy budget, and with minimal code changes, switch to use the external flash for logging. Current mechanisms supported by the logging abstraction include the radio, external flash and SD card.

3. EVALUATION

This section empirically evaluates the Camazotz platform's communication, energy, and sensing features.

3.1 Mobility

Flying foxes are active animals that can cover distances of up to 100 km at cruising speeds of 7-8 ms^{-1}. They participate in complex social behaviour while at roosting camps that frequently result in their location change. Our deployment setup includes a base station with 3G connectivity that is deployed within the roosting camp close to the ground. The Camazotz platform needs to be able to communicate with the base station from the surrounding trees, within a distance of 200 m, as well as enable bats-to-bat communication outside of roosting camps. In this section, we study the impact of the height and mobility of the Camazotz transceiver on the received radio signal quality. We study three antenna types to maximise packet reception rates at the base station.

3.1.1 Experimental Platform

We use AscTec Pelican UAV platform [22], which is a flexible quad-copter platform designed for easy integration with a variety of payloads, up to a maximum of 650 g. The

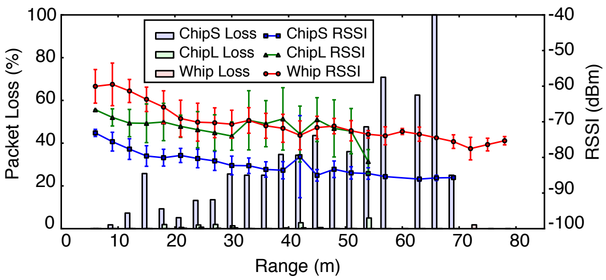


Figure 3: Comparison of mobile to base RSSI and packet loss for two chip antennas (large and small) and a whip antenna.

platform is equipped with inertial and GPS chips and an autopilot that enables non-experts to pilot the platform out of the box after a few minutes of training. Our payload consists of the Camazotz prototype with radio and GPS chips, high-capacity Li-Ion battery to power the prototype, and a mount for different test antennas. The maximum flight time with our payload is about 30 mins. Altogether, our experiments include more than 10 hours of flight data covering a distance of more than 20 km without any major incident, a testament to the robustness and reliability of today's UAV technology.

The Camazotz node on the UAV broadcasts packets with a payload of 32 bytes and a frequency of 8 packets per second. The base station node is installed at approximately 1.5 m above the ground and is equipped with a ground plate with a diameter of approximately 20 cm. We record the radio signal strength indicator (RSSI) for each received packet. The packet reception rate (PRR) is estimated using sequence numbers included in the broadcasted packets and each packet is timestamped by the PC time at the reception.

The Pelican platform provides a software development kit that enabled us to log GPS and inertial data from the Pelican autopilot. This data is useful in evaluating GPS accuracy, as well as correlating Camazotz radio performance to the relative speed, height, or distance between Camazotz and the base station. We use an XBee connected to a laptop to communicate with the UAV and recorded the autopilot data at 4 Hz. We use the UAV's GPS for latitude, longitude, and heading and UAV's inertial sensors for altitude and speed estimates to compensate for GPS errors. We have also written a Python interface to Google Earth that shows the location of the UAV in real time and can replay the recorded experiments.

3.1.2 Antenna Selection

We consider two basic antenna types for our platform: an EZConnect 868 MHz chip antenna manufactured by Fractus [9] and a quarter-wavelength whip antenna. We test two versions of the chip antenna as the ground-plane in the development kit was significantly larger than the footprint of our platform. The smaller configuration was designed to match the footprint of Camazotz.

We run experiments for each antenna flying the UAV along random trajectories, covering a number of different heights, speeds, and distances. The overall length of the recorded data for each antenna is approximately the same. The distance between the flying node and the base station is estimated from the UAV GPS data and the known location of the base station.

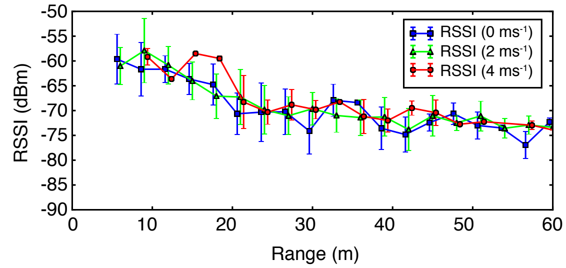


Figure 4: Correlation of mobile to base RSSI signal, conditional on the relative speed of the UAV and the base station.

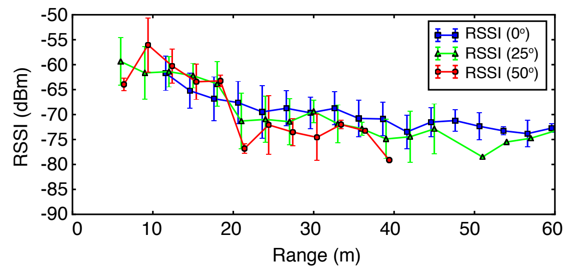


Figure 5: Correlation of mobile to base RSSI signal over their distance, conditional on the altitude angle between the UAV and the base station.

We plot our results in Fig. 3. The chip antenna with a small ground-plane (ChipS) is clearly performing the worst and experiences significant packet losses at distances of 20-30 m. Somewhat surprisingly, the simple whip antenna outperforms the unmodified chip antenna (ChipL) at most distances and experiences almost no packet loss at all tested points. In addition, its performance is much more dependable as shown by the smaller variance of the RSSI signal. Our conclusion is to use the quarter-wavelength whip antenna as it provides superior performance at a lower cost.

3.1.3 Impact of Speed

We next study the impact of the relative speed of the Camazotz radios on the packet reception rates. We have flown our UAV platform in a series of experiments designed to resemble flying fox flight patterns at up to half of their cruising speeds. Figure 4 does not show any significant correlation between the speed and the received signal quality, so the radio scheduling algorithm thus does not need to constrain packet transmissions based on the speed.

3.1.4 Impact of Angle

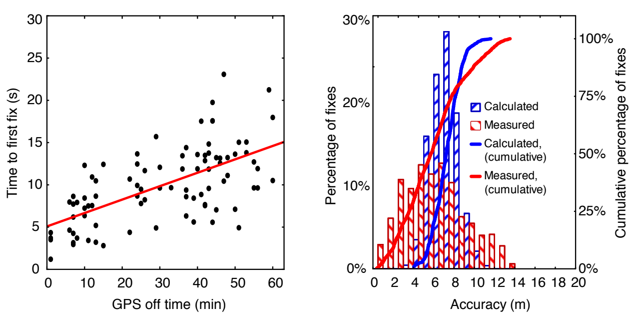
Finally, we study the impact of the node orientation on the radio reception. Due to the constraints on the payload of our UAV test platform, we did not study the impact of the node heading as simulating a bat would require attaching a one litre bottle of water to Camazotz. We thus focus our study on the altitude angle between the node and the base station. As the transmission pattern of antennas is not a perfect sphere, radio performance is expected to decrease at higher angles (when nodes are directly above base station).

Figure 5 confirms our expectations, albeit showing only a minor degradation of the signal quality at higher angles. We attribute this to the ground plate used at the base station that helps to reflect some of the energy from the antenna null areas. However, even with the ground plate, the radio communication is sensitive to the altitude angle which should be considered during the deployment phase. In particular, we need to refrain from installing the base station directly under the trees populated by flying foxes.

3.2 GPS

We conduct two different experiments to evaluate the performance of Camaztoz's GPS module. The first experiment uses a Camazotz board in a static outdoor setup, while in the second experiment the Camazotz board has been attached to a captive live flying fox in a large outdoor cage.

For the first experiment, we attach the Camazotz board to a tree on our campus to have similar conditions as in a camp. The GPS receiver has a partly unobstructed view of the sky. We configure the Contiki application running on the Camazotz to switch off the u-blox MAX-6 GPS receiver 60 s after a position fix has been acquired. During the off phase, only the backup voltage of the GPS module is active which powers its real-time clock and the RAM. Therefore, the GPS receivers can still keep the ephemeris information in RAM and is able to do a warm start. We select the off time interval uniformly at random between 10 s and 60 min and measure how long it takes to acquire the first fix after power to the module has been enabled again. The measurement results for the time to first fix are shown in Figure 6(a). Our results indicate that the time to first fix (TTFF) is correlated with the time interval the GPS receiver was switched off, confirming results from older GPS modules [6].



(a) (b)

Figure 6: GPS performance of Camazotz; (a) time to first position fix for various off-time intervals, (b) comparison of reported accuracy estimate and a measure of true accuracy.

During the experiment on the living flying fox, the Camazotz logged 1 Hz GPS data to its SD card, and continuously sent status update messages via radio to a base station nearby. We assess the true accuracy of the GPS against the accuracy reports from the GPS module. We set the true accuracy as the distance of the GPS locations from the known location of the animal for a period of time when it was roosting in a single location. We choose a one hour period of the day when we observed that the animal was in the one location, hanging from a roosting location and occasionally grooming and fanning itself. During this period the GPS was in tracking mode where it was collecting fixes continually at 1 Hz, collecting 3600 fixes. We took the average location of all of these fixes over the time period and use it as the true location of the animal. Geo-referenced high resolution imagery [11] with a spatial accuracy of 1 m was then used to confirm the coordinates for this location, which was considered the true location. To measure the accuracy we calculate the distance from each fix to this true roosting location, and for each fix compare this figure to the accuracy estimate calculated by the GPS unit.

Component	Power 100% (mW)	Duty Cycle %	Power DC (mW)
GPS	74	3	2.2
Radio	99	2	2
Cpu	13.2	5	0.7
Flash	40	1	0.4
Acc/Mag	2.6	10	0.3
Pressure/Temp	0.1	100	0.1
Mic	3.3	1	0.03
Totals	**232.2**		**5.7**

Table 3: Power consumption at 100% and target duty cycles of Camaztoz components.

Figure 6(b) summarises our results. The measured accuracy (M=5.9, SD=3.0) is significantly lower than the reported accuracy ((M=7.2 , SD=1.3); $t(7206)=24.2$, $p<0.01$) from the GPS module, with a minimum accuracy value reported by the GPS of 3.9 m, while the measured accuracy data indicates that 3% of the fixes were within 1 m accuracy. The calculated accuracy values are much more clustered than the measured values, with 87% of the calculated values being between 5 and 9 m. These results indicate that the GPS unit generally provides conservative estimates of its accuracy in our experiment, as the true positions are more accurate than the reported accuracy measurements suggest.

We note that the GPS results in our experiments are only indicative of the module's performance in our specific testing scenario. Both the TTFF and the reported accuracy may vary as flying foxes move to different environments. While this paper introduces GPS sampling based on multimodal sensor inputs, an interesting future direction for this work is to adapt GPS sampling schedules to observed variations in GPS module performance in addition to observed context.

3.3 Long-term Operation

3.3.1 Solar on collars

The Camazotz platform makes use of solar panels to help ensure long term operation. Figure 7 shows the result of an experiment logging solar charge current at 1 Hz that includes two Camaztoz platforms, one on a live bat and another nearby on the ground in full sun exposure. The large dips shown in the static node's solar charge current are caused by shadows from the structure of the bat enclosure that the device was deployed in. The measured solar charge current of the bat node is significantly lower than the the reference static node, as one would expect given the non optimal orientation of the bat node and also the bat's insistence on resting in a shady location for the majority of this experiment. The small peaks over 5 mA shown in the bat node's solar charge current occurred when small glimpses of sunlight were caught by the solar panel, and are more representative of what would be achieved depoyed on bats in the wild that tend to spend long periods in the sun while roosting.

3.3.2 Lifetime Implications

Building on these solar current experiments, we now ex-

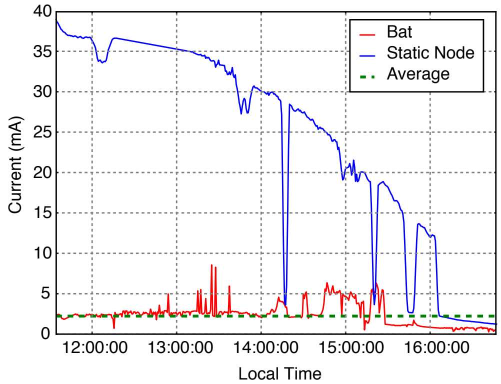


Figure 7: Solar current captured from static node versus bat node.

plore the lifetime implications for our nodes. Camazotz will have a 300 mAh Li-Ion battery with an average voltage of 3.8 V (range of about 3.3 - 4.3 V depending on charge state). The on-bat solar experiments indicate that we can obtain an average of at least 3 mA for 12 hrs from the solar panels, which equates to about 5.7 mW average power input for a full day.

We aim to keep the battery close to full charge to avoid trickle charging, so we design for energy neutral operation considering the energy consumption and harvesting. Table 3 shows the power consumption of the Camazotz components in full operation mode and in operation at our selected duty cycles. The average power consumption with these settings is just below 5.7 mW (recalling that 5.7 mW is a conservative estimate for harvestable energy), which meets the energy neutral target and promotes long-term operation subject to the lifetime of the physical components and the recharge cycles of the battery.

Note that within the allowable 3% duty cycle of the GPS module, setting a sampling schedule for the module remains an issue for further investigation. Our forthcoming paper [13] provides a detailed empirical analysis on the GPS tradeoffs involving the off time, target position accuracy and its corresponding energy consumption. We aim to characterise the performance of the newer u-blox MAX-6 GPS module on Camazotz and use a similar analysis to determine the most appropriate GPS schedules.

3.4 Activity Recognition

In addition to tracking where flying foxes go, we are interested in what they are doing. The key activities of interest are shown in Table 4. Flying is a key activity that requires position estimates at high sampling frequencies (ideally in the order of seconds) and should be trackable through the GPS, air pressure (for height), and potentially inertial sensors for wing beat frequency. Frequent daily interactions at roosting camps among multiple animals fighting for territory or in mating advances can be captured through a combination of distinctive sequential sounds and increased movement. Urinating and defecating are important to detect and localise for determining where and how flying foxes spread seeds from fruits they have eaten. For that reason, GPS fixes are desirable when these events occur. Detection is possible using the accelerometer to capture the instance that an animal switches from its normal upside down stance to a right side up stance. Grooming animals are typically in the upside down position yet moving their head/neck to groom themselves, which may be detectable through the inertial sensors, and using their claws to scratch their bodies, which creates a scratching sound. Resting is the default state for most animals in a roosting camp, which typically does not require the position lock and can be used as a baseline low activity state for differentiating from other states. The lack of a hardware motion trigger on the accelerometer indicates this state, and pressure sensors can be used to estimate the height at which animals are roosting for establishing hierarchies within a camp.

It is clear that detecting the above activities requires multiple sensory modalities, and in some cases the detection of an activity should trigger a position lock through the GPS. The remainder of this section empirically evaluates to what extent the sensory modalities on our platform can capture these activities of interest.

3.4.1 Audio

While acoustics associated with echolocating micro-bats has been well covered in the literature [10], not much attention has been given to using flying fox vocalisations as an automated means of monitoring them. Some very early work by Nelson [19] and relatively recent work by Parijs et al. [21] presents some characterisation of the different calls made by flying fox species. Adult and juvenile flying foxes emit calls within the human audible frequencies mostly during interaction events [17].

The in-built microphone on the Camazotz node is used to capture audio at a sampling rate of 22.4 kHz. This is sufficient to cover the full spectrum of sounds emitted by flying foxes based on our initial studies using high quality audio sampled at 96 kHz. These recordings at known roosting camp sites show the most energetic part of the signal to be within the 2 - 4 kHz range and the upper harmonics to start fading away around 8 kHz. The audio data used in this paper is first down sampled to 16 kHz and high-pass filtered with $f_c = 1$ kHz. We then process the audio stream via an energy based detector as described in [2] to extract acoustic events. These include vocalisations from the collared individual as well as other bats within range. The events include other background 'noise' such as bird calls and anthropogenic sounds depending on the geographical location of the roosting camp. In our dataset, we also have loud scratching sounds when the bat is scratching the collar node along with human voices, construction site sounds as well as motor vehicle sounds.

Amongst the bat vocalisations, we identify multiple different call patterns. We focus on the sustained repetitive call associated with aggressive interaction events [19]. We use a set of three simple features to detect these particular calls which are associated with interaction events: (1) mean sound level, (2) call duration and (3) mean normalised frequency. An example of a repetitive call associated with an interaction event along with these features are shown in Figure 8. To facilitate implementation on the Camazotz node, the features are based on calculating the mean signal energy and counting the number of zero crossings of a 1024 sample sliding window with an overlap of 50 %. This gives us a convenient and non-resource intensive method for extracting acoustic features with reasonable accuracy by heuristically setting the threshold levels. Figure 9 illustrates the process of selecting a suitable threshold for acoustic activ-

Activity	Sensors				Timing		
	Audio	Inertial	Air Pressure	Solar	Event Duration	Event Frequency	GPS Sampling Period
Flying		X	X		hours	daily	high
Interacting	X	X			seconds	frequent	on event
Urinating/Defecating		X			seconds	frequent	on event
Grooming	X	X			seconds	very frequent	none
Resting		X	X	X	hours	daily	infrequent

Table 4: Key activities of flying foxes, their timing profile, and the sensors we use to detect them.

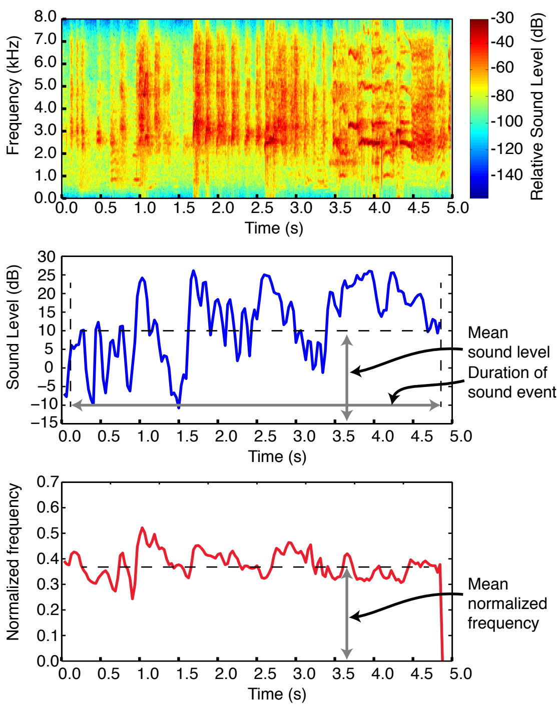


Figure 8: Top: spectrogram of typical audio interaction event. Middle: corresponding sound level and zero crossings. Bottom: normalised frequency. Arrows show derived acoustic features.

ity classification. Figure 9 plots accuracy, precision and the performance metric [15] as the threshold is increased from 0. The performance metric is the product of accuracy, precision, sensitivity and specificity and serves as an indicator for selecting a threshold which gives the highest accuracy while maintaining a high level of precision. Figure 9 also shows the receiver operator characteristic (ROC) curve which plots the true positive rate vs. the false positive rate as the threshold is varied. The indicated operating point corresponds to the selected threshold of 0.002. Two-fold cross validation was done over 1000 iterations to evaluate the performance of the classification by splitting the dataset in half. This resulted in a mean accuracy of 77.5 % and a mean precision of 70.5 % relative to manually marked ground truth obtained via video footage and external audio recordings.

3.4.2 *Inertial*

The inertial sensors on our platform enable the detection of activities such as interaction among multiple animals, urinating/defecating, and grooming behaviour, either individually or in combination with other sensors. For instance, accelerometers can be combined with acoustic sensor data to

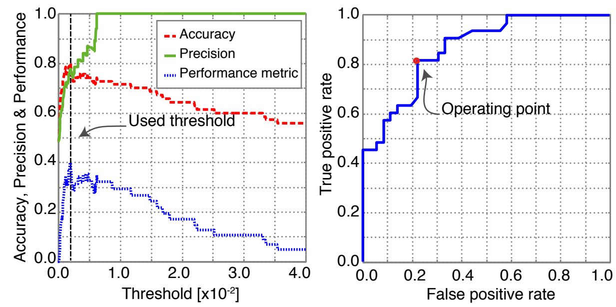


Figure 9: Plot of accuracy, precision and performance metric vs. classification threshold (left), and receiver operator characteristic (ROC) curve for acoustic activity classification (right) showing the operating point corresponding to the used threshold of 0.002.

detect interactions among multiple animals. Alternatively, accelerometers can independently detect the full reversal of orientation that occurs when flying foxes engage in waste removal from their bodies.

We examine accelerometer signals collected from a flying fox collar at 128 Hz during the captive bat experiments. Video footage and visual inspection serve as the ground truth for this experiment. In order to visually distinguish the angular inversion that occurs during urination activities, we compute the mean three-dimensional vector during a 7 min portion of the experiment. The reason for choosing the mean vector is that the flying fox remains in a down facing position for most of the experiment, which indicates that the mean vector should provide a decent estimate of the constant gravitational force and serve as a reference for orientation reversal. Figure 10 (top) shows the XYZ components of the accelerometer signal projected on the mean vector. There are clear sign inversions in all the accelerometer dimensions in two instances in the trace. However, using sign inversions to detect orientational flips is susceptible to corner cases where one of the accelerometer dimensions is orthogonal to the gravity vector.

We detect inversion events instead by computing the angle θ between the current 3-D acceleration vector $\vec{c}$ and the inferred gravity vector $\vec{g}$, using the following equation:

$$tan(\theta) = norm(\vec{g} \times \vec{c}, \vec{g} \cdot \vec{c}) \qquad (1)$$

where θ is in degrees, and *norm* is the vector norm function. The rationale for using angular shifts is that any 180° inversion in orientation will result in a significant shift in θ that is greater than 90° for a sustained period, which can only correspond to waste removal events in flying foxes.

Figure 10 (bottom) shows the resulting angles. The rectangular boxes indicate two detected instances of inversion events, while the left and right images show the correspond-

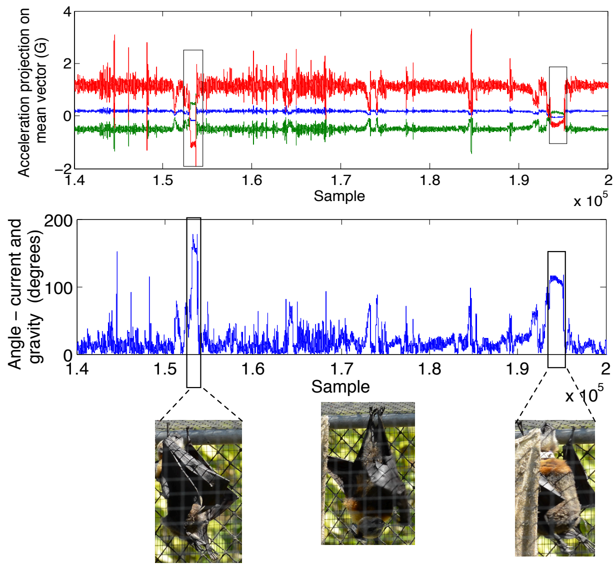
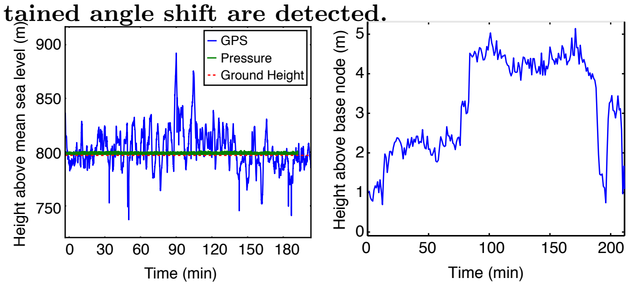


Figure 10: Top: Projected 3-D axis acceleration values over the duration of the experiment; Bottom: Angle between the inferred gravity vector and current acceleration vector. Two events with a sustained angle shift are detected.



(a) GPS verses air pressure height above mean sea level

(b) Flying fox altitude relative to base node.

Figure 11: Air pressure for estimating altitude.

ing video frames. The central image shows the typical flying fox orientation during the remainder of the experiment. Examining the signals corresponding to the two detected events, we can see a sustained angular shift of above 90° in (θ) for the two detected events.

In order to verify our ability to automatically classify inversion events on the Camazotz inertial signals, we manually marked the ground truth inversion events for 3 hrs of recorded on-bat accelerometer data during the afternoon, using the video footage for ground truth. The ground truth showed 11 true inversion events during this time period, with an average duration of 5.91 s for each event. We then ran a classifier on the entire dataset to detect angle-shift events by identifying contiguous samples of at least 4 s where the angle was shifted by at least 90^o. Our classifier detects all 11 true events, yielding 100% accuracy and precision.

3.4.3 Air Pressure

The altitude at which flying foxes fly or roost is of high significance to ecologists, in order to characterise individual and social behaviour. GPS is notoriously poor at providing altitude information, where the vertical error is estimated as twice the horizontal error on average. While a typical GPS fix will have a horizontal error within 10 m, the vertical error of 20 m does not provide sufficiently granular data for understanding fine-grained flying fox interactions, such as positional hierarchies in a roosting camp. We rely instead on air pressure sensors for altitude estimation. Air pressure itself can provide inaccurate estimates altitude because of variations in atmospheric conditions. However, air pressure measurements can use a ground-based reference measurement in order to provide fairly accurate estimates of the mobile nodes ground elevation. In the flying fox application, known roosting camps will have base station nodes, so it is easy to include an air pressure sensor at these nodes to serve as ground reference.

When flying foxes are near roosting camps, they can use the latest air pressure measurement from the nearest base station. When they are far away from roosting camps, we can revert to a nominal air pressure at sea level as a reference. An interesting direction for future work would be to try to fuse air pressure and GPS altitude data to determine if there is a performance gain for estimating altitude.

We conduct experiments with a collar-based mobile node that measures air pressure on a flying fox at a bat hospital. The flying fox is free to move within a large cage with a variable height of up to 5 m, and a base station on the ground measures air pressure for reference. Both the mobile node and the base station measure air pressure in Pa, which does not map linearly to altitude. We use the following equation to convert the sensor readings from each of the two nodes into the estimated height above mean sea level:

$$H = 44330 * (1 - (P/1013.25)^{\frac{1}{5.255}}) \qquad (2)$$

where P is the measured air pressure in hPa. In order to estimate the ground height of the mobile node, we simply take the difference between the H values from the mobile node and the base node.

Figure 11(a) compares the altitude estimation of GPS and air pressure on a Camazotz node on a bat collar. The air pressure estimate is based on the ground reference at the base station, which is located at 797 m above sea level. The figure clearly shows the stability and consistency of the altitude estimate based on air pressure compared to the extremely noisy GPS altitude estimate.

Figure 11(b) illustrates the estimated ground height (the difference between the bat and ground node altitudes from Figure 11(a)) of the flying fox during a field trial of nearly 6 hrs. The data has been averaged over 1 min time windows. During the first 20 min, the fox is being fitted with the collar in a 1 m high cage before being released into the larger cage for the remainder of the experiment. The dip at around 200 min into the experiment happens at feeding time when the bats descend. The height estimates were verified to be representative of the animal's movements through visual inspections and video recordings. Fluctuations in consecutive samples appear to be within 0 to 50 cm, which establishes an uncertainty bound for height estimates.

4. MULTIMODAL ACTIVITY BASED LOCALISATION

The tight weight, size, and energy constraints of long-term localisation mean that the GPS module has to be aggressively duty cycled. Because we require position fixes when flying foxes engage in activities of interest, we use the diverse

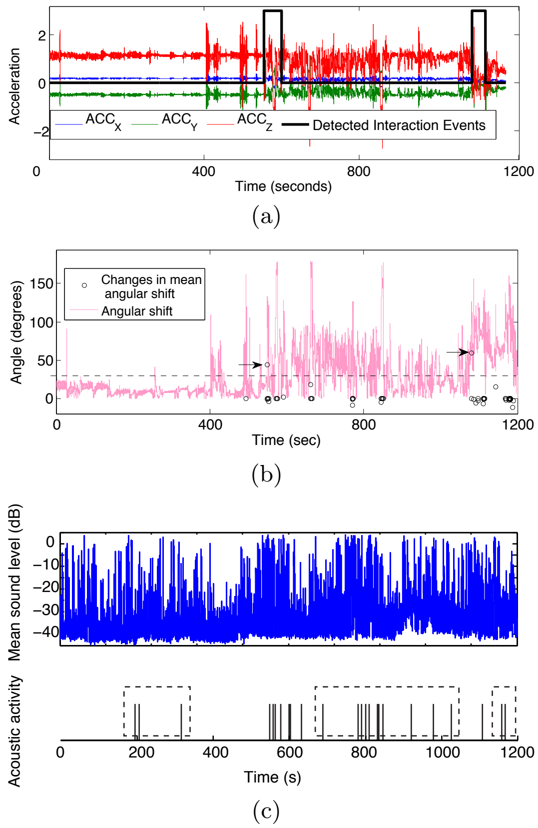


Figure 12: Activity detection; (a) accelerometer signal - thick black line indicating detected interaction events, (b) angular shift between gravity and current acceleration vector. The changes in mean angular shift clearly identify the start of the two true events, (c) mean sound level - dashed lines show detected acoustic interaction activity that involve nearby animals but not the collared animal.

sensor modalities on Camazotz to detect these activities. While some of these activities, such as urination/defecation, can typically be detected with a single sensor, others, such as interactions of multiple animals, require the fusion of multiple sensor outputs in order to determine that the activity is taking place and whether the collared animal is engaged in it.

We focus on detecting and locating interaction events that involve the collared animal interacting with nearby animals or the nearby animals interacting among themselves, as this aids in mapping the social dynamics within a roosting camp. We are particularly focused on longer interaction events that may last from 25 s up to 1 min rather than spurious interactions in the order of a few seconds, especially since localising this activity may require a multi-second start-up time from the GPS module. During these interactions, the animals tend to repeatedly bend their body from their upside-down stance, and on many occasions this movement is associated with multiple sequential vocalisations. Both the accelerometer and microphone can detect interactions involving the collared animal, but only the microphone also can detect interactions among nearby animals. We investigate further, using 20 min accelerometer and audio data traces from our captive bat experiments, and using video footage as ground truth.

For the accelerometer trace, we observe that interaction events exhibit much shorter term inversions than urination / defecation events in the accelerometer traces, sometimes for just above 10 ms, before reverting back to normal stances. What distinguishes this activity is the repetitiveness of the inversions within a window of several seconds. We can therefore distinguish interaction events through the average angular shift between gravity and the current orientation over a window in time corresponding to typical interaction event durations. In particular, interaction events involving the collared animals begin with an initial jerk where the animal is agitated and nearly changes orientation before engaging in repetitive short-term angular shifts.

We identify only two such events in our 3-hour data trace (with durations of 25 and 54 seconds) using video footage as ground truth. We use these two events to empirically define thresholds for interaction event detection through accelerometers to demonstrate the MAL concept, and we leave the validation of threshold for when more data becomes available. The accelerometer trace and true events are shown in Figure 12(a), while the angles are shown in Figure 12(b). It is clear that true events correspond to repeated short-term inversions of 120° or more in the angle trace, while some false events also exhibit sporadic angular shifts above 120°. We differentiate these shifts by averaging angular shifts. For every sample with at least 120° angular shift, we compute the average angular shift in the subsequent 54 second window, and take the derivative of the resulting average angular shift. The starting times of the two true events in our data trace correspond to the highest differentials in average angular shifts of 43.8° and 60° (indicated by arrows in Figure 12(b)), which capture initial jerks by a flying fox when engaging another fox in aggressive interactions. The next highest peak corresponding to a non-interaction event is at 18°. We therefore adopt 30° as our empirical threshold for the differential in mean angular shift to distinguish interaction events of the collared animal.

The mean sound level and detected interaction events are shown in Figure 12(c). Each vertical line in the acoustic activity plot represents an instance of sustained repetitive vocalisation lasting for approximately 5 s. As seen from this plot, acoustic activity of other bats within range is also captured by the in-built microphone of the Camazotz node and detected by the acoustic activity detection mechanism described in Section 3.4.1.

Table 5 summarises how MAL contributes to better characterisation of activities. While the accelerometer can capture the main interaction events of the collared animal, it does not provide any information on interactions among neighbouring animals, thereby missing two of the four events of interest. The audio sensor is capable of detecting all four events, but it is not able to distinguish which events involve the collared animal. It is only through the combination of these two sensor modalities that we can dissociate these two types of events.

MAL can achieve the event type dissociations with minimal increases to energy consumption over single-sensor triggered approaches. We analyse the proportion of detected events and the node power consumption that arises from each strategy. We use the component power consumption data from Table 3 and GPS lock time data from Figure 6(a)

Localisation Approach	Animal interactions		
	Collared	All	Dissociated
Duty cycled GPS	X		
Accelerometer-triggered	X		
Audio-triggered		X	
Accel. AND Audio	X		
Accel. OR Audio		X	X

Table 5: MAL can detect all events and dissociate interaction event involving collared animal or nearby animals.

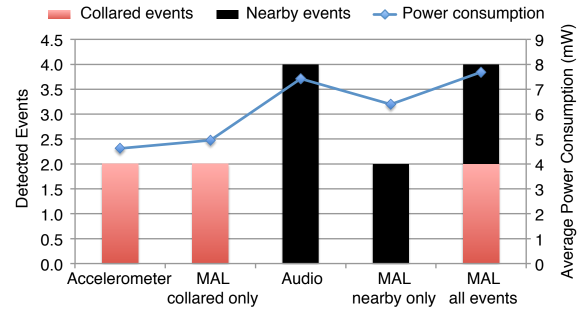


Figure 13: Performance of MAL against accelerometer- and audio-triggered GPS. MAL can be tuned to capture either interaction events of the collared animal, or nearby interaction events only. MAL can also detect and dissociate both types of interaction events with comparable power consumption to audio.

in our simulations. We compare a baseline approach of a duty cycled GPS with a period of 20 s with triggered GPS sampling approaches based on the accelerometer only, audio only, or on the combination of audio and accelerometer sensors. We group all detected ground truth interactions into events that meet the 25 s to 1 min duration constraint. A successful detection in our simulation is when the algorithm obtains at least one GPS sample during the event.

During the given time window, the duty cycled GPS module remains active for a total of 451 s (including lock times) and successfully obtains GPS samples during each of the four events of interest, yielding an overall node power consumption of around 33 mW. Figure 13 summarises the results of sensor-triggered GPS sampling. The accelerometer-triggered GPS manages to detect only two events (only the events from the collared bat) with a cumulative GPS active time of 21 s and power saving of 86 % over the GPS duty cycled approach. In comparison, the audio-triggered GPS can detect all four interaction events of interest while keeping the GPS active for a total of 64 s, corresponding to a node power consumption of 7.42 mW. However, the audio-triggered approach can only determine that interaction events are occurring nearby, but not whether the collared animal is involved.

MAL can be tuned to capture only interaction events involving the collared animal, with comparable detection to accelerometer and slightly higher power consumption for powering the audio sensor. Alternatively, MAL can be tuned to capture only nearby interaction events, yielding a 14% reduction in power consumption over audio and correct detection of the two interaction events involving only nearby animals. Triggering the GPS on the basis of both the accelerometer and audio activity detectors yields comparable energy consumption to audio and correctly dissociates the two types of detected events.

The main benefit of MAL is that it provides users with the flexibility to tune performance to their current activities of interest. If users are interested in collared bat interactions only, they can simply use accelerometer triggers for obtaining GPS samples and save energy in the process. If they are interested in the cumulative set of interaction events regardless of individual animal association with activities, then audio is sufficient. If, on the other hand, users are interested in pinpointing individual animals associated with each activity, multimodal triggering of the GPS can provide the data granularity for dissociating these event types.

5. RELATED WORK

The Networked Cow project [8] used PDAs with GPS and adhoc-mode WiFi to route position information to a base station. The work in [6] extends this cattle tracking application to use short-range radio for relative localisation alongside GPS. The ZebraNet project [5] reports individual position records for zebras every few minutes. In order to make the energy problem more tractable ZebraNet collars include a solar panel, which assume that the panels are resilient to normal animal activities. Positioning is done by GPS only, and the nodes propagate their information by flooding in order to facilitate data acquisition by the mobile sink. Dyo e al. [3] use a heterogeneous sensor network consisting of RFID-based tags and base stations to track European Badgers over a prolonged period of time and highlight the importance of interaction with domain scientists and early prototyping, which are also central to our methodology in design Camazotz. Our work shares the long-term monitoring goals and network topology with [3], but Camazotz includes GPS modules on the wildlife tags and aims to push the size, weight, and lifetime of the nodes to new limits through aggressive duty cycling based on MAL.

Anthony et al. [1] developed the CraneTracker system for long-range long-duration tracking of the endangered whooping Crane. Their platform, weighing about 100 g, includes GPS and inertial sensors as well as cellular and an Atmel RF230 radio for short-range communication. Their design aims at two GPS fixes/day and a communication latency of less than 24 hours. While our work also targets long-range and long-duration tracking of small birds, our target application tracking flying foxes has much stricter design goals. For instance, the device can not weigh more than 30 to 50 g or 5% of the bodyweight of the animals. Additionally, we aim for position logs at the frequency of at least once every half hour which results in a much higher utilisation of the GPS module. The combined smaller footprint and higher GPS sampling frequency for our application motivates our design of the Camazotz platform. The use of accelerometers has also been proposed as a low power indicator of movement to supplement GPS duty cycling [20] [14]. Guo et al. [12] also consider the use of directional and angular speed for cattle behaviour classification. The work in [7] addresses the tradeoff between localisation accuracy and energy efficiency. A key difference with our work is that we use multiple sensor modalities to trigger GPS duty cycling for more fine-grained activity detection.

Recently, Liu et al. [16] proposed a sample-and-process approach to dramatically reduce the active time for GPS position sampling by up to three orders of magnitude. While this approach is promising for reducing power consumption, it requires post-facto offline processing to recover positions and involves storing and transferring large amounts of data per fix. An interesting direction for future work is to explore the energy-implications of this sample-and-process approach for long-term flying fox tracking.

6. CONCLUSION

This paper has introduced the feature-rich lightweight Camazotz platform for long-term tracking of flying foxes. We have provided a comprehensive empirical evaluation of Camaztoz in both laboratory and on-animal experiments. Our results reveal a moderate radio communication dependency on communication angle in 3-D mobile environments, and confirm that whip antennas perform best. We have characterised the time-to-first-fix of our GPS design as a function of off-time on the ground. This was followed by on-bat experiments that showed most of the GPS positions that the GPS module accuracy estimate was generally conservative. We also evaluate the expected solar charge for our design, and plan the scheduling of our node components accordingly.

We have shown how multiple sensor modalities on Camazotz can individually or collectively detect flying fox activities. Based on these findings, we have proposed and evaluated the utility of Multimodal Activity-based Localisation, where multiple sensors can jointly trigger the GPS for localising interaction events. Our results demonstrate that combining sensor event detections can dissociate on-collar and surrounding interactions for fine-grained control of GPS sampling.

7. ACKNOWLEDGMENTS

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