Automated animal tracking for conservation and land management

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Introduction

An understanding of the ability of animals to disperse throughout landscapes is central to effective conservation planning and land management. Dispersal allows species to recolonise habitat after local extinctions, prevent inbreeding depression and alter their range to track environmental conditions (Hanski & Gilpin 1991; Simberloff 1988), and can be the key to population survival or extinction, especially in fragmented landscapes (Laurance 1990). Land managers charged with ensuring connectivity for native species between patches of habitat in both urban and agricultural settings often have scant information on existing levels of dispersal and how animals use different landscape elements. A poor understanding of the specific landscape elements required to maintain and re-establish connectivity often leads to management decisions being made using only general, theoretical or experience-based information (Cook *et al.* 2010; Hockings 2003). Central to the problem is the difficulty in obtaining direct measurements of dispersal and the use of different parts of landscapes (Taylor 1990) and a lack of adequate experimental controls (Simberloff & Cox 1987).

The lack of knowledge reflects the enormous difficulty of collecting suitable data. Trapping methods can only survey a limited proportion of a study area, and recapture rates can be low, limiting data quality. Wild animals are often difficult to find and difficult to recapture, so collecting sufficient data can take many years and the coordination of dozens of field workers (e.g. Driscoll & Henderson 2008). Many ecological events, including dispersal and migration, only occur rarely. Unless recapture rates are high and the study area is sampled intensively, it is virtually impossible to detect them over time scales that are typical of most studies.

Recent developments in satellite tracking have allowed these data to be collected for large animals. However, this technology is too heavy to be applied to smaller animals, which represent around 81% of bird species and 67% of mammal species (Wikelski *et al.* 2007). Effective conservation management requires knowledge of the movement and landscape use by a broad range of small birds, mammals, reptiles and insects. Current radio-tracking technology allows animals as small as beetles to be tracked, but the method is extremely labour intensive. A three-year project with a dedicated PhD student will often only collect good habitat use and dispersal data for one species, and only from a limited time of the year. The ability to collect more data, from more species, and in all seasons is essential for resolving the dispersal knowledge dilemma.

Radio tracking is a method by which recapture rates can be increased dramatically. By attaching a small transmitter to captured animals, radio receivers and directional antennas can be used to relocate them, typically by walking, driving, or even flying to the last known or anticipated location and using the angle of maximum signal strength to successively move closer to their current location. The time taken to find each animal limits the scope of the study, especially when individuals are widely distributed. Therefore tracking studies typically make a choice between tracking a limited number of individuals with high temporal resolution at the expense of replication (e.g. East & Hofer 1986) or tracking a larger number of individuals at intervals of 24 hours or more and forgoing detailed information about behaviour (e.g. Webb & Shine 1997). Obtaining more data requires that additional experienced field workers be recruited, and the hiring of professional field workers is often not feasible.

This thesis proposes that an automated radio tracking system be developed by integrating a range of existing technologies in a novel fashion. Such a system will permit cost effective and near-continuous tracking of hundreds of animals as small as 10 g over areas as large as a landscape management unit (approximately 10 * 20 km) using direction finding, mesh networking, and digital signal processing. The outcome of this project will provide three

orders of magnitude more dispersal information than current tracking technologies allow. These data will revolutionise our understanding of how animals move through managed landscapes and allow informed management decisions for the conservation of biodiversity and sustainable land management.

Automated Direction Finding

Automated wildlife radio tracking has been attempted many times using a range of methods. An early deployment by Cochran *et al.* (1965) used slowly rotating directional antennas on two 20-30 metre towers and 52 pairs of radio receivers, permitting 52 large mammals to be tracked simultaneously with a maximum range of 8 km, limited accuracy, and great expense. A more modern commercial system, the Sirtrack Auto-Track AT350, uses a single radio receiver that scans each animal's unique frequency in turn, reducing both the frequency of fixes and the cost of the system, though at a cost of $85000 and limited to three stations it was not particularly successful (P. Sargisson pers. comm. 2009). The rotating antenna method presents a challenge for long-term reliability in harsh locations and can use a significant proportion of the system's energy budget, which is typically constrained to battery-backed solar power in the wilderness. Another approach is to use an array of directional antennas and compare the strength of signals received at each. This is the method employed by the Automated Radio Telemetry System (ARTS) initiative in Barro Colorado Island, Panama. The high performance directional antennas it uses are expensive and large, and this system offers a directional accuracy of only 8°and a locational accuracy of 10 to 90 m, though the system is deployed very challenging mountainous, forested terrain (Kays *et al.*, submitted, cited in Mares *et al.* 2008).

For studies of wide-scale migration and site affinity, merely knowing whether an animal is present at or absent from a number of sites can be sufficient. Green *et al.* (2002)

recorded the movement of migratory birds through 75 km transects using omnidirectional antennas and a programmable radio scanner. This technique is appropriate for animals that can readily move large distances but may provide no useful data when used for small animals with home ranges measured in the tens of square metres. There has been some preliminary work on detecting small radio transmitters from low Earth orbit satellites, but without deploying a large satellite constellation this technique will be restricted to tracking migratory events at large spatial scales and with coarse time resolution (Wikelski *et al.* 2007).

Social network research has benefited from automated tracking systems such as ZebraNet (Juang *et al.* 2002; Zhang *et al.* 2004), EcoLocate (Markham & Wilkinson 2007), and Encounternet (http://encounternet.net). These use intelligent radio transponders that are able to detect and record their proximity to other tagged animals and fixed stations. This has the advantage of far lower power consumption than GPS tracking systems and the removal of the requirement to blanket the entire study area with radio receivers, but with larger minimum transponder weights (1.2 g in EncounterNet), it still not suitable for use with the very smallest animals.

In some cases it may be sufficient to know where groups of animals are rather than being able to discern their identities. Harmonic radar uses a cheap, very light, unpowered transponder to provide information about location only. This method has been used to monitor insect flight paths Riley & Smith (2002) and to facilitate the relocation of animals which are uniquely marked and can be identified once recovered Engelstoft *et al.* (1999); Webb & Shine (1997). The effectiveness of harmonic radar for ecological studies has generally been judged to be limited due to the cost of the off-the-shelf avalanche rescue systems generally employed and their limited range, which can be as low as 4 metres Webb & Shine (1997). Designing a high powered microwave radar presents a considerable technical challenge and is likely to be even more expensive, though this approach has been successfully implemented on small scales (Riley & Smith 2002).

Pseudo-doppler and Watson-Watt direction finding techniques use a single radio receiver to determine the direction of incoming signals by examining differences in either phase or amplitude across an array of typically four omni-directional antennas. Both techniques are used commercially and for wildlife research (e.g. Briner *et al.* 2003) but have a major disadvantage in that the antenna configuration reduces the system's sensitivity. The issue is compounded when the smallest wildlife transmitters are used, as they have output levels of 1 mW or less. The system developed by Briner *et al.* (2003) achieved a useful range of 30-40 metres (J-P. Airoldi, pers. comm. 2009), which limits its application to animals with a restricted home range. Preliminary field testing with a prototype pseudo-doppler receiver (Doppler DF Instruments, Santa Barbara, California) and commercial single-stage transmitters (Sirtrack Ltd, Havelock North) yielded similar ranges. Even worse, small animal movements that change the position and polarisation of the transmitter's antenna can greatly affect the signal strength at the receiver, and due to the relatively simple methods used to calculate signal direction, each receiver must listen for each animal in turn. However, the lower complexity and unit cost of the receivers when compared to rotating or fixed directional elements on large towers could compensate for the reduced range to some degree.

The Proposed System

Description

We propose the construction of a network of broadband multi-channel receivers that overcomes some of the limitations of existing solutions and allows new approaches to be investigated. This will take the form of a self-contained solar or wind powered base station platform that can be placed across a study landscape in a grid, with a spacing of at most twice the anticipated minimum detection range of the transmitters in use.

A multi-channel receiver allows the signals incident on each antenna element to be compared simultaneously. Coherently combining multiple signals allows signal to noise ratio and the detection range to be improved considerably. A minimum of five channels are required - the four cardinal directions and a further disambiguating channel, though the fifth antenna may prove unnecessary as long as bearings can be obtained from more than one base station. Further sensitivity may be obtained by adding another four channels with antennas polarised horizontally in order to allow for variations in animal transmitter antenna position, so the system will be designed in a modular fashion to allow additional sensors to be attached. In a lower-cost configuration, using only a single channel would allow presence/absence data to be recorded, which could be useful for tracking animals with larger ranges.

Rather than tuning to each animal's transmitter frequency in turn and waiting several seconds for a signal, which can take several minutes when many animals are tracked simultaneously (6.6 minutes per animal with 20 animals tracked in Leyrer *et al.* 2006), a broadband radio receiver captures all radio frequencies of interest and uses software defined radio (SDR) and digital signal processing (DSP) techniques to discern transmissions. At the same time, the amplitude and phase of each transmission can be compared between each antenna element to calculate the incident angle. This method allows animals to potentially be located every time their transmitter is active. Typically this would be set to around 40 times per minute for a transmitter designed for manual tracking. In order to triangulate signals, bearing estimates from multiple base stations are relayed to a data recording node over a backbone wireless mesh network where time-stamped location estimates will be saved and can potentially be uploaded to the Internet over a 3G connection or made available for field workers to access in real time using hand-held computers connected to the same wireless network.

Each base station is either programmed with its location during installation, or in the prototype, equipped with a low cost GPS receiver that allows it to determine its own

location and the current time accurately. The wireless mesh network uses self-organising routing protocols to discover adjacent base stations automatically and to route traffic around failed base stations or landscape features. Each base station will be equipped with its own high powered beacon transmitter, which allows neighbouring base stations to periodically calibrate calculated bearings of the transmission using its actual location. The self-organising mesh network will permit zero configuration installations of from one to hundreds of base stations. The prototype system is anticipated to consist of up to five base stations, with additional units contingent on available funding. A system of this size will be useful for investigating smaller habitat fragments, while a full system that is able to cover areas on the order of 10 * 20 km can be applied to larger reserves or a collection of fragments and intervening corridors.

Most of the locations that are interesting for ecological research are far from power sources, so it is necessary for each base station to be self-powered by solar or wind energy with a battery backup. As a considerable amount of power will be required to operate an entire base station continuously, at times where the system is operating purely off battery reserves it will be advantageous to conserve energy by operating at less than full potential. This can be achieved by examining recent animal movements and reducing the frequency of fixes. If no animal near one base station has moved for several hours, it would be sufficient to only power up the entire radio receiver once every few minutes rather than operating it continuously. If an animal is determined to be moving, the frequency of fixes can be increased, though still restricted to a level where the battery will not be exhausted overnight. It will also be possible for base stations to mutually conserve power. If one animal is visible to four base stations simultaneously, it is only necessary for two base stations, or even just one, to occasionally check its location while it is not moving. If movement is suspected, all base stations can be reactivated and the most accurate location estimate made.

Benefits

Compared to manual tracking techniques, the proposed automated solution will allow an increase in per-animal data from one to two location fixes per day to over 50000. The maximum number of animals that can be tracked simultaneously within a single study region is limited only by the number of non-overlapping frequency channels in use and the frequency stability of the transmitters. As an example, 5 MHz of bandwidth and a 10 KHz channel spacing allows 500 animals to be tracked. One benefit of the SDR approach is that software extensions can be applied in the future to accommodate larger, intelligent wildlife transmitters that share a single frequency but transmit a unique identifier code, or to automatically record data such as body temperature and battery life, which certain commercially available transmitters encode by varying transmission pulse rates.

As well as being labour intensive, the disturbance caused by field workers repeatedly contacting animals can introduce bias (Kerr *et al.* 2009; Caine 1990). With an automated system, animals need only be recaptured when transmitters must be recovered at the end of the study or when batteries must be changed. Furthermore, since transmitter pulse repetition rates are typically set for the convenience of field workers using manual scanning methods, pulse rate can be reduced with a corresponding increase in the transmitter's battery life. This will increase the length of time for which continuous data can be obtained and reduce the frequency of battery changes.

The establishment of the multidisciplinary partnerships between engineers and ecologists required to complete this research will also allow new ecological research avenues to be explored more readily than in the past (Benson *et al.* 2010). There is a great potential for the sensor network platform being developed to be extended with a range of other inputs to suit the needs of future research applications. These could include weather sensors operating at the micro-climate scale and video cameras. One suggested application is to examine the impact of fire on animal movement at the time of the fire itself. While such conditions would require that field workers vacate the area, an automated system can

continue to record temperatures and the movement of animals in the face of the fire front until the parts of the system necessarily exposed to the elements such as the antenna array and feed lines are destroyed.

Many interesting ecological questions could be investigated in detail if more data were available. For this project we plan to deploy a small-scale prototype in mallee fragments in New South Wales that were previously investigated by Driscoll (2004). Driscoll (2004) suggested that species that had declined within fragments had weaker dispersal powers or smaller effective population sizes. Knowledge of the home range size of decliners and widespread species in both continuous and fragmented habitat, combined with an estimate of population density, would add strength to inferences about their relative dispersal ability (Trewhella *et al.* 1988; Bowman *et al.* 2002). There would also be the possibility of detecting an actual dispersal event if an animal moves out of a fragment, or of finding evidence for a metapopulation if animals move between isolated fragments. Accurate information will allow animal dispersal through fragmented landscapes to be properly managed, thereby maximising the biodiversity outcomes from investment in conservation, and will enable better computer simulation of long-term processes such as fire or grazing mosaics, where dispersal is known to be important but data are currently unavailable for model parameterisation.

Original Contributions

The original contributions of this research are:

- The design of a multi-channel broadband software defined radio receiver and associated software that can infer the angle of arrival of multiple, simultaneous wildlife radio transmissions using digital signal processing and by communicating with all other receivers that detected the signal over a wireless mesh network, estimate the location of each transmission with a target accuracy of 5 to 10 m.

- The development of a software package that displays maps of animal movements in real-time and generates a range of summary outputs such as home range sizes which can be used to parameterise ecological management models.
- The development of algorithms that conserve power by reducing the frequency of signal processing by monitoring prior animal movements and anticipating the likelihood of future movements.
- Detailed insights into the real-time movement of a range of species, which will provide additional information on the home range, micro-habitat use, and ecology of these species and their interaction with a heterogeneous landscape.

Field Work

It is necessary for the prototype system to be tested outdoors so that its performance can be evaluated in non-ideal settings, which are typically characterised by trees and topography that limit direct line of sight and variable weather conditions. Initial tests have been conducted by positioning transmitters around the ANU campus. These were not attached to animals. A small-scale field trial will provide the opportunity to test a working system in non-ideal conditions and with real animals. It is anticipated that a prototype system will be ready for field trials in the second half of 2011.

Re-using a previously investigated study site such as mallee remnants in central New South Wales (Driscoll 2004) will provide further insights into the ecology of fragments and will allow comparisons to be made with prior trapping and genetic sampling techniques. Alternatively, collaboration with other field researchers using manual radio tracking techniques for their own studies will be arranged if possible. The additional information obtained by the automated radio tracking system will be provided to the collaborating researchers, and the installation of the system will be performed so as to not interfere with manual tracking, which can be carried out in parallel.

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