The Design and Evaluation of a Mobile Sensor/Actuator Network for Autonomous Animal Control

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ABSTRACT

This paper investigates a *mobile*, wireless *sensor/actuator* network application for use in the cattle breeding industry. Our goal is to prevent fighting between bulls in on-farm breeding paddocks by autonomously applying appropriate stimuli when one bull approaches another bull.

This is an important application because fighting between high-value animals such as bulls during breeding seasons causes significant financial loss to producers. Furthermore, there are significant challenges in this type of application because it requires *dynamic animal state estimation*, *real-time actuation* and *efficient mobile wireless transmissions*.

We designed and implemented an *animal state estimation algorithm* based on a state-machine mechanism for each animal. Autonomous actuation is performed based on the estimated states of an animal relative to other animals. A simple, yet effective, wireless communication model has been proposed and implemented to achieve high delivery rates in mobile environments. We evaluated the performance of our design by both simulations and *field experiments*, which demonstrated the effectiveness of our autonomous animal control system.

Categories and Subject Descriptors

C.2 [**Computer Systems Organization**]: Computer Communication Networks

General Terms

Algorithms, Design, Experimentation

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Keywords

Sensor/Actuator Networks, Application, Autonomous Animal Control

1. INTRODUCTION

Sensor networks and their applications have involved intensive research activities in the past few years. Most research activities to date have focussed on methods and applications for passing sensory data back to gateways or base stations [19, 24]; however in-network actuation, which is an integral part of sensor networks, has had less focus and experimental validation. Furthermore, nodes are typically deployed in static, pre-determined locations with sensor readings taken at regular intervals before each node multi-hops these measurements back to base for subsequent storage and analysis.

Whilst there is considerable scope for ongoing research in "back-to-base" type networks on topics such as optimal placement of nodes [13] and routing strategies [18, 11, 29], this paper focuses on applications for sensor networks which involve not only the need for *mobile nodes*, but also utilise *real time actuation*. These network types open up a whole new level of research opportunities and challenges in wireless sensor/actuation networks, and significantly expand the types of applications for which sensor/actuation networks can be used.

The application driver for the work described in this paper has arisen from a need within the livestock production community to seek ways to control aggressive behaviours of bulls in breeding paddocks. A high value animal such as a bull costs up to AU$20,000. The fighting between bulls during breeding season may result in serious injures to themselves, and the injuries reduce the value of them dramatically. Therefore, the protection of high-value animals such as bulls is of *critical importance* to the breeding industry.

The ability to prevent clashes between bulls thus removes the most common sources of serious injuries in groups of bulls. As such, our goal is to investigate mobile sensor and actuator networks as a means for providing increased spatial separation of bulls in breeding paddocks without human intervention.

Autonomous spatial management of cattle is a challenging task. Previous experimental work shows that cows are at least partly controllable by using stimuli [23, 5]. However, a good model, which can accurately predict the dynamic responses of all individuals, is difficult to design.

Our approach is to deploy a wireless *mobile* sensor and actuation network, which is capable of *estimating* the *dynamic states* of bulls, and performing *real time actuation* on the bulls from *location* and *velocity* observations. As it is a challenging task to implement a real-world mobile sensor/actuation network application which incorporates in-network processing and mobile wireless communications, our work builds on lessons in robust, adaptive system design from current sensor deployments (see Section 2), which focus primarily on simple data collection tasks (e.g., collect temperature and humidity data).

The purpose of this paper is to explicate these system contributions which enable *real time actuation*:

- We describe a *novel real world* sensing and *actuation application* (autonomous separation of bulls), which consists of many challenging tasks such as dynamic mobile object state estimations, and real time actuation.

- We design and implement: i) a mechanism to calibrate Global Position System (GPS) sensor measurements; ii) a simple yet effective communication model to transfer sensor measurements efficiently; iii) a robust state machine based mechanism to estimate the dynamic states of the mobile objects and perform appropriate actuation.

- We implement and evaluate the performance of our system by both simulations and *field experiments*, and demonstrate the robustness and effectiveness of the system.

In the rest of the paper, we discuss related work in significant sensor network deployments and applications (Section 2); describe the components, systems architecture and design contributions of our mobile sensor networks (Section 3); provide the detailed state machine-based algorithm for autonomous bull separation (Section 4); evaluate our design by simulations and field experiments, and discuss the results in Section 5. Section 6 concludes our work and describes future research directions.

2. RELATED WORK

Over the past few years, numerous applications and systems have been designed and evaluated based on sensor networks. In this section, we cover relevant research in sensor network deployments/applications, and autonomous animal tracking and control.

2.1 Sensor Network Deployment

Numerous sensor network applications have been proposed in areas such as habitat monitoring [1, 2], health [20], education [22], structure monitoring [17], automatic animal vocalization recognitions [12, 26], precision agriculture [8] and military [15, 6] in the past few years, some of significant sensor network deployments are:

- Habitat Monitoring on Great Duck Island [1]: In the Spring of 2002, researchers from College of the Atlantic in Bar Harbor and the Berkeley began to deploy a wireless sensor network to monitor microclimates on Great Duck Island. More than 100 nodes have been deployed and millions of readings have been transferred to a central database thousands of kilometers away via wireless channels since then.

- Scientists and engineers from UCLA and UCR have operated a 10 node, 100 microclimate sensor array at James Reserve over 12 months continuously [2]. Significant climate data has been stored in a database and is available for web queries. Apart from simple attributes like temperature, humidity, barometric pressure, and mid-range infrared, they are also collecting data from soil and video sources. They are extending the system to consist of more than 100 nodes and thousands of sensors for larger and deeper coverage.

- Belmont Cattle Station [7, 27]: researchers from CSIRO have instrumented a cattle farm in Belmont, a remote area in Queensland, Australia, with static and mobile sensors. The static nodes measure properties such as soil moisture while the mobile nodes are carried by the livestock to study animal behaviours. The nodes are powered by solar, and have been operating independently over one year.

- Industrial Sensornet Deployments [14]: Recently, two industrial sensornets have been deployed by the researchers and engineers from Intel and Arched Rock in a semiconductor plant and the North Sea oil field facility respectively. Sensornets are used to collect equipment vibration data for the purpose of preventative maintenance.

- Active Volcano Monitoring [28]: In the Summer of 2005, researchers from USA and Ecuador deployed a 16-node network, equipped with seismic and acoustic sensors, on Volcan Reventador, an active volcano in northern Ecuador. The sensornet was deployed over a three-kilometer aperture. Sensing data were routed over a multi-hop network to a long-distance base station, in where the data were logged and analyzed. The sensornet was deployed for a period of three weeks, and more than 200 events were detected within the period.

- Researchers from University of Hawaii have deployed a 60-node sensor network at Hawaii Volcanoes National Park, Hawaii Island, Hawaii, USA [4]. The goal of the sensornet is to study rare and endangered species of plants, by monitoring the plants using video sensors and their environment using microclimate sensors. Each node is a computer, which uses Wi-Fi as MAC protocol. Data is delivered using IP packets.

Current sensor network deployments are mostly static and perform simple data collection. In contrast, we have deployed a *mobile* sensor network that can perform *real time dynamic actuation* based on local sensor observations.

2.2 Autonomous Animal Control/Tracking

Previous experimental work in virtual fencing (no physical fence) has shown that cows are at least partly controllable by using a combination of audio warning signals and mild electrical stimuli [23, 5]; however, there is no good model which can accurately predict the responses of all individuals.

Other recent research has focused on training deer to avoid certain places using similar control signals [25], with limited success in initial trials.

The problem of spatial bull separation adds an extra level of complexity to the animal control problem, as constant communication must also take place between every animal inside a predefined range (See Section 4). A previous study on peer-to-peer communications between wireless sensor devices on cattle was undertaken, with initial results of the network performance presented [7]. The ZebraNet project [30] has also developed a system of animal tracking devices used on wild zebras where peer-to-peer networking techniques allow data to travel across the ad-hoc animal network to base for further analysis.

2.3 Summary

Previous sensor network deployments only perform data collection of sensor measurements such as temperature, humidity, barometric pressure, and video. While these deployments can provide unprecedented fine-grained environmental data to users, to the best of our knowledge, *real time actuation experiments* based on local mobile sensor measurements haven't been done. Previous studies on autonomous animal control shows that animals are partly controllable by using combination stimuli, however, it is difficult to design a static model which can predict responses of all individual animal accurately. Our approach of using a mobile wireless sensor/actuator network, described in next few sections, can perform real time actuation based on local sensor measurements of *dynamic animal states*.

3. SYSTEM ARCHITECTURE

Deployment of wireless sensor nodes onto cattle provides a new level of challenges when compared to the deployment of static nodes in the environment. Units must be robust enough to withstand the constant movement and jolting from animals and the method by which units are attached must be comfortable for long-term wear by animals. The following subsections outline the key issues in the design of suitable sensor network hardware for the experiments we conducted.

3.1 Hardware platform

The hardware platform we used was the Fleck^{TM} [21]. The Fleck^{TM} hardware platform was developed with robustness and reliability in mind, as well as ease of expandability for integrating a wide range of sensors and actuators.

The platform uses a similar architecture to the Mote [10] and is based around the Atmega 128 processor. The on-board radio is a Nordic 903 transceiver operating at 433MHz and 8MB on-board flash memory is also available. For this work we used a version of the Fleck^{TM} which contained a uBlox GPS receiver chip on board as well as multimedia card (MMC) for logging data.

When the GPS receiver is continually running, the Fleck^{TM} consumes a maximum of 518 mW in power. In order to sufficiently power the devices over the entirety of all experiments then, NiMH rechargeable batteries were used.

3.2 Cattle collars

The Fleck^{TM} board, along with the expansion stimuli board, were mounted inside IP55 rated plastic (ABS) boxes measuring 130x90x60mm. These boxes could then fit into the pocket of a specially designed collar, made from four-inch wide webbing, that went around each bull's neck. The collar also had pockets for the two batteries, GPS antenna and radio antenna. In addition a separate light head collar was attached, which contained two probes for application of the stimuli. A photo of a bull fitted with the equipment during the trial is shown in Figure 1.

Figure 1: Photo taken during trial of bull wearing collar containing Fleck^{TM} hardware, batteries and antennas. Note the number painted on side was to aid in visual identification of bulls during the trial.

Each collar weighed about 2.5 kg when fully fitted with the electronic hardware and batteries. In contrast, the typical bull wearing the collars weighed between 400 and 680 kg, thus the additional collar weight was deemed acceptable. To attach the neck and head collars, bulls were held in a standard cattle crush whilst a professional animal handler fitted the equipment.

An important aspect of the collar design was protection against damage by cattle. In our initial collar design we had a quarter-wavelength (20cm) whip RF antenna pointing out vertically from the top of the collar. Given the characteristics of a whip-antenna, this is optimal for obtaining maximum spatial distance for transmitting and receiving signals. We found however, that the cattle consistently destroyed the antenna within hours by either rubbing against a tree or even by co-operating with others to chew them off.

Given the seriousness of this problem, our solution was to lie the RF antenna flat along the top of the collar. This enabled the antennas to last about six weeks (given normal wear and tear), however this placement had an adverse effect on radio communications. The effect of this revised antenna orientation is discussed in far greater depth in Section 5 along with its consequences for the bull separation experiment.

As with previous animal control trials described in Section 2, we used a controlled electrical stimulus as the means of obtaining an initial behaviour response from cattle. (The strict precautionary steps we took for animal ethics and welfare purposes are outlined in Appendix A). In order to control the application of this stimuli, a separate electrical stimuli expansion board was developed such that the board could be controlled via digital input/output lines on the Fleck^{TM} board.

3.3 Software

All software running on the Fleck^{TM} hardware used the TinyOS [10] operating system and was written in the NesC [9] language. TinyOS is an event-driven, component-based

OS especially developed for platforms such as sensor network nodes with very limited resources.

All computation time was required to be kept at a minimum due to the need to keep processing incoming pings from other cattle as well as send out pings of updated position. As such, algorithms needed to be developed that could be executed very rapidly by the Fleck$^{\text{TM}}$ processor. The details of the algorithm will be introduced in next section.

4. A STATE MACHINE-BASED ALGORITHM FOR AUTONOMOUS BULL SEPARATION

In order to control animals, we must have some knowledge of their state. Whilst it is difficult, if not impossible, to fully define the states of cattle, we can infer some aspects of their behaviour state from measurable observations which are linked to their behaviours.

As mentioned in Section 3.1, the platform we used contained an on-board GPS chip. It is desirable to utilise all possible information available from the GPS sensors (i.e., positions, speeds and heading), to determine the relevant state information for the cattle control problem. We will introduce the techniques developed to perform this task in an efficient manner in this section.

4.1 GPS sensor calibrations

Coordinates representing positions on the earth can be given in two formats: (i) Spherical or (ii) Cartesian, where the GPS sensors we used could output in both of these formats. In the case of spherical coordinates, a position is represented by its latitude ϕ, longitude ρ and height above ellipsoid h. In the Cartesian case, the origin and orientation of the coordinate frame are dependent on the application and many well defined systems already exist.

For our application, the Earth Centered Earth Fixed (ECEF) coordinate frame was preferred, where the three axes $\{x, y, z\}$ are defined by setting one axis running through the poles of the Earth, and the other axes being mutually orthogonal and running through the centre of the Earth. Of particular interest was the ECEF velocities which were calculated by the chip directly from the raw pseudo-ranges of the satellites. This allowed significantly more accurate speed and heading information than would have been possible by calculating $\delta\phi$ and $\delta\rho$ values instead.

Our first step was to remove the unnecessary aspect of height from all calculations and thus bring all data into a two-dimensional subspace. To enable a rapid mapping to two-dimensions, given the resource constraints of the hardware platform, we define a single local tangent plane (LTP) which is tangential to the Earth's surface at the single point with latitude ϕ' and longitude ρ'. The mapping of ECEF velocities and positions to this plane $\{\hat{\mathbf{v}}, \hat{\mathbf{p}}\}$ is calculated as[1]

$$\hat{\mathbf{v}} = [v_n, v_e]' = \mathbf{Z}\,[v_x, v_y, v_z]' \qquad (1)$$

$$\hat{\mathbf{p}} = [p_n, p_e]' = \mathbf{Z}\,[p_x, p_y, p_z]' \qquad (2)$$

where

$$\mathbf{Z} = \begin{bmatrix} -sin(\phi')cos(\rho') & -sin(\phi')sin(\rho') & cos(\phi') \\ -sin(\rho') & cos(\rho') & 0 \end{bmatrix} \qquad (3)$$

In order to minimise error, ϕ' and ρ' are selected *a priori* at the centre of the area where cattle would be moving.

Given a set of N bulls $\mathcal{Z} = \{b_1, b_2, \ldots, b_N\}$ in a single paddock, we can calculate a number of parameters for each bull from the mapped ECEF information alone. For bull b_i and a received ping (single packet) from bull b_j, the following parameters were calculated:

1. d_{ij}: The distance between bull b_i and b_j in the projected LTP
2. θ_{ij}: The angle[2] between the direction vector between the positions of bull b_i and b_j and the heading vector of bull b_i
3. v_{ij}: The magnitude of the velocity of bull b_i projected onto the direction vector toward bull b_j.

These are calculated as:

$$d_{ij} = |\hat{\mathbf{p}}_\mathbf{j} - \hat{\mathbf{p}}_\mathbf{i}| \qquad (4)$$

$$\cos\theta_{ij} = \left(\frac{(\hat{\mathbf{p}}_\mathbf{j} - \hat{\mathbf{p}}_\mathbf{i}).\hat{\mathbf{v}}_\mathbf{i}}{|\hat{\mathbf{p}}_\mathbf{j} - \hat{\mathbf{p}}_\mathbf{i}|\,|\hat{\mathbf{v}}_\mathbf{i}|}\right) \qquad (5)$$

$$v_{ij} = |\hat{\mathbf{v}}_\mathbf{i}|\cos\theta_{ij} \qquad (6)$$

An illustration of the parameters for two bulls b_i and b_j is shown in Figure 2. This illustrates the case where parameters for bull b_i are calculated in reference to bull b_j. The way in which these parameters were used to estimate cow state is described in Section 4.3.

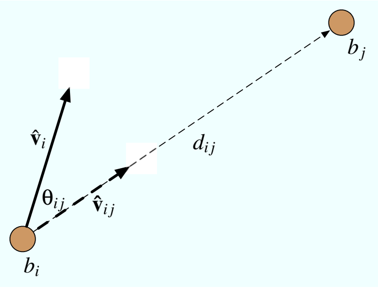

Figure 2: Illustration of parameters measured from bull b_i in reference to bull b_j

4.2 System communication model

As the first stage of our project, our goal was to design and evaluate a sensor/actuator system that could perform autonomous animal separations in small to medium size paddocks (up to 1 hectare or 100m × 100m). Therefore, all mobile nodes are within listening range, or a single-hop, from other nodes. As a result, we could implement a simple yet effective Medium Access Control (MAC) protocol which is collision free. For future larger paddocks, we plan to use MAC protocols, which have more features, such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [3]. Reliable routing and message delivery

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[1] This is similar to method used to calculate Northings and Eastings (NE), however for computational purposes only a single LTP mapping is calculated, rather than a separate LTP for each ϕ, ρ position as is the case for mapping to NE's.

[2] Note for efficient computation purposes, only $\cos\theta_{ij}$ needed to be calculated in the actual algorithm.

for resource-impoverished tiny devices in mobile and wireless environments are interesting and challenging tasks for future stages of the project, which are beyond the scope of this paper.

We used similar MAC state-machine as Mica2 [10] (see Figure 3). The default state for the radio is *idle*. Note that there is a 6.5ms delay in moving from the *pre-tx* state to the *tx* state and another 6.5ms delay in moving from the *tx* state to the *idle* state. In this protocol, collisions can only occur in the rare cases where two or more units select the same time slot in which to transmit. Because the sampling rate of our system is 2 Hz (500ms per sample), the probability for two mobile nodes to transfer at the same time is 6.5ms/500ms = 1.3%.

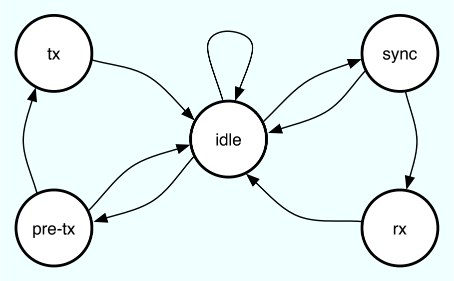

Figure 3: Illustration radio state machine when moving between states of idle, listening, receiving and sending.

Table 1: The format of a ping packet.

2 bytes	4 bytes	4 bytes	1 byte	4 bytes
Node_ID	Easting	Northing	*Local_state*	*Time_stamp*

Our system broadcasts ping packets (15 bytes in length) to exchange LTP data among animals. The format of ping packet is defined in Table 1. We notate the ping period for each node as T_p, the time for assembling and sending a ping from each node as T_s and the time to receive an incoming packet and process the information to determine bull state as T_r. An illustration of the timings for sending and receiving pings amongst three bulls is shown in Figure 4. In the diagram ϕ_i indicates a packet being sent from node i and φ_{ij} indicates a packet being received by node j which was sent from node i.

Table 2: Times for sending and receiving packets as used in our system.

T_p	T_s	T_r
500ms	30ms	2ms

Given the timings shown in Table 2, to ensure a reliable ping period of T_p = 500ms, we could have up to $N = 500/(30 + 2) \approx 15$ bulls in a paddock.

4.3 Algorithm Details

We model the dynamic behaviours of an animal by a state machine-based mechanism. The system defines a number of states prior to, during and after the application of stimuli based on the parameters of each animal as updated by each incoming ping packet. In particular, an animal's state is determined by its behaviour in reference to another bull. As such we assign a state variable α_{ij} meaning the state of bull i in reference to bull j.

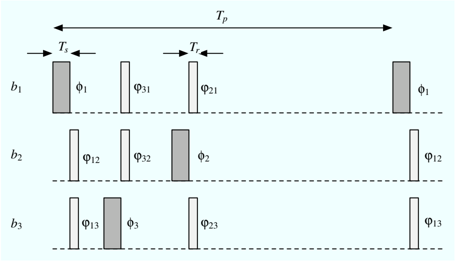

Figure 4: Illustration of timings of ping packets between three nodes. Given the nature of the experiment, all nodes are always on and can hear each other, thus the MAC layer can generally prevent clashes. In this figure, ϕ_i indicates a packet being sent from node i and φ_{ij} indicates a packet being received by node j which was sent from node i.

Further, we assign a state variable $\Lambda_i \in [0, 1]$ as:

$$\Lambda_i = \begin{cases} 0 & : \quad \text{No stimuli being applied to bull } i \\ 1 & : \quad \text{Stimuli being applied to bull } i \end{cases} \tag{7}$$

The application of stimuli, as described in Section 3.1, occurs at a pre-determined level for a varying period of time T_s. An exception to this fixed time period T_s occurs during "flight" responses of animals which shall be discussed later in this section.

We define the various possible values for α_{ij} prior to stimuli being applied being as:

$$\alpha_{ij} = \begin{cases} 0 & : \quad d_{ij} > \Omega_d \\ 1 & : \quad |\theta_{ij}| > \Omega_\theta \ \& \ d_{ij} \leq \Omega_d \\ 2 & : \quad v_{ij} < \Omega_v \ \& \ |\theta_{ij}| \leq \Omega_\theta \ \& \ d_{ij} \leq \Omega_d \\ 3 & : \quad v_{ij} \geq \Omega_v \ \& \ |\theta_{ij}| \leq \Omega_\theta \ \& \ d_{ij} \leq \Omega_d \end{cases} \tag{8}$$

where $\Lambda_i = 0 \ \forall \ \alpha_{ij}$ and Ω_d, Ω_θ and Ω_v are predetermined thresholds for distance, angle and projected speed respectively of bull i to bull j as illustrated in Figure 2.

We also define another two possible states during and after the application of stimuli as:

$$\alpha_{ij} = \begin{cases} 4 & : \quad |\hat{\mathbf{v}}_\mathbf{i}| < \Omega_{vf}, \ \Lambda_i = 1 \\ 5 & : \quad |\hat{\mathbf{v}}_\mathbf{i}| \geq \Omega_{vf}, \ \Lambda_i = 0 \end{cases} \tag{9}$$

where Ω_{vf} is a predetermined threshold for "flight speed". This is a rare case of an undesirable response to the stimuli, where the animal sprints forward rather than stopping or turning. In these cases the stimuli must be stopped immediately.

The values of thresholds Ω_d, Ω_θ, Ω_v, and Ω_{vf} are decided by the mobility patterns of animals. A non-aggressive bull tends to move slowly ($< 0.4m/s$); therefore, we used $\Omega_d = 20m$, $\Omega_v = 0.5m/s$, and $\Omega_{vf} = 2m/s$ in our field experiments (see Section 5). An aggressive bull tends to move directly toward its target; therefore, we used $\Omega_\theta = 30^\circ$ in the field experiments. Note that we obtained these threshold values from a number of animal behaviour studies undertaken in earlier experiments.

The interaction of these states is shown in Figure 5. It should be noted that whilst only being in state $\alpha_{ij} = 3$

triggers the stimuli, much computation time is saved by only checking the requirements to move to the next state up rather than all tests for other states.

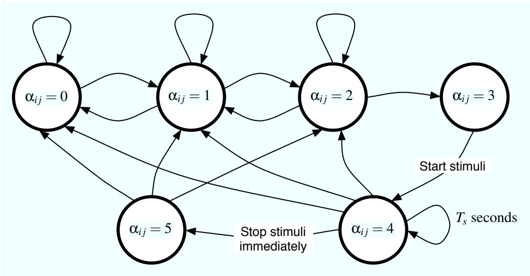

Figure 5: State machine running on each sensor node in bull-separation system. The definition of each state α_{ij} is as given in Equation (8) and (9).

5. EVALUATION

In this section, we evaluate the proposed mobile sensor and actuation system by both simulations and field experiments.

5.1 Goals, metrics and methodology

The goals of our evaluation are to study (i) whether our mobile sensor/actuator network can reduce the amount of fighting among aggressive animals, (ii) the robustness of proposed state machine-based algorithm, (iii) the performance of our communication protocol.

We use several metrics for evaluation.

- *Inter-animal distance distributions*: this metric characterizes the expected distance between each pair of animals. Because the probability of fighting between two animals is smaller when the distance between them is larger, ideally, the distance between two animals should be as large as possible.
- *Inter-animal distance vs. speed*: this metric characterizes the aggressive behaviours of bulls. The more aggressive a bull is, the higher speed it moves. Ideally, the speed of a bull should be as slow as possible when there is another bull nearby.
- *The trajectories of a bull prior and after stimuli*: this metric characterizes the effectiveness of the actuation. Because an aggressive bull tends to move straight at a high speed, ideally, a bull should change its trajectory significantly after actuation.
- *Delivery rate of communication protocol*: we study this metric as a function of distance between a sender and a receiver. This metric characterizes the probability of successful packet delivery at a given transmission distance. Ideally, it should be as close to 100% as possible.
- *The number of false positives and false negatives*: a false positive is defined as an actuation happening in a realistic environment (field experiment) but didn't happen in the perfect environment (simulation). A false negative is defined as an actuation didn't happen in realistic environment but happened in the perfect environment. Ideally, the number of false positives and false negatives should be 0.

The field experiment was designed to run over two days, with a control session (sensor network not activated) and a treatment session (sensor network activated) on each day. These sessions were run simultaneously in adjacent paddocks as shown in Figure 6. In each session, five bulls were placed in a 1 hectare paddock, with new bulls used on each day.

For treatment sessions, bulls entered the paddock one at a time, to enable all animals to be separated at the start of the experiment. As each bull entered the paddock, its collar device was remotely activated by a user sending a command from a laptop at the side of the paddock, as shown in Figure 6. A high-gain Yagi antenna was attached to the laptop to ensure the remote commands would be reliably transmitted and received. Likewise at the end of each treatment session, another command could be sent from the laptop to disable each device. Human observation was also in place throughout the experiments to immediately disable the devices if anything went wrong.

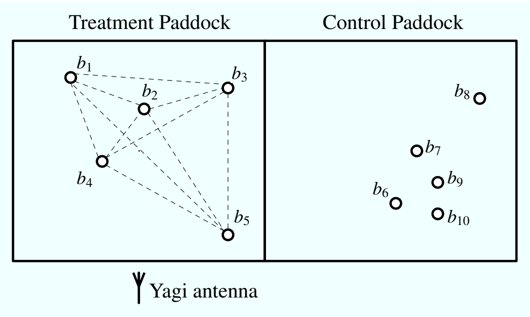

Figure 6: Illustration of field experimental setup.

Each treatment/control session ran for 40 minutes, where all relevant data was logged to a multi-media card for subsequent analysis. During both treatment sessions, video was also recorded for subsequent analysis and study by animal behaviour researchers. Manual observations were also recorded during the treatment sessions of any significant events, such false-negatives or false-positives, of the system.

In order to study the delivery rates of proposed communication protocol, an addition field experiment was run. In particular, we wished to quantitatively evaluate how a full mobile network would perform when nodes were mounted on moving objects.

To run this experiment, a group of 13 cows were fitted with the collars described in Section 3. For each cow, the following information was logged to a memory card: 1. Own GPS position, and time for each log; 2. Contents of each ping packet received. (ID and position of the sending node and time sent). We can calculate likelihood of the ping packet delivery rate against the distance based on these two parameters. The method used to derive this information is given in Appendix B.

5.2 Results

In general, the bull separation trial ran successfully over the two days, with the system described in this paper performing extremely well for the 40 minutes of both treatment sessions. In the second treatment session one of the devices failed to remotely activate due to electrical problems, which accounts for false-negatives (bulls coming in contact, see Figure 7) that occurred.

Figure 7 plots the histograms of inter-bull distances between treatment and control sessions. In treatment session 1, a clear reduction of distances occurs at 10m. The occurrences less than this distance were a result of bulls passing close by each other but not directly at each other (see Figure 8), thus no stimuli was applied. In the treatment session 2, the hardware failure of one of the devices meant that more cases of bulls directly contacting could occur.

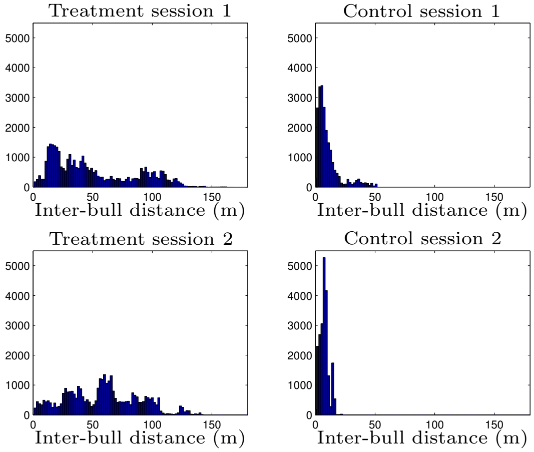

Figure 7: Histograms of bull separation distances for treatment (bull separation activated) and control sessions.

Figure 8 plots the inter-animal distance against the speed of the animals. It shows that in the treatment session, bulls who came within close contact of each other (less than 10 meters), were always slowly moving (less than 0.2 m/s). In the control session, bulls ran significantly faster (around 0.8m/s) when in close proximity. This demonstrates that bulls behaved far less aggressively in the treatment session.

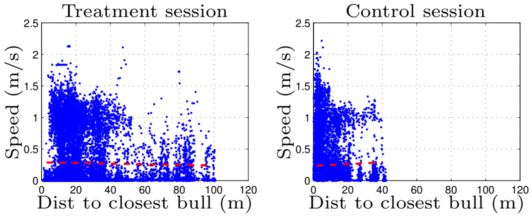

Figure 8: Scatter plot of distance to closest bull vs. speed for a treatment and control session. The dotted line is the least-squares linear-regression fit of the data.

Figure 9 plots the trajectories for four different bulls for the first time they received a stimuli and likewise in Figure 10, for the same four bulls in a later occurrence of receiving a stimuli in the same session. Note that each of the bulls tend to turn around more directly as the session goes by, which demonstrate the effectiveness of actuation. In all cases, bulls would instantly respond to the electrical stimuli when applied.

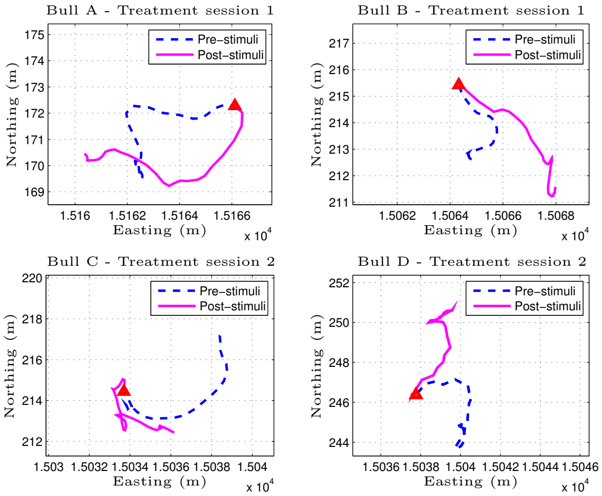

Figure 9: Plots of bull trajectories before and after stimuli (state $\alpha_{ix} = 4$) for the first time four different bulls received a stimuli. Results are spread over treatment sessions from day 1 and day 2.

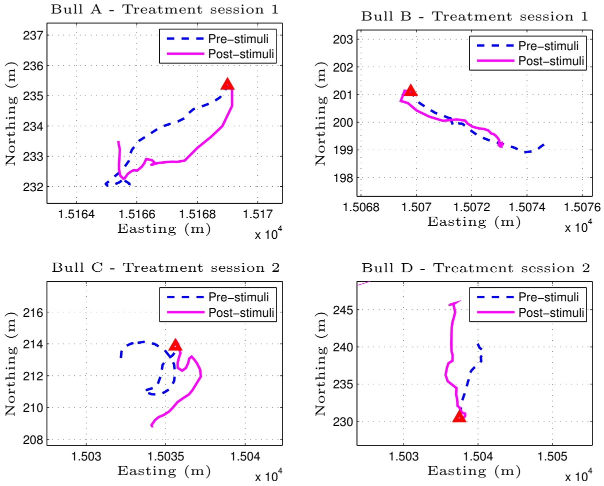

Figure 10: Plots of bull trajectories before and after stimuli (state $\alpha_{ix} = 4$) for the same four bulls as in Fig. 9, but this time later in the treatment session.

Figure 11 plots the likelihood of ping packet delivery rate by animals as a function of distance apart. It shows the delivery rate of ping packets is around 60% within 144 meters (the maximum distance between two points within a 1 hectare paddock) under mobile environment. Figure 11 verifies the results from static sensor network research [29] that the delivery rate gradually decreases as the distance between sender and receiver increases. Node mobilities add further dynamics to the transmission model. Instead of tradition "unit disk" transmission model, future networking research should take this wireless transmission behaviour into account when designing new routing and MAC protocols for mobile sensor networks.

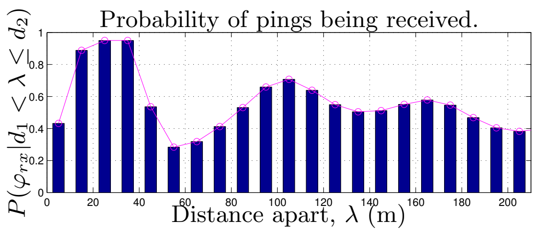

Figure 11: Illustration of $P(\varphi_{rx}|d_1 < \lambda \leq d_2)$ for varying d_1 and d_2 with bin sizes of 10m. (Figure sourced from [27].

A counter-intuitive observation is that the ping packet receive likelihood is low in the 10m around each animal with $P(\varphi_{rx}|0 < \lambda \leq 10m) = 0.42$. This result can be explained by the factor in the non-standard horizontal orientation of the quarter wavelength antennas on the top of each collar as described in Section 3.2.

Table 3: The percentage of false positive and false negative

	Session 1	Session 2
false positive	1.95%	1.1%
false negative	8.88%	5.30%
false positive (±2 seconds)	0.79%	0.34%
false negative (±2 seconds)	7.51%	4.54%

Table 3 shows the performance of the proposed state-machine based actuation algorithm in the actual field experiment compared to how the algorithm would be predicted to perform in a perfect simulated environment with no packet loss, hardware problems, etc. As shown in Table 3, in the mobile environment where packet delivery rate is around 60%, the probability of both false positive state (stimuli applied when it shouldn't have been) and false negative state (stimuli not applied when it should have been) is low (around 1% for false positive, and around 8% for false negative over all). This demostrates the robustness of proposed algorithm.

Note that a significant number of false positives and false negatives happened within 2 seconds of perfect state estimates as shown in the third and the fourth rows, because of the latency of packet delivery and state computations/estimations. Figure 12 further illustrates this phenomenon by comparing example states from a simulation of the algorithm and states as logged from the field trial. Therefore, a simple filter looking for consistency over 2 second window would improve the robustness of the system.

6. CONCLUSION AND FUTURE WORK

We have presented the design and evaluation of a *mobile sensor/actuator* network system for autonomous bull separation; a real world application characterized by mobile communications, state-estimations of dynamic mobile objects and real time actuation. Our system increased the distances between bulls in treatment sessions by a significant amount when compared with control sessions. We evaluated the proposed state machine-based estimation algorithm by comparing results from *field experiments* with simulations of the algorithm in perfect environments. These results demonstrate effectiveness of proposed algorithm.

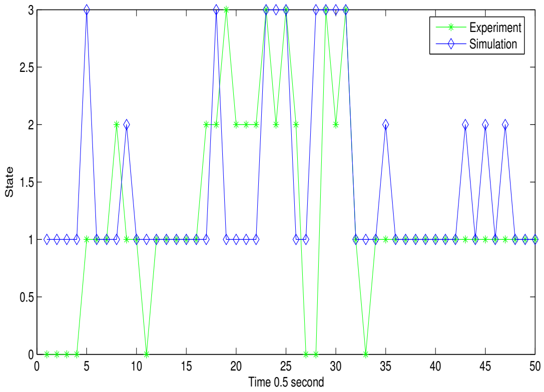

Figure 12: State comparison between experiments and simulations.

Having validated our system approach, we are planning to deploy mobile sensor/actuator systems in significantly larger paddocks. More advanced communication protocol needs to be developed to handle mobile multi-hop routing and message collisions. Additional work is also required to solve various algorithmic issues such as animals getting cornered in paddocks as well as better strategies to solve undesirable animal responses such as the "flight response". Further, it is desirable to research novel power-scavenging strategies to extend the life of mobile cattle nodes given nodes currently only last 4 days. In particular, finding optimal ways to power down the GPS chip when each animal is exhibiting little movement would save significant amounts of power.

The combination of sensor network research with animal behaviour study is an exciting one, and we believe holds rich research problems for the future. As sensor network platforms continue to become cheaper and have more computing power, the potential for these types of applications will continue to grow rapidly into the future. More details about our related research can be found at: http://www.sensornets.csiro.au.

7. ACKNOWLEDGEMENT

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APPENDIX

A. ANIMAL ETHICS AND WELFARE

Our research group places the highest priority on the need to treat animals involved in experiments in a humane and thoughtful manner, and to ensure the best possible standards of health and wellbeing. We adhere strictly to the standards of our National Code of Practice for the Care and use of Animals for Scientific Purposes and operate in compliance with all the relevant legislation on animal welfare. As a result, all our studies with monitoring and managing animal behaviour are carefully designed, with each experiment requiring approval by an Animal Ethics Committee as a legal requirement.

Should a hardware or software failure cause the actuation module to constantly zap an animal, a hardware override will stop zapping after 10 seconds. This override will persist until the Fleck$^{\text{TM}}$ device toggles an input/output line.

As a further surety, we have worked closely with an experienced animal welfare research group to monitor animal stress hormone levels during the research. The result of this work shows clearly that the levels of animal stress during our experiments are well within the range of typical stresses experienced by animals (e.g. being weighed) in their normal production environments [16].

B. CALCULATING THE MAXIMUM LIKELIHOOD (ML) OF DELIVERY RATE VS. THE DISTANCES

Firstly, by using the GPS position samples over time from each animal, the overall probability density function (pdf) of inter-animal distance λ could be calculated over all animals. We notate this density function as $p(\lambda)$.

Secondly, by taking the contents of the received ping packets, we know the position and time of a sending animal when the ping was sent. By interpolating through time, we could also estimate the position of the receiving animal and thus calculate the probability density function of inter-animals distances given the event of ping being received, φ_{rx}. We notate this density function as $p(\lambda|\varphi_{rx})$.

In both cases we used a maximum-likelihood (ML) approach, via the Expectation Maximization (EM) algorithm, to estimate $p(\lambda|\varphi_{rx})$ and $p(\lambda)$, from the trial ping and GPS data respectively, as a mixture of Gaussian densities. The plots of the probability density functions are shown in Figure 13.

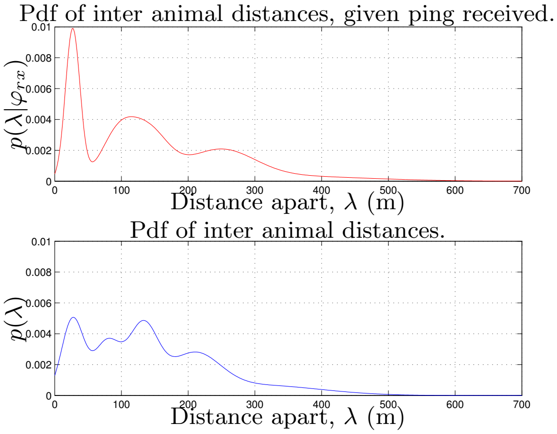
We can also calculate the total number of ping packets φ_{total} that would have been received over all nodes if there was no packet loss as:

$$\varphi_{total} = N(N-1)T_{av}F_p \tag{10}$$

where N is the number of animals (nodes), T_{av} is the time of the experiment and F_p is the ping frequency for each node. For the experiment run, we had $N = 13$, $T_{av} = 3.8$ days, and $F_p = 1$. Therefore, the total number of ping packets that should have been received, with no packet loss, is $\varphi_{total} = 853632$.

Given the actual recorded number of received ping packets over all nodes $\hat{\varphi}_{total}$, we can calculate the *a priori* likelihood $P(\varphi_{rx})$ of a ping packet being received as:

$$P(\varphi_{rx}) = \frac{\hat{\varphi}_{total}}{\varphi_{total}} \tag{11}$$


Pdf of inter animal distances, given ping received.

Pdf of inter animal distances.

Figure 13: Illustration of $p(\lambda|\varphi_{rx})$ and $p(\lambda)$ as estimated from the trial ping and GPS data using maximum-likelihood techniques.

For this experiment we recorded $\hat{\varphi}_{total} = 531119$ received ping packets over all nodes bringing the *a priori* likelihood for ping packet reception to $P(\varphi_{rx}) = 0.62$.

Using Bayes rule, we can calculate the probability density function for a ping packet being received, given a distance λ between animals (nodes), as:

$$p(\varphi_{rx}|\lambda) = \frac{P(\varphi_{rx})p(\lambda|\varphi_{rx})}{p(\lambda)} \tag{12}$$

Thus in order to calculate the *a posterior* likelihood of a ping packet being received when two animals (nodes) are a certain distance apart $P(\varphi_{rx}|d_1 < \lambda \leq d_2)$, we can calculate this, using Equation (12), as:

$$\begin{aligned} P(\varphi_{rx}|d_1 < \lambda \leq d_2) &= \frac{P(\varphi_{rx})P(d_1 < \lambda \leq d_2|\varphi_{rx})}{P(d_1 < \lambda \leq d_2)} \\ &= \frac{P(\varphi_{rx})\int_{d_1}^{d_2} p(\lambda|\varphi_{rx})d\lambda}{\int_{d_1}^{d_2} p(\lambda)d\lambda} \end{aligned} \tag{13}$$

We can thus apply Equation (13) to the data from the experiment to calculate the likelihood of ping packets delivery rate by animals as a function of distance apart as shown in Figure 11.