Environmental Sustainability

Sensor and Actuator Networks: Protecting Environmentally Sensitive Areas

Advances in wireless sensor and actuator networks (WSANs) can enable the spatial control of large herds of cattle through virtual fencing, to protect environmentally sensitive regions from damage.

Our planet is at risk of significant and irreversible damage. Increasing population levels and rapid natural resource consumption place an immense strain on our environment. Given clear evidence of significant changes in global climate conditions affecting a wide range of ecosystems, we must find ways to better manage our natural resources if we are to sustain our lifestyle.

Our work focuses on protecting environmentally sensitive areas threatened by damage from cattle herds. Many areas exist in which installing conventional fencing is cost and labor prohibitive, such as along river banks, scattered riparian areas, or steep terrain regions. Such areas are either large areas inappropriate for grazing or sensitive areas where cattle can cause significant damage, such as erosion along river banks or the destruction of valuable plant species in riparian zones. With an estimated global population of more than 1.3 billion cattle covering grassland areas totaling 10 million square km, the global impact of animal agriculture is enormous and poor livestock management can result in significant and widespread environmental degradation in sensitive areas.

Wireless sensor networks (WSNs)—large networks of embedded devices, containing microcomputers, radios, and sensors—provide the platform for a low-cost, radically new instrument to measure and understand the natural world. Several recent studies have focused on building reliability into long-term, environmental sensor networks, and others have focused on embedding mobile nodes with animals and tracking them. Our systems not only monitor herds and the surrounding environment but also can change animal behavior to assist environmental stewardship. We achieve this through virtual fencing—keeping cattle away from selected areas without a physical fence. This article addresses the problem of sustainable agriculture and presents our use of embedded-device networks to protect environmentally sensitive areas.

Observing Animals and the Environment

Previously we developed a large-scale, outdoor pervasive computing system that measures the state of a complex agricultural system. We designed the system to measure a wide range of variables to simultaneously try and understand the state of climate, soil, pasture, and animals.

Virtual fencing extends our initial work so that actuation decisions are made in the network to support the stewardship of the surrounding environment. We focus on models for relating position, velocity, and inertial observa-
tions from animals to specific levels of an animal’s state. In particular, we focus on two classes of state: an individual animal’s behavior and an animal’s relation to a virtual fence line bordering an environmentally sensitive area. This article primarily deals with the latter state.

Our system comprises a network of mobile embedded devices (nodes) designed to observe the state of large cattle herds while monitoring the state of the surrounding natural environment. All mobile nodes can undertake actuation on the basis of observations made by the node or other network nodes. Figure 1 shows a high-level illustration of the path from observations to actuation.

To obtain observations from the environment, we started by using static-node networks that measure air temperature and soil moisture and in which measurements are multihopped back to base every few minutes. By deploying nodes in grid-like patterns, roughly 150 meters apart, we clearly identified pasture regions that hold high and low amounts of water content. To increase our observations’ spatial coverage, we investigated using small camera nodes that return compressed images of specific pasture areas. Our current work investigates the level of correlation between soil moisture measurements and camera observations of grass condition.

**Hardware**

We use a hardware platform that’s part of a family of devices known as Fleck, inspired by the original Berkeley mote (see Figure 2a). These devices incorporate several key design features that make the platform ideal for a wide range of applications, including outdoor, long-term deployments—our focus here. The platform uses a Nordic NRF905 transceiver with a theoretical maximum data rate of 100 kilobits per second. However, the realistic data rate is roughly half of this.

You can easily expand the platform by adding additional sensor interface boards (daughterboards), in which the expansion connectors for interface boards carry power (switched by the node), Serial Peripheral Interface (SPI) inputs, serial and analog inputs, and digital inputs and outputs. Figure 2 shows our virtual fencing system, in which each mobile node contains GPS, audio, and electrical pulse boards.

The animal collar (see Figures 2e–g) consists of a head harness and an adjustable nylon collar. The collar holds three waterproof boxes, one for the electronics at the top and two for the batteries underneath. Altogether, the two battery compartments can house 24 AA batteries, which provide 16,200 milliamperes per hour (mAh) of capacity. Speakers attached to the head harness play audio, and the box at the top houses the remaining electronics. Positioning the battery compartments at the base of neck acts as a counterweight to hold steady the electronics box on top of the neck.

**Software**

Figure 3a shows the architecture for the application software running on our mobile nodes. The system design lets us log all data locally for further postprocessing to a Secure Digital card, stream a compressed version of the trajectory data over environmental nodes when they’re in range, and remotely monitor the experiments’ status. The RX module also receives new fence positions sent out from the network gateway over the environmental network and onto cattle. The virtual fencing algorithm is the key module in the application layer.

The WSN operating system community splits across two broad approaches—event-based and thread-based systems—with healthy debates about the relative merits of each. We’ve developed our own operating system, FleckOS (FOS), which falls into the latter category. FOS provides a priority-based, nonpreemptive (cooperative) threading environment with separate stacks for each thread, which allows for a simple concurrent programming model without semaphores. All application software on both mobile and static nodes ran on top of FOS.
Virtual Fencing Protocol

Virtual fencing seeks to extend the basic principle of the commonly used electric fence. Instead of controlling animal location using a physical fence, we use a combination of auditory and mild electrical stimuli applied by a position-aware device worn by the animal. Strict animal ethics requirements guide all such experiments to ensure animal welfare. The ethics behind this approach parallel the principle behind conventional electric fences in which animals have a visual association with the fence location. With the virtual fence, a quiet acoustic sound identifies the fence’s location. When the animals cross this virtual fence, they receive a mild electrical stimuli. They quickly learn to associate this stimuli with the sound, which influences their future actions.

Virtual fencing isn’t a new concept—the first papers on the topic appeared in 1990 before commercial GPS was operational. In the late 1990s and early 2000s, researchers in the US studied small-scale experimentation with GPS positioning. Recent work has investigated the application of a broader range of stimuli types and their effects on animals’ abilities to learn fence locations.

We seek to expand recent experi-
ments by solving the remaining issues with virtual fencing—the ability to manage commercial herd sizes in a wide range of natural environments over long time periods. To achieve this, we emphasized improved techniques for applying stimuli to animals based on estimates of their behavior relative to virtual fence lines.

Assuming virtual fence lines are comprised of piecewise straight lines, we derive three main observations from the GPS measurements in Figure 3b in which \( v \) is the animal’s velocity vector, \( n \) is the shortest distance to the virtual fence line, and \( \theta \) is the angle between the animal heading and the virtual fence line. These three observations act as inputs for a behavior-based state machine (see Figure 3c), in which states are based on a finite set of known animal responses to virtual fence lines. Within each state, we’ve developed a different strategy for applying audio or electrical stimuli to get animals to leave the exclusion zone (EZ) in the most effective manner.

We found the flight-response state particularly interesting. This is a rare case, in which animals run into the EZ rather than pausing or turning back. When this happens, the system will automatically deactivate the virtual fence until the desire to rejoin the herd prompts the animals to cross back into the non-EZ.

**Experiments**

We performed a series of multiday experiments using embedded devices to keep cattle away from environmentally sensitive areas. Figure 4 shows our experiments, conducted at Belmont Research Station, a 3,260 hectare station on the eastern coast of Queensland, Australia. The research station is adjacent to the Fitzroy, a major river featuring numerous pasture types and native species. This area provided an ideal environment to test pervasive devices on environmental sustainability issues.

**Real-time monitoring**

Real-time monitoring of the system’s state was crucial for ethical reasons and to validate the system’s performance. So, we designed the system to spatially control the animal herds’ location and return real-time information about their state. We monitored the herd using environmental nodes that provided a multihop backlink to the base.

One of the first major uses of WSNs for animal monitoring was in zebra tracking as part of the ZebraNet project. In this system, animal GPS data taken every few minutes would hop in a peer-to-peer fashion to other animals when they came in range. (More sophisticated systems for ad hoc routing of data through large networks of mobile
cattle nodes have also been proposed to make a trade-off between the power used by animal-mounted devices and the power used by fixed sinks for data uploading.\(^{12,13}\)

Unlike the ZebraNet project, we wanted to return trajectory information from each animal as often as possible to let us closely monitor VF experiments during these early, long-term experiments. To achieve this, we developed an algorithm that performs online summarization of position data within the buffer, where the algorithm naturally accommodates data input (GPS sample rate) and output rate (opportunity to upload to sink) mismatch, and also provides a delay-tolerant approach to data transport. If the trajectory buffer is full, the algorithm discards those samples containing the least amount of information first.

Given our device’s memory limitations, we chose a buffer size of 15 position samples, which let us take position samples every 10 seconds, assuming that the animal nodes would sometimes disconnect from the static sink nodes for several minutes. Based on this procedure, our system backend lets us continually visualize the state of the herd within Google Earth (see Figure 5).

**System performance**

Our current experiments involve keeping herds of approximately 40 cattle away from environmentally sensitive regions. In our initial experiments, we defined virtual fence lines that separate acceptable grazing areas from sensitive regions or EZs. Figure 6a illustrates the results of a multiday trial and overlays all trajectories of animals near the fence line along with the locations where we applied audio and electrical stimuli. Because of the system’s learning process, animals would sometimes go as much as 5 meters into an EZ before turning around. In practice, we’d recommend placing a virtual fence line 5 to 10 meters away from a sensitive zone to account for the learning process as well as allow for the typical GPS error rate of plus or minus three meters.

Figure 6b shows another perspective of the system’s performance for an area of roughly 1.2 km × 1.2 km. This diagram provides a color map of various regions’ occupancy along a virtual fence line. It shows that cattle tend to group up when attempting to cross a virtual fence line. However, cattle generally spread out across larger areas in the allowable grazing regions. An area of occupancy roughly 500 meters into the EZ is the result of a rare case of flight response, in which two animals ran through the virtual fence line.

**Closing the Loop**

Earth observation data offers valuable, complementary information to sensor network measurements. Whereas sensor networks can provide data measurements at a very high temporal resolution, satellite earth observation systems such as those in Figure 7 can provide measurements at a broad spatial scale that wouldn’t be cost effective with ground-based sensor network technology. By combining these measurement sources, the opportunity arises to interpolate sparse observations to a much finer temporal resolution over the vast spatial extents made possible with satellite observation.

In the case of environmental virtual fencing, earth observation data provides the means to close the loop on the whole environmental management system. We now have access to increasingly sophisticated methods\(^{14}\) that can provide estimates of parameters—such as pasture species, biomass, quality, and height parameters—over large spatial extents, down to the finest spatial resolution of the multispectral data (for example, 4 m\(^2\) for the Ikonos satellite). Estimates of physical parameters, such as pasture growth rate,\(^{15}\) combine multispectral measurements with local meteorological data, such as rainfall, temperature, or soil moisture, in complex growth models that we can refine for particular pasture types in defined geographical regions.

Subsequently, we could use this information to identify overgrazing of pasture areas, ongoing damage to river

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**Figure 5. Google Earth interface used during virtual fencing trials. Data coming back over environmental nodes gives the position of cattle as well as their behavior state and status of actuation.**
banks, or signs of stress from overuse in riparian zones. As environmental sensor networks become more ubiquitous in both the static environment and on animals, we’ll be able to protect new geographic zones by communicating information over environmental sensor networks about new virtual fence lines. We could essentially move large animal herds across the landscape in a timely fashion to minimize the environmental damage while maintaining sufficient animal inputs.

Our experiments demonstrate the feasibility of spatial control of large cattle herds using sensor and actuator networks and provide a potentially new approach to environmental protection in cattle production systems. Despite these early successes, we will need to run longer experiments over several months to fully investigate the technical and animal science challenges that lie ahead.

Integrating these types of systems with earth observation information will help us better understand and manage the natural environment, and we’ll undoubtedly see these systems become more ubiquitous as issues around sustainable agriculture and environmental stewardship become increasingly important. As we gain confidence in and knowledge about the types of real-time decisions that sensor networks in the environment can make, we might well see a radical shift in the future management of farm enterprises.

ACKNOWLEDGMENTS

The authors thank Les Overs, Stephen Brosnan, and John Whitham for their assistance in hardware development, and Karina Tate and Chris O’Neil for their assistance in running experiments.


