Proceedings of the 2004 IEEE
International Conference on Robotics & Automation
New Orleans, LA • April 2004

Virtual Fences for Controlling Cows

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***Abstract*—We describe a moving virtual fence algorithm for herding cows. Each animal in the herd is given a smart collar consisting of a GPS, PDA, wireless networking and a sound amplifier. Using the GPS, the animal's location can be verified relative to the fence boundary. When approaching the perimeter, the animal is presented with a sound stimulus whose effect is to move away. We have developed the virtual fence control algorithm for moving a herd. We present simulation results and data from experiments with 8 cows equipped with smart collars.**

I. INTRODUCTION

In this paper we describe a robotic system for automatically herding animals such as cows in the absence of physical fences. The target for our control algorithms, i.e., the cow, has natural mobility so that actuation is not an issue. Our goal is to constrain the location of the animal. We rely on the animal's natural mobility to move, and provide a system that controls this motion in a way that is applicable to herding.

Herding is a very labor intensive activity. Cattle and sheep graze over large paddocks that are created using fences. A typical farm has several paddocks separated by fences. Animals are rotated frequently between paddocks to prevent overgrazing of any one pasture. This is a very labor-intensive activity that has not benefited from the technical revolution in automation, computing and communication. Farmers spend huge amounts of time and money fixing and maintaining fences. Herding the animals is done with large teams of humans over long periods of time. This is physically hard work, often carried out in extreme weather conditions.

We have developed algorithms and physical experiments that combine sensor networks with motion planning in order to eliminate the need for physical fences on farms. Our work can be viewed as some first steps toward automatically controlling the location of individual animals as well as the herd. Intuitively, virtual fences have the functionality of the wired dog fences but do not use wires and can be easily moved by networked programming. Our virtual fence methodology can also be used to monitor the grazing behavior of these animals in order to create models that will lead to better land and pasture utilization. This will optimize the resource utilization and provide automation support and ease the activities of animal farmers.

Our virtual fences combine GPS localization, wireless networking, and motion planning to create a fence-less approach to herding animals. Each animal is given a smart collar consisting of a GPS unit, a Zaurus PDA, wireless networking, and a sound amplifier. The animal is given the boundary of a virtual fence in the form of a polygon specified by its coordinates. The location of the animal is tracked against this polygon using the collar GPS. When in the neighborhood of a fence, the animal is given a sound stimulus whose volume is proportionate to the distance from the boundary, designed to keep the animal within boundaries. Cattle domain experts have suggested using a library of naturally occurring sounds that are scary to the animals (a roaring tiger, a barking dog, a hissing snake) and randomly rotating between the sounds. Our preliminary experiments indicate that cows respond to such an artificial force field of sounds by moving in the direction in which they are heading.

A static virtual fence can be used to enforce a grazing area for the animals. The virtual fence can be dynamic by automatically and gradually shifting its location. The result is moving the animal to a different location. The motion plan for shifting the fences is developed using paddock geography, where obstacles correspond to trees, rocks, rivers, etc. Our approach has then flavor of potential fields and is inspired by previous models for herding animals. Cows react to their environment by being attracted to, or repelled from various features in the environment. Cows are repelled from obstacles (such as real fences, rivers, rocks) to perform obstacle avoidance, and are attracted to other cows for protection as a herding instinct. The repelling forces have effect only over a short range, modeling the "flight distance" of the cow. Grazing behavior is modeled as a periodic force or random duration and direction (although generally straight, to match observations of real cows). The startle behavior of the virtual fence can be implemented as a large force that turns the cow very quickly.

To slowly herd the cattle, we move the virtual fence reactively over time. We avoid moving the fence "into" a stationary animal, since this may result in unpredictable behavior. Instead, the fence moves in the desired direction at a given speed provided that no animal is within a fixed distance of the fence. This implicitly relies on the random motion of the cows to move the overall herd.

The smart collars are tasked with the virtual fence coordinates and virtual fence motion plan using multi-hop ad-hoc networking because the pastures are too large for single hop messages to reach all the animals.

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We have implemented these algorithms in simulation and deployed 10 smart collars on cows at Cobb Hill Farms in Vermont. Our physical experiments targeted four issues: (1) collecting data to create a grazing model for the cows, which is used in the fence control algorithm; (2) collecting connectivity data and information propagation data, which is used to determine the multi-hop routing method for networking the herd; (3) collecting stimulus response data for individual animals; and (4) collecting response data for the virtual fence. Our preliminary results are encouraging. We believe that moving virtual fences can be an effective method for herding animals, but many challenging research issues remain open.

II. STATE OF THE ART

There are two fundamentally different approaches to controlling animal position: a physical agent such as a sheepdog or robot, and a stimulation device worn by the animal. In the first category there is the pioneering work of Vaughan[1] who demonstrated a mobile robot that was able to herd a flock of ducks to a desired location within a circular pen. In the second category there are a number of commercial products used to control domestic pets such as dogs. These typically employ a simple collar which provides an electric shock when it is in close proximity to a buried perimeter wire. This allows for a simple collar but requires an installed infrastructure which is prohibitively expensive (to install and maintain) for large scale agriculture.

The application of smart collars to control cattle is discussed in detail by Tiedemann and Quigley[2], [3] who were concerned with controlling cattle grazing in fragile environments. Their first work[3], published in 1990, describes experiments in which cattle could be kept out of a region by remote manually applied audible and electrical stimulation. They note that cattle soon learn the association and keep out of the area, though sometimes cattle may go the wrong way. Cattle learn to associate the audible stimulus with the electrical one and they speculate that the acoustic one may be sufficient after training. More comprehensive field testing in 1992 is described in [2] and identified issues about the need to train animals to associate stimulus with spatial restrictions. This issue is also discussed by Anderson[4].

The idea of using GPS to automate the generation of stimuli was proposed by Marsh[5]. GPS technology is widely used for monitoring position of wildlife. Anderson [4], [6], [7] builds on the work of Marsh to include bilateral stimulation, different audible stimuli for each ear so that the animal can be better controlled. The actual stimulus applied appears to consist of audible tones followed by electric shocks.

III. THE VIRTUAL FENCE ALGORITHM

To implement the virtual fences, we need a way to represent them and compare them to the cow's position as reported by the GPS unit. This representation should allow for simple computations. We must then decide what level of stimulus to apply based on the cow's position.

In our algorithms, a fence is represented by a point F_p and a normal vector F_n. The point F_p is given in (latitude,longitude) coordinates, although higher-level interfaces such as the GUIs described in Sec. V-B.3 use relative distances internally and convert to the absolute coordinates when sending the fences to the collars. F_p can be simply any point along the fence, and F_n points perpendicularly into the safe half-plane. If the fence is to move, it is instantiated with a non-zero velocity F_v, in m/s. The point is then moved as a function of time along the normal, $F_p(t) = F_p(0) + \gamma F_n F_v t$ (where γ converts from meters to lat/long coordinates).

This representation allows a simple calculation to determine whether the cow is behind the fence. The collar first computes the cow's position relative to the fence x_r by subtracting the F_p from the cow's absolute position x_a. The distance d that the cow is behind (or in front of) the fence is then computed as the dot product of x_r with F_n. If d is positive, the cow is in the desired region, while if it is negative, the cow is behind the fence. To compute the exact distance correctly, x_r first converted to meters, since the F_n is defined based on equal units in each direction. This is all done with nothing more complex than multiplication.

For most applications, several fences will be present. Since each gives a safe half-plane, setting up a number of fences with their normals pointing toward each other gives a polygon of free space. To do position checking in this case, the algorithm computes a d value for each fence, and reports the fence and distance that the cow is farthest behind (the most negative d). This is necessary to ensure the cow does not appear to be close to safety when it is in fact far behind another fence.

To present a stimulus, the simplest option is to produce a sound of a given volume when the cow goes behind the fence. This can be done by testing the sign of the cow's fence distance. However, the cows may be able to better understand the location of the fence when a graduated stimulus is used which gets stronger the farther the cow is behind the fence. This can be done by generating a sound with volume proportional to $-d$. Finally, a more complex procedure is to monitor d over time, and stop the stimulus as soon as the cow begins to move toward the desired region. This is done by keeping track of d_{max}. If the cow's current distance is smaller, a stimulus is not produced.

IV. SIMULATION EXPERIMENTS

To test the various virtual fence techniques, we developed a Matlab simulator that models the behavior of a herd of cows both with and without the virtual fence stimulus. We were inspired by Vaughan's duck simulator, but extended the animal model to account for the differences between the species as well as their environments. Most importantly, while we also use potential fields to model the effects of one animal's position on another's motion, we explicitly model the stress of each animal and use this to affect the animal's behavior. The animals have a two-state behavior model, walking and grazing, each with associated speeds and durations. In terms of motion, we use the potential force as a force on the cow, but model

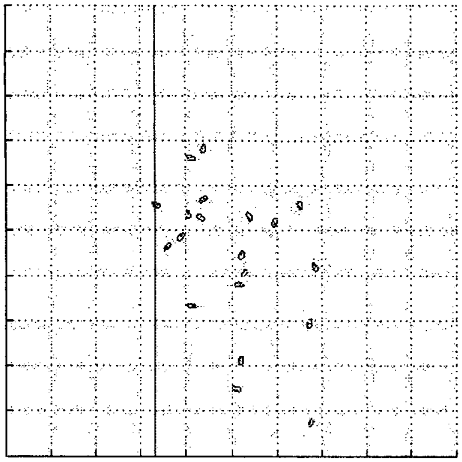


Fig. 1. Screenshot from the simulation of the virtual fence algorithm. Twenty cows are represented by ellipses, and one fence is shown as a vertical line.

the cows as non-holonomic and give them a maximum angular velocity. If the virtual force given by the potential fields is not closely aligned with the cow's current direction, the cow will turn until the force causes it to walk in a reasonable direction. A snapshot from the simulation, showing a 50×50 m area containing 20 elliptical cows, is presented as Fig. 1.

In the simulation, stress is created by the fence stimulus as well as the nearby presence of other fast-moving animals or isolation from the herd. An animal in a low stress condition will alternate between grazing and walking, choosing a direction of walking randomly but biased toward the direction it is pointing. Unstressed animals also exhibit very little herding instinct (as observed in the field) until they get very distant from each other. An animal that is experiencing high stress will move toward other animals, and will not resume grazing until its stress has gone down. The stress level of an animal decays over time.

In addition to using stress, the stimulus has an immediate effect on the motion of the animal. We have used two different models, each of which take inspiration from field observations. In the first model, a stimulus causes the animal to quickly turn approximately 90°. This behavior was also observed in [3]. In the second model, the cow walks forward for a short time when stimulated.

To test the algorithms against these models, we ran virtual fences on a simulated herd with widely varying parameters. The overall goal was to move the virtual fence slowly into the herd and test how quickly the herd moved away from the encroaching fence. This was tested with different values for the grazing speed and walking speed of the cows, the level of herd-attraction and the probability that a stimulus would have the desired effect. We found that the parameters affected the overall speed of the herd in front of the fence and the number of stimuli that were applied, but in all cases the herd did move in the desired direction.

We also tested both the orientation-aware fences and the orientation-neutral fences for both stimulus response models. Our expectation was that if the cow tends to go forward when stimulated, it would be necessary to sense the cow's orientation and only apply stimulus when the cow is pointing in the direction we wish it to move. In the simulation, this turned out not to be necessary, since after receiving the stimulus, the cow would have increased stress and return back toward the herd even if it initially went the wrong way. However, this is very dependent on the nature of the stress model.

V. PHYSICAL EXPERIMENTS

An aerial view of our experimental site at Cobb Hill farm is shown in Figure 2a.

A. The Smart Collar Hardware

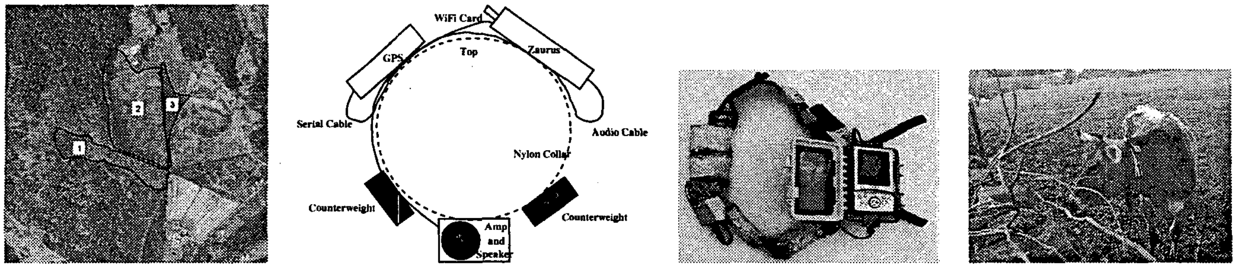
Figure 2b shows the components of a collar. The computer is a Zaurus PDA with a 206MHz Intel StrongArm processor, 64MB of RAM, with an additional 128MB SD memory card. It runs Embedix Linux with the Qtopia window manager. The Zaurus has a serial port and stereo sound port. A Socket brand 802.11 compact flash card provides a wireless network connection. An eTrex GPS unit is connected to the serial port of the Zaurus. A small Smokey brand guitar amplifier is used to reproduce sounds from the Zaurus audio port. A fully assembled collar is shown in Figure 2c. Figure 2d shows a cow wearing an early version of the collar.

The collar is not fully waterproof, though it is fairly water resistant since the GPS and audio amp are well sealed and the speaker has a plastic cone. The Zaurus is enclosed in a plastic case which gives it some water resistance, although the holes for the cables will allow some water in. The batteries in the Zaurus are the limiting factor in how long the collar will run, giving about two hours and forty minutes of life. The audio amplifier and speaker will produce about 90 to 100dB volume at a one foot range, depending on the nature of the sound.

The Zaurus has a custom kernel which allows running the WiFi card in ad-hoc peer-to-peer mode. This allows us to do multihop forwarding of messages for better connectivity within the herd. Ssh and scp are installed to allow remote login to the Zaurus and field upgrades of software. Each Zaurus is also configured with a shell terminal program and has a foldup keyboard for accessing and running programs directly from the console. A laptop computer is used as a basestation for sending commands to the collars. A Cantenna brand directional WiFi antenna is used with the basestation to improve communication range to the herd. Future versions of the collar will likely be built using an embedded processor with an integrated GPS unit, wireless network, audio, and digital compass and designed for extended battery life and full time outdoor use.

B. Software Infrastructure

The components of the software used in the experiments are as follows:



(a) (b) (c) (d)

Fig. 2. (a) Aerial view of Cobb Hill farm. The fields where experiments were conducted are outlined in black. North is up. The photo displays an area approximately 1 km on a side. (b) The components of the Smart Collar include a Zaurus PDA, WiFi compact flash card, eTrex GPS, protective case for the Zaurus, an audio amplifier with speaker, and various connecting cables. (c) A fully assembled Smart Collar, with PDA case open. (d) A cow with a collar.

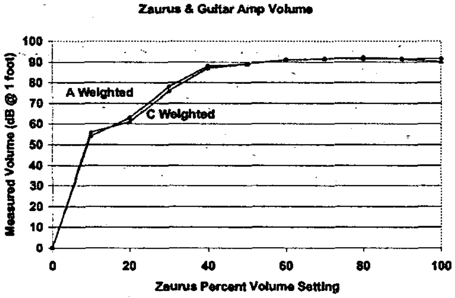


Fig. 3. Volume of sound produced for Zaurus volume settings. The "C Weighted" notation indicates the sound level meter has applied a filter to adjust for the frequency response of the human ear. The A Weighted curve doesn't have this compensation.

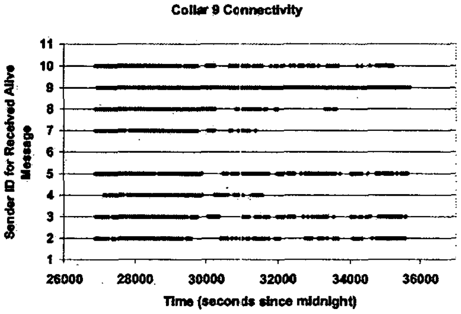


Fig. 4. Time history of Alive messages received by collar 9 in a typical experiment.

1) Fences and Sounds: A fence is essentially defined as a point on the surface of the earth, a "safe" direction, and a velocity. Thus fences are infinite lines with one half plane defined as being desirable for the cows to remain within. The velocity can be used to move the fence over time toward or away from the specified direction. Fences can be added or removed at any time and several of them can be created at once from definitions stored in a file. Several fences can be combined to create convex polygonal shapes. When the GPS readings indicate a cow has crossed a fence a sound is triggered. The sounds are stored in WAV format files and can be selected from a list to be played on the Zaurus audio device. The sounds used in our experiments included:

- car-crash
- cow
- cow-moo
- cymbal-loop
- dog-bark
- dog-bark2
- helicopter
- lion
- panther-roar
- storm-thunder
- storm-thunder2
- tiger
- wildcat
- wolf-howl
- air-brake
- high-pitch-squeal

The volume of sounds is controllable on a percentage scale from zero to 100 percent. All fences use the currently selected sound and volume, which can be changed without redefining the fences. Figure 3 shows the relationship between the Zaurus sound settings, which are expressed on a percentage scale, and the actual volume produced by the Zaurus/amplifier combination. The curve becomes flat around 40 percent due to the amplifier becoming saturated and starting to clip. This results in a progressively harsher sound as the volume is raised which is perceived as louder, but which is not actually louder.

The fence module also reads and interprets the GPS data which arrives every two seconds when the GPS has a good lock on the satellites. It also sends a periodic Alive message indicating the collar is functional.

2) Message Handling: Wireless network and Unix pipe messages are used to control the software. The same message format is used interchangeably for both message types. This allows messages to be sent locally, which is useful for testing, and remotely via WiFi for field experiments. All WiFi messages are multihop, being forwarded once by each collar, to improve range and connectivity within the herd. There are two message channels, one outgoing from a basestation and one incoming to the basestation. The outgoing channel is used for defining fences, manually triggering sounds, setting sound type and volume. The incoming channel carries "Alive" messages indicating a collar is active, and acknowledgment messages for receipt and proper interpretation of messages.

Figure 4 shows an example of the connectivity achieved between collars over time. In the first half of this graph there is very good connectivity during the time the cows were all together in the barn. Near the middle, around 30,000 seconds,

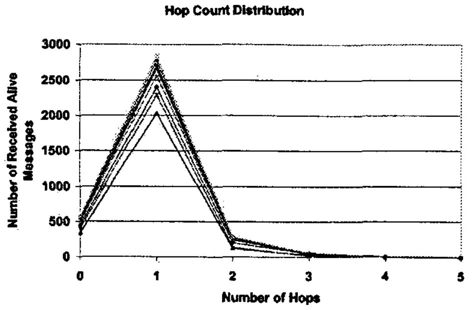


Fig. 5. Average number of hops for an Alive message to reach the basestation.

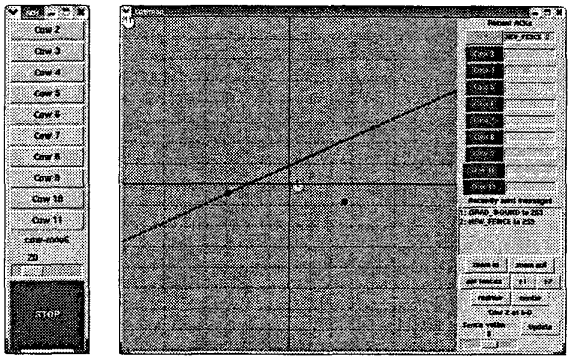
most connectivity is lost as the cows are walking end to end along a narrow path out to the field. On the right side of the graph connectivity varies as the cows wander around the field, their bodies and tall wet grass being the main causes of signal obstruction. Connectivity to collar 7 is lost before 32000 seconds because of an equipment malfunction.

Figure 5 shows the number of hops required for an Alive message to reach the laptop basestation during an experiment. Most messages are relayed only once to reach their destination which indicates good connectivity between collars. Dynamic graphs of the message routing have shown us that connectivity among the herd is usually quite good since the cows tend to stay near each other. Connectivity with the base station was problematic in that there is a tradeoff in staying far enough away to not influence the herd (they are very curious and friendly) and staying close enough to maintain radio contact. WiFi networks are essentially line of sight and are blocked completely at times by the cows bodies. Switching to VHF transmitters to improve basestation connectivity is an option we are considering.

3) Experiment Control: Both text and GUI control programs are used to manage the collars in the field. The text control program can be run on a Zaurus or Linux laptop and allows setting and deleting fences, setting type and volume of sound, and manually triggering a sound. The GUI control programs include the functionality of the text program, and add buttons for triggering sounds on specific cows, a map display showing current cow locations and status (i.e., relationship to fence boundary and whether a sound is playing), and a status display showing whether Alive messages have been received recently from each cow.

Figure 6 shows the control GUIs. The software programs on the collars and basestation are started and stopped with shell scripts for easy reconfiguration.

4) Logging and Time Synchronization: A variety of information is logged on the collars for experimental and debugging purposes including GPS location, GPS time, messages received, messages forwarded, and messages sent. All log entries are accompanied by a time and date stamp. To ensure accurate timestamps across the several programs in the collar system the Zaurus clock is initially synced to the GPS timestamp. Then a getimeofday() system call is used in the various programs to log the current time. The drift in the Zaurus clocks is sufficiently low to provide good time sync for the duration of experiments which typically last two or three hours. Log data is post processed using custom written scripts in a variety of languages.



1: GRAD_SOUND to 253
2: NEW_FENCE to 253

(a) (b)

Fig. 6. GUIs used on laptops to monitor field experiments. (a) Sound control GUI. Pressing a button triggers the current sound on a specific cow. Current sound and volume can also be selected. (b) Map control GUI. Shows the last reported position of each cow, whether it is currently playing a sound, and whether an Alive message has been received recently. Buttons and text boxes in upper right show recent command acknowledgments from collars.

C. Experimental Methodology

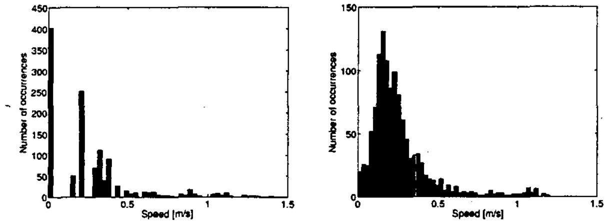
The sounds used to stimulate the cows were chosen to explore the effectiveness of a range of sounds. Animal sounds include dogs, wolves, large cats, and cows. We have disturbing sounds of a mechanical nature such as high-pitch-squeal, air brake, cymbal, helicopter, and car crash, and the natural sound of thunder. Some sounds such as the cow sounds were meant to be attractive sounds, while most of the sounds are meant to induce an avoidance behavior.

We used the methods of direct observation, video taping, and taking notes to evaluate the effectiveness of these sounds in producing desirable reactions. We made use of a sound level meter to determine the volume levels of sounds.

We used the GPS measurements of position and velocity to study the cows reaction to sounds. Did they avoid spaces beyond fences? Did they change direction? Did they change walking speed? Looking for correlations between sound events and changes in the GPS data was a primary analysis method, though we found it limited by the resolution and accuracy of the GPS data. Our observations and the GPS data were used to build a model of cow grazing behavior. Based on that model we then tried to control the behavior of the cows.

D. Acquiring a Grazing Model

Methodology: Our first field experiments were conducted to attempt to verify the two-state grazing model used in simulation. The first experiment involved five collars placed on cows which were released into field 1. These collars were populated only with the GPS devices and used their built-in



(a) (b)

Fig. 7. Histogram of speed of one cow over a period of 40 minutes. (a) Based on raw GPS differences (b) Based on a 10-second moving average speed. Note difference in vertical scales.

tracking function. However, this function is designed to track human hikers who tend to move at a higher and more constant speed, and so this did not give sufficient temporal resolution to test our models. A second experiment with eight full collars on cows in field 2 allowed for better collection of data, which we were then able to analyze. The eight collars were put on the cows in the morning, and the PDAs recorded GPS positions every two seconds until the battery ran out. Very few sounds were created during this experiment, and all the data presented in this section is from before any sounds were played, so this should be a good record of baseline behavior for this herd.

Data: In order to look at an appropriate sample of the cows' behavior, we present only the data from after the cows had reached the field. A histogram of the velocity for one cow is presented in Fig. 7. Each sample represents the difference in consecutively recorded positions, usually two seconds apart. Due to the resolution of the GPS data, we also present a 10-second moving average of the speed data. These plots represent data collected from one cow, but other cows in the herd display very similar overall velocity profiles.

Discussion: These data show that the cows have a wide range of speeds throughout the day, although the distribution is not exactly bimodal. Instead we see that they spend a large amount of their time moving quite slowly, and the rest of the time at higher, but differing, speeds. The average speed for the grazing behavior is under 0.2 m/s — this is too slow to be reliably detected by consecutive GPS readings, but can be determined from the smoothed speed data. For this cow, using the smoothed speed gives a fairly smooth distribution that peaks at about 0.16 m/s. Setting a cutoff for the grazing of 0.4 m/s gives a mean grazing speed of 0.167 m/s. The cows also spend a significant time at higher speed, presumably walking from one grazing spot to another. This behavior takes place about 15% of the time (183 raw samples or 165 smoothed samples above 0.4 m/s from 1200 total samples). However, the walking takes place at a fairly uniform range of speeds up to 1.25 m/s, rather than a single walking speed as originally supposed.

E. Individual Response

Methodology: In all field experiments we visually observed the behavior of individual cows, both away from the herd and when amongst the herd. We often video taped moments of interest and have the data logs from all experiments as a basis for analyzing individual behavior. GPS velocity data was also used to correlate stimulus events with changes in velocity.

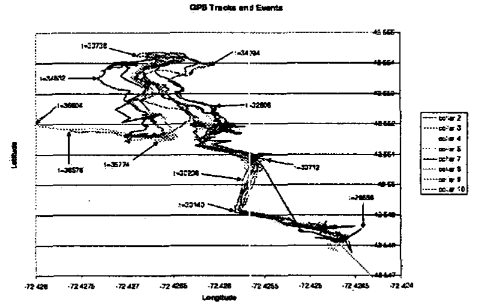


Fig. 8. GPS position track of eight cows, moving as a herd, over time. A few timestamps give some sense of how the cows wandered with respect to each other.

Data: Figure 8 shows a GPS location track for eight cows moving as part of a herd of 14 cows over time. They start out in the barn, follow a path to the field, and then wander to the far side of the field and back. In addition to the position tracks, the timestamps on the graph give a rough idea of how the herd moved and how spread out they were over time. For an idea of scale, the trek from one end of the field to the other covered a distance of about 300 meters.

A single sound sometimes had an effect on some of the cows and had no effect when tried on other cows. Some cows never reacted to sounds, while others were more sensitive. Observed reactions to a stimulus sound varied widely and included stop eating and look up, no reaction, stop eating, look up, then walk a short distance, usually forward, etc. (see Table I).

The velocity of an individual can be derived from the GPS tracking data to discover if a cow reacted to a sound stimulus by changing speed. Figure 9 shows a time history of the speed for a cow in our second experiment. The asterisks denote when a sound was played. In this case there seems to be a good correlation between sound events and the cow being in motion. However, some of the animals responded in a less correlated way. Two difficulties in interpreting this kind of data are, first, cows may already be in motion when stimulated, and second, the GPS data is very coarse in time (a reading every two seconds) which makes it difficult to judge if the cows motion was actually in reaction to the stimulus.

Table I shows some of the observed responses. Time increases from top to bottom in the table. Orientation and reaction direction are specified using "hours on the clock" notation where noon is North. Volume is percent volume setting on the Zaurus. We generally noted that repeated and louder sounds were more effective in eliciting a response. Cows would often react to the first instance of a sound and then not react to further instances. Waiting a half hour would sometimes result in them reacting again to an initial sound.

cow	orientation	sound/volume	react direction	react magnitude	comments
10	6	air/50	6	1 step	rapid 3 in a row, startled
10	6	air/50	-	-	2 in a row, nothing
10	6	dog/40	-	-	lifted head, looked to one side
10	6	dogx4/50	12	6 steps	walked forward while sound was on
3	-	air/40	-	-	very startled, shuddered at each sound
3	-	air/26	-	-	no reaction
3	-	air/60	-	-	no reaction
3	-	air/80	-	-	no reaction, habituated ? (we were close to the cow)
3	-	dog/50	-	-	no reaction
8	12	airx6/50	12	walked	started walking for duration of walk (initial 2s delay), actually moved toward us
8	12	airx6/50	-	-	no reaction (her back to us)
8	12	cymb/50	12		walked for duration
8	12	dog/50	10		cow and neighbour moved
8	12	dog/50	-	-	no reaction
8	12	cymb/50	-	-	no reaction
8	12	hiss/50	-	-	no reaction
8	12	crash/50	-	-	no reaction, neighbours looked up
8	12	air/100	-	-	flicked her tail
8	12	dog/100	-	-	no reaction

TABLE I

OBSERVED REACTION TO STIMULUS.

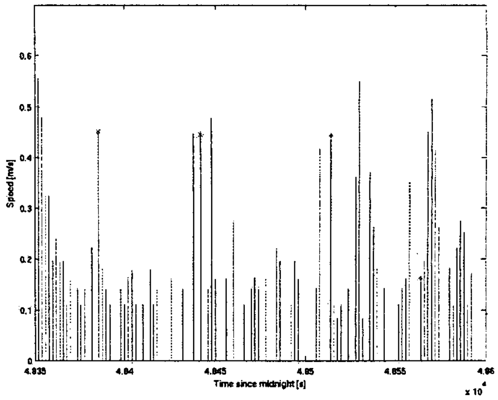


Fig. 9. Velocity of cow 10 versus time with sound stimulus events noted by asterisks. There appears to be good correlation between sound events and cow motion.

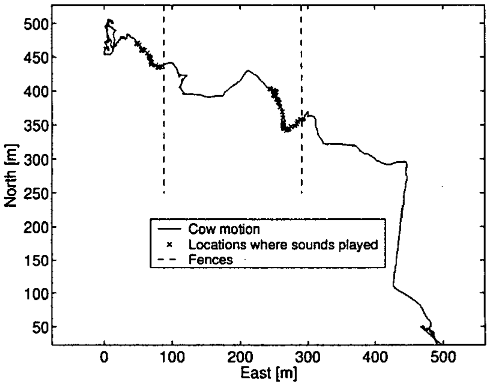


Fig. 10. Trace of the position of cow #10 during an experiment with two virtual fences. The cow started in the barn, at the SE corner of the plot. Locations where sounds were played automatically are shown. The long straight line to the north is the walk from the barn to the field, which is not considered in our analysis. After the first fence (to the east) timed out, no sounds played until a second fence (to the west) was created.

Discussion: Some cows definitely reacted strongly to a sound stimulus, though they often quickly became inured to it, and stopped reacting. The orientation of the cow before the stimulus was applied played a role in determining what direction a cow moved, if it moved. Further research into effective stimulus methods and into invoking directional behavior are needed. Much louder sounds may be more effective. Sounds accompanied by something visible such as a puff of smoke may be more effective and provide some steering capability.

F. Virtual Fence Experiments

Methodology: In the final field experiment, we used a total of six collars to test the effects of the virtual fence on the herd. These collars were put on the cows with one virtual fence already present, allowing us to be sure that the fence would be present even if we experienced communication failures. The cows were sent into field 1, with a north-south oriented virtual fence located across the paddock about one third of the way up. We observed the cows' reactions visually to supplement the logged data. After the cows had moved through the preset fence and the fence had timed out, a second north-south fence was instantiated near the top of the paddock (approximately under the "1" label in Fig. 2). Both fences used the graduated volume algorithm, with a value of 7%/m for the first fence and 5%/m for the second.

Data: Of the six collars, two performed very well for the duration of the experiment, two performed well but for a shorter time (perhaps due to battery failure) and two had poor to nonexistent GPS signal, probably due to rotation of the collars on the cows' necks. Figure 10 shows data from one cow's collar over the entire experiment. Both fences are shown here relative to the cow's travels in the field. This figure shows the sounds being applied at the correct locations for both fences. We also show a closeup of another collar's data, showing that the fence worked correctly over multiple crossings, with the fence timeout resetting as desired. In addition, to analyze the effects of the fence, we looked at the speeds of all the cows during the times sounds were being played relative to the rest of the time.

Discussion: Our visual observations were that in general, the cows noticed the sounds, but either ignored them or did not make the desired association with their position. For two of

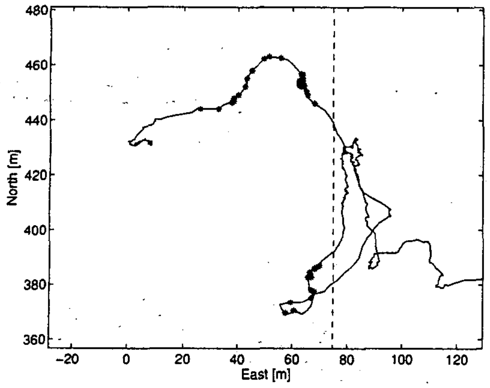


Fig. 11. Trace of the position of cow #9 during the virtual fence experiment. A small portion of the experiment is shown, during which the cow walked past the fence on two separate occasions, showing correct behavior of the virtual fence algorithm.

the cows, we observed the animal stop grazing when the sound was played, look up and walk slowly in a different direction. However, this new direction was not sufficiently different to take the cow into safe territory, and further sounds seemed to be ignored. We also observed one cow essentially ignore the sounds entirely. We were told that the cows tended to be motivated to reach the top of this paddock, especially first thing in the morning, and this motivation may have been too strong for the sounds to overcome. However, the second fence nearer the top of the hill was also not effective at keeping the animals on the desired side.

We also analyzed the logged data for the two cows that recorded good data for both fences. For both cows, the logs seem to indicate that the first fence slowed the cows' progress toward the top of the hill. This was determined by comparing for each cow (1) the cow's speed between entering the field and reaching the first fence and (2) the cow's speed while the first fence was causing sounds to be played. For cow 10, the average speeds for these two time periods were 0.380 m/s and 0.255 m/s respectively, and for cow 9, 0.590 m/s and 0.388 m/s respectively. For both, this difference is significant at the 0.01 level using a t-test, and the form of the speed distributions for these time periods looks quite similar. Later speed data is less convincing. For cow 9, after the first fence stops making noise, up through and including when the second fence makes noise, its speed did not change significantly, whereas for cow 10 there was a speed increase between the fences and decrease for the second fence. For both cows, once they had reached the top of the field, their speed and range decreased significantly (again, using a t-test with a 0.01 significance level), both just under 0.2 m/s on average, similar to the grazing speeds seen in the earlier experiment.

VI. CONCLUSION

It is obvious that the range of sound stimuli we tried were not very effective, although we did observe some reactions. Though we were aware of other research showing good response to electric shock type stimuli, we were faced with some fairly stringent requirements in our use of a stimulus. One was an admitted squeamishness on our part in shocking cattle. More importantly, the cows we worked with are a small herd of dairy cattle owned by a cooperative and are very like pets, with individual names. Shocking peoples pets was not an option, and might have had ramifications in milk production. Legal requirements by Dartmouth University also led us to choose a sound stimulus for our initial tests. In our future work we plan to run experiments with beef cattle on an open range in Australia. These animals will be rather different from the Cobb Hill dairy herd, since they are semi-wild (they see people perhaps every six months) and are not habituated to farm life, needing to protect themselves from predators for example. Input from animal behaviorists will be sought in designing an effective collar system for exploring our virtual fencing algorithms.

Acknowledgments

The authors would like to thank Simon Holmes a Court for inspiring us to think about this problem and for great technical insights into cows nd herding. Our cow domain knowledge is provided by Bud and Eunice tockmanship School (stockmanship.com) who teach low-stress cow herding control to farmers, Heytesbury Beef Australia and Cobb Hill Farms, Vermont. We especially thank Steven, Kerry and Paul at Cobb Hill for their assistance and enthusiasm and the use of their cows for these experiments. We thank Lorie Loeb for facilitating our work. Tom Temple assembled the cow collars. Jenni Groh provided invaluable advice on the experimental procedure. The experimental part of this work has been done under protocol assurance A3259-01 given by the Institutional Animal Care and Use Committee (IACUC) of Dartmouth College.

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