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.
A. Related Work

II. The Virtual Fence Algorithm

III. 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 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 [1]. 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.

IV. Physical Experiments

A. The Cobb Hill Farm

An aerial view of Cobb Hill farm is shown in Figure 2. The three fields in which experiments were conducted are shown outlined in black. Field 1 is a long narrow field on the side of a steep hill, the top of which is on the left in the photo. There are two strips of bushes and trees dividing the field into three parts. The cows can walk around the dividers to reach the higher pastures. The trees in the dividers and the trees around the edge of the field provide shade. Figure 3a is a view of field 1. Field 2 is a larger field with much more open area. It is also on the side of a hill, the top of which is the left edge of the field in the photo. Trees around the West and South sides provide shade. The field is open with few obstructions (a stand of trees near the north end and a few steep inclines.) Figure 3b is a view of field 2. Field 3 is a narrow pasture that
(a) (b) (c)

Fig. 3. Photos of fields at Cobb Hill used for experiments. (a) View of field 1 from the top of the hill looking East. (b) View of field 2 looking West. (c) View of field 3 looking North.

Fig. 2. 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.

gradually widens out. Trees on the east edge provide shade. The land in field 3 is relatively flat with no obstructions to movement. Figure 3c is a view of field 3.

The entrances to all three pastures are located where they all join. The farm buildings, including the barn where the cows are sheltered, can be seen near the bottom edge of the photo, beneath the large white trapezoidal areas (which are crops). A water tank is located half way up field 1 on the South side, and at the entrances to fields 2 and 3.

The cows are let out early in the morning, between 7 and 8:30am, and return in the evening around 5pm. Their habit is to wander fairly quickly to the far end of each field, and then wander around slowly till evening.

B. The Smart Collar Hardware

Prototypes of a Smart Collar were constructed using commercial off-the-shelf components that are readily available. Figure 4 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 Qttopia 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 ??.

Figure ?? 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. This can be used to best effectiveness by putting the Zaurus to sleep and having its calendar program wake it up at a preprogrammed time. 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 audio amp goes into a high impedance mode when not in use or when the battery runs out, causing a periodic buzzing noise to be picked up from the GPS serial cable, which might be disturbing to the cows. For this reason the audio amp has been slightly modified to change its input impedance to reduce the noise crosstalk. 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.

C. Software Infrastructure

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

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. 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 active, and acknowledgment messages which indicate a command has been received and properly interpreted.

Figure ?? 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, 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 ?? 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 ?? shows the control GUI’s. 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 sync’d to the GPS timestamp. Then a gettimeofday() 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.
D. Experimental Methodology

The sounds used to stimulate the cows were chosen to explore the effectiveness of a range of sounds. Thus we have animal sounds including 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 we have 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 also made use of a sound level meter to understand what volume levels of sounds we were producing. 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.

E. 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 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. ?? 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.

F. Individual Response

Methodology: Data: Discussion:

G. 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 ?? 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 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.

V. CONCLUSION

We have a great project!

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