A Mobile Sensor Network Using Autonomously Controlled Animals

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1. Introduction

Recent research has demonstrated that it is possible to use wireless communication to deliver brain stimulation to guide the movements of rats through a variety of terrains [1, 2], by stimulating multiple brain regions to produce stimulus cues for various commanded movements [3], and also rewards to reinforce these movements [4, 5]. The rats can be controlled not only while in direct line of sight of a human controller, but also by teleoperation, using signals transmitted from a wireless video camera mounted on the animal's backpack. Remotely guided rats or other animals are ideal for search and rescue operations because they are highly adept at negotiating difficult 3D terrain, in both light and dark. Since these are natural functions, one can easily elicit such behaviors in the guided rats by simply instructing them to go left or right while moving through spaces of arbitrary difficulty, complexity and novelty. The animals autonomously choose their own methods for traversing particular obstacles. Primarily for these reasons, they can be more effective than mechanical robots in search and rescue applications. They can also be trained to detect and home in on specific sensory targets, allowing them to be used as biosensors.

Applications of this animal sensor network have great importance to society, including natural disaster recovery (finding trapped people and hazards), homeland security (search for explosives, bio-agents, etc. in containers, cargo ships), military operations (e.g. minesweeping). Although current experiments are with guided rats, similar training and control methodologies can be developed to guide other types of animals. The network technology and sensor data processing algorithms will also be applicable to sensor networks using robots

2. System and Operation

Presently, a human operator must be within the radio transmission range of a rat to manually guide the rat. For search and rescue missions as well as other applications, one must be able to deploy many rats and autonomously guide and coordinate them. We develop technologies that enable the set-up and operation of a mobile sensor network consisting of a coordinated set of trained animals and possibly mechanical robots, remotely guided by a command center. In the targeted search and rescue application, teams of animals (and possibly robots) would be sent into a disaster site, looking for human survivors or other targets, and sending the captured information back to the command center. Each animal will carry a backpack, containing a microprocessor, a wireless transceiver, a video camera and other positioning sensors (e.g. compass and GPS), as well as a battery. The wireless transceiver will enable uploading sensor data to the command center, and downloading guidance command to the animals. The microprocessor will execute autonomous control algorithms to steer the animals to follow desired search paths and to generate appropriate "reward" signals, based on animal motion trajectories deduced from the video and other sensor data. The sensor data will also be analyzed at the command center, to visualize the disaster site, conduct path planning for the animals, and to initiate rescue efforts when necessary. Small animals such as rats can only carry limited weight (100 grams) and have limited running time (2 hours with periodic rest). Therefore, only low-weight and low-power devices can be installed in the backpack, and any locally executed computation algorithms must be extremely simple. These are unique challenges facing the design of the system.

2.1. Network Architecture and Task Allocation Among Sensors

Given the absence of fixed network infrastructure and the very short wireless transmission range typical in such applications, communications between the animals and the command center will be conducted using an ad hoc network infrastructure, in which adjacent animals will help relay the information. To reduce the bat-

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tery load on each animal and the complexity of guiding many animals simultaneously, we assign different tasks to different animals. *Seekers* are trained to use olfactory and other senses to find a particular kind of target, e.g. people in the rubble, explosives, and drugs. Seekers carry a camera and a low power wireless communication system. They will transmit the visual and other sensor data at low power to nearby followers who will re-transmit this data at higher power through the network. *Followers* are trained to closely follow a seeker everywhere. They receive low power high bandwidth (e.g. uncompressed) signals from their seeker, process (including compression) them, and then transmit them through the network at higher power. The followers' purpose is to off-load power and weight from the seekers. Thus, while a seeker carries a video camera, its follower could carry a GPS device (which helps to locate the seeker as well as its follower). *Relays* form a chain of repeaters to ensure the connectivity between the seeker/follower and the command center. Their sole purpose is to help relay the sensor information from the seekers back to the command center, rather than to search for desired targets. In addition to animal relays, stationary mechanical relays can be jettisoned by animals or put in place by other means. From the network perspective, we do not distinguish between a seeker and its follower, and rather consider the pair as one node.

2.2. Training and guidance for different animals

With the task allocation among animals, regular teleoperation is necessary only for the seekers. Seeker animals will be guided to search through a treacherous field and possibly go into holes. This will be done mostly through the autonomous control algorithm running on their backpacks (which will generate both motion commands and reward stimuli), but external teleoperation will be invoked when necessary. On the other hand, the follower and relay animals will be trained to maintain radio connectivity with their neighbors and will be rewarded for staying in radio contact with their neighboring nodes. A follower has a pre-assigned seeker that it must follow closely, whereas a relay needs to discover its neighbors and moves in a way such that it is always connected with two or more neighboring nodes. The controllers in their backpacks will help to guide them to stay a proper distance from their neighbors and regain connectivity once lost, with minimal guidance from the remote center.

3. Wireless Network Communication

The wireless network communication of this system will address several unique challenges imposed by the need for the network of seeker and relay animals to configure itself, the harsh radio propagation environment, tight constraints on equipment size and weight, and the critical importance of battery energy conservation. To meet these challenges, a cluster of interrelated research studies, including network topology design, routing algorithms, media access control techniques, radio resources management, radio propagation modeling, and mobility modeling, will be comprised. The wireless communication investigations will interact closely with the studies of animal behavior, animal control, and sensor data processing and transmission.

3.1. Network Topology and Information Routing

Routing in ad hoc networks is one of the most active areas of research in wireless networks. Existing routing protocols can be roughly classified as proactive or reactive. Based on the operation mode, a protocol is proactive if it attempts to maintain a consistent view of the entire network and compute up-to-date routes to all other destinations. On the other hand, a protocol is reactive if it only performs route discovery for a destination when there is data to be sent to that destination. Location-aware routing can reduce the routing overhead when the location information is available. All these possible types of routing will be investigated for our system. In the animal sensor network, there are typically two kinds of messages: sensor data (e.g., video or pictures captured by the seeker) and control messages. Control messages are short, and may need to be sent frequently between the control center and the animals and among groups of animals. The destination of a control message can be any rat. Data messages are long, and are sent only from seekers to the control center. Both data and control messages have latency and loss constraints. Given these differences, it may be best to use different routing algorithms for control messages and data messages. Routing schemes, which should meet the special requirements and be simple and efficient enough, are under investigation.

3.2. Transport protocol

In a departure from ad hoc networks in other studies, the network topology of this sensor network will be controlled. The simplest topology is one-dimensional, with a chain of relays between each seeker and the con-

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trol center. However, a more complex topology including redundant paths may be desirable from the point of view of robustness and efficiency. In previous work [9, 10, 11, 12], it has been shown that multipath transmission improves the quality of the received signal. We will investigate if multipath transmission is achievable and helpful in our special system. One difference between our system and the usual wireless network is that while it is desirable to deliver the sensor information in a timely manner to the control center, delayed sensor data frames are still of some use because these frames can be archived at the control center for later review and backtracking to make sure the search is complete. We therefore propose that packets be cached so that if the network is temporarily partitioned, the cached packets can be retransmitted when connectivity is restored [13].

4. Backpack Prototype Development

We have designed and implemented the hardware of backpacks and set up a simple wireless ad hoc network by using static routing. In future work, we will implement the proper dynamic routing algorithm in the backpack by software. The current backpack is still too heavy for a rat to carry. However, it is light enough for a bigger animal, and we believe that the weight can be further reduced by current or future integration techniques. The following devices are used in our backpack.

1) Cerfcubes from Intrinsyc Software

Intrinsyc software provides IBM PowerPC based Cerf boards which are based on the Linux 2.4 kernel. The CerfCube 405EP is a platform with an IBM 405EP microprocessor and a Netgate mini PCI card. 802.11b WLAN protocol is used for wireless communication.

2) Axis 205 network camera from Axis Communications

Axis 205 is a network camera based on Linux. It has its own IP address and a built in web server.

3) NetGate EL-2511 MP Plus 802.11b miniPCI card

The cubes by Intrinsyc are not provided with any wireless accessories. We select the NetGate EL-2511 MP Plus 802.11b miniPCI card, with Intersil PRISM 2.5 chipset.

4) Antennas

With an antenna in each cube, two cubes can hear each other within a distance of 6 feet.

A simple network with a camera, two cubes and a laptop has been set up as follows. The network camera is linked by a cable to cube1. In the real network, the camera will be carried by the seeker, cube1 will be carried by the follower, and the link between them should be wireless. In future work, we will attach the camera to an 802.11b wireless card. Cube2 serves as a relay between cube 1 and the laptop, the control center. This network is currently operational and the video captured by the camera can be transferred and shown on the laptop.

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