A Mobile Ad Hoc Bio-Sensor Network

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***Abstract*— Recent research shows that animals can be guided remotely by stimulating regions of the brain. Therefore, it is possible to set up an animal mobile sensor network for search and rescue operations. Applications of such an animal sensor network have great importance to society, including natural disaster recovery, homeland security and military operations. In this paper, The system architecture and operation is introduced, and major challenges and issues are discussed. Because of its unique challenge, a simple and efficient routing scheme is devised for this special ad hoc network. Each animal needs to carry a backpack to perform sensing and network communications. The implementation of a backpack prototype is presented, and a simple network is set up to capture and transfer video sensor data.**

I. 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 behavior in 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.

In this paper, we will first introduce the system architecture and major technical issues of the system design in section II, the routing in this mobile ad hoc sensor network in section III and then focus on the backpack hardware implementation in section IV.

II. System Overview

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 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, possibly 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 (about 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 in the design of the system.

A. Network Architecture and Task Allocation among Sensors

Given the absence of fixed network infrastructure and the very short wireless transmission range typical in such

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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 battery 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. A seeker carries a camera and a low power wireless communication system. It 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 them, and then transmit them through the network at higher power. The followers' purpose is to off-load power and weight from the seekers. *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. Figure 1 illustrates the operation of the proposed network.

B. 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.

C. Research Components and Technical Issues

Such a mobile sensor network with controlled animals consists of several inter-related research components that are summarized below.

(1) *Animal training and behavior modelling*, which develops automated training and rewarding techniques for guided rats to perform different functions.

(2) *Sensor data processing and transmission*. The video and other sensor data will be processed locally to deduce motion trajectories of seeker animals, based on which the autonomous controller can guide the animal movement. The sensor data (together with the estimated trajectory information) will also be sent back to the control center, to create a visualization of the explored site, which is necessary for high-level path planning and coordination of different seeker animals. In order to accomplish these goals, signal processing algorithms and simple video compression algorithms need to be developed. Due to the erratic and uncontrollable motion of the camera (mounted on the animal), these schemes will require considerable computation and hence power to reliably determine the motion between successive frames. On the other hand, since these operations must be done in real-time at the animal site using the hardware/software installed in the backpack, the designed algorithms must be computationally simple and robust to sensor noise, while meeting the performance objective.

(3) *Cooperative control of animal sensors*. Cooperative control techniques, which can autonomously guide and reward a large set of animals with different tasks, need to be investigated. The design of the control system depends on the obtainable feedback regarding the past trajectories of individual animals, radio connectivity between neighboring animals, and the location of neighboring animals. It also depends on trainable stimulus responses of the animal (what type of motion commands animal can respond to via stimulus cues), desirable stimulation profiles (motion guidance precision, reward frequencies, etc.). The control strategy for relay animals also depends on the optimal relay distances and motion patterns.

(4) *Wireless communications*. 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 problems, including network topology design, routing algorithms, media access control techniques, radio resources management, radio propagation modeling, and mobility modeling, need to be addressed.

In the physical layer, radio propagation characteristics, both in open fields and under rubble piles, need to be examined. Based on the resulting channel characteristics, how to position the relays and guide their movement will be investigated to provide good connectivity between seekers and the command

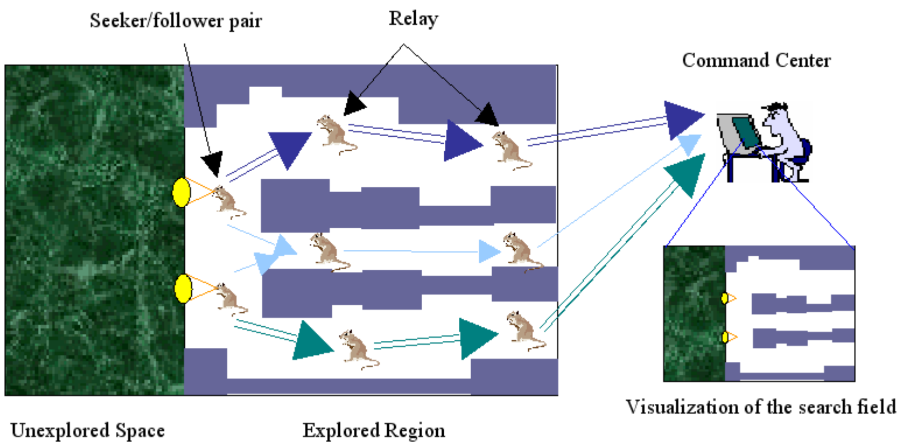

Fig. 1. Illustration of the animal sensor network.

center, while minimizing the number of relays and transmission power.

In the network layer, a simple and efficient routing scheme is needed for this special mobile ad hoc network. We will discuss this in detail in section III. Based on proper networking layer protocols, transport protocols will be investigated to withstand frequent link failures and dynamically changing link connectivity. One difference between this network to a usual sensor 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.

(5) *Backpack development*, which will be introduced in section IV.

III. Routing in the Mobile Ad Hoc Sensor Network

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 protocols will be investigated for our system.

In an 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. 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, are under investigation.

We consider flooding techniques for control messages. In flooding, when a node receives a packet, it first checks the sequence number of the packet. If the packet has not been received before, the node broadcasts it to all its neighbors; otherwise, it discards the packet. Clearly, this mode of routing uses more resources, since each node will forward the packet once in a connected network. However, given the short length and importance of delivering such messages quickly, this may be an acceptable cost.

For data messages, using location-aware routing can reduce the redundancy, so that a packet will be forwarded only by a subset of nodes in the network. An example is DREAM, a proactive, location-aware routing protocol assuming a flat-mesh network architecture [8]. It assumes that every node knows its geographical coordinates. A node stores the location of all other nodes in its location table and uses the table for packet forwarding. In our application, the overhead associated with broadcasting the location information in DREAM can be reduced because the direction of data messages is always from rats to the control center.

A simple routing algorithm we propose for data messages works as follows. In our sensor network, it is not practical to depend on GPS to get the location knowledge of animals, since the animal sensors may work underground or in an environment where GPS does not work well. Therefore, instead of using the exact location of each node in the system, we use the hop number to approximate the distance from a node to the final destination, typically the control center. We call this routing algorithm as hop-aware flooding.

When the control center sends a packet, which could be a control message or an acknowledgement for a data message, the packet will be forwarded to the nodes (animals) by flooding, as presented before. A *hop number* field is attached to the packet and set to 0. Each node in the system maintains its *distance* to the control center denoted by D hops. When a node receives a packet which is originally sent by the control center, it checks the *hop number* field. We denote the value of the *hop number* field of the packet by N. If $D > N+1$, set $D = N+1$. The reason to do that is because a node may receive packets originally from the control center by multiple routes with different hop counting, and the distance between the node and the control center should be the minimum number of hops a packet travels. However, the *distance* D should have a *life time* T, since the node may move further away from the control center and the distance may have to be updated by a larger number of hops. Therefore, when D is out of time, simply set $D = N+1$ for any N. Then, if the packet is forwarded according to the flooding policy, the *hop number* field of the packet is updated to D. By doing this, each node in the system will have the knowledge of how many hops it is from the control center. The selection of T is related to the mobility of the nodes. If the topology changes rapidly, T should be small so that D can be updated more frequently.

In the network, each data packet (originally sent by the seeker/follower) includes a *sender distance* field. We denote the value of this field as d. When the seeker/follower sends out a data packet, it sets d to its own distance from the control center. When a relay receives a data packet, it first checks the sequence number as in flooding to see if the packet has been received before. If yes, it discards the packet; otherwise, it further compares its distance D to the sender's distance d attached to the packet. If $D+L < d$, where L is a constant, it forwards the packet and replaces d by D; otherwise, it discards the packet. This process continues till the control center is reached. By doing this, a relay only forwards a data packet which is sent by a node further away (in hops) (when $L = 0$) or at most $L-1$ hops closer (when $L > 0$) than itself to the control center. Therefore, bandwidth is saved.

If each node always maintains its distance (in hops) D up to date, $L = 0$ will be sufficient for all data messages to reach the control center when the network is connected. However, since a node may move after it recent update of its distance D, and no node in its power range is closer (in hops) to the control center after it moves, a larger L will be necessary so that the data message can still be forwarded by someone. There is a tradeoff between the redundancy and the loss rate. In this paper, we define the redundancy as $\frac{W}{N}$, where W is the number of packet copies generated by relays and N is the number of

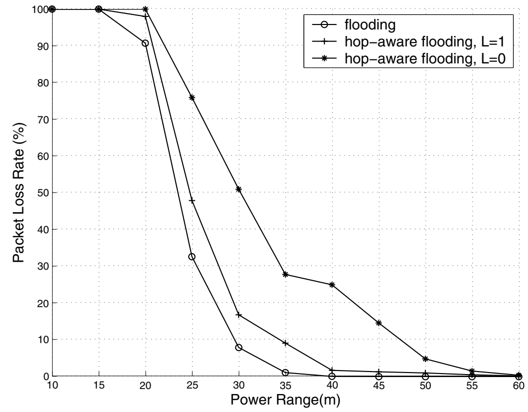

Fig. 2. The loss rate for different power ranges.

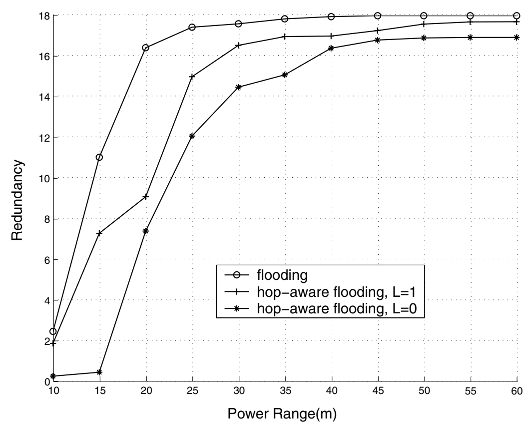

Fig. 3. The redundancy for different power ranges.

original packets generated by the seeker. For example, if the seeker has sent out 1000 packets and the redundancy is 20, the relays totally forward 20,000 packet copies. With a smaller L, the redundancy will be lower but the loss rate could be higher. When L increases, the loss rate will reduce while the redundancy will increase. The selection of L is relevant to the mobility and the power range of the nodes.

We simulated the hop-aware flooding scheme in an ad hoc network with 20 nodes in a 100m by 100m region and compared it to flooding. All nodes are randomly placed in the region initially. Each node first chooses a random destination in the region, and then moves toward it at a constant speed. When it reaches the destination, it makes a decision whether it will pause for a constant time interval (1.0 second in our simulation) or start another movement right away. Figures 2 and 3 show the loss rate and redundancy, respectively, of the hop-aware flooding (when L is 0 and 1) and the flooding. We assume that the moving speed of each node is 0.1m/s, which is close to the speed of a rat. We can see that when $L = 1$, the loss rate of the hop-aware flooding scheme is higher but close to that of the flooding, while its redundancy is lower.

IV. Backpack Prototype Development

We have designed and implemented an early version of the backpack and set up a simple wireless ad hoc network. 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 [6]

Intrinsyc software provides IBM PowerPC based Cerf boards which are based on the Linux 2.4 kernel. The CerfCube 405EP is a low-cost, high-performance, low-power reference design platform with an IBM 405EP microprocessor at its core. In combination with a Netgate mini PCI card, these devices become powerful devices which can communicate using the 802.11b WLAN protocol. The CPU board consists of 32MB flash memory and 32MB RAM. The boards also have an external Ethernet interface.

2) 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 the Intersil PRISM 2.5 chipset.

3) Antennas

Two cubes cannot communication with each other without antennas when the distance between them is more than 3 inches. When an antenna is used for each cube, two cubes can hear each other within a distance of 6 feet.

4) Axis 205 network camera from Axis Communications [7]

Axis Communications produces network cameras which are based on Linux. The model we used is the Axis 205 and has its own IP address and a built in web server. Its features, such as three different resolutions (up to 640 x 480) and a frame rate of 30 frames/second in all resolution modes, make it suitable for our application. The system consists of a 32 bit RISC CPU, a motion JPEG compression chip, works on a Linux 2.4 kernel and has 8MB of RAM and a 2MB flash memory. It can be directly connected to the Ethernet port of the Intrinsyc device.

A cube (a backpack without camera) is shown in figure 4. A simple network was set up with a video camera, a laptop (serving as the control center) and four relay nodes. Sensor data can be forwarded to the control center by using fixed routing, flooding, and a hop-aware flooding scheme. In future work, we will expand the network with more relay nodes and test its performance under different conditions.

Fig. 4. A cube to be carried by a follower or a relay.

V. Conclusion

In this paper, we introduce a mobile ad hoc sensor network using autonomously controlled animals. In this network, animals are allocated different tasks, so that a seeker/follower pair will capture the sensor data (e.g., video or pictures), and relays will help forward the data to the control center. Such an animal sensor network will have great importance to society, including natural disaster recovery, homeland security and military operations. A new routing scheme, hop-aware flooding, is devised for this special mobile ad hoc network. The performance of this new scheme is studied by simulations and compared to flooding. A backpack prototype which will be carried by animals has been implemented, and a simple network has been set up. In future work, we will expand the network with more nodes for testing under different scenarios, and further reduce the weight of the backpack to make it light enough for small animals such as rats.

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