StAR: Ad-Hoc Wireless Networking for Autonomous Multi-Robot Coordination

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Abstract—**In this paper we describe preliminary results from a collaborative effort between UCSC's Internetworking Research Group (i-NRG) and ITAM's Robotics Lab focusing on enabling multiple, autonomous robots to collaborate in carrying out special-operation type tasks such as disaster recovery and emergency response. To this end, we have been developing a distributed, multi-robot architecture with distributed vision and wireless ad hoc networking capabilities. We present results from initial experimentation while discussing future work.**

Index Terms—Ad-Hoc, Wireless, Networking, Multi-Robot, Autonomous

I. Introduction

For the past two decades, robotics has been an area of considerable research and consequently, impressive advances have been accomplished. However, in order for robotics to continue to have considerable impact in real world applications researchers still have to overcome a wide range of challenges posed by single robot design all the way to multiple, collaborative robot architectures. Moreover, such efforts are often highly multi-disciplinary, exploiting developments from various other fields, such as artificial intelligence, biology, software engineering, human-computer interfaces, etc. In particular, in multi-robotic systems, where robots collaborate in carrying out tasks, networking plays a crucial role as robots must communicate with one another.

In this paper we describe a recent collaborative effort between researchers in networking at UCSC and in robotics at ITAM. One of the long-term goals of the project is to develop new paradigms for the operation and coordination of multiple mobile robots targeting, in particular, emergency response operations such as disaster recover and rescue. These mission-critical applications can greatly benefit from the use of robots as the tasks to be undertaken in such operations are often highly life-threatening to emergency response crews. In this paper, we highlight not only the inter-disciplinary nature of this research but also point out challenges in the individual domains. In the networking domain, we are extending protocols developed originally for networks with uninterrupted connectivity with new capabilities to make them applicable to scenarios with frequent and long-lived connectivity interruptions. In the area of robotics, we are extending robotic architectures developed originally for RoboCup [1] by incorporating additional sensing, processing, and communication capabilities. We also present results from preliminary experiments we have conducted using four fully autonomous small-size robots equipped with a local camera and ad hoc networking capabilities executing a simplified surveillance application.

II. Search and Rescue

In recent years robots have demonstrated their usefulness in undertaking life-threatening human tasks. Among these, Urban Search and Rescue (USAR) [4] has been an area where robotics is starting to have an important impact [5]. For instance, robots can play a crucial role in searching and rescuing survivors trapped under buildings collapsed due to major disasters such as earthquakes. Challenges in these rescue operations are posed by factors such as the unstable nature of the collapsed structures, hard to reach spaces, lack of oxygen, and hazards resulting from fire, toxic gases, or other chemicals. To date, specialized sensory equipment has been used in assisting rescuers, yet this technology is mainly used from outside the disaster perimeter. In the case of rescue robots, currently they are often remotely operated, resulting in a number of limitations, such as:

(a) The number of robotic devices required in conducting a large-scale search and rescue operation is significant, requiring a large number of trained human controllers.

(b) Coordination between human-controlled, tele-operated robotic devices is hard, limiting the possibility of shared decision support systems.

(c) Poor environmental conditions, such as low visibility, make human maneuvering of robotic devices difficult.

(d) Tele-operation relies on continuous availability of robust communication channels and power sources, including the use of wirelines.

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In order to get closer to survivors, scientists have been currently experimenting with mobile robots of various shapes, sizes, and capabilities [6]. Robots can help in the overall search and rescue operation by producing maps of how to reach a survivor's location, helping in asserting survivors' conditions and existing hazards, etc. One unavoidable challenge is that search and rescue robots must become more autonomous, interacting with human controllers only for higher-level decision making. A key consideration in carrying out these rescue missions will be the ability for robots to communicate with crew members when far away or even if they are sporadically connected. Ad-hoc networking, i.e., the ability to relay communication through participating nodes, will play an increasingly important role in such sparsely connected, energy-constrained multi-robot systems. Another important consideration is the fact that sparse connectivity may mean that frequently there may be no direct path between source and destination. This implies that core functions such as network routing will have to be robust to frequent, possibly long lived connectivity disruptions.

III. Leveraging Related Products

From the robotics perspective, the Robotics and Biorobotics Laboratories at ITAM are involved in the development of biologically inspired models to test hypothesis on animal behavior and their linkage to neuroscientific studies. These models are helping the development of new adaptive architectures such as rat-inspired learning and its application to robot exploration [2]. Additionally, in the context of RoboCup, ITAM's Eagle Knights competes in a number of soccer leagues including Small-size and Four-Legged where robots are programmed and in certain cases also built by the participating teams. RoboCup also includes non-soccer competitions. One noteworthy example is a search and rescue venue known as RoboCup Rescue [3].

The i-NRG lab at UCSC is currently involved in several ad-hoc sensor networking related projects. Like the Eagle Knights Small-Size RoboCup team, these projects involve the integration of custom-built hardware with ad-hoc network protocols specifically designed for the environments in which they are used, as well as the data that is to be delivered. Experience with each of these projects, some of which are described below, is being leveraged into the Eagle Knights project.

The CARNIVORE system [7] (Carnivore Adaptive Research Network in Varied Remote Outdoor Environments) was born from the desire to further understand the interplay between coyotes, their predators and their ecosystem in the Santa Cruz mountains. Custom collars have been developed that contain a 3-axis accelerometer, GPS, storage space, and communication capabilities. Collared coyotes will continually sense and transmit data to static base stations deployed in the area, and the data will later be aggregated and used to analyze their behavior. Similar to the Eagle Knights project, the network topology is quite sparse, resulting in a network that is rarely connected. Similar mechanisms will be used to ensure that messages are delivered in a timely fashion to the sink nodes.

In Meerkats [8], we have been building a wireless battery-powered wide-area surveillance system incorporating both sophisticated vision algorithms and a power-management scheme (for lifetime maximization). Unlike the Eagle Knights project, the Meerkats network is static, allowing the use of more traditional ad-hoc networking. Detailed analysis of power consumption has enabled the network to be designed such that lifetime is maximized. Power monitoring enables a distributed resource manager to instruct nodes to turn on or off their components such as the wireless card and USB camera.

The SEA-LABS project [9] (Sensor Exploration Apparatus utilizing Low Power Aquatic Broadcasting System) has been designed to monitor remote coral reefs. It is also on battery power, and thus must adhere to strict power-consumption guidelines for sensing and communication. The fact that the system will be deployed in remote, hard to access regions mandates the need for minimal maintenance and extremely long lifetime. Furthermore, the harsh environment and large distance between nodes (up to 8km) requires that the networking be designed with reliability as a key consideration. A successful deployment in the Monterey Bay has provided initial data, and a full deployment in the Midway Atol is planned for the near future.

These are just a few examples of mostly sensor network systems, both static and mobile. In the specific case of multi-robot systems for disaster recovery and emergency response applications, robot teams collaborating in rescuing or reconnaissance operations need to be deployed in arbitrarily wide areas with tortuous terrain and subject to communication impairments such as interference, noise, signal fading, etc. Thus, new extensions to existing robots as well as wireless mobile ad hoc networking are required to take into account stringent and adverse environmental conditions in search and rescue scenes. Accordingly, the initial goal of the collaboration between ITAM´s Robotics Laboratory and UCSC's i-NR is to extend the existing multi-robot platform with local sensing and wireless, mobile, disruption-tolerant ad-hoc networking capabilities. In this paper, we describe the project's activities including some preliminary experimental results. is organized as follows. The organization of the remainder of the paper is as follows: Section IV describes extensions to existing ITAM's Eagle Knights RoboCup Small-Size architecture by adding local vision and ad-hoc networking capabilities; Section V discusses current work at UCSC in developing protocols for environments with episodic connectivity; Section VI presents preliminary results from an experimental testbed composed of static and mobile nodes evaluating the ad hoc networking protocols for frequent and long-lived disconnection; finally, Section Vii presents our concluding remarks and directions for future work.

IV. Multi-Robot Coordination

A major constraint in the small-size league architecture (illustrated in Figure 1) is the vision system, that receives images from cameras mounted on top of the field, processes them, and sends information to the robots on the field. This "global" vision system limits mobility of the robots to the soccer field while keeping them under full camera view. By providing a local vision system, i.e., robots equipped with their own cameras, we avoid this restriction. For this purpose we have extended our robot design to include a Web cam located where the dribbler and kicker used to be. The camera is connected to a Crossbow Stargate [10] as shown in Figure 2. The Stargate, which is also outfitted with an 802.11 wireless card, is a relatively powerful, small form factor, single-board computer that has found applications in ubiquitous computing and wireless sensor networking. It is based on Intel's 400MHz X-Scale processor and has 32MB flash memory and 64MB SDRAM and provides PCMCIA and Compact Flash connectors on the main board. It also has a daughter board with Ethernet, USB and serial connectors. The Web cam used is a Logitech QuickCam Pro 400 which is connected through the USB port; the 802.11 network interface is an Ambicom Wave2Net IEEE 802.11b compact flash wireless card. The operating system on the Stargate is the Stargate version 7.2, an embedded Linux system (kernel version 2.4.19).

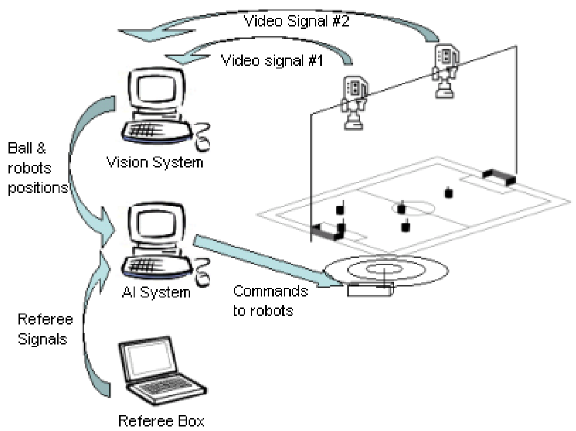

Fig. 1. ITAM's Eagle Knights RoboCup Small-Size league system architecture. A number of computers remotely control the state of the game. The Vision System receives images from the cameras mounted on top of the field and sends information about relevant objects to the AI System producing remote commands to the robots in the field. A Referee Box send game signals to both teams.

The original communication transceiver was replaced by a direct wire connecting the main robot board with the Stargate while moving the Vision- and AI System computations to the local Stargate. Since the Stargate runs a Linux-based operating system, porting previous robot code written in C did not become a major issue although not all functionality was required. The block diagram for the robot design is shown in Figure 4. Due to size constraints we took out the kicker and dribbler to make space for the local camera. The Stargate was put on top of the robot as previously shown.

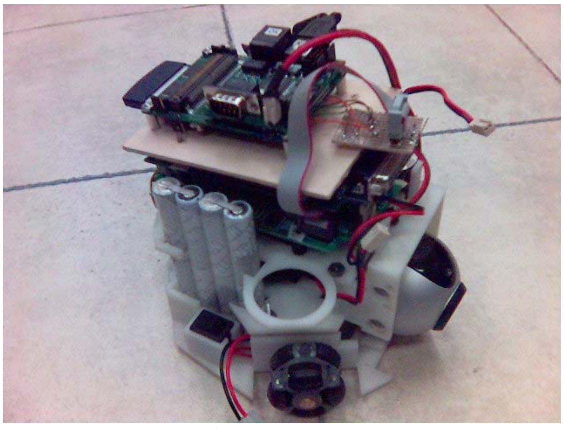

Fig. 2. Eagle Knights modified robot having local camera and 802.11 communication capabilities. The original robot architecture is maintained although replacing the transceiver with a direct linkage to the Crossbow Stargate (on top) managing wireless communication and local vision. Note how we replaced the kicker and dribbler with the camera due to camera.

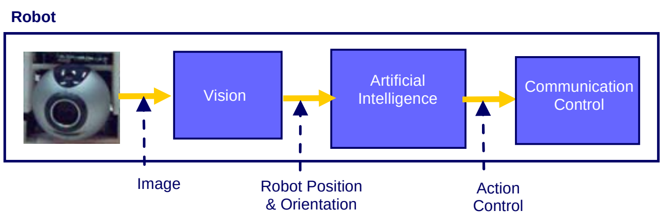

Fig. 3. Extended Small-Size robot architecture. Visual input from a camera mounted on the robot itself is processed by the Vision module to provide the AI module with robot positions and orientations. The AI module sends action command to the robot locally. Communication control is available for networking with other robots or a remote computer.

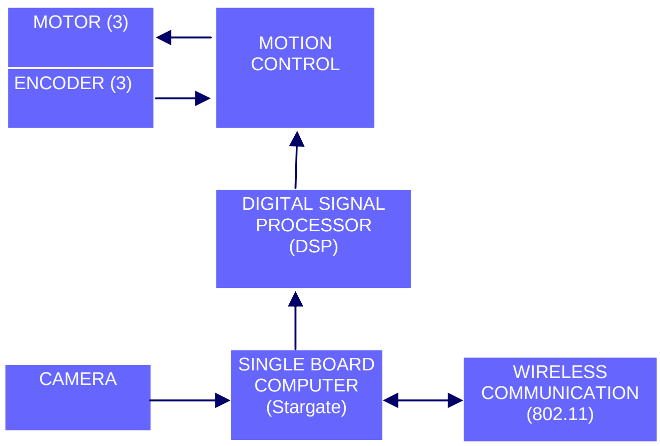

Fig. 4. Extended Small-Size robot block diagram. A DSP receiving remote signals via a wireless transceiver control three (or four) motors for omni-directional movement. Additionally, the DSP control a dribbler and a kicker control mechanism.

V. Wireless Ad-Hoc Networking

In the RoboCup Small-Size soccer league, robots are very close to each other on the field. This means that all robots are within transmission range of one another which makes routing of messages between computer and robot, or between robots, trivial; any robot can send a message to any other robot in a single transmission. For other applications, however, as the range of robot mobility is extended, nodes may be too far apart to communicate directly, requiring messages to be routed through intermediate robots to reach their destination. In such situations, known as multi-hop ad hoc networks, nodes must cooperatively establish routes and forward messages in order to maintain communication.

In terms of ad-hoc networking protocols, the Stargate used in our system architecture is shipped with AODV [11], the Ad hoc On-demand Distance Vector routing protocol. AODV has been designed under the assumption that end-to-end paths are available at least most of the time. In other words, it is assumed that the network is connected most of the time and that disconnections, when they happen, are short lived. However, as previously discussed, in some applications such as disaster recovery or emergency response scenarios, end-to-end connectivity cannot be guaranteed; in fact, it may turn out that the network is not connected during most of its operational lifetime. For this reason, we have developed StAR (Steward Assisted Routing), a routing protocol for networks in which links are often unavailable due to mobility or other types of disruptions (e.g., channel impairments). Below, we describe both AODV and StAR.

A. AODV

Unlike traditional wired networks, multi-hop ad hoc networks (MANETs) require a routing protocol that can respond quickly to node failures and topology changes. AODV is an example of an on-demand routing protocol. It establishes a route between a source-destination pair only when the source node has data to send to the destination. This notion is in contrast to proactive routing protocols commonly used in the Internet, which can afford the luxury of maintaining all routes since they rarely change. Because routes can change very quickly in MANETs, the signaling overhead required to maintain all routes at all times can be prohibitively high. AODV's route establishment phase consists of two main control messages, the RREQ (route request) and RREP (route reply). A robot, when desiring to send a message to another robot, must send a route request for the destination. This request is broadcast to all neighbors and relayed by intermediate nodes until it reaches the destination, or a robot with a route to the destination, at which time a route reply message is sent back to the source robot. This message sequence establishes the (temporary) route so that data packets may be forwarded from source to destination. For a much more detailed description of AODV, the reader is referred to the AODV RFC [11].

The major failing point of AODV, and other on-demand routing protocols such as DSR [12], occurs when there is no existing end-to-end path from source to destination, and the route discovery phase fails. This happens after a number of unsuccessful attempts to establish the route (where the number of attempts is usually a parameter of the protocol) assuming the disconnection is long lived. In this case, data packets are dropped, and the destination does not receive the intended messages. Additionally, by retrying to establish a route multiple times, MANET proactive routing protocols like AODV repeatedly incur route discovery overhead.

B. StAR

The main objective of StAR is to be robust to frequent connectivity disruptions that can be arbitrarily long lived. To this end, StAR takes advantage of node mobility and uses *steward* nodes to carry messages on behalf of the source. For each connected partition in the network, a *steward* in designated for each destination. In the specific case of the application at hand, i.e., emergency response, robots that are expected to have communication with the destination in the near future are designated as stewards. For example, if there is a single moving robot who communicates with all other stationary nodes, this robot is likely to be nominated as the steward for all destinations. Messages are sent to the associated steward, who will store them until a route to the destination (or a better steward) is available.

StAR routes messages using a combination of global (network-wide) contact information and local (intra-partition) route maintenance. The topological location of active destinations in the network is propagated through periodic broadcasts, or contact exchanges, between neighbors. These broadcasts occur at a fixed interval if there are nearby nodes, and contain only those entries in the routing table that may have changed since the last broadcast to the same set of neighbors. The message includes a unique sequence number indicating the broadcast from which the information came.

Initially, each node nominates itself as the local steward for each destination, and therefore does not route messages to any neighbor. As updates are received from neighbors that advertise better local stewards, routes are formed. The ranking of stewards is based on the most recently heard sequence number for a destination, or route length if two nodes have the same destination sequence number. In a connected network (i.e, a network in which there are connected routes between all robots), each tree will be rooted at the destination itself and messages routed directly to the destination.

Thus, route maintenance results in one tree per destination of interest in each partition, where each tree is rooted at the locally nominated steward for that destination. Note that it is possible (and quite likely) that a node can be the steward for more than one destination at any given time, and the tree for each destination will contain precisely the same nodes and links.

VI. Experiments and Results

In addition to outfitting each robot with a local camera and ad hoc networking capabilities, we have loaded them with a simplified surveillance application. Each robot is defined as either a source (sensor) node or a destination (sink) node. It is the responsibility of source nodes to acquire images of their surroundings through the webcam at 5-second intervals and transmit them to a designated sink. Because there may be no direct route to the sink at the time the image is taken, StAR ensures that the image is buffered at some intermediate node until a route toward the destination exists. We are currently experimenting with a wide range of network topologies using StAR on the extended Eagle Knight robot architecture for comparison with standard on-demand routing protocols, e.g., AODV.

In what follows, we define three experiments using four fully autonomous small-size robots in order to examine protocol performance under various scenarios. In each experiment described below, we modify the mobility of the sensor and sink nodes to provide more or less connectivity in the network. All experiments last five minutes, during which time each sensor node captures a 230KB image every five seconds, resulting in a total of 30 images per sensor. We measure the number of images that are successfully sent to the sink to determine the effectiveness of the routing protocol.

A. *Experiment 1: Static Network*

We first examine the behavior of a network with four static nodes, two of which are sensors. The distance and obstacles between each node are different, as shown in Figure 5, which leads to intermittent connectivity between some node pairs. Most notably, the connectivity between the sink (node 7), and one of the sensors (node 3) is often unavailable due to the many walls between them requiring images to be routed through node 1. Table I compares the delivery rates of AODV and StAR. Both protocols deliver more than 75% of the captured images, however, StAR is able to deliver all 60 images, since it handles the intermittent connectivity between nodes 3 and 7 either by buffering the images at the source until a route can be established, either directly, or through intermediate node 1.

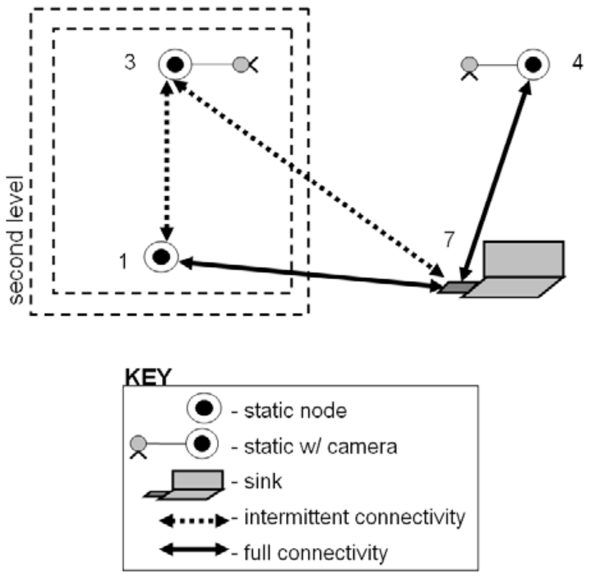

Fig. 5. Topology for Experiment 1: Static network. Sensor node 3 sends images to sink node 7 through intermediate node 1 when direct communication to the sink is unavailable.

TABLE I
PERFORMANCE OF AODV AND STAR IN TOPOLOY 1

	Image Deliveries	Ratio Delivered
AODV	46	76.67%
StAR	60	100.00%

B. *Experiment 2: Static Sensors with Mobile Intermediate Node*

In this experiment, all sensor nodes remain static, while an intermediate relay node moves to enable network connectivity. As shown in Figure 6, two of the sensor nodes 1 and 3 sometimes have connectivity with the sink, while the third sensor node 4, never has direct connectivity. Mobile node 2 enables connectivity between sensor node 4 and the sink, allowing images to be transmitted over a three-hop route (4 – 2 – 1 – 7).

Table II shows the performance of the two routing protocols in experiment 2. AODV does not take advantage of the added connectivity provided by mobile node 2, and therefore fails to deliver any images from sensor node 4. Using StAR, however, the mobile node carries the images until a route can be established through node 1 to the sink. StAR is therefore able to successfully deliver all 90 images. Like the previous experiment, the poor connectivity between the sink and sensor node 3 makes it difficult for AODV to deliver images because of its inability to buffer the images until a route can be established.

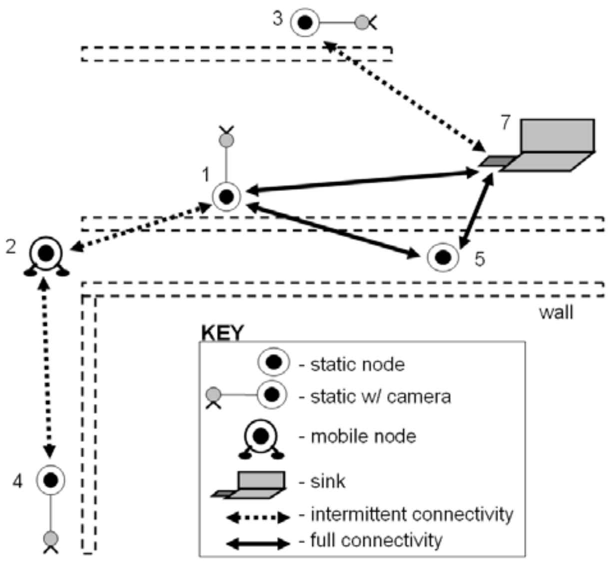

Fig 6. Topology for Experiment 2: Static sensors with mobile intermediate node. Static sensor node 4 sends images to sink node 7 through intermediate mobile node 2 and static node 1.

TABLE II
PERFORMANCE OF AODV AND STAR IN TOPOLOY 2

	Image Deliveries	Ratio Delivered
AODV	48	51.11%
StAR	90	100.00%

C. *Experiment 3: Mobile Sensors with Static Intermediate Node*

This experiment is representative of a situation where mobile sensor nodes are deployed to gather information before relaying it to static sink nodes. In this topology, shown in Figure 7, two mobile nodes with attached cameras had limited connectivity to static relay nodes. The static nodes all had intermittent connectivity due to obstacles and distance. The mobile nodes ranged at a distance from the sink, never coming into direct contact. Again, as shown in Table III, StAR shows a large improvement over the standard AODV routing protocol. Because the source sensor nodes are able to buffer images until a relay node is available, and that relay node can in turn buffer the images until a direct path to the destination is available, the protocol delivers nearly every captured image.

Another discovery worth mentioning is that when we performed this type of experiment, the transmission of the images, although complete in terms of the number of images received, in some cases did not get the entire image across. Most probably this is due to the fact that if the mobile sensor node is in the middle of a transmission when it goes out of range, only part of the picture arrives, making it impossible to view it at the sink. One way to handle this problem is to employ a proactive reliability mechanism based on transmitting redundant data. In case of packet loss, the original image can be re-generated using the packets that got through (provided that routing was able to deliver a sufficient number of packets). The level of redundancy should be set based on the reliability of the underlying routing protocol.

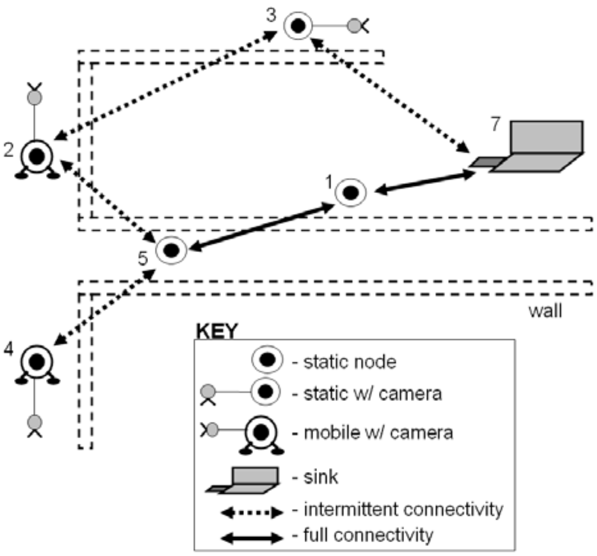

Fig 7. Topology for Experiment 3: Mobile sensors with static intermediate nodes. Mobile sensor nodes 2 and 4 send images to sink node 7 through intermediate static nodes 5 and 1.

TABLE III
PERFORMANCE OF AODV AND STAR IN TOPOLOY 3

	Image Deliveries	Ratio Delivered
AODV	41	45.56%
StAR	89	98.89%

VII. CONCLUSION

In this paper, we presented preliminary results from collaborative research work between the robotics laboratory at ITAM and the internetworking research group at UCSC in incorporating vision-based sensing and ad-hoc networking capabilities in small autonomous mobile robots. The robots used were developed at ITAM originally targeting RoboCup Small-Size league competitions. In the context of this project, we extended the robot architecture to satisfy the needs of emergency rescue applications. More specifically, the robots were adapted so they can operate outside the limited soccer field in a more autonomous fashion. The main hardware modifications involved including a Crossbow Stargate single-board computer connected to a local web camera and a 802.11 communications device. In terms of software, algorithms previously designed for remote execution have been ported to the Stargate for local processing. Additionally, we have ported ad-hoc communication protocols developed by the networking group at UCSC to operate on the Stargates.

As proof of concept, we carried out a number of experiments to showcase and evaluate the communication capabilities of the resulting robotic system. We have experimented with various static and mobile multi-node configurations to test how effectively sensor nodes can deliver images to a sink. We show that the proposed routing protocol was quite efficient handling disruptions due to both node mobility and poor link quality.

Our long-term goal in this collaborative effort is to be able to deploy multiple robots in real world applications such as search and rescue where advanced communication capabilities are required. Our current work in this direction is to extend the capabilities of both the robots and networking. More specifically, we plan to add additional autonomous networking-based control in the robots to enable the, e.g., to make decisions during network failures; for example, a robot may decide to search for locations where communication can be reestablished.

It should be noted that we have chosen to extend the RoboCup small-size league architecture since the robots were built by our group and can easily be modified and extended with other devices as needed (e.g., having two cameras, additional communication devices, etc). Other robotic platforms were considered as well including the already discontinued Sony AIBO. Based on evaluations previously done at ITAM's robotics lab, the small-size robot used in this project has at least twice the speed of the Sony AIBO, while our latest small-size generation has more than four times the AIBO speed. Current plans involve using our latest small-size robot models. Finally, this project does not limit itself to ground robots but also to unmanned aerial vehicles (UAVs).

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