

Interacting with Sensor Networks

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Abstract— We develop distributed algorithms for sensor networks that respond by directing a target (robot or human) through a region. The sensor network models the event levels sensed across a geographical area, adapts to changes, and guides a moving object incrementally across the network. We describe a device we call a *Flashlight* for interacting with the sensor field. This interaction includes collecting navigation information from the sensors in the local neighborhood, activating and deactivating specified areas of the sensor network, and detecting events in the sensor network. We report on hardware experiments using a physical sensor network consisting of Mote sensors.

I. INTRODUCTION

We wish to create more versatile information systems by using autonomous and distributed sensor networks: thousands of small sensors, equipped with limited memory and actuation capabilities will autonomously organize themselves and move to track a source and convey information about its location to a human user, and to the rest of the team. Such distributed active mobile sensor networks are pervasive computing systems, well-suited for tasks in extreme environments, especially when the environmental model and the task specifications are uncertain and the system has to adapt to it. A collection of active sensors can follow the movement of the source to be tracked, for example a chemical plume as it spreads in the air, a fire to localize its source, or a herd of sheep grazing on the Taihape farms.

An ad-hoc network is formed by a group of mobile hosts upon a wireless local network interface. It is a temporary network formed without the aid of any established infrastructure or centralized administration. A sensor network consists of a collection of sensors distributed over some area that form an ad-hoc network. Each sensor is equipped with some limited memory and processing capabilities, multiple sensing modalities, and communication capabilities. Previous work in sensor networks has concentrated on communication protocols for static sensor networks. Often the network topology is unknown and the network has to discover the best route for a packet.

In this paper we focus on mobile sensor networks, where each sensor node is capable of actuation, sensing, and communication. We examine the user interaction with a massively distributed sensor network. The user may be a robot or a human traversing the network.

More specifically, we build on important previous work by [1], [9], [8], [7], [2] and examine in more detail sensor net-

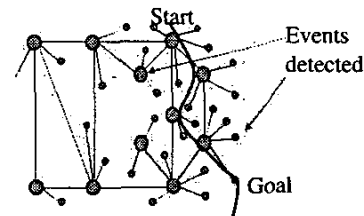


Fig. 1. Navigating along the safest path as computed incrementally by sensors in a sensor network.

works that provide directions to a moving user. We developed a device we call a *Flashlight* for interacting with the sensor field. This interaction includes collecting navigation information from the sensors in the local neighborhood, activating and deactivating specified areas of the sensor network, and detecting events in the sensor network. We describe the Flashlight and present protocols for each of these tasks. Finally, we discuss an implementation of our Flashlight protocols on a physical sensor network consisting of 48 Mote sensors [3], [4] and present our experimental data.

II. MOTIVATION: A DISTRIBUTED PROTOCOL FOR GUIDING NAVIGATION

Sensors detect information about the area they cover. They can store this information locally or forward it to a base station for further analysis and use. Sensors can also use communication to integrate their sensed values with the rest of the sensor landscape. Users of the network (robots or people) can use this information as they traverse the network. We illustrate this property of a reactive sensor network in the context of a guiding task, where a moving object is guided across the network along a safe path, away from the type of danger that can be detected by the sensors.

The guiding application can be formulated as a robotics motion planning problem in the presence of obstacles. The interesting areas of the sensor network are those where sensors have triggered. They can be represented as obstacles. Such areas may include excessive heat (from volcanoes, fire, etc), people, etc. We assume that each sensor can sense the presence or absence of such an event. An event configuration protocol run across all the nodes of the network creates the event map. We do not envision that the network will create an accurate

geometric map, distributed across all the nodes. Instead, we wish for the nodes in the network to provide some information about how far from the event each node is. If the sensors are uniformly distributed, the *smallest number of communication hops to a sensor that triggers "yes" to the event* is a measure of the distance. The goal is to find a path for the moving object that moves toward the events (or avoids them, depending on the application.) The user may ask the network regularly for where to go next. The nodes within broadcasting range from the user supply the next best step.

Inspired by [5], we developed several protocols for the distributed guidance problem across sensor networks and reported the details of these algorithms in [6]. The map can be constructed incrementally and adaptively as an artificial potential field using hop-by-hop communication (see Figure 1). The "obstacles" correspond to events and have repulsing values and the goal has an attracting value. The potential field is computed in the following way. Each node whose sensor triggers "event" diffuses the information about the event to its neighbors in a message that includes its source node id, the potential value, and the number of hops from the source of the message to the current node. This message is used to update the potential value at the current node. The node then broadcasts a message with its new potential value and number of hops to its neighbors.

The potential field information stored at each node can be used to guide an object equipped with a sensor that can talk to the network in an on-line fashion. The safest path to the goal can be identified with a distributed protocol using dynamic programming. A user of the sensor network can get continuous feedback from the network on how to traverse the area. The user asks the network for where to go next. The neighboring nodes reply with their current values. The user sensor chooses the best possibility from the returned values.

III. AN INTERACTION DEVICE: THE FLASHLIGHT

The navigation guidance application is an example of how simple nodes distributed over a large geographical area can assist with global tasks. This application relies on the ability of the network user to interact with the network as a whole and with specific nodes in the network. This interaction is directed at retrieving data from the network (such as collecting local information from individual nodes and collecting global maps from the network) and injecting data into the network (such as configuring the network with a new task or reprogramming its nodes).

The ability to re-task and reposition sensors in a network by sending state changes or uploading new code greatly enhances the utility of such a network. It allows different parts of the network to be tailored to specific tasks, capabilities to be added or changed, and information to be stored in the nodes in the network. When robots or people interact with the network, the sensors become an extension of the user capabilities, basically extending their sensory systems and ability to act over a much large range.

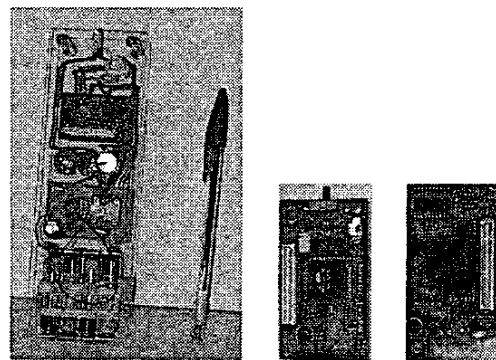


Fig. 2. The left figure shows the Flashlight prototype. The center figure shows a Mote board. The right figure shows the Mote sensor board.

We have developed a hand-held device that allows a user of the network (a human or a robot) to interact with the network as a whole or to talk to individual nodes in the network. This device is called a *sensory Flashlight* and is based on the optical flashlight metaphor. When pointed in a specific direction, the Flashlight collects information from all the sensors located in that direction and provides its user with sensory feedback. The device can also issue commands to the sensors in that direction.

Applications of the Flashlight device for interacting with the sensor network include: (1) Guiding robots or people along paths that may change over time; (2) Reconfiguring a wireless sensor network in a patterned way; (3) Interacting with a wireless sensor network, both consuming and providing information stored within the network, changing and reacting to its topology, re-tasking the network; (4) Invisible markup of a geographic region with information; (5) Sensor management; and (6) Efficiency improvements in message routing.

In this section we describe the Flashlight hardware and illustrate its capabilities with algorithms for three tasks: (1) using the Flashlight to activate or deactivate a specified area of the sensor network; (2) using the Flashlight to detect events in the sensor network; and (3) using the Flashlight to provide guidance feedback across the sensor network. We also describe the implementation of these algorithms and present experimental data.

A. The Hardware

The Flashlight prototype we designed and built is shown in Figure 2(left). This device can be carried by a human user or placed on a mobile robot (or flying robot) to interact with a sensor field. The *beam* of the Flashlight is sensor-to-sensor, multi-hop routed RF messages which send or return information.

The Flashlight consists of an analog compass, alert LED, pager vibrator, a 3 position mode switch, a power switch, a range potentiometer, some power conditioning circuitry, and a microcontroller based CPU/RF transceiver. The processing and RF communication components of the Flashlight and

the sensor network are Berkeley Motes [4], shown in Figure 2(center,right). A switch selects the sensor type (light, sound, temperature, etc.) When the user points the Flashlight in a direction, if sensor reports of the selected type are received from any sensors in that direction, a silent vibrating alarm activates. The vibration amplitude can be used to encode how far (in number of hops) was the sensor that triggered. The potentiometer is used to set the detection range (calibrated in number of network hops from sensor to sensor.) The electronic compass supplies heading data indicating the pointed direction of the device.

The Flashlight uses one Berkeley Mote (<http://today.CS.Berkeley.EDU/tos/>) as a main processor and sensor board. The Mote handles data processing tasks, A/D conversion of sensor output, RF transmission and reception, and user interface I/O. It consists of an Atmel ATmega128 microcontroller (with 4 MHz 8 bit CPU, 128KB flash program space, 4K RAM, 4K EEPROM), a 916 MHz RF transceiver (50Kbits/sec, 100ft range), a UART and a 4Mbit serial flash. A Mote runs for approximately one month on two AA batteries. It includes light, sound, and temperature sensors, but other types of sensors may be added. Each Mote runs the TinyOS operating system.

A moving Flashlight interacts with a wireless sensor network consisting of Mote sensors. The sensors are currently programmed to react to sudden increases in light and temperature intensity, but other sensory modes are possible. The Flashlight and all sensors know their location coordinates. These are currently provided to each sensor, but the location parameters can be acquired with GPS or with a calibration procedure.

B. The Communication Protocols.

The Flashlight has three modes, Activate Sensors, Deactivate Sensors, and Detect, selected by the mode switch. In this section we describe each of these protocols.

1) *Route Updates*: The Route Update protocol establishes a *multi-hop* path from each sensor to the Flashlight (see Figure 3(Left)). These paths are then used by other functions of the Flashlight to collect data from the sensors.

In all modes the device sends out Route Update messages every t seconds which are used and forwarded by the sensors to determine a valid *multi-hop route* to the Flashlight. These routes depend on the network configuration and may change over time.

The Route Update (RU) messages are 32 bytes and consist of the Flashlight Network ID, the Network IDs for the last k hops and the CRC checksum.

Each sensor uses this information to store the network ID of a parent through which it can route messages to the Flashlight (see Algorithm 1). The messages are propagated across the entire sensor network in a hop-by-hop fashion. Each sensor prevents loops by allowing only RU messages from its parent node until a timeout limit is reached. After the timeout, the sensor chooses the first rebroadcasting node it hears as its parent. The CRC checksum is used to discard corrupted

Algorithm 1 The Route Update routing algorithm.

```

1: if NumberOfHops < k * MessageSize then
2:   if RouteIsSet AND MessageIsFromParent then
3:     Set route timeout
4:     Increment message hop count
5:     Add network ID to message hop history
6:     Broadcast updated message
7:   if NOT RouteIsSet then
8:     Record route to Flashlight
9:     Set route timeout
10:    Increment message hop count
11:    Add network ID to message hop history
12:    Broadcast updated message

```

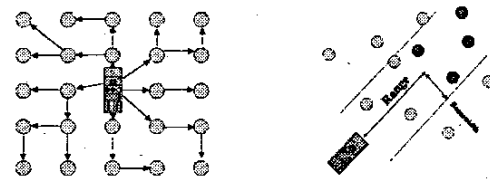


Fig. 3. (Left) A snapshot of the sensor network after each sensor has established a multi-hop route to the Flashlight. (Right) The directional activation of sensors. A VR message travels in a specified direction. The sensors contained within a given range (shown in black) have been selected.

messages since TinyOS has minimal measures for preventing message collisions.

2) *Activate/Deactivate Region*: The Flashlight can turn on all the sensors in a specified geographical area to *activate* the area or it can turn them off to *deactivate* that area. Activate allows the network and its user to collect higher-resolution information about given locations when all the sensors in the area are on. Activate can be augmented with a probabilistic component that selects only a fraction of the sensors in the area. Deactivate allows the network to switch off all (or a fraction of) the sensors in an area. This functionality is especially useful during a quiet period, when no events trigger and sleeping sensors preserve battery power to extend the network lifetime.

In the Activate mode the Flashlight sends out a Vector Route message regularly (in the current implementation, each 1.1 seconds.) The Vector Route (VR) message is 32 bytes long and consists of the following information:

- 2 bytes - Flashlight Network ID
- 4 bytes - Flashlight Latitude
- 4 bytes - Flashlight Longitude
- 2 bytes - Range to travel in feet
- 2 bytes - Direction to travel
- 2 bytes - Beamwidth
- 2 bytes - Hop count
- 4 bytes - Unique message ID
- 1 byte - Activate/Deactivate flag
- 1 byte - mode flag
- 2 bytes - CRC checksum

Algorithm 2 The Vector Route routing algorithm.

```
1: if ThisMessageID  $\neq$  AnyOfLastkMessageIDs then
2:   Update message ID list
3:   Calculate Flashlight direction vector
4:   Calculate perpendicular to Flashlight vector that goes
   through the sensor location
5:   Find point on Flashlight vector that is closest to this
   sensor
6:   Calculate distance of sensor from Flashlight beam center
7:   if the point on Flashlight vector is not behind the
   Flashlight then
8:     DistanceFromBeam = distance of sensor from Flash-
   light beam center
9:     DistanceFromFlashlight = distance of sensor from
   Flashlight
10:    if (Range < DistanceFromFlashlight) AND (Dis-
   tanceFromBeam < Beamwidth) then
11:      Activate or Deactivate sensor based on flag
12:      Rebroadcast Vector Route message
```

Algorithm 3 The Detect routing algorithm.

```
1: if RouteIsSet AND (RouteTimeOut > 0) AND (ThisMes-
   sageID  $\neq$  PreviousMessageID) then
2:   PreviousMessageID = ThisMessageID
3:   Add network ID to hop history
4:   Send the data message to parent
```

Algorithm 2 shows the Vector Route protocol that is used to activate an area. At a top level, a message carrying the geometry of an area (specified as a direction *dir* and distance *dis* from the device) message propagates through the network in *dir*, selecting all the sensors that are at least *dis* away. Each sensor uses the message information and its local state to determine whether it is part of the activation area or not. This protocol can be extended easily to accommodate areas of any given geometry.

3) *Detect*: Activated sensors watch for events and send messages to the Flashlight using the paths computed with Route Update messages. The Flashlight can store time-stamped sensor triggers in a database for later use. Sensor detects can also be used instantly to present feedback about the direction and distance to the sensor that triggered. Such feedback can be used to provide locomotion direction for a robot or human traversing the sensor field to find the sensor that triggered. More detailed information and history may be stored locally on the sensor for future consumption.

Sensor Detect messages contain the coordinates of the sensor and sensor data. In our implementations, we have used light and temperature intensity data.

Detect messages are generated from a sensor when it detects a change in its current sensory values, based on a threshold. Detect messages are then forwarded from sensor to sensor along the routes previously established by the RU

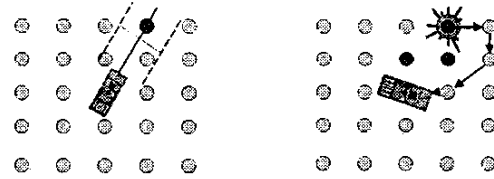


Fig. 4. (Left) A snapshot of the sensor network after an area of the network (the red node) has been activated. (Right) A sensor detect event is forwarded to the Flashlight along a multihop route.

messages (see Figure 4(Right)). Upon reaching the Flashlight, the heading toward the detection and the number of hops to the sensor that triggered are stored in a table. The Flashlight gives feedback to a human user by lighting its LED and turning on a vibration if its current physical heading matches a heading stored in the table. The vibration amplitude depends on the number of hops to the the sensor that triggered.

C. Motion Guidance

The Flashlight can be used for directional feedback in motion guidance applications, especially as directed to first responders such as firefighters. Consider a burning building with a sensor net deployed along all the walls. The sensors know their relative location. People trapped in the building could alert the outside world of their location by activating the nearest sensor. In response to this activation, the safest path to the exit from the building can be computed by the sensor network and delivered to an outside base station. A human user or robot can use the Flashlight to get step-by-step guidance through the building to the sensor that triggers. At each sensor location, the user queries the sensor net for the next direction of movement. The sensor net returns that direction packaged as a message. The user then scans across all possible directions with the Flashlight. When the Flashlight gets pointed in the correct direction, the light LED turns on and the user knows to head that way.

We have implemented this scenario using the following assumptions. The sensors are deployed by hand along building corridors and initialized with their location. The sensors are spread so that the Flashlight will talk to one sensor at a time only. The sensor net computes a tree of exit paths—that is, there are no loops in the paths.

Algorithm 4 shows the protocol for computing a path to the exit. The key idea is to assign sensor nodes id nodes that are proportional to how far each sensor is (in number of hops) to the exit. This id scheme leads to a simple algorithm for determining the way out: the sensor with the lowest message id that can be heard indicates the direction out.

Given such a sensor deployment scheme, a Flashlight user can find the exit using the protocol described in Algorithm 5. The Flashlight queries the network for the next best direction. The sensors in the current communication neighborhood respond. The Flashlight selects the sensor with the lowest id and computes the direction to that sensor. The user scans directionally with the Flashlight. When the Flashlight compass

Algorithm 4 The guidance algorithm for assigning network ID to sensors. A lower ID indicates the way out. Sensors are assumed to be deployed and powered up one at a time and placed so they are separated by a distance greater than the max RF range.

```
1: Sensor powered on
2: while  $t$  timer still counting down do
3:   receive and store all messages
4: if No messages received then
5:   Assume this is first sensor and assign ID=1
6: else
7:   Increment highest received network ID by one and use
   that as ID for this sensor
8: while forever do
9:   Broadcast this sensors location and network ID and the
   location of the next sensor in chain that leads to way
   out
```

Algorithm 5 The guidance algorithm by which the flashlight indicates the way out.

```
1: while forever do
2:   Wait for a message to be received {Sensors have been
   deployed one at a time so ID's are sequential} {with
   decreasing ID indicating the way out.}
3:   Of all messages received so far, use the one with lowest
   network ID for the flashlights location
4:   From same sensor message get direction to next sensor
5:   Light up and vibrate if flashlight is pointed in direction
   of way out
```

detects that the device is pointed in the computed direction, the LED and vibrator turn on, signaling the user the way to go.

This protocol can be instantiated easily for a robot user instead of a human user: The robot needs a sensor that can communicate with the network. In response to a direction computed from the sensor network, the robot will move in that direction.

IV. EXPERIMENTS

We have implemented the Flashlight communication infrastructure described in Section III and Section II and verified their correctness. We also implemented two guidance applications. The first application computes the safest path across a dangerous region—for example across a forest fire or a contaminated compound. In this application, the sensors are assumed to record danger levels. The safest path across the sensor field is then computed and updated incrementally, as the danger levels change [6]. In the second application, we use this system to guide a firefighter or robot to a victim trapped in smoke; we then guide the people out. In this application, a sensor triggers (for example by user contact). A path from this sensor to an outside base station is then computed. The Flashlight interacts with the sensors one-by-one, each time giving the next direction of movement to the user.

These applications have been implemented using the Flashlight we built and a 48 node Mote sensor network running our communication protocols. These experiments were also used to collect data about the effectiveness of our communication protocols.

A. Experimental Setup

We have placed 48 Mote sensors in a grid pattern and in a U-shaped pattern for all our evaluation experiments (see Figure 5). The sensors were provided with location coordinates corresponding to a horizontal separation of 32.4 feet and a vertical separation of 35.4 feet. The Flashlight was placed at the location of one of the grid sensors and given its coordinates¹. A software adjustment allows us to scale down the area covered by the sensor network to carry out experiments on a desk top. We adjusted the transmission power of the Mote sensors to a half a foot using the digital potentiometer.

It is generally difficult to collect data from a distributed set of unsynchronized sensors, because it is not possible to collect the correct time-stamped information in a central repository. Instead, we used the three LEDs on the Motes. We programmed different patterns of lights to correspond to the events we were interested in monitoring. We videotaped the experiments. Then we manually post-processed the video to determine the time sequence of the events of interest. This procedure gives us a resolution of $1/30^{th}$ of a second for our timing measurements.

B. Beam accuracy experiments

In the first experiment we measured the accuracy of the beam estimation in the Vector Route algorithm (see Algorithm 2). We ran the Vector Route algorithm and observed the sensors that were identified to be within the beam width (these sensors' LED lit up.) We placed the Flashlight at one corner of the sensor grid and repeated the Vector Route algorithm for several orientations. We then computed the distance of each activated sensor from the actual beam center path. The distances for each angular increment were averaged and the results are shown in Figure 6.

Since the beam width parameter was chosen at 50 feet, we expected the average distance to the beam to be less than 50 feet. In general, the algorithm did quite well, with the sensors that were activated being mostly within the beam. We observed some error in the experiments conducted around a Flashlight heading around true North and West. We believe these errors are due to the non-homogeneous magnetic environment where the experiment was conducted. This introduced nonlinearities in the compass readings within the Flashlight. Such nonlinearities are likely to show up in actual use as well, hence a magnetic compass is not the best device to use for getting bearing.

¹By placing the Flashlight at grid corners we accomplish "virtual grids" of 200 sensors.

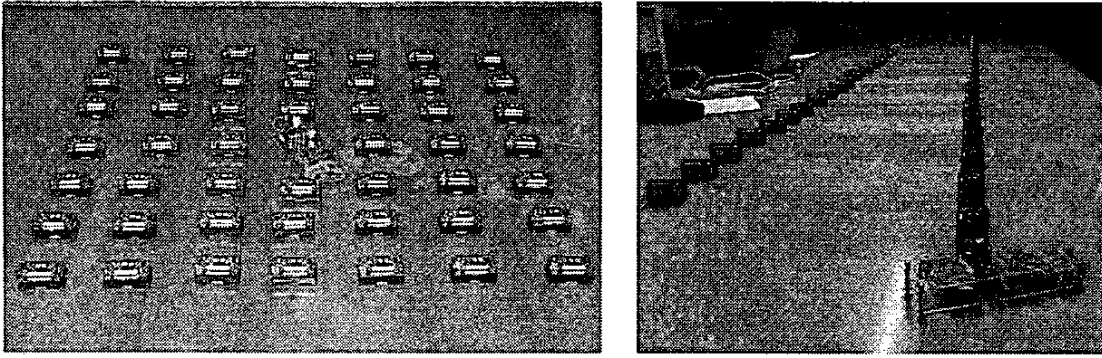


Fig. 5. (Left) The Mote grid testbed. (Right) The Mote U-shape testbed.

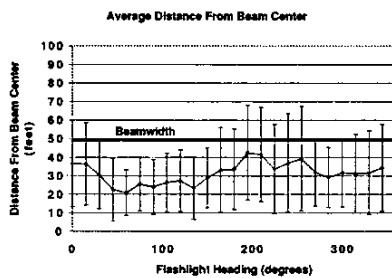


Fig. 6. The average beam width for selected sensors for a suite of Vector Route messages. The x axis shows the Flashlight heading. The y axis shows the average distance from the beam center of the selected sensors for the given Flashlight heading.

C. Message propagation latency experiments

In a different set of experiments, we measured the message propagation latency for Route Update and Vector Route messages. To maximize the number of hops in the network we used the U-shaped testbed. All the sensors were given the same location, so that they would all be within the beamwidth of a VR message simultaneously and propagation time from the start to the end of the chain could be measured. Note that messages often jump over more than one sensor along the chain due to the variability of RF transmission/reception range. Thus, although we had 48 sensors, the max hop range for the network was less. The results for the RU message propagation times are shown in Figure 7(Left). Since RU messages are instantly forwarded, the propagation latency is quite low, under a quarter second for most of the sensors to achieve a valid route.

The results for the VR message propagation times are shown in Figure 7(Right) for sensor activation times. Here we see that the propagation times are much longer due to the computation load².

²Trigonometry is expensive for a 4MHz 8 bit microcontroller with no floating point co-processor and software implemented multiplies and divides.

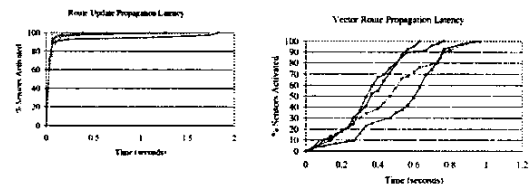


Fig. 7. (Left) The Route Update message propagation latency. (Right) Vector Route message latency. The x axis is time. The y axis shows sensor percentage. The curves correspond to different experiments.

D. Directional Guidance

We have deployed 12 Mote sensors along corridors in our building and used the Flashlight and the communication infrastructure presented here to guide a human user out of the building. Figure 8 shows the map. The Flashlight interacted with sensors to compute the next direction of movement towards the exit. For each interaction, the user did a rotation scan until the Flashlight was pointed in the direction computed from the sensor data. The user then walked in that direction to the next sensor. Each time we recorded the correct direction and the direction detected by the Flashlight. The directional error was 8% (or 30 degrees) on average. However, because the corridors and office doorways are wide, and the sensors sufficiently dense, the exit was identified successfully. The user was never directed towards a blocked or wrong configuration. An interesting question is how dense should the sensors be, given the feedback accuracy.

V. CONCLUSIONS

We have discussed sensor networks that can interact with robot or human users. We have described the Flashlight, an interaction device for sending commands to the sensor network and discussed several protocols in the context of navigation guidance applications: activating a given area of the sensor network, deactivating a given area of the sensor network, detecting events in the sensor network and using these events for navigation. We have implemented these protocols on a

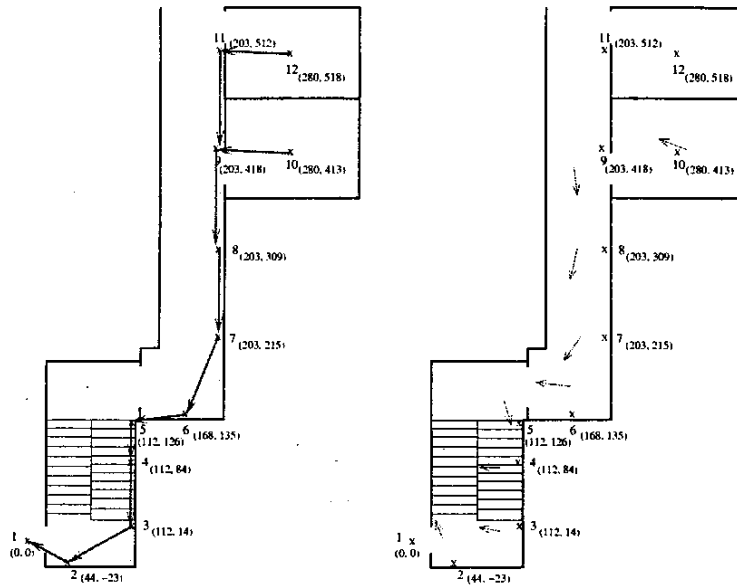


Fig. 8. (Left) The floor map for the directional guidance experiment. Arrows indicate the correct direction to be detected by the Flashlight. (Right) The floor map for the directional guidance experiment with the Flashlight feedback directions marked on it.

network of 48 Mote sensors and presented some experimental data collected from this testbed.

This work has given us several insights into using ad-hoc networks for robot interactions with sensor networks. Data loss is not rare in sensor networks. This is due to network congestion, transmission interference, and garbled messages. We observed that the transmission range of one direction may be quite different from that of the opposite direction. Thus, the assumption that if a node receives a packet from another node, it can send back a packet is too idealistic. Network congestion is very likely when the message rate is high. This is aggravated when the nodes in proximity of each other try to send packets at the same time. For a sensor network, because of its small memory and simplified protocol stack, congestion is a big problem. The uncertainty introduced by data loss, asymmetry, congestion, and transient links is fundamental in sensor networks and should be carefully considered in developing models and algorithms for systems that involve sensor networks.

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