Distributed Search and Rescue with Robot and Sensor Teams

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1 Motivation

We consider search and rescue applications in which heterogeneous groups of agents (humans, robots, static and mobile sensors) enter an unknown building and disperse while following gradients in temperature and concentration of toxins, and looking for immobile humans. The agents deploy the static sensors and maintain line of sight visibility and communication connectivity whenever possible. Since different agents have different sensors and therefore different pieces of information, communication is necessary for tasking the network, sharing information, and for control.

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 and distributed over some area that form an ad-hoc network. Our heterogeneous teams of agents (sensors, robots, and humans) constitute distributed adaptive sensor networks and are 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. Applications of this work cover search and rescue for first responders, monitoring and surveillance, and infrastructure protection.

We combine networking, sensing, and control to control the flow of information in search and rescue in unknown environments. Specifically, this research examines (1) localization in an environment with no infrastructure such as a burning building (for both sensors and robots) (2) information flow across a sensor network that can localize on the fly for delivering the most relevant and current information to its consumer, maintaining current maps, and automating localization; (3) using feedback from the sensor network to control the autonomous robots for placing sensors, collecting data from sensors, and locating targets; and (4) delivering the information gathered from the sensor network (integrated as a global picture) to human users. The paper will detail our technical results in these 4 areas and describe an integrated experiment for navigation in burning buildings.

2 Localization

Localization in dynamic environments such as posed by search and rescue operations is difficult because no infrastructure can be presumed and because simple assumptions such as line of sight to known features can not be guaranteed. We have been investigating the use of low cost radio beacons that can be placed in the environment by rescue personnel or carried by robots. These radio beacons provide range to a receiver and since their position is unknown to start and can potentially

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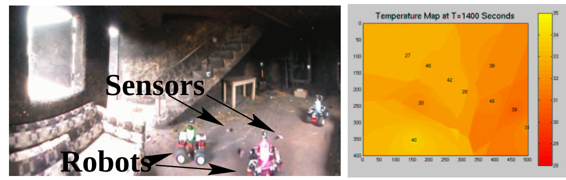

Figure 1: (Left) An ad-hoc network of robots and Mote sensors deployed in a burning building at the Allegheny Fire Academy, Aug 23, 2002 (from an experimental exercise involving CMU, Dartmouth, and U. Penn). (Right) The temperature gradient graph collected using an ad-hoc network of Mote sensors.

change during operation, it is necessary to localize both the receiver and the beacons simultaneously. This problem is often known as Simultaneous Localization and Mapping (SLAM) although typically a receiver is able to measure both range and bearing to features.

We have adapted the well-known estimation techniques of Kalman filtering, Markov methods, and Monte Carlo localization to solve the problem of robot localization from range-only measurements [KS02] [SKS02]. All three of these methods estimate robot position as a distribution of probabilities over the space of possible robot positions. In the same work we presented an algorithm capable of solving SLAM in cases where approximate a priori estimates of robot and landmark locations exist. The primary difficulty stems from the annular distribution of potential relative locations that results from a range only measurement. Since the distribution is highly non-Gaussian, SLAM solutions based on Kalman filtering falter. In theory, Markov methods (probability grids) and Monte Carlo methods (particle filtering) have the flexibility to handle annular distributions. Unfortunately, the scaling properties of these methods severely limit the number of landmarks that can be mapped. In truth, Markov and Monte Carlo methods have much more flexibility than we need; they can represent arbitrary distributions while we need only to deal with very well structured annular distributions. What is needed is a compact way to represent annular distributions together with a computationally efficient way of combining annular distributions with each other and with Gaussian distributions. In most cases, we expect the results of these combinations to be well approximated by mixtures of Gaussians so that standard techniques such as Kalman filtering or multiple hypothesis tracking could be applied to solve the remaining estimation problem.

3 Information Flow

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 have developed distributed protocols for navigation tasks in which a distributed sensor field guides a user across the filed [LdRR03]. We use the localization techniques presented above to compute environmental maps and sensor maps, such as temperature gradients. These maps are then used for human and robot navigation to a target, while avoiding danger (hot areas).

Figure 1(Right) shows the layout of a room in which a fire was started. We have collected a temperature gradient map during the fire burning experiment as shown in Figure 1. The Mote sensors[1] were deployed by hand at the locations marked in the figure. The sensors computed multi-hop communication paths to a base station placed at the door. Data was sent to the base station over a period of 30 minutes.

We used the structure of the data we collected during the fire burning exercise to develop a navigation guidance algorithm designed to guide a user to the door, in a hop-by-hop fashion. We have deployed 12 Mote sensors along corridors in our building and guide a human user out of the building. Using an interactive device that can transmit directional feedback called a Flashlight [PR02] a human user was directed across the field. 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.

4 Control of a Network of Robots

Robots augment the surveillance capabilities of a sensor network by using mobility. Each robot must use partial state information derived from its sensors and from the communication network to control in cooperation with other robots the distribution of robots and the motion of the team. We treat this as a problem of formation control where the motion of the team is modeled as an element of a Lie group, while the shape of the formation is a point in shape space. We seek abstractions and control laws that allow partial state information to be used effectively and in a scalable manner.

Our platforms are car-like robots equipped with omnidirectional cameras as their primary sensors. The communication among the robots relies on IEEE 802.11 networking. By using information from its camera system each robot is only able to estimate its distance and bearing from their teammates. However, if two robots exchange their bearing to each other, they are also able to estimate their relative orientations [SDF$^+$01]. We use this idea to combine the information of a group of two or more robots in order to improve the knowledge of the group about their relative position.

We have developed control protocols for using such a team of robots in connection with a sensor network to explore a known building. We assume that a network of Mote sensors previously deployed in the environment guide the robots towards the source of heat. The robots can modify their trajectories and still find the building exit. The robots can also switch

[1] Each Mote sensor (http://today.CS.Berkeley.EDU/tos/) consists of an Atmel ATMega128 microcontroller a 916 MHz RF transceiver 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.

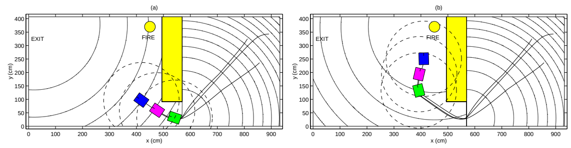

Figure 2: Three robots switching motion plans in real time in order to get information from the hottest spot of the building. In (b) a gradient of temperature is obtained from a network of Mote sensors distributed on the ground.

between the potential fields (or temperature gradients) computed and stored in the sensor network (see Figure 2). The first switch occurs automatically when the first robot encounters a Mote sensor at a given location. The robots move toward the fire and stop at a safer distance (given by the temperature gradient). They stay there until they are asked to evacuate the building, at which point they use the original potential field to find the exit.

5 User Feedback

When robots or people interact with the sensor network, it becomes an extension of their capabilities, basically extending their sensory systems and ability to act over a much large range. We have developed software that allows an intuitive, immersive display of environments. Using, panoramic imaging sensors that can be carried by small robots into the heart of a damaged structure, the display can be coupled to head mounted, head tracking sensors that enable a remote operator to look around in the environment without the delay associated with mechanical pan and tilt mechanisms.

The data collected from imaging systems such as visible cameras and IR cameras are displayed on a wearable computer to give the responder the most accurate and current information. Distributed protocols collect data from the geographically dispersed sensor network and integrate this data into a global map such as a temperature gradient that can also be displayed on a wearable computer to the user.

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