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AI, The Fundamental Social Aggregation Challenge, and the Autonomy of Hybrid Agent Groups

# Robotic Sensor Networks for Environmental Monitoring

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**Abstract**

Robotic Sensor Networks composed of robots and wireless sensing devices hold the potential to revolutionize environmental sciences by enabling researchers to collect data across expansive environments, over long, sustained periods of time. We report progress on building such systems for two applications. The first application is on monitoring invasive fish (common carp) in inland lakes. In the second application, the robots act as data mules and collect data from sparsely deployed wireless sensors.

In the last two decades, significant research effort has been devoted to building wireless sensor networks. The technology has now advanced to the level that off-the-shelf solutions are commercially available for applications such as soil monitoring. However, networks of stationary sensors have certain limitations which hinder their wide applicability: Not every sensor can be made small and inexpensive. Further, managing and maintaining the network becomes challenging if a dense sampling of the environment is needed. On the other hand, if a large area is covered sparsely, the network may not be connected.

Robots can augment the capabilities of sensor networks since they can carry larger loads (and hence a wide range of sensors) and collect dense measurements. They can operate autonomously and sample the environment in an adaptive fashion. They can also interact with stationary sensors by improving their connectivity. They can even deploy, relocate and recharge stationary sensors.

Recently, we have been working on two robotic systems for environmental monitoring applications. In the next two sections, we briefly report our progress so far and present an overview of research challenges.

## Monitoring Invasive Fish

Invasive fish, such as the common carp, pose a major threat to the ecological integrity of North American freshwater ecosystems. Recent studies in small lakes have established that the common carp aggregates densely at certain times and places, and can be controlled by targeting these aggregations using netting (Bajer, Chizinski, and Sorensen 2010). Therefore, it is possible to use radio-tagged carp to accurately locate the presence of large carp populations. This technique has been successfully used to study and control carp populations in small lakes in Minnesota where biologists manually track radio-tagged carp. Unfortunately, manually locating tagged fish in large, turbid bodies of water remains an almost impossible task.

We have been working on building a robotic system for finding, accurately localizing and actively tracking radio-tagged fish. We envision a system composed of multiple robotic vehicles (surface and ground vehicles) and stationary sensors which can autonomously operate on and around a lake for extended periods of time. Toward this goal, we built an autonomous boat and developed algorithms to search for and actively localize a target. The system was tested in extensive field trials. A description of an early prototype of this system can be found in (Tokekar et al. 2010). Since carp aggregations happen in winter when the lakes are frozen, we have also developed a similar ground-based system which can operate on ice. See Figure 1. In the next two subsections, we present a brief summary of the system's search and tracking capabilities.

Figure 1: Two autonomous vehicles for tracking radio-tagged fish **Left:** 6 ft robotic boat during a field trial. **Right:** Ground robot on a frozen lake.

### Search

The first task of the robotic system is to find radio-tagged fish. To design an efficient search strategy, the motion of the target (fish) must be modeled. We started with the assumption that the fish are (mostly) stationary during the experiment. In this case, the search problem reduces to a coverage problem. In order to incorporate domain knowledge

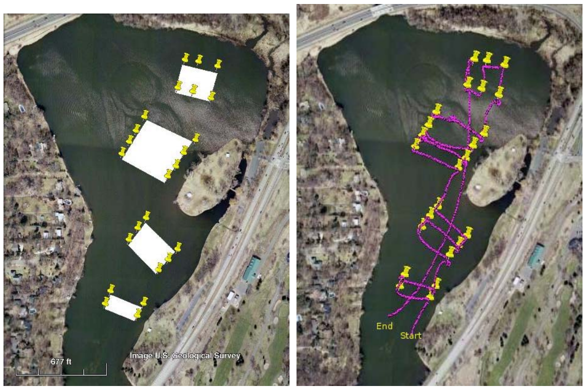


Figure 2: **Left:** The setup in Lake Keller, MN for the coverage experiment. Light rectangles in the image show the regions of interest to be covered. Each region is marked with waypoints which are placed such that the regions are covered by boustrophedon paths when the waypoints are visited. The dimensions of Lake Keller are approximately 900 m $\times$ 350 m. **Right:**The GPS trace of the path taken by the boat during the experiment. The trail shows that the boat covered all four regions by visiting all the waypoints robustly. The boat traveled approximately 2.5 km in 36 minutes of the run.

about possible target locations, we formulated a new coverage problem in which the input is a list of rectangles to be covered by the robot. The goal is to move in such a way that every point in the input rectangles is within the robot's communication range at some point. Our solution first computes a tour that visits the rectangles. When a rectangle is visited, it is completely covered by a simple back-and-forth sweep. We showed that this solution is within a constant factor of the optimal tour (Branson et al. 2011). The algorithm was implemented and tested in field trials (Figure 2).

We are currently working on developing search strategies which address the motion of the fish. In the absence of fish motion models, one possibility is to formulate this task as a pursuit-evasion game in which players have limited sensing capabilities (Isler, Kannan, and Khanna 2006).

### Active Tracking/Localization

By rotating a directional antenna, it is possible to estimate the bearing of the fish. Multiple bearing measurements can be merged to obtain an accurate estimate of the location of the target. Once a fish is found, the robot switches to target localization mode. In our system, each bearing measurement takes roughly two minutes, and the sampling resolution is low (typically 15 degrees). Therefore, it is crucial that the measurement locations be selected to yield accurate estimates as quickly as possible.

We started with evaluating the performance of two well-known and commonly used heuristics for active localization (Tokekar, Hook, and Isler 2011). The first one greedily picks the next measurement location to minimize the expected uncertainty after the measurement. The second heuristic generalizes the first one by enumerating over all $k-$step measurement sequences. This approach becomes computationally infeasible for $k > 4$. In field experiments, the greedy strategy performed reasonably well. We observed that the additional computational load necessary for executing the $k$-step strategy is not warranted.

More recently, we were able to design a "cautious" greedy strategy with provable performance guarantees (Vander Hook, Tokekar, and Isler 2012). The strategy represents the uncertainty with an ellipse and alternates between its axes. At each step, it moves so as to reduce the uncertainty along the active axis. Fields experiments confirm that the target can now be localized within one meter.

Our ongoing work on target localization is two-fold. We are trying to extend our strategy to moving targets. Designing active localization strategies for multiple targets is an interesting yet challenging research problem.

## Robotic Data Mules

Collecting data from stationary sensors can be a time-consuming task. Data collection process can be automated by adding wireless communication capabilities to the sensors. However, if the sensing locations are far apart, additional relay nodes may be needed to ensure the connectivity of the network. An alternative is to use robots as data mules to gather the data from the sensors. This approach has two major benefits: Since the robots can move close to the sensors, the energy required for communication is minimized. This can improve the life-time of the stationary sensors significantly. Second, the robots can collect additional data along the way. For example, the stationary sensors can be collecting soil moisture and temperature for extended periods of time. The robots can complement this data with transects of dense air temperature, crop height etc. measurements.

In (Tekdas et al. 2008), we built a proof-of-concept system and demonstrated that significant energy savings can be obtained by using robots as data mules. In (Bhadauria, Tekdas, and Isler 2011), we studied the problem of computing the robots' path so as to minimize the data collection time. The data collection time includes the travel time as well as the time to download the data from the sensors. We have also proposed an opportunistic version of the algorithm which downloads the data from a sensor as soon as the robot can hear it with high quality. Field experiments showed that the opportunistic algorithm adds robustness against errors in navigation. Robots' mobility is useful for addressing changes in wireless characteristics that may happen over time (e.g. due to changes in the environment). In (Tekdas, Karnad, and Isler 2009), we presented strategies for robots to adaptively find good download locations to reduce the energy spent in wireless communication.

We are now working on incorporating more sophisticated communication models to our strategies. It has been observed that the *download time* from a wireless device as a function of distance often exhibits a two-ring behavior: There is an inner ring, centered at the sensor, within which the download time is low. It is possible to download data from a second outer ring but the download time is higher. Algorithms for data collection under this model are presented in (Bhadauria, Isler, and Tekdas 2011).

## Concluding Remarks

Building robotic sensing systems for environmental applications is a challenging frontier for robotics research. Such systems must operate for extended periods of time in unstructured, complex domains. This requires addressing numerous issues at the systems level (e.g. energy efficiency and robust operation) and developing new optimization algorithms for coverage, search, tracking, sensor and path planning for multi-robot, multi-sensor systems. As the field advances, robots can help us solve immense environmental problems our planet is facing.

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