Using Mobile Sensing Nodes for Dynamic Boundary Estimation

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ABSTRACT

This abstract enumerates the challenges in using motion-enabled wireless sensors to characterize boundaries. It also provides a brief overview of our work in boundary estimation and outlines a novel three-dimensional testbed designed to support experiments in boundary estimation.

Keywords

Boundary estimation, mobile sensor networks, mobile computing challenges

1. INTRODUCTION

The detection of delineation between regions in large physical spaces is a highly desirable capability across many domains. Scientists, regulating authorities and public safety officials are interested in studying the propagation of gases and fluids in physical environments. Example applications include the tracking and monitoring of poisonous gases, oil and chemical spills in terrestrial and marine environments, algae blooms and fire spreading. Although some distributed phenomena can be studied using the remote sensing capabilities of satellites or radars, there are many cases where remote observation becomes more challenging in obstructed environments such as urban settings, dense forests and indoor environments. Remote sensing is also practically infeasible with some types of chemical sensing where sensors are required to have physical contact with the chemicals being sensed. Despite the fact that boundary estimation is not an entirely new problem, and has been studied in other domains, its application over large regions imposes a new set of challenges that remain to be addressed. Some initial work in determining boundaries with static sensor networks [6,9] has shown that large deployment densities and heavy-duty computation are required to accurately characterize boundaries with irregular shapes. In this abstract we advocate that scalable systems composed of mobile computing and sensing platforms make a good technology candidate for the development of efficient and reliable boundary estimation methods that can potentially relax the deployment density requirements and at the same time provide more accurate boundary descriptions.

Figure 1 illustrates a simple two-dimensional example of boundary estimation in a town setting. A set of mobile sensor nodes are deployed at a set of predefined observation posts in a town setting to monitor for toxic clouds. Once a toxic cloud is detected, nodes reposition themselves around the perimeter of the cloud and start moving around the cloud to give a more accurate description of its perimeter. In an ideal system one would also require the nodes to return back to their observation posts after the plume is dealt thus creating a reusable system. Figure 2 depicts a hybrid scenario where sensors mounted on cars roaming around the town can give further information about the toxic plume. Even these simple scenarios present a set of challenges that need to be addressed.

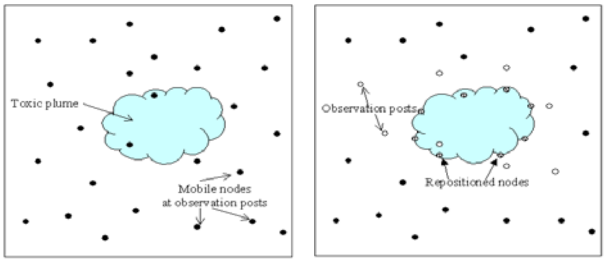

Figure 1 a) Mobile nodes deployed to detect and estimate a toxic plum, b) nodes reposition themselves around the boundary of the plum

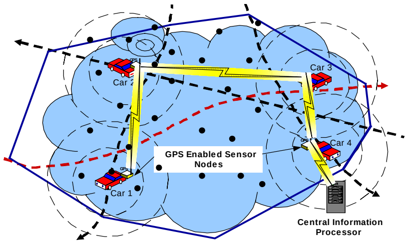

Figure 2 Using uncontrolled mobility to collect information about a boundary

Our presentation begins with an enumeration of the aforementioned challenges, followed by a brief overview of the related work. We conclude with an overview of our efforts towards addressing this problem.

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2. Mobile Computing Requirements for Boundary Estimation

The ultimate goal for distributed boundary estimation is to develop a set of robust and provably correct schemes for describing boundaries using a set of mobile and wirelessly connected nodes. The realization of such a task entails the joint consideration of mobile networking and boundary estimation issues. What is needed for these schemes is an intelligent set of motion control primitives that allows the collaborative control of nodes according to the sensed stimuli. The mobility decisions should be localized, and should preserve network connectivity and take energy and latency requirements into consideration. Moreover since node mobility is often hindered by cost and terrain obstructions in many environments, designers should also consider hybrid approaches that exploit pre-existing sources of mobility. In a town setting for example, sensors mounted on public transportation and public service vehicles to monitor for toxic gases. This sensory information could be used as inputs a set of autonomous mobile nodes that will move in the area of interest to detect the boundary.

Although the design requirements are very application specific, the simple scenario discussed here outlines a set of emerging challenges for the mobile computing community that are enumerated below:

a) *Connectivity maintenance* – Coordinated node motion decisions for detecting and describing boundaries should also preserve network connectivity.

b) *Efficient motion coordination primitives* – Mobile nodes need to coordinate themselves through a set of coordination primitives based on neighborhood relationships that also consider the energy and latency tradeoffs. In the case of toxic plume detection, latency can be life critical.

c) *Reusability* – Economically feasible boundary estimation systems should be designed for reusability. Estimation algorithms should be designed so that they can detect and describe multiple boundaries in space and time. A possible solution would be to have nodes return to a set of pre-determined observation posts after a boundary has been described and dealt with.

d) *Node selection* – In many situations, boundary estimation can be performed efficiently by using a fraction of the nodes in the vicinity of a phenomenon. To accommodate such situations, boundary estimation algorithms should select a suitable subset of the nodes to participate in the estimation process, while preserving the rest of the nodes for future tasks.

e) *Leveraging uncontrolled mobility* – Controlled mobility is often challenged by current technology limitations so it is still hard to imagine autonomous mobile platforms that can go everywhere. Pre-existing mobile entities could be exploited to mitigate these issues by attaching sensors to these entities. When monitoring for poisonous gases, sensors could be attached to public transportation and public safety vehicles that roam around the town. This implies the development of an appropriate set of intelligent information harvesting mechanisms that fully leverage the combination of controlled and uncontrolled mobility.

f) *Energy/latency awareness* – Practical designs need to consider the energy cost of mobility and communication. Moreover, in many applications related to toxic plume detection, the latency associated with the description of the boundary is life critical. This implies that a suitable boundary estimation algorithm should provide a set of latency guarantees for the detection of a chemical plume.

g) *Sensing attributes* – The properties of sensors need to be closely considered during the algorithm development phase. For instance certain types of chemical sensors are point sensors, that is, they need to have direct contact with the chemical being sensed before they can detect it. This attribute will make them unsuitable for use with boundary detection algorithms that assume that each sensor has a sensing radius associated with it like the cases considered in previous coverage work [1].

h) *Boundary properties* – It is expected that different classes of boundary estimation algorithms will have to be designed for different classes of boundaries. Each class of algorithms should consider the boundary attributes. Is the boundary static or dynamic, is there a specific diffusion pattern related to the boundary. Does the boundary have a gradient? In addition to estimating the boundaries, mobile computing systems may become an enabling technology for scientists interested in the study of boundary behaviors?

i) *Energy replenishment strategies* – Since untethered mobile nodes have finite energy, it is natural to consider a set of strategies in which nodes reorganize themselves so that they can occasionally reach a limited set of recharging stations where they can refuel.

j) *Relation to other problems* – To operate effectively in obstructed environments, nodes should be location aware and should have some knowledge of coverage. This suggests that boundary estimation should either jointly consider node localization and coverage, or should use a set of pre-existing solutions and consider the corresponding accuracies.

k) *Synchronization requirements* – Fully distributed mobile node coordination may require synchronous operation. The tradeoffs and requirements of synchronous and asynchronous operation in relation with the communication capabilities of the mobile nodes should be carefully considered.

3. Related Work

The study of boundaries has been traditionally explored in the image processing community [7,8]. These approaches use rigorous centralized processing based on a global view of the image. The limited availability of global view in distributed phenomena hinders the direct application image processing algorithms to the boundary estimation. Researchers in mobile robotics have explored an alternative set of approaches related to boundary estimation. In [7,8] Marthaler et al. present a set of collective motion mechanisms based on energy minimizing curves or “snakes” from image processing. Both algorithms are driven with an environmental detector function that follows a predefined gradient to the plume. Using this function a set of autonomous robots can be placed around the plume. This approach assumes some prior knowledge about the boundary and its concentration. The problem of identifying a target using a set of autonomous robots has been also studied in search problems [5]. These problems can provide a starting point for the development of search algorithms with which mobile nodes can search and identify a plume. A preliminary evaluation of the latency and energy cost of such coordinated searches is presented in [5]. Another recent approach in mobile robotics based on computational geometry constructs is described in [1].

More recent efforts in the sensor networks community have resulted in a collection of schemes related to edge detection in static sensor fields. The work in [2], propose and compare three alternative schemes for edge detection: a statistical approach, a filter-based approach, and a classifier-based approach. Another approach for edge detection is presented in [6]. This approach makes use of the concept of dual space to transform points into lines and lines into points. Despite its elegance, the complexity of this approach on non-linear boundaries makes less applicable in recognizing odd-shaped boundaries created by natural phenomenon. More recently another method for estimating Lipschitz continuous boundaries in static sensor networks is proposed in [9]. This begins with a uniform rectangular partition of the sensor domain and uses a hierarchical pruning strategy that prunes back the original partition to obtain a non-uniform partition adapted to the boundary. The main drawback of static approaches is that they require dense sensor deployments and have limited resolution. We anticipate that the intelligent use of mobility will help to alleviate many problems and will relax the deployment density requirements. At the same time mobile nodes can trace boundaries, thus improving the accuracy of boundary description.

4. Our Approach

Our initial study of boundary estimation is focused on the creation of *reusable* sensor fields estimating boundaries. Our initial formulation assumes that the boundaries are static and that sensors have a point-sensing-range. The point-sensing range assumption implies that a sensor cannot detect the boundary from a distance. It needs to have contact with the boundary in order to detect it. The primary focus of our approach is in the selection of a subset of sensors to participate in the boundary estimation process. The selection is based on the proximity of the mobile nodes to other nodes inside the boundary. Once the selection is complete, the nodes follow a distributed coordination algorithm to reposition themselves along the boundary. Rather than completely describing the shape of the boundary, the selected mobile nodes try to create a perimeter that encloses the boundary.

To better understand the problem constraints and underlying challenges and to quantify the energy costs and tradeoffs between mobility, communication and computation we have also designed a three-dimensional testbed described in Figure 3. This testbed will enable us to instrument complex scenarios that will provide experiment support for boundary estimation. The testbed is comprised of a three-dimensional indoor structure that supports two types of mobile nodes, suspended and nodes-on-wheels. The suspended nodes that can move in the on the *x, y, z*-axes emulating spider-like motion and the nodes-on-wheels have a robotic mechanism so they can roam on the testbed floor. To create artificial boundaries, our tested includes a set of heat and light sources and a projector mounted on the ceiling for projecting boundary images on the testbed floor.

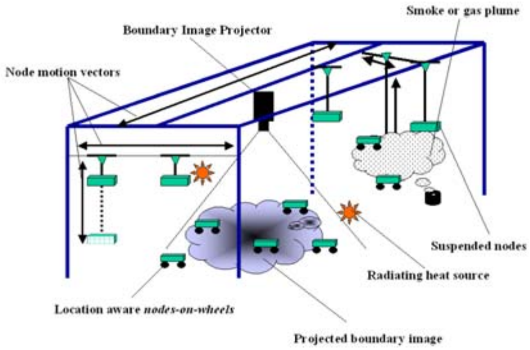

Figure 3 The ENALAB sensor network testbed for boundary estimation

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