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Boundary tracking and estimation of pollutant plumes with a mobile sensor in a low-density static sensor network

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ABSTRACT

Static sensor networks are used to detect concentrations of pollutants exceeding critical thresholds or to delineate the boundaries of contaminated regions in the air or in water. As the density of sensors deployed in the field may be locally insufficient to accomplish this task, it is necessary to add adaptive mobile sensors to the permanent sensing infrastructure. We propose a method for tracking and estimating the boundary of a dynamic plume with a mobile sensor in addition to binary below/above threshold signals from a low-density static sensor network. It is a heuristic method with low computational effort, which is efficient in terms of sensor movement. Neither prior information about the plume nor meteorological data is required. Our approach is applicable for dynamic plumes and operating with a small number of static sensors. We evaluate several variations of the method and parameter combinations using a plume simulated with the atmospheric dispersion model RIMPUFF. We give a number of practical recommendations.

1. Introduction

There are numerous scenarios in research and in emergency response where scientists have to estimate the location and the extent of environmental phenomena. Prominent examples are poisonous chemicals in the air or in water, oil spills, ash clouds, and forest fires. Often it is not necessary to model

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a complete concentration field as a basis for decision making, but the relevant information is the location of the boundary of the phenomenon, i.e. the area where a critical threshold is exceeded. In many cases scientists and decision makers can use data from a network of measurement stations deployed in the field. However, the density of these permanent in-situ sensor networks may be insufficient to adequately estimate environmental boundaries. Additional mobile sensors can be used to collect the missing information. For monitoring the boundaries of highly dynamic phenomena it is necessary to provide these mobile sensors with an intelligent and adaptive sampling strategy. To be able to deploy mobile sensors ad hoc in the field, for instance in a time-critical emergency situation, such a sampling strategy should not depend on any prior information about the observed phenomenon or about the local meteorological conditions.

Mobile sensing strategies for environmental monitoring have been proposed by researchers from multiple disciplines such as (geo)informatics, robotics and automation, signal processing, or control. There are methods for different purposes as for example for locating an emission source (Li et al., 2001; Ishida et al., 2001; Russell et al., 2003; Lochmatter and Martinoli, 2009) or for tracking a moving plume (Brink and Pebesma, 2013). There are several techniques for estimating, covering and tracking the boundaries of environmental phenomena using in-situ sensors. A survey is given in Srinivasan et al. (2012). The majority of these use high density sensor networks. Only a few authors address the problem with mobile sensors with adaptive behavior. A method for generating contour plots using a group of four mobile sensors is presented by Zhang and Leonard (2005). The sensors move along the contour while maintaining a formation that minimizes the least mean squared error in the estimated field and its gradient. Dantu and Sukhatme (2007) propose a technique for a mobile sensor detecting a contour in a scalar field. The sensor computes the local spatial gradient of the field by communicating with a number of static neighboring sensors and performs gradient decent towards the contour. Srinivasan et al. (2008) describe a method for a small number of mobile sensors approaching and covering a contour jointly by a combination of gradient decent and spreading movement. Subchan et al. (2008) and White et al. (2008) present a method for cooperative path planning of two mobile sensors to detect and model the shape of a contaminant cloud. The mobile sensors move through the cloud and the boundary is approximated using splinegons through the entry and exit points. Sinha et al. (2009) extent this work elaborating on coordination of more than two mobile sensors. These authors assume that the contaminant cloud is spreading slowly compared to the sensor movement, with negligible change between entry and exit times of a sensor moving through the cloud.

Kemp et al. (2004) propose a heuristic algorithm for the surveillance of underwater perimeters by unmanned vehicles. From outside the perimeter a vehicle moves towards a known point inside the perimeter, being inside the perimeter it moves away from this point, until it detects a perimeter crossing. Then it starts tracking the perimeter by turning clockwise while being inside the perimeter and counter clockwise while being outside. This method is further developed by Jin and Bertozzi (2007). They introduce an angle correction to increase efficiency, which is based on the assumption that the boundary between the last two crossing points and beyond is a straight line. The applicability of these sensor movement strategies has only been evaluated for static phenomena, or the authors assume that the movement of the sensing vehicles is much faster than that of the observed phenomenon.

We adapt the method proposed by Jin and Bertozzi (2007) for tracking the boundary of a dynamic plume in an environment where a low-density static sensor network is installed. The above threshold signals in the static network are used to approximate the location and the movement of the plume center. Two modifications of the algorithm further increase its efficiency and account for plume dynamics using this additional information:

1. *Movement correction towards the center of the plume:* Instead of assuming a straight boundary as proposed in Jin and Bertozzi (2007) we correct the sensor orientation towards the perpendicular line of the connecting line between the sensor location and the estimated center of the plume. This orientation correction is performed whenever the sensor crosses the boundary and in case the sensor remains outside the plume for more than three consecutive measurements.
2. *Adding the predicted plume movement to the sensor movement to account for plume dynamics:* In every sensor turn the turning angle is added by the angle resulting from the linear combination of the regular sensor movement direction and the estimated plume movement.