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Optimising sampling designs for the maximum coverage problem of plume detection

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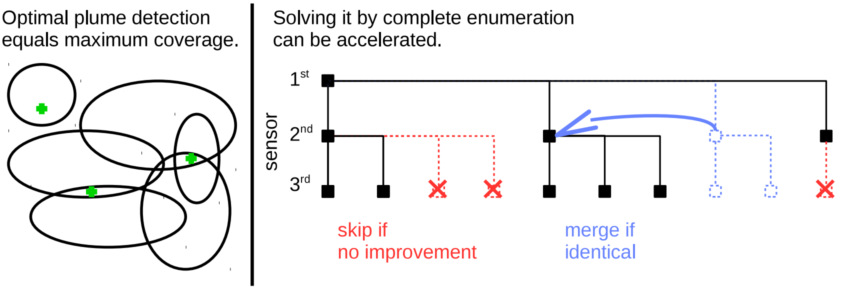
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Sampling design for plume detection is a variation on the maximum coverage problem.
- Complete enumeration can be accelerated by taking advantage of plume similarity.
- Optimal sampling designs often share common sensors and build fences towards sources.
- Greedy search is likely to find almost optimal and sometimes optimal designs.
- Heuristics found single optimal sensors, spatially almost optimal results were rare.

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ABSTRACT

The location of sensors to detect outbreaks of hazardous plumes in the atmosphere can be improved by considering possible paths

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of such plumes. Atmospheric dispersion models can provide simulations of such paths under realistic weather conditions. Numeric simulation always goes along with discretisation, and if a plume is detected or not can be regarded as a binary question. Thus optimising the locations of a fixed number of sensors can be regarded as finite; in fact it is a variety of the classical maximum coverage problem. We present an algorithm to completely solve this problem. It is based on complete deep tree search that finds all globally optimal sensor configurations, but the effort is reduced by skipping non-promising configurations and deleting redundant data. To determine the effort and to learn about optimal sensor configurations, the algorithm was tested on several scenarios based on plume simulations or on random data. This was completed by some theoretical results on the effect of problem size and plume detection probability on the effort. Finally we used the determined optimal configurations to evaluate two well known heuristics: greedy search and a genetic algorithm.

1. Introduction

Our motivation comes from radiological emergency preparedness. One of the main purposes of radioactivity monitoring is detection of accidental radioactive plumes. Such potential plumes can only be emitted from one of the few, known locations of nuclear facilities and then be dispersed by the wind. Therefore the potential distribution of radioactivity in the atmosphere can be modelled by a sample of possible plumes, generated by an atmospheric dispersion model—rather than by a parametric random field. The aim was to find the locations where a given number of sensors can best detect these plumes; this means, detect as many of the sample plumes as possible. Discretisation through numeric modelling reduced the problem to be finite and thus solvable by complete enumeration. However, this can be very time consuming, as the number of possible sensor configurations grows more than exponentially with the size of the problem; therefore we propose a new Accelerated Complete Search (ACS) algorithm. It returns all globally optimal sensor configurations, but is accelerated by skipping and merging configurations.

In Section 2 we give an overview over the state of the art of spatial sampling design optimisation. Next we define our problem and show how it relates to the classical maximum coverage problem, and we give the heuristics that are common to solve it in Section 3. This is the basis for our new Accelerated Complete Search algorithm that is defined in Section 4. The following sections address the evaluation of this ACS algorithm: in Section 5 we theoretically deduce some aspects of the influence of problem size and plume detection probability on the effort. Full evaluation of the effort under various conditions is done empirically. The setup of the test scenarios, including the software and data used for the plume simulations, is given in Section 6. As the effort of ACS is high, heuristics remain an important alternative and the globally optimal sensor configurations provide an objective benchmark to assess them. Greedy search is the classical deterministic heuristic to solve this problem and the probabilistic binary genetic algorithm looked promising in similar settings (Helle and Pebesma, 2013), therefore we repeated all tests with these algorithms. The empirical results about the effort of ACS, about properties of optimal sampling configurations, and about the goodness of the heuristics are given in Section 7, followed by a final discussion in Section 8.

2. Optimisation algorithms for spatial sampling

Spatial sampling design has been an issue in environmental research since decades. Here we want to give an overview of this field. In most applications, spatial sampling designs are either based