Information Fusion 36 (2017) 130–148

Contents lists available at ScienceDirect

Information Fusion

journal homepage: www.elsevier.com/locate/inffus

A review of source term estimation methods for atmospheric dispersion events using static or mobile sensors

Michael Hutchinson[a], Hyondong Oh[b,*], Wen-Hua Chen[a]

[a] Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, United Kingdom
[b] School of Mechanical and Nuclear Engineering, UNIST, Ulsan, South Korea

ARTICLE INFO

Article history:
Received 25 August 2016
Revised 26 October 2016
Accepted 14 November 2016
Available online 15 November 2016

Keywords:
Source estimation
Inverse modelling
Boundary tracking
Atmospheric dispersion
Optimisation
Bayesian inference
Source localisation
Dispersion modelling

ABSTRACT

Understanding atmospheric transport and dispersal events has an important role in a range of scenarios. Of particular importance is aiding in emergency response after an intentional or accidental chemical, biological or radiological (CBR) release. In the event of a CBR release, it is desirable to know the current and future spatial extent of the contaminant as well as its location in order to aid decision makers in emergency response. Many dispersion phenomena may be opaque or clear, thus monitoring them using visual methods will be difficult or impossible. In these scenarios, relevant concentration sensors are required to detect the substance where they can form a static network on the ground or be placed upon mobile platforms. This paper presents a review of techniques used to gain information about atmospheric dispersion events using static or mobile sensors. The review is concluded with a discussion on the current limitations of the state of the art and recommendations for future research.

1. Introduction

The growing threat of terrorism [1], the Fukushima nuclear accident (2011) [2] and the Eyjafjallajökull volcanic eruption (2010) [3] are significant events with a detrimental impact on public health and several industries including aviation and transport. What these events have in common is the dispersal of hazardous material into the atmosphere. Atmospheric transport and dispersion (ATD) models are used to forecast the spread of the contaminants to provide emergency responders with crucial intelligence to aid efficient response and post emergency assessment. For an accurate forecast, several variables are needed as an input to the model including, but not limited to: meteorological data, the strength of the release and its location. In general, sparse meteorological data are available from local weather stations or even across the globe. The strength, location and time of the release are often unknown, and thus should be inferred from relevant sensor measurements.

For visibly detectable substances, such as volcanic ash, satellite images are the preferred form of measurement data [3]; however, this approach is limited in terms of spatial and temporal resolution of the satellite and obstruction by clouds. Alternatively, sensors that can measure the concentration of ash or a chemical, biological, radiological or nuclear (CBRN) substance are available. The determination of source parameters from these sensor measurements is a problem in inverse modelling; the inverse problem is highly non-linear, ill-posed [4] and subject to input data that is typically sporadic, noisy and sparse [5]. Traditionally, with regards to CBRN source term estimation (STE), a network of static sensors on the ground are used to estimate the source term as illustrated in Fig. 1. A benefit of this approach lies in early detection near places of strategic importance (e.g. nuclear power-plant sites). However, for accidents or deliberate attacks in random places, it is infeasible to cover all regions of importance with sensors dense enough to determine the source before it has spread significantly.

With the technological developments in sensing and robotics, mobile sensors such as unmanned aerial vehicles (UAVs) are now well equipped for STE. Mobile sensors provide the additional ability to perform boundary tracking of the contaminant and source seeking to aid in the emergency response. Boundary tracking will provide a direct picture of the spatial extent of the contaminant without modelling efforts. For instance, mobile sensors have been employed to determine the spread of a range of boundaries such as oil spills [6], forest fires [7], ocean temperatures [8] and the growth of harmful algae bloom [9]. Since the ultimate goal of STE is to predict the spread of hazardous material, the boundary can be used as a means to verify the source estimate. In addition, the detected boundary can be used as additional observa-

* Corresponding author.
E-mail address: h.oh@unist.ac.kr (H. Oh).

http://dx.doi.org/10.1016/j.inffus.2016.11.010

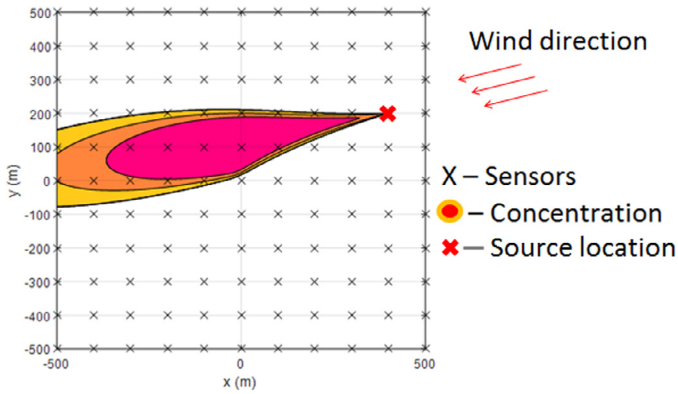

Fig. 1. Example of a static sensor network.

tional data within STE algorithms and to constrain the parameter space. Source seeking will attempt to drive the robot to the location of an emitting source without a direct attempt to estimate the release rate; similarly to boundary tracking, this provides an estimate without modelling efforts. Using mobile sensors for STE introduces an additional area of research concerning how to optimally move the sensor in order to produce the best estimate of source parameters in the minimum amount of time or effort. The method is related to a number of robotics research areas such as autonomous search, multiple robot cooperation, informative path planning and control.

In this paper, the techniques used to gain information about atmospheric dispersion events are explored where the substance is not detectable visibly. This includes STE using static or mobile sensors, boundary tracking and source seeking. Although there are a few reviews on STE using static sensors [4,10,11], this paper aims to provide a more up to date and thorough review, featuring many new developments in the area and also an extension to the application of mobile sensors.

This paper is organised as follows. Section 2 provides a brief discussion of dispersion modelling, the adjoint source-receptor relationship and STE datasets. Section 3 contains a review of STE techniques using a static network of sensors. Section 4 presents a review of the literature on the use of mobile sensors to gain information of dispersing phenomena, specifically boundary tracking, source seeking and STE. Section 5 provides conclusions and recommendations for future research.

2. Preliminary background

Dispersion modelling, the adjoint source-receptor relationship and experimental dispersion datasets are of high importance to source term estimation and will be referred to several times throughout this paper. However, since they are not the main focus of this review, a brief outline is provided in this section. For more detailed information on atmospheric dispersion an interested reader is referred to [12].

2.1. Dispersion modelling

Atmospheric transport and dispersion models are used to estimate the dispersion of pollutants into the atmosphere. Models in the literature vary in terms of applicable scenarios, assumptions and complexities. Five types of fundamental dispersion models exist along with a number of hybrids and extensions of them as below:

- Box models [13]
- Gaussian plume models [14]
- Lagrangian models [15]
- Eulerian dispersion models [16]
- Dense gas models [17,18].

A comprehensive list of atmospheric transport and dispersion (ATD) models is provided by the US Environmental Protection Agency (EPA), including sections for recommended and alternative models. For more information a review can be found in [19]. In this section, the Gaussian plume model is described in further detail as it has been popular throughout the literature in STE due to its simplicity and fast computation. The key parameters in the model are the atmospheric turbulence coefficients σ_y and σ_z which represent standard deviations that describe the crosswind and vertical mixing of the pollutant. Several derivations of these values exist where a popular approach is based on Pasquill's atmospheric stability class [20]. The equation of the Gaussian plume is derived from the turbulent diffusion equation by assuming homogeneous, steady state flow and a steady state point source, resulting in:

$$C(x,y,z,Q) = \frac{Q}{\bar{u}\sigma_y\sigma_z 2\pi}\left(\frac{-y^2}{2\sigma_y^2}\right)\left[\exp\left(\frac{-(z-h)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+h)^2}{2\sigma_z^2}\right)\right] \tag{1}$$

where C is a concentration at a given position, Q is the release rate, x, y and z are the downwind, crosswind and vertical distances, and $\bar{u}$ is the mean wind speed at the height h of the release [3]. Several extensions of the Gaussian plume model exist to overcome some of its limiting assumptions such as the Gaussian puff model.

2.2. The adjoint source-receptor relationship

The adjoint source-receptor relationship is created by an inverse run of an ATD model from a sensor. Effectively the ATD model is run where sensors act as sources and meteorological variables such as wind speed are reversed. Concentrations expected at that sensor can then be calculated for any source term by computing the inner product of the source distribution and the adjoint concentration field [21].

Within the literature, the adjoint source-receptor relationship has been used standalone to estimate the source term [22], and to quantify the uncertain relationship/sensitivity between source parameters and sensor concentration readings [23]. By using the adjoint, the number of potentially expensive dispersion model runs can be significantly reduced as a single adjoint can be used to test multiple inferences [21]. This provides great benefit in scenarios which prefer a complex and computationally expensive ATD model. However, the adjoint can be limited by non-linearities in the concentration field and, in some complex scenarios (e.g. urban environments), the backwards and forwards dispersion runs will not match. This can be caused by effects from building interactions or puff splitting. Nonetheless, these complex events have seen limited research in the literature on STE.

A simplified version of the adjoint models are back trajectory techniques, where only the inverse run is used. The method is effective in splitting up regions where a source may occur by incorporating null sensor measurements to determine where it is likely the source is not present [24], effectively reducing the parameter space for the location estimate. The backward trajectory techniques have a number of limitations. The most critical of which is the reliance on accurate and rich meteorological information. Under situations where meteorological data are inaccurate, unreliable or unavailable, the accuracy of STE will suffer. Despite this, the method is effective when used to define likely source regions as an initial guess in estimation algorithms.