PhD Proposal Form

Title:

Recursive estimation of spatial random structure using an autonomous sensor.

Required Student Background: Filtering Theory, Stochastic Processes, Non-linear Signal Processing, Shape/Pattern theory

Supervisors

Maria-João Rendas, 70%, I3S, sensor-driven navigation
José Leitão, 30%, IST, Non-linear Filtering and Estimation theory
Patrick Luyten, Mumm[1], physical (circulation and transport) models

Innovative aspects

To apply non-linear estimation techniques to represent the knowlegde acquired by a mobile sensor about the geometric structure of the spatial field that surrounds it, and to use this knowledge to design effective observation strategies to estimate a number of associated features. The results of the study will be applied to the problem of detecting a leaking source in a turbulent flow.

Description

The goal of this thesis is to design recursive decision and estimation model-based algorithms that guide in an efficient way an autonomous sensor in order to observe certain features of the *random binary field* inside which it moves.
A **Bayesian approach** will be pursued, assuming that the geometry of the observed random field is well modeled by a *non-homogenous Random Closed Set* (RCS) [4], for which a parametrized form of the distributions of the two underlying random processes, the point process (that describes the spatial distribution of the objects that compose the field) and the shape process (that describes the geometry of the individual objects) is known. RCS models have been shown to describe in an appropriate manner the geometric characteristics of many (binary) natural fields (e.g. the dispersion and shape of tree images in aerial photography, of benthic biological colonies,...), and have been shown to be tractable environmental models for autonomous robots' navigation [5, 6]. In this work, the field will be assumed static.
The desired features are modelled as known functions of the parameters of the RCS distributions (in particular of the intensity function of the point process). Formally, we desire to recursively update the posterior distribution of the parameters of the distributions of the shape and point processes, that efficiently summarises the information collected by the sensor, and provides the necessary information to design efficient observation strategies. Currently studied solutions are particle filters [7] (that represent the density by the distribution of a cloud of points in parameter space) and the propagation of Gauss mixtures [8,9]. The latter approach has the advantage of being able to macroscopically flag multi-modal (ambiguous) situations, which can be used to trigger active observation actions.

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The feasibility of the approach has been tested, under simplistic models of the spatial random field, in [10], and one of the main goal of this thesis is to integrate in the estimation step random models with physical plausibility. Conditions for the existence *of consistent* estimators of different parameters of the intensity function will be studied, and a characterisation of the rate of convergence of the adaptive observer should be established.

The work will consider a specific application framework, wich will be used to guide the choice of models and constrain the admissible observation stategies: *locating the source of a polluting product dispersed in a turbulent flux*, using the measures taken along its trajectory by a moving chemical sensor. This problem finds applications in several tasks of environmental protection. The characteristics of the turbulent flux create highly localised regions of large concentration of the leaking product, enabling its detection even at large distances from the polluting source.
The problem of guiding an autonomous sensor towards the source of a product being dispersed in a turbulent (non-stationnary, non-homogeneous, highly spatially discontinuous) has been the subject of recent studies, e.g. [1,2]. As an alternative to exhaustive coverage of the surveyed area, necessarily inefficient and time-consuming, or to gradient-climing like techniques, that require large integration times, and thus impose a very slow progression of the platform, a number of research groups have been studying the transposition of animal foraging behaviours to this problem. These approaches, whose feasibility has been confirmed by real experiments [3], are affected by three major drawbacks: (i) they are critically dependent on the possibility of measuring on board the moving sensor the dominant fluid velocity, which is very difficult in real situations, given the non-stationnary and non-homogenous nature of turbulent fluxes; (ii) they are critically dependent on a set of heuristically tuned parameters (that determine the oscillation between periods of counter-flux progression and search periods, as well as the form of the search trajectories used) which are in the approaches presented held constant during all search mission, i.e., in regions near and far away from the source; (iii) they only use the information contained in the positive measures (product detection) neglecting the information about the field’s geometry contained in the regions of weak product density. Consideration of the parametrized random spatial models that will be used in this thesis enables the formal analysis of the performance of these heuristic approaches, and should enable efficient adaptive tuning of its defining parameters.

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[2] A. T. Hayes, A. Martinoli, R. M Goodman. (2002) Distributed Odor Source Localization. Special Issue on Artificial Olfaction, Nagle, H. T., Gardner, J. W., and Persaud, K. (Eds.), IEEE Sensors 2(3), 260–271.

[3] J.A. Farrell, S. Pang, (2003), Chemical Plume Tracing Experimental Results with a REMUS AUV , Proc. *OCEANS 2003*.

[4] D. Stoyan, W.S. Kendall, J. Mecke (1995), *Stochastic Geometry and its Applciations*, John Wiley & Sons.
[5] S. Rolfes, ”*Stochastic Geometry: An approach to featureless perception-based robot navigation*”, Phd Thesis, Lab. I3S, Université de Nice Sophia Antipolis, December 2002.
[6] S. Rolfes, M. J. Rendas, ”*Statistical environment representation for navigation in natural environments*”, Robotics and Autonomous Systems, Elsevier, Vol. 41, pp 129-136, 2002.
[7] A. Doucet, S. Godsill, C. Andrieu, *On sequential Monte Carlo sampling methods for Bayesian filtering*, Statistics and Computing Series, Springer Science & Business Media B.V., 2000.
[8] J. Leitão and J. Moura, *Acquisition in Phase Demodulation: Application to Ranging in Radar/Sonar Systems*. IEEE Transactions on Aerospace and Electronic Systems, 31 (2):581-599, April 1995.
[9] J. Leitão and M. Figueiredo, *Absolute phase image reconstruction: a stochastic nonlinear filtering approach*, in IEEE Transactions on Image Processing, vol. 7, no. 7, pp. 868-882, June 1998.
[10] Maria-João Rendas, *Stochastic Maps for Chemical Plume Tracing under Turbulent Flow*, Proc. IFAC Conf. On Intel. Autonomous Vehicles, Lisbon, Portugal, July 2004.

Required Infrastructures
Hardware: No special needs. Software: Numerical models of transport in turbulent fluxes.

Mobility Plan
The fellow will be based at I3S. He/she should spend a period of ¾ months at Mumm, with the goal of developing and tuning the prior stochastic Random Set Models for the random dispersion, making several visitis to IST for complementary guidance in the formulation of the non-linear estimator.

Added value of SIGNAL for this study
This study requires the combination of competencies in sensor-driven perception, random geometric models, non-linear filtering as well as domain specific expertise about the physical models governing the dispersion in turbulent fluxes, and exploits in an exemplar manner the complementary competencies of members of Signal.

External Impact/ Other Participants
The potential impact of the application of advanced signal models and processing techniques in the area of environmental survey has been presently recognised, and several sucessfull initiatives to attract Statistics and Signal Processing Departments to a closer collaboration with environmental agencies have been documented, of which the Geophysical Statistics Program at the National Center for Atmospheric Research, USA/Canada, is a large scale exemple[2]. The study proposed here appears in the continuity of an on-going collaboration between I3S and Mumm in the area of adaptive

[2] Geophysical Statistics Program at the National Center for Atmospheric Research, Final Project Report DMS-9312686 7/93-7/99, December 15, 2004,

survey design, and will help increase the both the awareness of the Statistical Signal Processing community to the opportunities and needs of this important area, as well as increase the recognition of the impact of sophisticated signal processing methodologies in enviromental sciences.