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Concurrent multi-target localization, data association, and navigation for a swarm of flying sensors

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Abstract

We are developing a probabilistic technique for performing multiple target detection and localization based on data from a swarm of flying sensors, for example to be mounted on a group of micro-UAVs (unmanned aerial vehicles). Swarms of sensors can facilitate detecting and discriminating low signal-to-clutter targets by allowing correlation between different sensor types and/or different aspect angles. However, for deployment of swarms to be feasible, UAVs must operate more autonomously. The current approach is designed to reduce the load on humans controlling UAVs by providing computerized interpretation of a set of images from multiple sensors. We consider a complex case in which target detection and localization are performed concurrently with sensor fusion, multi-target signature association, and improved UAV navigation. This method yields the bonus feature of estimating precise tracks for UAVs, which may be applicable for automatic collision avoidance. We cast the problem in a probabilistic framework known as modeling field theory (MFT), in which the pdf of the data is composed of a mixture of components, each conditional upon parameters including target positions as well as sensor kinematics. The most likely set of parameters is found by maximizing the log-likelihood function using an iterative approach related to expectation-maximization. In terms of computational complexity, this approach scales linearly with number of targets and sensors, which represents an improvement over most existing methods. Also, since data association is treated probabilistically, this method is not prone to catastrophic failure if data association is incorrect. Results from computer simulations are described which quantitatively show the advantages of increasing the number of sensors in the swarm, both in terms of clutter suppression and more accurate target localization.

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1. Introduction

This paper describes a probabilistic technique for performing multiple target detection and localization based on data from a swarm of flying optical sensors, for example to be mounted on a group of micro-UAVs (unmanned aerial vehicles). In this approach, target detection and mapping are performed concurrently with data association and sensor tracking. This fact gives our method a performance advantage, in principle, over most existing techniques in which detection and data association are performed as separate steps [1–3]. We cast the problem in a probabilistic framework known as modeling field theory (MFT), in which the pdf of the data is composed of a mixture of components, each conditional upon parameters including target positions as well as sensor kinematics [1,4–6]. The most likely set of parameters is found by maximizing the log-likelihood function using an iterative approach related to expectation-maximization. In terms of computational complexity, this approach scales linearly with number of targets and sensors, which represents a significant improvement over most existing methods. Also,

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since data association is treated probabilistically, this method is not prone to catastrophic failure if data association is incorrect.

The problem falls under the broader area of "swarm intelligence", which is currently an active area of research. In military surveillance applications, progress in swarm intelligence is expected to revolutionize the ways in which unmanned aerial vehicles (UAVs) are used. The value and potential of UAVs have been demonstrated in recent military conflicts, where they have been used for dangerous and/or tedious missions to reduce the risk of human casualties. It is felt that UAV cooperation and swarming behavior may yield advantages that will make UAVs, in general, even more valuable [7–9]. The most obvious advantage would be an increase in mission success rates due to improved UAV survivability—hostile defenses would be taxed by the sheer numbers in the swarm. Also, swarms might be deployed in smart ways to increase the efficiency of the geographical coverage. Finally, having access to swarms of sensors may make it easier to detect and discriminate low signal-to-clutter (S/C) targets by exploiting correlations between different, complementary, sensor types and/or different aspect angles. In a sense, the collection of small sensors on individual UAVs would be equivalent to a wide aperture, which can be exploited to yield much better location and velocity estimates for targets, as well as better detection and discrimination performance.

In order to make deployment of UAV swarms feasible, it will be necessary for UAVs to operate more autonomously than is currently possible [7,9]. Presently UAVs operate more or less like "binoculars with wings" with human operators performing most duties, including low-level functions like image analysis/interpretation and obstacle/collision avoidance. Human operators (and data links from UAVs to operators) would become quickly overwhelmed attempting to control an entire swarm of UAVs. The approach discussed in this paper is designed to reduce the load on human operators by providing computerized interpretation of images from multiple sensors. A by-product of the approach is a set of precise tracks for both targets and UAVs that may be applicable to automatic collision avoidance.

One might think it unnecessary to compute UAV positions, since these can be measured directly using onboard inertial devices and global-positioning systems (GPS). However, the accuracy of GPS and inertial measurements may be too rough to allow a particular target's image (signature) in one frame to be reliably associated with its corresponding image in another frame (we discuss this "data association problem" below in more detail), especially if there are many closely spaced targets. For example, the typical accuracy of GPS is on the order of ±10 m [10]. Also, while inertial devices and GPS measure absolute position, they do not measure position relative to potential obstacles. The algorithm described here provides a framework for fine-tuning information from a GPS using outputs from visual (or other) sensors. Thus, in this problem the term "sensor fusion" not only describes combining information from multiple visual sensors, but it also describes combining outputs from visual sensors with outputs from GPS sensors. For optimum performance, all functions need to be performed concurrently [2,3]: signature association requires accurate UAV tracking, while accurate localization of targets and UAVs requires signature association.

The algorithm works as follows. Consider the case in which multiple UAVs fly over a group of targets, acquiring digitized images (image frames) at multiple times. Within these images, we refer to the group of pixels associated with each target as a "signature". For each signature in each image frame the data set consists of (a) a vector of classification features computed from the signature, (b) the position of the signature on the image focal plane, (c) the time of acquisition for the corresponding image frame, and (d) (optional) the output of onboard GPS or inertial devices. From the aggregate data, we wish to identify targets of interest, and compute precise tracks for both UAVs and objects in the scene. This task is accomplished within the framework of *modeling field theory* (MFT) [1], as follows. First, a model of the data is developed, where model parameters include locations and features of targets, and coefficients of UAV equations of motion. By incorporating sensor errors, a statistical model is obtained. The parameters are then estimated by maximizing the log-likelihood function, which gives a quantitative measure of how well the model fits the set of measured data.[1] MFT maximizes the likelihood in the space of all parameters and all possible mappings between targets and data, to associate signatures with targets and iteratively solve for the parameters in an efficient manner. Thus, we are not plagued with a combinatorial search during data association like other optimum techniques such as *multiple hypothesis tracking* (MHT). In Sections 2 and 5 we further compare our technique with existing approaches.

Modeling field theory (MFT) is a general approach used to combine both physical and statistical models [1]. Whereas statistical analysis is a standard tool for analyzing a single physical process, standard techniques are not appropriate when multiple, competing, physical processes are involved, including statistical uncertainty and unknown physical parameters. However, MFT is explicitly designed for these types of problems. Historically, MFT describes biological systems in which neuronal fields are determined by physical and statistical models [1]. In practice, the convergence of MFT can be proven using expectation-maximization (EM), although prior to MFT EM was never before applied in this manner. Section 2 discusses in more detail how MFT relates to other EM-based approaches.

The paper is organized as follows. Section 2 provides a review of the relevant literature, and a comparison of our

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[1] Of course, the log-likelihood will only measure the "goodness of fit" between the model and the data to the extent that the general form of the model is correct.

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