Introduction to the Issue on Multitarget Tracking

MULTITARGET tracking has a long history spanning over 50 years and it refers to the problem of jointly estimating the number of targets and their states from sensor data. Today, multitarget tracking has found applications in diverse disciplines, including, air traffic control, intelligence, surveillance, and reconnaissance (ISR), space applications, oceanography, autonomous vehicles and robotics, remote sensing, computer vision, and biomedical research. During the last decade, advances in multitarget tracking techniques, along with sensing and computing technologies, have opened up numerous research venues as well as application areas.

The multitarget tracking problem in the presence of false alarm and sensor probability of detection less than unity is much more complex than the standard filtering problem. Apart from process and measurement noises in the dynamic and measurement models, respectively, one has to contend with much more complex sources of uncertainty, such as the measurement origin uncertainty, data association, false alarm, missed detections, and births and deaths of targets. The goal of this special issue is to explore recent advances in the theory and applications of multitarget tracking with a focus on novel algorithms and methods.

Our special issue begins with a tutorial by Mahler on finite set statistics (FISST) for multitarget detection and tracking. In contrast to the data association-based traditional algorithms such as multiple hypothesis tracking (MHT) and joint probabilistic data association (JPDA), the finite set statistics (FISST)-based data association-free Bayesian multitarget filtering algorithms, introduced by Mahler, have gained a great deal of attention in the tracking community during the last decade. This tutorial summarizes the FISST concepts and techniques for multisensor, multitarget detection and tracking and sets the foundation for multitarget filtering algorithms such as the probability hypothesis density (PHD), cardinalized PHD, (CPHD), and multi-Bernoulli filters.

After the tutorial, the next two papers investigate new techniques for joint multitarget filtering and parameter estimation. Knowledge of parameters such as bias in sensor states and measurements, and uncertainty in clutter intensity and detection probability profile commonly arise in multisensor multitarget tracking systems. Accurate estimation of such parameters is crucial for the subsequent quality of target state estimates. These two papers address this parameter estimation problem in a multitarget context with the advantage of not requiring data association. The paper by Ristic *et al.* presents a particle PHD filter for bias estimation in sensor calibration. The paper by Vo *et al.* presents a multitarget multi-Bernoulli filter that can accommodate nonlinear models and adaptively learns nonhomogeneous clutter intensity and probability of detection while filtering.

The next three papers deal with the technique known as track before detect (TBD)—an approach that is applicable in scenarios with low signal-to-noise ratios where it is often necessary to work with raw measurements without a detection process. The paper by Nannuru *et al.* presents a computationally-tractable approach to process measurements from superpositional sensors via the PHD/CPHD concepts. Experiments using acoustic amplitude sensors and a radio-frequency tomography sensor system show promising performance. Next, the paper by Yi *et al.* develops a computationally efficient TBD approach to multiple targets. In particular, the high dimensional maximization problem in dynamic programming based TBD is suboptimally solved by utilizing gating to cluster adjacent targets—an approach that enables independent treatment of target groups leading to significant computational savings. Finally, Davey *et al.* review recent developments in Histogram Probabilistic Multi-Hypothesis Tracker (H-PMHT) and present a unified framework for H-PMHT suitable for various appearance models that characterize the likelihood of the sensor image.

The papers in the Multiple Detection Systems category explore techniques to address an important practical issue that multitarget trackers have to contend with in certain surveillance systems. The common assumption in most conventional tracking algorithms is that a target can generate at most one measurement per scan. However, in certain applications such as the over-the-horizon radar (OTHR) tracking problem, multiple detections per scan can arise from a point-target due to multipath propagation. Thus, in addition to the measurement origin uncertainty, this problem also introduces propagation mode uncertainty. The paper by Sathyan *et al.* presents a novel algorithm called multiple detection MHT (MD-MHT) to effectively track multiple targets in such multiple detection systems. This problem is also addressed by Habtemariam *et al.*, where they develop an algorithm termed multiple detection JPDA (MD-JPDA) and compare its performance with the Posterior Cramér–Rao Lower Bound (PCRLB). Finally, multiple detections can also arise in extended target tracking whereby high-resolution sensors generate multiple detections per scan from the same target. A CPHD filter-based technique, which relaxes the Poisson assumptions in target and measurement numbers, is presented by Lundquist *et al.* for such extended target tracking problems.

The next two papers are in the Extensions to PHD Filtering category. Specifically, we have two original contributions that enrich the tools for PHD/CPHD filtering. The work by Pace *et al.* establishes a connection between the PHD recursion and spatial branching processes, which gives a generalized Feynman–Kac systems interpretation of the PHD filtering equations and enables the derivation of mean-field implementations. This work provides a principled means for obtaining target tracks and alleviates the need for pruning, merging and clustering for the estimation of multitarget states in particle PHD filtering. Following this, the work by Lundgren *et al.* derives equations for a CPHD filter for the case of spawning of targets under the assumption that the cardinality distribution of the spawning targets is either Bernoulli or Poisson. Their simulations show that the proposed filter responds faster to a change in target number due to spawned targets than the original CPHD filter.

With the advent of sensor networks, distributed multitarget tracking is becoming an important problem. In this special issue, we have two independent works on distributed PHD/CPHD filtering. The paper by Battistelli *et al.* presents

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a consensus CPHD filter for distributed multitarget filtering over a network of sensors. This is a fully distributed, scalable and computationally efficient solution for heterogeneous and geographically dispersed network of sensors with sensing, communication and processing capabilities. The second paper, by Uney *et al.*, develops algorithms for distributed multisensor multitarget tracking (DMMT) by combining a generalized version of covariance intersection, based on exponential mixture densities with random finite sets. Subsequently, the authors derive PHD recursions and implement the algorithm using sequential Monte Carlo (SMC) methods.

Apart from the above papers on various aspects of multitarget tracking, there are other specific problems and theoretical issues we have considered as well. The remaining part of this special issue is devoted to three papers representing a few promising directions. The first paper, by Boquel *et al.*, explores the multitarget tracking problem with state constraints available for multiple scans. It develops a robust sequential Markov Chain Monte Carlo (MCMC)-based multi-scan state constrained smoother to fully exploit the potential benefits guaranteed by a knowledge-based smoother for this problem. The subsequent paper, by Lee *et al.*, presents the first solution for simultaneous localization and mapping (SLAM) with dynamic targets. In particular, it employs the concept of single-cluster PHD filtering for SLAM with both dynamic and static features, taking into consideration the challenges that SLAM presents over target tracking with stationary sensors, such as changing fields of view and a mixture of static and dynamic map features.

Finally, we have a theoretical contribution relating to the asymptotic efficiency of the PHD filter. Although the PHD filter has been receiving considerable attention during the last decade, mostly from an implementation perspective, very little is known about its asymptotic performance. The paper by Braca *et al.* is an original study which shows that in the static case, the PHD asymptotically behaves as a mixture of Gaussian components, whose number is the true number of targets, and whose peaks approach the neighborhood of the classical maximum likelihood estimates.

Clearly, the papers in this special issue span a wide range of important theoretical and practical topics in multitarget tracking. We hope that this special issue will promote future research and inspire novel approaches to address the many important multitarget tracking challenges. Some potential areas of future research include computationally efficient, robust, and scalable distributed tracking algorithms for large scale networks, particularly with the ability to cope with bandwidth constraints and data degradation; tracking algorithms related to big data; algorithms for space object tracking—a challenging problem for the safety of future space missions and international security; and integrated tracking and sensor control for multisensor multitarget systems. Finally, error bounds, optimality, and consistency of multitarget trackers are fundamental issues that need attention—ones that will enrich multitarget tracking theory and provide further insights into algorithm design for specific applications.

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