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Overview of Bayesian sequential Monte Carlo methods for group and extended object tracking

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ABSTRACT

This work presents the current state-of-the-art in techniques for tracking a number of objects moving in a coordinated and interacting fashion. Groups are structured objects characterized with particular motion patterns. The group can be comprised of a small number of interacting objects (e.g. pedestrians, sport players, convoy of cars) or of hundreds or thousands of components such as crowds of people. The group object tracking is closely linked with extended object tracking but at the same time has particular features which differentiate it from extended objects. Extended objects, such as in maritime surveillance, are characterized by their kinematic states and their size or volume. Both group and extended objects give rise to a varying number of measurements and require trajectory maintenance. An emphasis is given here to sequential Monte Carlo (SMC) methods and their variants. Methods for small groups and for large groups are presented, including Markov Chain Monte Carlo (MCMC) methods, the random matrices approach and Random Finite Set Statistics methods. Efficient real-time implementations are discussed which are able to deal with the high dimensionality and provide high accuracy. Future trends and avenues are traced.

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1. Motivation: Why is group and extended object tracking important? Differences and similarities

In recent years there has been an increasing interest in tracking a number of objects moving in a coordinated and interacting fashion. There are many fields in which such situations are frequently encountered: video surveillance, sport events, biomedicine, neuroscience, meteorology, situation awareness and search rescue operations, to mention but a few. Although individual objects in the group can exhibit independent movement at a certain level, overall the group moves as one whole, synchronously with respect to the individual entities and avoiding collisions.

Terminology. *Groups* are structured objects, formations of entities moving in a coordinated manner, whose number varies over time because targets can enter a scene, or disappear at random times. The groups can split, merge, can be relatively near to each other or move independently of each other. What is typical for group formations is that they maintain certain patterns of motion. Some typical examples are: formations of aircrafts and ships, respectively, for air traffic control, sea, harbor or land surveillance [45,124], flocks of bird migration trajectories for ecological purposes, tracking groups of cells [38,107,149,127] (for in vitro purposes, stem cells, cardiovascular treatment and other medical diagnostics), a group of robots (for industrial tasks), a group of football players [152] in sport videos, convoys of vehicles and groups of pedestrians for traffic management [3]. Within this broad range of problems, one can distinguish two main classes: (1) tracking of multiple groups with only a few components per group, which is called *small groups tracking*, and (2) groups with a relatively large number of constituents whose individual members cannot be easily distinguished, termed *large groups*. Large groups are also often referred as to *crowds* or *clusters*.

A related but distinct is the problem of tracking extended objects, such as a cyclist and maritime vessels [5]. *Extended objects* cannot be considered as points but instead have a spatial extent characterizing their size or volume [74]. They are usually modeled

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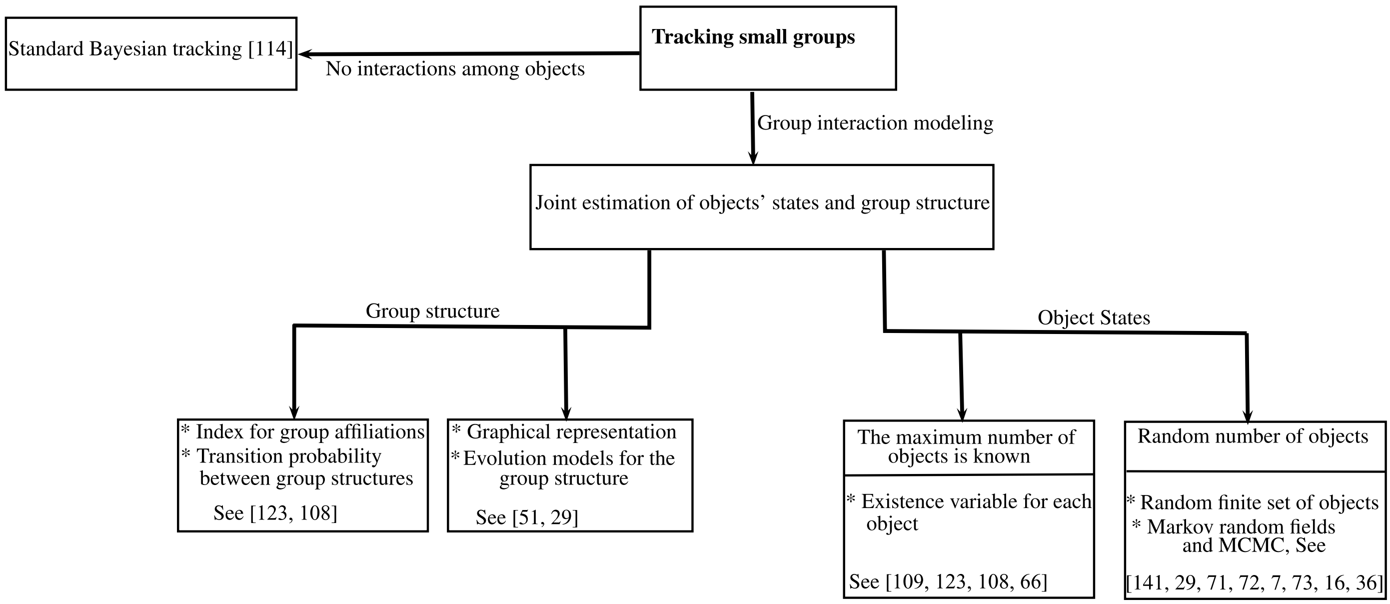

Fig. 1. Taxonomy of sequential Monte Carlo methods for tracking a small number of groups with only a few objects.

with simple geometrical shapes which are typically circles [111], ellipses [117], rectangles [10,11,51,55,56], closed contours or arbitrary shapes such as star-convex contours [9]. Other examples are tracking a cloud [69,122] of radio-active materials and a human face or hand in video [21]. Human body limb tracking is also often referred to extended target tracking.

Challenges and differences. The challenges in solving the task for groups with a small number of components differ from those of groups with a large number of components. In small groups it is possible to model the interactions and interrelationships between the components within a group. The difficulties with groups of hundreds or thousands of objects (such as pedestrians and riots in video surveillance and radar based tracking of hundreds of aircraft) are mainly due to two reasons: (1) the individual objects cannot be distinguished/identified within the group, (2) the information and features extracted by the sensors are not sufficient to track those objects. Hence, one considers the aggregated motion of the whole group. In small groups one can estimate the states of each particular object and parameters characterizing the size or volume of the group. In large groups by contrast, one typically considers the group as a geometric shape and its centre coordinates.

Similarities. Both groups of objects and extended objects give rise to a large, varying number of measurements and require a flexible framework able to deal with all these challenges. Although the methods for solving these two kinds of problems vary, there is a common approach in which both extended and large group of targets are seen as the same problem. The large group or extended object is surrounded with a shape (e.g. a circle) and the center and extent of this shape are sequentially computed based on the incoming data. Consequently, in this paper, the choice is made to classify the existing works in the literature into methods dealing with small groups and method dealing with large groups and for extended objects.

This classification of extended/group objects is according to whether: (1) the group/extended object is rigid and unchanging in shape/size, (2) whether individual entities can be tracked dynamically and interact with one another.

Examples of non-rigid extended objects are radioactive clouds. They can be spawn and also disappear. The group tracking and non-rigid extended object tracking lead to dynamic state and varying parameter estimation. Rigid extended targets such as submarines, ships, have fixed shapes and fixed size. This leads to dynamic state and static parameter estimation.

1.1. Objectives

The aim of this paper is to expose the reader to the various aspects of the problems of group and extended object tracking, underlying difficulties, and the key factors facilitating their solution in the context of Bayesian estimation. An overview of the state-of-the-art concepts and methodologies underlying contemporary Monte Carlo-based group and extended object tracking schemes is provided. The taxonomy of methods is given in Section 1.2 and background knowledge in Section 2. Methodologies for small group tracking are described in Section 3 and for large groups and extended objects in Section 4. The high dimensionality of the problem and the need of real time implementation calls for efficient algorithmic implementations, in a distributed and parallelized way, which are discussed in Section 5. Future avenues are summarized in Section 6.

1.2. Taxonomy of methods for multiple groups and extended object tracking

Over the past decade various methods have been developed for group and extended object tracking. These can be divided into two broad classes depending on the underlying complexities:

1. Methods for a relatively small number of groups, with a small number of group components [51,109,76,6].
2. Methods for groups comprised of hundreds or thousands of objects (normally referred to as cluster/extended object/crowd tracking): track before detect methods for extended objects [18,17], Poisson likelihood approaches [48,49,120,22], groups' extent parameter estimation and random matrix techniques [5,8,75,74,46], parametric level curves [69,122], and random finite sets [94,143,136,137,86,91], including the Bernouli random finite set filters [116,113].

Figs. 1 and 2 present the taxonomy of methods for tracking small groups and respectively large groups/extended objects. Details are given in the next sections.

Results for small groups with a fixed number of targets are presented in [66,48,139,42]. These SMC algorithms exploit point

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