Cambridge University Press
978-0-521-87628-5 - Fundamentals of Object Tracking
Subhash Challa, Mark R. Morelande, Darko Mušicki and Robin J. Evans
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FUNDAMENTALS OF OBJECT TRACKING

Kalman filter, particle filter, IMM, PDA, ITS, random sets . . . The number of useful object tracking methods is exploding. But how are they related? How do they help to track everything from aircraft, missiles and extra-terrestrial objects to people and lymphocyte cells? How can they be adapted to novel applications? *Fundamentals of Object Tracking* tells you how.

Starting with the generic object tracking problem, it outlines the generic Bayesian solution. It then shows systematically how to formulate the major tracking problems – maneuvering, multi-object, clutter, out-of-sequence sensors – within this Bayesian framework and how to derive the standard tracking solutions. This structured approach makes very complex object tracking algorithms accessible to the growing number of users working on real-world tracking problems and supports them in designing their own tracking filters under their unique application constraints. The book concludes with a chapter on issues critical to the successful implementation of tracking algorithms, such as track initialization and merging.

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William of Ockham

Frustra fit per plura, quod fieri potest per pauciora
(It is vain to do with more what can be done with less)

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Preface

Tracking the paths of moving objects is an activity with a long history. People in ancient societies used to track moving prey to hunt and feed their kith and kin, and invented ways to track the motion of stars for navigation purposes and to predict seasonal changes in their environments. Object tracking has been an essential technology for human survival and has significantly contributed to human progress.

In recent times, there has been an explosion in the use of object tracking technology in non-military applications. Object tracking algorithms have become an essential part of our daily lives. For example, GPS-based navigation is a daily tool of humankind. In this application a group of artificial satellites in outer space continuously locate the vehicles people drive and the object tracking algorithms within the GPS perform self-localization and enable us to enjoy a number of location-based services, such as finding places of interest and route planning. Similarly, tracking of objects is used in a wide variety of contexts, such as airspace surveillance, satellite and space vehicle tracking, submarine and whale tracking and intelligent video surveillance. They are also used in autonomous robot navigation using lasers, stereo cameras and other proximity sensors, radiosonde-enabled balloon tracking for accurate weather predictions, and, more recently, in the study of cell biology to study cell fate under different chemical and environmental influences by tracking many kinds of cells, including lymphocyte and stem cells through multiple generations of birth and death.

This book is an introduction to the fascinating field of object tracking and provides a solid foundation to the collection of diverse algorithms developed over the past 60 years by academics, scientific researchers and engineers. Historically, advances in the field of object tracking were a result of the systematic extension of methods that worked under severely restrictive ideal-world conditions to less restrictive real-world conditions. The advances were often a result of inspired innovations by scientists incorporating either more descriptive object dynamics models and/or sensor measurement models and associated statistical methods/approximations to deal with them. This led to a repertoire of extremely valuable, sometimes apparently unrelated techniques and tools to solve real-world object tracking problems. Most of the books on object tracking present the methods as a collection of these diverse algorithms.

However, all these techniques have firm foundations in recursive Bayesian logic. They can be formulated and derived in a Bayesian probabilistic framework. The aim of this book is to present such a unifying approach along with the latest advances in efficient computational algorithms for real time implementation. We have designed this book to provide a thorough understanding of object tracking to the growing number of engineers and researchers working on or contemplating working on real-world object tracking problems and to students in university programs in engineering and statistics.

In Chapter 1, we introduce the generic object tracking problem and propose a generic Bayesian solution. We refer to an object being tracked as a target, to use the common engineering language, and develop a general approach to solve the problems considered in the book. At the end of the chapter we briefly review the major tracking algorithms used by practitioners in the field. All object tracking algorithms use estimation or filtering as a core component. The Kalman filter, extended Kalman filter, unscented Kalman filter, point mass filter and particle filter are examples of algorithms developed to solve several generic estimation and filtering problems. In Chapter 2, these algorithms are derived as approximations to the recursive form of Bayes' theorem. These algorithms also form the basis of tracking a single target that is moving at approximately constant speed. Tracking a maneuvering target has led to a rich literature on filtering, including the generalized pseudo-Bayesian filter, the interacting multiple model filter, and many others. These approaches and their Bayesian foundations are considered in Chapter 3.

A unique feature of tracking arises because the sensor measurements from which track estimates must be extracted contain "false" detections. A plethora of techniques aimed at addressing this problem are described in the literature. The nearest neighbor filter, probabilistic data association filter and the like are derived in Chapter 4. Most of these techniques assume that the target exists. However, in reality, there can be uncertainty about whether a target exists or not. A class of object tracking algorithms introduces the concept of the existence of objects as a random jump Markov process and estimates its probability from the available observations. Integrated track splitting (ITS) and its derivatives (e.g., integrated probabilistic data association) fall into this category and we introduce them in Chapter 5. These algorithms are applicable for both single- and multiple-object tracking.

The task of the multiple-object tracker is not only to estimate the state of each object, but also to provide an estimate of the number of objects. The number of objects can be inferred from ITS- or IPDA-type algorithms (see Chapter 5); the process is not part of the algorithm itself. The randomly varying finite set gives a method to model the multi-object tracking problem in such a way that the tracker can estimate the number of objects along with the state of each individual object. Random-set-based modeling is introduced in Chapter 6. The resulting Bayesian random-set-based trackers and their approximations, such as probability hypothesis density (PHD) and cardinalized PHD, are introduced in the chapter. It also demonstrates how the random set formalism leads to object-existence-based filters, such as the IPDA and joint IPDA algorithms introduced in Chapter 5.

Most target tracking systems use filtering and/or prediction techniques that use the current sensor measurements to obtain best estimates at the current time or into the future. However, significant situational awareness can be gained by improving the estimates of the past target states using current measurements. Such an approach is traditionally referred to as smoothing. Chapter 7 presents the Bayesian foundations of smoothing as well as certain approximations. The smoothing framework of this chapter is extended in Chapter 8 to deal with out-of-sequence measurements. Finally, Chapter 9 introduces key tricks and methods in implementing object tracking algorithms, e.g., track initiation, merging and termination, and provides insights into how object tracking methods are realized in real applications. The chapter gives a systematic framework to design these practical object tracking methods.

A useful way of assessing an algorithm's performance in the real world is to compare its performance with the best achievable performance. Indicators of best achievable performance include the Cramér–Rao bound (CRB), Barankin bound (BB) and Weiss–Weinstein bound (WWB), and others. We present the performance bounds for all the real-world scenarios in their respective chapters.

The object tracking algorithms described in the book are at times elaborate and mathematically and notationally extensive due to the realistic engineering situations they address. We provide illustrative examples on how to use the methods presented in each chapter on representative real-world problems, and these are also expected to help the reader with a better understanding of these algorithms. We hope that the unification of all the object tracking approaches under the Bayesian probabilistic paradigm makes it possible for any reader at the first-year university level in statistics to comprehend the material and master the techniques.

We are grateful to the many colleagues and students who have helped us through the years in developing some of the material in this book. Specifically, we wish to mention Dr. Khalid Aboura and Dr. Rajib Chakravorty, who helped us in pulling

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