"Multitarget-Multisensor Tracking: Principles and Techniques"

Yaakov Bar-Shalom and Xiao-Rong Li

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Reviewed by Fred Daum

This book covers algorithms to address the following practical and important problem: your sensor or sensors give you measurements from a number of closely-spaced objects, but you are not sure which measurement came from which object. This subject is important because one of the best ways to ruin the performance of a carefully designed Kalman filter or discrimination algorithm is to put the wrong data into it. In practice, sensors generally have false detections due to noise and clutter, erroneous measurements of object coordinates due to noise, missed detections of real obiects, target maneuvers, unresolved measurements, and all of these real world phenomena are considered in detail in this book. The emphasis is on practical algorithms which perform well in the real world and run in real time on some reasonable computer with 1995 technology.

Professor Bar-Shalom is one of the world's experts in this field, and this book is the summary of his research and experience over the last several decades. The book also includes the work of his numerous graduate students and collaborators in industry. A major attraction of this book is the realistic examples, using sensors including radar, sonar, passive infrared and visible sensors. For example, a version of the target tracking algorithm described on pages 566-583 was used successfully in the Arrow anti-ballistic missile system, with infrared images of targets subtending tens of pixels on a focal plane array. Another example of realism is the performance evaluation for a phased array radar tracking algorithm (pp. 68-69) using six target scenarios, including: "incoming anti ship missile . . . which drops and performs 7g weaves . . . aircraft flying a racetrack pattern . . . a dogfight yo-yo maneuver . . ." Other practical applications include: air traffic control, sonar, image processing.

This book includes over 600 pages of text, algorithms, equations, block diagrams, curves showing quantitative performance of algorithms, flowcharts, numerous references, very useful annotated bibilographies at the end of each chapter, a good index, a few homework problems with solutions, and helpful suggestions about what conferences to attend. It is clearly-written, buzzword-free and a pleasure to read owing partly to the humorous and insightful nuggets sprinkled throughout the text. For example, we learn that the Kalman filter is the "workhorse of tracking," whereas the α-β-γ filter is the "mule of tracking. It has been suggested at one time to outlaw this filter, which dates back to the fifties." This assessment agrees with my own experiences whenever I have used an α-β-γ filter rather than a Kalman filter, I have regretted it. The reference to the 'fifties is relevant due to the extremely rapid advance in computer technology. In particular, the cost of fast random access memory has decreased by over seven orders of magnitude per bit since 1960, and the cost of throughput has dropped by a comparable amount. The throughput of the CRAY-1 "super computer" is about 160 Mflops; this machine (costing $8 million in 1976) is now literally a museum piece on display at the Smithsonian in Washington, DC; today the same throughput can be achieved with a single VLSI chip costing only a thousand dollars. Moreover, a single board with 16 such VLSI chips has 2.5 Gflops of throughput, plenty of memory with a superb interconnection network, and costs the same as a Jaguar XJ6. The reason for dwelling on computer technology is that it has a profound effect on algorithms and performance for tracking in a dense multiple target environment with or without multiple sensors.

In the context of this book, the authors describe algorithms ranging from low throughput (PDA and JPDA), to

Table 1. Comparison of Multiple Target Tracking Formalisms

Formalism or Algorithm	Time Horizon Considered (No. of Samples)	Number of Data Association Hypotheses	Unresolved Data Modelled In Algorithm	Relative Performance in Dense Multiple Target Environments		Computational Complexity	
				Unresolved Data	Resolved Data	Exact Solution	Approximate Solution
Nearest Neighbor	1	1	No	Poor	Poor	Low	Low
Nearest Neighbor - M	1	1	Yes	Fair	Poor	Low	Low
Probabilistic Data Association (PDA)	1	1	No	Poor	Fair	Low	Low
Joint Probabilistic Data Association (JPDA)	1	1	No	Fair	Good	Exp	Medium
JPDAM	1	1	Yes	Good	Good	Exp	Medium
Nearest Neighbor JPDA	1	1	No	Fair	Good to Excellent	Poly	Low
Assignment	1	1	No	Fair	Good to Excellent	Poly	Medium
Dynamic Programming (Viterbi)	Many	1	No	Poor	Good	Poly	Medium
Hough Transform	Many	1	No	Fair	Good	Poly	Medium
Multiple Hypothesis Tracking (MHT)	Many	Many	No	Good	Optimal	Exp	High
MHT-M	Many	Many	Yes	Best	Excellent	Exp	High
Morefield	Many	Many	No	Fair	Excellent	Exp	High
Symmetric Measurements EKF	Many	Many	No	?	Good	Poly	High
Symmetric Measurements Exact Nonlinear Filter	Many	Many	No	?	Excellent	Exp	High
Branching	Many	Many	No	Fair	Excellent	Bounded	Med to High
Branching - M	Many	Many	Yes	Good	Excellent	Bounded	Med to High
Multi-Dimensional Assignment	Many	Many	No	Good	Excellent	-	High
Multi-Dimensional Assignment - M	Many	Many	Yes	Excellent	Excellent	-	High
Exact N-Best Hypotheses	Many	N	No	Good	Excellent	-	Med

moderate throughput (IMM and assignment using relaxation), to high throughput (MHT). The acronyms PDA, JPDA, IMM and MHT are defined in the glossary at the end of this review. In this sense, the book is up to date and covers the full spectrum of algorithms, from low throughput to high throughput. On the other hand, there are some notable lacunae in the list of algorithms covered. In particular, there is no mention of the so-called "N-Best" multiple-scan assignment algorithm developed by Danchick and Newnam [1], which is perhaps the algorithm of choice today, combining excellent performance with medium computational complexity (Table 1). More generally, it would be useful in a book of this type to have a single table (like Table 1) that summarizes all of the several dozen available algorithms, along with some quantitative measure of performance and computational complexity. All practitioners in this field carry around such a table in the back of their heads; it would be interesting to see what Professor Bar-Shalom's table looks like.

Notwithstanding these comments, this book contains several excellent quantitative performance comparisons between various algorithms. For instance, page 365 shows a nice plot comparing three algorithms (PDA, JPDA and JPDAM) for a dense multiple target environment with unresolved measurements. I have written elsewhere [2] that the issue of unresolved measurements is more important than data association in almost all practical applications, and yet 99% of the literature focuses on data association algorithms, whereas less than 1% of the literature on multiple target tracking mentions unresolved measurements. This book is an improvement on the norm, as it devotes 2.6% of its pages to the subject of unresolved measurements.

At Raytheon, we have used PDA, JPDA, NNJPDA, NNJPDAM, multiple-scan assignment and several versions of IMM on numerous radar systems for diverse applications. We can testify to the fact that these algorithms work in the real world, in severe clutter, jamming, with target maneuvers, in a dense multiple target environment. Moreover, the performance of these algorithms is vastly superior to a nearest neighbor chi-square test (Table 1, next page).

Everyone interested in multiple target tracking will profit from reading this book, ranging from beginners to experts and academic researchers to hard boiled engineers, who may only be interested in quickly coding an algorithm with performance that is "good enough." The prerequisites for this book are minimal: elementary probability and matrix algebra; if you know about Kalman filters, your background is adequate. There are no mathematical theorems in this book, but there are a few derivations of important formulas for those who are interested. The level of mathematical rigor is about average for graduate engineering texts, and only a few experts will be annoyed by the lack of explicit hypotheses for certain results; for example, there are no regularity conditions stated for the Cramer-Rao bound, but this is traditional in engineering texts. It goes without saying that in this book the measurements are modelled in discrete time (which is the practical case of interest for engineers), rather than continuous time as in a large body of highly mathematical academic papers on estimation theory. Moreover, the authors do not waste our time with edifying but often irrelevant mathematical technicalities which somehow slip into much of the literature (e.g., Hilbert spaces in Kalman's 1960 paper, as well as Banach, Sobolev, Hausdorff and Besov spaces in the current academic control theory literature); such technicalities are not always irrelevant, but rather it's simply not where the action is (see note 1). I know that my gratuitous comments will annoy some people; however, such annoyance is minor compared to the time and money wasted on irrelevant technicalities in much of the literature and many graduate schools. If my remarks can spare even one graduate student from such torture, then it is worthwhile (see note 2). It is refreshing to read a book like this one, in which there is plenty of solid Bayesian theory used to derive and evaluate practical algorithms, rather than a melange of buzzwords (fuzzy-chaotic-wavelets implemented with massively parallel optical neural nets).

The reader has undoubtedly figured out I like this book. Therefore, in order to present a more balanced review, I feel compelled to conclude with the obligatory nit-picking.

First, there is no mention of countermeasures (i.e., jamming, chaff, debris, infrared flares, etc.); such countermeasures are one of the major reasons for being interested in multiple sensors and sophisticated algorithms in a dense multiple target environment. Second, although the authors briefly note the shortcomings of the extended Kalman filter (EKF), they only mention a few alternatives to the EKF (with no references), and they only cover one alternative in detail (hybrid polar-Cartesian coordinates). Moreover, the credit for the hybrid coordinate filter is due to Raman Mehra whose paper [3] is not mentioned in this book. There are two dozen major alternatives to the EKF which deserve at least some mention in a book like this; for example, a few survey papers that could be added include [4, 5 and 6]. Third, this book does not cover the crucial issues of waveform design, measurement pattern design or sensor design [2].

A final practical note is in order; to get a copy of this book contact Professor Yaakov Bar-Shalom, Box U-157, Storrs, CT 06269-3157; Fax: 860-486-2447; e-mail: ybs@ee.ucomm. The price of the book per copy is a nonlinear function of the number of copies ordered: $120. for 1, $110. for 2, $100. for 3, $90. for 4, $85. for 5, and $80. for 6 or more copies. Needless to say, everyone will want a copy of this book.

GLOSSARY

- **PDA** = "Probabilistic Data Association," a data association algorithm that considers one track and N measurements on a single scan.
- **JPDA** = "Joint Probabilistic Data Association," a data association algorithm that jointly considers M tracks and N measurements on a single scan.
- **JPDAM** = Modification of JPDA, which explicitly considers the possibility of unresolved measurements.
- **NNJPDA** = "Nearest Neighbor JPDA," modification of JPDA, which uses a maximum likelihood rule rather than the conditional mean.
- **IMM** = "interacting multiple models," an approxim ation to the optimal Bayesian algorithm for adaptively weighting multiple Kalman filters or EKFs or alternatives to EKF.
- **MHT** = "Multiple Hypothesis Tracking," optimal Bayesian algorithm which considers all possible hypotheses of data association over all time.

NOTES

1. Consider Professor Arnold's eloquent remarks (first half of page 8 in [11]).
2. Everybody agrees that mathematics is useful, powerful, and highly relevant to science and engineering; the only question is: What kind of math is most useful in a specific application? For example, Bourbaki vs. Courant-Hilbert or perhaps Halmos vs. Strand? There is also an issue of near term vs. far term payoff; yesterday's abstraction is often today's practical algorithm. It is important not to stifle research that may have a long term payoff. For example, in the expert hands of Traub, Wozniakowski and Wasilkowski [7]. Banach spaces yield powerful bounds on computational complexity for algorithms producing approximate solutions. In this case abstraction results in simplicity, a well known paradigm. Another example is Bezout's theorem in projective space, which in the hands of Smale and Shub yields a practical algorithm for solving a system of nonlinear equations, which routinely produces accurate solutions for problems where Newton's method fails completely [8]. Moreover, engineers have sometimes come a cropper by not

respecting Fubini's theorem; for example, the formula for the conditional mean in [9] is exactly correct for Gaussian densities but it gives the wrong answer for Gaussian mixtures [10]. In summary, mathematics is wonderful, and Professor Bar-Shalom's book helps to balance the literature by deriving practical algorithms using mathematics that is relevant and readily accessible to engineers.

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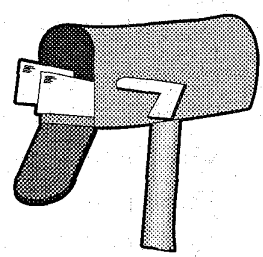
From Our Mailbox:

Simple Solutions to Complex Problems: Crime



There is a yearly Crime Conference in Utrecht, The Netherlands. I was invited to speak on "Crime in America." Fortunately, ***Playboy*** had recently published a well-illustrated feature on organized crime, a great source for slides. Also, I had access to film footage of recent riots and looting in Detroit and Washington. So, armed with slides and film it was possible to produce an acceptable multi-media presentation.

Then reality set in. During the question period someone asked, "How would you go about solving the crime problem?" ***Playboy*** hadn't prepared me for this. I heard myself mumble something about a man on a white horse. Mercifully, there weren't many more questions.

Upon returning to home base, I headed to the library to research the problem. Surprisingly, Adam Smith had already done the research and had written a book about it: ***Lectures on Police***. This is the record of a series of lectures he had given at the University of Glasgow. All the while Adam Smith was lecturing, the University had a brilliant engineer, James Watt, busily inventing a new steam engine. The social implications of this new technology were not lost on Adam Smith. He envisioned a new world of wealth and freedom based on this newly-invented source of power. A world of abundance, free of poverty; world free of crime, without prisons or police. The Industrial Revolution had begun. With Watt's new engine, a factory could be established wherever there was a promising supply of labor. This was the answer to the problem of crime that had been wanting. Here's what Adam Smith told his students: "The establishment of commerce and manufactures, which brings about independence, is the best police for preventing crime."

When you read Thomas Jefferson, a pattern begins to take shape. Of course he was big on independence; here's what he had to say about dependence: "Dependence begets subservience and venality, suffocates the germ of virtue and prepares fit tools for the designs of ambition."

Freedom seems to be a theme common to the subject of crime. Nobel laureate Dennis Gabor writing on the topic said: "Let us avoid the greatest dangers while leaving as much freedom as possible for those who come after us, lest the rulers of the nations be tempted towards the last refuge of a scoundrel, the Police State."

Adam Smith writes in much the same vein: "It is not so much the police that prevent the commission of crimes, as the having as few persons as possible to live upon others."

In days of yore, highwaymen were common predators. It was customary to write your Will and set your affairs in order before making a trip from Glasgow to Edinburgh. Adam Smith had great hopes for Watt's new steam engine. He commented that the ranks of highwaymen would be depleted when they found they could make "better bread" at an honest job. The abundance produced by the new factories encouraged him to conclude: "To eliminate crime, make commodities too cheap to steal."

— *John Jackson*
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