Target Tracking
Le 1: Introduction

Gustaf Hendeby

Div. Automatic Control
Dept. Electrical Engineering
gustaf.hendeby@liu.se

LINKÖPING UNIVERSITY

1 Course Information
2 Multi-Target Tracking Overview
3 Examples
4 Problem Formulation
5 Summary

LINKÖPING UNIVERSITY

Course Information

Multi-Target Tracking Course, Fall 2025

Aim

The aim of the course is to provide an introduction to *multi-target tracking* (MTT); both theoretical and practical aspects. After the course a student should be able to explain the basic ideas underlying MTT and feel confident to implement the fundamental methods.

Course activities:

- 7 (8?) lectures where the theoretical aspects of MTT are explained.
- 1 lecture/seminar on ethical aspects.
- 1 guest lecture: Per Boström-Rost, Saab Aeronautics.
- 1 ethical aspects lecture
- Practical coding exercises, performed on your own.

Responsible:

- Gustaf Hendeby (gustaf.hendeby@liu.se)

Course homepage:

- `https://mtt.edu.hendeby.se`

Course Content

- Single-target tracking (STT)
- Motion and sensor models:
  - Common tracking models
  - Maneuvering targets (IMM)
  - Clutter
- Multi-target tracking (MTT):
  - Association
  - Track logic
  - Global Nearest Neighbor (GNN) Tracker
  - Multi-Hypotheses Tracker (MHT)
- Outlook, modern methods:
  - Track before detect (TkBD)
  - RFS/FISST:
    - Probability hypothesis density (PHD)
    - Multi-Bernoulli
    - Poisson multi-Bernoulli mixture (PMBM)
  - Track-to-track fusion (T2TF)
- Ethical considerations

Course Examination

Three independent parts with different focuses:

1. Basic theory and understanding: exam (2 ETCS credits)

   Theory is examined in a brief written exam.

2. Implementation and practice: exercises (4 ETCS credits)

   Implementation skill and practical knowhow are examined using assignments during the course.

3. Research related work: project (3 ETCS credits)

   Use course skills extensions on the topic for a larger tracking project, preferably related to your research. Individually or in a group of two.

Course Prerequisites

Familiarity with:

- Basic probability theory
- State-space models
- Bayesian estimation methods
  - Kalman filter (KF)
  - Extended Kalman filter (EKF)
  - Unscented Kalman filter (UKF)
  - Particle filter (PF)
- Coding in MATLAB or similar (for the exercises)

Suitable background material

- Sensor Fusion course (TSRT14): `http://www.control.isy.liu.se/student/tsrt14`
- Selected sensor fusion videos: `https://mtt.edu.hendeby.se/prerequisite.html`
- F. Gustafsson, L. Ljung, and M. Millnert. *Signal processing.* Studentlitteratur, 1. edition, 2010.
- F. Gustafsson. *Statistical Sensorfusion.* Studentlitteratur, 3. edition, 2018.
- T. Kailath, A. H. Sayed, and B. Hassibi. *Linear Estimation.* Prentice-Hall, Inc, 2000. ISBN 0-13-022464-2.
- S. M. Kay. *Fundamentals of Statistical Signal Processing: Estimation Theory*, volume 1. Prentice-Hall, Inc, 1993. ISBN 0-13-042268-1.

Lecture Schedule (preliminary)

Le	Topic	Date		Ex
1	Introduction	Sept 16	15–16	
1b	Preliminaries	Sept 16	16–17	
2	Models for Target tracking	Sept 19	13–15	
3	Single target tracking	Sept 25	15–17	Ex 1
4	Multi-target tracking (1/2): GNN, JPDA	Oct 16	13-15	Ex 2
5	Multi-target tracking (2/2): MHT	Fall		Ex 3
6	Random Finite Sets: PHD, etc	Fall		
6b?	Random Finite Sets: PHD, etc part 2	Fall		
7	Guest lecture	Fall		
8	Various topics (TkBD, T2T, ETT)	Fall		
9	Ethical aspects	Fall		

- Lectures are in Large conference room in Visionen, unless otherwise stated.
- Exercises are due at the end of the course.
  (Doing them as the course progresses is highly recommended!)
- Dates are preliminary, check homepage and e-mail for updates.

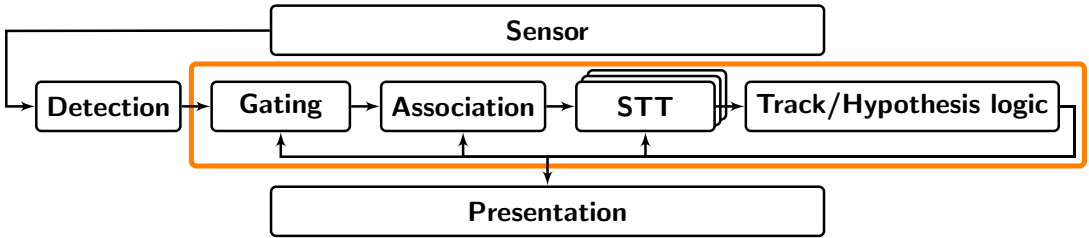
Course Literature

- Selected papers handed out during the course will be enough to follow the course.
- For a fairly complete overview of the target tracking problem, methods, and algorithm collected in one place, the following books are good entry points.
  - S. S. Blackman and R. Popoli. *Design and analysis of modern tracking systems*. Artech House radar library. Artech House, Inc, 1999. ISBN 1-5853-006-0.
  - Y. Bar-Shalom, P. Willett, and T. Xin. *Tracking and Data Fusion: A Handbook of Algorithms*. Yaakov Bar-Shalom Publishing, 2011. ISBN 0-9648-3-127-9.

Multi-Target Tracking Overview

LINKÖPING UNIVERSITY

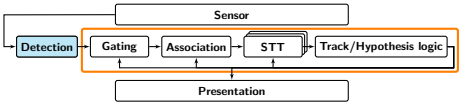
Multi-Target Tracking: conceptual view



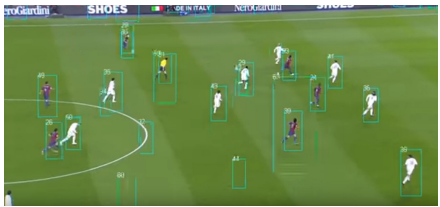
Components

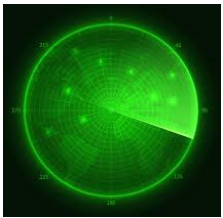
1. Detections/Observations
2. Gating
3. Association
4. Single-target tracking
5. Track and hypothesis logics
6. Presentation

Multi-Target Tracking: detection

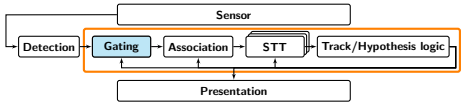


- Considered done in this course
- Sensor level signal processing
- Heavily sensor dependent

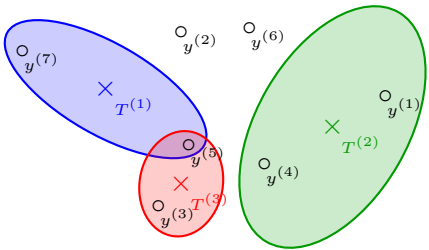




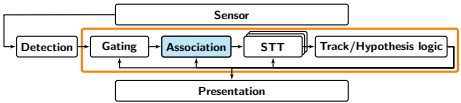
Multi-Target Tracking: gating



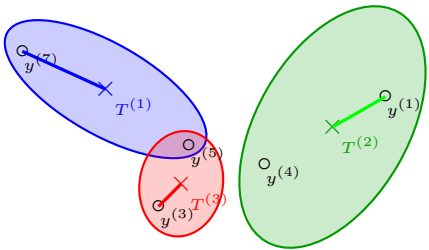
- Determine which observations could come from known targets
- Reduce tracking complexity



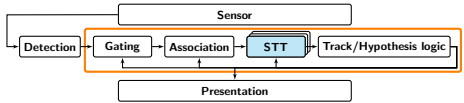
Multi-Target Tracking: association



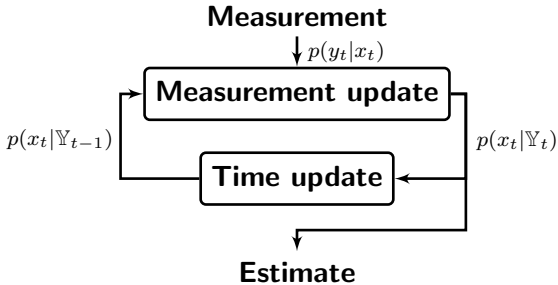
- Match observations to targets
- One or many different associations



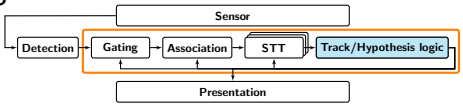
Multi-Target Tracking: STT



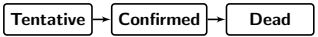
- Performed for each target independently, given associated observations
- Standard methods: EKF, UKF, PF, ...
- Yields state and uncertainty, given the association hypothesis



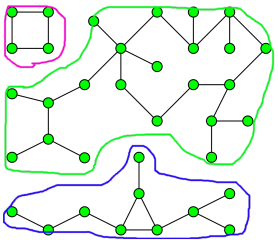
Multi-Target Tracking: track/hypothesis logic



- Compute probability of given track/association hypothesis
- Track management: birth, death
- Clustering for efficiency

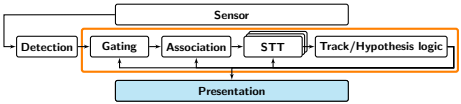


Track logic



Clustering independent parts

Multi-Target Tracking: presentation



- How to present the result?
- Not addressed in the course

Tracking Examples

Selected examples

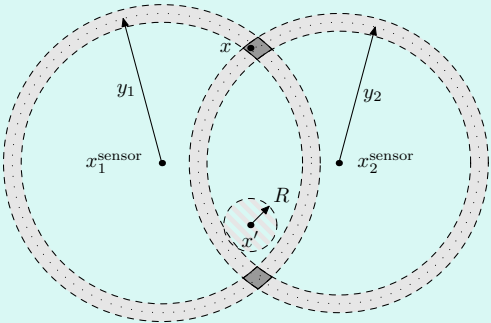
Selected examples (single target tracking/filtering and multiple target tracking):

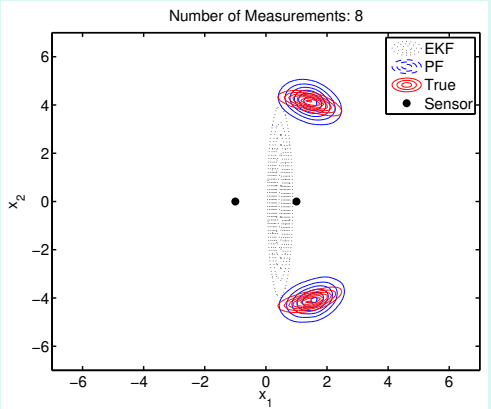
STT Range-only measurements
STT Multiple models for maneuvering target tracking (IMM)
STT Track before detect
MTT Nearest Neighbor CV-model
MTT MHT
MTT PHD-filtering

STT: Range-Only Tracking

Range-Only Measurements

Performance, and performance measures for RO:

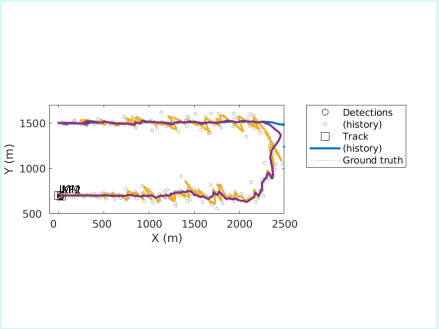




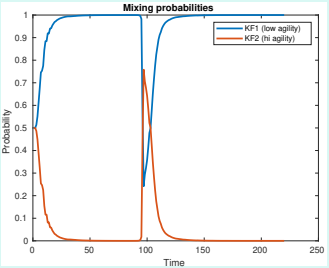
STT: Maneuvering Target

The IMM method for two models

A radar tracking application is presented using the IMM method with two filters. One filter is used to handle a straight flying path accurately, whereas the other is used to manage maneuvers. Due to the nonlinearities in the measurement equation an EKF is used for the estimation.



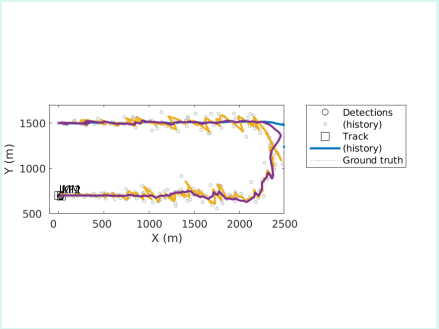
https://youtu.be/DVkCzdku2SQ



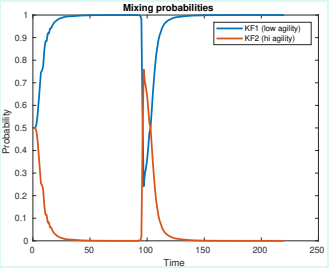
STT: Maneuvering Target

The IMM method for two models

A radar tracking application is presented using the IMM method with two filters. One filter is used to handle a straight flying path accurately, whereas the other is used to manage maneuvers. Due to the nonlinearities in the measurement equation an EKF is used for the estimation.



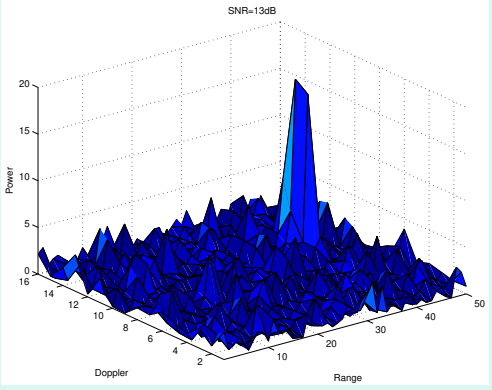
https://youtu.be/DVkCzdku2SQ



STT: Track-Before-Detect (TkBD)

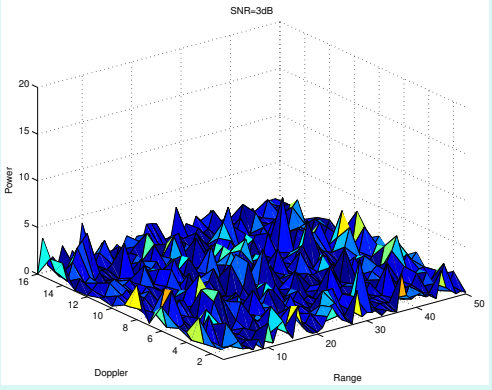
Track without first detecting the target

SNR=13 dB



Easy to detect a point target.

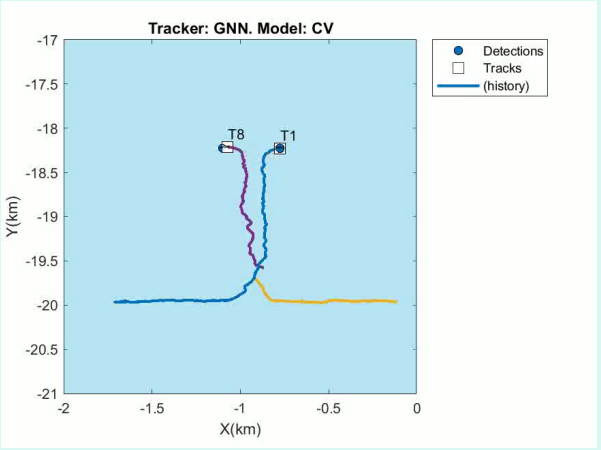
SNR=3 dB



Hard to detect a point target.

MTT: GNN CV-model

Global nearest neighbor tracking

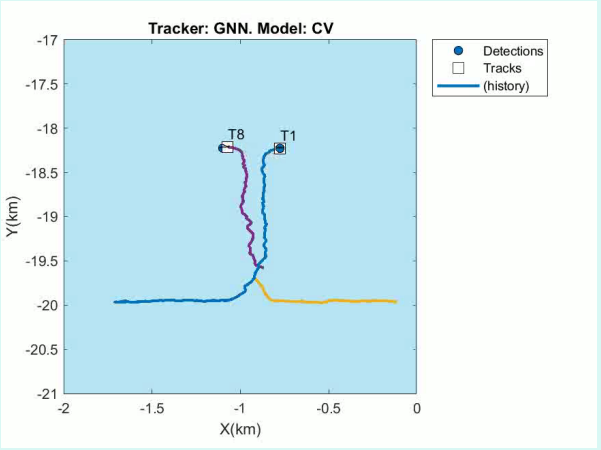


https://youtu.be/WPA2z-kw1wg

- *Global nearest neighbor* (GNN) tracker
- Simple *constant velocity* (CV) model
- Problems handling the mixed level of agility

MTT: GNN CV-model

Global nearest neighbor tracking



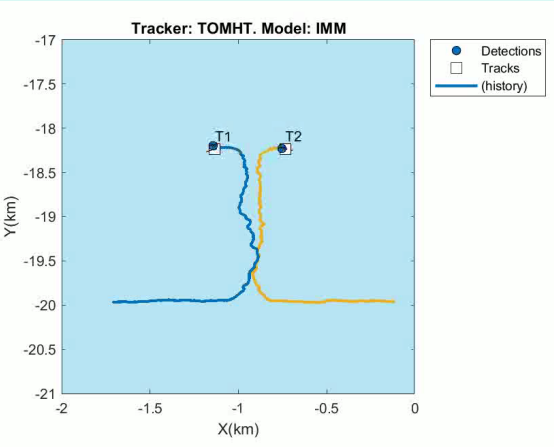
https://youtu.be/WPA2z-kw1wg

- *Global nearest neighbor* (GNN) tracker
- Simple *constant velocity* (CV) model
- Problems handling the mixed level of agility

MTT: MHT IMM

Multi-hypothesis tracking

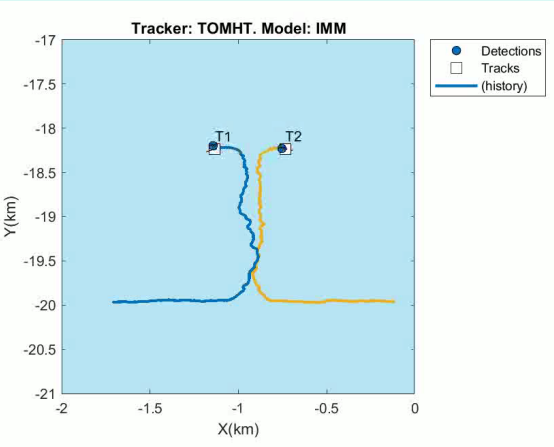
- *Multi-hypothesis tracker* (MHT) resolves measurement ambiguities
- *Interacting multiple models* (IMM) better captures the mixed level of agility



MTT: MHT IMM

Multi-hypothesis tracking

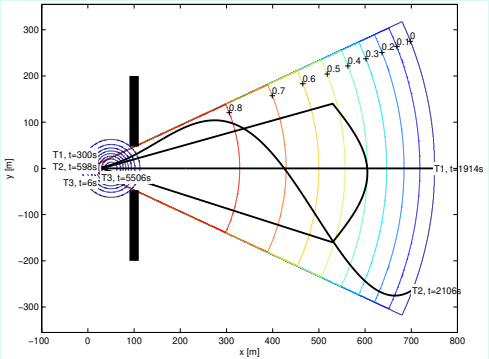
- *Multi-hypothesis tracker* (MHT) resolves measurement ambiguities
- *Interacting multiple models* (IMM) better captures the mixed level of agility



MTT: PHD Filter Example

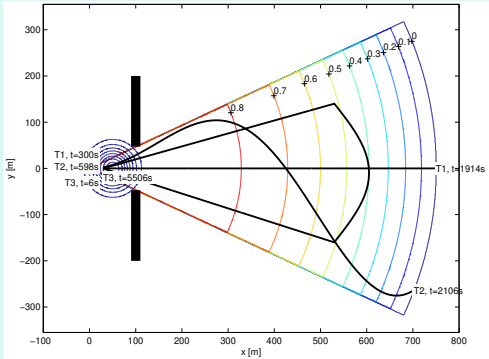
Random finite set tracking

Standard GMPHD filter



https://youtu.be/PJimgDB3X88

Modified GMPHD filter



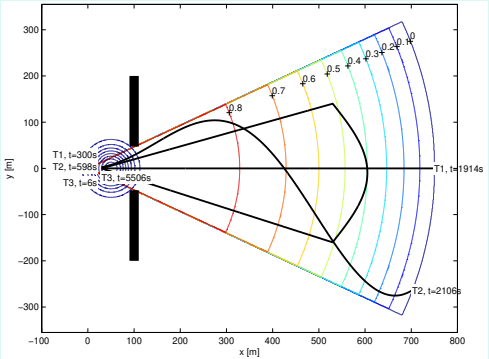
https://youtu.be/cAL3ynfVZAk

- Probability of detection dies off as a 3rd-degree polynomial, inspired by real data

MTT: PHD Filter Example

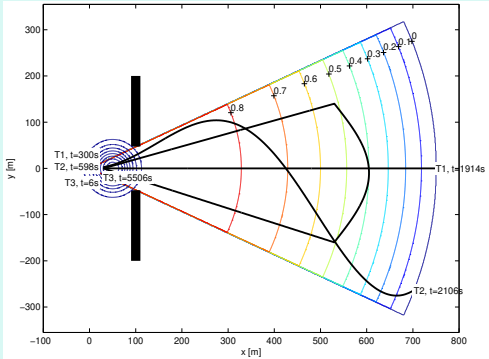
Random finite set tracking

Standard GMPHD filter



https://youtu.be/PJimgDB3X88

Modified GMPHD filter



https://youtu.be/cAL3ynfVZAk

- Probability of detection dies off as a 3rd-degree polynomial, inspired by real data

Problem Formulation

Problem Formulation (1/3)

Definition: Target

A **target** is anything whose state (x) is of interest to us.

- The state can change over time with a dynamics which is itself unknown.
- Measurements/detections/observations (y^i) comes from uncertain origin.
- There are false measurements, $P_{\text{FA}} > 0$.
- Some measurements are missing, $P_{\text{D}} < 1$.
- Generally have no initial guess or estimate of the target state.

Problem Formulation (2/3)

Definition: Target tracking

Target tracking is the estimation of the number of targets present in the tracking volume and theirs states.
In its most general and abstract form, it is a special case of dynamic estimation theory.

Problem Formulation (2/3)

Definition: Target tracking

Target tracking is the estimation of the number of targets present in the tracking volume and theirs states.
In its most general and abstract form, it is a special case of dynamic estimation theory.

Object tracking

Target tracking is sometimes denoted **object tracking**. The word target is by some attributed with a negative/aggressive connotation, as something one intend to shoot down. It is argued, cars use object tracking not target tracking to obtain situational awareness.

Problem Formulation (3/3)

Definition: Track

A **track** is a sequence of measurements that has been decided or hypothesized by the tracker to come from a single source.

- Usually, instead of the list of actual measurements, sufficient statistics is maintained, *e.g.*, mean and covariance in the case of a KF, particles in the case of a PF.
- In general, each measurement must be classified as either belonging to an existing track, a new track, or as being a false measurement.

Target Types

Point target A target that can result in at most a single measurement in a scan.

- This means its extension is comparable to the sensor resolution.
- However, an extended target can also be treated as a point target by tracking its centroid or corners.

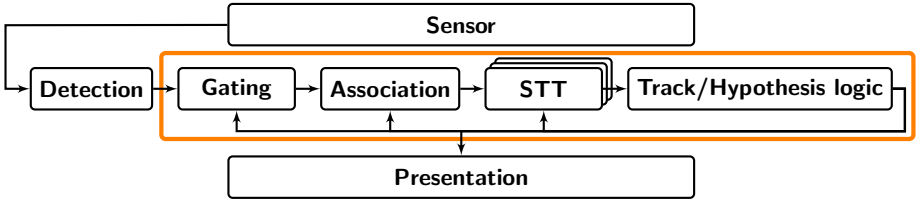
Extended target A target that can result in multiple measurements in a single scan.

Unresolved targets This denotes a group of close targets that can collectively result in measurements in the sensor.

Dim target This is a target whose signal energy is very low. These can be tracked much better with *track before detect* (TkBD) type approaches.

Summary

Summary



- Multi-target tracking is the problem of decide how many targets are present and how they move, given measurements with imperfections.
- Classic MTT can be divided in several stages: gating, association, single target tracking, track/hypothesis logic, and presentation.
- Single target tracking: Kalman type filters, particle filters

Decide what your ambitions are for the course!

Gustaf Hendeby

www.liu.se

LINKÖPING UNIVERSITY