EE793 Target Tracking: Lecture 2
Introduction to Target Tracking

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Outline

Introduction to Target Tracking

- Measurements
- Targets
- Multiple Sensors

Introduction to Target Tracking (TT)

Definition

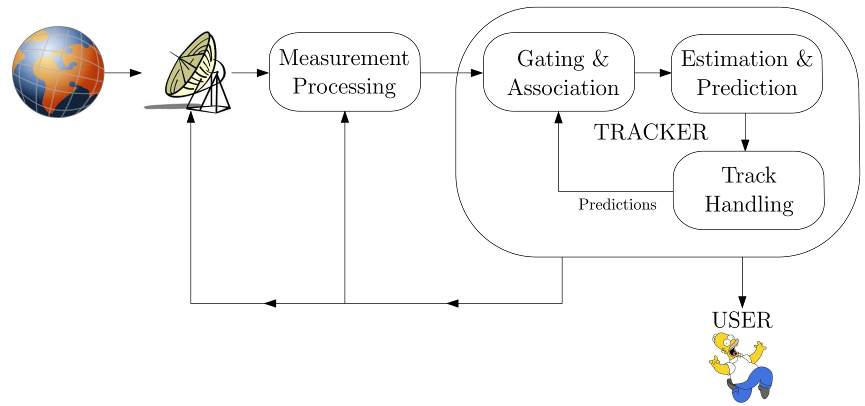
A **target** is anything whose state is of interest to us.

- State we are interested in can change with time with a certain dynamics which is itself unknown.
- Measurement origins are uncertain.
- There are false measurements $P_{FA} > 0$.
- Some measurements are missing $P_D < 1$.
- We generally have no initial guess or estimate.

Definition

Target tracking, in its most general and abstract form, is a realistic version of dynamic estimation theory.

A Conventional TT System



Measurements

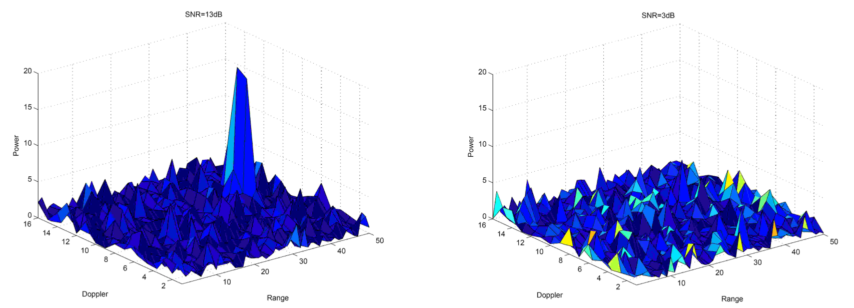
Definition

The term **measurement** contains all observed quantities included in a (possibly processed) report output from a sensor.

- Measurement (pre)processing generally includes a form of thresholding (measurement detection) process.
- Information loss during the thresholding is evident. In very low SNR scenarios, thresholding might not be used, which leads to Track Before Detect algorithms with high computation cost.
- We consider *point* or *contact* measurements.
- This means lots of processing that is out of hands of the TT-engineer. What is P_D, what is P_{FA}? Good modeling of measuring process must be obtained.

Measurements

Thresholding Illustration with a Radar



(a) SNR=13 dB. A high SNR makes it easy to detect the point target.

(b) SNR=3 dB. A low SNR makes the target hard to detect in a cluttered environment.

Figures taken from: Y. Boers, H. Driessen, J. Torstensson, M. Trieb, R. Karlsson, F. Gustafsson, "Track-before-detect algorithm for tracking extended targets," *IEE Proceedings – Radar, Sonar and Navigation*, vol.153, no.4, pp.345–351, August 2006.

Measurements

Types of point measurements:

- Kinematic measurements e.g.,
  - Position (pixel indices),
  - Range,
  - Range rate (radar doppler),
  - Bearing.
- Attribute measurements e.g.,
  - Signal strength,
  - Intensity,
  - Aspect ratio,
  - Target type.

We are going to be concerned with only the kinematic measurements.

Measurements

Types of measurement sources:

- One of targets that has been previously observed;
- A new target;
- False alarm (clutter).

Clutter

- A false measurement (false alarm or clutter) in tracking terminology generally refers to the concept of persistency.
- In other words, a persistent false alarm (clutter) is considered a target to be tracked even if we are not interested in what or where it is.
- If one of our interesting targets gets in the vicinity of uninteresting false targets, we become prepared.

Measurements: Modeling

Target originated measurements:

$$y_k = h(x_k^j) + e_k$$

Example models:

- Simple Cartesian

$$y_k = \begin{bmatrix} \mathsf{x}_k^j & \mathsf{y}_k^j \end{bmatrix}^T + e_k$$

- Bearing only

$$y_k = \arctan(\mathsf{y}_k^j / \mathsf{x}_k^j) + e_k$$

- Range

$$y_k = \sqrt{(\mathsf{x}_k^j)^2 + (\mathsf{y}_k^j)^2} + e_k$$

- log range (received signal strength (RSS))

$$y_k = \alpha \log\left((\mathsf{x}_k^j)^2 + (\mathsf{y}_k^j)^2\right) + e_k$$

Measurements: Modeling

Target originated measurements:

- No sensor is perfect.
- In addition to sensor measurement noise e_k, there is a detection process with probability $P_D < 1$ in many sensors.
- Detection probability P_D can be a characteristics of the sensor (raw measurement processing algorithm) as well as the target state, i.e., P_D might depend on the specific target position and velocity and it can vary from target to target.
- It is generally difficult to find an exact formula for P_D. Approximations and heuristics abound.
- Every obtained measurement from the sensor includes two sources of information:

1. Detection info P_D;
2. The actual value of the measurement y_k.

Measurements: Modeling

Clutter: Non-persistent measurements which are not originated from a target.

- Prior information is important.
  - Clutter maps are sometimes existent.
  - Sensor (processing algorithm) characteristics
    - Some characteristics might be available from the manufacturer.
    - Experiments might be performed.
- The case of minimal prior info

- Number of FAs in a region with volume V is modeled as a Poisson distribution with clutter rate β_{FA} (number of FAs per area per scan). P_D is included in P_{FA}.

$$P_{FA}(m_k^{FA}) = \frac{(\beta_{FA} V)^{m_k^{FA}} \exp(-\beta_{FA} V)}{m_k^{FA}!}$$

- Spatial FA distribution: Uniform in every region with volume V.

$$p_{FA}(y_k) = \frac{1}{V}$$

Targets: Tracks

Definition

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 held e.g., mean and covariance in the case of a KF, particles in the case of a PF.
- Generally each arriving measurement must start or update a track. Hence tracks must be classified and must not be treated equally.

Targets: Tracks

Track types: According to their different life stages, tracks can be classified into 3 cases.

- **Tentative (initiator):** A track that is in the track initiation process. We are not sure that there is sufficient evidence that it is actually a target or not.
- **Confirmed:** A track that was decided to belong to a valid target in the surveillance area. This is one end of initiation process.
- **Deleted:** At the other end of the initiation process, this is a track that is decided to come from all random FAs. All of its info should be deleted.

Targets: Types

We can characterize targets considered in target tracking into categories depending on their size with respect to sensor resolution (depends on target-sensor distance too).

- **Point target:** A target that can result in at most a single measurement.
  - This means its magnitude is comparable to sensor resolution.
- **Extended target:** A target that can result in multiple measurements at a single scan.
  - Sometimes, an extended target can also be treated as a point target by tracking its centroid or corners.
- **Unresolved targets:** This denotes a group of close targets that can collectively result in a single measurement in the sensor.
- **Dim target:** This is a target which results in returns that cannot be separated from noise by simple thresholding. These can be tracked much better with track before detect (TBD) type approaches.

Targets: Modeling

- General state space model

$$x_k = f(x_{k-1}) + w_k$$

- Example models
  - (Nearly) constant velocity model

$$x_k \triangleq \begin{bmatrix} \mathsf{x}_k \\ v_k^{\mathsf{x}} \end{bmatrix} = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \mathsf{x}_{k-1} \\ v_{k-1}^{\mathsf{x}} \end{bmatrix} + \begin{bmatrix} T^2/2 \\ T \end{bmatrix} a_k$$

  where $a_k \sim \mathcal{N}(0, \sigma_a^2)$ is a white noise.
  - (Nearly) constant acceleration model

$$x_k \triangleq \begin{bmatrix} \mathsf{x}_k \\ v_k^{\mathsf{x}} \\ a_k^{\mathsf{x}} \end{bmatrix} = \begin{bmatrix} 1 & T & T^2/2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathsf{x}_{k-1} \\ v_{k-1}^{\mathsf{x}} \\ a_{k-1}^{\mathsf{x}} \end{bmatrix} + \begin{bmatrix} T^2/2 \\ T \\ 1 \end{bmatrix} \eta_k$$

  where $\eta_k \sim \mathcal{N}(0, \sigma_\eta^2)$ is a white noise.

Targets: Modeling

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  where $\eta_k \sim \mathcal{N}(0, \sigma_\eta^2)$ is a white noise.
  - How to select the noise parameters?

Targets: Modeling

- (Nearly) Coordinated turn model, i.e., nearly constant speed, constant turn rate model
- State with Cartesian velocity $x_k \triangleq \left[\; \mathsf{x}_k \quad \mathsf{y}_k \quad v_k^{\mathsf{x}} \quad v_k^{\mathsf{y}} \quad \omega_k \; \right]^T$.

$$x_k = \begin{bmatrix} 1 & 0 & \frac{\sin(\omega_{k-1}T)}{\omega_{k-1}} & -\frac{1-\cos(\omega_{k-1}T)}{\omega_{k-1}} & 0 \\ 0 & 1 & \frac{1-\cos(\omega_{k-1}T)}{\omega_{k-1}} & \frac{\sin(\omega_{k-1}T)}{\omega_{k-1}} & 0 \\ 0 & 0 & \cos(\omega_{k-1}T) & -\sin(\omega_{k-1}T) & 0 \\ 0 & 0 & \sin(\omega_{k-1}T) & \cos(\omega_{k-1}T) & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} x_{k-1} + \begin{bmatrix} T^2/2 & 0 & 0 \\ 0 & T^2/2 & 0 \\ T & 0 & 0 \\ 0 & T & 0 \\ 0 & 0 & 1 \end{bmatrix} \eta_k$$

- There are versions with polar velocity.
- This model was taken from [Bar-Shalom (2001)].

Targets: Filtering

When measurements corresponding to a target are obtained, the calculation of the sufficient statistics is done via state estimators (filters).

- Early tracking systems: very low computational capacity $\Longrightarrow$ Steady state Kalman filters: $\alpha-\beta$ and $\alpha-\beta-\gamma$-filters. Kept only an integer **quality indicator** instead of covariance.
- Kalman filters (KFs) and extended KFs are the most common approaches.
- Unscented KF (UKF) and other sigma-point approaches got much criticism (and undermining) from "orthodox" people in the field when they were first introduced. Particle filters (PFs) were despised.
- With the ever increasing computational resources, they are now commonly accepted as valid methods for target tracking.

Targets: Model Mismatch

- State estimators for kinematic models are sophisticated low-pass filters.
- The bandwidth of the filter is a trade-off between
  1. Following the target motion
  2. Reducing the noise (clutter,measurement noise)
- The model mismatch problem in target tracking is called **maneuvers**.
- Unlike the common concept of maneuvers in real life, a maneuver might not necessarily be a higher order motion than that of the filter model.
- When one is using a high order model and the target is assuming a lower order model than the filter, this is also a valid maneuver for target tracking filters.
- This is because, the filter could have been using a lower order model and reduced the noise levels even more.

Targets: Model Mismatch

Definition

A **maneuver** is any motion characteristics that the target is assuming other than the model used by the filter.

- Maneuvers degrade the filter performance and makes the estimators susceptible to noise and clutter.
- Maneuvers, hence, should be checked continuously.
- Since target maneuvers are often in a set of finite number of models, multiple model approaches (Interacting multiple model (IMM) filter being the most famous) became popular.
- Using all possible models at the same time made hypothesis checks about maneuvers unnecessary.

Targets & Measurements

Definition

Association is the process of assigning measurements to existing tracks or existing tracks to measurements (measurement-to-track association vs. track-to-measurement association).

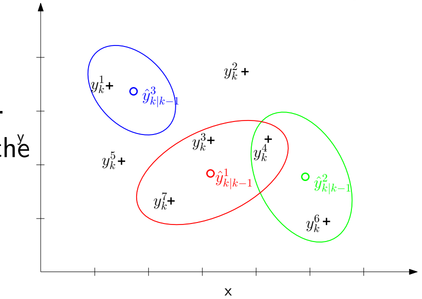
- In a classical air traffic control (ATC) application, there are hundreds of targets and measurements.
- Possible combinations are incredibly many.
- Not all of the possible associations are physically feasible.
- One must exclude these highly unlikely combinations from further consideration as soon as possible.

Targets & Measurements

Definition

Gating is the process of using prior information or the sufficient statistics for a track to exclude the possibility of assigning a measurement to the track. The region in the measurement space that the measurements are allowed to be assigned to the target is called as the **gate**.

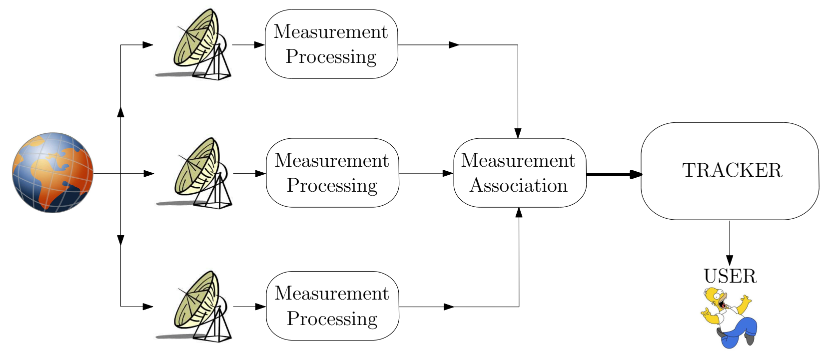
- Using maximum velocity assumptions about the target can give coarse gates.
- More detailed gates are formed using the predicted measurement means and innovations (measurement prediction) covariances of the track.



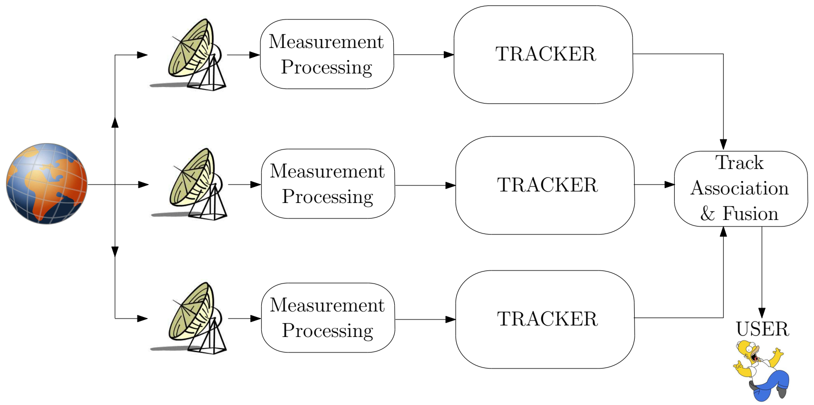
Targets & Measurements

- Even if gating reduces the number possible association combinations, there still remains some association uncertainty.
- These are handled by some other association algorithms:
  - Nearest neighbors (NN) (single, in general, non-global (local) hard decision)
  - Global nearest neighbors (GNN) (single unique hard decision)
  - (Joint) probabilistic data associations (JPDA) (soft decisions, i.e., no decision or decision with probabilities)
  - Multi hypothesis tracking (MHT) (making hard but multiple decisions and keeping them until sufficient evidence arrives)
- What association algorithm to use depends on the SNR of the system and amount of computational resources that can be allocated to association.

Multiple Sensors: Centralized Tracking Case



Multiple Sensors: Decentralized Tracking Case



Multiple Sensors

Architecture Issues:

- Centralized approach is optimal.
- Communication constraints make it unattractive because measurement communication rates are generally higher than track communication rates.
- Some of the computations can also be distributed in the decentralized case.
- System's **susceptibility to failures** in the tracking center is also an important issue.
- We are going to concentrate on the decentralized architecture.

Multiple Sensors

Definition

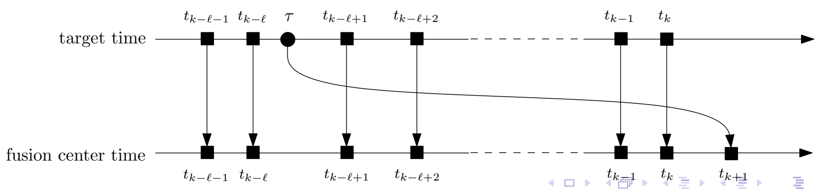
Registration: Alignment of the coordinate axes of two or more local sensors/trackers and finding the correspondences between them.

Definition

Bias: Registration errors.

Definition

Out of sequence measurements: Measurements delayed in the communication which arrive into the fusion center after a more current measurement from the same source has already been processed.



Multiple Sensors

Definition

Track association: Process of deciding whether two or more tracks obtained from local trackers are coming from the same source.

Definition

Track fusion: Process of combining the sufficient statistics of two or more tracks from local trackers when they are associated to each other.

Important issue: Correlation between the local estimation errors although the local sensors measurement errors are independent.

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