Hybrid Estimation for Unmanned Aircraft Systems Detect and Avoid

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Motivation

- Airspace integration for Unmanned Aircraft Systems (UAS) flights beyond vision line of sight
- Replace pilot vision functionality through appropriate sensors
- The need for Detect and Avoid (DAA): UAS must be able to identify the non-cooperative intruder aircraft for integration into National Airspace System (NAS)
  - Certifiable DAA sensors

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Motivation

- RTCA MOPS (Radio Technical Commission for Aeronautics - Minimum Operational Performance Standards) – Phase II[1]
  - Extended requirements for UAS operation, much larger scope through different airspace classes
  - Sensors and architectures to enable DAA equipment to be installed on a wider range of UAS (Phase 1 focused on large high-performance UAS)
- Analyze operations and encounters of smaller UAS at low altitude
  - Allow the use of airborne non-cooperative sensors (no ADS-B) and with less performance than the Phase 1 Air-to-Air Radar (new MOPS for Electro-Optical sensors)

[1] Detect and Avoid (DAA) DRAFT White Paper Phase 2 (RTCA Paper No. 144-17/SC228-051) - June 5, 2017

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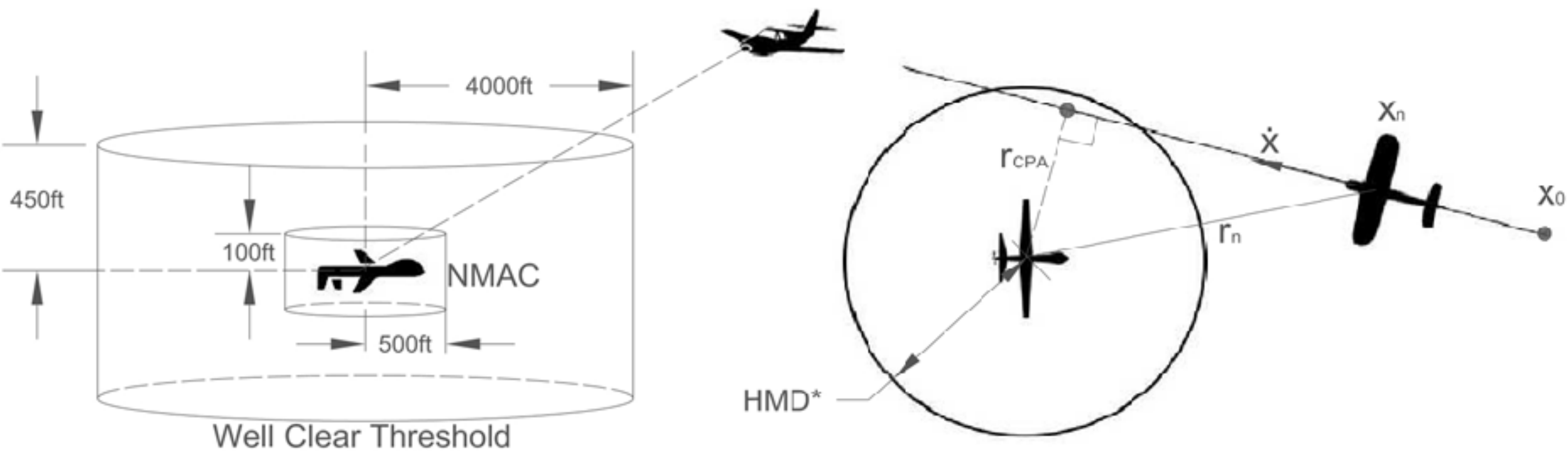
Contributions/Objectives

- Develop new methods to apply safety standards in Detect and Avoid (DAA) functions with a maneuvering intruder
  - Advance previous work that have used linear predefined trajectories
  - Generate random trajectories using an established Encounter Model
  - Target Tracking
    - Multiple Model Adaptive Estimation (MMAE)
    - Interactive Multiple Model (IMM)
  - **Hazard States Error Analysis** using the IMM
  - **New method** for Closest Point of Approach (CPA) estimation based on the IMM prediction

Self-Separation

- Self-separation: visual requirement to remain well clear[2]
  - Well clear threshold (WCT) definition (RTCA SC-228)[3]:
    - Time to horizontal closest point of approach (CPA): $\tau = 35$s
    - Horizontal miss distance of 4000ft and vertical miss distance of 450ft



[2] 14 CFR 91.113

[3] RTCA SC-228, Draft DAA MOPS, V3.3, Apr 2016

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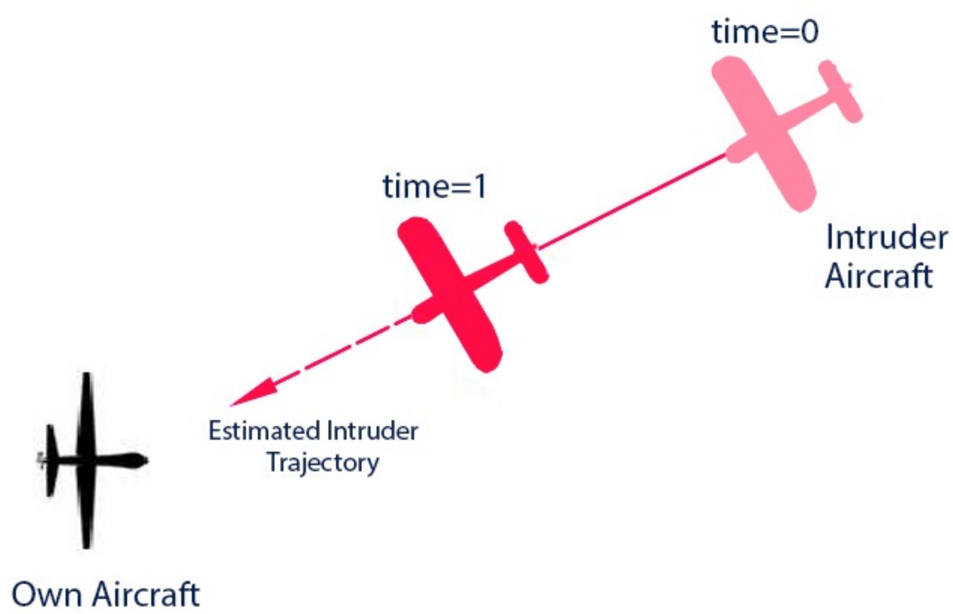
Target Tracking



- Our own aircraft has to detect and estimate the intruder aircraft trajectory
- Uncertainty in the measurement due to estimation error
  - As the DAA sensors gets more measurements, our estimated trajectory error decreases

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Target Tracking

- Tracking maneuvering targets
- Two main difficulties:
  - Measurement uncertainty (sensor noise)
  - Unknown intruder aircraft intent
- A potential solution is a Kalman filter (KF)
  - Limited in performance for such problems
  - Single motion model
  - Response to dynamics changes as the target maneuvers

Multiple Model Approach

- Another alternative is the Multiple Model Adaptive Estimation (MMAE) for state estimation
  - Account for different target behavior
  - It is assumed that the system obeys one of a finite number of dynamic models
  - Multiple filters (running in parallel) estimate the states of targets with changing dynamics
- These systems are called hybrid
  - Continuous dynamics
  - Discrete mode changes (multiple model)

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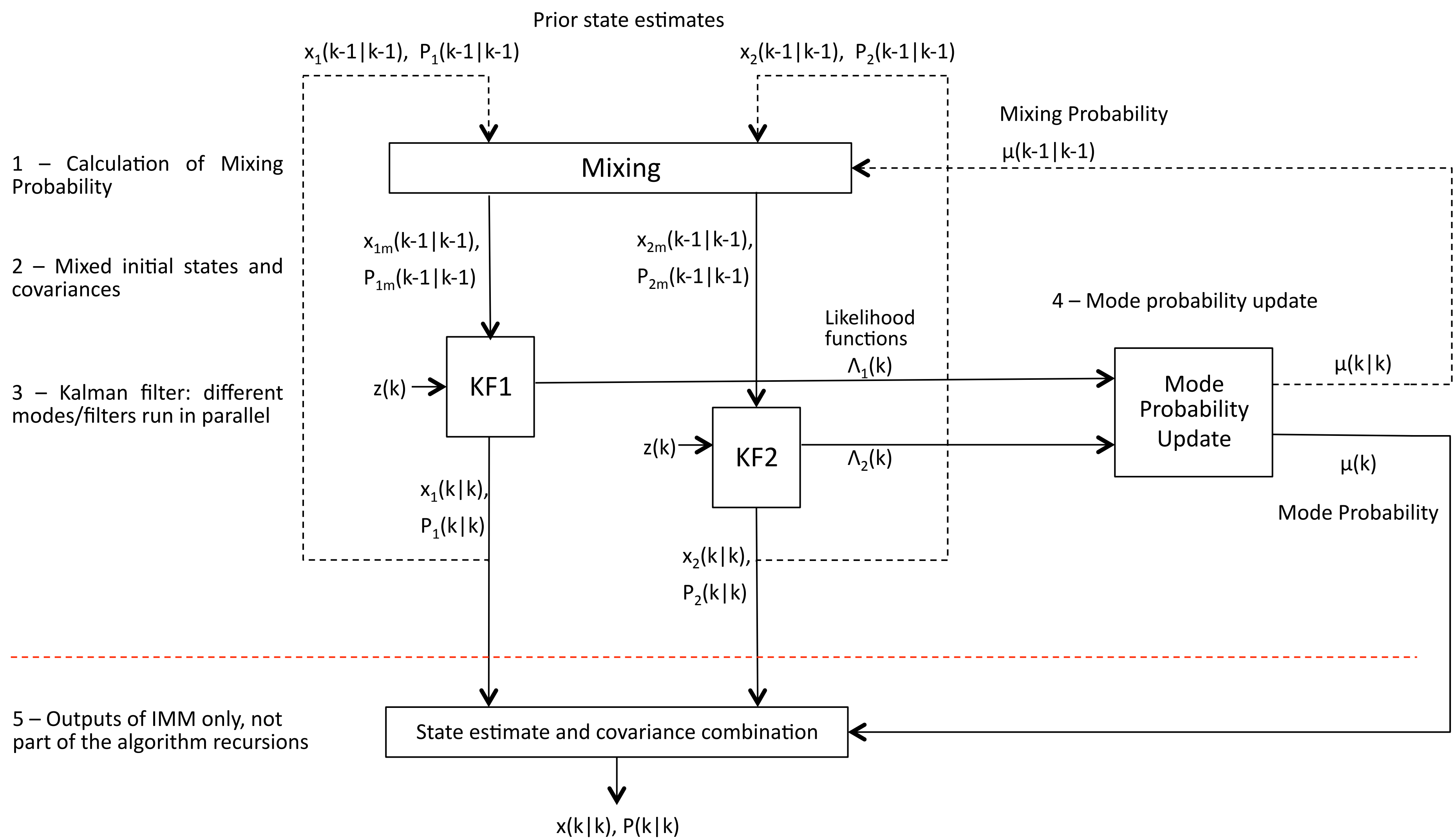
IMM Algorithm

- Optimal MMAE estimation: must account for any potential estimation history
  - Would require r^k filters (estimation histories) for *r* modes and *k* epochs
- The Interactive Multiple Model (IMM) algorithm
  - State estimate is computed under each possible current model using *r* filters
  - Each filter uses a different combination of the previous estimates
    - Mixed initial conditions
  - Target dynamics modeled with simple kinematics (corresponding to an individual mode)
- Typically, IMM is a good compromise between complexity and performance, [4] to be evaluated in our specific problem

[4] Bar-Shalom, Y., Kirubarajan, T., & Li, X. (2007). Estimation with applications to tracking and navigation:. New York, NY: Wiley

IMM Algorithm



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Encounter Model - Overview

- How do we define intruder trajectories for the IMM analysis
- Another tool that we are using is an encounter model
  - Simulations that can represent realistic trajectories
  - They are generated with the same likelihood as found in real aircraft trajectories
- MIT Lincoln Lab Encounter Model: based on US radar data [5]
  - Trajectory construction is not provided with the encounter model
  - The initial conditions do not specify position or direction of velocity
  - It gives as output initial conditions and control variables for each time step

[5] Kochenderfer, M., et al., Uncorrelated Encounter Model of the NAS. Project Report ATC-345, MIT Lincoln Lab, 2008

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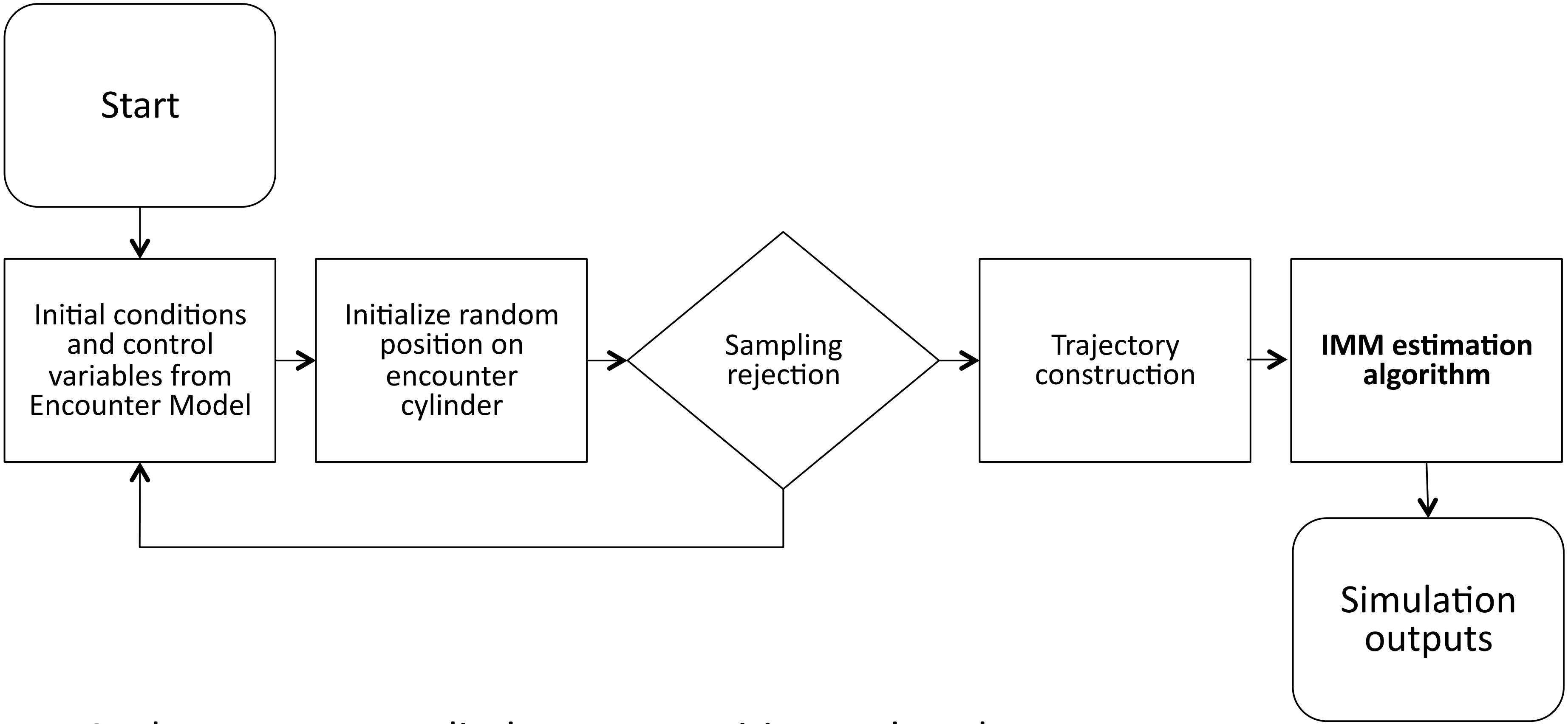
Simulation Steps



- At the encounter cylinder, start position and angle:
  - The encounter cylinder is assumed to have ± 3000ft height [10]/ 5.5 NM radius
  - Intruder aircraft starts at a random position at the encounter cylinder surface, at a random heading angle

[10] RTCA SC-228, Draft DAA MOPS, V3.3, Apr 2016

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IMM - Modes

- Based in an ATC scenario[7,8,9], the motions of an aircraft can be summarized as ascent/descent, straight level flight, turning, and change of speed
    - Mode 1 - Constant Velocity
    - Mode 2 - Constant Velocity 3D (non-zero $\dot{h}$)
    - Mode 3 - Coordinated Turn
    - Mode 4 - Coordinated Turn 3D (non-zero $\dot{h}$)
    - Mode 5 - Constant Linear Acceleration
    - Mode 6 - Constant Linear Acceleration 3D (non-zero $\dot{h}$)

[7] Kochenderfer, M., et al., Uncorrelated Encounter Model of the NAS. Project Report ATC-345, MIT Lincoln Lab, 2008
[8] Li, X. R., & Bar-Shalom, Y. (1993). Design of an interacting multiple model algorithm for air traffic control tracking. IEEE Transactions on Control Systems Technology, 1(3), 186–194
[9] Bar-Shalom, Y., Kirubarajan, T., & Li, X. (2007). Estimation with applications to tracking and navigation:. New York, NY: Wiley

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IMM - Transition Matrix

- Transition Matrix of the Markov Chain (M_{ij}) – used on the mode probability update - is based on Encounter Model runs (10^6), with 1 second timesteps
  - Homogeneous Markov Chain: time-invariant

$$\mathbf{M}_{ij} = \begin{bmatrix} 0.98038 & 0.00692 & 0.00562 & 0.00093 & 0.00508 & 0.00108 \\ 0.02536 & 0.96022 & 0.00246 & 0.00509 & 0.00200 & 0.00487 \\ 0.03263 & 0.00280 & 0.95063 & 0.00646 & 0.00624 & 0.00123 \\ 0.01280 & 0.01891 & 0.01456 & 0.94566 & 0.00172 & 0.00636 \\ 0.02551 & 0.00250 & 0.01098 & 0.00077 & 0.95314 & 0.00710 \\ 0.00926 & 0.01860 & 0.00204 & 0.01147 & 0.01049 & 0.94814 \end{bmatrix}$$

  - The mode probability initial values:

$$\boldsymbol{\mu_{ip}} = \begin{bmatrix} 0.55117 & 0.15393 & 0.10708 & 0.04781 & 0.09292 & 0.04709 \end{bmatrix}$$

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Hazard States

- At the definition of the Hazard States in the **DAA MOPS**
  - Calculation of the CPA is time based

$$CPA = \sqrt{(d_x + v_{rx} t_{CPA})^2 + (d_y + v_{ry} t_{CPA})^2}$$

$$t_{CPA} = max(0, -\frac{d_x v_{rx} + d_y v_{ry}}{v_{rx}^2 + v_{ry}^2})$$

where: $v_{rx} = \dot{x}_2 - \dot{x}_1$ is the relative horizontal velocity in the x dimension

$v_{ry} = \dot{y}_2 - \dot{y}_1$ is the relative horizontal velocity in the y dimension

$d_x = x_2 - x_1$ is the current horizontal separation in the x dimension

$d_y = y_2 - y_1$ is the current horizontal separation in the y dimension

- Vertical separation for alerting performance requirements are based on actual altitudes
  - We assume constant vertical velocity to account for the lookahead time alert criteria

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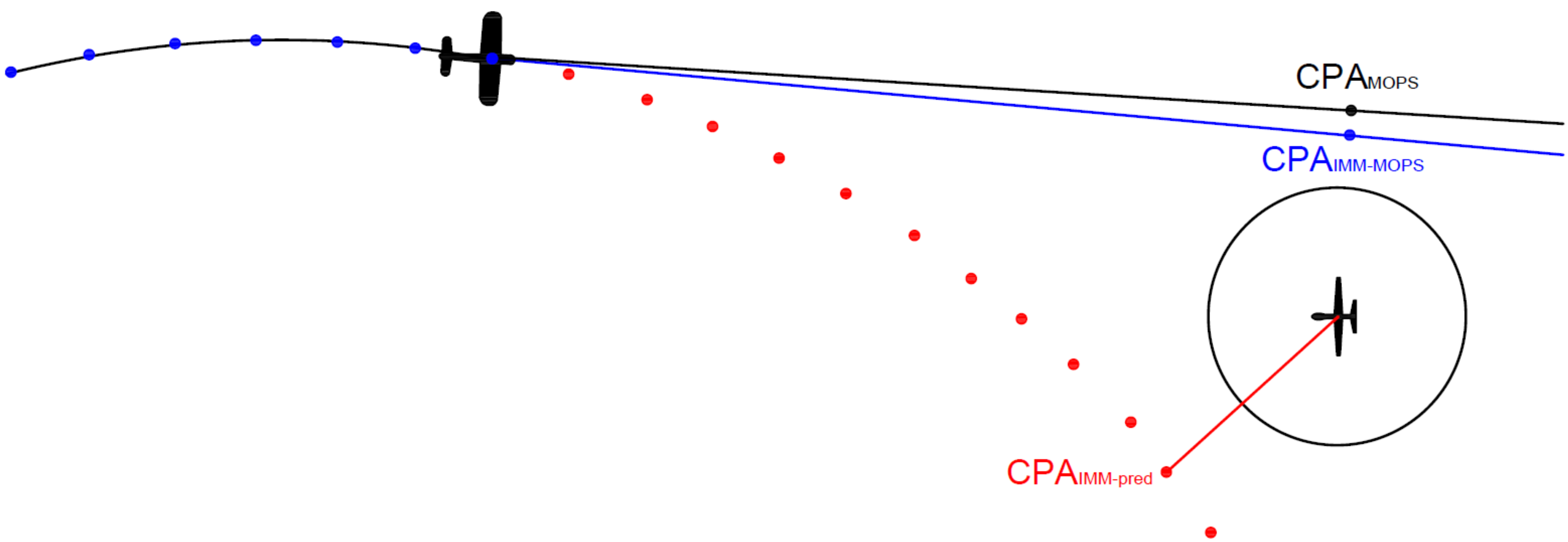
CPA Calculation

- In order to minimize prediction errors on the Hazard States, we introduce a new method instead of using the MOPS calculations (which are based on a linear trajectory propagation)
  - Use Kalman prediction step as estimation for CPA **(IMM Prediction)**

- There will be four main different **CPA definitions**:
  - **<u>MOPS:</u>** using the formula as defined by the MOPS
  - **<u>IMM-MOPS:</u>** using the formula as defined by the MOPS and the best trajectory estimation by the IMM
  - **<u>IMM-Predicted:</u>** estimated closest point of approach calculated at each timestep, using the IMM prediction (new method)
  - **<u>True:</u>** only known after the simulation has ended (influenced by future mode switches)

IMM Prediction

- Under maneuvers, the Hazard States estimation will be changing at each timestep



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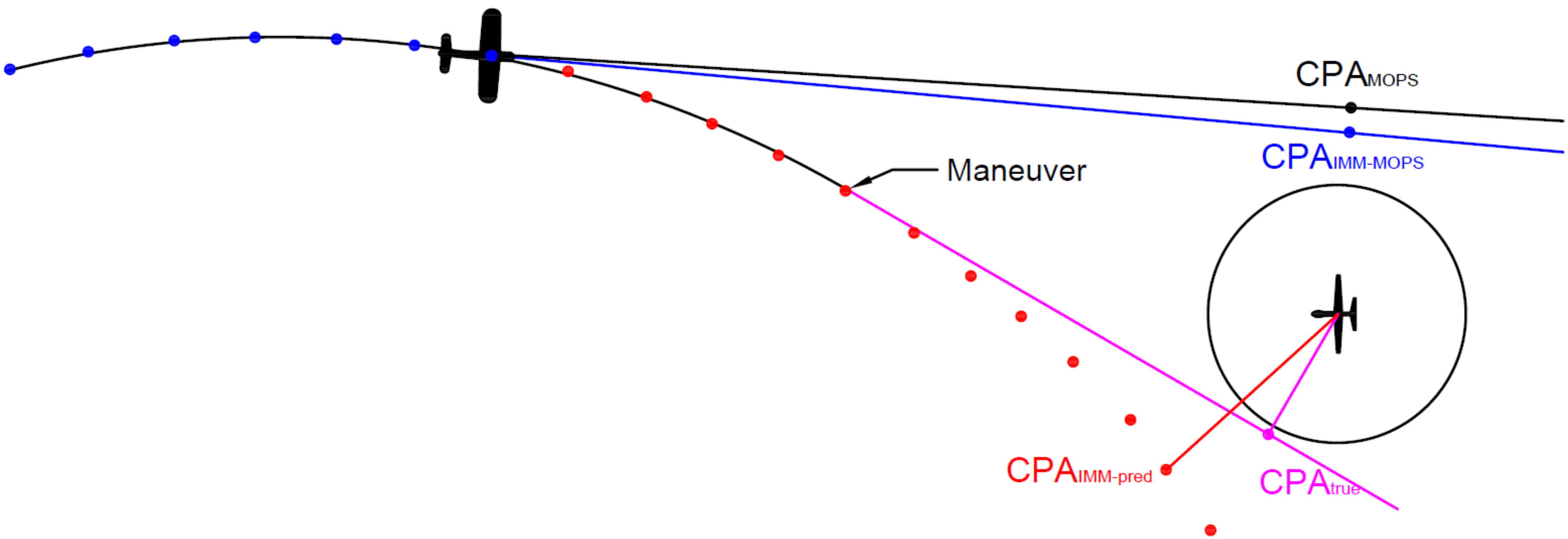
IMM Prediction

- We don’t know future aircraft intent (maneuver changes)
  - Using the knowledge of the current maneuver can improve our estimation
  - Our estimation will get better as the IMM recognizes the maneuver



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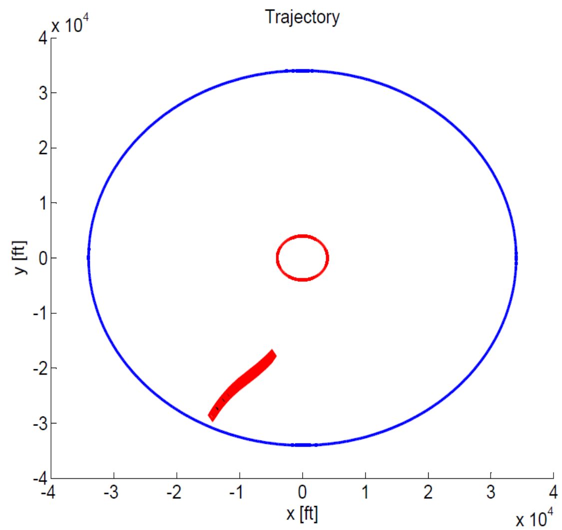
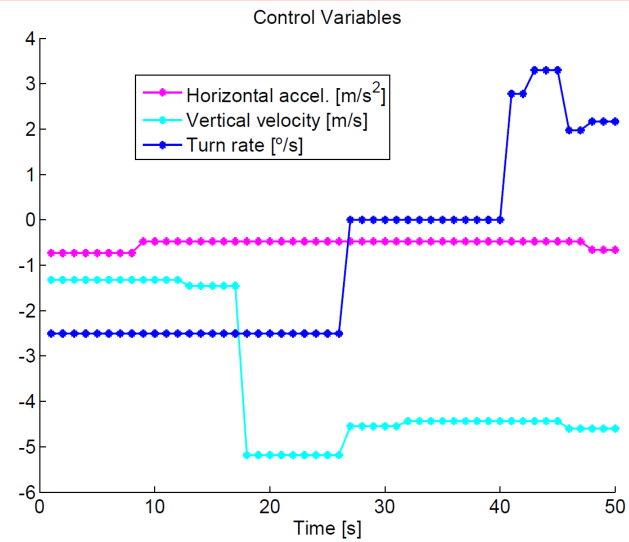
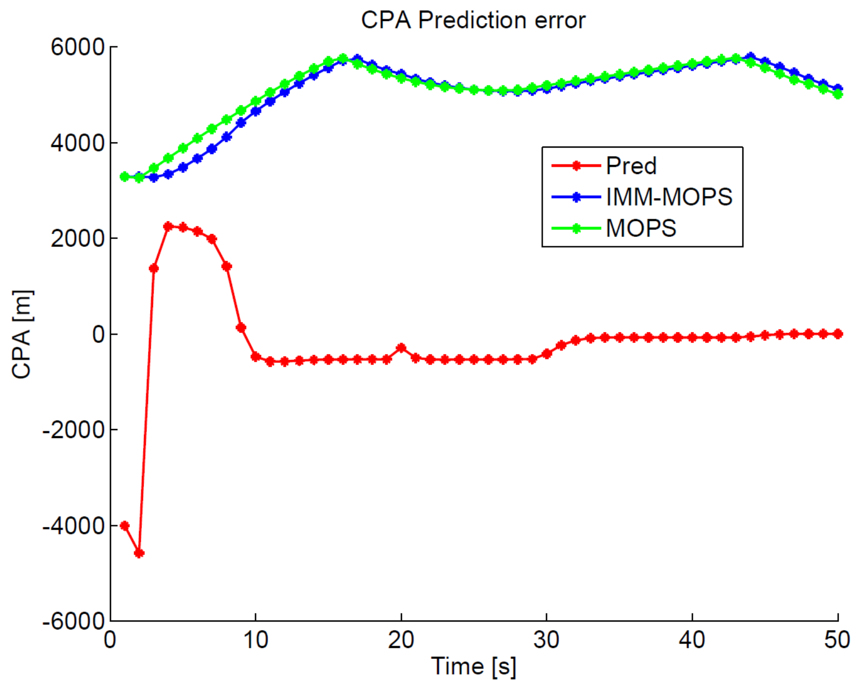
Simulation

- Own aircraft: linear trajectory, constant velocity of 200kt
- Intruder aircraft: randomly generated by the encounter model
- Simulation time: 50s / sample rate: 1Hz
- Zero ***sensor noise***

IMM Prediction - Results







IMM Prediction - Discussion

- The estimation get better after the IMM recognizes the maneuver and adapts to the new predictions

- The overall prediction error when compared to the True CPA is considerably reduced using the new method

- Use the Encounter Model together with these tools for a safety evaluation
  - Based on the NMAC/LoWC probability associated with the encounter rate

$$P(LoWC) = \lim_{N_s \to \infty} \sum_{j=1}^{N_s} P(LoWC|E_j)$$

$$\lambda_{enc} = \rho \bar{V}$$

$$\lambda_{LoWC} = P(LoWC)\lambda_{enc}$$

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Summary

- Developing new tools for evaluate a DAA system performance with a maneuvering intruder
  - Define system requirements

- In this work, we investigated an intruder dynamics estimation method using an Interactive Multiple Model approach
  - Using an established encounter model to generate trajectories which include maneuvering intruders in proportion of their likelihood of occurence

- Developed a new method for Hazard States estimation based on the IMM prediction

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Future Work

- Future research:
  - Further analysis on the error sources (*mode transition adaptation; mode transition prediction; modeling error; sensor noise*)
  - Considerations with respect to Field of Regard from the MOPS[11]
    - ± 110 with respect to the longitudinal axis
    - ± 15 vertically referenced to the flight path
  - Safety evaluation based on the NMAC/LoWC probability associated with the encounter rate

[11] RTCA MOPS for Air-to-Air Radar for Traffic Surveillance

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Thank you!

Questions?

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