Advanced Statistical Signal Processing for Next Generation Trajectory Prediction

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Outline

I. Introduction

II. Aircraft Models

III. Flight Intent

IV. From KF (single model MMSE estimation) to IMM (mode-based KF)

V. Perspectives

Introduction

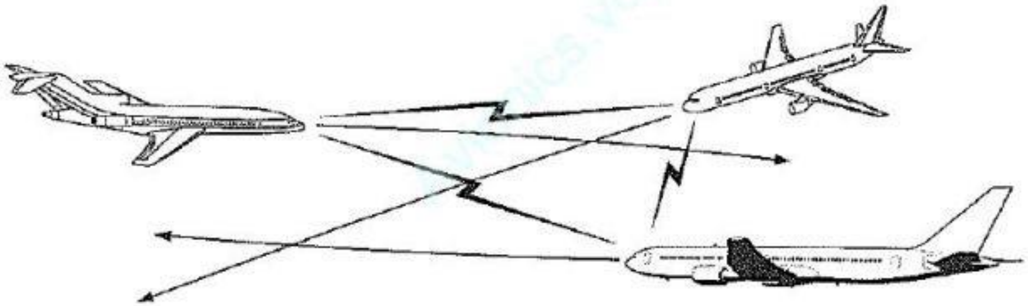
I. The future Air Traffic Management (ATM) system

II. Medium-Term Conflict Detection (MTCD)

III. Reduction of False Alarms

IV. Enabling Self-Separation

V. 4D Trajectories



Our Approach: Next Generation Trajectory Prediction via Estimation Theory

Trajectory Prediction

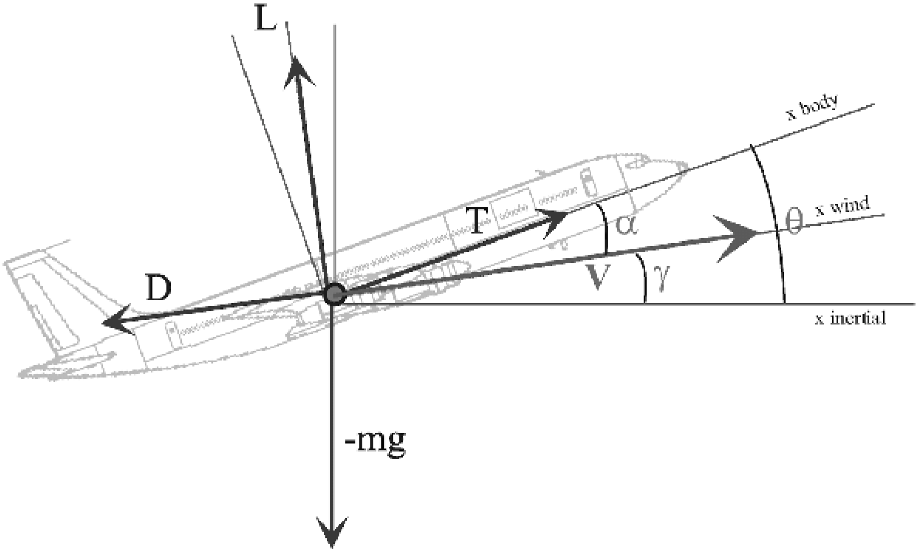
I. **Aircraft Dynamics Model (point-mass model)**

II. **Aircraft Performance Model (BADA4.x)**

III. **Flight Intent**

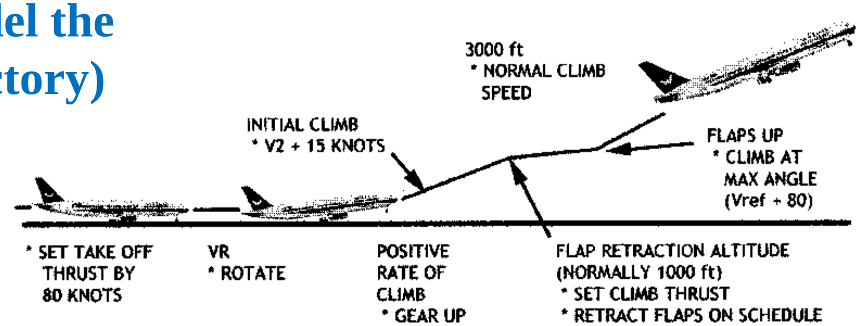
IV. **Initial State**

V. **Estimation Approach**



Flight Intent

What if the model can change through time?
A single model cannot accurately model the behavior of the system (aircraft trajectory)



Elevator and Throttle

$$\mathrm{c}_i\left(\boldsymbol{x},\ \boldsymbol{u},\ \boldsymbol{p}\right) = 0; \quad i \in \{1,\ 2\}$$

$$v_{CAS} - 300\mathrm{kt} = 0$$
$$T - T_{idle} = 0$$

An Example: Fixed Throttle Setting

$$T - T_{idle} - \pi(T_{max} - T_{idle}) = 0; \pi \in [0, 1]$$

Controlling the ground flight path angle (FPA)

$$\gamma - \gamma_g = 0$$

Controlling the Vertical Speed

$$VS = \frac{dh_p}{dt} \Rightarrow VS = \frac{\tau - \Delta\tau}{\tau}.v.sin(\gamma)$$

Controlling the Energy Share Factor

$$k = (1 + \frac{v}{g}.\frac{dv}{dh})^{-1} \Rightarrow \gamma = arcsin(\frac{T_{idle} - D}{m.g}.k)$$

TP is an Estimation Problem

State Vector

$$\mathbf{x} = [v, h, m, \tau, p]$$

Measurement Vector

$$\mathbf{y} = [v, h_p, \frac{dh}{dt}, VS, V_{CAS}, M]$$

Parameters and Input Vectors

$$\mathbf{p} = [\pi, VS, \gamma_g, k] \quad \mathbf{u} = [T, \gamma]$$

FPA-Thrust(idle)

$$\mathbf{p} = [\pi, \gamma_g]$$

Fixed Throttle and Controlling FPA

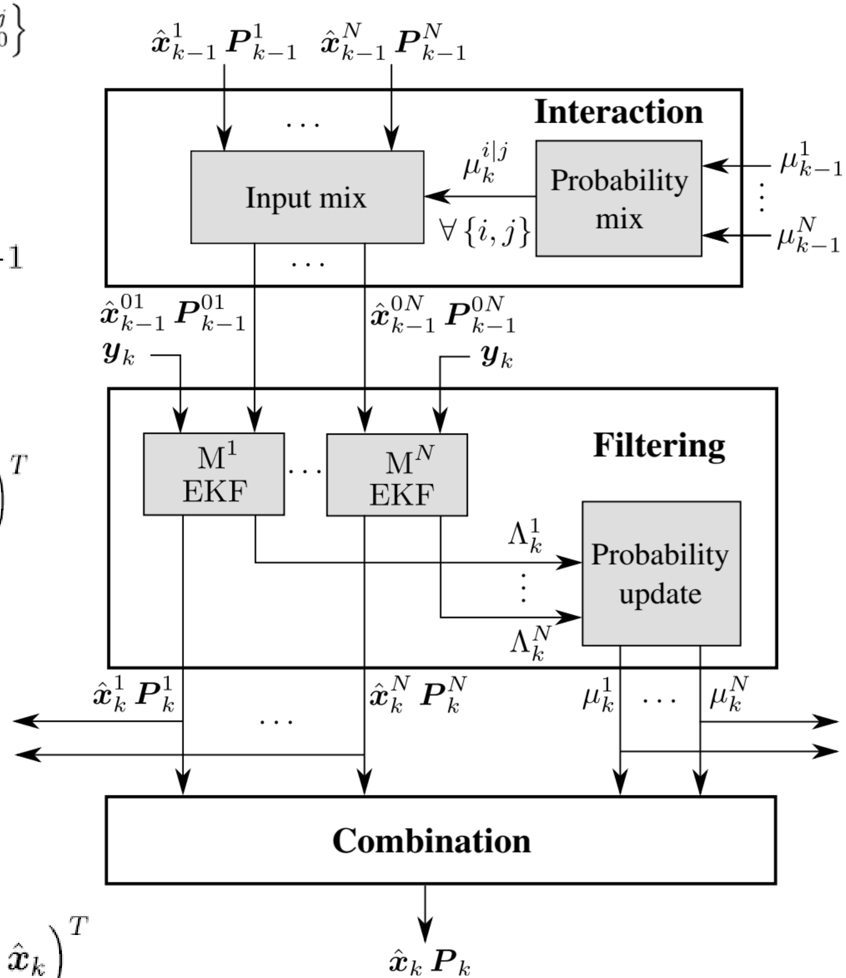
State-space Model Formulation

$$\mathbf{x_k} = \mathbf{f}\left(\mathbf{x_{k-1}}, \mathbf{u_{k-1}}, \mathbf{p}\right) + \mathbf{q_{k-1}}$$

$$\mathbf{y_k} = \mathbf{h}\left(\mathbf{x_k}, \mathbf{u_k}, \mathbf{p}\right) + \mathbf{r_k}$$

From KF to IMM[1] (mode-based KF)

$$p_{ij} = P\left\{\mathrm{M}_k^j | \mathrm{M}_{k-1}^i\right\} \qquad \mu_0^j = P\left\{\mathrm{M}_0^j\right\}$$



Interaction

$$\bar{c}_j = \sum_{i=1}^{N} p_{ij}\mu_{k-1}^i\,; \quad \mu_k^{i|j} = \frac{1}{\bar{c}_j} p_{ij}\mu_{k-1}^i$$

$$\hat{\boldsymbol{x}}_{k-1}^{0j} = \sum_{i=1}^{N} \mu_k^{i|j} \hat{\boldsymbol{x}}_{k-1}^i$$

$$\boldsymbol{P}_{k-1}^{0j} = \sum_{i=1}^{N} \mu_k^{i|j} \boldsymbol{P}_{k-1}^i \left(\hat{\boldsymbol{x}}_{k-1}^i - \hat{\boldsymbol{x}}_{k-1}^{0j}\right)\left(\hat{\boldsymbol{x}}_{k-1}^i - \hat{\boldsymbol{x}}_{k-1}^{0j}\right)^T$$

Filtering

$$\bar{c} = \sum_{i=1}^{N} \Lambda_k^i \bar{c}_i\,; \quad \mu_k^i = \frac{1}{\bar{c}} \Lambda_k^i \bar{c}_i$$

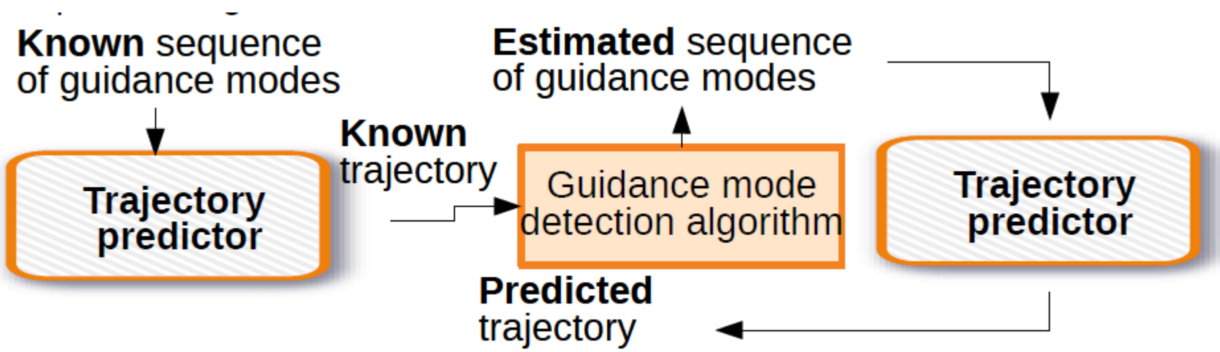
Combination

$$\hat{\boldsymbol{x}}_k = \sum_{i=1}^{N} \mu_k^i \hat{\boldsymbol{x}}_k^i$$

$$\boldsymbol{P}_k = \sum_{i=1}^{N} \mu_k^i \boldsymbol{P}_k^i \left(\hat{\boldsymbol{x}}_k^i - \hat{\boldsymbol{x}}_k\right)\left(\hat{\boldsymbol{x}}_k^i - \hat{\boldsymbol{x}}_k\right)^T$$

[1] Dalmau, Ramon, Marc Pérez-Batlle, and Xavier Prats. "Real-time Identification of Guidance Modes in Aircraft Descents Using Surveillace Data." *2018 IEEE/AIAA 37th Digital Avionics Systems Conference (DASC)*. IEEE, 2018.

Identification of Guidance Modes



Phase	M		End condition	
	VT1	VT2	VT1	VT2
1	ALT-SPEED		$\Delta s = 20\,\mathrm{NM}$ (distance)	
2	VS-CAS	MACH-THR	$h_p = \mathrm{FL}280$	$v_{CAS} = 300\,\mathrm{kt}$
3	CAS-THR		$h_p = \mathrm{FL}110$	
4	DEC-THR		$v_{CAS} = 230\,\mathrm{kt}$	$v_{CAS} = 250\,\mathrm{kt}$
5	CAS-THR	FPA-CAS	$h_p = 3000\,\mathrm{ft}$	

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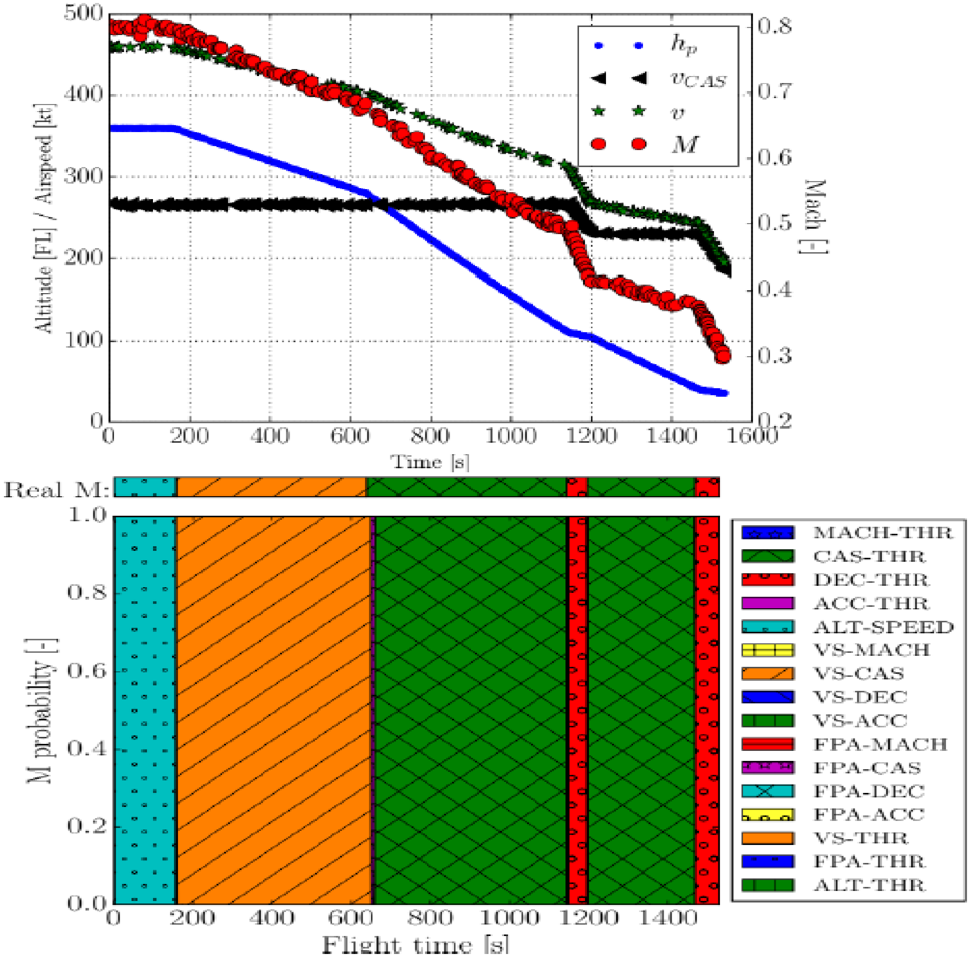

ALT-Speed
VS-CAS
CAS-THR
DEC-THR
CAS-THR

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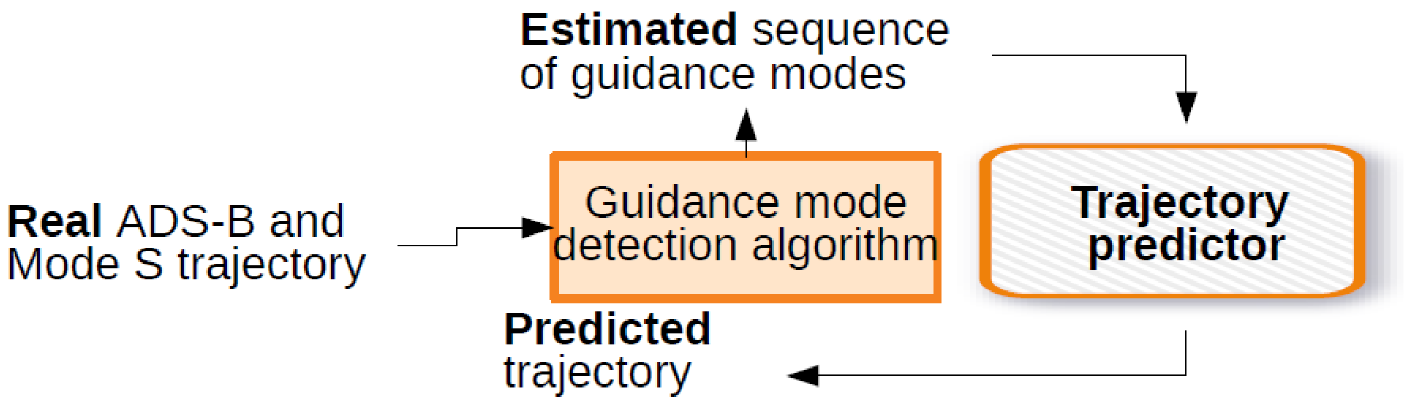

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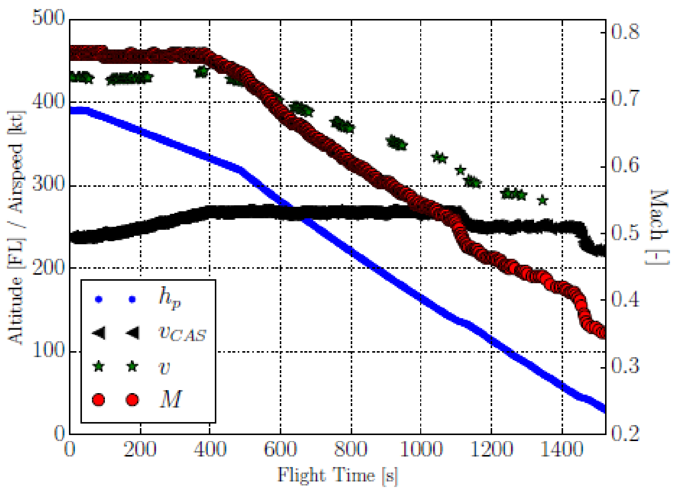

(a) Altitude and speed

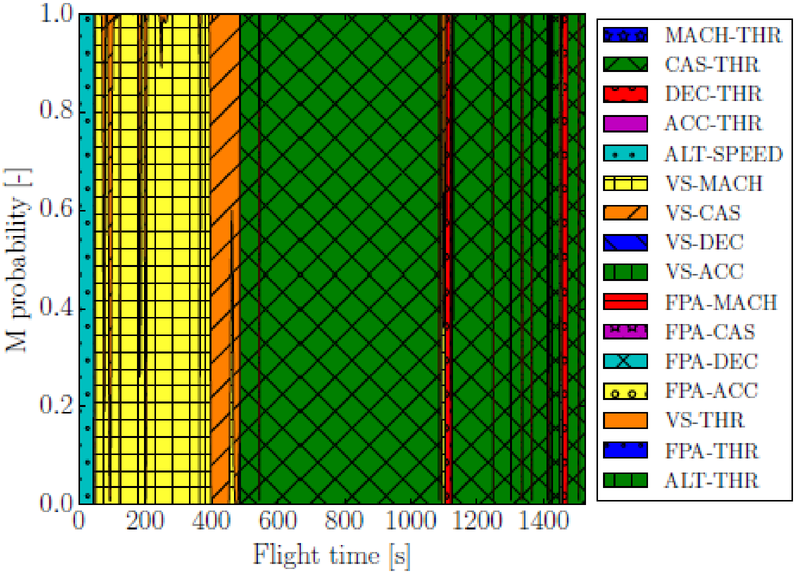

Fig. 6. Model probabilities for the real trajectory

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Perspectives

Preliminary results using the IMM: good guidance mode estimation [1]

To be explored:

I. **Improve the system and uncertainty models (i.e., 2D to 3D, wind, …)**

II. **New estimation techniques (alternatives to the IMM)**

III. **Optimal vs Robust vs Adaptive approaches**

IV. **From centralized to cooperative (Self-separation)**

V. **From single to multiple aircraft TP**

That's only the beginning of this story…

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Thank you for your attention

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