

# EXPLORATION DE DONNÉES POUR L'OPTIMISATION DE TRAJECTOIRES AÉRIENNES

Cédric Rommel

Directeurs de thèse: Frédéric Bonnans, Pierre Martinon  
Encadrant Safety Line: Baptiste Gregorutti

Soutenance de thèse, 26 octobre 2018



- 1 Context - *Chapter 1*
- 2 System Identification - *Chapter 4*
- 3 Trajectory Acceptability - *Chapters 5 and 6*

# CONTEXT

# MOTIVATION

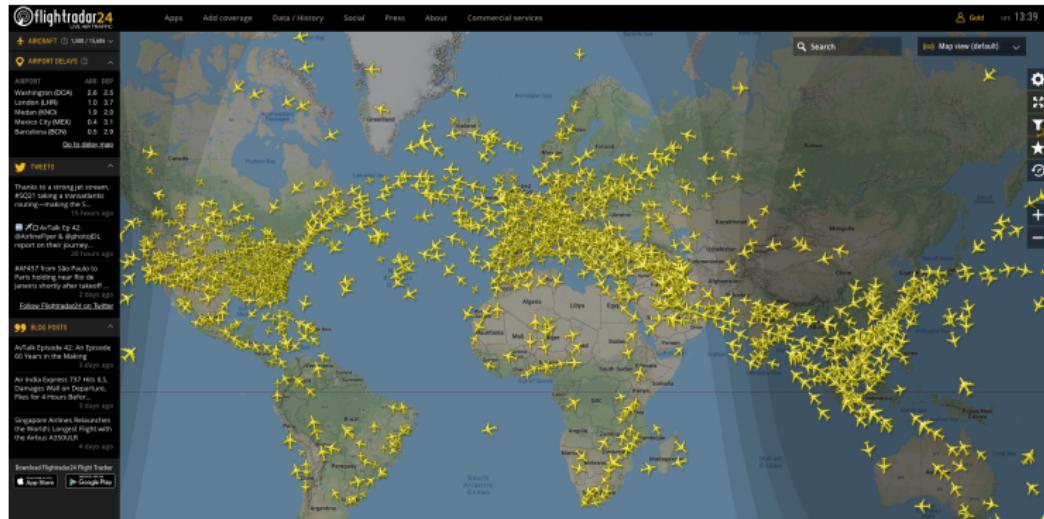


FIGURE: World air traffic - source: [www.flightradar24.com](http://www.flightradar24.com)

# MOTIVATION

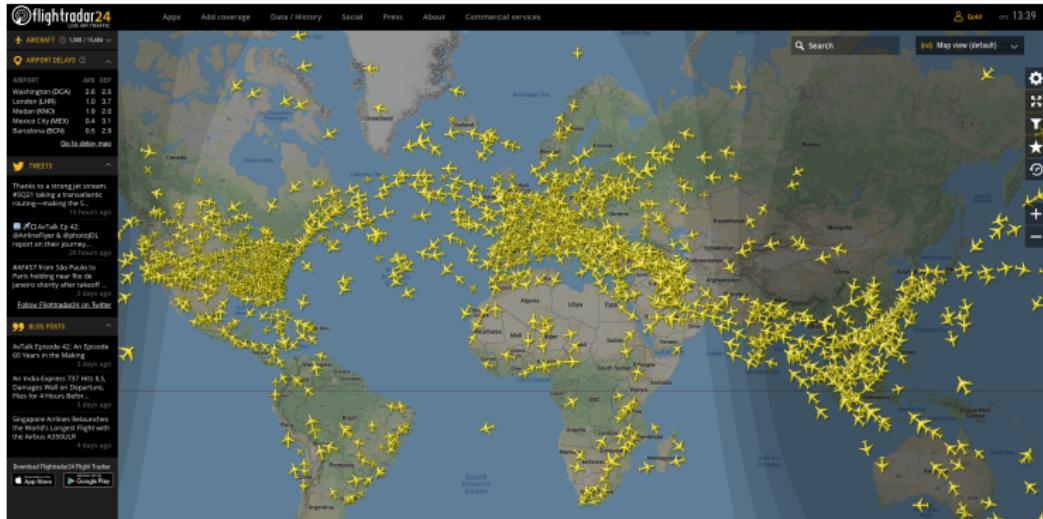


FIGURE: World air traffic - source: [www.flightradar24.com](http://www.flightradar24.com)

- 20 000 airplanes — 80 000 flights per day,

# MOTIVATION

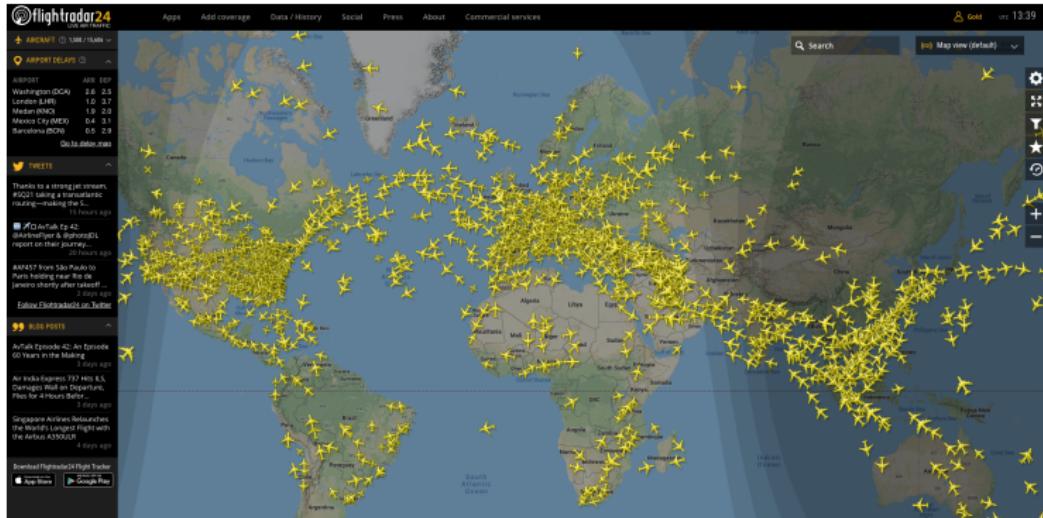
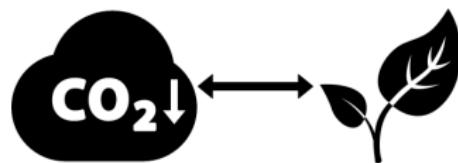


FIGURE: World air traffic - source: [www.flightradar24.com](http://www.flightradar24.com)

- 20 000 airplanes — 80 000 flights per day,
- Should double until 2033,

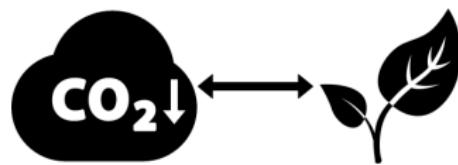
# MOTIVATION

- Most polluting means of transportation,



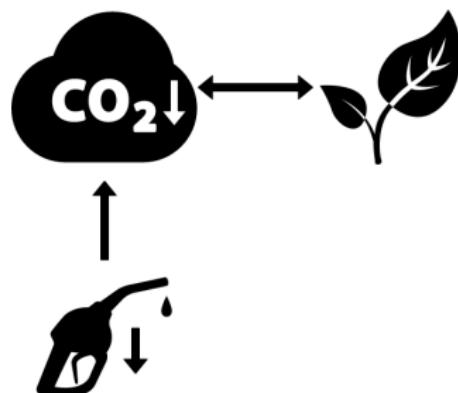
# MOTIVATION

- Most polluting means of transportation,
- Responsible for 3% of  $CO_2$  emissions,



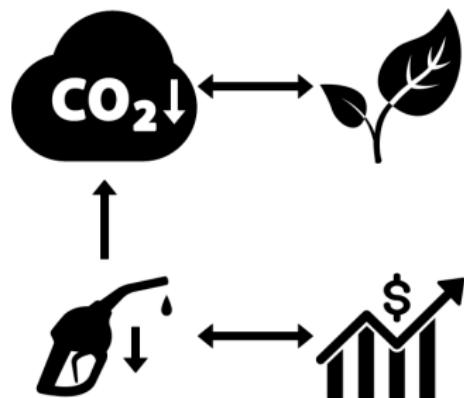
# MOTIVATION

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# MOTIVATION

- Most polluting means of transportation,
- Responsible for 3% of  $CO_2$  emissions,
- Fuel  $\simeq$  30% of an airline operational cost,



# MOTIVATION

How to tackle this problem ?

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- New hardware ?

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- **Better use of existing fleet,**

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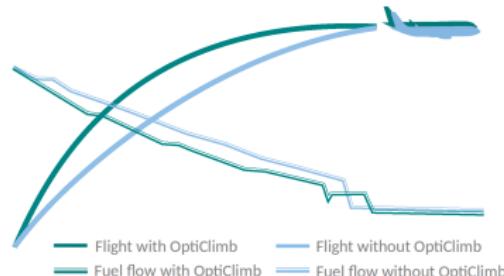
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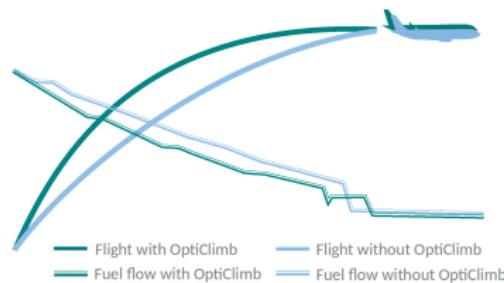
- New hardware ?
- **Better use of existing fleet,**
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- Mostly rectilinear trajectories at full thrust,



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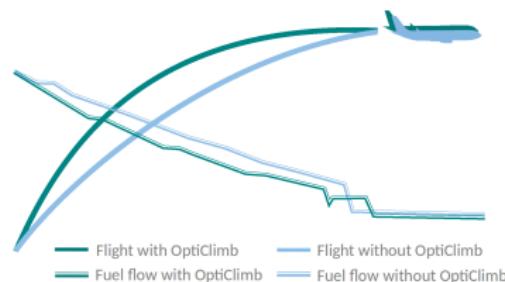
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# OPTICLIMB



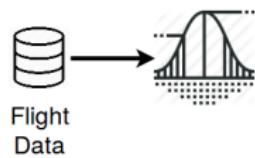
Flight  
Data

**Time**



*Many days before flight...*

# OPTICLIMB

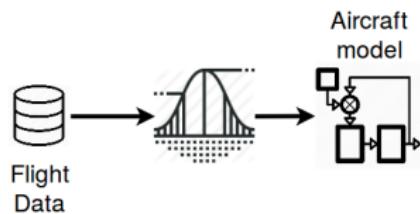


Flight  
Data

**Time**

*Many days before flight...*

# OPTICLIMB

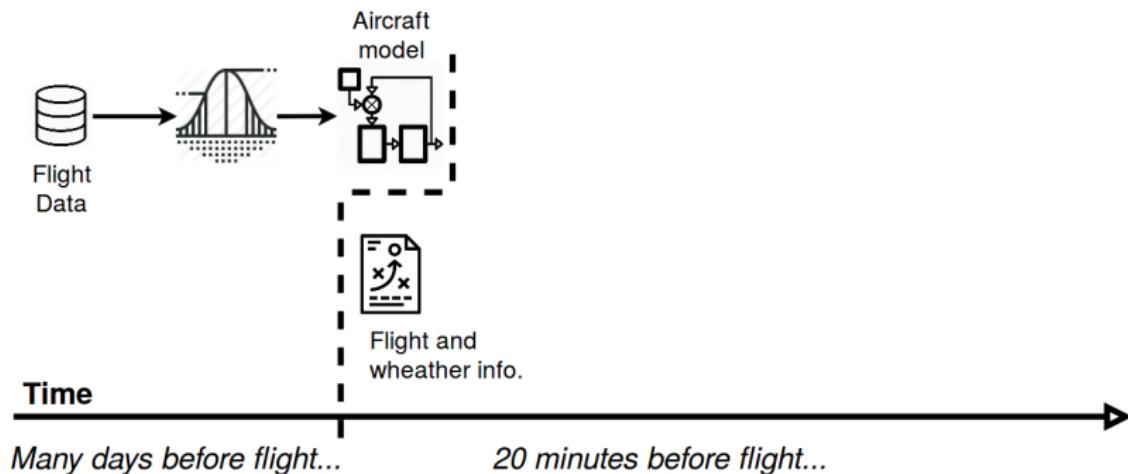


**Time**

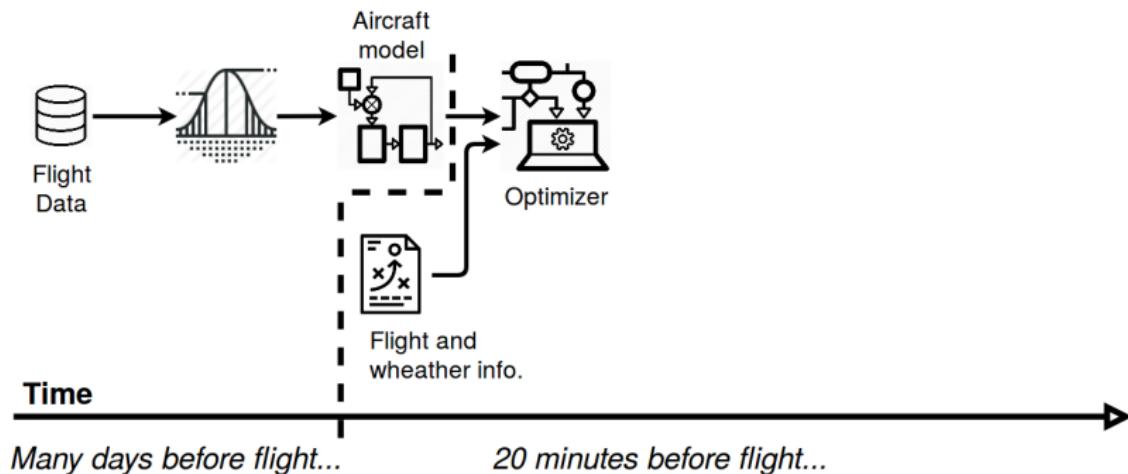


*Many days before flight...*

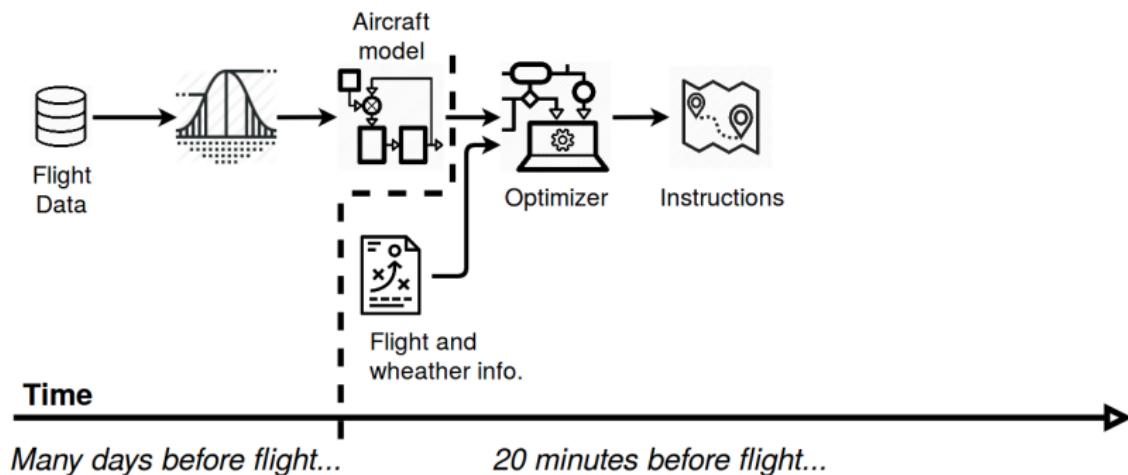
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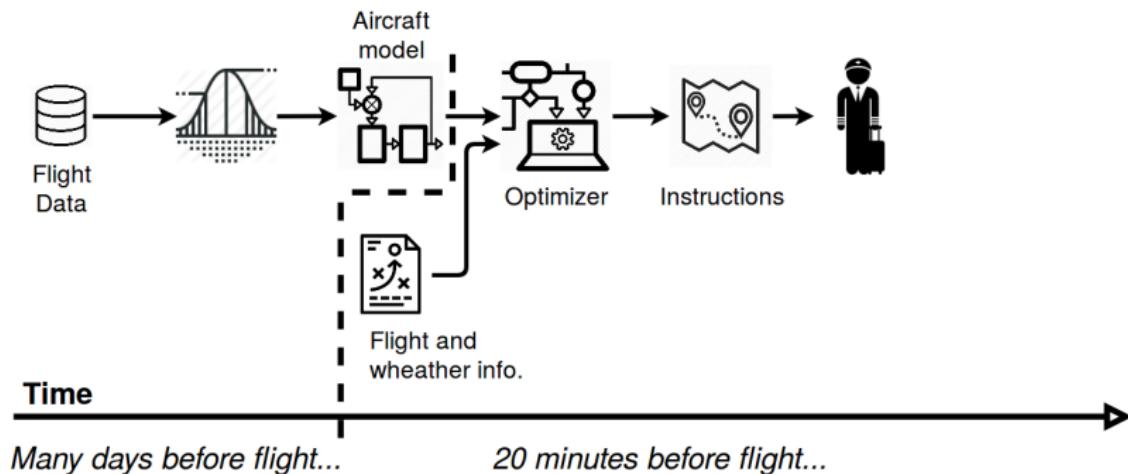
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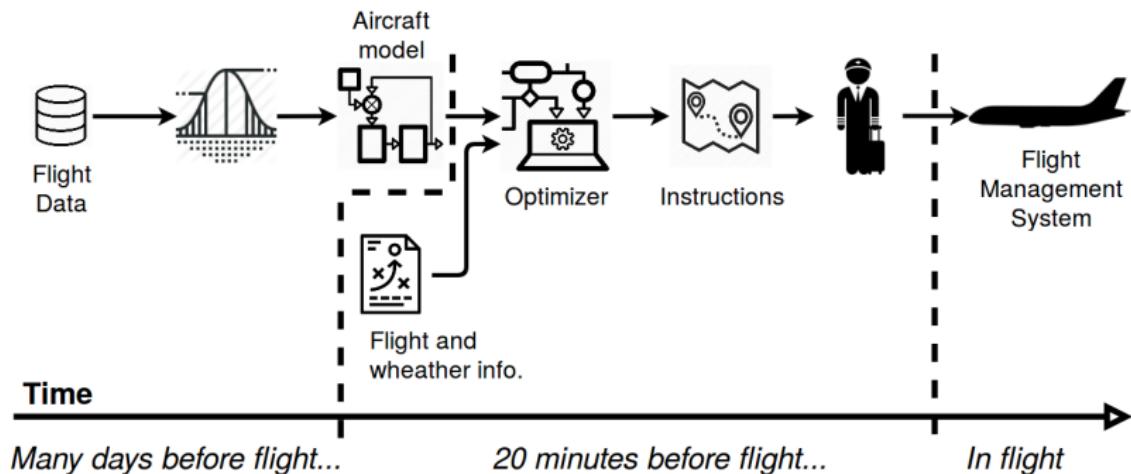
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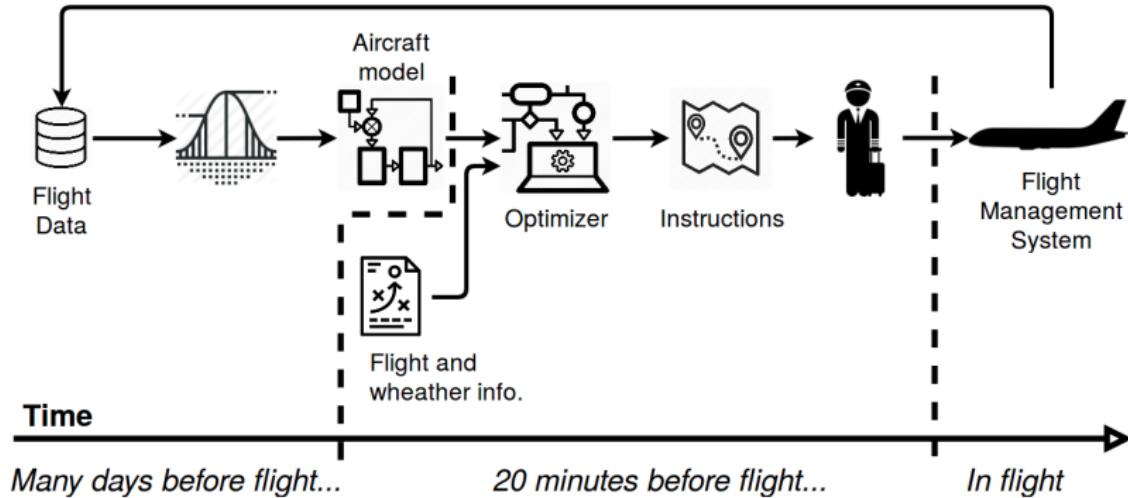
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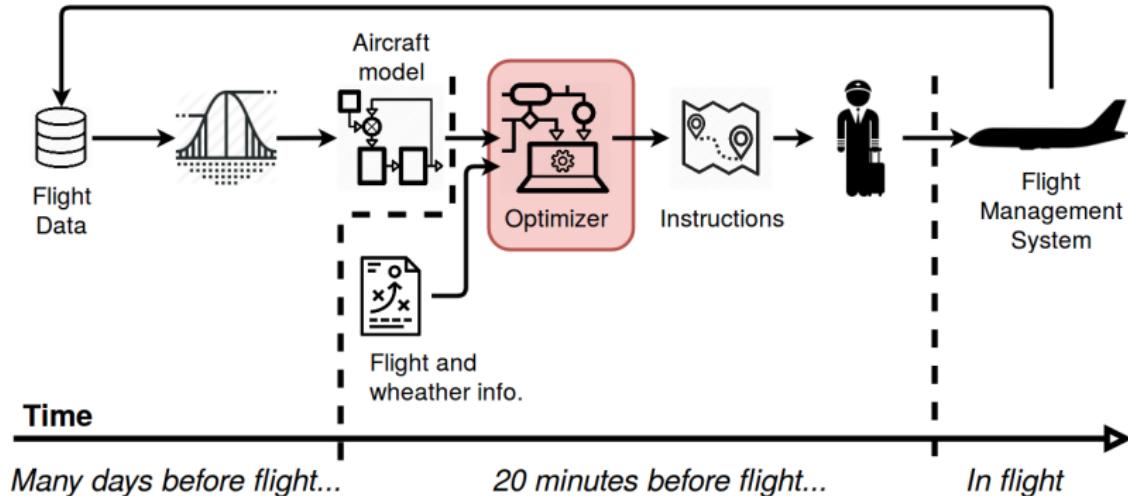
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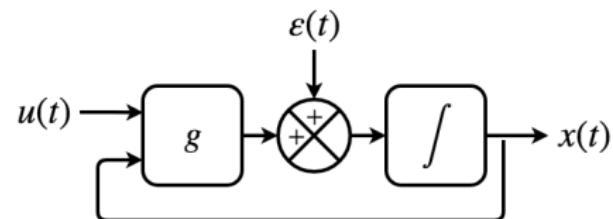


# OPTICLIMB



# TRAJECTORY OPTIMIZATION

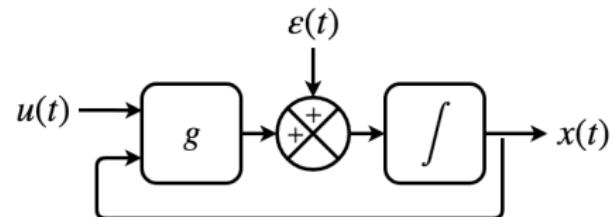
# TRAJECTORY OPTIMIZATION



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Dynamics:

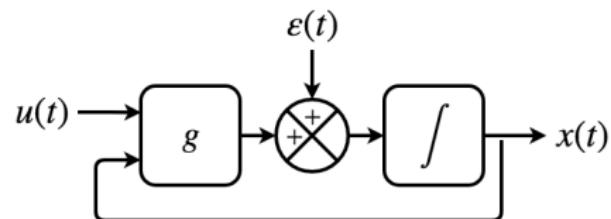
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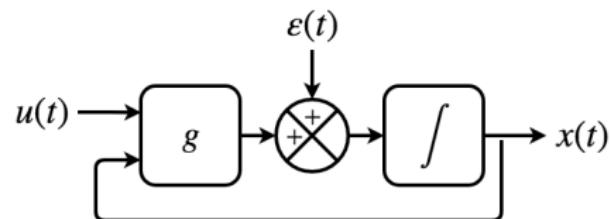


Optimization objective:  $\int_0^{t_f} C(\mathbf{u}(t), \mathbf{x}(t)) dt$

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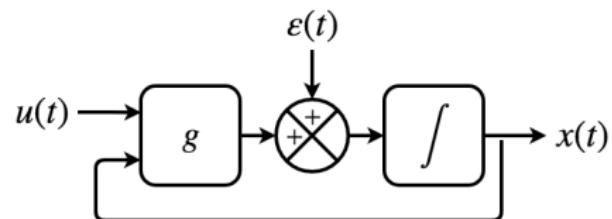


Optimization objective:  $\int_0^{t_f} C(\mathbf{u}(t), \mathbf{x}(t)) dt \Leftarrow \text{min}$ ,

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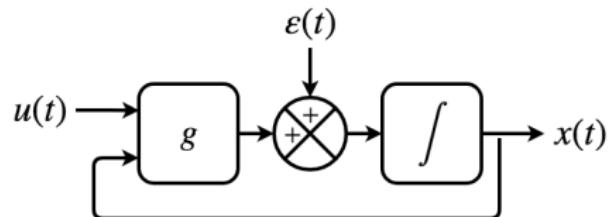


Optimization objective:  $\int_0^{t_f} C(\mathbf{u}(t), \mathbf{x}(t)) dt \Leftarrow \text{↗, } \text{📍, } \text{⌚️}$

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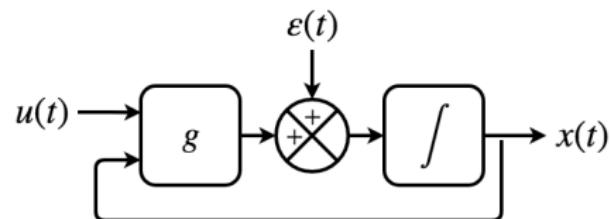
Flight constraints:

{

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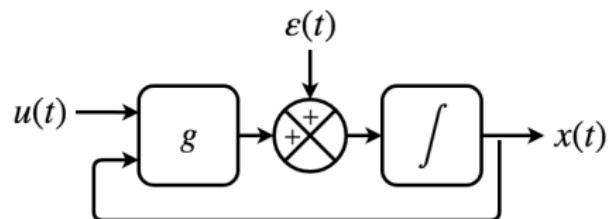
$$\left\{ \begin{array}{l} \Phi(\mathbf{x}(0), \mathbf{x}(t_f)) \in K_\Phi \end{array} \right.$$

Initial and final conditions

# TRAJECTORY OPTIMIZATION

Dynamics:

$$\dot{x}(t) = g(\mathbf{u}(t), \mathbf{x}(t)) + \varepsilon(t)$$



Optimization objective:  $\int_0^{t_f} C(\mathbf{u}(t), \mathbf{x}(t)) dt \Leftarrow \text{fuel}, \text{path}, \text{time}$

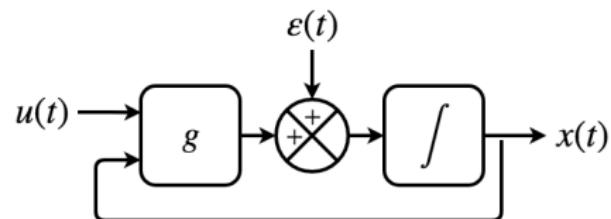
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Initial and final conditions  
Flight domain  
Operational path constraints

# TRAJECTORY OPTIMIZATION

## OPTIMAL CONTROL PROBLEM

$$\begin{aligned} & \min_{(\mathbf{x}, \mathbf{u}) \in \mathbb{X} \times \mathbb{U}} \int_0^{t_f} C(\mathbf{u}(t), \mathbf{x}(t)) dt, \\ \text{s.t. } & \left\{ \begin{array}{ll} \dot{\mathbf{x}}(t) = g(\mathbf{u}(t), \mathbf{x}(t)) + \varepsilon(t), & \text{a.e. } t \in [0, t_f], \\ \Phi(\mathbf{x}(0), \mathbf{x}(t_f)) \in K_\Phi, & \\ \mathbf{u}(t) \in U_{ad}, \quad \mathbf{x}(t) \in X_{ad}, & \text{a.e. } t \in [0, t_f], \\ c(\mathbf{u}(t), \mathbf{x}(t)) \leq 0, & \text{a.e. } t \in [0, t_f]. \end{array} \right. \end{aligned} \quad (\text{OCP})$$

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## SYSTEM IDENTIFICATION



Black box

# TRAJECTORY OPTIMIZATION

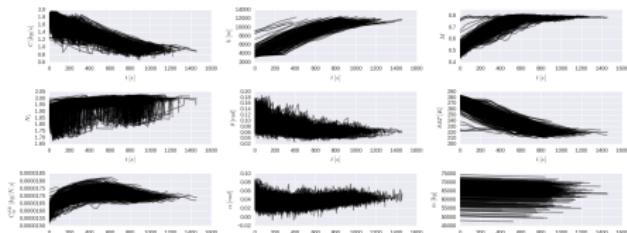
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## SYSTEM IDENTIFICATION



Black box



QAR data

# TRAJECTORY OPTIMIZATION

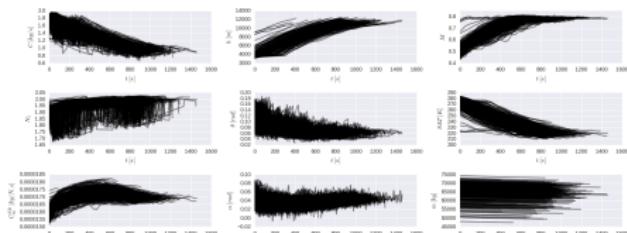
## APPROXIMATE OPTIMAL CONTROL PROBLEM

$$\begin{aligned} & \min_{(\mathbf{x}, \mathbf{u}) \in \mathbb{X} \times \mathbb{U}} \int_0^{t_f} C(\mathbf{u}(t), \mathbf{x}(t)) dt, \\ \text{s.t. } & \left\{ \begin{array}{ll} \dot{\mathbf{x}}(t) = \hat{g}(\mathbf{u}(t), \mathbf{x}(t)), & \text{a.e. } t \in [0, t_f], \\ \Phi(\mathbf{x}(0), \mathbf{x}(t_f)) \in K_\Phi, & \\ \mathbf{u}(t) \in U_{ad}, \quad \mathbf{x}(t) \in X_{ad}, & \text{a.e. } t \in [0, t_f], \\ c(\mathbf{u}(t), \mathbf{x}(t)) \leq 0, & \text{a.e. } t \in [0, t_f]. \end{array} \right. \end{aligned} \quad (\text{A OCP})$$

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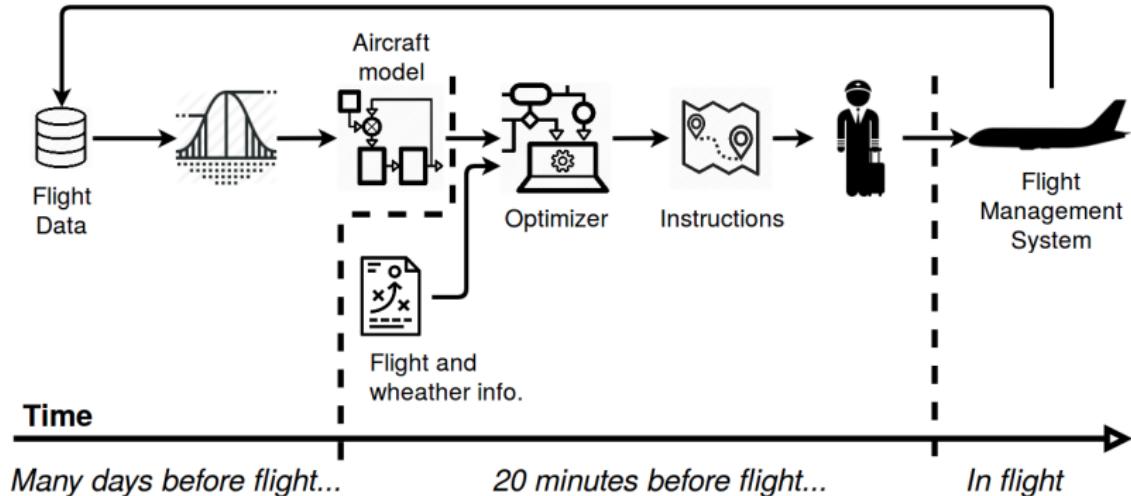


Black box

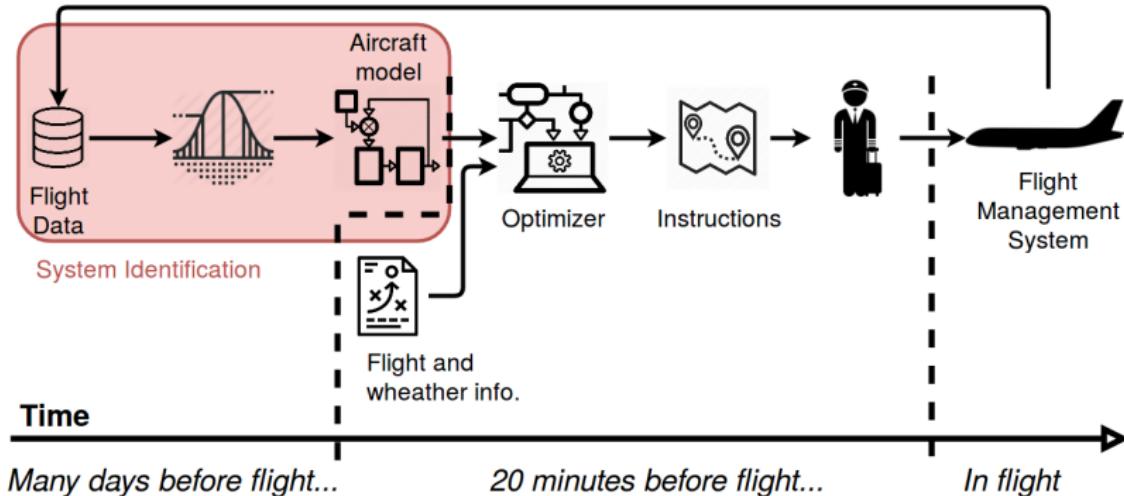


QAR data

# SYSTEM IDENTIFICATION

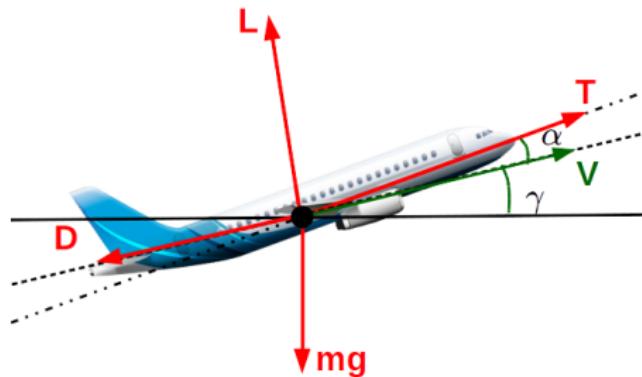


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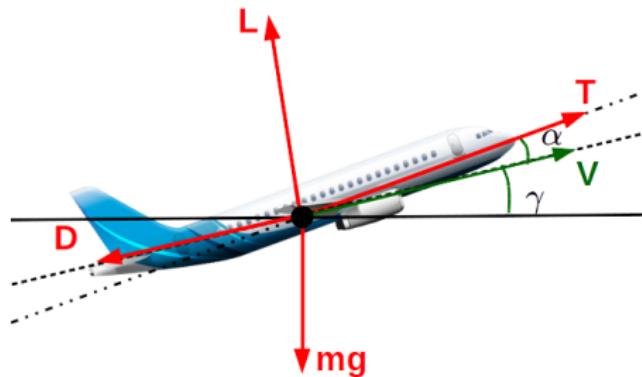


# SYSTEM IDENTIFICATION

# FLIGHT DYNAMICS

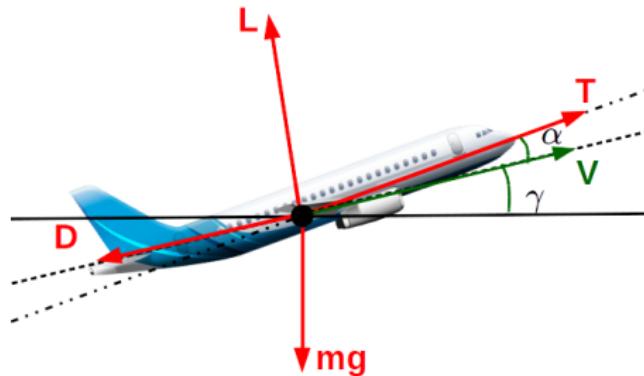


# FLIGHT DYNAMICS



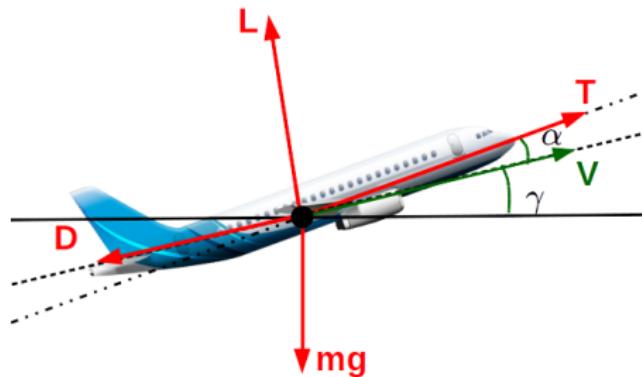
$$\left\{ \begin{array}{l} \dot{h} = V \sin \gamma \\ \dot{V} = \frac{T \cos \alpha - D - mg \sin \gamma}{m} \\ \dot{\gamma} = \frac{T \sin \alpha + L - mg \cos \gamma}{mV} \\ \dot{m} = -\frac{T}{I_{sp}} \end{array} \right.$$

# FLIGHT DYNAMICS



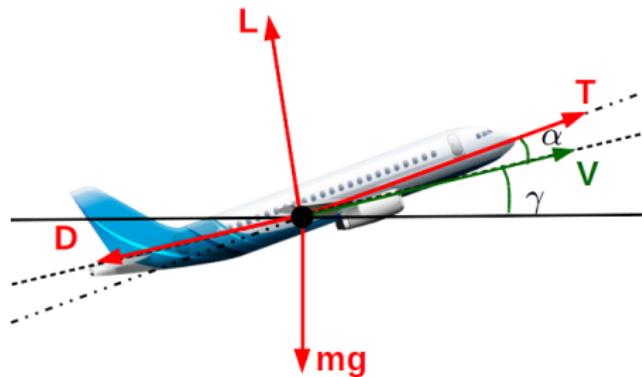
$$\left\{ \begin{array}{l} \dot{h} = V \sin \gamma + \dot{W}_z \\ \dot{V} = \frac{T \cos \alpha - D - mg \sin \gamma - m \dot{W}_{xv}}{m} \\ \dot{\gamma} = \frac{(T \sin \alpha + L) \cos \mu - mg \cos \gamma - m \dot{W}_{zv}}{mV} \\ \dot{m} = -\frac{T}{I_{sp}} \end{array} \right.$$

# FLIGHT DYNAMICS



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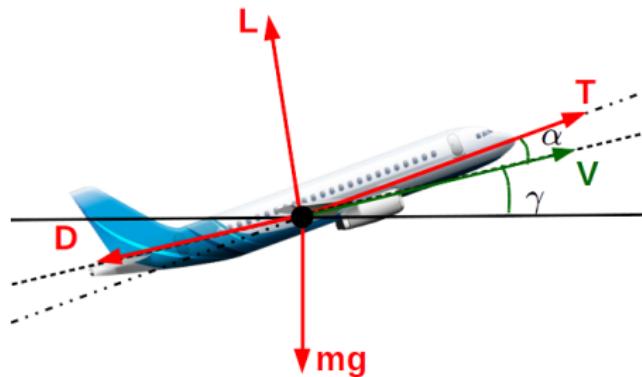
# FLIGHT DYNAMICS



States:  $x = (h, V, \gamma, m)$

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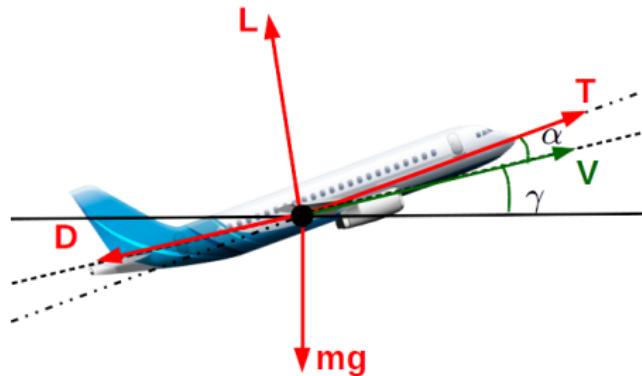
# FLIGHT DYNAMICS



**States:**  $x = (h, V, \gamma, m)$   
**Controls:**  $u = (\alpha, N_1)$

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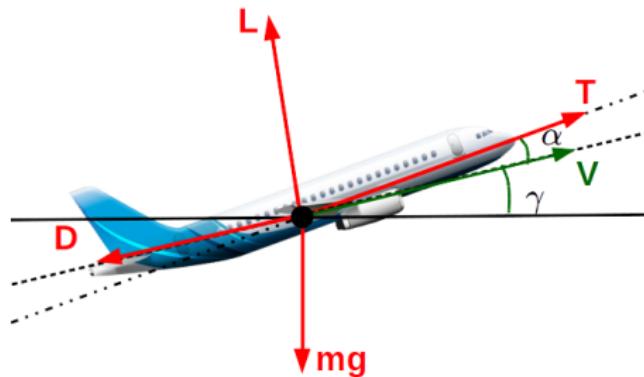
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**Unknown functions of  $x, u$**

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# PHYSICAL MODELS OF NESTED FUNCTIONS

$$\begin{cases} T \text{ function of } (N_1, M, \rho) \\ D \text{ function of } (q, M, \alpha) \\ L \text{ function of } (q, M, \alpha) \\ I_{sp} \text{ function of } (SAT, M, h) \end{cases}$$

# PHYSICAL MODELS OF NESTED FUNCTIONS

$$\begin{cases} T \text{ function of } (N_1, M, \rho) = \varphi_T(\mathbf{x}, \mathbf{u}) \\ D \text{ function of } (q, M, \alpha) = \varphi_D(\mathbf{x}, \mathbf{u}) \\ L \text{ function of } (q, M, \alpha) = \varphi_L(\mathbf{x}, \mathbf{u}) \\ I_{sp} \text{ function of } (SAT, M, h) = \varphi_{I_{sp}}(\mathbf{x}, \mathbf{u}) \end{cases}$$

# PHYSICAL MODELS OF NESTED FUNCTIONS

$$\begin{cases} T = N_1 \times P_T(\rho, M), \\ D = q \times P_D(\alpha, M), \\ L = q \times P_L(\alpha, M), \\ I_{sp} = SAT \times P_{Isp}(h, M), \end{cases}$$

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$$\begin{cases} T = X_T \cdot \theta_T, \\ D = X_D \cdot \theta_D, \\ L = X_L \cdot \theta_L, \\ I_{sp} = X_{Isp} \cdot \theta_{Isp}, \end{cases}$$

# PHYSICAL MODELS OF NESTED FUNCTIONS

$$\begin{cases} T = X_T \cdot \theta_T, \\ D = X_D \cdot \theta_D, \\ L = X_L \cdot \theta_L, \\ I_{sp} = X_{Isp} \cdot \theta_{Isp}, \end{cases}$$

$$X_T = N_1(1, \rho, M, \rho^2, \rho M, M^2, \dots)$$

$$X_D = q(1, \alpha, M, \alpha^2, \alpha M, M^2, \dots)$$

$$X_L = q(1, \alpha, M, \alpha^2, \alpha M, M^2, \dots)$$

$$X_{Isp} = SAT(1, h, M, h^2, hM, M^2, \dots)$$

# PHYSICAL MODELS OF NESTED FUNCTIONS

$$\begin{cases} T(\mathbf{x}, \mathbf{u}, \boldsymbol{\theta}_T) = X_T \cdot \boldsymbol{\theta}_T, \\ D(\mathbf{x}, \mathbf{u}, \boldsymbol{\theta}_D) = X_D \cdot \boldsymbol{\theta}_D, \\ L(\mathbf{x}, \mathbf{u}, \boldsymbol{\theta}_L) = X_L \cdot \boldsymbol{\theta}_L, \\ I_{sp}(\mathbf{x}, \mathbf{u}, \boldsymbol{\theta}_{Isp}) = X_{Isp} \cdot \boldsymbol{\theta}_{Isp}, \end{cases}$$

$$X_T = N_1(1, \rho, M, \rho^2, \rho M, M^2, \dots)$$

$$X_D = q(1, \alpha, M, \alpha^2, \alpha M, M^2, \dots)$$

$$X_L = q(1, \alpha, M, \alpha^2, \alpha M, M^2, \dots)$$

$$X_{Isp} = SAT(1, h, M, h^2, hM, M^2, \dots)$$

# STATE-OF-THE-ART

# STATE-OF-THE-ART

- Output-Error Method

$$\{u_f\}_{f \in \mathcal{F}}$$

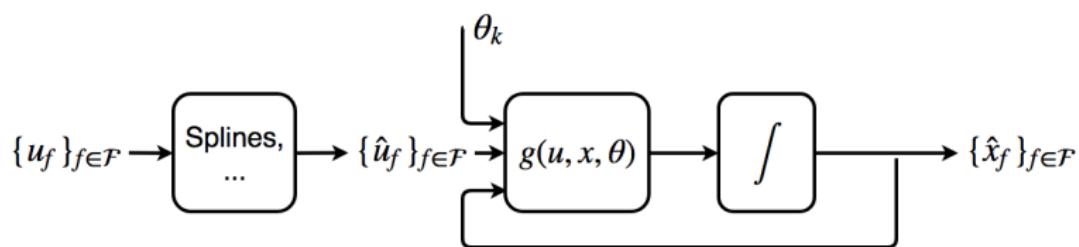
# STATE-OF-THE-ART

- Output-Error Method



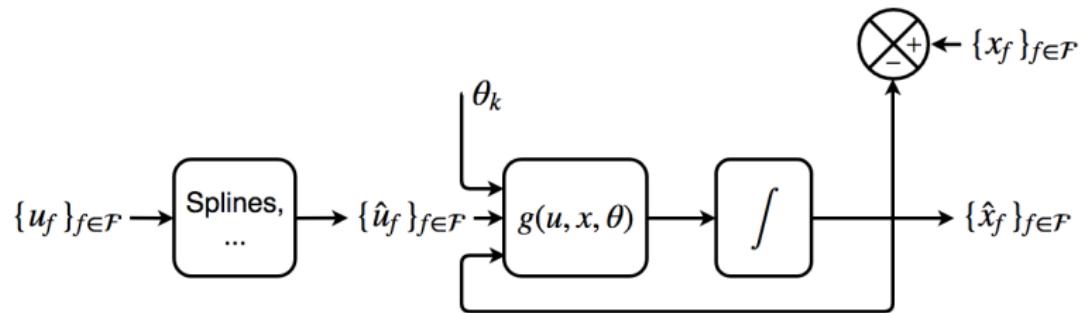
# STATE-OF-THE-ART

- Output-Error Method



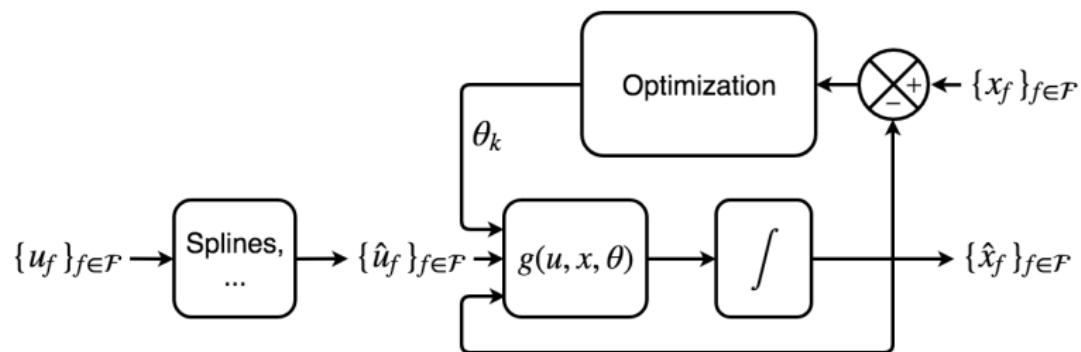
# STATE-OF-THE-ART

## ■ Output-Error Method



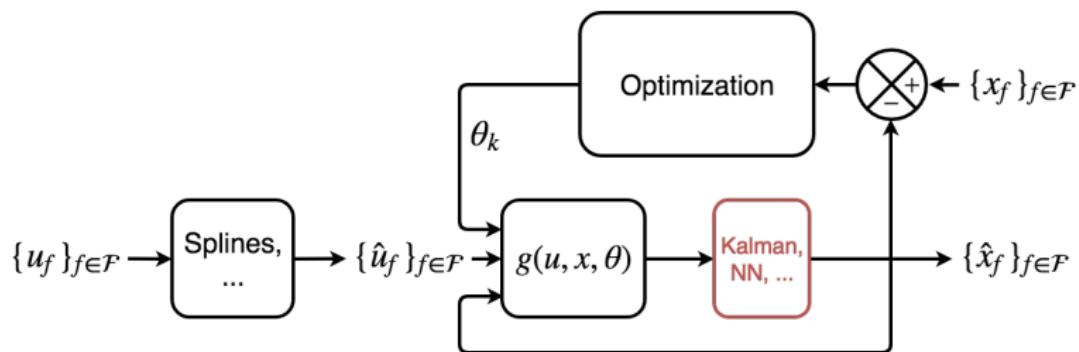
# STATE-OF-THE-ART

- Output-Error Method



# STATE-OF-THE-ART

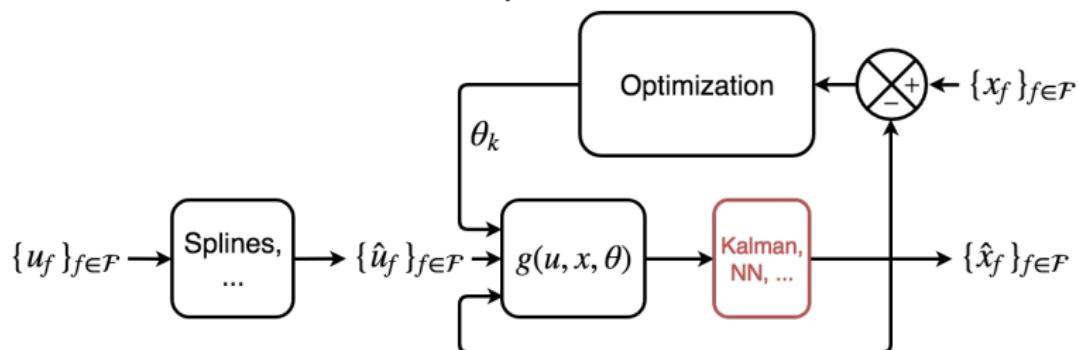
- Output-Error Method
- Filter-Error Method



# STATE-OF-THE-ART

- Output-Error Method
- Filter-Error Method

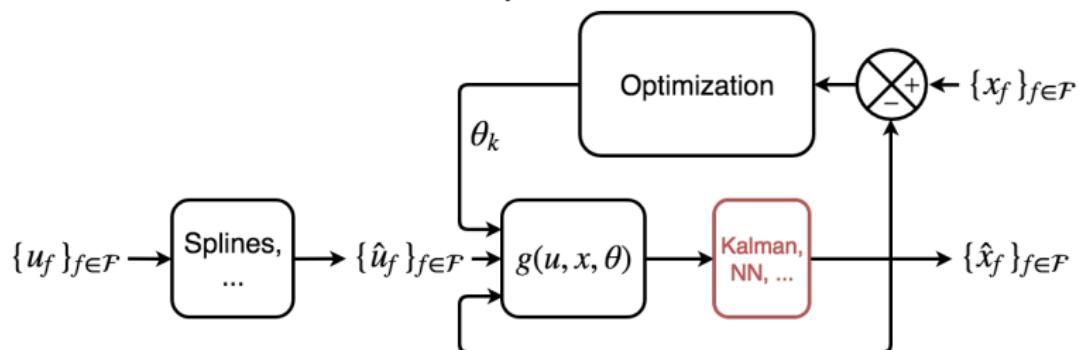
} Less scalable to many trajectories



# STATE-OF-THE-ART

- Output-Error Method
- Filter-Error Method

} Less scalable to many trajectories



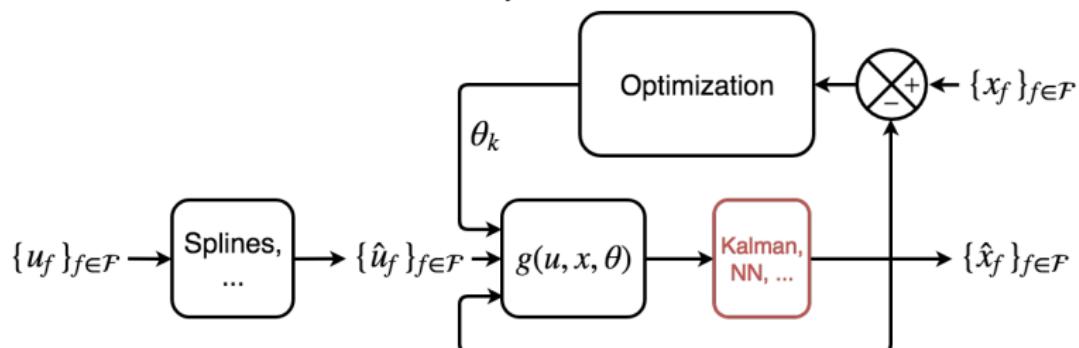
- Equation-Error Method

$$\dot{\mathbf{x}}(t) = g(\mathbf{u}(t), \mathbf{x}(t), \boldsymbol{\theta}) + \varepsilon(t), \quad t \in [0, t_f]$$

# STATE-OF-THE-ART

- Output-Error Method
- Filter-Error Method

} Less scalable to many trajectories



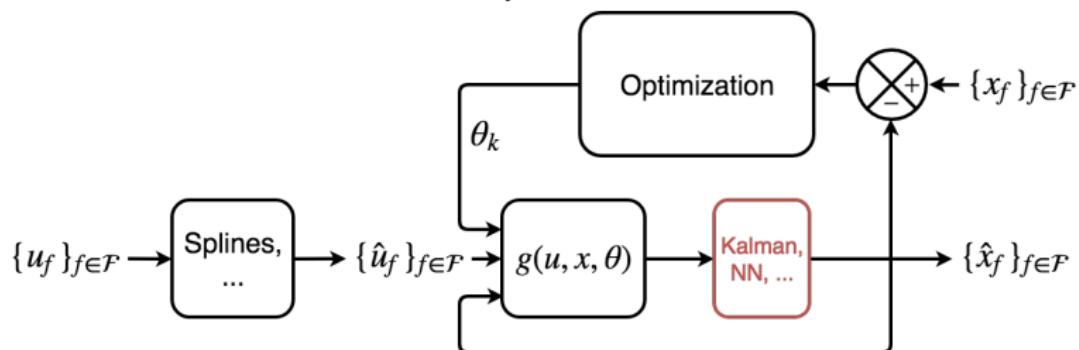
- Equation-Error Method

$$\dot{x}_i = g(\mathbf{u}_i, \mathbf{x}_i, \boldsymbol{\theta}) + \varepsilon_i, \quad i = 1, \dots, N$$

# STATE-OF-THE-ART

- Output-Error Method
- Filter-Error Method

} Less scalable to many trajectories



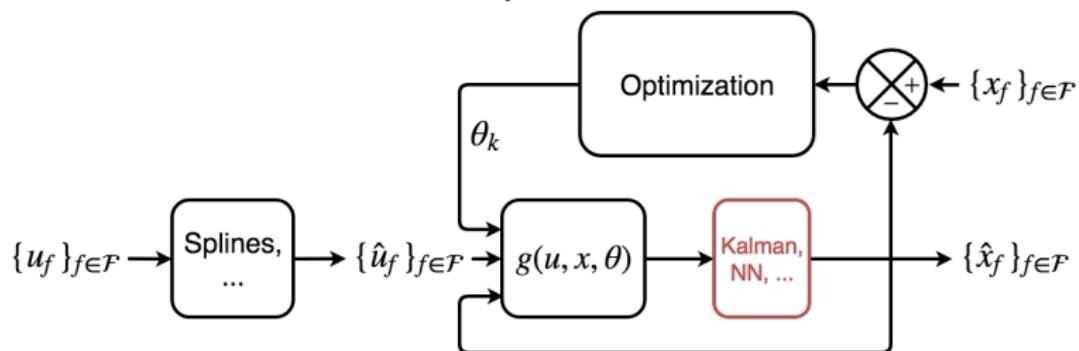
- Equation-Error Method

$$\min_{\theta} \sum_{i=1}^N \ell(\dot{x}_i, g(\mathbf{u}_i, \mathbf{x}_i, \theta))$$

# STATE-OF-THE-ART

- Output-Error Method
- Filter-Error Method

} Less scalable to many trajectories



- Equation-Error Method

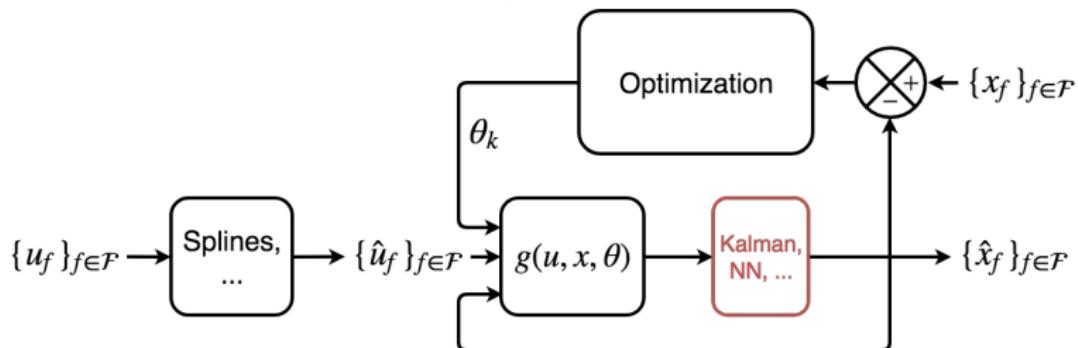
Ex: *(Nonlinear) Least-Squares*

$$\min_{\theta} \sum_{i=1}^N \left\| \dot{x}_i - g(\mathbf{u}_i, \mathbf{x}_i, \theta) \right\|_2^2$$

# STATE-OF-THE-ART

- Output-Error Method
- Filter-Error Method

} Less scalable to many trajectories



- Equation-Error Method

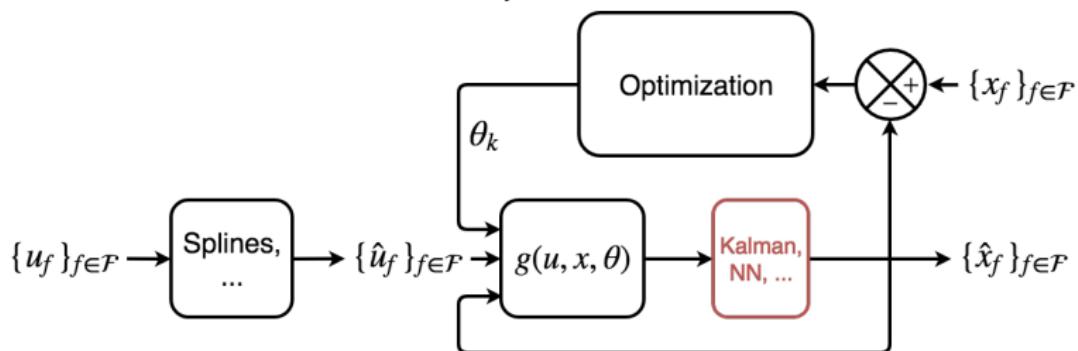
Ex: *(Nonlinear) Least-Squares*

$$\min_{\theta} \sum_{i=1}^N \| Y(\mathbf{u}_i, \mathbf{x}_i, \dot{\mathbf{x}}_i) - G(\mathbf{u}_i, \mathbf{x}_i, \dot{\mathbf{x}}_i, \theta) \|_2^2$$

# STATE-OF-THE-ART

- Output-Error Method
- Filter-Error Method

} Less scalable to many trajectories



- **Equation-Error Method**

Ex: (Nonlinear) Least-Squares

$$\min_{\theta} \sum_{i=1}^N \| Y(\mathbf{u}_i, \mathbf{x}_i, \dot{\mathbf{x}}_i) - G(\mathbf{u}_i, \mathbf{x}_i, \dot{\mathbf{x}}_i, \theta) \|_2^2$$

# LEVERAGING THE DYNAMICS STRUCTURE

$$\left\{ \begin{array}{l} \dot{h} = V \sin \gamma \\ \dot{V} = \frac{T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T) \cos \alpha - D(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_D) - mg \sin \gamma}{m} \\ \dot{\gamma} = \frac{T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T) \sin \alpha + L(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_L) - mg \cos \gamma}{mV} \\ \dot{m} = -\frac{T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T)}{I_{sp}(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_{Isp})} \end{array} \right.$$

# LEVERAGING THE DYNAMICS STRUCTURE

$$\left\{ \begin{array}{l} \dot{h} = V \sin \gamma \\ \dot{V} = \frac{T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T) \cos \alpha - D(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_D) - mg \sin \gamma}{m} \\ \dot{\gamma} = \frac{T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T) \sin \alpha + L(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_L) - mg \cos \gamma}{mV} \\ \dot{m} = -\frac{T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T)}{I_{sp}(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_{Isp})} \end{array} \right.$$

- Nonlinear in states and controls

# LEVERAGING THE DYNAMICS STRUCTURE

$$\left\{ \begin{array}{l} \dot{h} = V \sin \gamma \\ \dot{V} = \frac{T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T) \cos \alpha - D(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_D) - mg \sin \gamma}{m} \\ \dot{\gamma} = \frac{T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T) \sin \alpha + L(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_L) - mg \cos \gamma}{mV} \\ \dot{m} = -\frac{T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T)}{I_{sp}(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_{Isp})} \end{array} \right.$$

- Nonlinear in states and controls
- Nonlinear in parameters

## LEVERAGING THE DYNAMICS STRUCTURE

$$\left\{ \begin{array}{l} \dot{h} = V \sin \gamma \\ m\dot{V} + mg \sin \gamma = T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T) \cos \alpha - D(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_D) \\ mV\dot{\gamma} + mg \cos \gamma = T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T) \sin \alpha + L(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_L) \\ 0 = T(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_T) + \dot{m}l_{sp}(\mathbf{u}, \mathbf{x}, \boldsymbol{\theta}_{lsp}) \end{array} \right.$$

- Nonlinear in states and controls
- Nonlinear in parameters

# LEVERAGING THE DYNAMICS STRUCTURE

$$\left\{ \begin{array}{l} \dot{h} = V \sin \gamma \\ m\dot{V} + mg \sin \gamma = (X_T \cdot \theta_T) \cos \alpha - X_D \cdot \theta_D + \varepsilon_1 \\ mV\dot{\gamma} + mg \cos \gamma = (X_T \cdot \theta_T) \sin \alpha + X_L \cdot \theta_L + \varepsilon_2 \\ 0 = X_T \cdot \theta_T + \dot{m}(X_{Isp} \cdot \theta_{Isp}) + \varepsilon_3 \end{array} \right.$$

$$\underbrace{Y(\mathbf{u}, \mathbf{x}, \dot{\mathbf{x}})} \quad \underbrace{G(\mathbf{u}, \mathbf{x}, \dot{\mathbf{x}}, \boldsymbol{\theta})}$$

- Nonlinear in states and controls
- ~~Nonlinear in parameters~~ → Linear in parameters

# LEVERAGING THE DYNAMICS STRUCTURE

$$\left\{ \begin{array}{l} \dot{h} = V \sin \gamma \\ m\dot{V} + mg \sin \gamma = (\mathbf{X}_T \cdot \boldsymbol{\theta}_T) \cos \alpha - X_D \cdot \boldsymbol{\theta}_D + \varepsilon_1 \\ mV\dot{\gamma} + mg \cos \gamma = (\mathbf{X}_T \cdot \boldsymbol{\theta}_T) \sin \alpha + X_L \cdot \boldsymbol{\theta}_L + \varepsilon_2 \\ 0 = X_T \cdot \boldsymbol{\theta}_T + \dot{m}(\mathbf{X}_{Isp} \cdot \boldsymbol{\theta}_{Isp}) + \varepsilon_3 \end{array} \right.$$

$$\underbrace{Y(\mathbf{u}, \mathbf{x}, \dot{\mathbf{x}})} \quad \underbrace{G(\mathbf{u}, \mathbf{x}, \dot{\mathbf{x}}, \boldsymbol{\theta})}$$

- Nonlinear in states and controls
- ~~Nonlinear in parameters~~ → Linear in parameters

# LEVERAGING THE DYNAMICS STRUCTURE

$$\left\{ \begin{array}{l} \dot{h} = V \sin \gamma \\ Y_1 = X_{T1} \cdot \theta_T - X_D \cdot \theta_D + \varepsilon_1 \\ Y_2 = X_{T2} \cdot \theta_T + X_L \cdot \theta_L + \varepsilon_2 \\ Y_3 = X_T \cdot \theta_T + X_{Ispm} \cdot \theta_{Isp} + \varepsilon_3 \end{array} \right.$$

- Nonlinear in states and controls
- ~~Nonlinear in parameters~~ → Linear in parameters

# LEVERAGING THE DYNAMICS STRUCTURE

$$\left\{ \begin{array}{l} \dot{h} = V \sin \gamma \\ Y_1 = X_{T1} \cdot \theta_T - X_D \cdot \theta_D + \varepsilon_1 \\ Y_2 = X_{T2} \cdot \theta_T \sin \alpha + X_L \cdot \theta_L + \varepsilon_2 \\ Y_3 = X_T \cdot \theta_T + X_{Ispm} \cdot \theta_{Isp} + \varepsilon_3 \end{array} \right.$$

- Nonlinear in states and controls
- ~~Nonlinear in parameters~~ → Linear in parameters
- Structured
- Coupling

# LEVERAGING THE DYNAMICS STRUCTURE

$$\left\{ \begin{array}{l} \dot{h} = V \sin \gamma \\ Y_1 = X_{T1} \cdot \theta_T - X_D \cdot \theta_D + \varepsilon_1 \\ Y_2 = X_{T2} \cdot \theta_T \sin \alpha + X_L \cdot \theta_L + \varepsilon_2 \\ Y_3 = X_T \cdot \theta_T + X_{Ispm} \cdot \theta_{Isp} + \varepsilon_3 \end{array} \right.$$

- Nonlinear in states and controls
- ~~Nonlinear in parameters~~ → Linear in parameters
- Structured
- Coupling ↪ **Multi-task Learning**

# MULTI-TASK REGRESSION

General:

Aircraft:

$$\begin{cases} Y_1 = X_{c,1} \cdot \theta_c + X_1 \cdot \theta_1 + \varepsilon_1 \\ Y_2 = X_{c,2} \cdot \theta_c + X_2 \cdot \theta_2 + \varepsilon_2 \\ \vdots \\ Y_K = X_{c,K} \cdot \theta_c + X_K \cdot \theta_K + \varepsilon_K \end{cases}$$
$$\begin{cases} Y_1 = X_{T1} \cdot \theta_T - X_D \cdot \theta_D + \varepsilon_1 \\ Y_2 = X_{T2} \cdot \theta_T + X_L \cdot \theta_L + \varepsilon_2 \\ Y_3 = X_T \cdot \theta_T + X_{lspm} \cdot \theta_{lsp} + \varepsilon_3 \end{cases}$$

**Coupling parameters** , **Task specific parameters**

# MULTI-TASK REGRESSION

General:

Aircraft:

$$\begin{cases} Y_1 = X_{c,1} \cdot \theta_c + X_1 \cdot \theta_1 + \varepsilon_1 \\ Y_2 = X_{c,2} \cdot \theta_c + X_2 \cdot \theta_2 + \varepsilon_2 \\ \vdots \\ Y_K = X_{c,K} \cdot \theta_c + X_K \cdot \theta_K + \varepsilon_K \end{cases}$$
$$\begin{cases} Y_1 = X_{T1} \cdot \theta_T - X_D \cdot \theta_D + \varepsilon_1 \\ Y_2 = X_{T2} \cdot \theta_T + X_L \cdot \theta_L + \varepsilon_2 \\ Y_3 = X_T \cdot \theta_T + X_{lspm} \cdot \theta_{lsp} + \varepsilon_3 \end{cases}$$

**Coupling parameters**, **Task specific parameters**

Many other examples:

- *Giant squid neurons* [FitzHugh, 1961, Nagumo et al., 1962],
- *Susceptible-infectious-recovered models* [Anderson and May, 1992],
- *Mechanical systems*,...

# MULTI-TASK REGRESSION

General:

Aircraft:

$$\begin{cases} Y_1 = X_{c,1} \cdot \theta_c + X_1 \cdot \theta_1 + \varepsilon_1 \\ Y_2 = X_{c,2} \cdot \theta_c + X_2 \cdot \theta_2 + \varepsilon_2 \\ \vdots \\ Y_K = X_{c,K} \cdot \theta_c + X_K \cdot \theta_K + \varepsilon_K \end{cases}$$
$$\begin{cases} Y_1 = X_{T1} \cdot \theta_T - X_D \cdot \theta_D + \varepsilon_1 \\ Y_2 = X_{T2} \cdot \theta_T + X_L \cdot \theta_L + \varepsilon_2 \\ Y_3 = X_T \cdot \theta_T + X_{lspm} \cdot \theta_{lsp} + \varepsilon_3 \end{cases}$$

Coupling parameters , Task specific parameters

Multi-task Linear Least-Squares:

$$\min_{\theta} \sum_{k=1}^K \sum_{i=1}^N (Y_{k,i} - X_{c,k,i} \cdot \theta_c - X_{k,i} \cdot \theta_k)^2$$

# MULTI-TASK REGRESSION

General:

Aircraft:

$$\begin{cases} Y_1 = X_{c,1} \cdot \theta_c + X_1 \cdot \theta_1 + \varepsilon_1 \\ Y_2 = X_{c,2} \cdot \theta_c + X_2 \cdot \theta_2 + \varepsilon_2 \\ \vdots \\ Y_K = X_{c,K} \cdot \theta_c + X_K \cdot \theta_K + \varepsilon_K \end{cases}$$
$$\begin{cases} Y_1 = X_{T1} \cdot \theta_T - X_D \cdot \theta_D + \varepsilon_1 \\ Y_2 = X_{T2} \cdot \theta_T + X_L \cdot \theta_L + \varepsilon_2 \\ Y_3 = X_T \cdot \theta_T + X_{lspm} \cdot \theta_{lsp} + \varepsilon_3 \end{cases}$$

Coupling parameters , Task specific parameters

Multi-task Linear Least-Squares:

Block-sparse Coupling Structure

$$\min_{\theta} \sum_{i=1}^N \left\| \begin{pmatrix} Y_{1,i} \\ \vdots \\ Y_{K,i} \end{pmatrix} - \begin{pmatrix} X_{c,1,i} & X_{1,i} & 0 & 0 & \dots & 0 \\ X_{c,2,i} & 0 & X_{2,i} & 0 & \dots & 0 \\ \vdots & 0 & 0 & \ddots & 0 & 0 \\ X_{c,K,i} & 0 & 0 & \dots & 0 & X_{K,i} \end{pmatrix} \begin{pmatrix} \theta_c \\ \theta_1 \\ \vdots \\ \theta_K \end{pmatrix} \right\|_2$$

# MULTI-TASK REGRESSION

General:

Aircraft:

$$\begin{cases} Y_1 = X_{T1} \cdot \theta_T - X_D \cdot \theta_D + \varepsilon_1 \\ Y_2 = X_{T2} \cdot \theta_T + X_L \cdot \theta_L + \varepsilon_2 \\ Y_3 = X_T \cdot \theta_T + X_{lspm} \cdot \theta_{lsp} + \varepsilon_3 \end{cases} \quad \begin{cases} Y_1 = X_{c,1} \cdot \theta_c + X_1 \cdot \theta_1 + \varepsilon_1 \\ Y_2 = X_{c,2} \cdot \theta_c + X_2 \cdot \theta_2 + \varepsilon_2 \\ \vdots \quad \quad \vdots \\ Y_K = X_{c,K} \cdot \theta_c + X_K \cdot \theta_K + \varepsilon_K \end{cases}$$

**Coupling parameters**, **Task specific parameters**

Multi-task Linear Least-Squares:

Block-sparse Coupling Structure

$$\min_{\theta} \sum_{i=1}^N \left\| \begin{pmatrix} Y_{1,i} \\ Y_{2,i} \\ Y_{3,i} \end{pmatrix} - \begin{pmatrix} X_{T1,i} & -X_{D,i} & 0 & 0 \\ X_{T2,i} & 0 & X_{L,i} & 0 \\ X_{T,i} & 0 & 0 & X_{lspm,i} \end{pmatrix} \begin{pmatrix} \theta_T \\ \theta_D \\ \theta_L \\ \theta_{lsp} \end{pmatrix} \right\|_2^2$$

# MULTI-TASK REGRESSION

General:

Aircraft:

$$\begin{cases} Y_1 = X_{T1} \cdot \theta_T - X_D \cdot \theta_D + \varepsilon_1 \\ Y_2 = X_{T2} \cdot \theta_T + X_L \cdot \theta_L + \varepsilon_2 \\ Y_3 = X_T \cdot \theta_T + X_{lspm} \cdot \theta_{lsp} + \varepsilon_3 \end{cases} \quad \left\{ \begin{array}{l} Y_1 = X_{c,1} \cdot \theta_c + X_1 \cdot \theta_1 + \varepsilon_1 \\ Y_2 = X_{c,2} \cdot \theta_c + X_2 \cdot \theta_2 + \varepsilon_2 \\ \vdots \qquad \qquad \vdots \\ Y_K = X_{c,K} \cdot \theta_c + X_K \cdot \theta_K + \varepsilon_K \end{array} \right.$$

**Coupling parameters**, **Task specific parameters**

Multi-task Linear Least-Squares:

Block-sparse Coupling Structure

$$\min_{\theta} \sum_{i=1}^N \|Y_i - X_i \theta\|_2^2$$

with  $\theta = (\theta_c, \theta_1, \dots, \theta_K) \in \mathbb{R}^p$ ,  $p = d_c + \sum_{k=1}^K d_k$ ,  
 $Y_i \in \mathbb{R}^K$  and  $X_i \in \mathbb{R}^{K \times p}$ .

# FEATURE SELECTION

Our model:

$$T = N_1(\theta_{T,1} + \theta_{T,2}\rho + \theta_{T,3}M + \theta_{T,4}\rho^2 + \theta_{T,5}\rho M + \theta_{T,6}M^2 + \\ \theta_{T,7}\rho^3 + \theta_{T,8}\rho^2M + \theta_{T,9}\rho M^2 + \theta_{T,10}M^3 + \theta_{T,11}\rho^4 + \\ \theta_{T,12}\rho^3M + \theta_{T,13}\rho^2M^2 + \theta_{T,14}\rho M^3 + \theta_{T,15}M^4).$$

# FEATURE SELECTION

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$$T = N_1(\theta_{T,1} + \theta_{T,2}\rho + \theta_{T,3}M + \theta_{T,4}\rho^2 + \theta_{T,5}\rho M + \theta_{T,6}M^2 + \theta_{T,7}\rho^3 + \theta_{T,8}\rho^2M + \theta_{T,9}\rho M^2 + \theta_{T,10}M^3 + \theta_{T,11}\rho^4 + \theta_{T,12}\rho^3M + \theta_{T,13}\rho^2M^2 + \theta_{T,14}\rho M^3 + \theta_{T,15}M^4).$$

Mattingly's model [Mattingly et al., 1992]:

$$T = N_1(\theta_{T,1}\rho + \theta_{T,2}\rho M^3).$$

# FEATURE SELECTION

Our model:

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$$T = N_1(\theta_{T,1}\rho + \theta_{T,2}\rho M^3).$$

⇒ High risk of overfitting

# FEATURE SELECTION

Our (sparse) model:

$$T = N_1(\theta_{T,1} + \theta_{T,2}\rho + \theta_{T,3}M + \theta_{T,4}\rho^2 + \theta_{T,5}\rho M + \theta_{T,6}M^2 + \theta_{T,7}\rho^3 + \theta_{T,8}\rho^2M + \theta_{T,9}\rho M^2 + \theta_{T,10}M^3 + \theta_{T,11}\rho^4 + \theta_{T,12}\rho^3M + \theta_{T,13}\rho^2M^2 + \theta_{T,14}\rho M^3 + \theta_{T,15}M^4).$$

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$$T = N_1(\theta_{T,1}\rho + \theta_{T,2}\rho M^3).$$

Sparse models are:

- Less susceptible to overfitting,

# FEATURE SELECTION

Our (sparse) model:

$$T = N_1(\theta_{T,1} + \theta_{T,2}\rho + \theta_{T,3}M + \theta_{T,4}\rho^2 + \theta_{T,5}\rho M + \theta_{T,6}M^2 + \theta_{T,7}\rho^3 + \theta_{T,8}\rho^2M + \theta_{T,9}\rho M^2 + \theta_{T,10}M^3 + \theta_{T,11}\rho^4 + \theta_{T,12}\rho^3M + \theta_{T,13}\rho^2M^2 + \theta_{T,14}\rho M^3 + \theta_{T,15}M^4).$$

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Sparse models are:

- Less susceptible to overfitting,
- More compliant with physical models,

# FEATURE SELECTION

Our (sparse) model:

$$T = N_1(\theta_{T,1} + \theta_{T,2}\rho + \theta_{T,3}M + \theta_{T,4}\rho^2 + \theta_{T,5}\rho M + \theta_{T,6}M^2 + \theta_{T,7}\rho^3 + \theta_{T,8}\rho^2M + \theta_{T,9}\rho M^2 + \theta_{T,10}M^3 + \theta_{T,11}\rho^4 + \theta_{T,12}\rho^3M + \theta_{T,13}\rho^2M^2 + \theta_{T,14}\rho M^3 + \theta_{T,15}M^4).$$

Mattingly's model [Mattingly et al., 1992]:

$$T = N_1(\theta_{T,1}\rho + \theta_{T,2}\rho M^3).$$

Sparse models are:

- Less susceptible to overfitting,
- More compliant with physical models,
- More interpretable,

# FEATURE SELECTION

Our (sparse) model:

$$T = N_1(\theta_{T,1} + \theta_{T,2}\rho + \theta_{T,3}M + \theta_{T,4}\rho^2 + \theta_{T,5}\rho M + \theta_{T,6}M^2 + \theta_{T,7}\rho^3 + \theta_{T,8}\rho^2M + \theta_{T,9}\rho M^2 + \theta_{T,10}M^3 + \theta_{T,11}\rho^4 + \theta_{T,12}\rho^3M + \theta_{T,13}\rho^2M^2 + \theta_{T,14}\rho M^3 + \theta_{T,15}M^4).$$

Mattingly's model [Mattingly et al., 1992]:

$$T = N_1(\theta_{T,1}\rho + \theta_{T,2}\rho M^3).$$

Sparse models are:

- Less susceptible to overfitting,
- More compliant with physical models,
- More interpretable,
- Lighter/Faster.

# BLOCK-SPARSE LASSO

Lasso [Tibshirani, 1994]:  $\{(X_i, Y_i)\}_{i=1}^N \subset \mathbb{R}^{d+1}$  i.i.d sample,

$$\min_{\boldsymbol{\theta}} \sum_{i=1}^N (Y_i - X_i \cdot \boldsymbol{\theta})^2 + \lambda \|\boldsymbol{\theta}\|_1.$$

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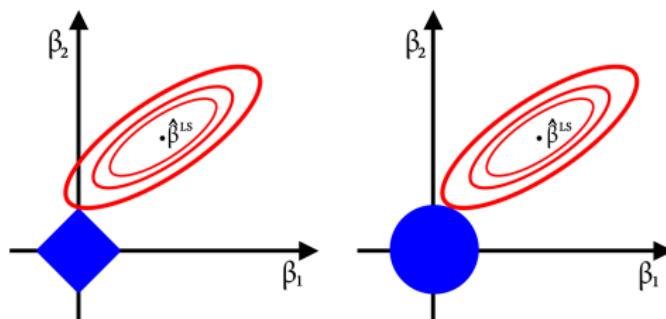


FIGURE:  $^1$ Sparsity induced by  $L^1$  norm in Lasso.

# BLOCK-SPARSE LASSO

$$\min_{\boldsymbol{\theta}} \sum_{k=1}^K \sum_{i=1}^N (Y_{k,i} - X_{c,k,i} \cdot \boldsymbol{\theta}_c - X_{k,i} \cdot \boldsymbol{\theta}_k)^2$$

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$$\min_{\beta} \sum_{i=1}^N \|Y_i - B_i\beta\|_2^2 + \lambda_c \|\beta\|_1$$

with  $\beta = (\boldsymbol{\theta}_c, \frac{\lambda_1}{\lambda_c} \boldsymbol{\theta}_1, \dots, \frac{\lambda_K}{\lambda_c} \boldsymbol{\theta}_K) \in \mathbb{R}^p$ ,  $p = d_c + \sum_{k=1}^K d_k$ ,  
 $Y_i \in \mathbb{R}^K$  and  $B_i \in \mathbb{R}^{K \times p}$ .

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with  $\boldsymbol{\theta} = (\boldsymbol{\theta}_c, \boldsymbol{\theta}_1, \dots, \boldsymbol{\theta}_K) \in \mathbb{R}^p$ ,  $p = d_c + \sum_{k=1}^K d_k$ ,  
 $Y_i \in \mathbb{R}^K$  and  $X_i \in \mathbb{R}^{K \times p}$ ,

In practice, we choose  $\lambda_k = \lambda_c$ , for all  $k = 1, \dots, 3$  and

$$X_i = \begin{pmatrix} X_{T1,i} & -X_{D,i} & 0 & 0 \\ X_{T2,i} & 0 & X_{L,i} & 0 \\ X_{T,i} & 0 & 0 & X_{Ispm,i} \end{pmatrix}, \quad Y_i = \begin{pmatrix} Y_{1,i} \\ Y_{2,i} \\ Y_{3,i} \end{pmatrix}$$

# STRUCTURED FEATURE SELECTION STATE-OF-THE-ART

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Difference with Block-sparse Lasso

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Multi-task Lasso [Obozinski et al., 2006]	Not same pattern for every task.

# BOOTSTRAP IMPLEMENTATION

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training data  $\mathcal{T} = \{(X_i, Y_i)\}_{i=1}^N \subset \mathbb{R}^{K \times (K+1)} \times \mathbb{R}^K$ ,

**Require:** number of bootstrap replicates  $b$ ,

$L^1$  penalty parameter  $\lambda_c$ ,

- 1: **for**  $k = 1$  **to**  $b$  **do**
  - 2:   Generate bootstrap sample  $\mathcal{T}_k$ ,
  - 3:   Compute Block sparse Lasso estimate  $\hat{\theta}^k$  from  $\mathcal{T}_k$ ,
  - 4:   Compute support  $J_k = \{j, \hat{\theta}_j^k \neq 0\}$ ,
  - 5: **end for**
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- Consistency even under high correlations proved in Bach [2008],
- Efficient implementations exists: LARS [Efron et al., 2004].

# PROBLEM WITH INTRA-GROUP CORRELATIONS

$$\min_{\theta} \sum_{i=1}^N \|Y_i - X_i \theta\|_2^2 + \lambda_c \|\theta\|_1 \Rightarrow \hat{\theta}_T = \hat{\theta}_{Ispl} = 0!$$

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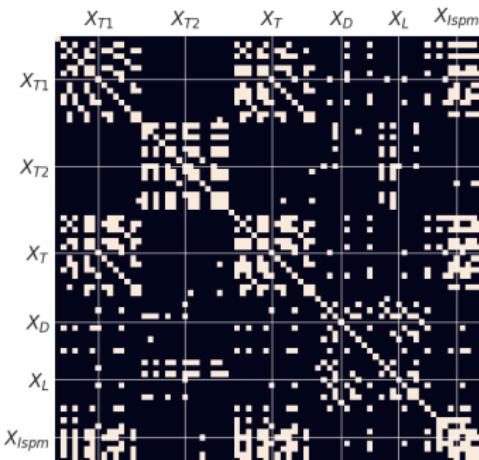
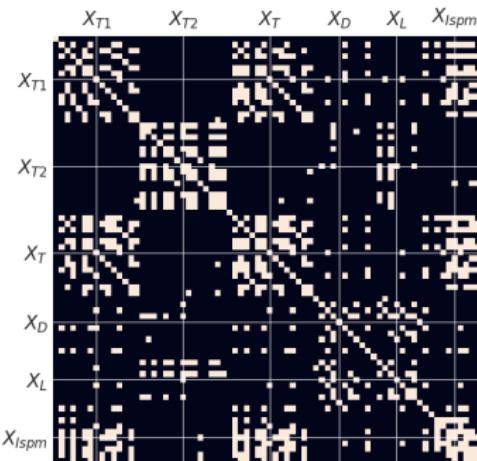


FIGURE: Features correlations  
higher than 0.9 in absolute  
value in white.

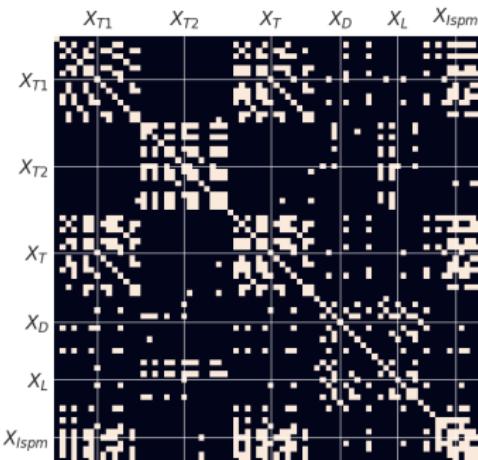
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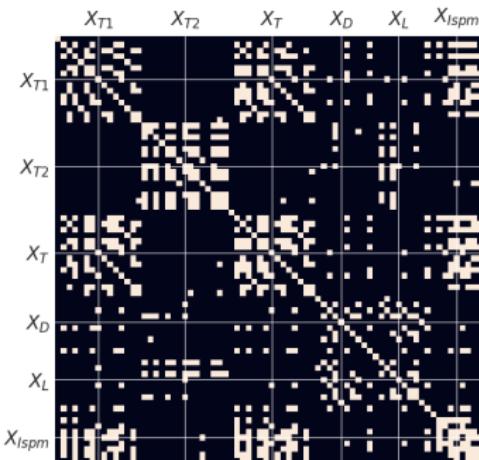


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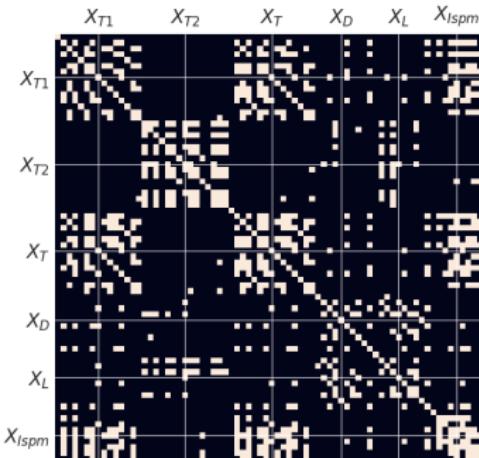
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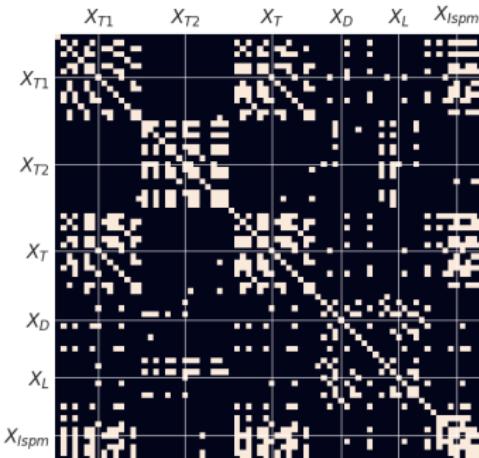


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$\Rightarrow$  Generalized Tikhonov

$$(\boldsymbol{\theta} - \tilde{\boldsymbol{\theta}})^\top Q (\boldsymbol{\theta} - \tilde{\boldsymbol{\theta}}) = \|\Gamma(\boldsymbol{\theta} - \tilde{\boldsymbol{\theta}})\|_2^2,$$

where  $\tilde{\boldsymbol{\theta}}$  is a prior and  $Q \in \mathbb{R}^{P \times P}$ .

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$$\min_{\theta} \sum_{i=1}^N \|\tilde{\mathbf{Y}}_i - \tilde{\mathbf{X}}_i \theta\|_2^2 + \lambda_c \|\theta\|_1$$

$$\tilde{\mathbf{Y}}_i = \begin{pmatrix} Y_{1,i} \\ Y_{2,i} \\ 0 \\ \lambda_t \tilde{I}_{sp,i} \end{pmatrix}, \quad \tilde{\mathbf{X}}_i = \begin{pmatrix} (X_{T1,i})^\top & -(X_{D,i})^\top & 0 & 0 \\ (X_{T2,i})^\top & 0 & (X_{L,i})^\top & 0 \\ (X_{T,i})^\top & 0 & 0 & (X_{Ispm,i})^\top \\ 0 & 0 & 0 & \lambda_t (X_{Isp,i})^\top \end{pmatrix},$$

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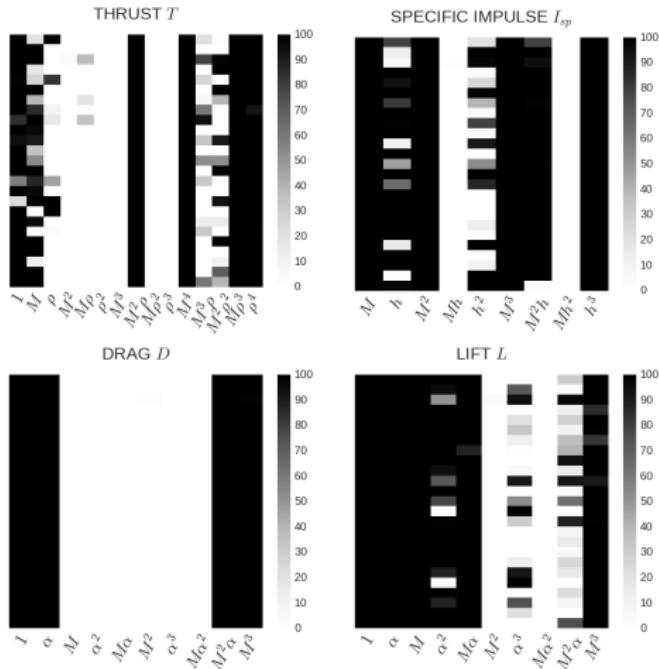
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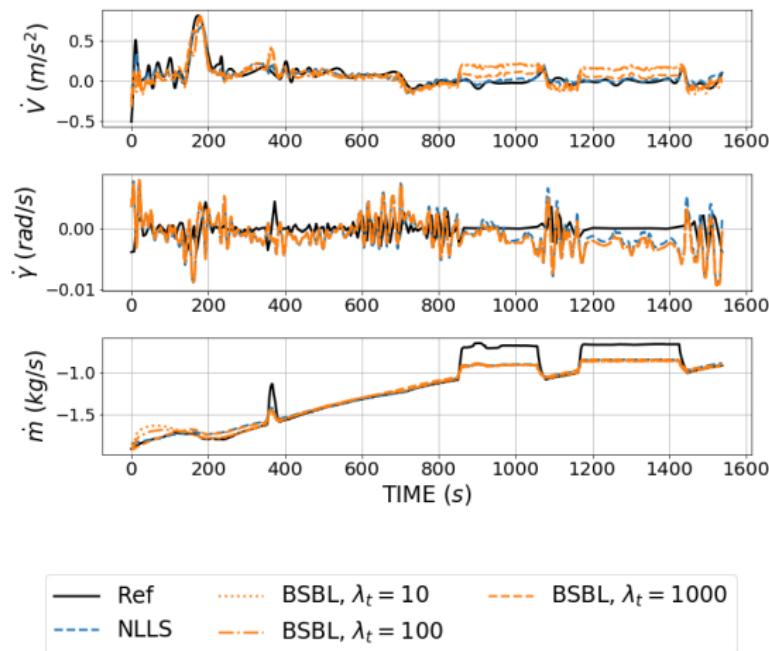
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Feature selection results for the thrust, drag, lift and specific impulse models.

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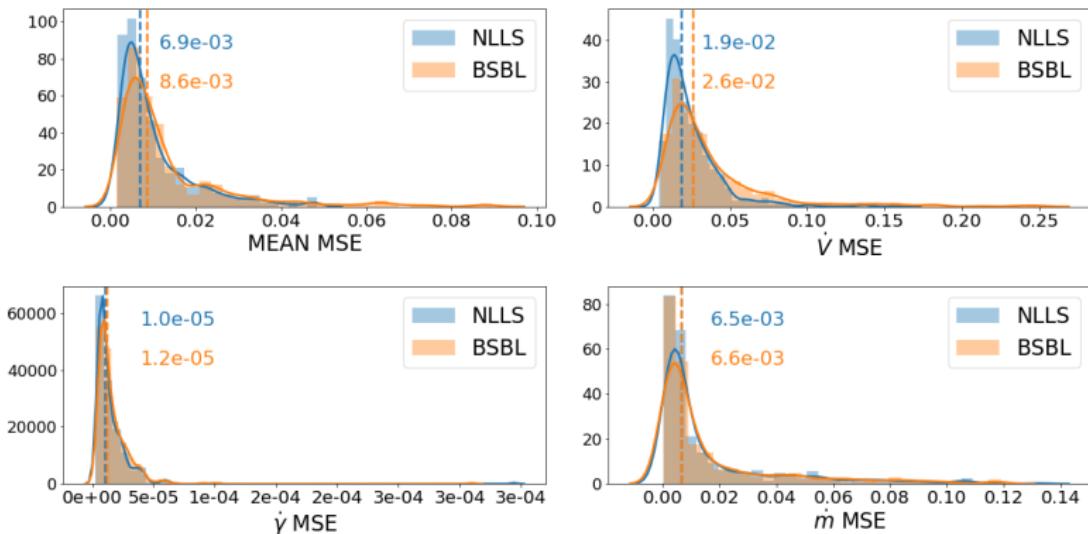
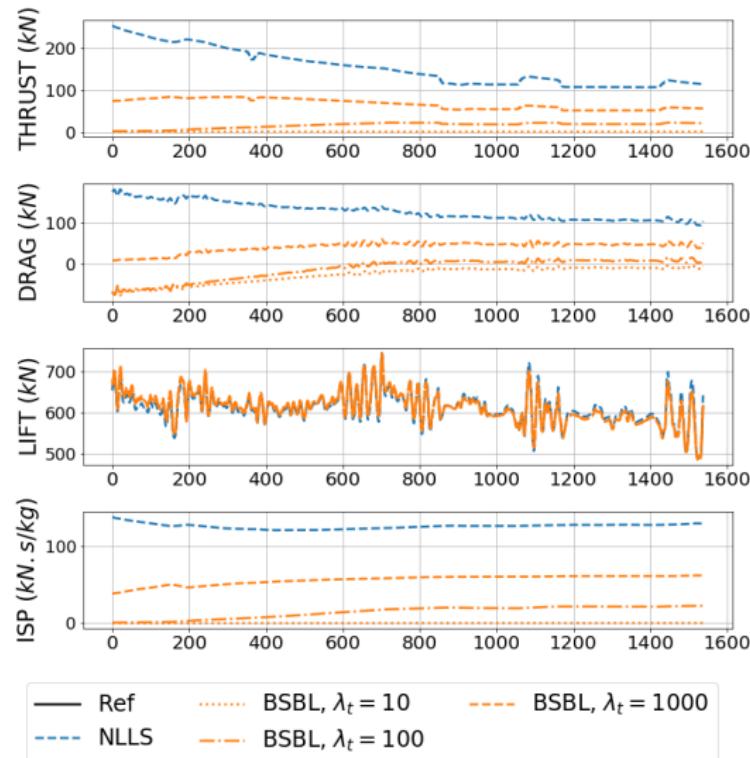


FIGURE: Leave-one-out off-sample errors distributions for nonlinear least-squares NLLS and block-sparse bolasso BSBL. Median errors are annotated and marked by dashed vertical lines.

# REALISM OF HIDDEN ELEMENTS



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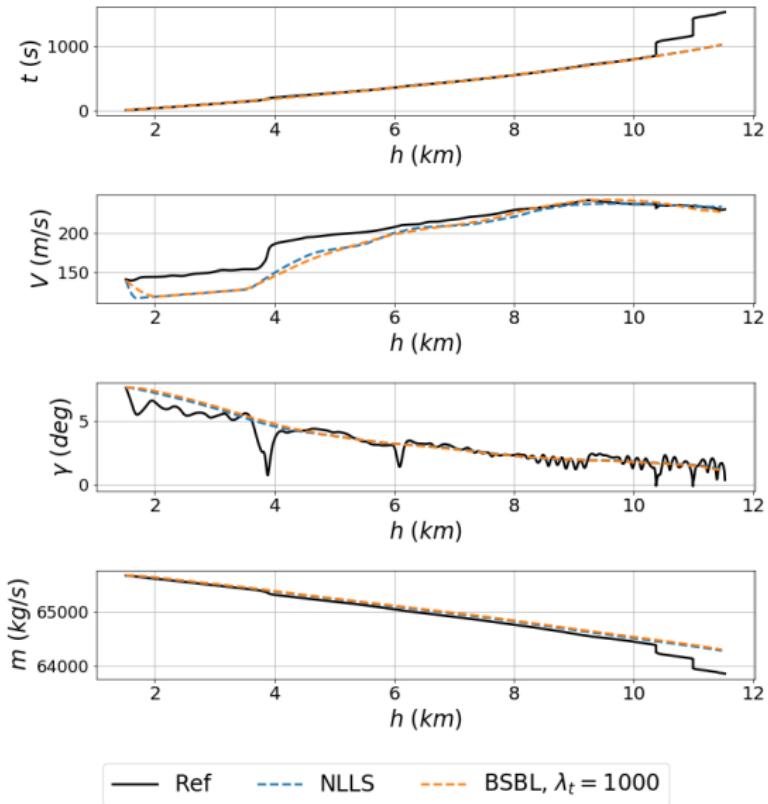
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For practical applications:  $t \leftrightarrow h$

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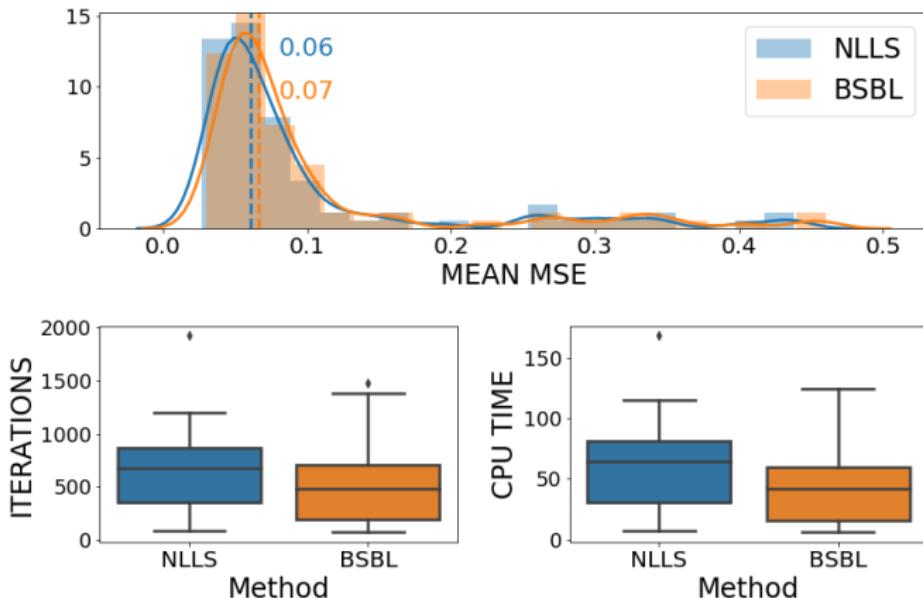


FIGURE: Distribution of the off-sample simulation error and boxplot of the optimization number of iterations and CPU time.

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$$\begin{aligned} & \min_{(\mathbf{x}, \mathbf{u}) \in \mathbb{X} \times \mathbb{U}} \int_0^{t_f} C(\mathbf{u}(t), \mathbf{x}(t)) dt, \\ \text{s.t. } & \left\{ \begin{array}{l} \dot{\mathbf{x}}(t) = \hat{g}(\mathbf{u}(t), \mathbf{x}(t)), \quad \text{a.e. } t \in [0, t_f], \\ \text{Other constraints...} \end{array} \right. \end{aligned} \tag{AOCP}$$

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Air Traffic Control<sup>2</sup>

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Air Traffic Control<sup>2</sup>

**How can we quantify the closeness from the optimized trajectory to the set of real flights?**

# OPTIMIZED TRAJECTORY LIKELIHOOD

- $X \sim f_{\theta^*}$ ,
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**How likely is it to draw the optimized trajectory from the law of  $Z$  ?**

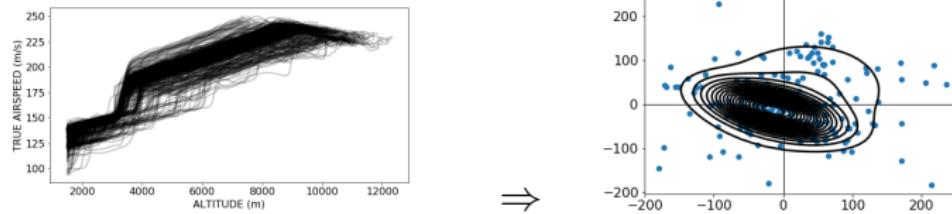
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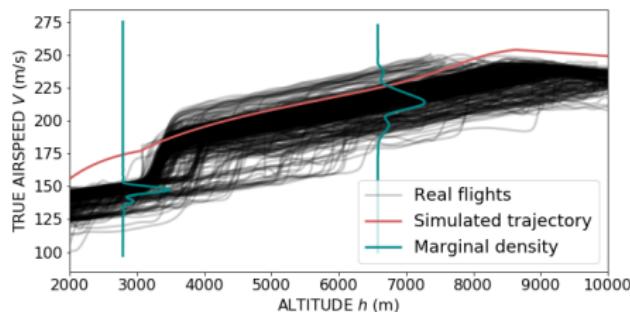
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- Standard approach in Functional Data Analysis: use Functional Principal Component Analysis to decompose the data in a small number of coefficients
- Or: we can use the marginal densities



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## MEAN MARGINAL LIKELIHOOD

$$\text{MML}(Z, \mathbf{y}) = \frac{1}{t_f} \int_0^{t_f} \psi[f_t, \mathbf{y}(t)] dt,$$

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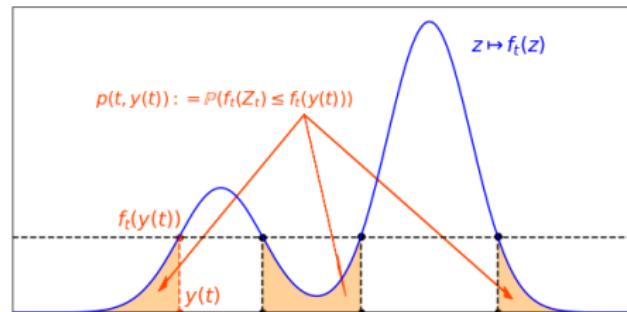
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or the confidence level

$$\psi[f_t, \mathbf{y}(t)] := \mathbb{P}(f_t(Z_t) \leq f_t(\mathbf{y}(t))).$$



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In practice, the  $m$  trajectories are sampled at variable discrete times:

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Hence, we approximate the MML using a Riemann sum which aggregates consistent estimators  $\hat{f}_{\tilde{t}_j}^m$  of the marginal densities  $f_{\tilde{t}_j}$ :

$$\text{EMML}_m(\mathcal{T}^D, \mathcal{Y}) := \frac{1}{t_f} \sum_{j=1}^{\tilde{n}} \psi[\hat{f}_{\tilde{t}_j}^m, y_j] \Delta \tilde{t}_j.$$

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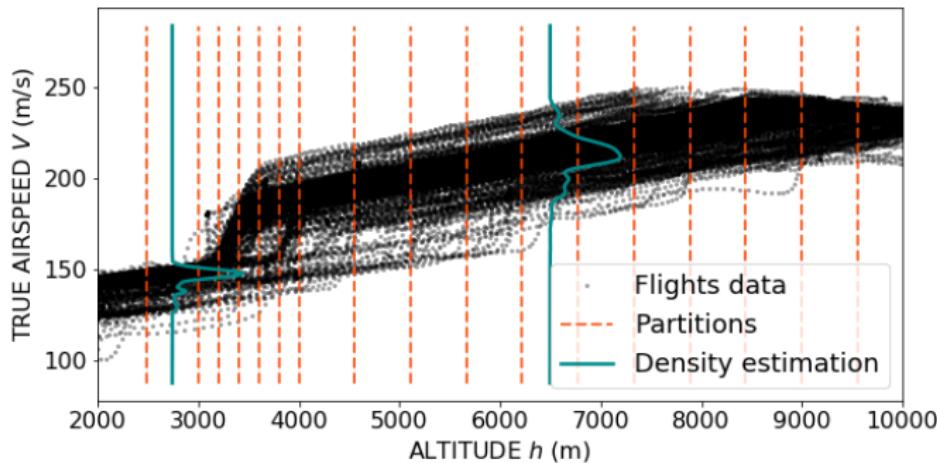
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- 1 We can apply SOA conditional density estimation techniques, such as LS-CDE [Sugiyama et al., 2010],
  - 2 **We can use a fine partitioning of the time domain.**

# PARTITION BASED MARGINAL DENSITY ESTIMATION



Idea: to average in time the marginal densities over small bins by applying classical multivariate density estimation techniques to each subset.

# CONSISTENCY

We denote by:

- $\Theta : \mathcal{S} \rightarrow L^1(E, \mathbb{R}_+)$  multivariate density estimation statistic,
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ASSUMPTION 1 - POSITIVE TIME DENSITY

$\nu \in L^\infty(E, \mathbb{R}_+)$  density function of  $T$ , s.t.

$$\nu_+ := \text{ess} \sup_{t \in \mathbb{T}} \nu(t) < \infty, \quad \nu_- := \text{ess} \inf_{t \in \mathbb{T}} \nu(t) > 0.$$

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ASSUMPTION 3 - SHRINKING BINS

The homogeneous partition  $\{B_\ell^m\}_{\ell=1}^{q_m}$  of  $[0; t_f]$ , with binsize  $b_m$ , is s.t.

$$\lim_{m \rightarrow \infty} b_m = 0, \quad \lim_{m \rightarrow \infty} mb_m = \infty.$$

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## ASSUMPTION 4 - I.I.D. CONSISTENCY

- $\mathcal{G}$  arbitrary family of probability density functions on  $E$ ,  $\rho \in \mathcal{G}$ ,
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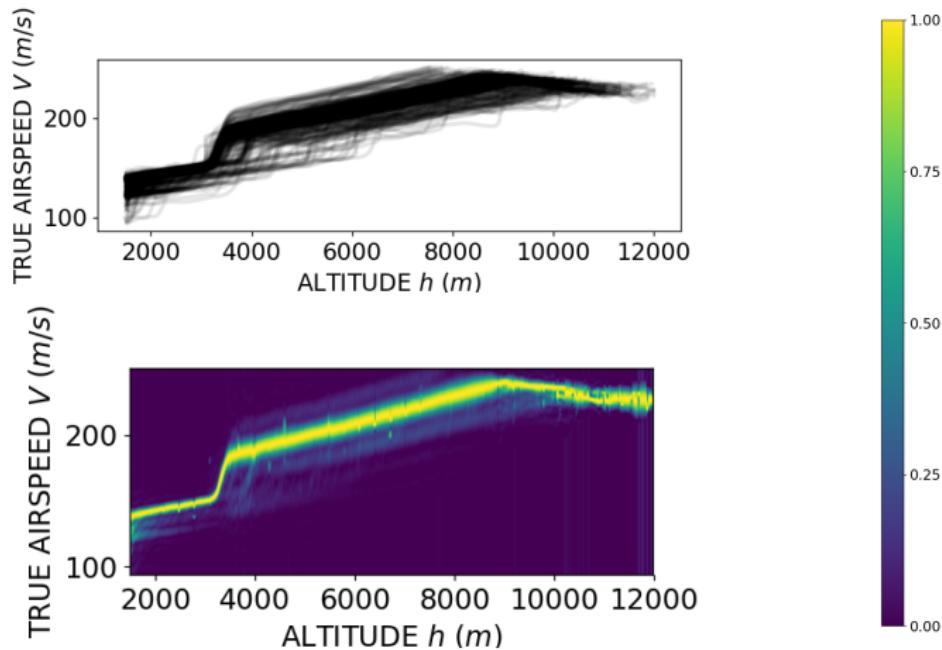
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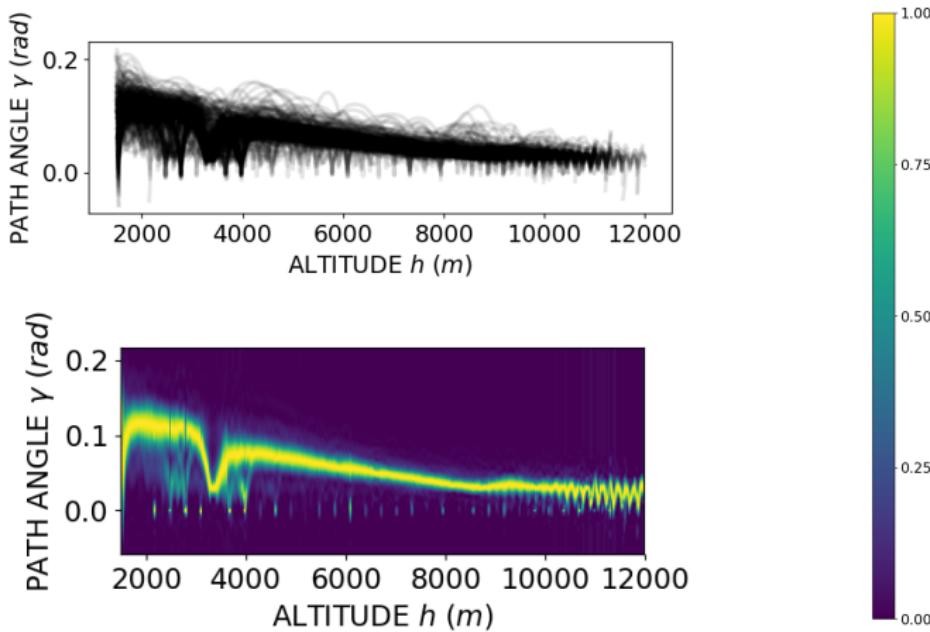
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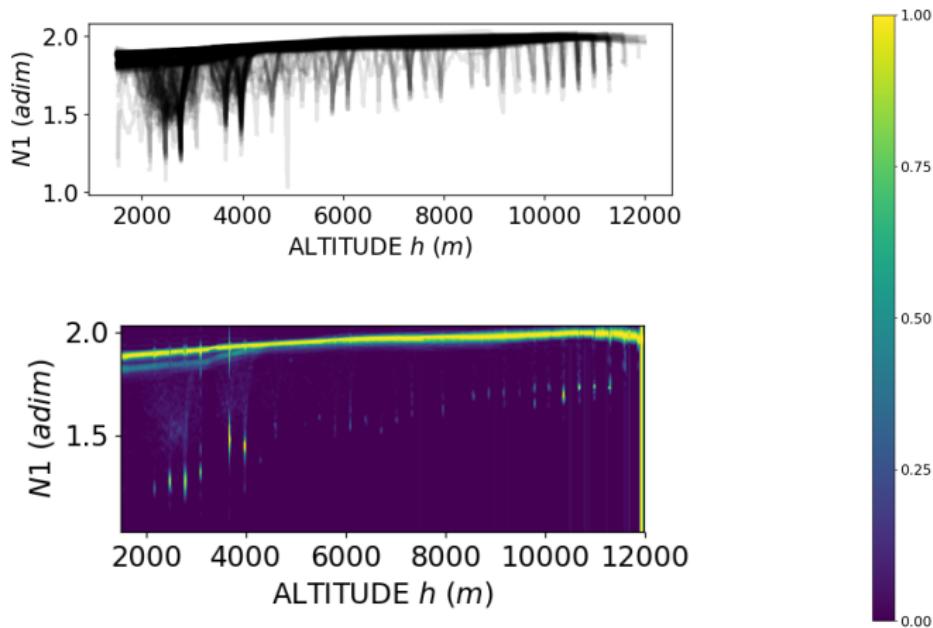
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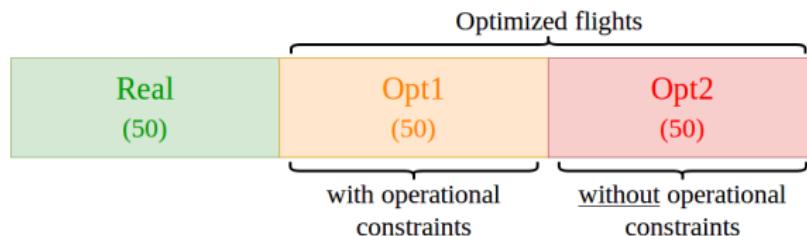
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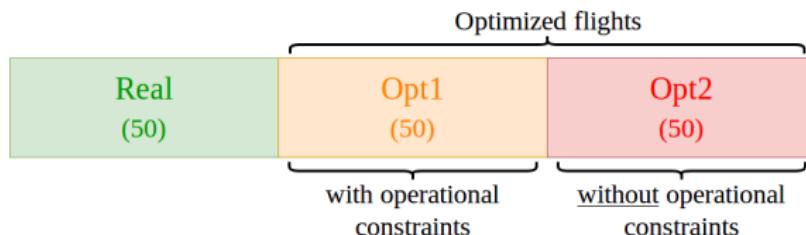
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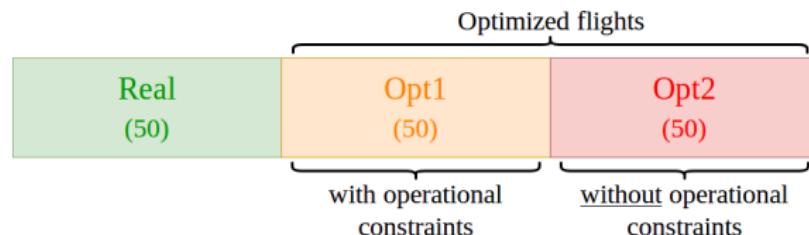


- Discrimination power comparison with (gmm-)FPCA and (integrated) LS-CDE:

VAR.	ESTIMATED LIKELIHOODS		
	REAL	OPT1	OPT2
MML	<b><math>0.63 \pm 0.07</math></b>	<b><math>0.43 \pm 0.08</math></b>	<b><math>0.13 \pm 0.02</math></b>
FPCA	$0.16 \pm 0.12$	$6.4\text{E-}03 \pm 3.8\text{E-}03$	$3.6\text{E-}03 \pm 5.4\text{E-}03$
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FPCA	$0.16 \pm 0.12$	$6.4\text{E-}03 \pm 3.8\text{E-}03$	$3.6\text{E-}03 \pm 5.4\text{E-}03$	20s
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The MML can be used not only to assess the optimization solutions, but also to penalize the optimization itself:

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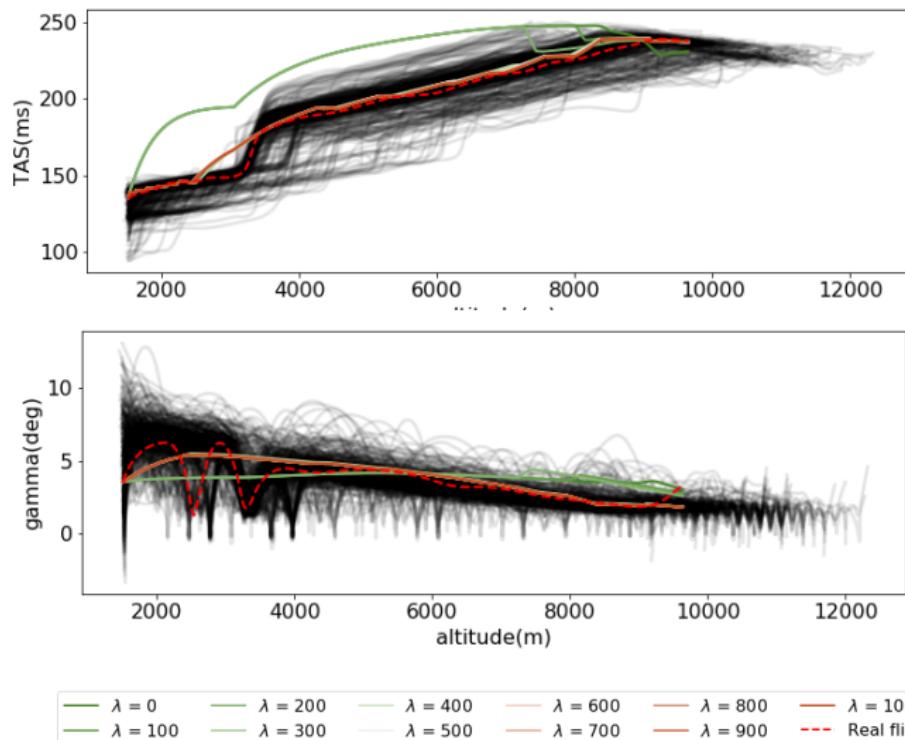
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- $\lambda$  sets trade-off between a fuel minimization and a likelihood maximization,

# PENALTY EFFECT



# CONSUMPTION X ACCEPTABILITY TRADE-OFF

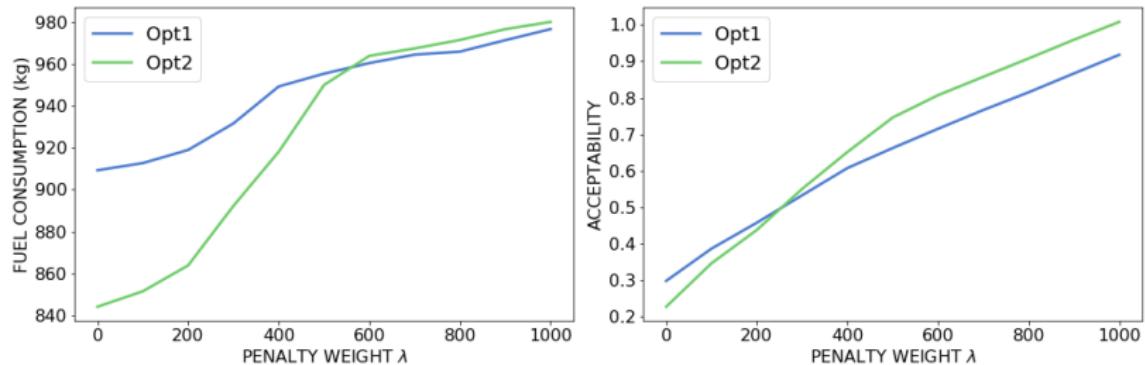


FIGURE: Average over 20 flights of the fuel consumption and MML score (called acceptability here) of optimized trajectories with varying MML-penalty weight  $\lambda$ .

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  - Showed that it can be used in optimal control problems to obtain solutions close to optimal, and still realistic.

**THANK YOU FOR YOUR ATTENTION**

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