

Active fault-tolerant control of aircraft for flutter suppression in the presence of control surface faults

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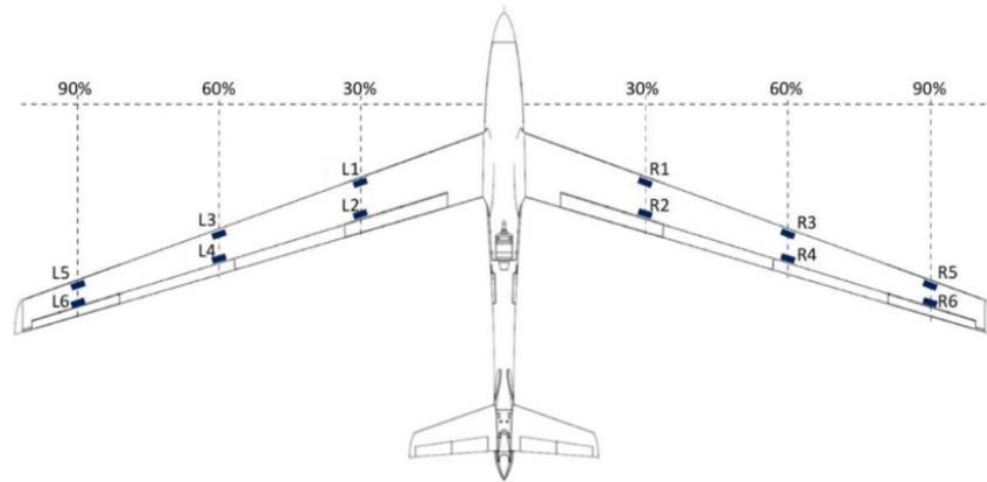
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Context

Objectives :

- Reduction of **stiffening devices** for flexible structures, of weight, and therefore a **reduction in fuel consumption**.
- Validation on the FLEXOP simulator.



IMU configuration

Developpment of solutions des solutions:

- **model-based**
- **Fault tolerance to control surface control faults,**
- **Optimal control of an aircraft performances**
- **Under flutter phenomenon **avoidance**.**



Active fault-tolerant flutter control problem

Flutter is a **fluid-structure interaction** phenomenon that:

- Beyond a **specific speed**
- Induces **unstable oscillations**,
- Loss of lift, destruction of wings

Complex problem :

- **High-order multi-physics** model (need for a reduced-order model).
- Fast fault **identification** and **adaptation**.



Approach

Supervisory control based on the « dwell-time » theory τ_D [1] :

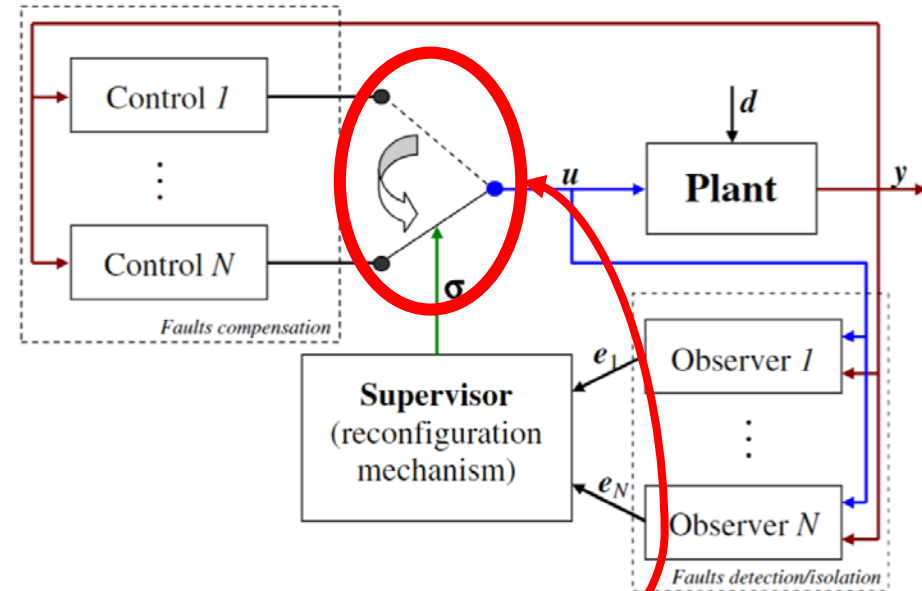
- **Estimation problem of operating modes** and not of faults.
- **Fault tolerance is ensured by a bank of pre-calculated controllers.**

Advantages of the approach:

- **Guaranteed stability**, even in the face of **decision errors**.
- **Fast adaptation**.

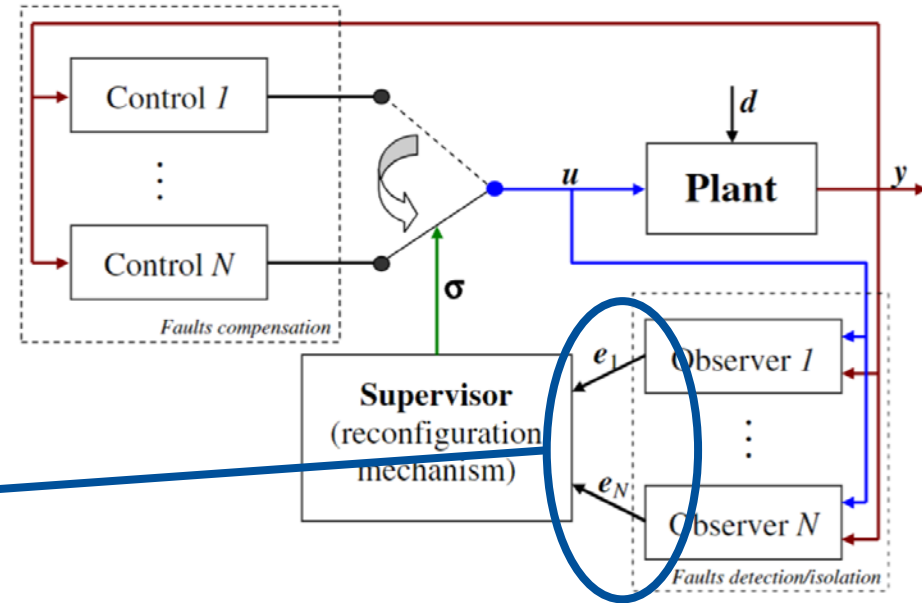
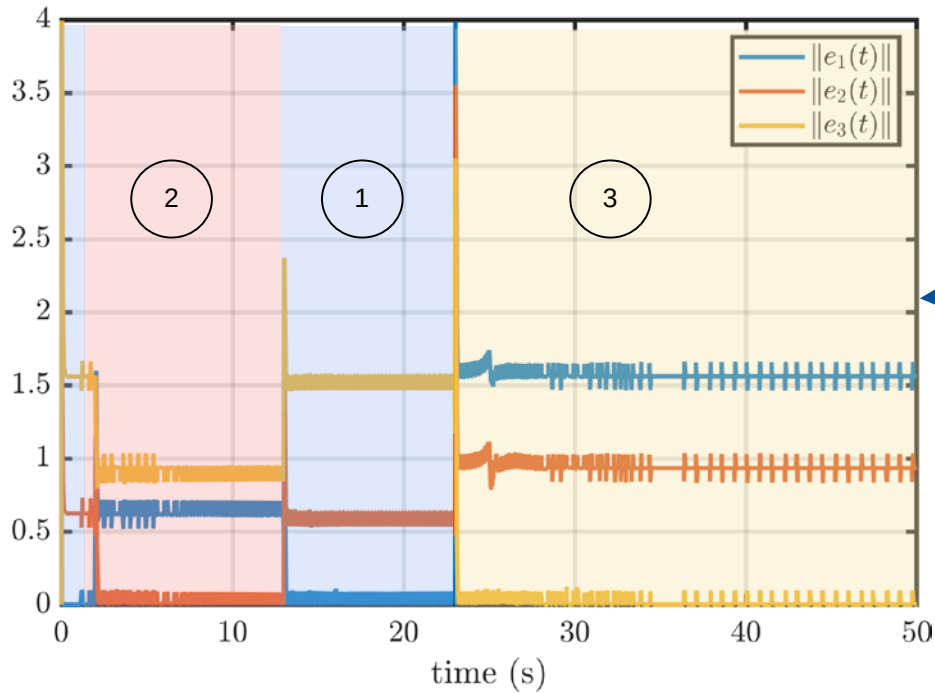
Complexity :

- **Switching** → non-linearity
- **Switched systems theory**



[1] D. Efimov, J. Cieslak et D. Henry, Supervisory fault-tolerant control with mutual performance optimization, International Journal of Adaptive Control and Signal Processing, 27, pp. 251-279 (2013)

Approach



1. Nominal mode
2. Left aileron is locked
3. Right aileron is locked

Philosophy of switched systems

(Autonomous) switched system defined by :

$$\dot{x}(t) = A_{\sigma(t)}x(t)$$

- Switching sequence $\sigma(t)$.

During a switching event :

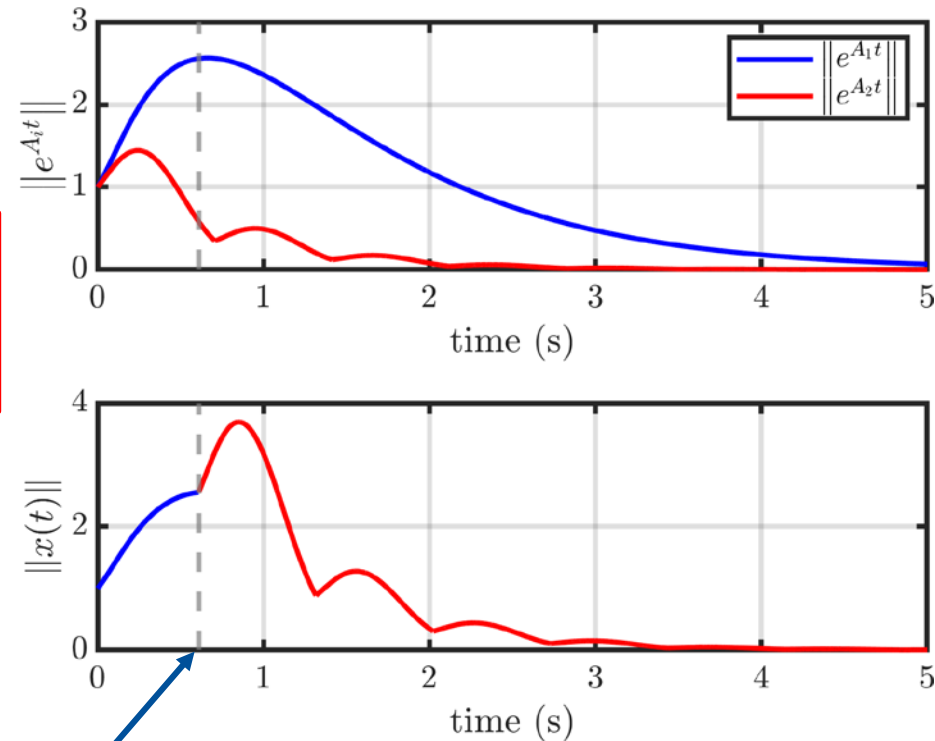
- Temporary increase in the state norm:

$$\forall t \in [t_k, t_{k+1}[, \|x(t)\| \leq \beta e^{-\alpha(t-t_k)} \|x(t_k)\|$$

$$\beta > 1$$

Need to impose a **sufficiently slow switching policy** to guarantee stability :

- Minimum dwell-time.
- Average dwell-time.



Switching instant

Computation of the minimum (average) dwell-time

Approach based on the **state norm** :

$$\forall i \in P, \|e^{A_i t}\| \leq \beta e^{-\alpha t}$$

with :

- α the smallest decay rate.
- $\beta = \max(\text{cond}(V_i)), A_i = V_i D_i V_i^{-1}$

Minimum (or average) dwell-time :

$$\tau_a = \tau_D = \frac{\ln(\beta)}{\alpha}$$

Approach based on the **Multiple Lyapunov Functions (MLF)**:

$$\forall i \in P, \begin{cases} A_i^T P_i + P_i A_i \leq -\eta P_i \\ P_i \leq \mu P_j, \forall j \in P \setminus \{i\} \end{cases}$$

with :

- η a decay rate constraint.
- μ constraint on the jump of the MLF :

$$\tau_a = \tau_D = \frac{\ln(\mu)}{\eta}$$

Exponential stability if the switching sequence $\sigma(t)$ respects the minimum dwell-time constraint:

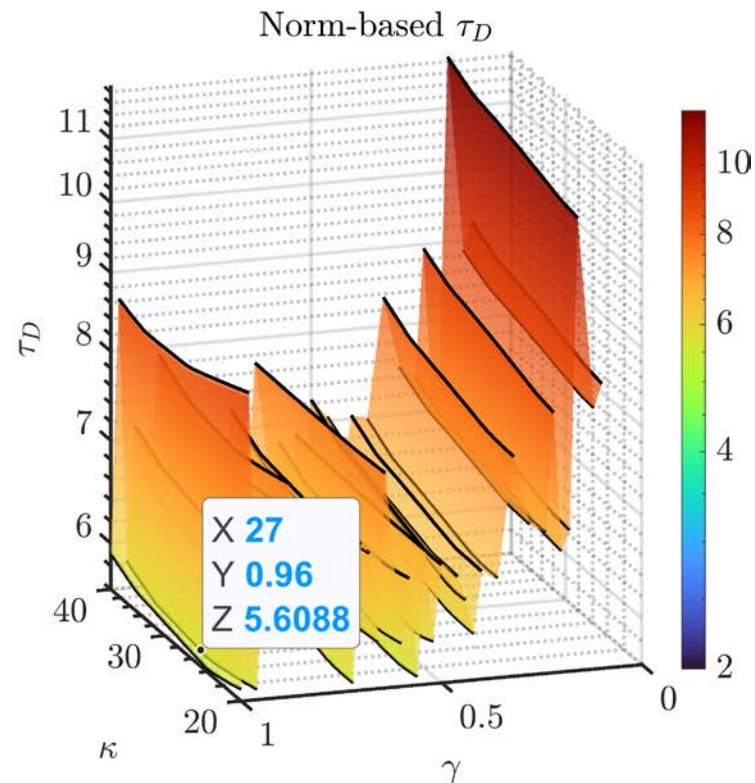
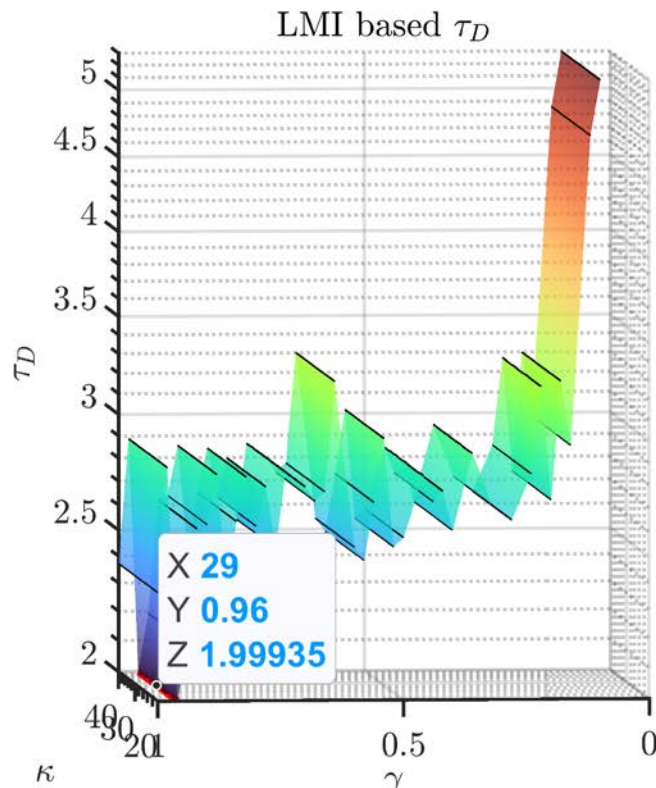
$$\tau_D(\sigma) \geq \tau_D.$$

How to solve this BMI(P_i, P_j, η, μ) in order to guarantee the minimality of $\frac{\ln(\mu)}{\eta}$?

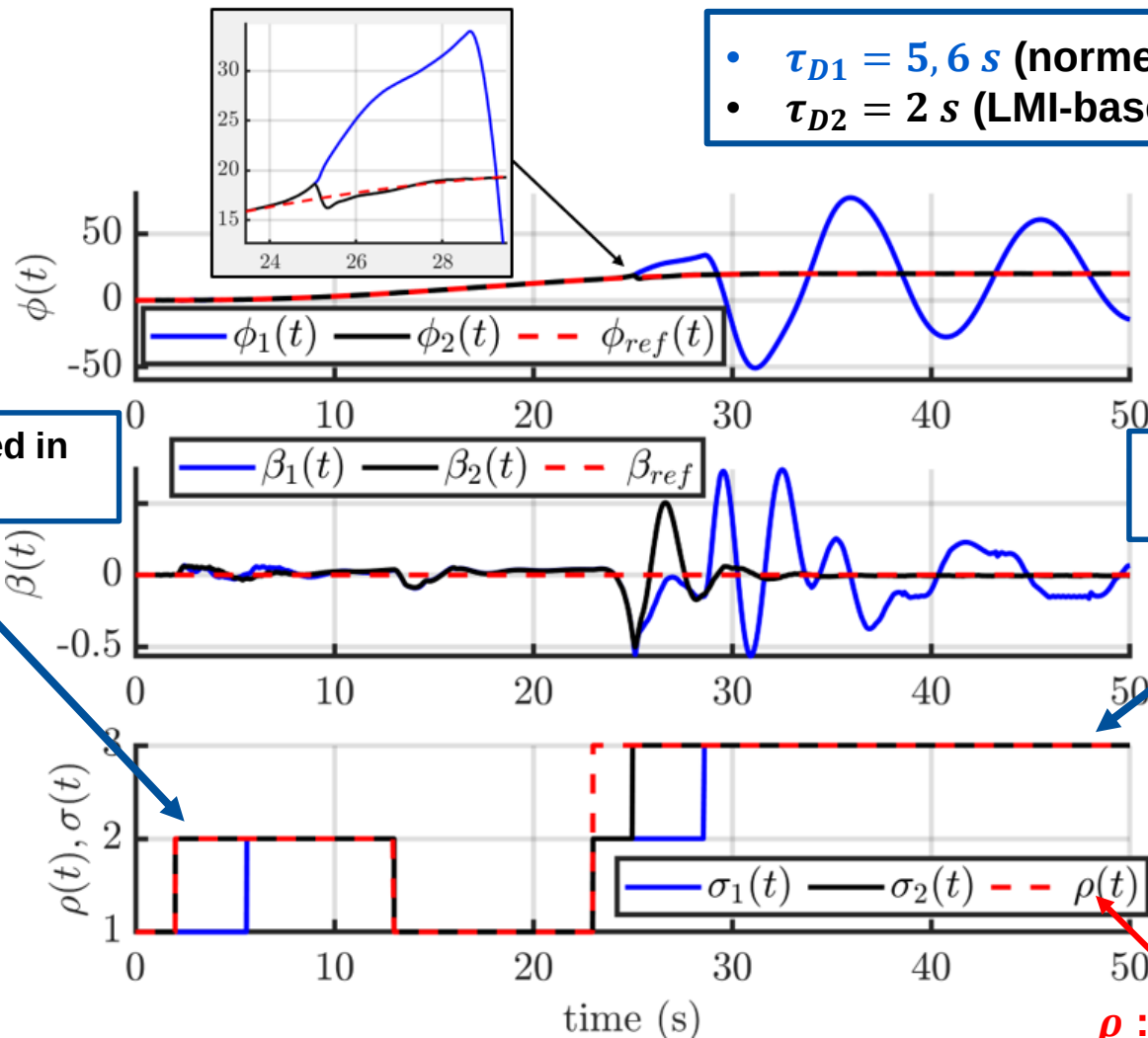
Proposition of an algorithm to find the **optimal** $\frac{\ln(\mu)}{\eta}$ ratio.

Application to the F8C aircraft

- Selection of the H_∞ controllers (relative bandwidth γ) / observers (poles κ) minimizing τ_D .
- ⇒ Application to the control of the F8C lateral mode.



Application to the F8C aircraft



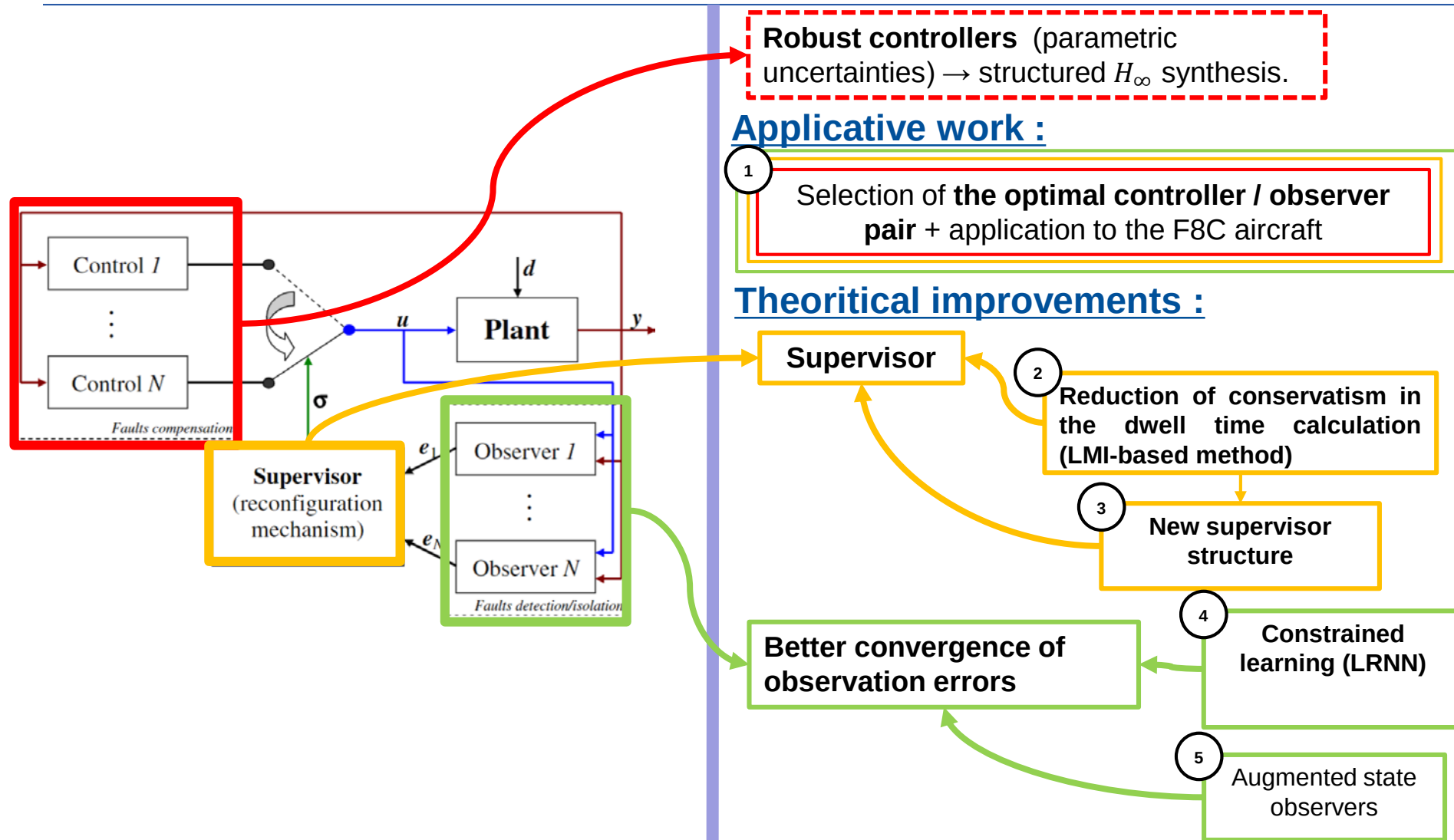
- $\tau_{D1} = 5,6 \text{ s}$ (normed-based method)
- $\tau_{D2} = 2 \text{ s}$ (LMI-based method)

Left aileron locked in place

Right aileron locked in place

ρ : System mode

Conclusion



Conclusion

Unsuccessful theoretical work:

- **Augmented observers with learned non-linearities (RNNs, RENs), theoretical and practical limitations:**
 - Choice of **training data**
 - **Complex theoretical proof of stability** (due to the non-linearity + switching)

Application model

Flexop / Flipased

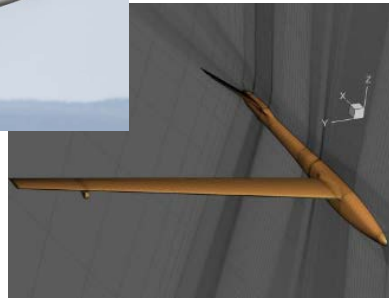
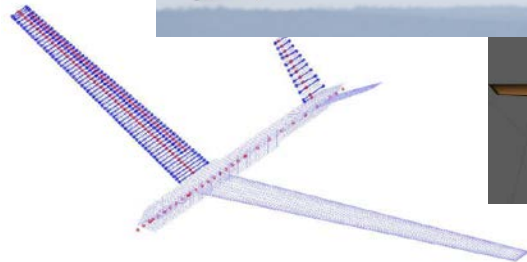
Linearized model of the aircraft.

Pros:

- **High-fidelity**, validated with experimental data

Associated difficulties:

- Very high dimensional LMIs



Use of SHARPy



Pros:

- **Very modular** open-source Python code.
- **Choice of benchmark** (so its size)



Questions

Merci pour votre attention !

