Flow Control: TD4-2

Overview

- General issues, passive *vs* active…
- Control issues: optimality and learning *vs* robustness and rough model
- Model-based control: linear model, nonlinear control
    - Linear model, identification
    - Sliding Mode Control
    - Delay effect
    - Time-delay systems
- Introduction to delay systems
    - Examples
    - Much a do about delay? Some special features + a bit of maths
    - Time-varying delay
- Model-based control: nonlinear model, nonlinear control
    - Overview of MF's PhD: Sliding Mode Control
    - Application to the airfoil
    - ➡ Application to the Ahmed body (MF and CC'PhDs)

…

- Machine Learning and model-free control: + 4h with Thomas Gomez

Reducing Car Consumption by Means of a Closed-loop Drag Control

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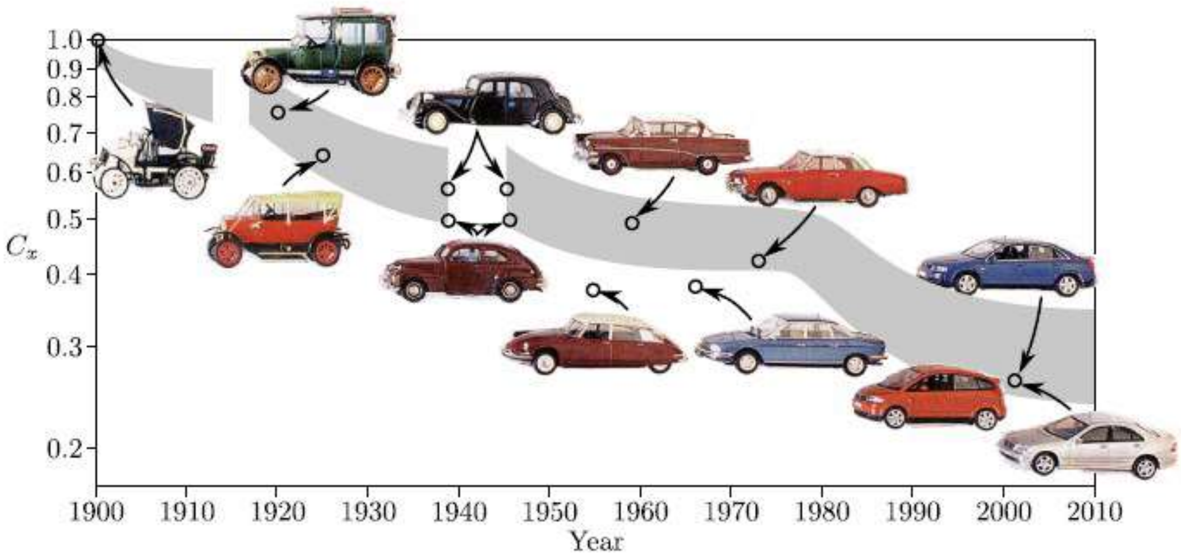
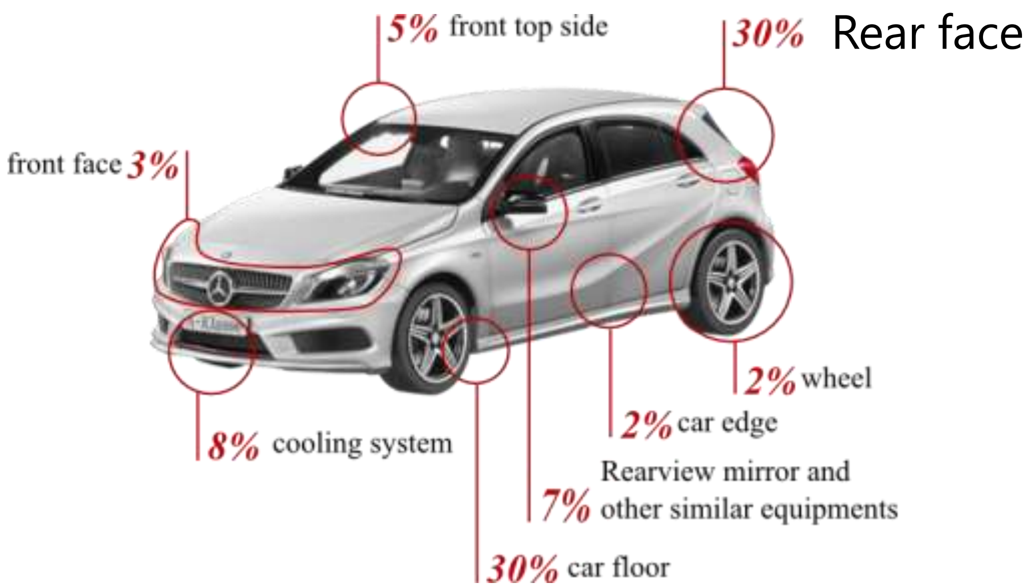
Transportation industry



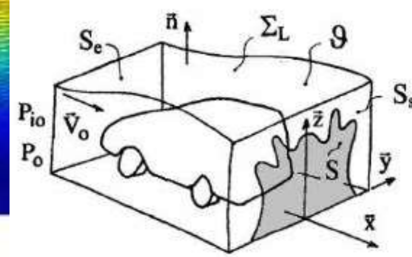


PROBLEM

Reduce gas consumption

Automotive problem

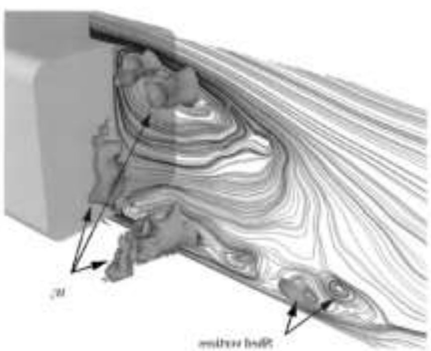
Flow configuration

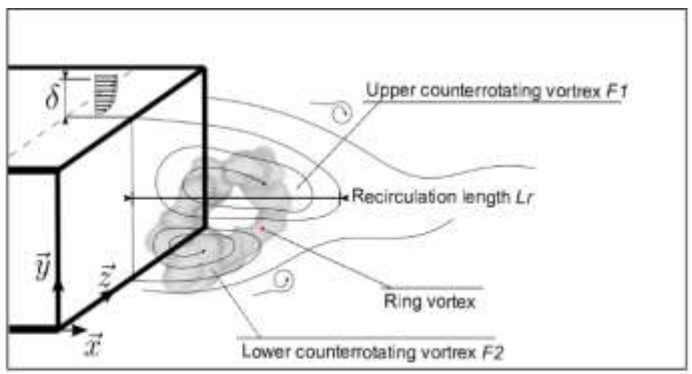


PROBLEM

Reduce gas consumption

Drag reduction





$$F_D = \iint_{S_w} (Pt_\infty - Pt_{S_w}) d\sigma + \frac{1}{2}\rho V_\infty^2 \iint_{S_w} \left(\frac{V_z^2}{V_\infty^2} + \frac{V_z^2}{V_\infty^2}\right) d\sigma - \frac{1}{2}\rho V_\infty^2 \iint_{S_w} \left(1 - \frac{V_x}{V_\infty}\right)^2 d\sigma$$

Automotive problem

Methods of flow control

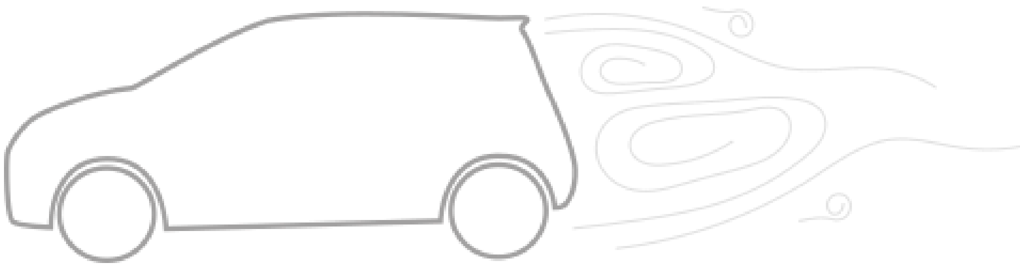
Passive control
(Small variation in the geometric configuration)
Limitations of design requirements

Active control (Injection of momentum)

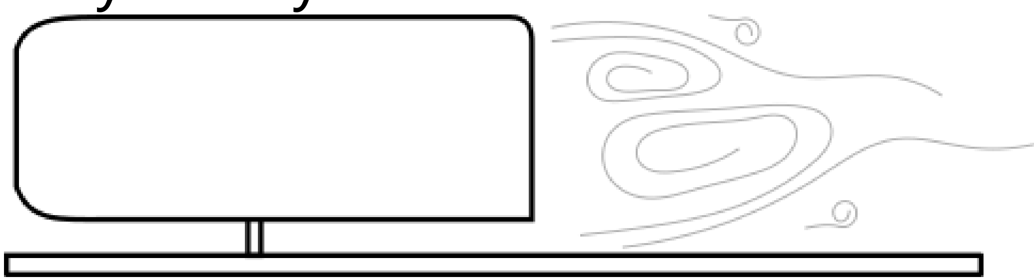
C_AIR LOUNGE

Transportation industry

Physical system: Case II – Vehicle



Physical system: Case I – Ahmed body

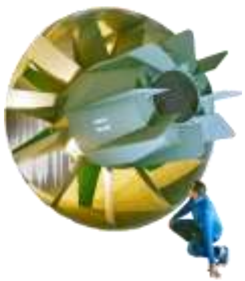


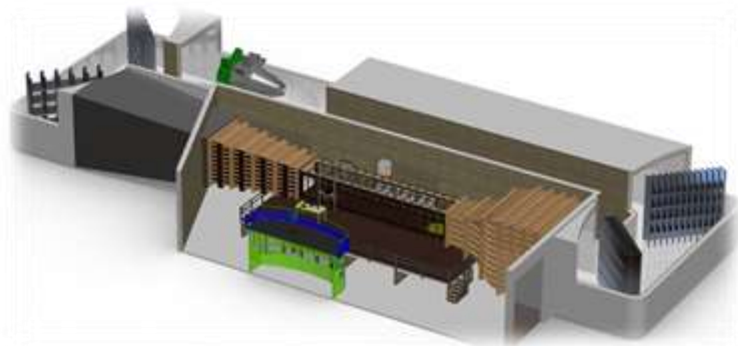
PROBLEM

Reduce gas consumption

Drag reduction

Wind tunnel





<u>Characteristics:</u>

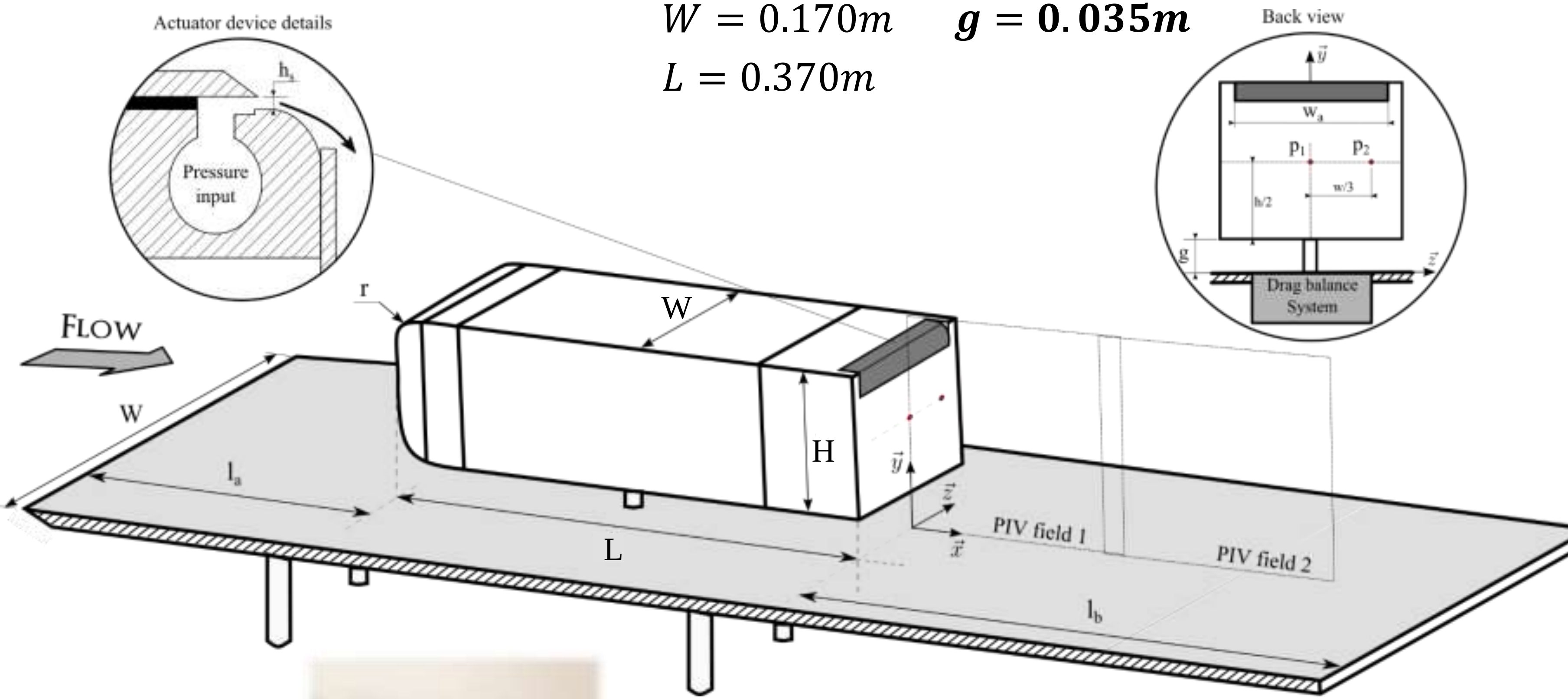
✓Closed-loop wind tunnel
✓Max. velocity 60m/s 200km/h)
✓Optimal test section:
2m x 2m, length 10m

Physical System I – Ahmed body

$H = 0.135m$ $\quad r = 0.05m$

$W = 0.170m$ $\quad \boldsymbol{g = 0.035m}$

$L = 0.370m$

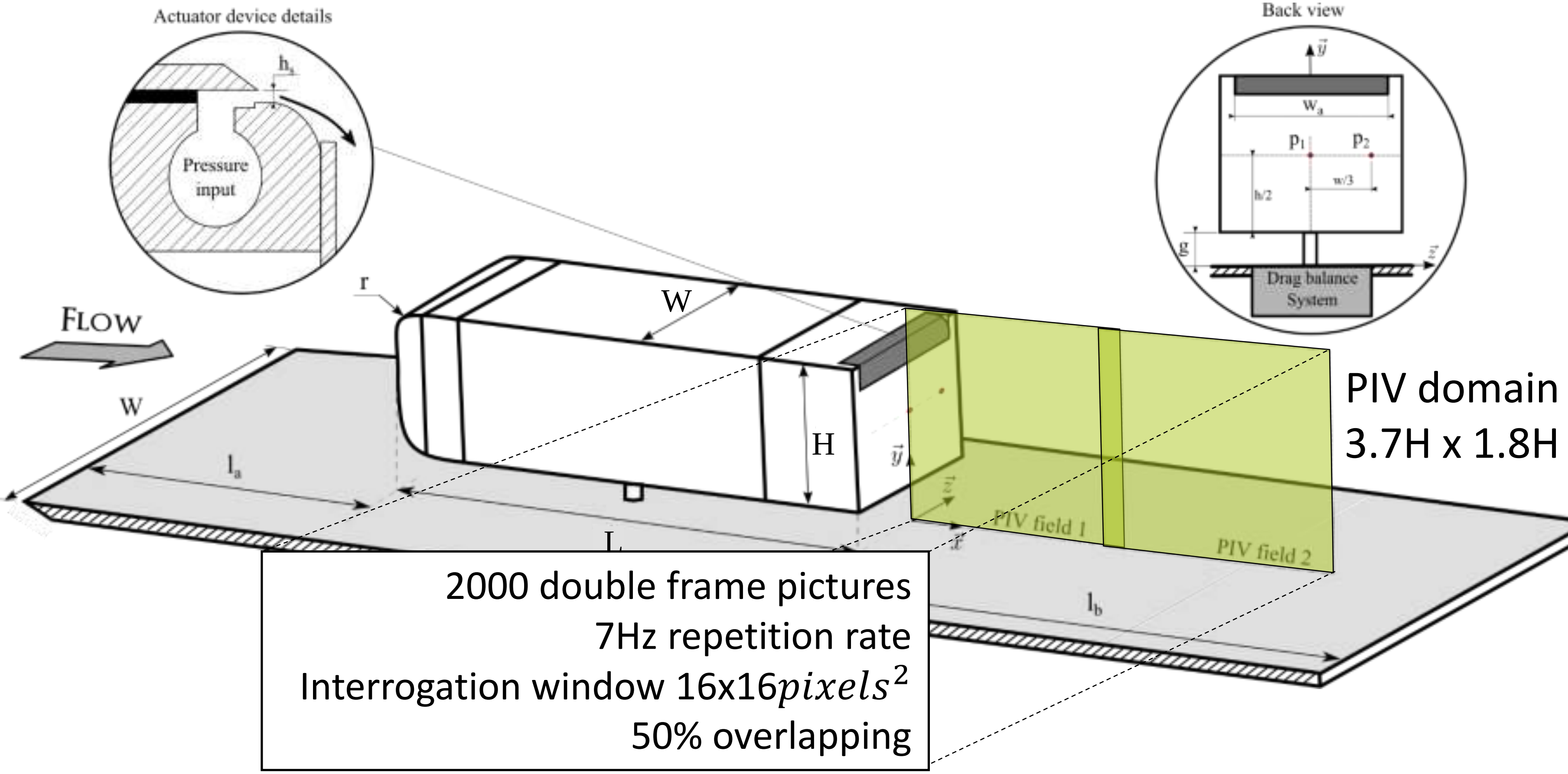


$U_\infty = 10m/s$

$Re_{hH} = 9x10^4$

Physical System

PIV



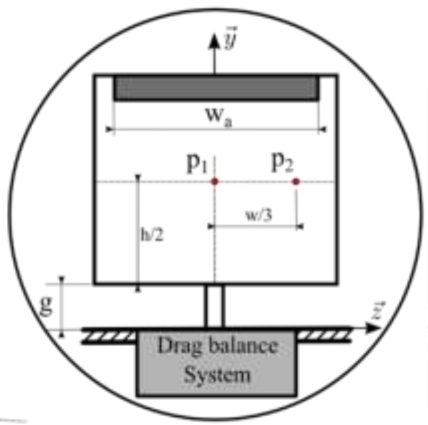
PIV domain
3.7H x 1.8H

2000 double frame pictures
7Hz repetition rate
Interrogation window 16x16$pixels^2$
50% overlapping

Sensor and actuator characteristics

Sensor

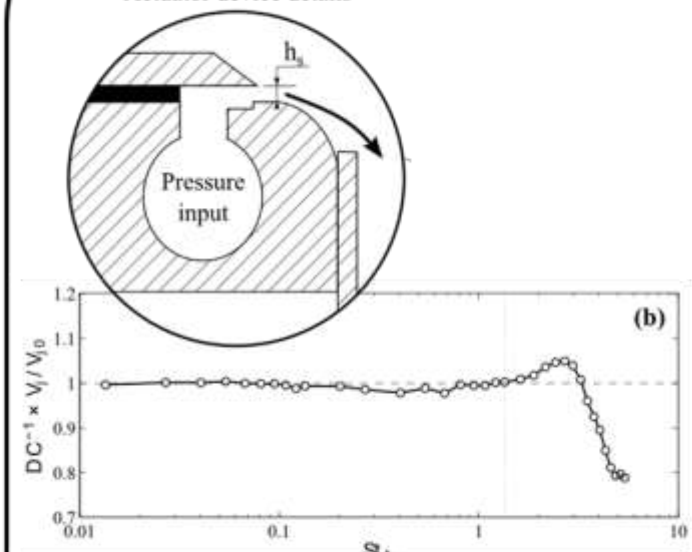
Back view



- A force and torque balance:
  - Drag, lift and drift
  - Sensing range up to 165N
  - Error 0.03N
- 2 sub-miniature piezo-resistive Kulite sensors:
  - Nominal measurement range of 35Kpa
  - Sampling frequency 10KHz

Actuator

Actuator device details

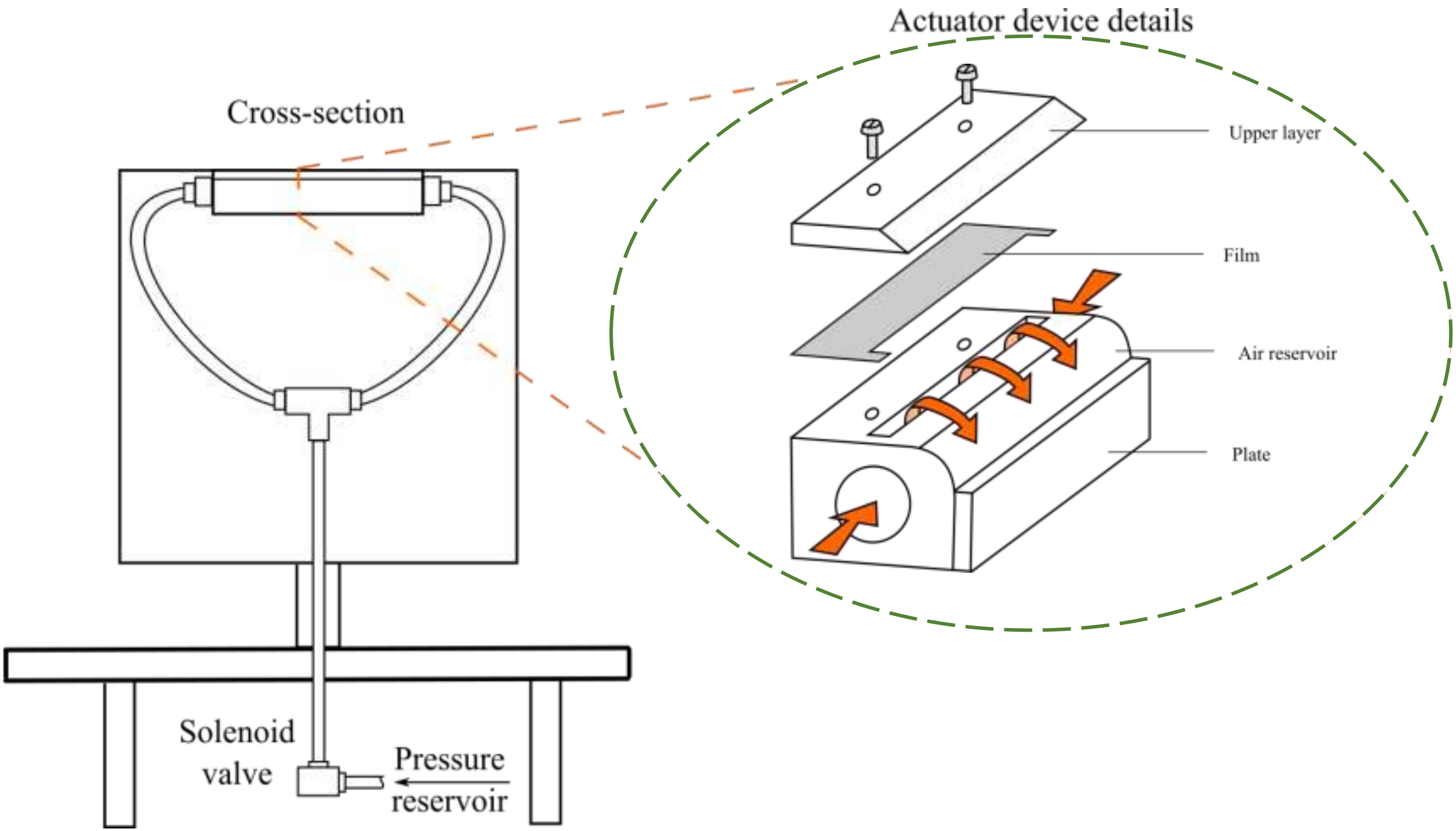


- Actuator slit (width $h_s = 0.1mm$ and a length $w_a = 150mm$)
- Pressure supplied by a compressor
- Pulsed blowing driven by a FESTO-MH2 solenoid valve
- Velocities up to 30m/s (@ 6bar)

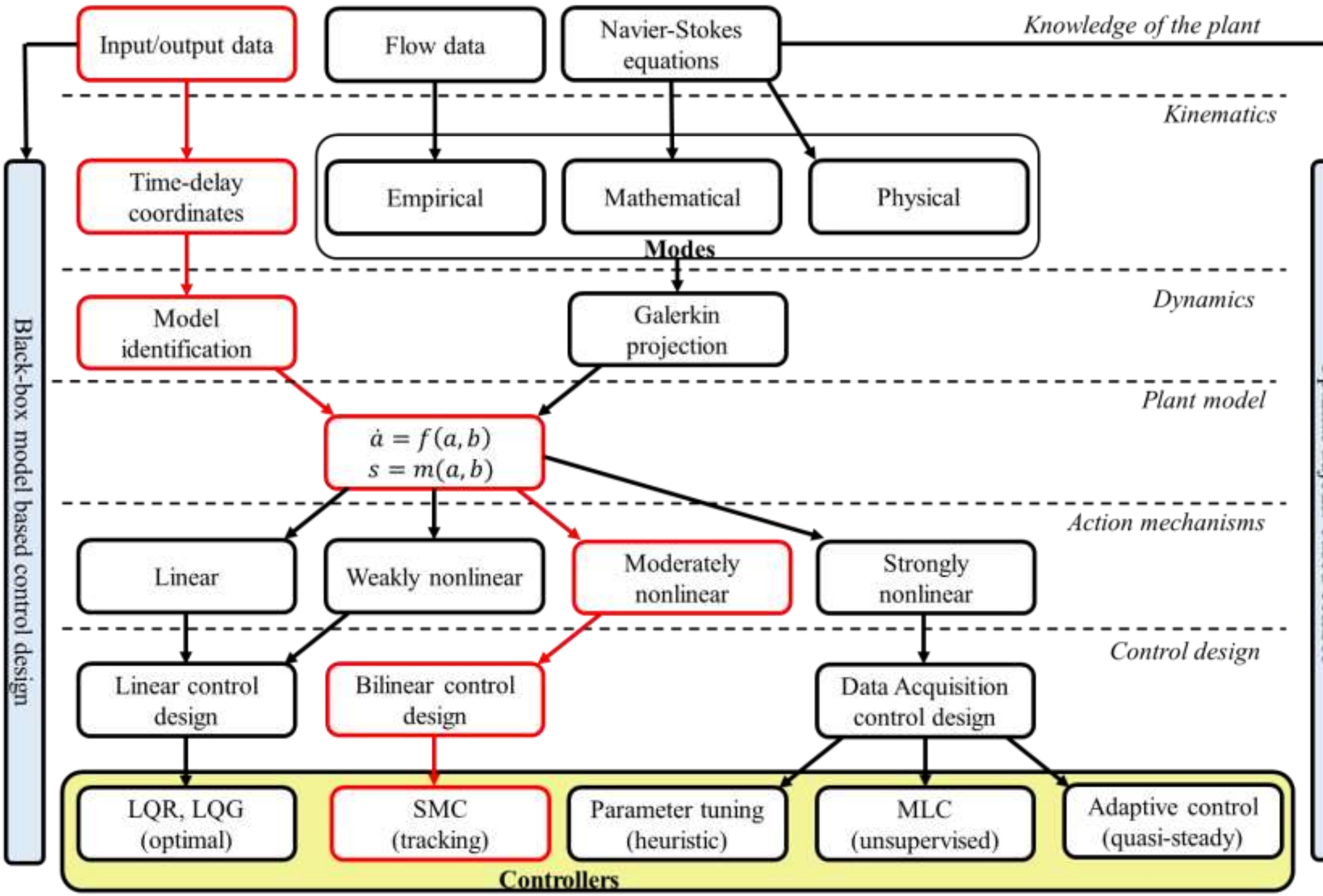
Jet velocity
V_j

Steady jet velocity
$V_{j0} = 16m/s$

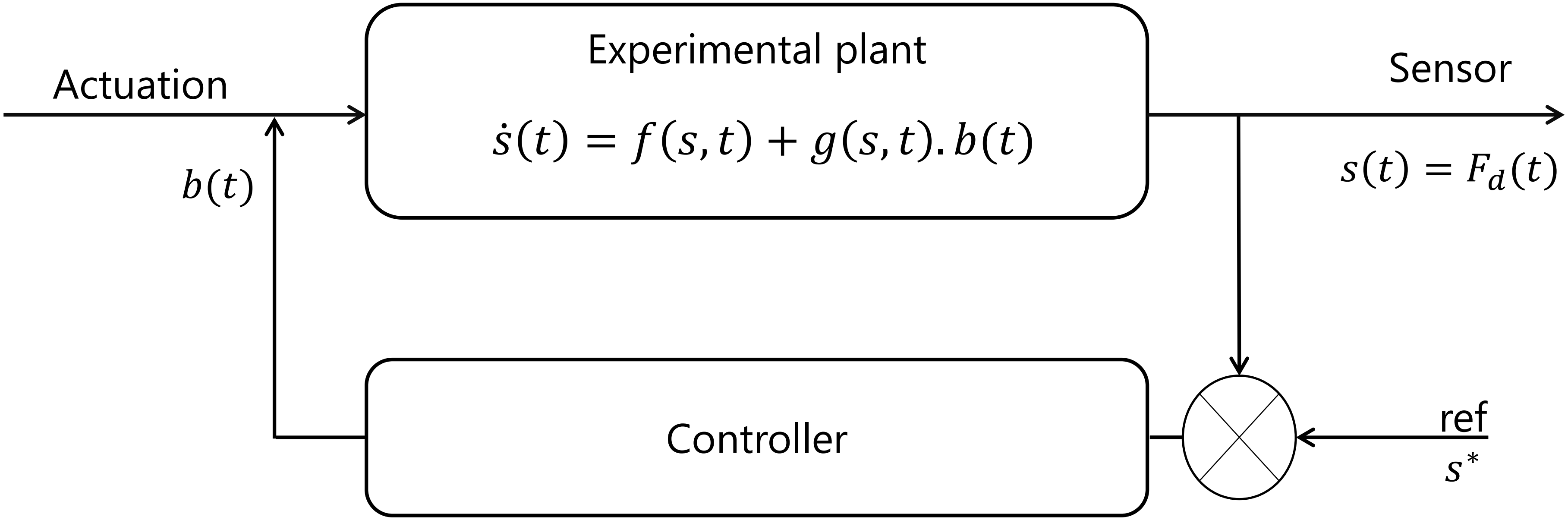
Flow control



Flow control

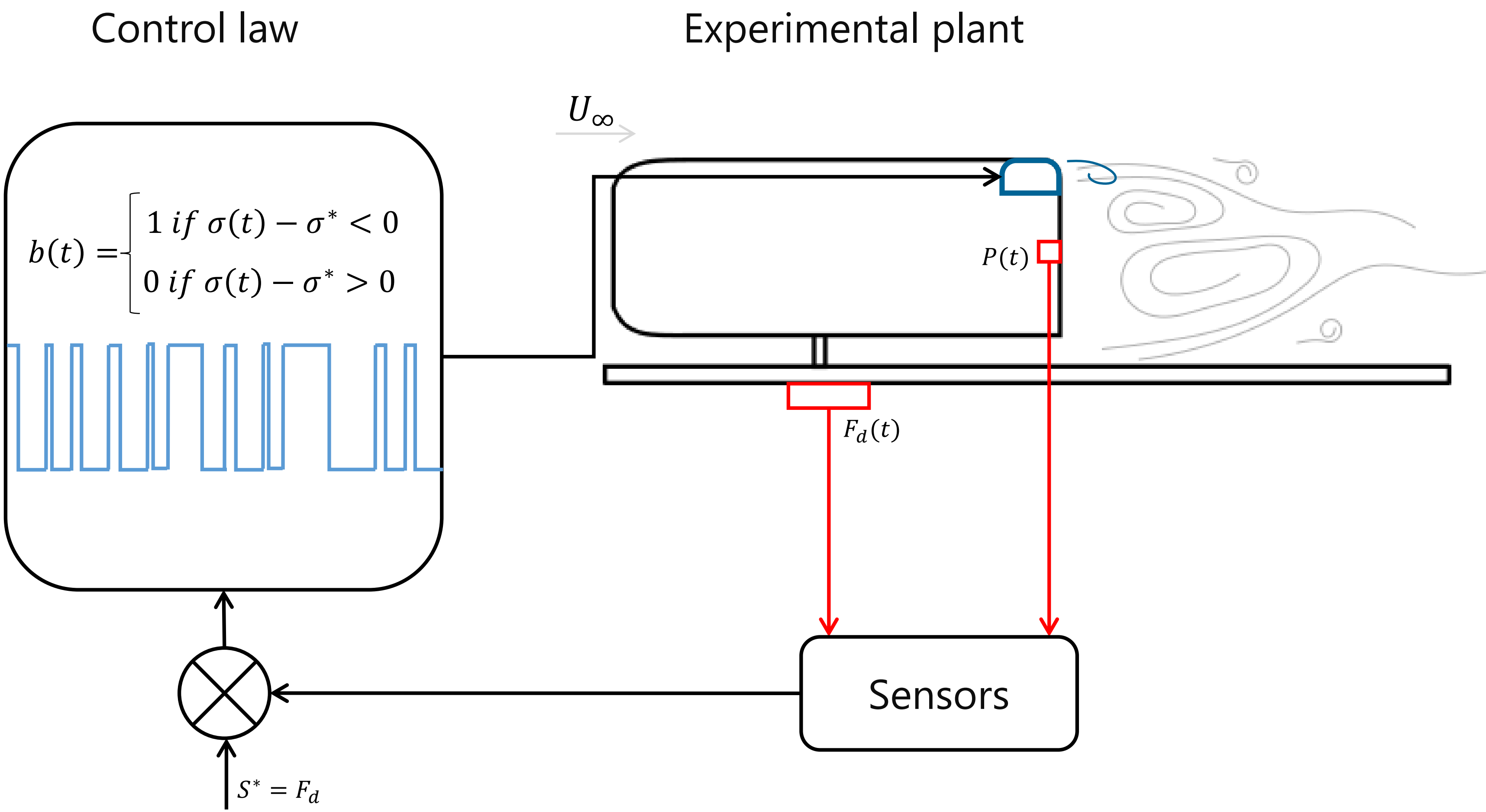


Sliding Mode Control



Feingesicht et al. (2017) Int. J. Robust Nonlinear Control

SMC


Control law
Experimental plant
U_∞
$b(t) = \begin{cases} 1 \; if \; \sigma(t) - \sigma^* < 0 \\ 0 \; if \; \sigma(t) - \sigma^* > 0 \end{cases}$
$P(t)$
$F_d(t)$
Sensors
$S^* = F_d$

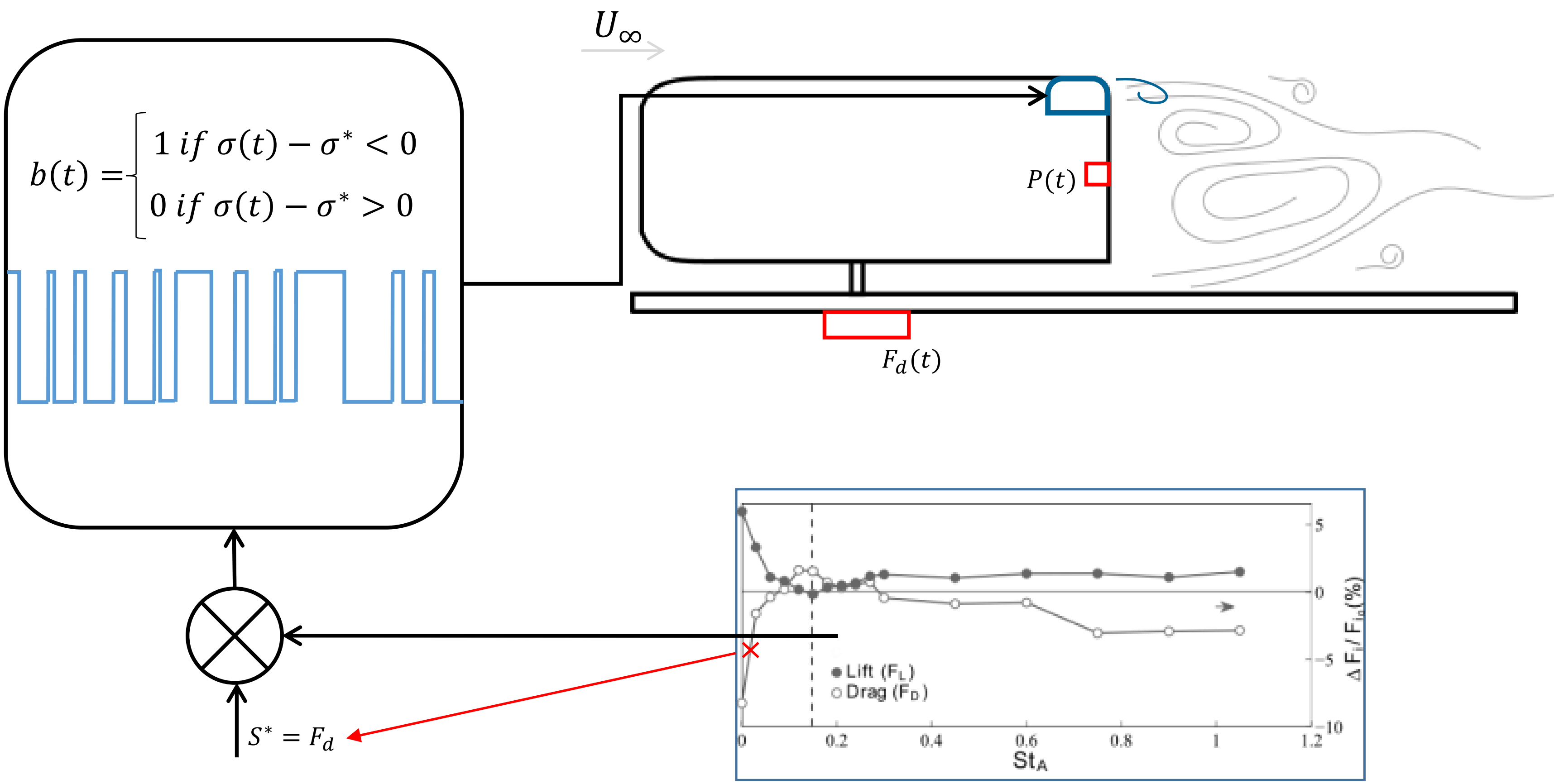
SMC

Choose s^* → Reaching phase → Sliding phase

Reaching phase
- Wait for s(t) to arrive to s*

Sliding phase
- Keep s(t) at s*

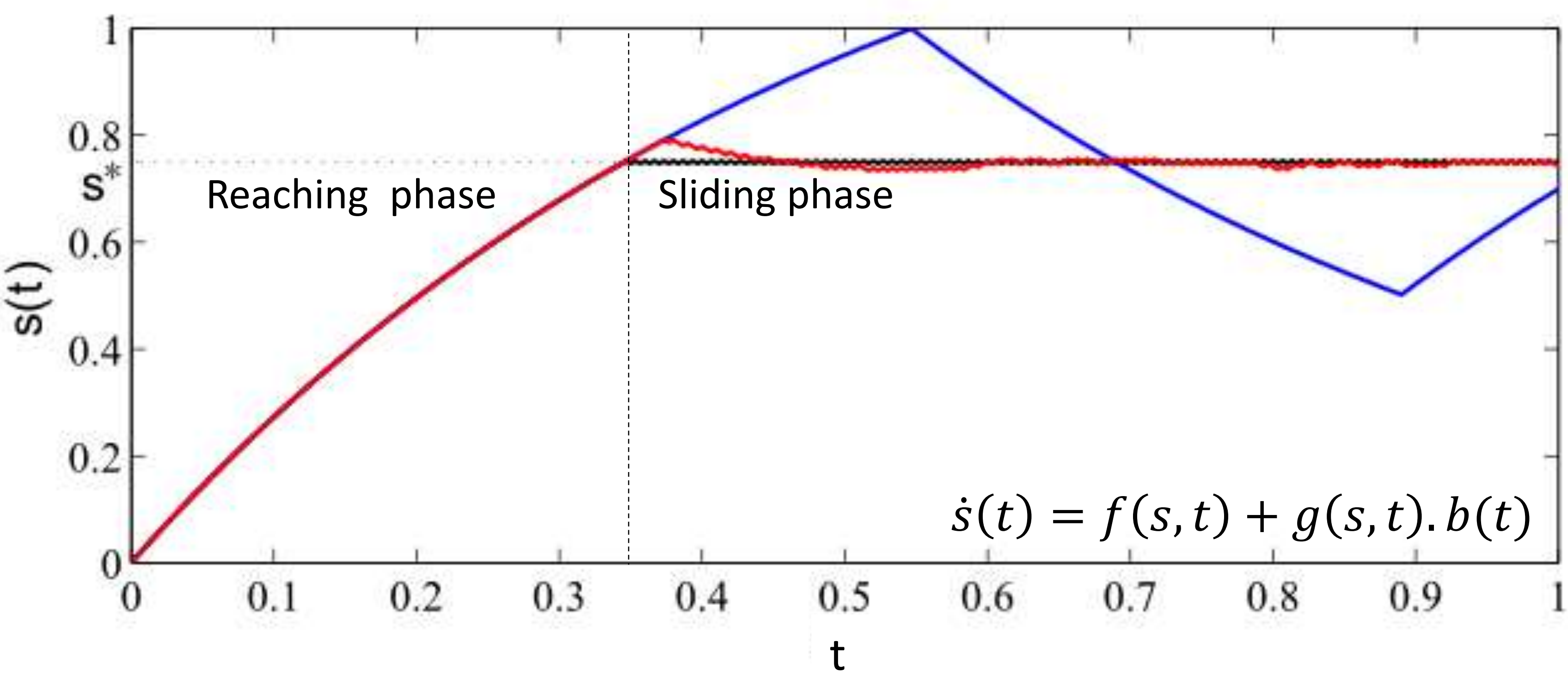
SMC


$b(t) = \begin{cases} 1 \; if \; \sigma(t) - \sigma^* < 0 \\ 0 \; if \; \sigma(t) - \sigma^* > 0 \end{cases}$
U_∞
$P(t)$
$F_d(t)$
$S^* = F_d$
Lift (F_L)
Drag (F_D)
St_A
$\Delta F_i / F_{i0}$ (%)
0
0.2
0.4
0.6
0.8
1
1.2
5
0
-5
-10

SMC

Choose s^* → Reaching phase → Sliding phase

- Wait for s(t) to arrive to s*
- Keep s(t) at s*



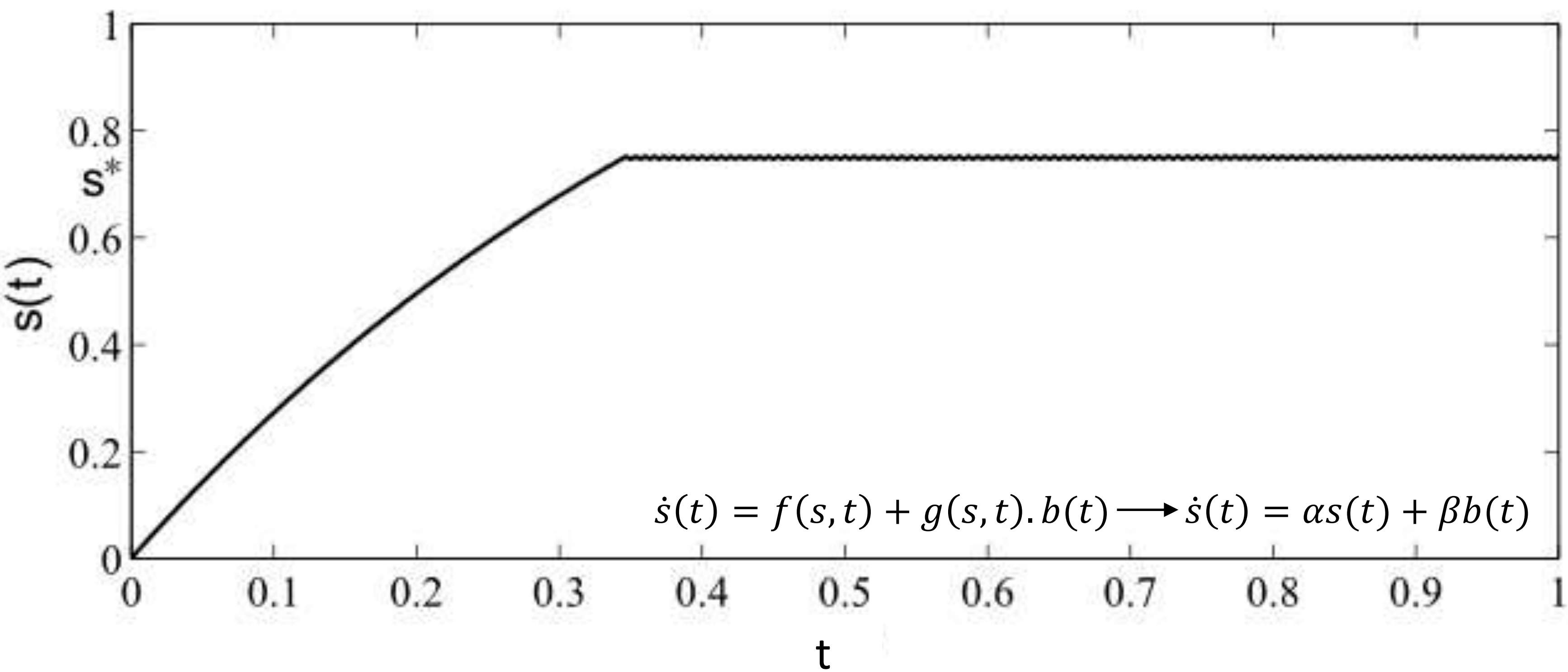
Feingesicht et al. (2017) Int. J. Robust Nonlinear Control

SMC

$$\dot{s}(t) = \alpha s(t) + \beta b(t)$$

$$\sigma^* = s(t)$$

$$b(t) = \begin{cases} 1 \; if \; \sigma(t) - \sigma^* < 0 \\ 0 \; if \; \sigma(t) - \sigma^* > 0 \end{cases}$$

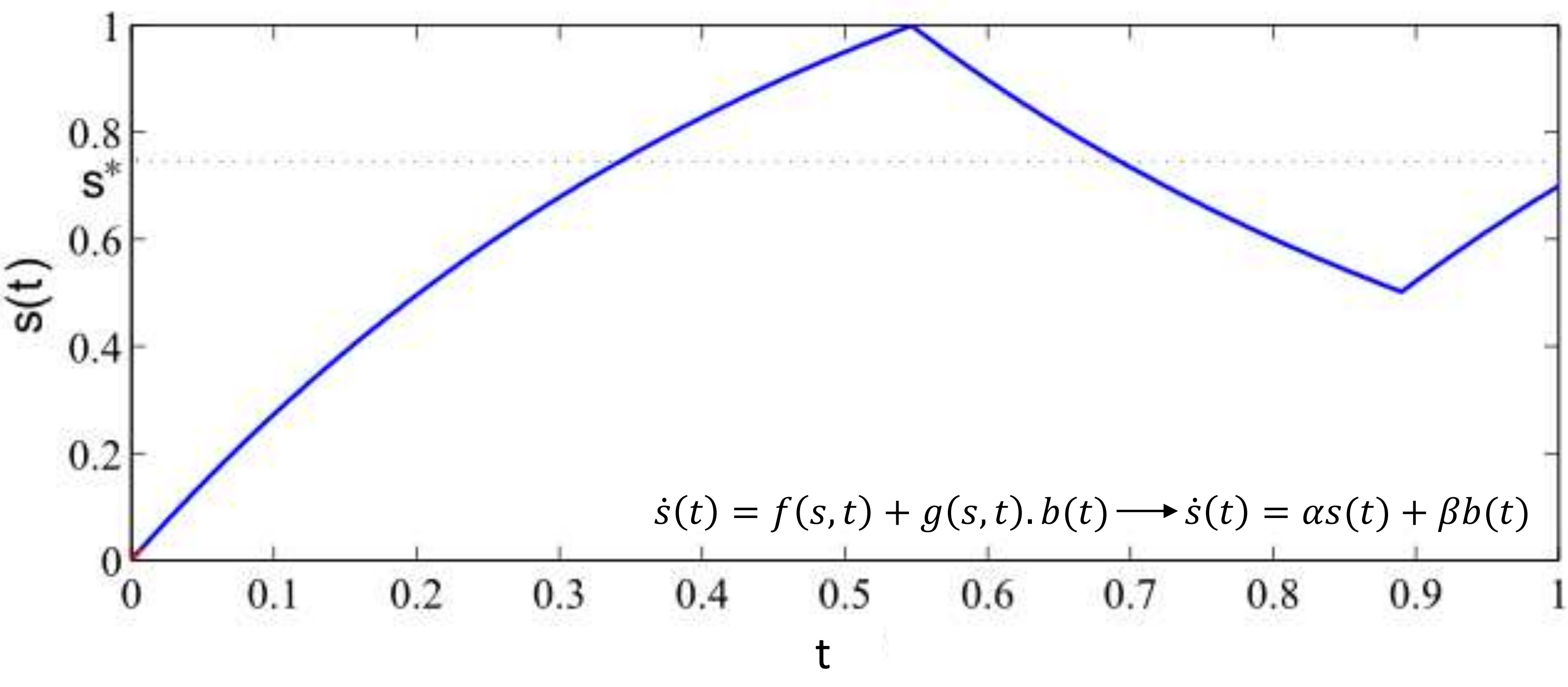


SMC

$$\dot{s}(t) = \alpha s(t) + \beta b(t-h)$$

$$\sigma^* = s(t)$$

$$b(t) = \begin{cases} 1 \ if \ \sigma(t) - \sigma^* < 0 \\ 0 \ if \ \sigma(t) - \sigma^* > 0 \end{cases}$$

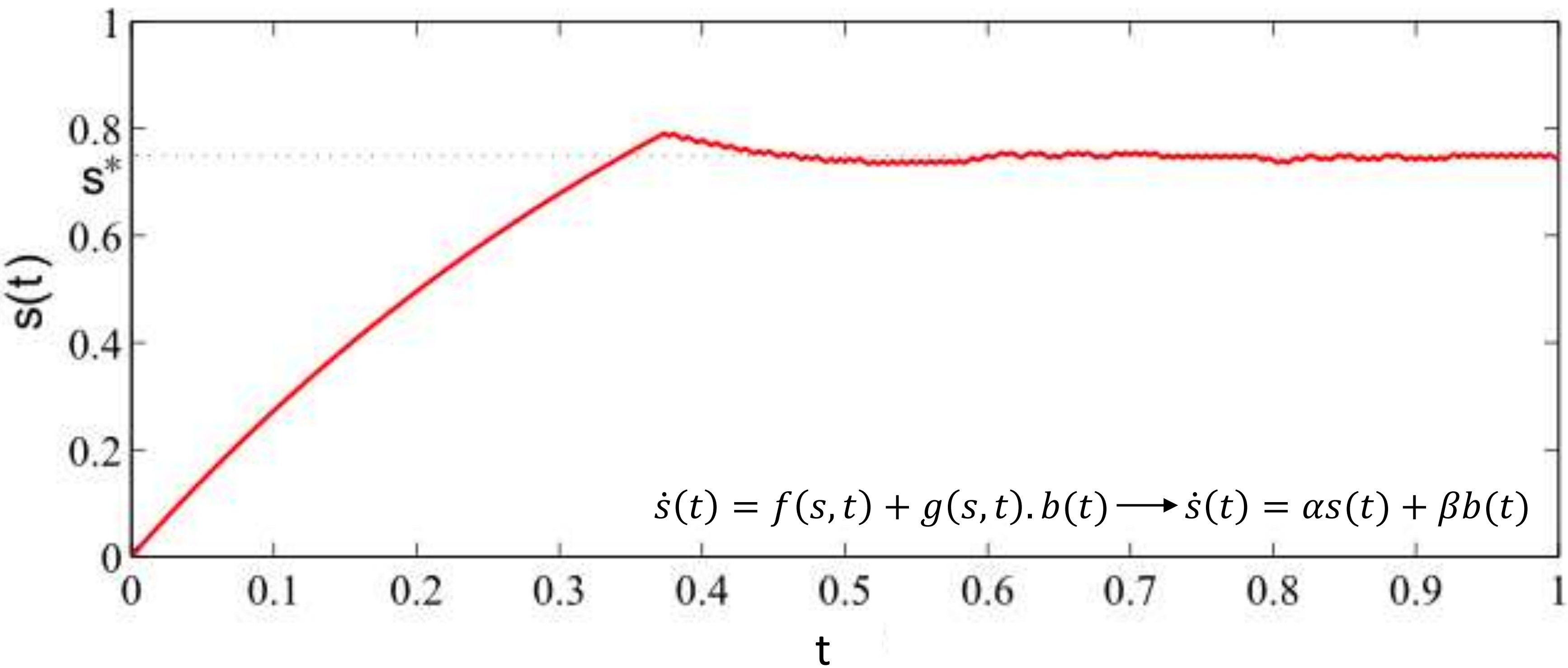


SMC

$$\dot{s}(t) = \alpha s(t) + \beta b(t-h)$$

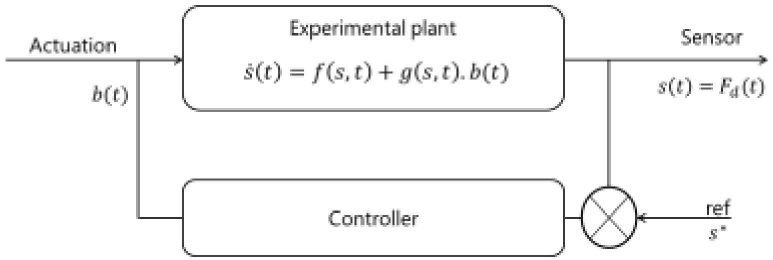
$$\sigma^* = s(t) + \beta \int_{t-h}^{t} b(p)dp$$

$$b(t) = \begin{cases} 1 \; if \; \sigma(t) - \sigma^* < 0 \\ 0 \; if \; \sigma(t) - \sigma^* > 0 \end{cases}$$



SMC

Identification



Sensor without delay

$$\dot{s}(t) = \alpha_1 \underbrace{s(t-h)}_{\text{Sensor with delay}} - \overbrace{\alpha_2 s(t)}^{\text{Sensor without delay}} + (\beta - \gamma s(t-h) + \gamma(t-\tau))b(t-h)$$

Sensor with delay

$$FIT(\%) = \left[1 - \frac{\left\| S_{exp} - S_{sim} \right\|_{L_2}}{\left\| S_{exp} - \overline{S_{exp}} \right\|_{L_2}} \right] x\ 100\% = 53\%$$

$$\alpha_1 = 27.37 \quad \alpha_2 = 32.70 \quad \beta = 1.97 \quad \gamma = 1.92 \quad \tau = 0.18 \quad h = 0.01$$

Feingesicht et al. (2017) Int. J. Robust Nonlinear Control

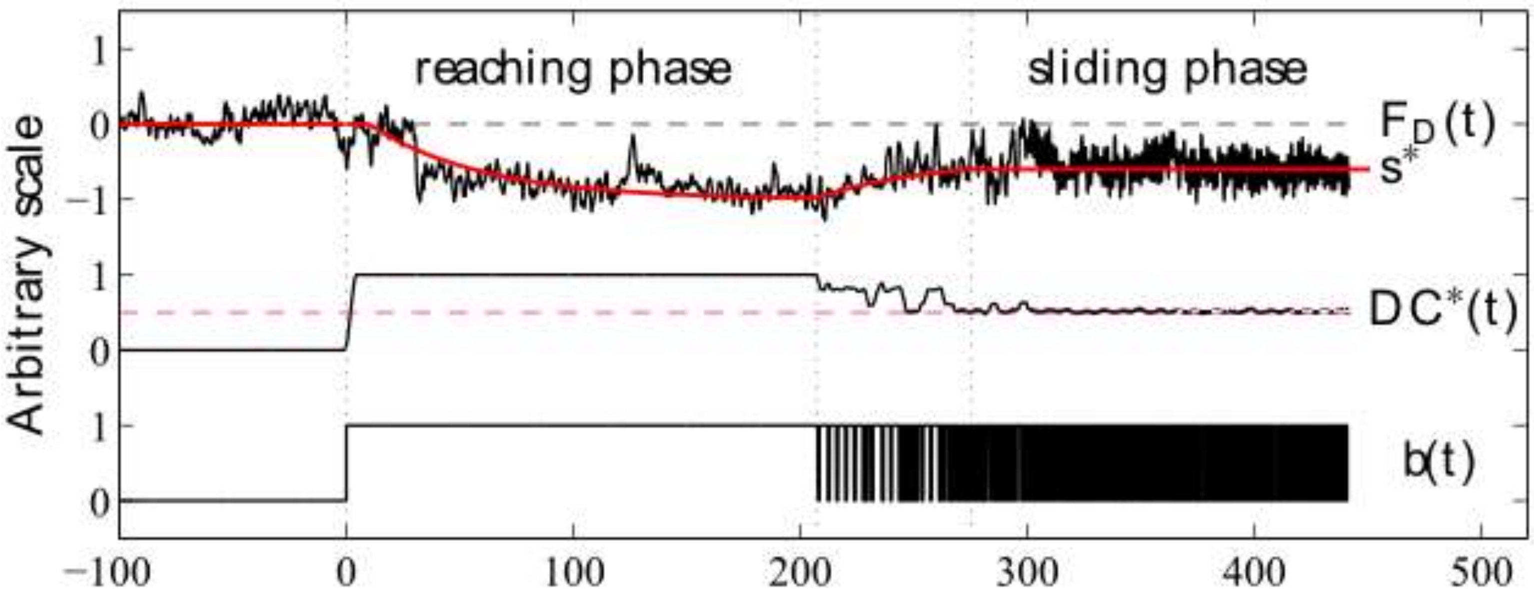
SMC

Sliding mode control

$$b(t) = \begin{cases} 1 \; if \; \sigma(t) - \sigma^* < 0 \\ 0 \; if \; \sigma(t) - \sigma^* > 0 \end{cases}$$

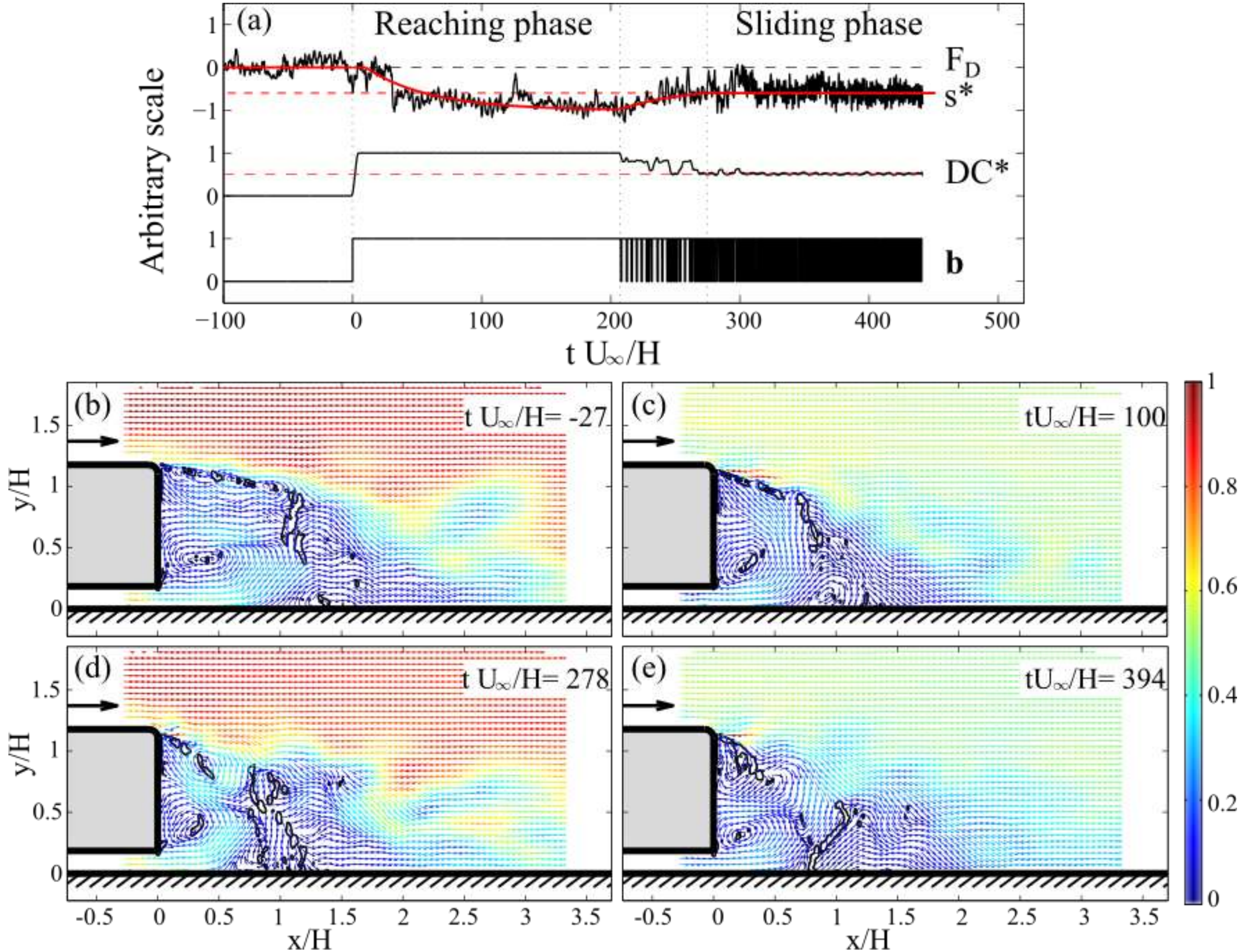
$$\dot{s}(t) = \alpha s(t) + \beta b(t-h)$$

$$\sigma^* = s(t) + \gamma \int_{t-\tau+h}^{t} s(p)dp + \int_{t-h}^{t} \big(\alpha_1 s(p) + (\beta - \gamma s(p) + \gamma s(p-\tau+h)\big) b(p))dp$$



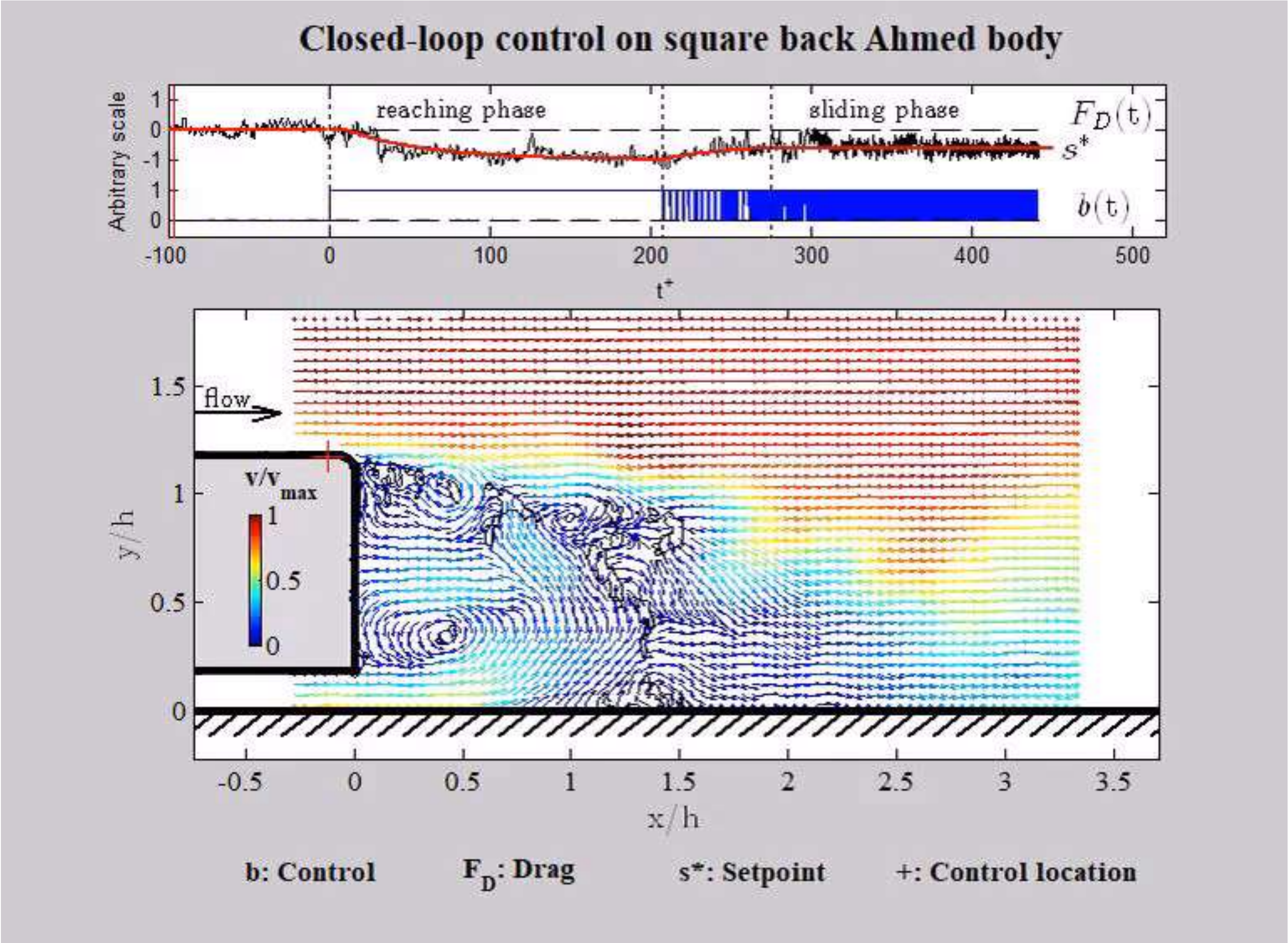
$t^+ = t\, U_\infty / H$

SMC



(a)
Reaching phase
Sliding phase
Arbitrary scale
F_D
s*
DC*
b
t U∞/H
(b)
t U∞/H= -27
(c)
tU∞/H= 100
(d)
t U∞/H= 278
(e)
tU∞/H= 394
y/H
x/H

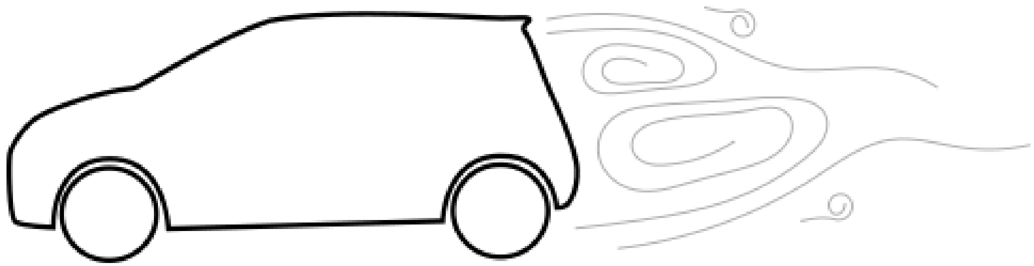
SMC


Closed-loop control on square back Ahmed body
reaching phase
sliding phase
$F_D(t)$
s^*
$b(t)$
Arbitrary scale
t+
flow
v/v max
1
0.5
0
y/h
x/h
b: Control
F D: Drag
s*: Setpoint
+: Control location

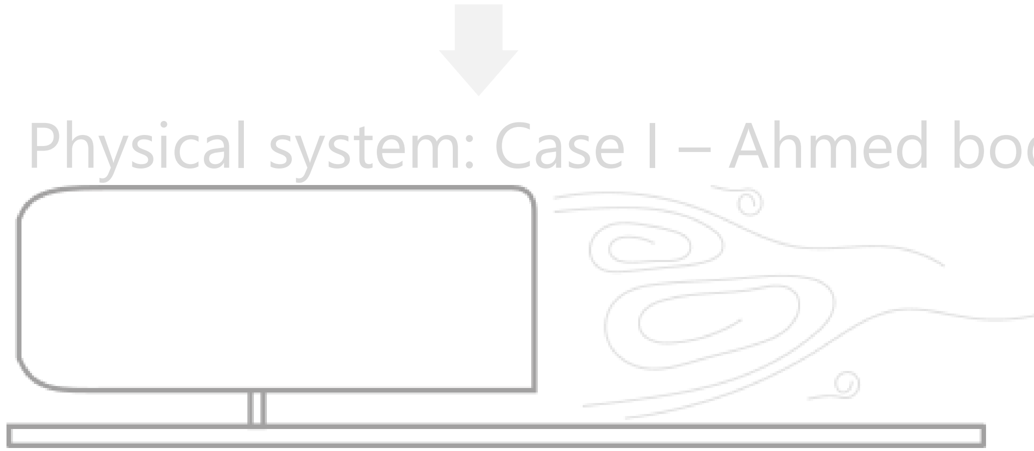
https://www.youtube.com/watch?v=ZZ0qxbEBm8s

Transportation industry

Physical system: Case II – Vehicle



Physical system: Case I – Ahmed body



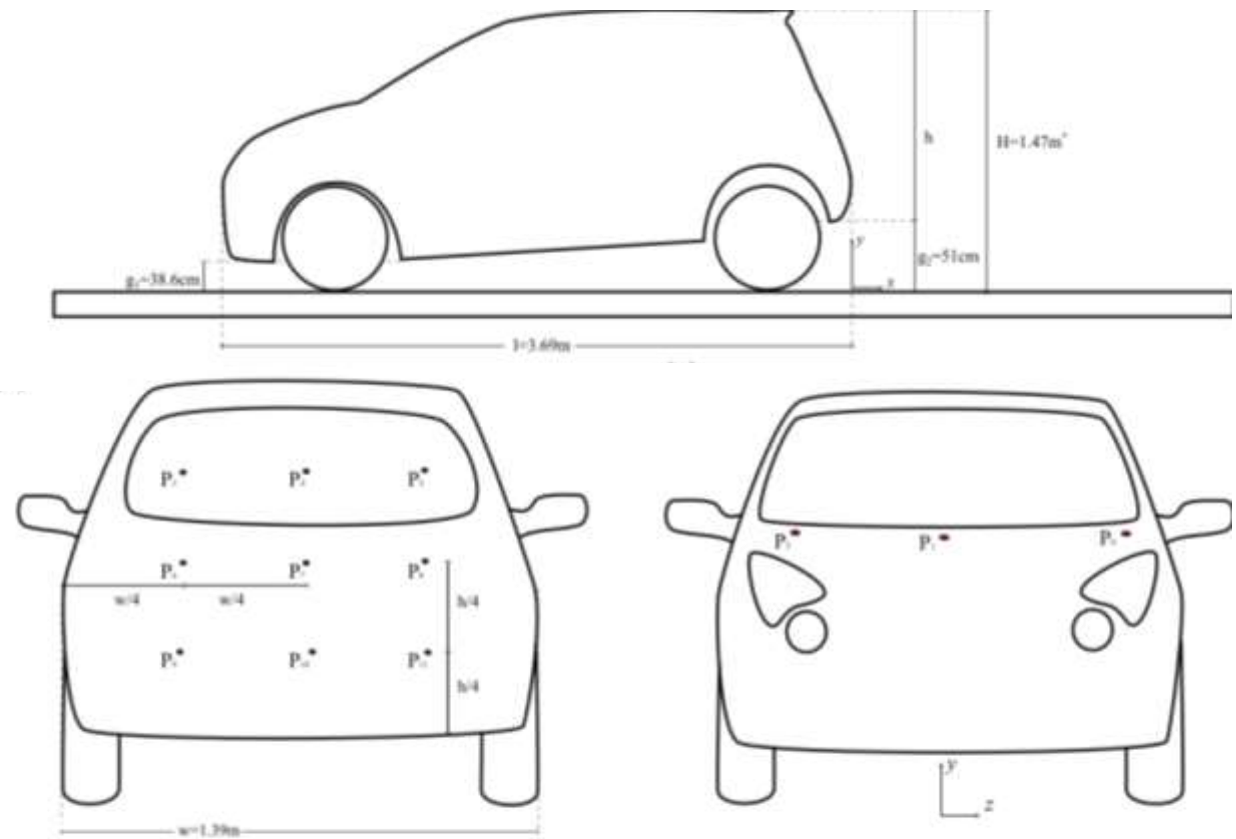
PROBLEM

Reduce gas consumption

Drag reduction

Physical System II – Real car

Measurement mechanisms



Race track located at Clastres (North of France)

Physical System II – Real car

Measurement mechanisms

Onorato’s relation

$$F_D = \iint_{S_w} \left(P_t^{\infty} - P_t^{S_w} \right) d\sigma \; - \frac{\rho U_\infty^2}{2} \iint_{S_w} \left(\frac{{U_y^2}^2}{U_{\ \infty}} + \frac{{U_z^2}^2}{U_{\ \infty}} \right) d\sigma \; + \frac{\rho U_\infty^2}{2} \iint_{S_w} \left(1 - \frac{{U_x^2}^2}{U_{\ \infty}} \right) d\sigma$$

Onorato, M. et al (1984) *SAE, SP-569,International congress and Exposition*, Detroit: pp. 85-93

Measurement mechanisms

Onorato's relation

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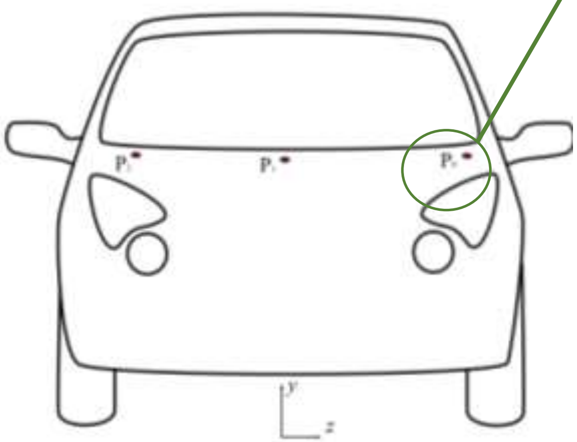
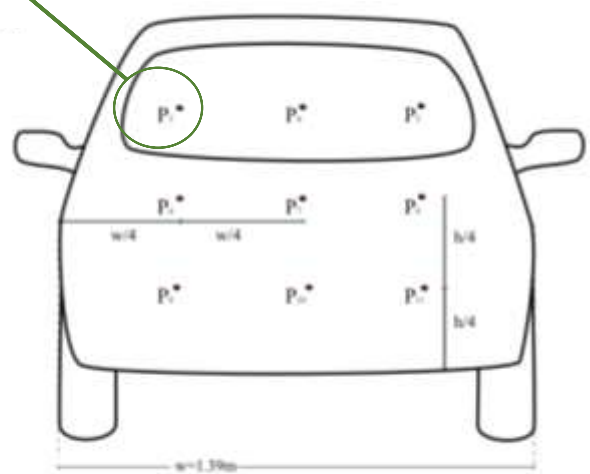
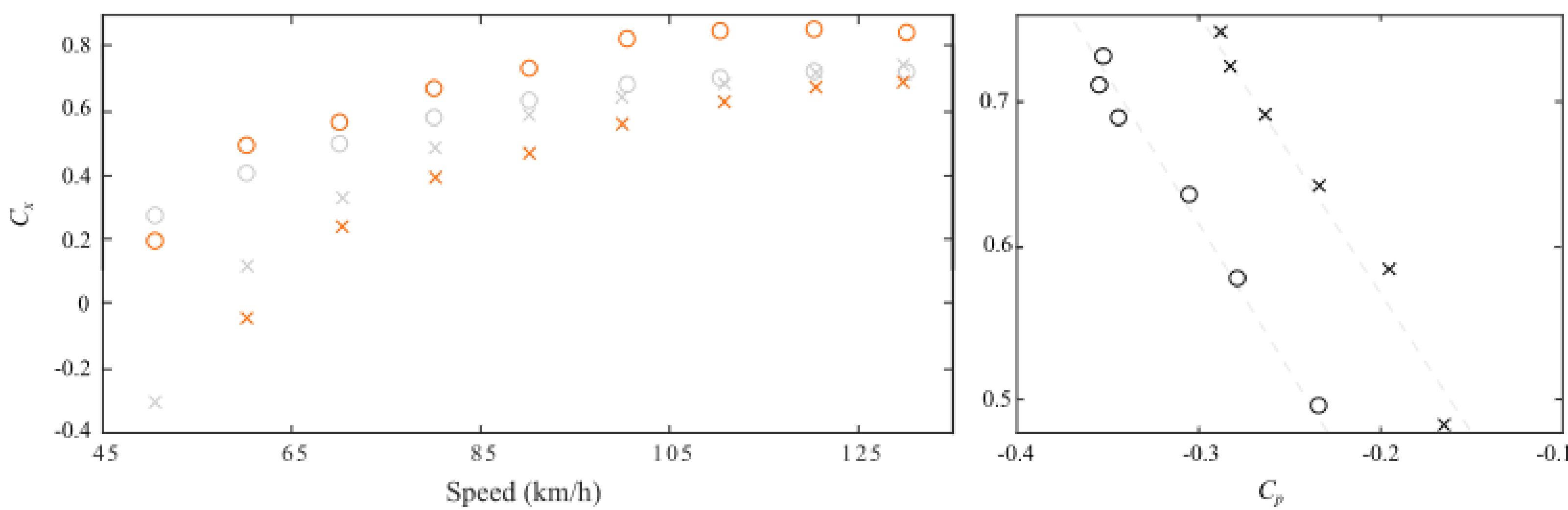




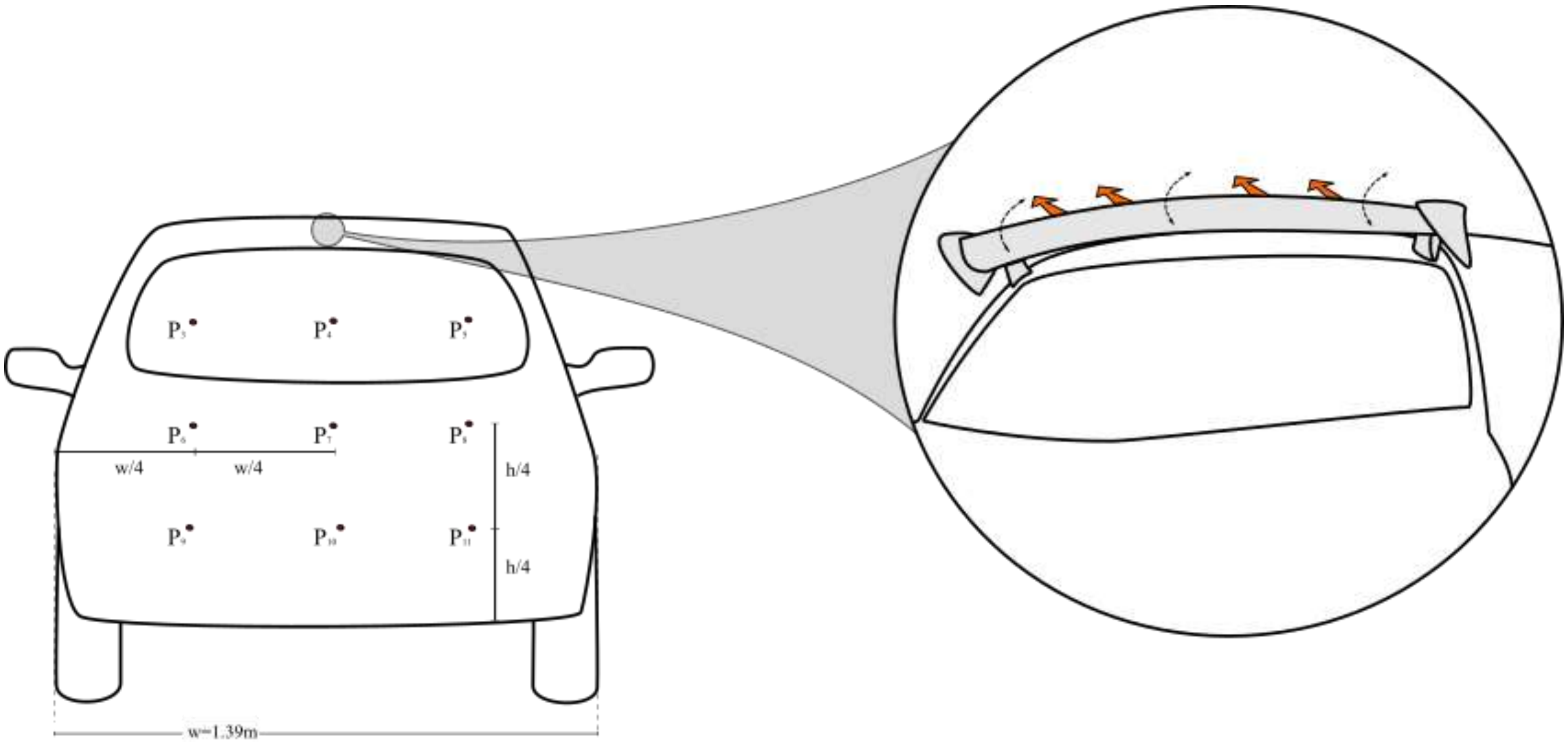
Results



○ Direction I: departure to arrival

× Direction II: arrival to departure

Future project – Flow control



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References

Journal:

SISO model-based control of separated flows, *Internat. Journal of Robust & Nonlinear Control*, 2017
M. Feingesicht, A. Polyakov, F. Kerherve and J. P. Richard,

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Nonlinear Control for Turbulent Flows, *IFAC 2017 World Congress*, Toulouse, July 2017
M. Feingesicht, A. Polyakov, F. Kerherve and J. P. Richard

Model-Based Feedforward Optimal Control Applied to a Turbulent Separated Flow, *IFAC 2017*
M. Feingesicht, A. Polyakov, F. Kerherve and J. P. Richard

A bilinear input-output model with state-dependent delay for separated flow ctrl, *ECC 2016* Aalborg
M. Feingesicht, C. Raibaudo, A. Polyakov, F. Kerherve and J. P. Richard

Reducing Car Consumption by Means of a Closed-loop Drag Control
C. Chovet, M. Feingesicht et al., *VEHICULAR 2018, Venice*

Patent:

Dispositif de contrôle actif du recollement d'un écoulement sur un profil.
M. Feingesicht, A. Polyakov, F. Kerherve and J. P. Richard

Book:

Mathématiques pour l'ingénieur (chap.6: Systèmes à retard) https://hal.archives-ouvertes.fr/hal-00519555
J. P. Richard et al., 2009 (available online)

What’s next?

Spotter


Twingo GT

Dreams…