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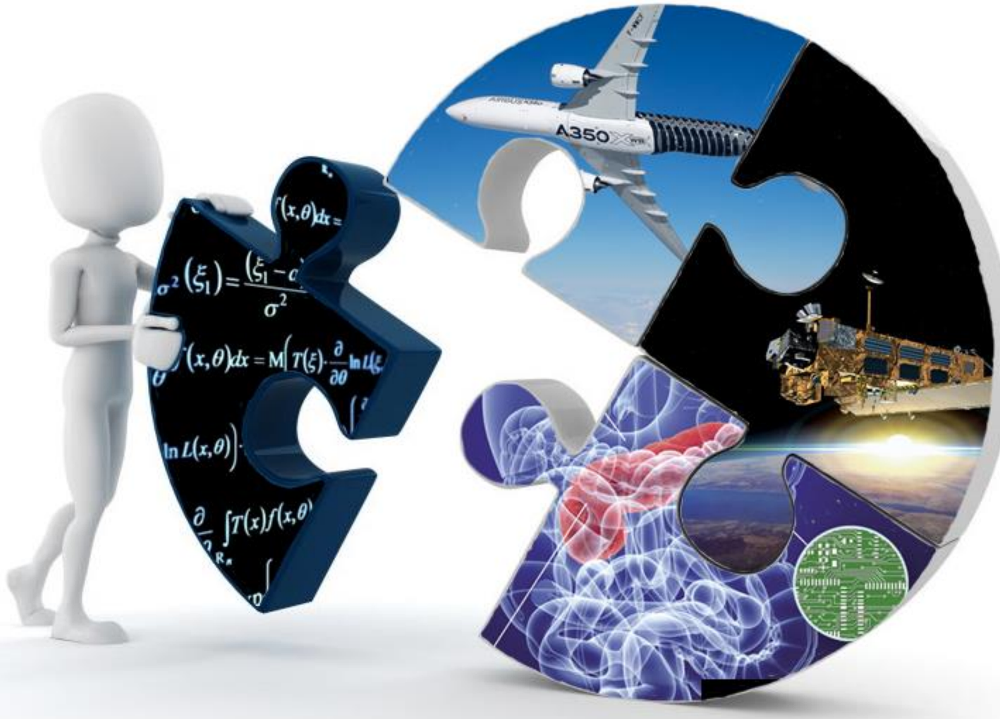

From a current industrial practice in biomedical engineering to a generic health-aware supervisory control framework

[Jérôme Cieslak](#)

From contributions of: Denis Efimov, David Henry, David Gucik-Derigny

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Outline

- A public health problem: diabetes (3 slides)
- One technological solution: Automated Insulin Delivery (AID) system (6 slides)

- Towards a Generic Health-Aware Supervisory Control Framework (8 slides)
- Basic academic example (8 slides)

25 slides for 45 min, my challenge

J. Cieslak, et al., Hybrid health-aware supervisory control framework with a prognostic decision-making, Advances in Diagnostics of Processes and Systems: Selected Papers from the 14th International Conference on Diagnostics of Processes and Systems (DPS), September 21–23, 2020, Zielona Góra (Poland)

Public Health challenge

Diabetes

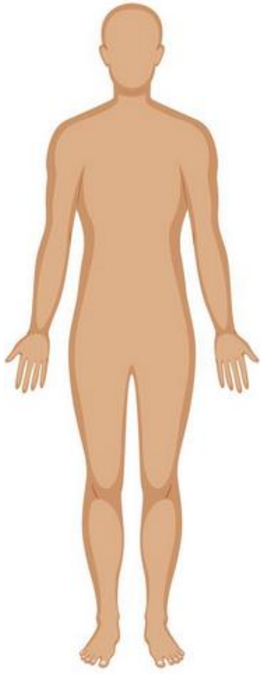
A public health problem: diabetes 1/3

Preliminary: The best self-control is Mother Nature

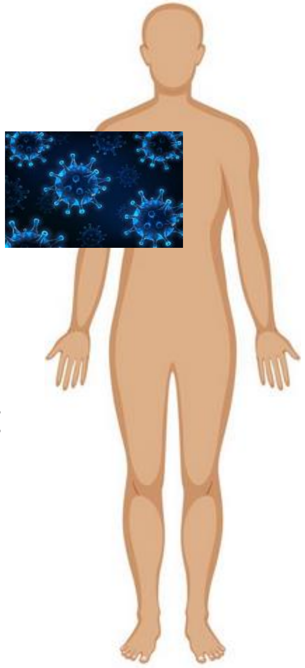
> **Open question 1**: is it possible to find the concept of health-aware control in a nature-inspired way?

Basic example:

Healthy subject



Sick Patient



Body temperature increases

« Virus » has been killed

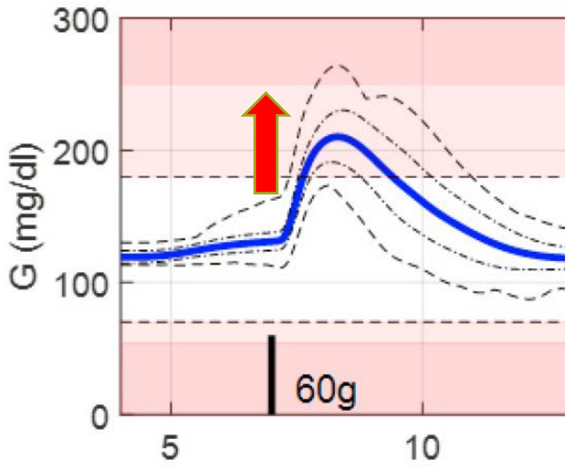
Temperature falls to regulate again at 37°.

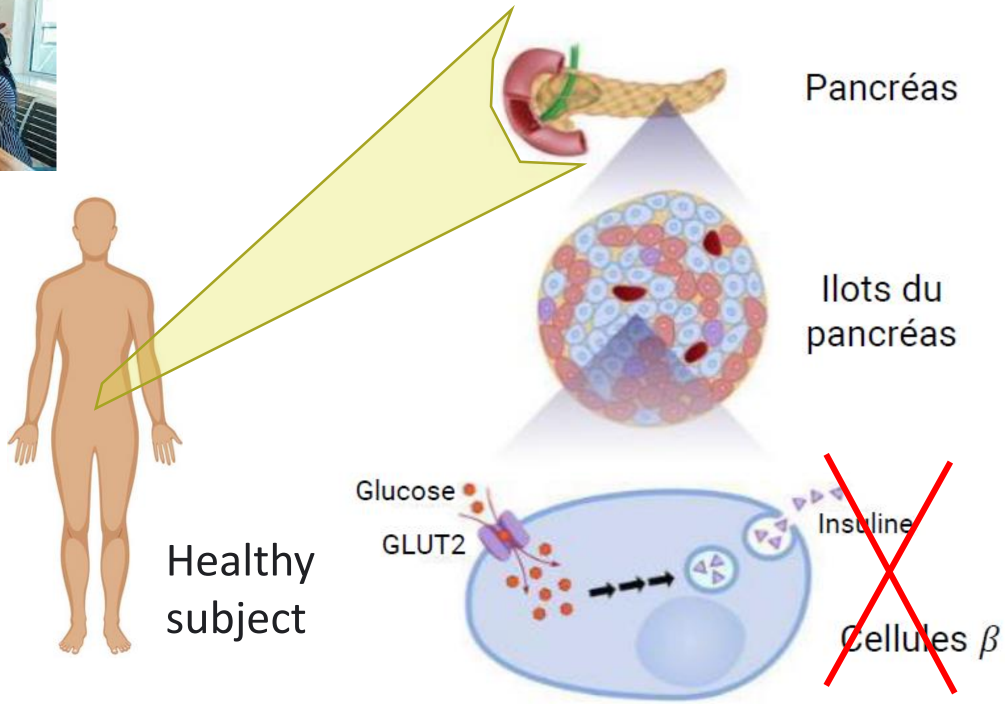
Temperature regulation at 37° C

A public health problem: diabetes 2/3

What is the diabetes? Blood glucose has to remain within the normoglycaemia range (70 mg/dL - 180 mg/dL)

Setting the scene





Type 1 diabetes:

An autoimmune disease linked to the destruction of β-cells, which regulate blood glucose level in the body

Inability of the body to produce insulin

Danger for the health

A public health problem: diabetes 3/3

Some numbers about Type 1 diabetes (T1D)

- Accounts for 5-10% of the 415 million cases of diabetes estimated worldwide in 2016, which are expected to rise to 642 million by 2040.
- In France, the number of T1D patients covered by the health insurance scheme is estimated at 316,700.
  - The ENTRED survey reported that 38% of T1D patients had inadequate blood glucose regulation, meaning that 120,400 patients had failed to achieve metabolic control of their diabetes.
  - The DIALOG study found that between 40,000 and 100,000 T1D patients had experienced severe hypoglycaemia, irrespective of the type of insulin therapy, 11% of whom (between 4,500 and 11,000 patients) required emergency medical treatment.

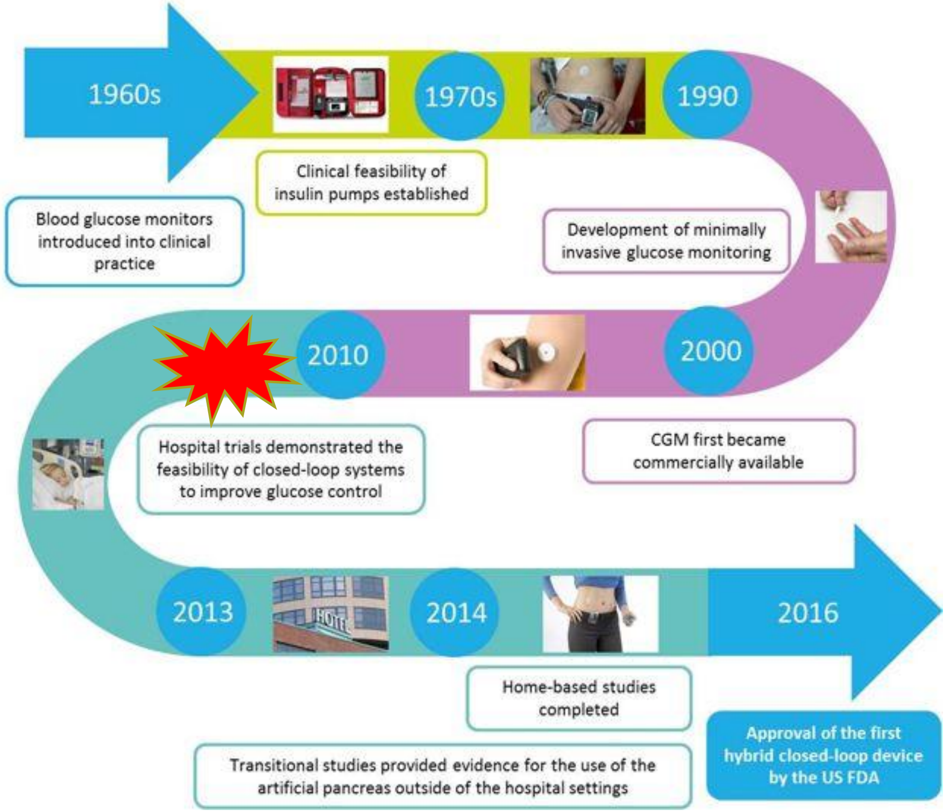
→ Need (€, human, …) to use health technology to innovative care

One technological solution: Automated Insulin Delivery (AID) system

One technological solution: Automated Insulin Delivery (AID) system 1/6

State of the art: We have come a long way, but…

First insulin pump designed by Kadish in 1960 [1]



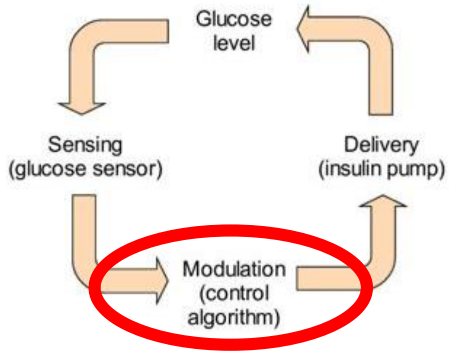
C. Big Blue Brick (1978), one of the first marketed insulin pump [1].
D. Minimed Paradigm 522/722 (2006)
E. Nowadays.

Breakdown in the therapeutic treatement

[1] Alsaleh, et al. *"Insulin pumps : from inception to the present and toward the future : Insulin pumps : Past, present, and future"*. J. of Clinical Ph. and Th., 35(2), 2010

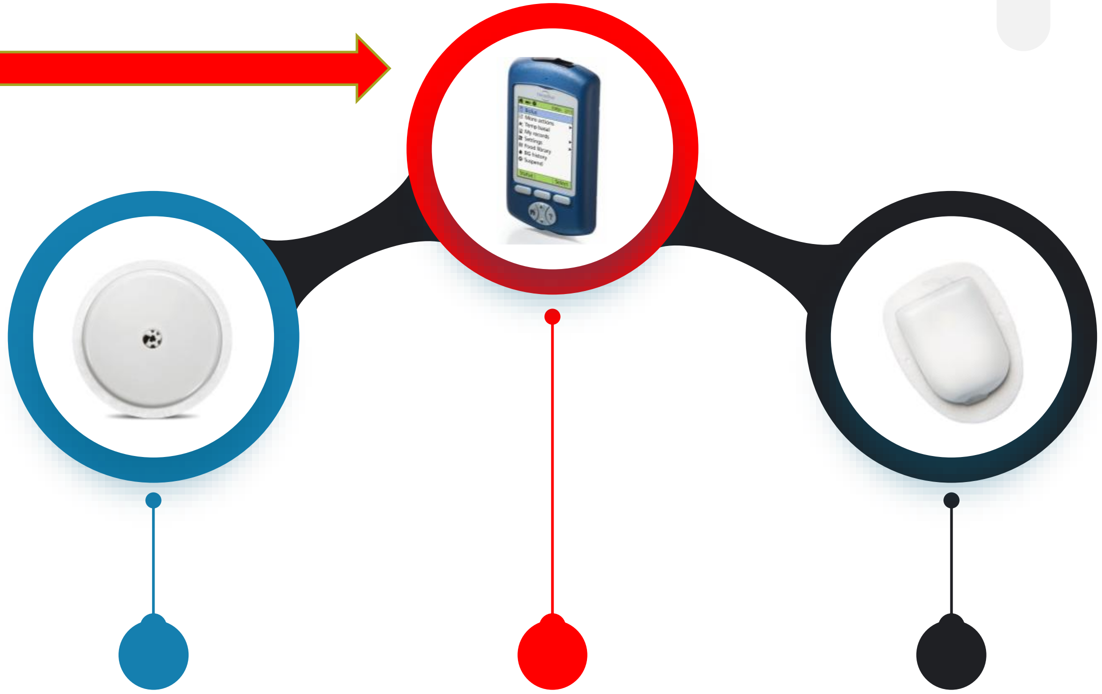
One technological solution: Automated Insulin Delivery (AID) system 2/6

What is this breakdown care?



SISO problem with a lot of delays in the loop

Improving patient comfort (reducing the mental burden, etc.) by giving more and more autonomy to medical devices



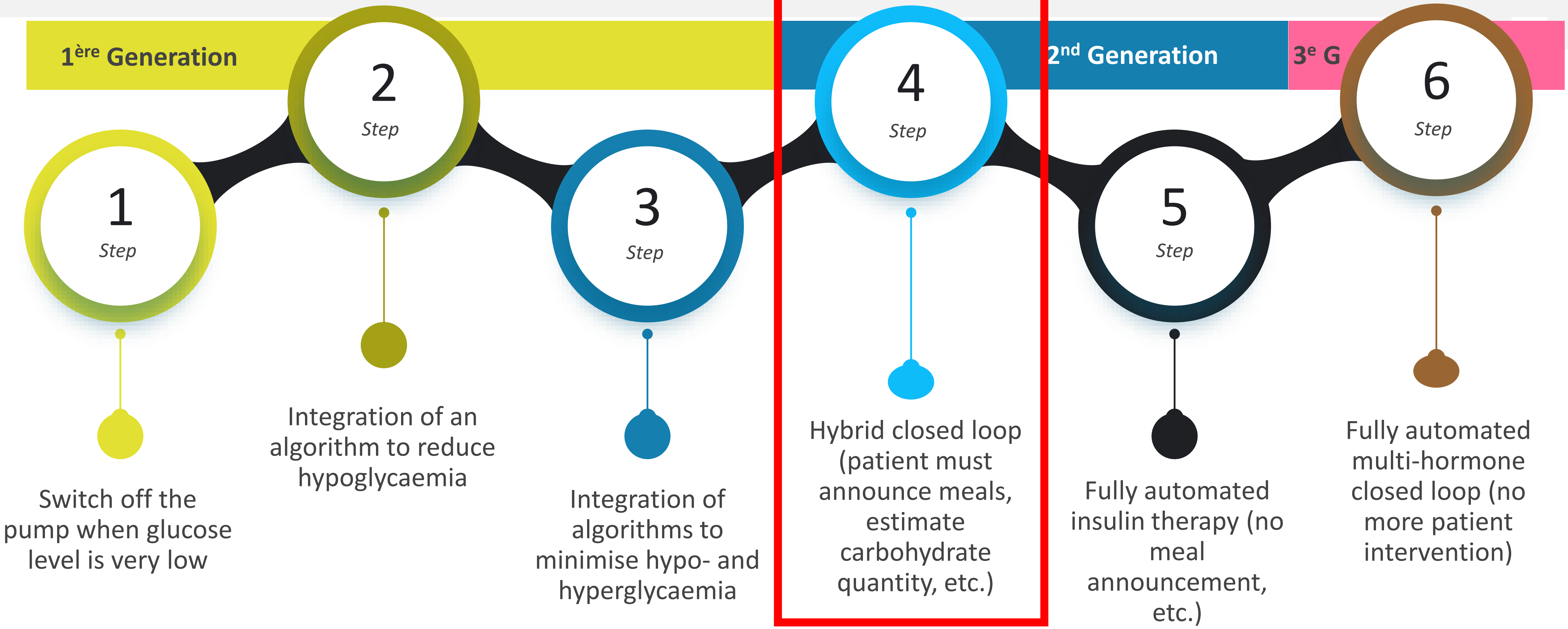
Continuous Glucose Monitoring (CGM) sensor

Algorithms which drive the amount of insulin delivered by the pump

Insulin Pump

Stay in the normo-glycemia range

One technological solution: Automated Insulin Delivery (AID) system 3/6



[2] *Trevitt et al*. Artificial pancreas device systems for closed-loop control …, **JDST** 10(3): 714-723 (2016)

One technological solution: Automated Insulin Delivery (AID) system 4/6

2nd Génération

4
Etape

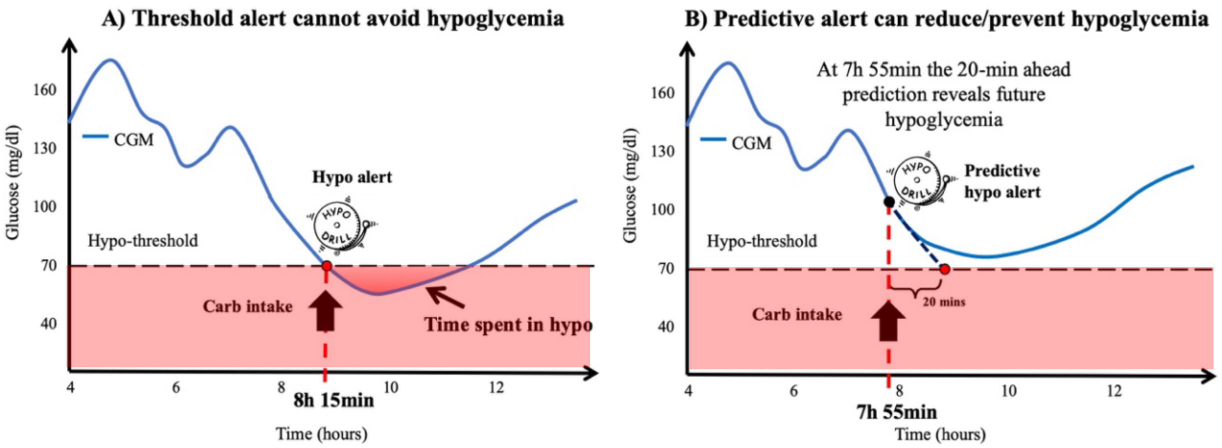
5
Etape

Hybrid closed loop (patient must announce meals, estimate carbohydrate quantity, etc.)

Fully automated insulin therapy (no meal announcement, etc.)

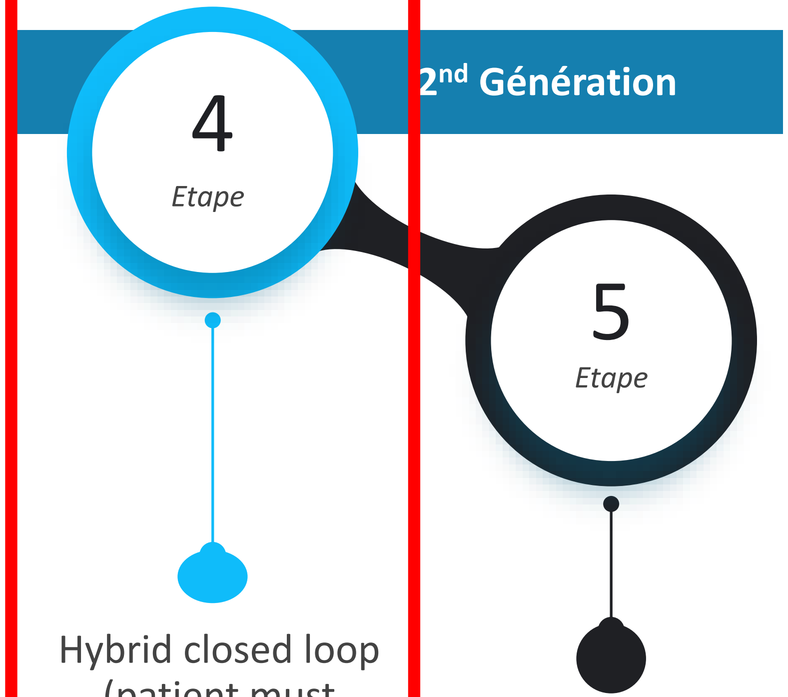
AID system is driven by several algorithms, e.g.

- **Prediction algorithms:** the goal is to prevent hypoglycemia by forecasting such critical (solution for step 2)



M. Vettoretti et al., "Advanced Diabetes Management Using Artificial Intelligence and Continuous Glucose Monitoring Sensors", sensors, 2020

One technological solution: Automated Insulin Delivery (AID) system 5/6



Hybrid closed loop (patient must announce meals, estimate carbohydrate quantity, etc.)

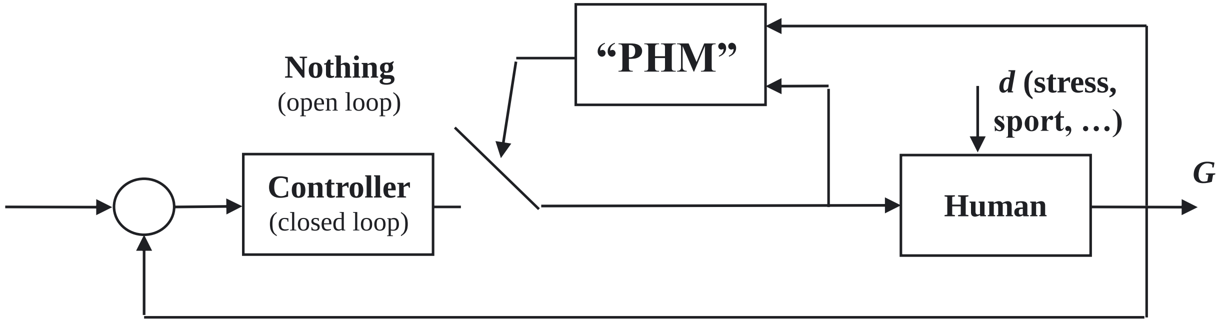
Fully automated insulin therapy (no meal announcement, etc.)

AID system is driven by several algorithms, e.g.

Prediction algorithms are used in control policy, it seems to be **compliant with the concept of HAC**

A. Zhong et al., "Effectiveness of Automated Insulin Management Features of the MiniMedc 640G Sensor-Augmented Insulin Pump » Diabetes technology & therapeutics, 18(10), 2016

"… Automated insulin management features of the MiniMed 640G sensor-augmented pump system include suspension in response to predicted low sensor glucose (SG) values (''suspend before low''), suspension in response to existing low SG values (''suspend on low''), and automatic restarting of basal insulin delivery upon SG recovery. "



One technological solution: Automated Insulin Delivery (AID) system 6/6

There are needs:

- To develop new original prognosis algorithm (*finger crossed, it is the topic of MIMICbio project which has been submitted to AAPG 2024 call*)
  - ❑ **PRC,** *CE51 - Sciences de l'ingénierie et des procédés,* **AAPG2024 ANR**

- To propose a unified framework which can provide some stability guarantees:
  - In a deterministic context
  - In a stochastic context

Open question 2: High variability and the propagation of uncertainties: is there a rule for defining the degree of abstraction?

Open question 3: Is it of interest to developp verification tools for HAC solution, i.e. a control policy able to integrate prognosis information?

Go back to the expertise of audience: we switch now on FTC problem

Generic Health-Aware Supervisory Control Framework

See you later health!

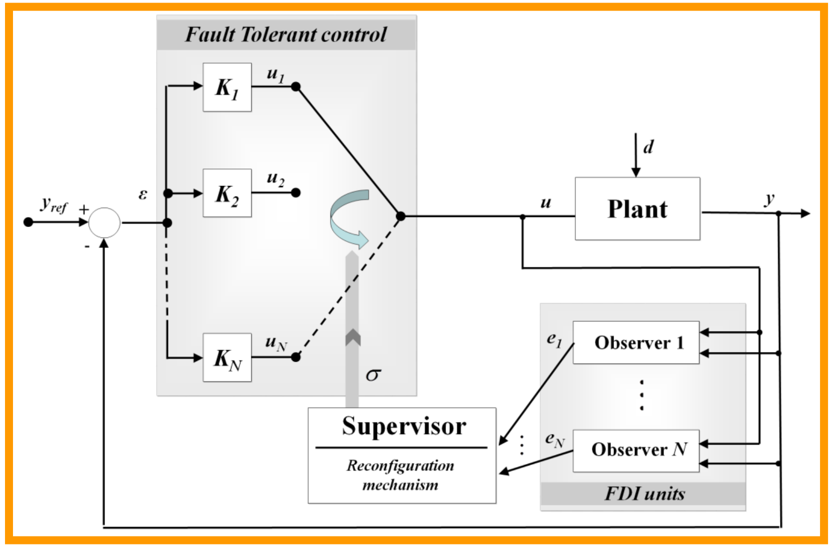
Generic Health-Aware Supervisory Control Framework 1/8

What type of assumptions? What theoretical tool?

In literature, HAC solution can be formulated by using for instance Model Predictive Control (MPC), LPV control, learning solution or Switching Control.

Assumptions:

- LTI plant which bounded exogenous uncertainties
- We have a bank of LTI controllers designed for each operating mode
- A bank of Luenberger observers has been used to identify operating mode
- Distinguishability (capacity of discerning all operating modes between them) property is true
- RUL is assumed to be exogenous



[5] Efimov D., *et al.*: Supervisory fault-tolerant control with mutual performance optimization. Int J. of Adapt. Cont. and Sig. Proc., 27, 251-279 (2013).

Generic Health-Aware Supervisory Control Framework 2/8

Focus on dynamical models and the core control architecture

N controllers:

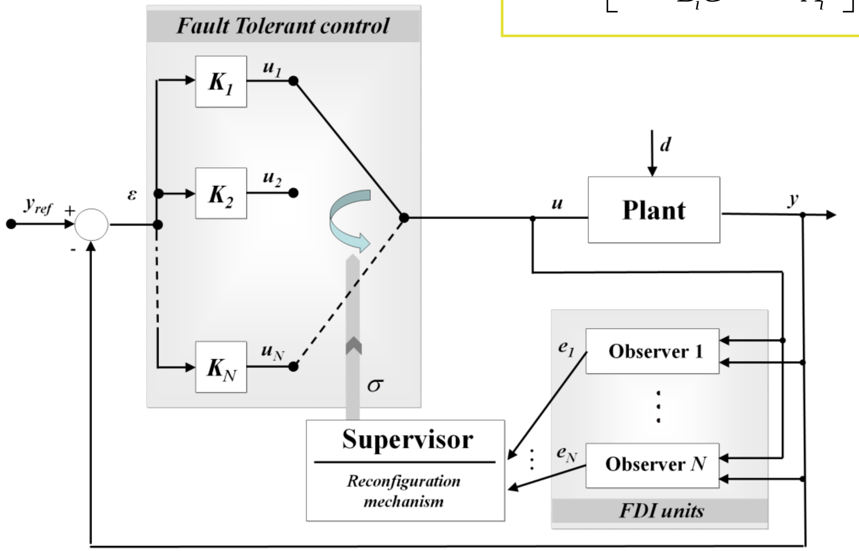
$$\dot{\tilde{x}}_i = \tilde{A}_i \tilde{x}_i + \tilde{B}_i (y_{ref} - y), \quad u_i = \tilde{C}_i \tilde{x}_i + +\tilde{D}_i (y_{ref} - y),$$

$$i = 1, \dots, N$$

Plant for one operating mode: $\dot{x} = A_i x + B_i u + G_i d, \quad y = Cx$

$$i = 1, \dots, N, \quad N > 1$$

$$H_i = \begin{bmatrix} A_i - B_i \tilde{D}_i C & B_i \tilde{C}_i \\ -\tilde{B}_i C & \tilde{A}_i \end{bmatrix}$$



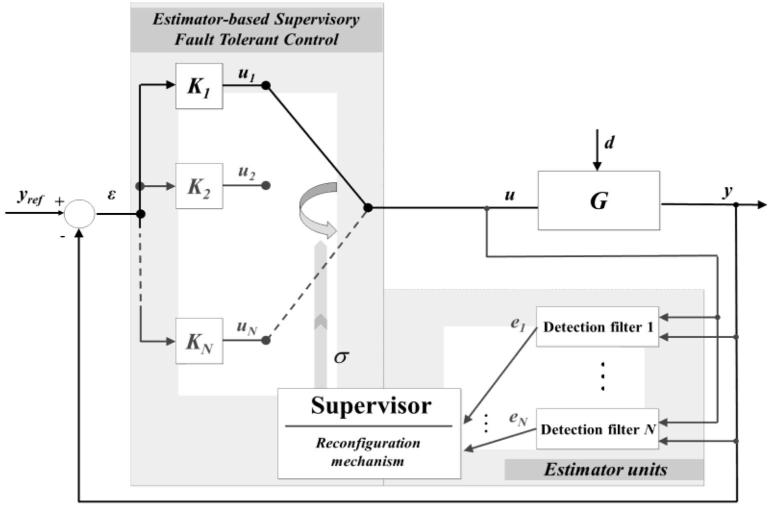
N Luenberger estimators:

$$\dot{z}_i = A_i z_i + B_i u + L_i (y - C z_i)$$

$$\dot{e}_i = (A_i - L_i C) e_i + G_i d - L_i n \qquad \text{(matched case)}$$

Generic Health-Aware Supervisory Control Framework 3/8

Introduction of dwell-time concept



For any plant index $i \in I$ *, there exists* $C_1 > 0$, $C_2 > 0$, $C_3 > 0$ *and* $\eta > 0$ *such that:*

$$|e_i(t)| \le C_1 |e_i(0)| e^{-\eta t} + C_2 \|d\| + C_3 \|n\|$$

Switching logic uses the "error signal definition"

$$t_0 = 0, t_{k+1} = \underset{t \ge t_k + \tau_D}{\arg\inf} \left\{ |e_{\sigma(t_k)}(t)| > |e_j(t)|, j = 1, \dots, N, j \ne \sigma(t_k) \right\}$$

$$\sigma(t_k) = \arg\min_{1 \le j \le N} |e_j(t_k)|, k \ge 0$$

$$\sigma(t) = \sigma(t_k) \quad \text{for all} \quad t_k \le t < t_{k+1}, k \ge 0$$

$t_k, k \ge 0$ $\tau_D > 0$

$| \mathbf{e}_{\sigma(t_k)}(t) | > | \mathbf{e}_l(t) |$ $| \mathbf{e}_{\sigma(t_{k+1})}(t) | > | \mathbf{e}_r(t) |$

Switching mechanism is frozen

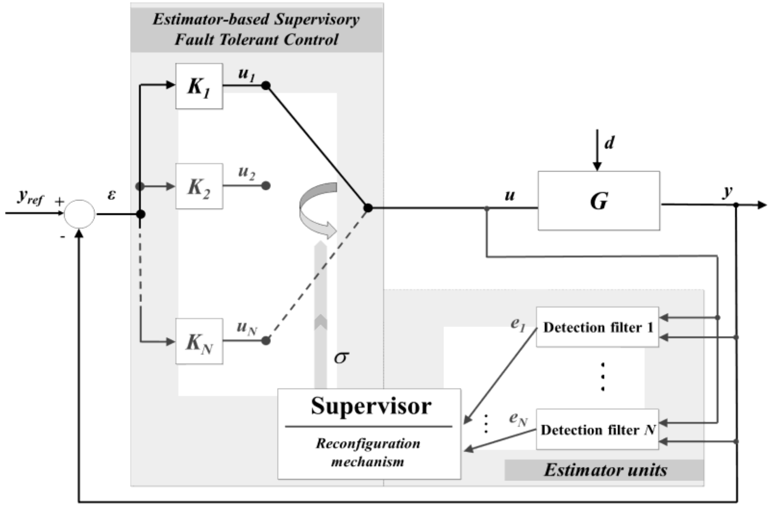
t

t_k $t_{k+1} = t_k + \tau_D$ $t_{k+1} + \tau_D$ t_{k+2}

$\sigma(t_{k+1}) = l$ $\sigma(t_{k+2}) = r$

Generic Health-Aware Supervisory Control Framework 4/8

From linear algebra manipulation…



Supervisory control setup can be characterized by the following equations for $j = 1,\dots N,\ j \neq k$

$$
\begin{cases}
\dot{x} = A_i x + B_i(\tilde{C}_k \tilde{x}_k + \tilde{D}_k y_{ref} - \tilde{D}_k y) + G_i d \\
\quad = (A_i - L_i C)x + B_i \tilde{C}_k \tilde{x}_k + (L_i - B_i \tilde{D}_k)Cz_k + (L_i - B_i \tilde{D}_k)Ce_k + B_i \tilde{D}_k y_{ref} + G_i d + (L_i - B_i \tilde{D}_k)n \\
\dot{\tilde{x}}_k = \tilde{A}_k \tilde{x}_k + \tilde{B}_k y_{ref} - \tilde{B}_k y = \tilde{A}_k \tilde{x}_k - \tilde{B}_k Cz_k - \tilde{B}_k Ce_k + \tilde{B}_k y_{ref} - \tilde{B}_k n \\
\dot{z}_k = A_k z_k + B_k(\tilde{C}_k \tilde{x}_k + \tilde{D}_k y_{ref} - \tilde{D}_k y) + L_k(y - Cz_k) \\
\quad = B_k \tilde{C}_k \tilde{x}_k + (A_k - B_k \tilde{D}_k C)z_k + (L_k - B_k \tilde{D}_k)Ce_k + B_k \tilde{D}_k y_{ref} + (L_k - B_k \tilde{D}_k)n \\
\dot{z}_j = A_j z_j + B_j(\tilde{C}_k \tilde{x}_k + \tilde{D}_k y_{ref} - \tilde{D}_k y) + L_j(y - Cz_j) \\
\quad = B_j \tilde{C}_k \tilde{x}_k + (L_j - B_j \tilde{D}_k)Cz_k + (A_j - L_j C)z_j + (L_j - B_j \tilde{D}_k)Ce_k + B_j \tilde{D}_k y_{ref} + (L_j - B_j \tilde{D}_k)n
\end{cases}
$$

The tip

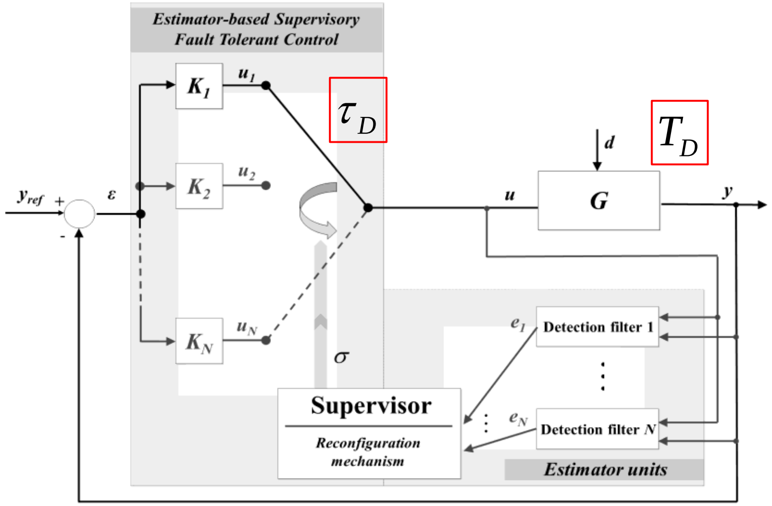
From the measurement: $y = Cx + n$

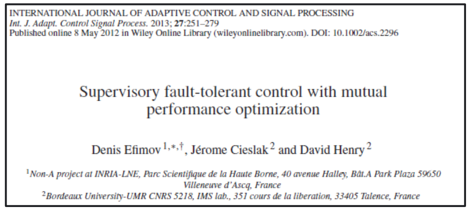
From the definition of error signal: $e_k = x - z_k$

$$\Rightarrow \quad y = Ce_k + Cz_k + n$$

Generic Health-Aware Supervisory Control Framework 5/8

… to derive theorem/corrolary





INTERNATIONAL JOURNAL OF ADAPTIVE CONTROL AND SIGNAL PROCESSING
Int. J. Adapt. Control Signal Process. 2013; **27**:251–279
Published online 8 May 2012 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/acs.2296

Supervisory fault-tolerant control with mutual performance optimization

Denis Efimov[1,*,†], Jérome Cieslak[2] and David Henry[2]

[1]*Non-A project at INRIA-LNE, Parc Scientifique de la Haute Borne, 40 avenue Halley, Bât.A Park Plaza 59650 Villeneuve d'Ascq, France*
[2]*Bordeaux University-UMR CNRS 5218, IMS lab., 351 cours de la liberation, 33405 Talence, France*

Introducing $\Psi = [z_k^T \;\; \tilde{x}_k^T \;\; x^T \;\; z_1^T \cdots z_N^T]^T$ *such that* $z_1^T \cdots z_N^T$ *does not contained* z_k^T*, we have:*

$$\dot{\Psi}_k = W_{k,i}\Psi_k + V_{k,i}Ce_k + \tilde{G}_i d + \bar{G}_i y_{ref} + \bar{\bar{G}}_i n$$

where $V_{k,i} = [(L_k - B_k\tilde{D}_k)^T \;\; -\tilde{B}_k^T \;\; (L_i - B_i\tilde{D}_k)^T \;\; (L_1 - B_1\tilde{D}_k)^T \cdots (L_N - B_N\tilde{D}_k)^T]^T$

$\tilde{G}_i = [0 \;\; 0 \;\; G_i^T \;\; 0 \cdots 0]^T \qquad \bar{\bar{G}}_i = [(L_k - B_k\tilde{D}_k)^T \;\; -\tilde{B}_k^T \;\; (L_i - B_i\tilde{D}_k)^T \;\; (L_1 - B_1\tilde{D}_k)^T \cdots (L_N - B_N\tilde{D}_k)^T]^T$

$\bar{G}_i = [(B_k\tilde{D}_k)^T \;\; \tilde{B}_k^T \;\; (B_i\tilde{D}_k)^T \;\; (B_1\tilde{D}_k)^T \cdots (B_N\tilde{D}_k)^T]^T$

and $W_{k,i}$ *is left block triangular and the blocks are:*

$$\underbrace{H_k, (A_i - L_iC), (A_1 - L_1C), \cdots, (A_N - L_NC)}$$

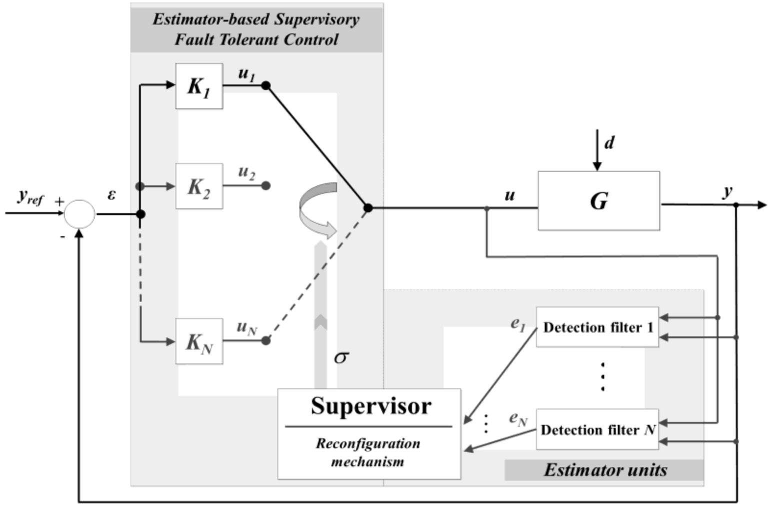
Under previous assumption, all blocks on the main diagonal are Hurwitz

To prove that input / output stability is guaranteed (even if the bank of observers fails, during a short period, to identify the correct operating mode) if:

- C1: the <u>time interval between 2 control switches</u> is higher or equal to the dwell-time $\boxed{\tau_D}$, *see Theorem 4*
- C2: the <u>time interval between 2 consecutive faults</u> (or changes of the plant) is higher than the dual dwell-time $\boxed{T_D}$, *see Corollary 4,*

Generic Health-Aware Supervisory Control Framework 6/8

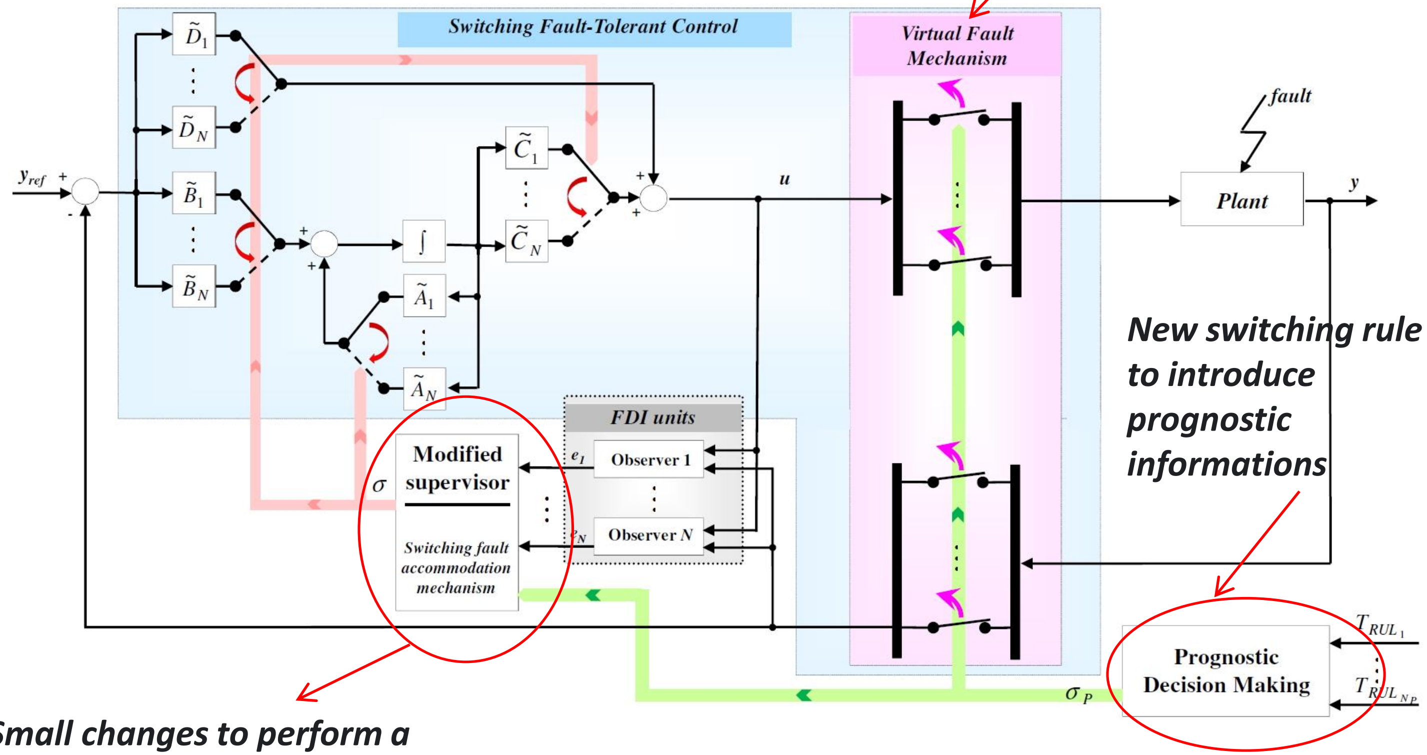
Towards HAC paradim



Stability guarantees are still true

J. Cieslak, et al., Hybrid health-aware supervisory control framework with a prognostic decision-making, Advances in Diagnostics of Processes and Systems:

New mechanism to forecast the fault accommodation

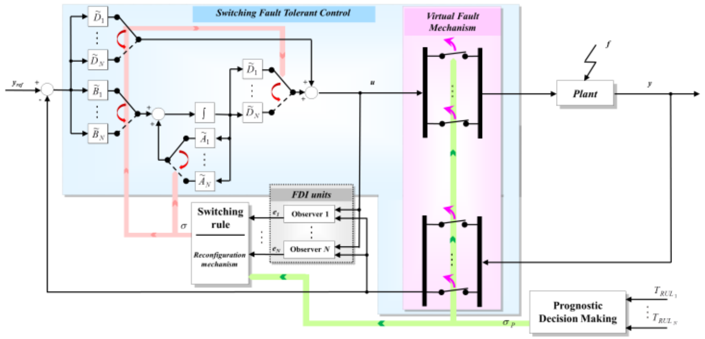


New switching rule to introduce prognostic informations

Small changes to perform a synchronized switch with the VFM

Generic Health-Aware Supervisory Control Framework 7/8

Focus on changes

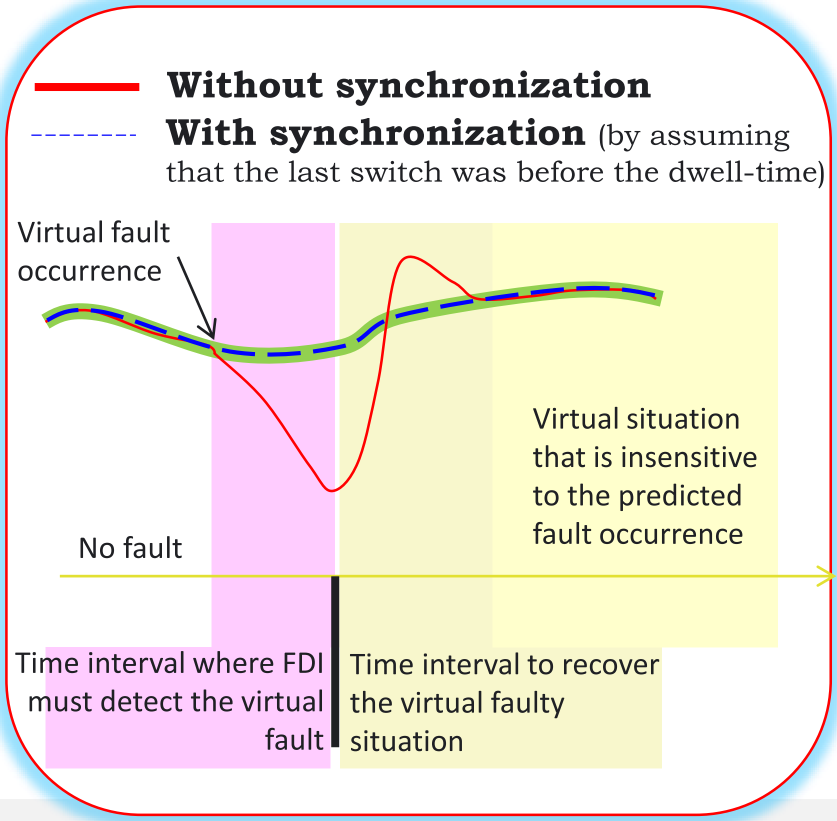


Modified supervisor:

Inputs: σ_P, e_i, $i \in \mathcal{M} = \{1, \cdots, N\}$

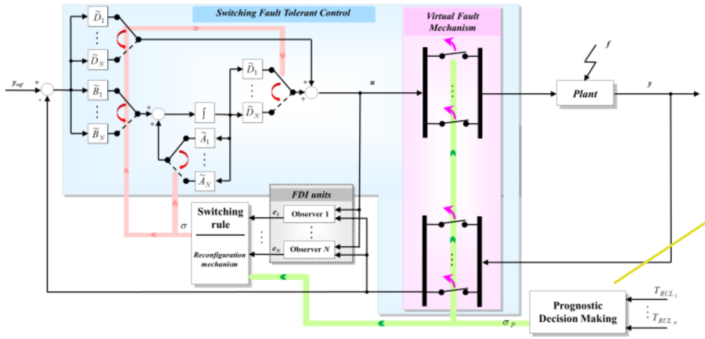
$k \leftarrow$ current sampling time
$t_k \leftarrow$ last control switching $(t_k < k)$
$l_s \leftarrow$ last selected index $\sigma(t_k)$
$\tau_D \leftarrow$ dwell-time value, see (12)
$h \leftarrow$ design parameter
for each e_i, $i \in (\mathcal{M} - \{\sigma(t_k)\})$ **do**
  if $|Ce_{\sigma(t_k)}(t)| > h\,|Ce_i(t)|$ **then**
    if $k \geq t_k + \tau_D$ **then**
      $t_k = k$;
      $l_s = \arg\min |Ce_i(k)|$;
    end if
  end if
end for
for σ_P **do**
  if *Edge* $\{\sigma_P(k)\}$ **then**
    if $k \geq t_k + \tau_D$ **then**
      $t_k = k$;
      $l_s = \sigma_P(k)$;
    end if
  end if
end for
$\sigma(k) = l_s$;

The only change with original algorithm has been highlighted in green to perform a synchronized switch with the VFM



Generic Health-Aware Supervisory Control Framework 8/8

Focus on changes



Prognostic Decision-Making:

Inputs: $T_{rul_j},\ j \in \mathcal{N}^* = \{2, \cdots, N_P\}$ 1

$k \leftarrow$ current sampling time
$t_r^P \leftarrow$ last switching time $(t_r^P < k)$
$l_s \leftarrow$ last selected index $\sigma_P(t_r^P)$
$T_D \leftarrow$ dual *dwell-time*, see (14) 2
$\eta \leftarrow$ design parameter
for each $T_{rul_j},\ j \in (\mathcal{N}^* - \{\sigma_P(t_r^P)\})$ **do** 3
  if $|T_{rul_j}(k)| < \eta T_D$ **then**
    if $k \geq t_r^P + T_D$ **then**
      $t_r^P = k;$
      $l_s = \arg\min |T_{rul_j}(k)|;$
    end if
  end if
end for
$\sigma_P(k) = l_s;$

- *Only critical actuator can be monitored*
  1 ***by prognosis scheme, i.e N_p<N***

- ***Already identified situations covered by***
  2 ***prognosis schemes are removed from the set of possible situations***

- ***The product ηT_D must be seen like a***
  3 ***constant tuning parameter to know when we are close to the end of actuator life and reduce de facto the actuator workload.***

Basic Academic Example

Academic example 1/8

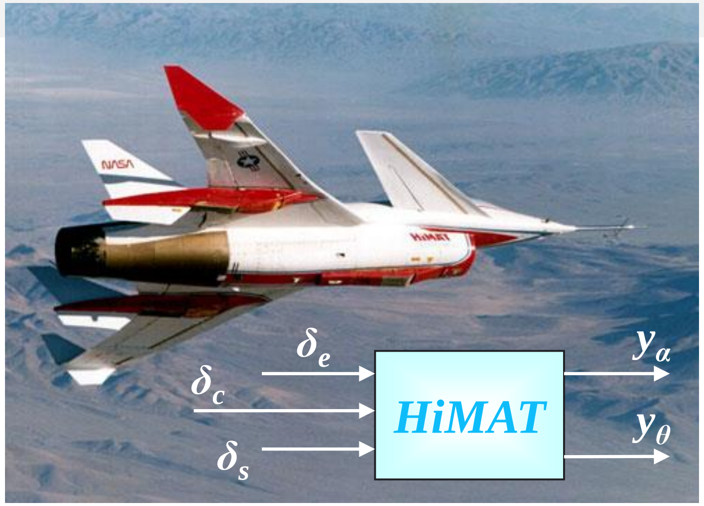
Example

The overall strategy is illustrated using the open-loop unstable *HiMAT* vehicle (Hou *et al*, 2010, AIAA JGCD).

δ_e = *elevons*
δ_c = *canards flaps*
δ_s = *elevators*

→ *Monitored by a prognosis scheme*

Angle of attack = y_α
Pitch angle = y_θ

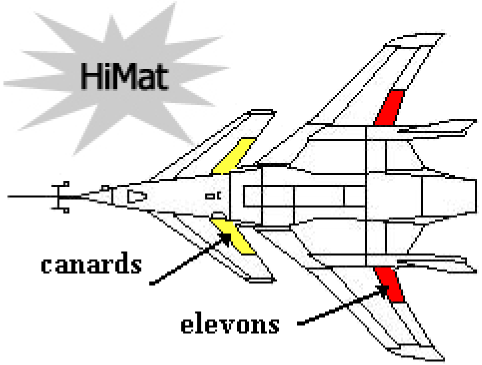


Considered switched systems:

$$\dot{x}(t) = A_i x(t) + B_i u(t) \qquad i = 1,2,3 \qquad u = (\delta_s, \delta_e, \delta_c)^T$$

$$A_1 = \begin{bmatrix} -1.0772 & 0.96528 \\ 9.068 & -1.5077 \end{bmatrix}, B_1 = \begin{bmatrix} -0.17211 & -0.12245 & -0.01431 \\ -7.9948 & -4.955 & 5.0369 \end{bmatrix}$$

$$A_1 = A_2 = A_3, \quad B_2 = B_1 \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad B_3 = B_1 \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



Academic example 2/8

Design

- ***Controller design*** Three control laws possessing integral action are designed using a linear quadratic approach.

- ***Detection filters*** Luenberger-type observers are considered with poles arbitrarily fixed to [-16,-15], [-56,-55] and [-6,-5] respectively.

- ***Computational issues***

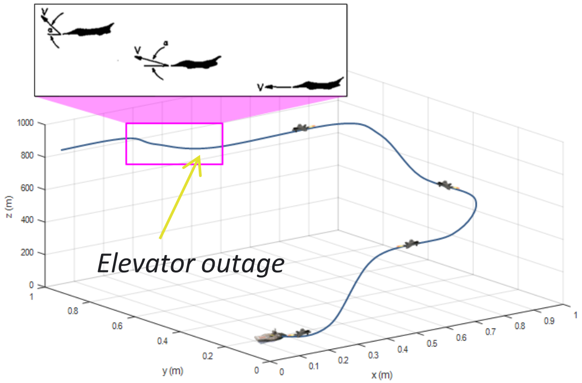
  τ_D and T_D has been computed according to [5]. It follows that:

  $\tau_D = 1.5793$ $\qquad$ $T_D = 21.3207$

  A threshold for VFM has be fixed by taking into account T_D and the tuning parameter: $\eta = 1.5$

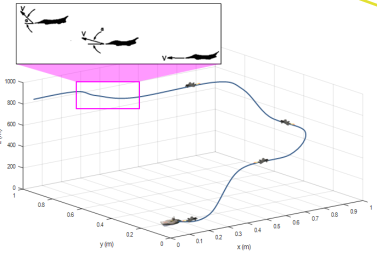
- ***Simulation results***

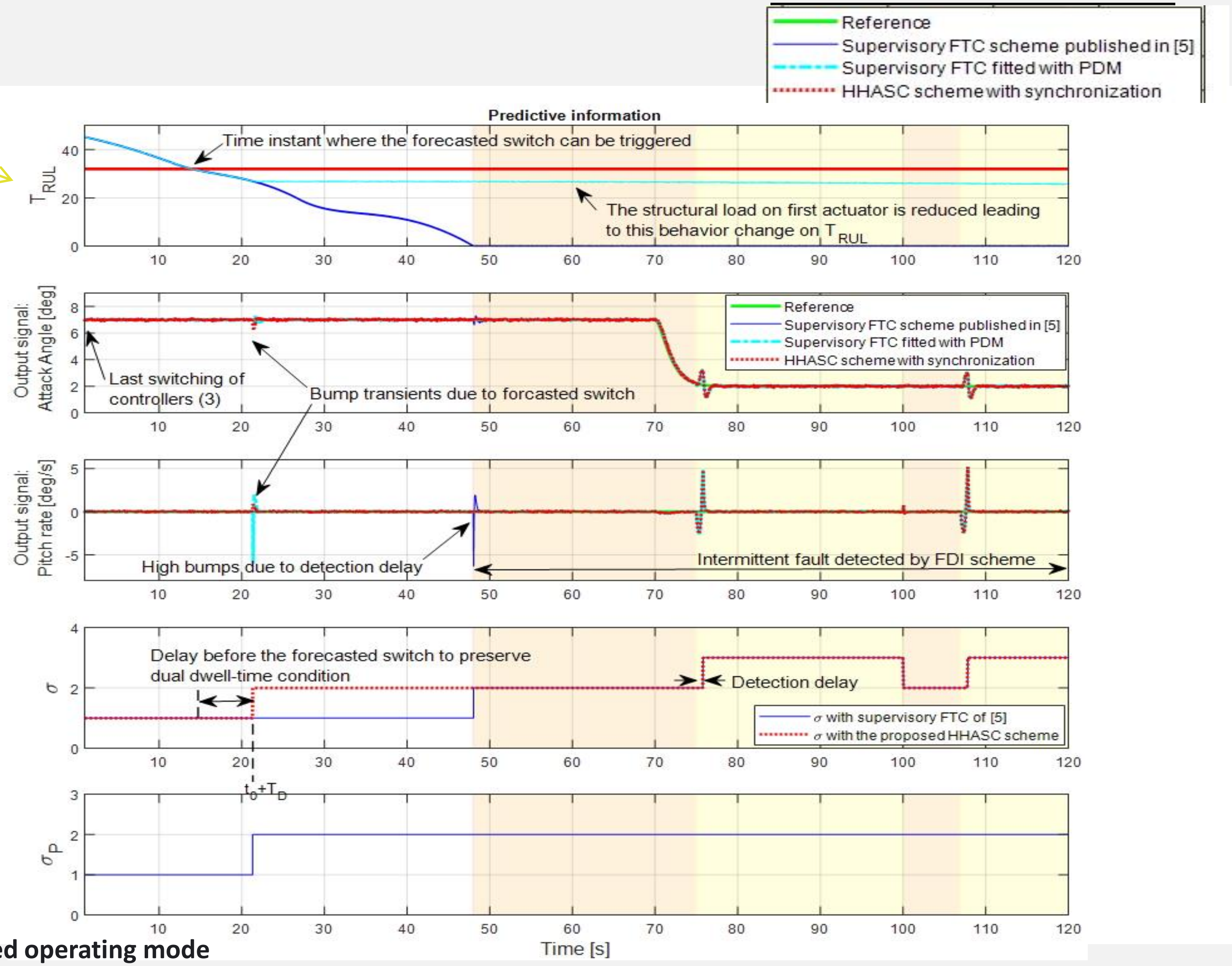
The elevator outage will appear at 48 *s* and the intermittent failure case has been considered during [75, 100] *s* and [107, 120] *s*.



Academic example 3/8

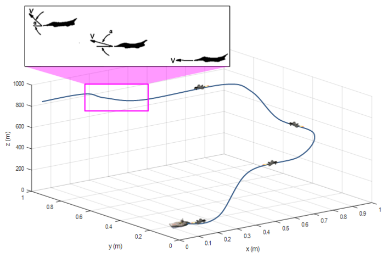
Only available for one actuator

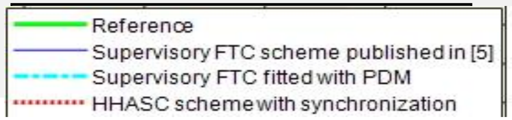


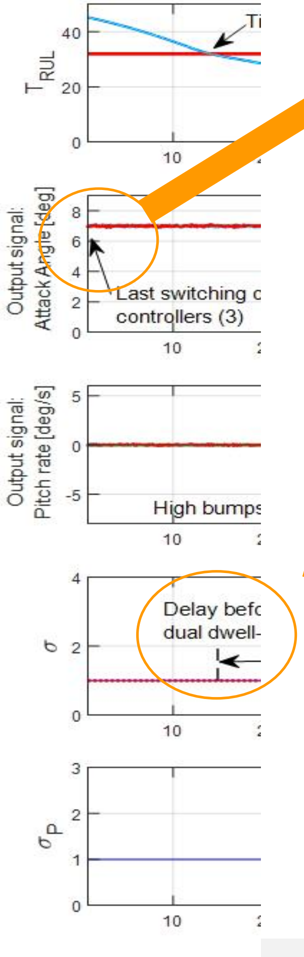


Forecasted operating mode

Academic example 4/8







To guarantee the closed loop stability, it is now possible to have a (virtual or real) change in the plant only when the minimal admissible time interval T_D is expired.

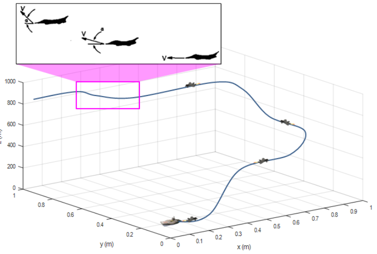
There is no commutation thanks to the rectangle in green introduced in Algorithm 2 to maintain the stability conditions

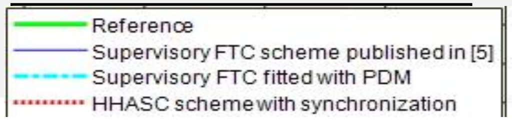
Prognostic Decision-Making:

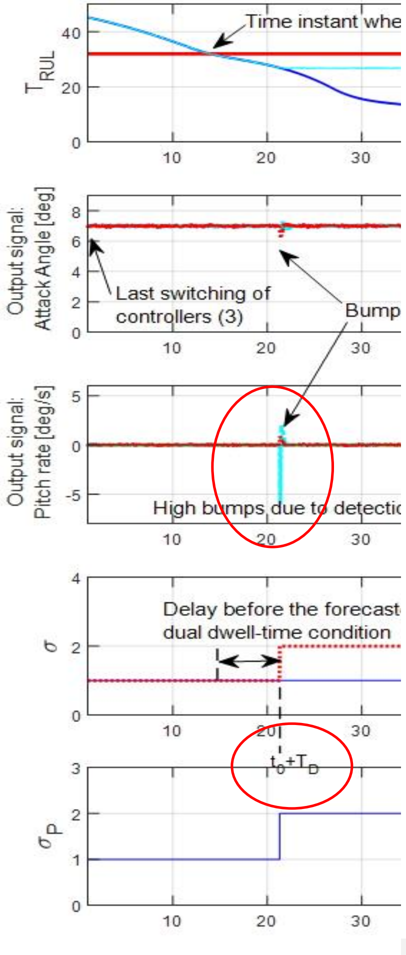
Inputs: $T_{rul_j}, j \in \mathcal{N}^* = \{2, \cdots, N_P\}$

$k \leftarrow$ current sampling time
$t_r^P \leftarrow$ last switching time ($t_r^P < k$)
$l_s \leftarrow$ last selected index $\sigma_P(t_r^P)$
$T_D \leftarrow$ dual *dwell-time*, see (14)
$\eta \leftarrow$ design parameter
for each $T_{rul_j}, j \in (\mathcal{N}^* - \{\sigma_P(t_r^P)\})$ **do**
  if $|T_{rul_j}(k)| < \eta T_D$ **then**
    if $k \geq t_r^P + T_D$ **then**
      $t_r^P = k$;
      $l_s = \arg\min |T_{rul_j}(k)|$;
    end if
  end if
end for
$\sigma_P(k) = l_s$;

Academic example 5/8





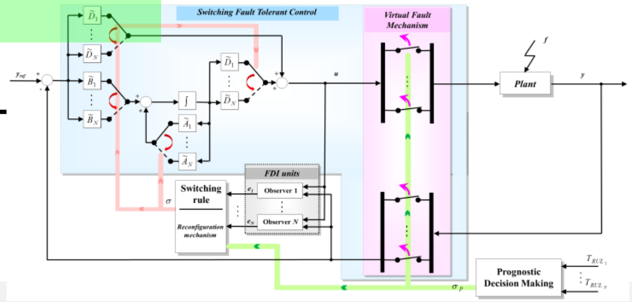


Modified supervisor:

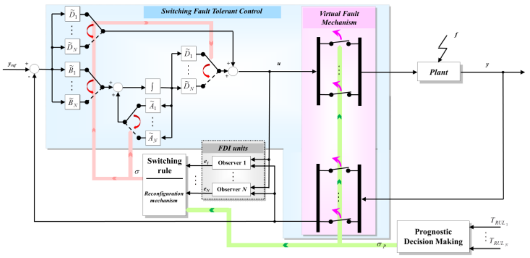
Inputs: $\sigma_P,\ e_i,\ i \in \mathcal{M} = \{1, \cdots, N\}$

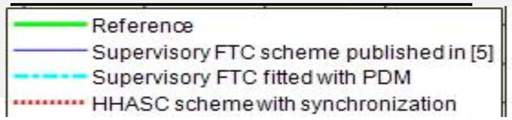
$k \leftarrow$ current sampling time
$t_k \leftarrow$ last control switching $(t_k < k)$
$l_s \leftarrow$ last selected index $\sigma(t_k)$
$\tau_D \leftarrow$ dwell-time value, see (12)
$h \leftarrow$ design parameter
for each $e_i,\ i \in (\mathcal{M} - \{\sigma(t_k)\})$ **do**
  if $|Ce_{\sigma(t_k)}(t)| > h\,|Ce_i(t)|$ **then**
    if $k \geq t_k + \tau_D$ **then**
      $t_k = k;$
      $l_s = \arg\min |Ce_i(k)|;$
    end if
  end if
end for
for σ_P **do**
  if $Edge\{\sigma_P(k)\}$ **then**
    if $k \geq t_k + \tau_D$ **then**
      $t_k = k;$
      $l_s = \sigma_P(k);$
    end if
  end if
end for
$\sigma(k) = l_s;$

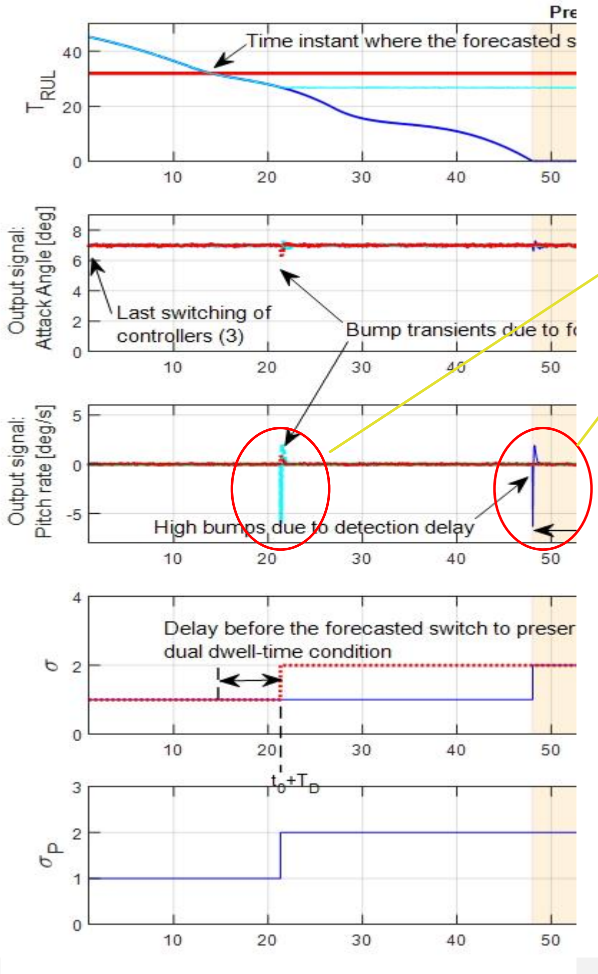
Switches of VFM and switching control have been **performed at the same time**: it is the synchronized solution that avoid undesirable transients.



Academic example 6/8







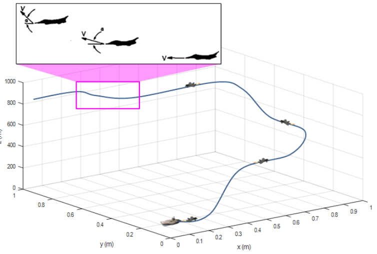
It can be seen similar transient behaviors for cyan and blue lines!

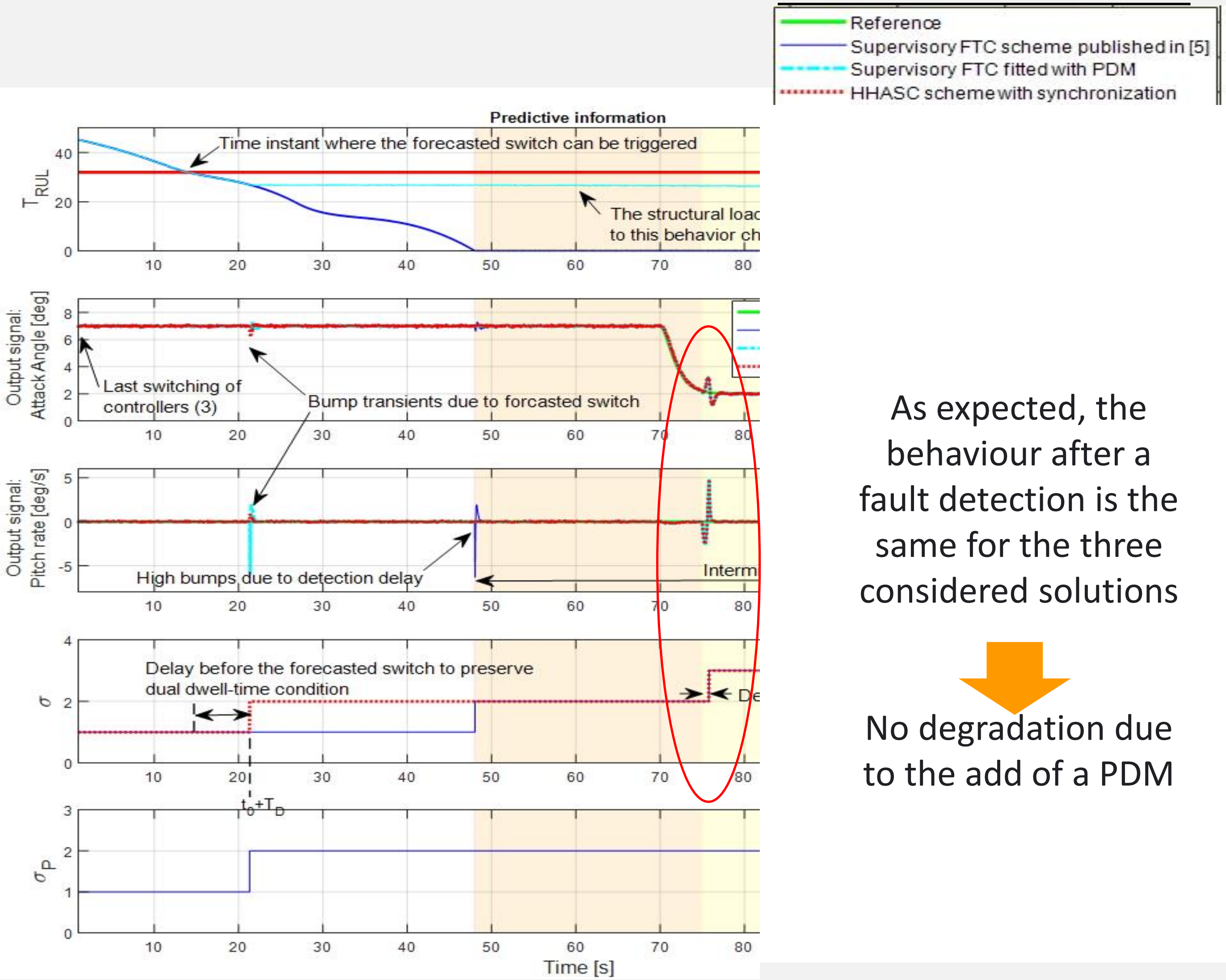
Is it normal?

Yes, since the FDI unit detects a fault (virtual or real, it doesn't matter)

The necessity to synchronize the switches of VFM and switching control is clearly highlighted

Academic example 7/8

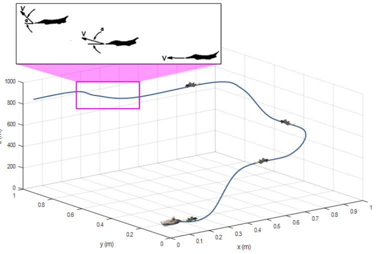


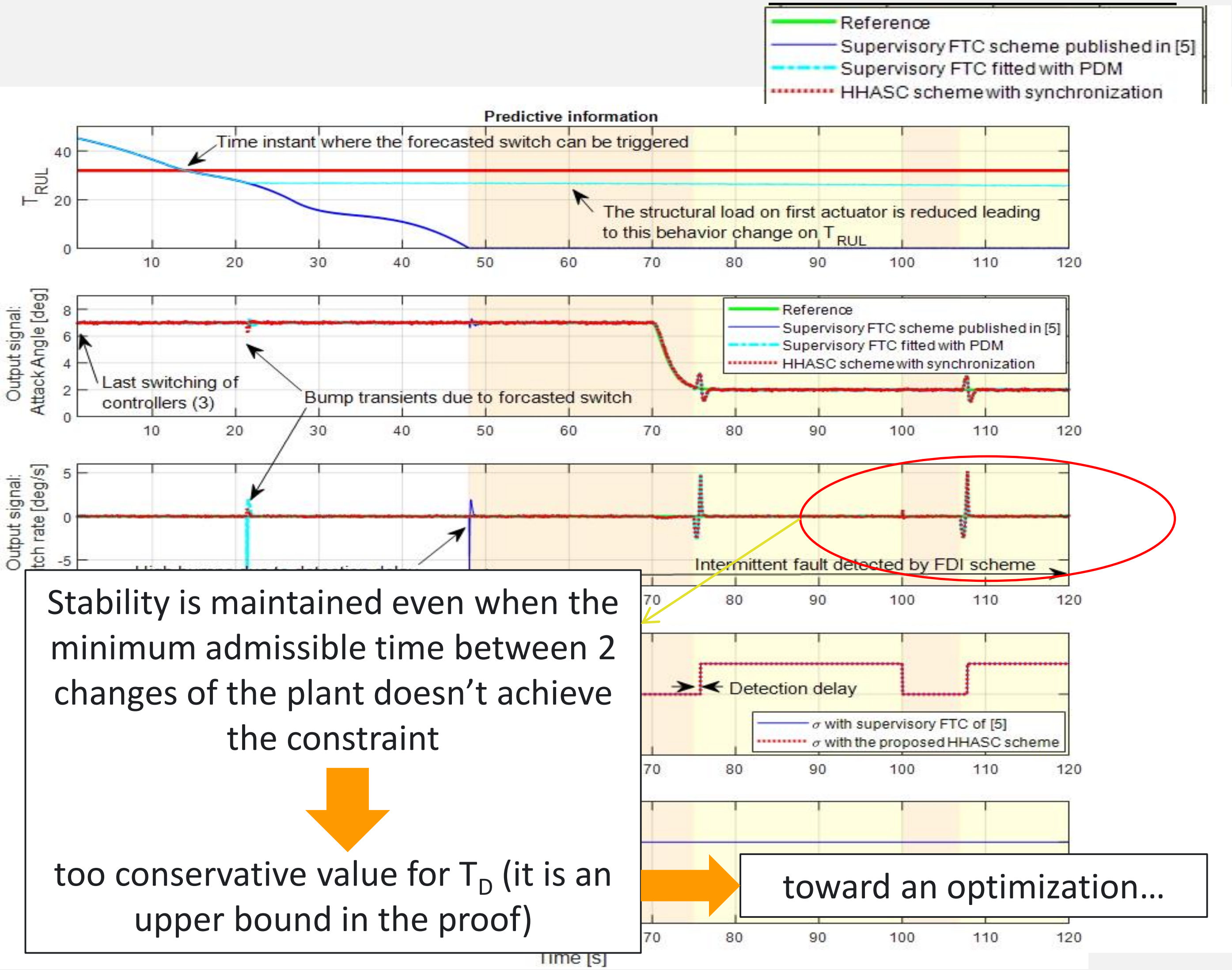


As expected, the behaviour after a fault detection is the same for the three considered solutions

No degradation due to the add of a PDM

Academic example 8/8





Stability is maintained even when the minimum admissible time between 2 changes of the plant doesn't achieve the constraint

too conservative value for T_D (it is an upper bound in the proof)

toward an optimization…

Closing words

Closing words

One preliminary work. Researchers which can work in HAC field

David Henry ⇕ David Gucik-Derigny

reliable prediction?

Jérôme Cieslak ⇕ Christophe Combastel

Open question 1: is it possible to find the concept of health-aware control in a nature-inspired way?

Open question 2: High variability and the propagation of uncertainties: is there a rule for defining the degree of abstraction?

Open question 3: Is it of interest to developp verification tools for HAC solution, i.e. a control policy able to integrate prognosis information?

Open question 4: Is it of interest to alleviate the assumption of exogeneous RUL?

Thanks for your attention