Fault-Tolerant Control Methods Design: Applications to UAVs Testbed

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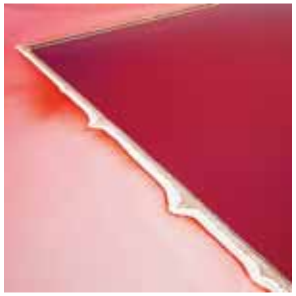
OUTLINES

- Context
- Fault Tolerant Control
  - Problem statement
  - Principle and some definitions
  - Active FTC under fault effectiveness
    - under critical fault
    - under severe fault
- Fault Tolerant Control versus Health
  - Definitions
  - Overactuated Systems
  - Heuristic approach - Optimal reliable FTC method
  - PHM for UAV (battery case)
- Fleet Control of UAVs
  - Cooperative Control based on Multi-agent systems
  - Cooperative FTC design
- Conclusions and Perspectives



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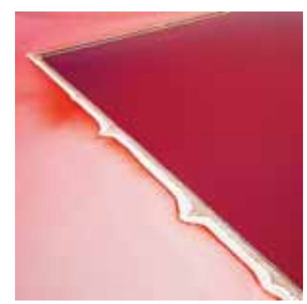

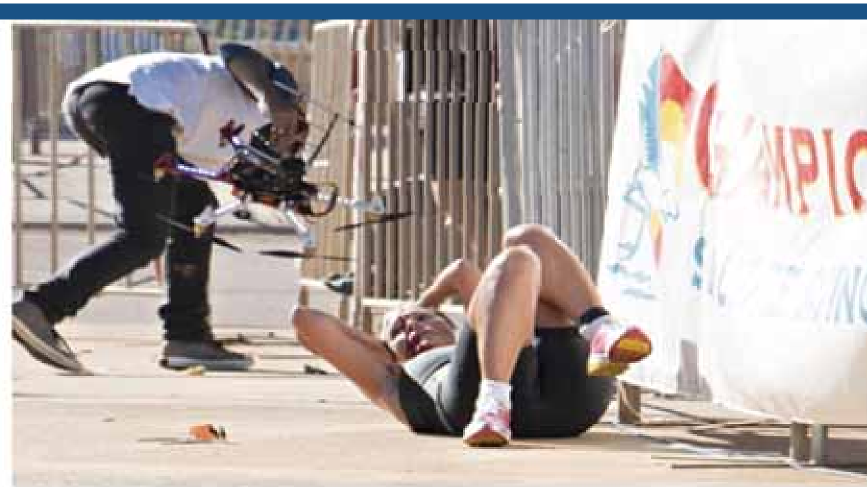

Pushing the wrong button: Bad button placement lead to drone crashes. http://arstechnica.com

Drone crashes in Nice beach, May 2014

Vigilance drone crashes in Goma airport. Jan 2014

Drone crashes database: http://dronewars.net/drone-crash-database/

Scope… IFAC TC 6.1. SAFEPROCESS

IFAC International Federation of Automatic Control

"Complex systems are vulnerable to **faults or failures** such as defects in components and/or instruments or in controllers or in control loop. **Faults or failures** can cause undesired reactions, consequences as damage to technical parts of the plant, to human life, to the environment and great significance of the vested economic value…."

Sensor or actuator failure, equipment fouling, feedstock variations, may affect controller performance and as many as 60% of industrial controllers problem [*] .

[*] Harris, T. J., Seppala, C., and Desborough, L. D., *A review of performance monitoring and assessment techniques for univariate and multivariate control systems*. Journal Process of Control 9, 1-17 (1999)

Scope… IFAC TC 6.1. SAFEPROCESS

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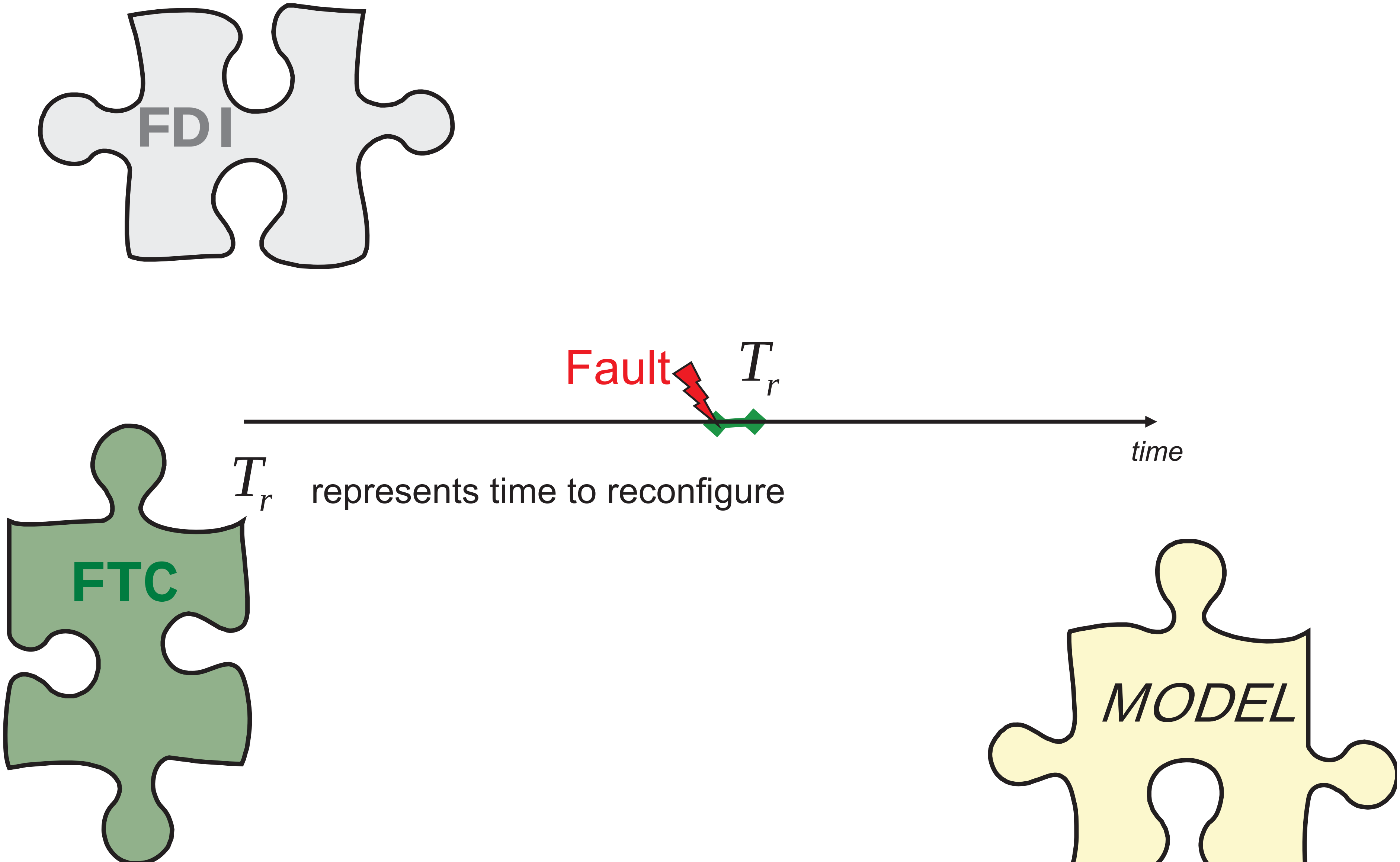
"…..
The main objective of the **Fault Detection and Isolation (FDI)** research area, widely addressed from several points of view in the last years, is to study methodologies for identifying and exactly characterizing possible incipient faults arising in predetermined parts of the plant. After accurate diagnosis, the next natural step is to design new control law in order to tolerate the fault, namely to guarantee pre-specified performances for the faulty system. This is the main aim of a **Fault Tolerant Control (FTC)** system."

Context and aim



General Context

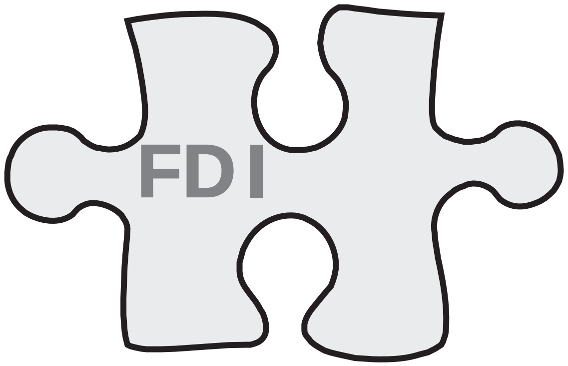
The main objective of the Fault Diagnosis research area, widely addressed from several points of view in the last years, is to study methodologies for identifying and exactly characterizing possible incipient faults arising in predetermined parts of the plant. The natural step, after an accurate diagnosis, is Fault Tolerant Control design. Fault tolerance is the ability of the controlled system to maintain control objectives despite the occurrence of a fault.

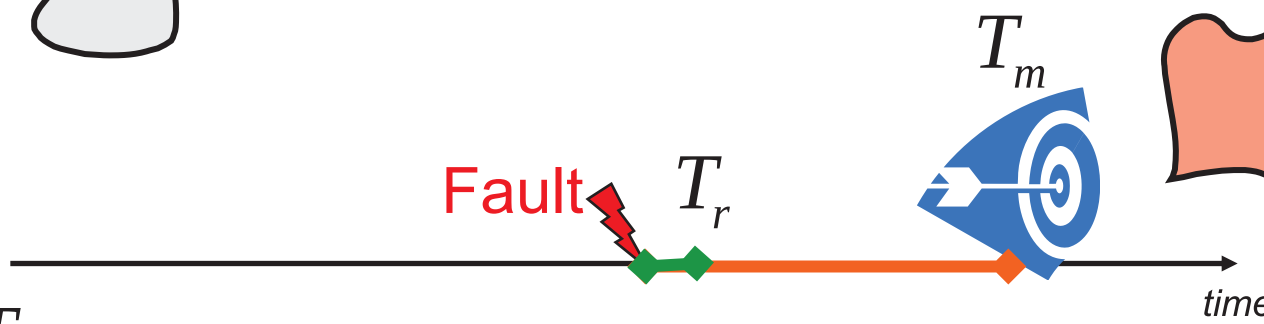
General Context

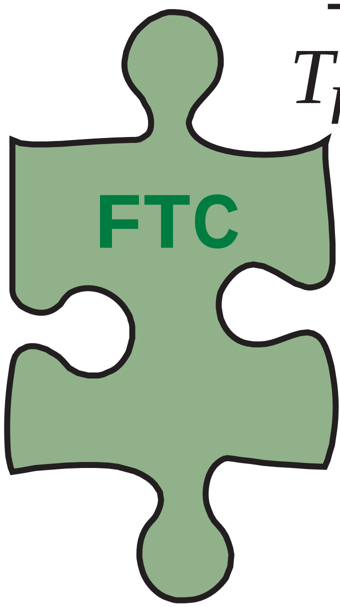
The main objective of the Fault Diagnosis research area, widely addressed from several points of view in the last years, is to study methodologies for identifying and exactly characterizing possible incipient faults arising in predetermined parts of the plant. The natural step, after an accurate diagnosis, is Fault Tolerant Control design. Fault tolerance is the ability of the controlled system to maintain control objectives despite the occurrence of a fault.

Reliability should play an important role in the design phase of **FDI** and **FTC** systems. **Reliability** is the probability that an item will perform its required function, under given conditions, for a stated time interval. **Reliability** is therefore a measure of the probability of successful performance of a system over a period of time. Due to this definition it comes natural to consider reliability as a subjective concern in the analysis and design of **FDI** and **FTC** systems.

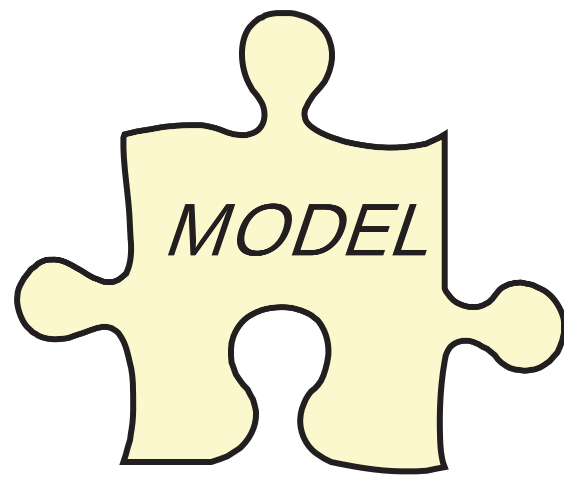
Context and aim



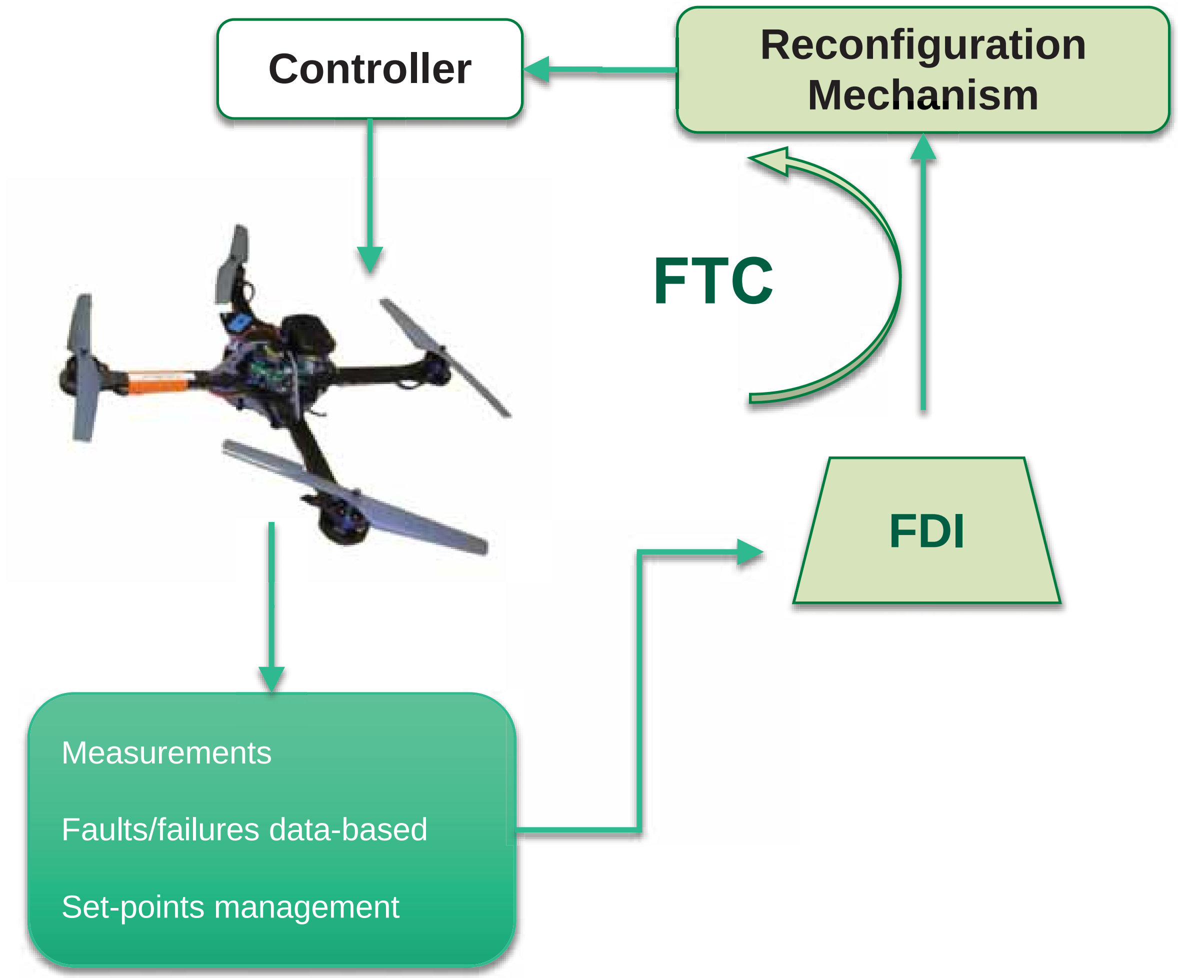




T_m represents period between fault occurrence and the end of expected mission



FDI / FTC & Prognosis Health Management



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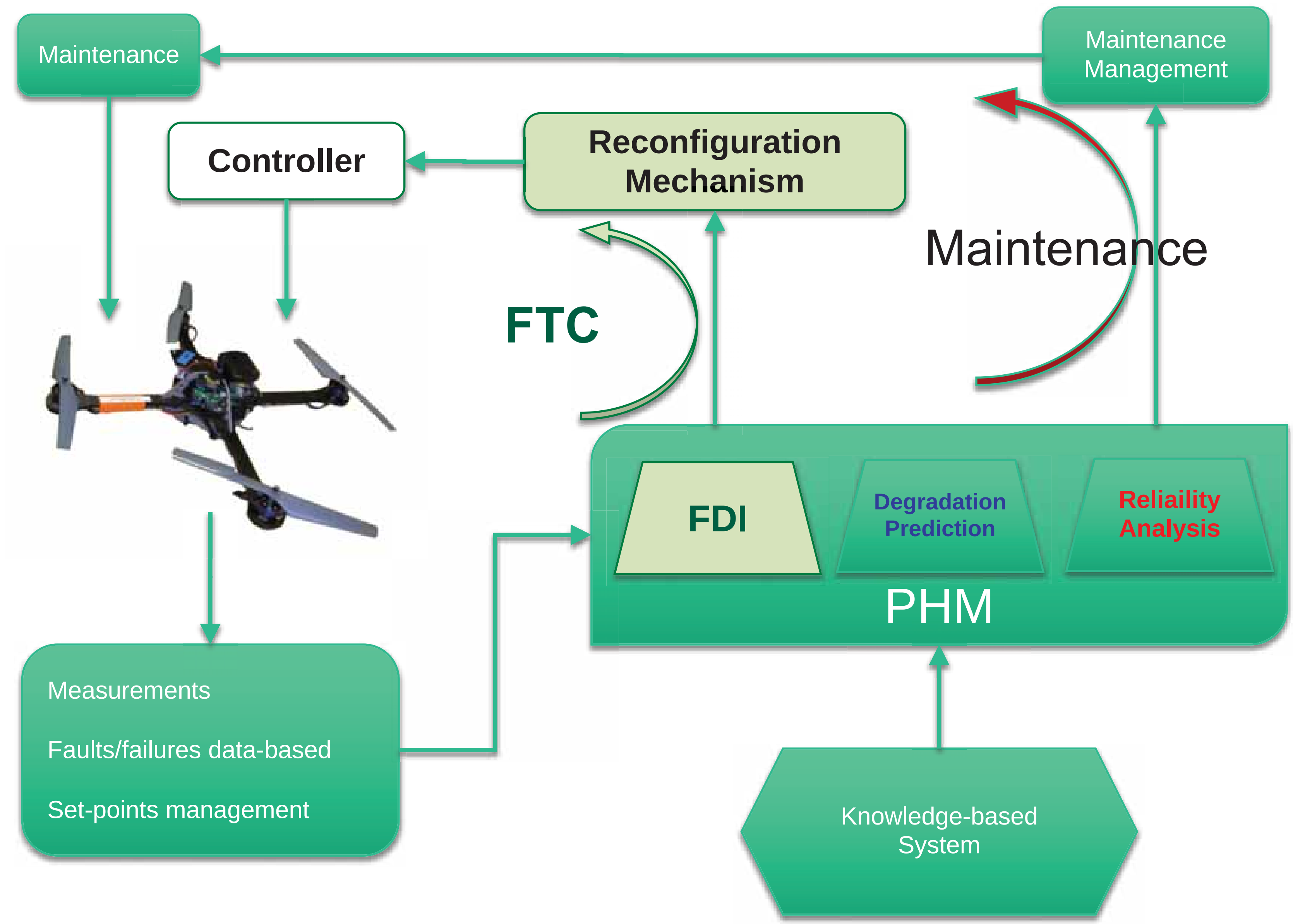
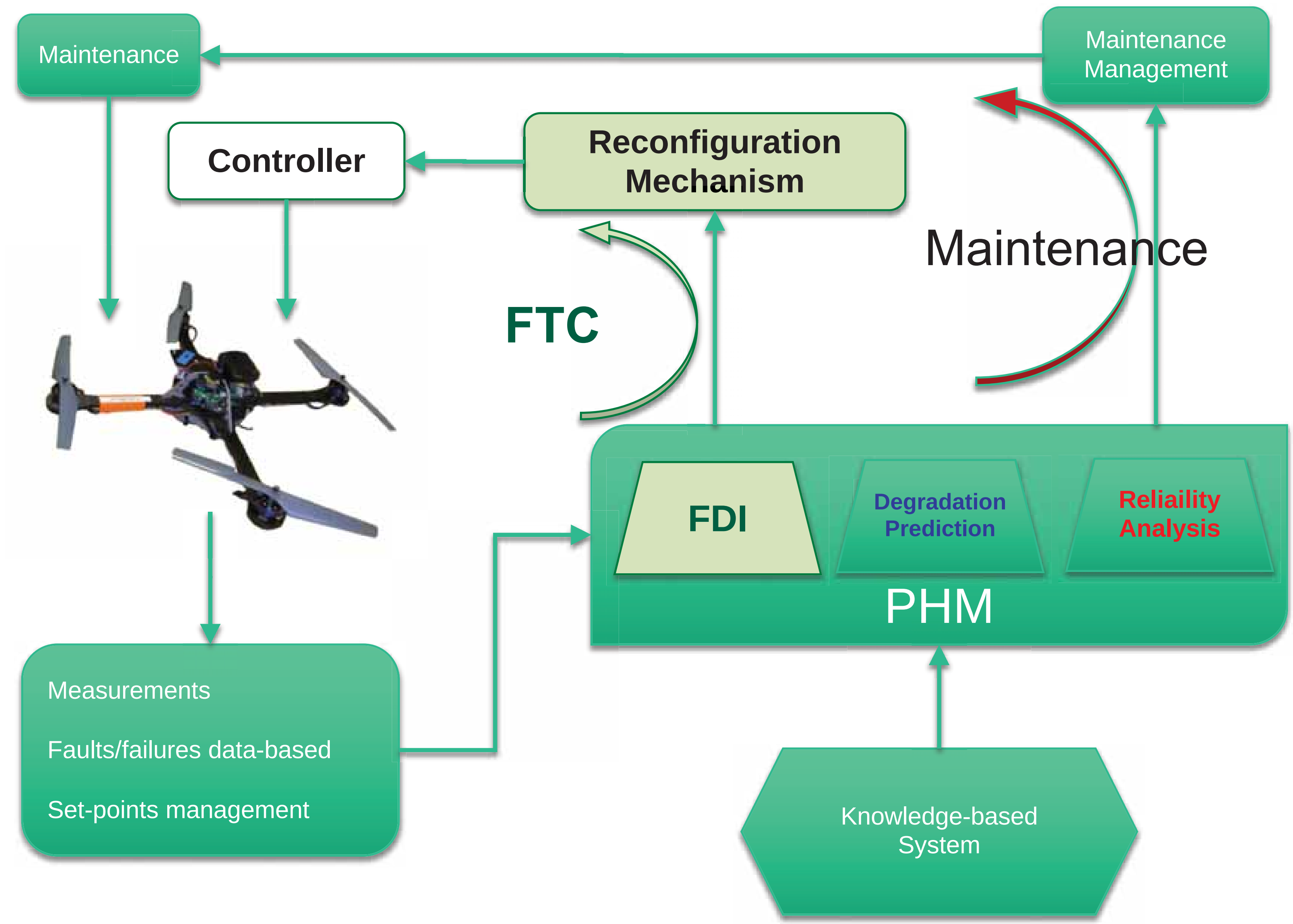


Health aware oriented Control Strategy



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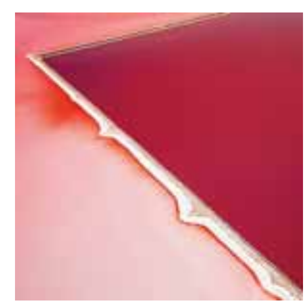

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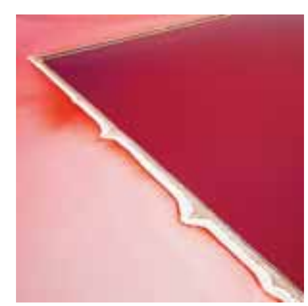
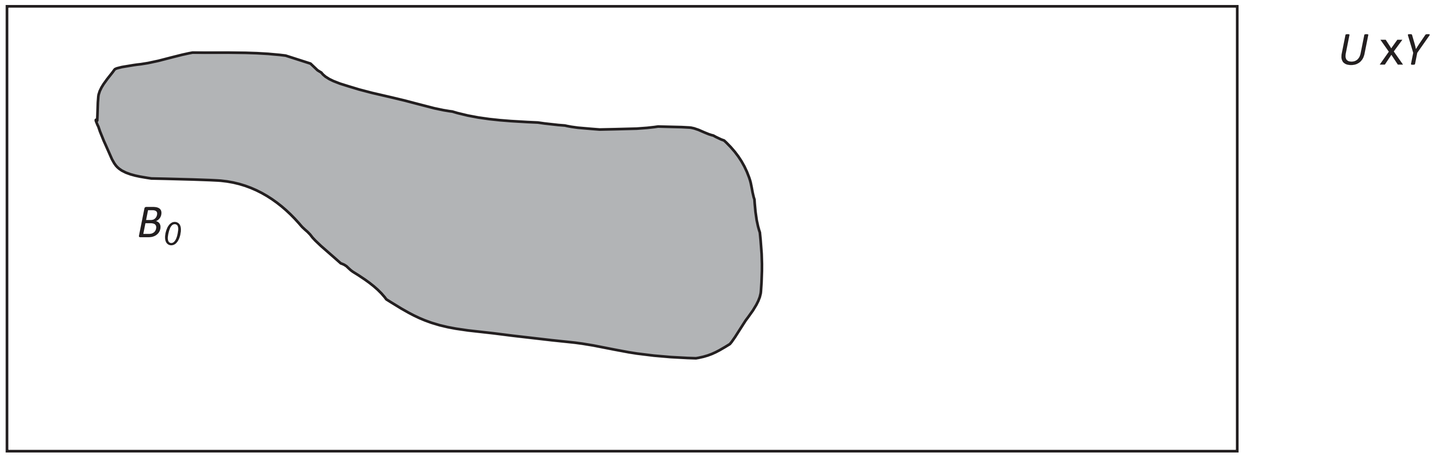
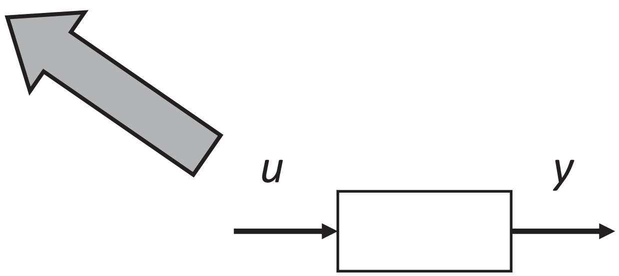


Behavior of the system

Behaviour B of the faultless open loop system





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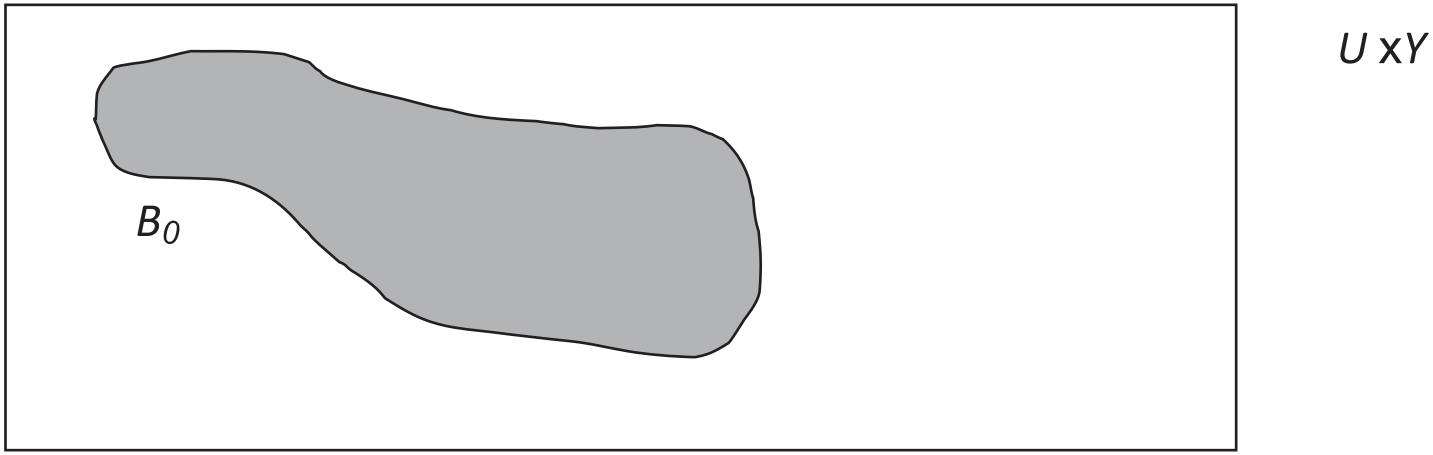
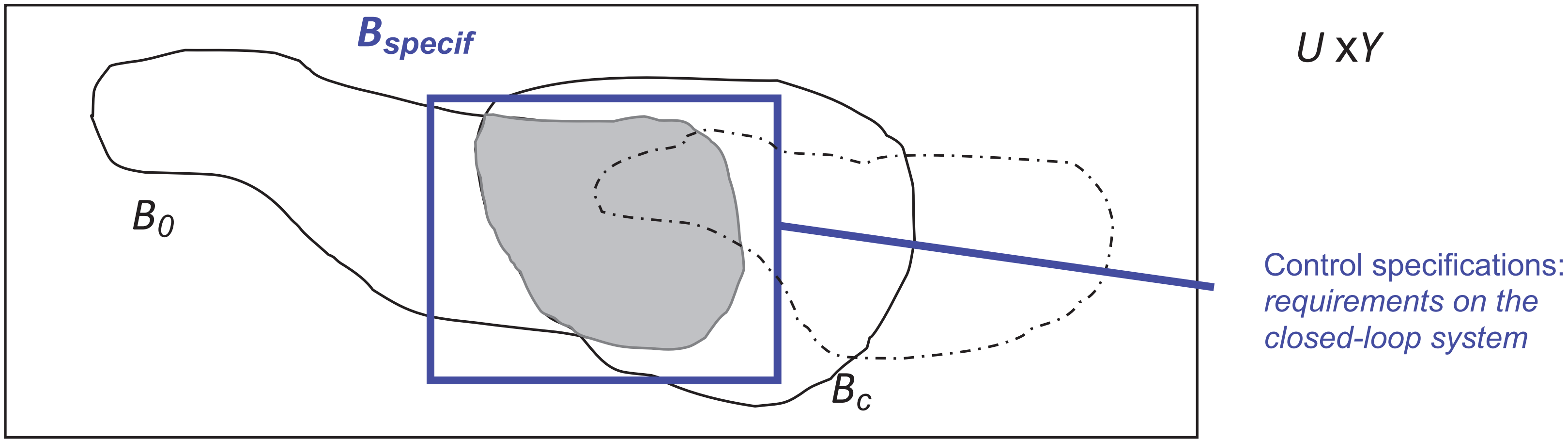


Behaviour B of the closed-loop system



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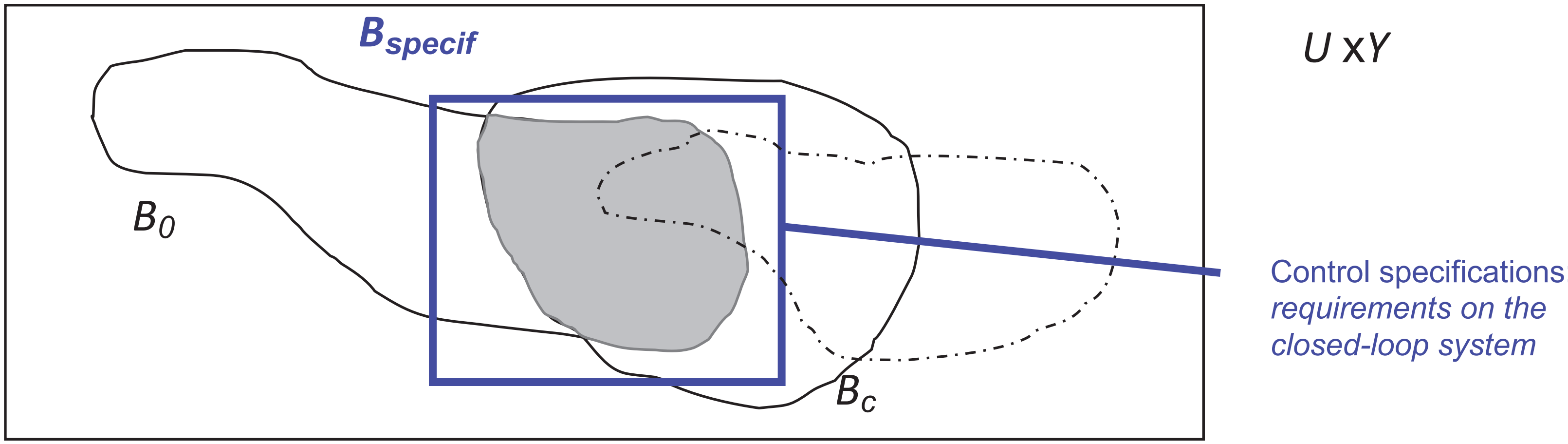
Behaviour B of the faultless closed-loop system



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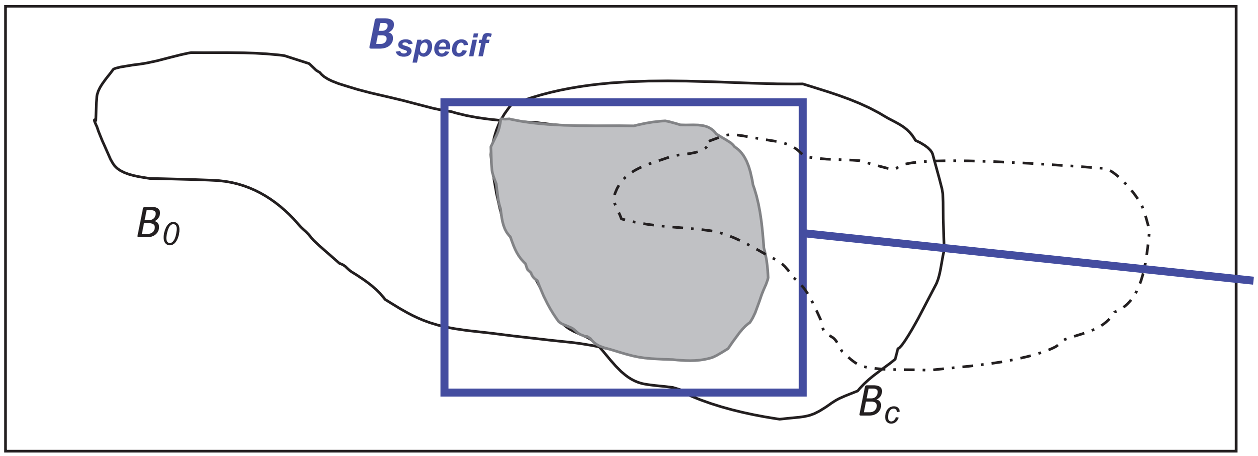


$U \times Y$

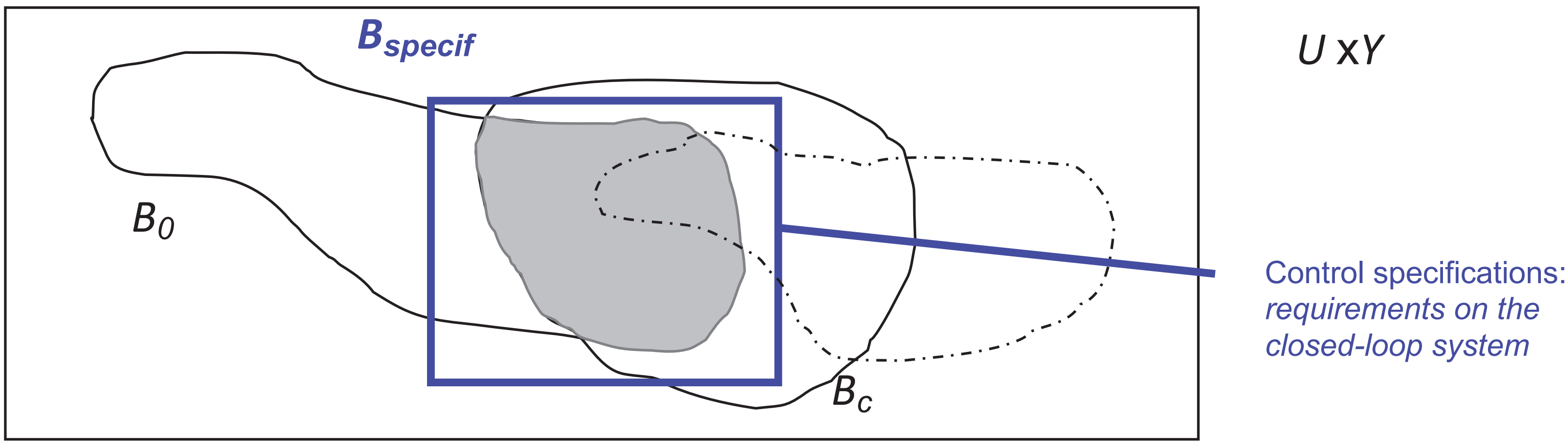
Control specifications:
requirements on the closed-loop system

faultless system → Faulty system

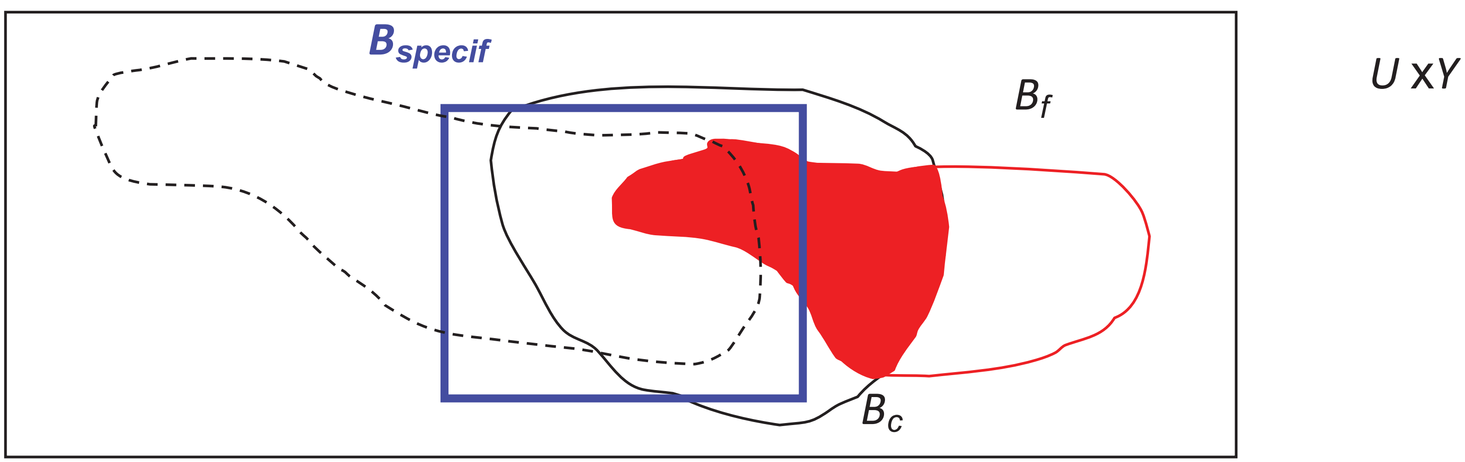
Fault ***f*** **:** Deviation of the system structure (actuator gain degradation, sensor out of order…),
Deviation of the system parameters from the nominal situation (wear, leakage, …)

Problem statement

Behaviour *B* of the faultless closed-loop system

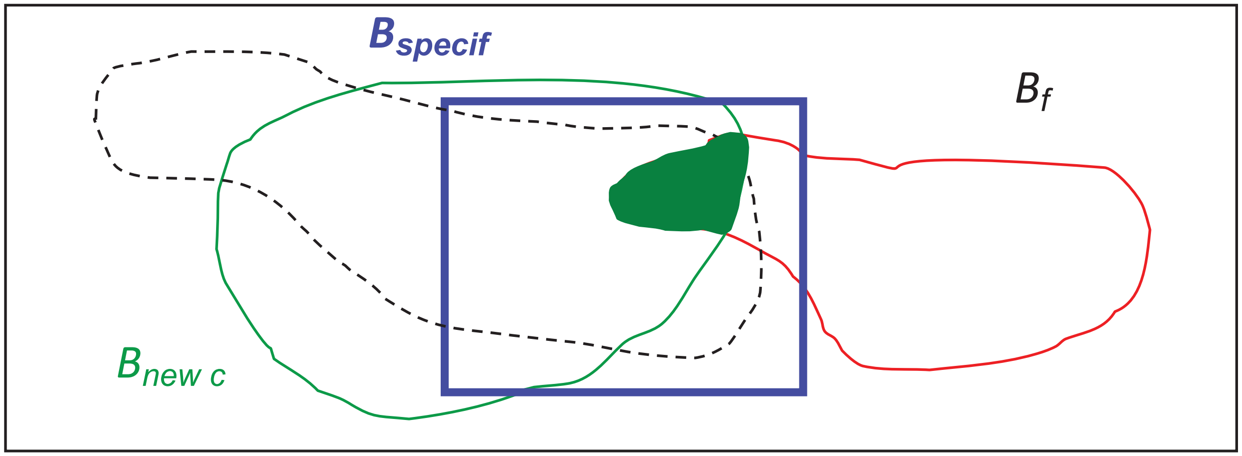


Behaviour *B* of the **faulty** closed-loop system



Problem statement

Behaviour B of the **faulty** closed-loop system with controller re-design



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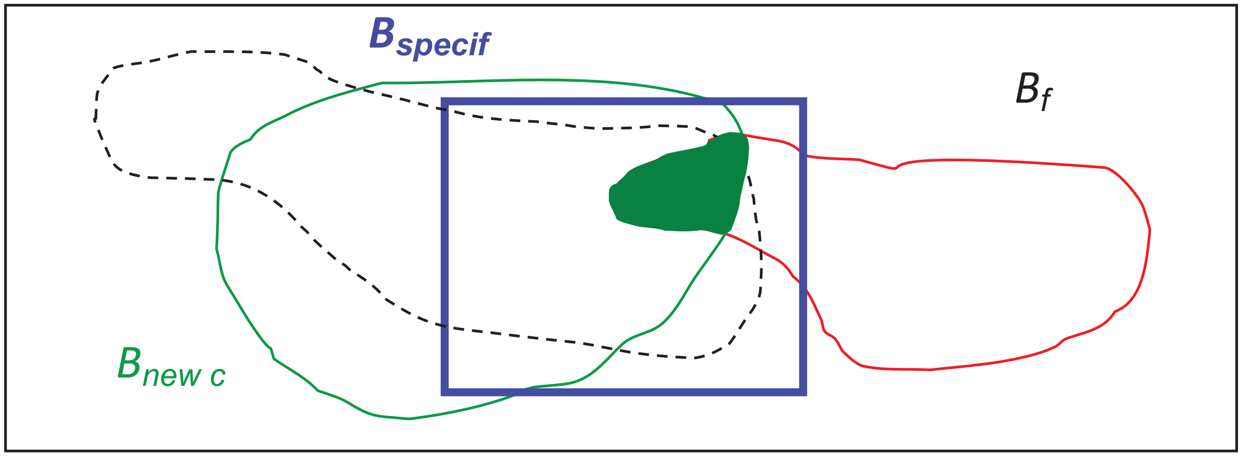

✓ *Fault Tolerant Control system*

System capable to maintain current performances closed to desirable performances and stability conditions in the presence of component and/or instrument faults *;* Accept reduced performance as a trade-off.

FTC – 80% Wing Loss – Septembre 2010 - Rockwell

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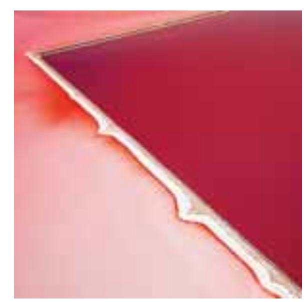
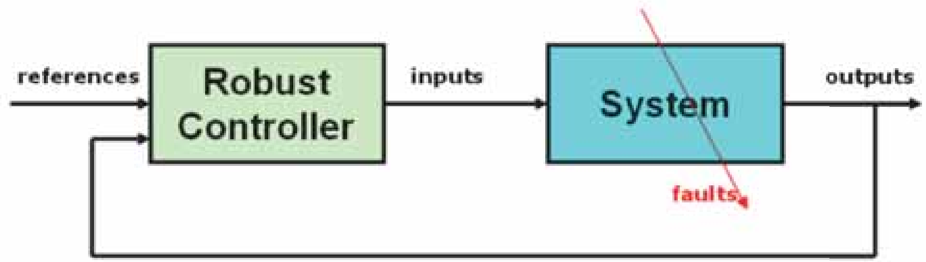


Definitions

Passive FTC:



- **Passive FTC** are mainly based on robust control theory. Non require on-line detection, it could be very conservative, and only for small failures.

[*] J. Jiang and X. Yu Fault-tolerant control systems: A comparative study between active and passive approaches Annual Reviews in Control, 2013

Definitions

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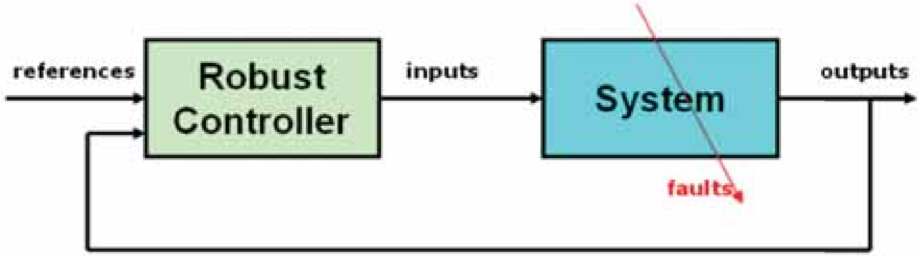
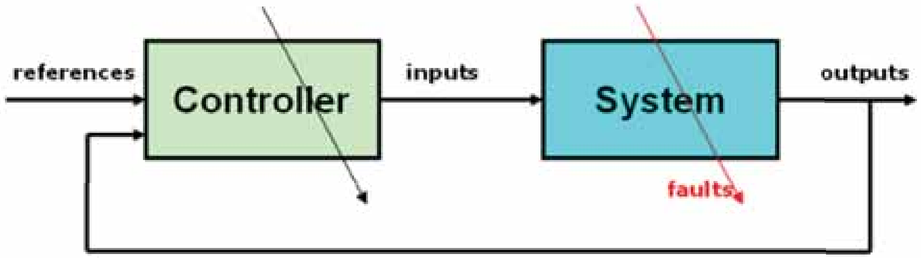


Active FTC:



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- **Active FTC** integrates a re-configurable mechanism (adaptation) intended to preserve both *stability* and *performance*.

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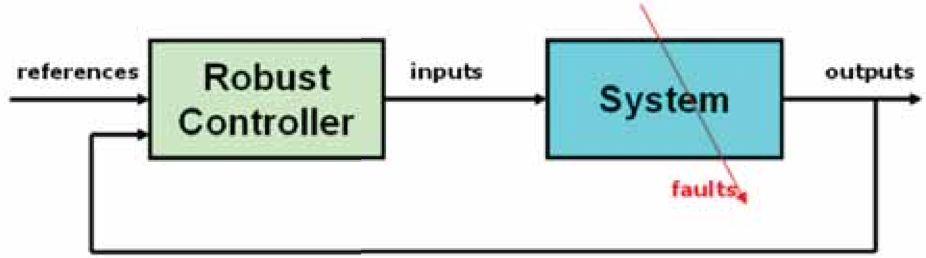
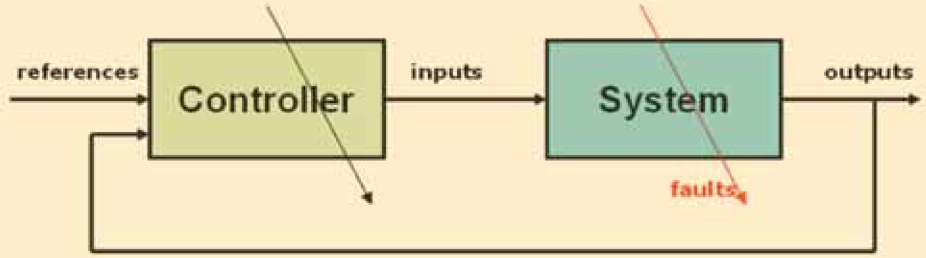


Active FTC:



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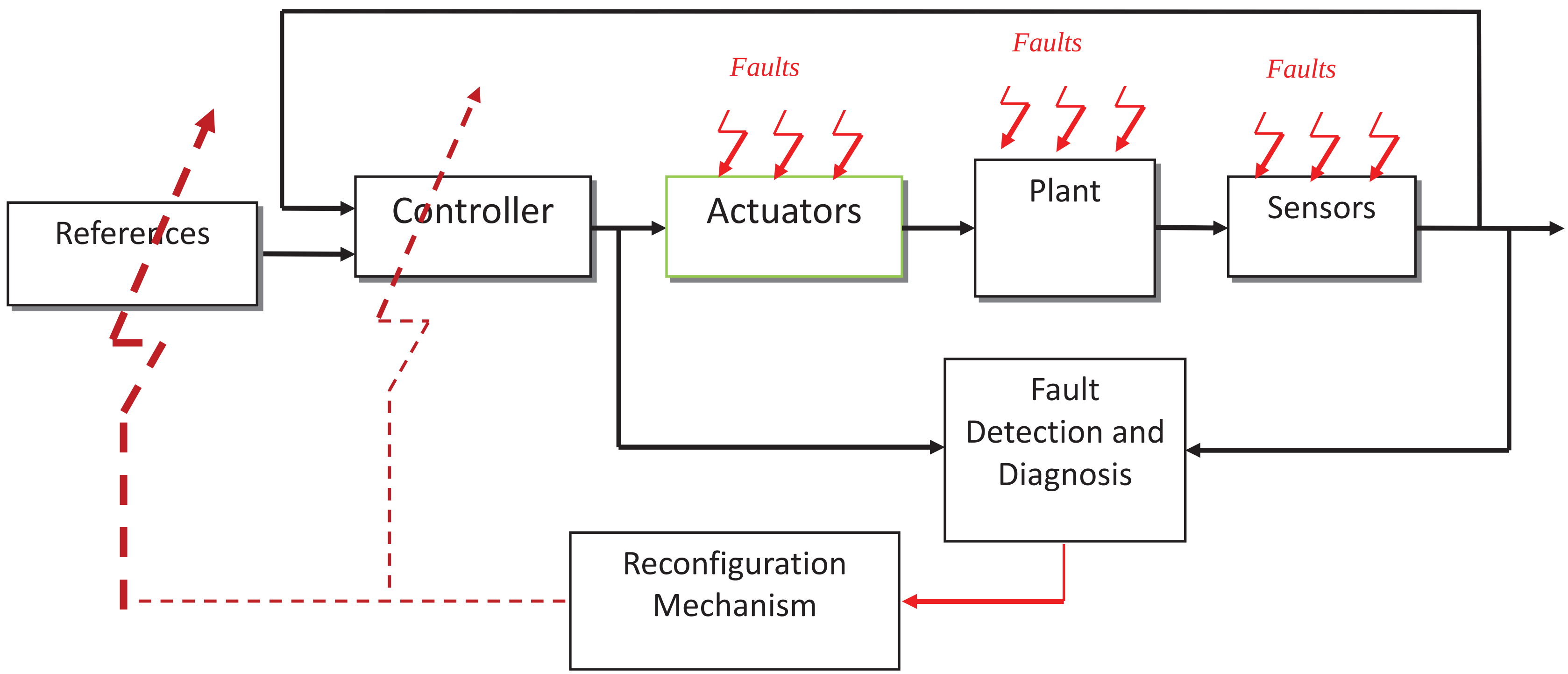
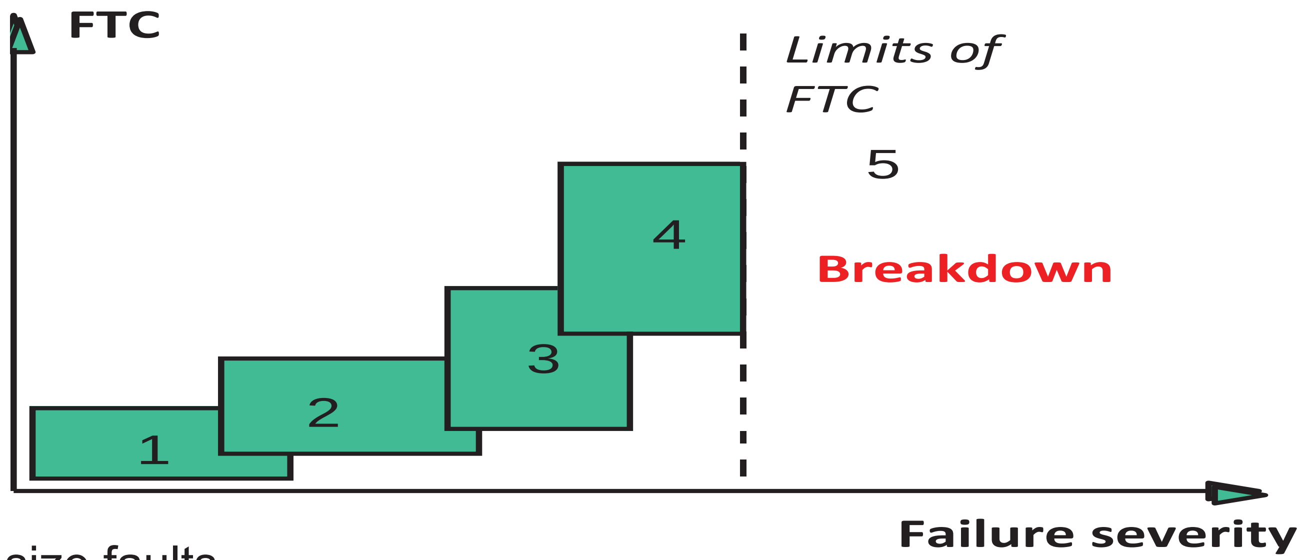
FTC - General Scheme - Reconfiguration



Caution: Controllability, Detectability and reconfigurability properties (Structure Analysis can be considered) should be studied before to synthesize FTC.

Rq: Adaptive methods and Predefined Faulty Multiple models Adaptive approaches(MMAE Family) have been omitted in the presentation

FTCS: What is possible to do ?



1 : Small size faults
Robust control (no FDI module)

2 : Non critical faults: biais,drifts, loss of actuating effectiveness
Disturbance rejection , adaptive control,.. *Interaction Control-FDI*

3 : Critical faults leading to saturations or unstability ;
Control reconfiguration ; *Modified objective, still acceptable*

4 : Severe faults : inoperant actuator, loss of a sensor ;
Modified objective, degraded performances

A reference to start ….

ELSEVIER

Annual Reviews in Control 32 (2008) 229–252

Annual Reviews in Control

www.elsevier.com/locate/arcontrol

Bibliographical review on reconfigurable fault-tolerant control systems

Youmin Zhang [a,*], Jin Jiang [b,1]

[a] *Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Quebec H3G 1M8, Canada*

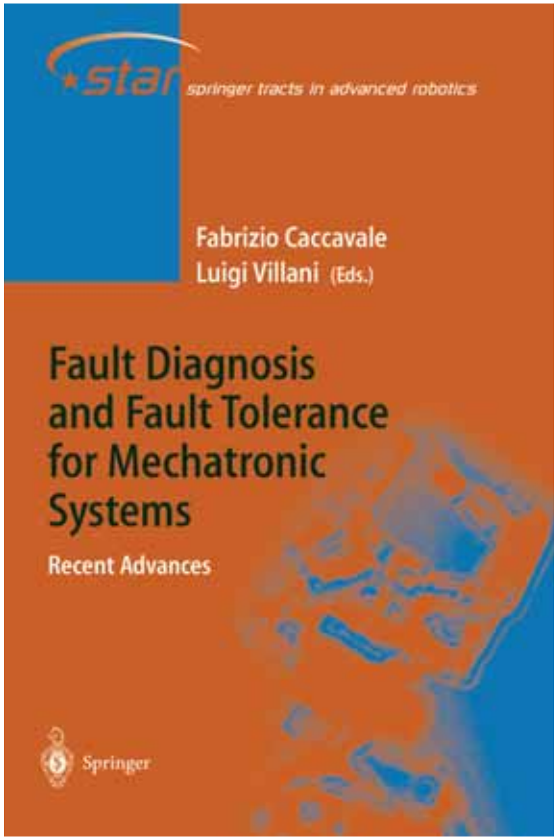
[b] *Department of Electrical and Computer Engineering, The University of Western Ontario, London, Ontario N6A 5B9, Canada*

Received 15 July 2007; accepted 23 March 2008

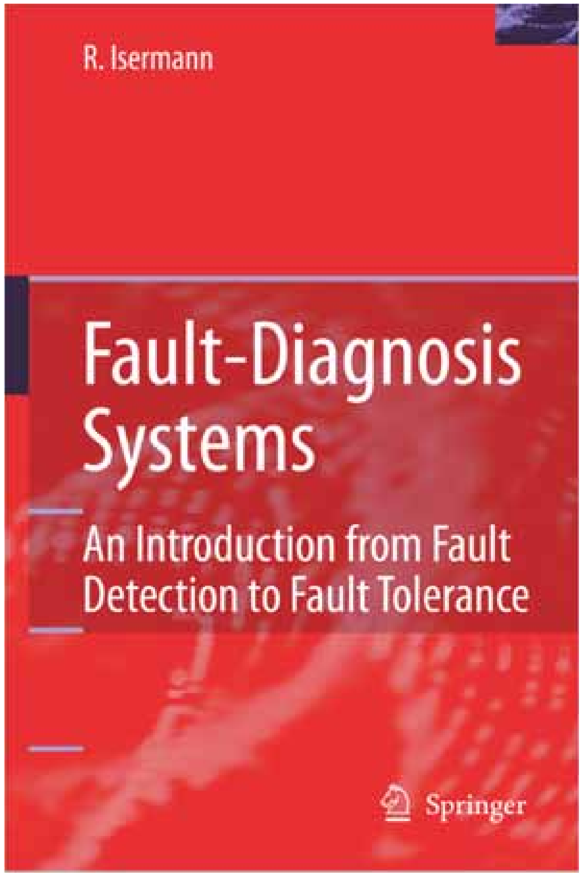
[*] More than **300** papers have been classified, defined, identified ….

“FTC design applied on Various Models (LTI, LPV, nonlinear…)”

Some books …

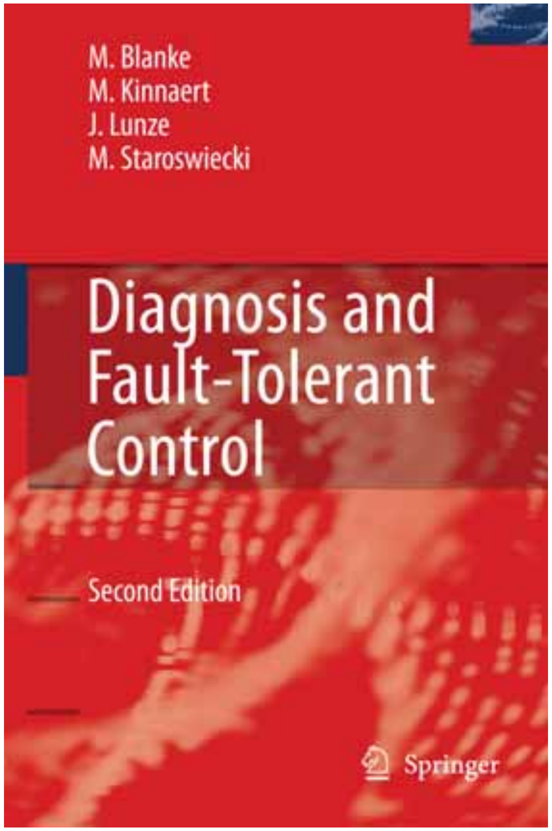


2003

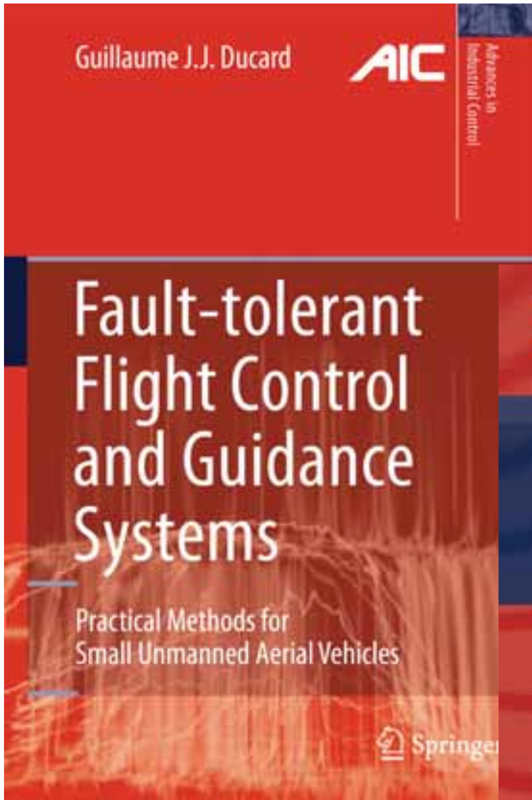


2006

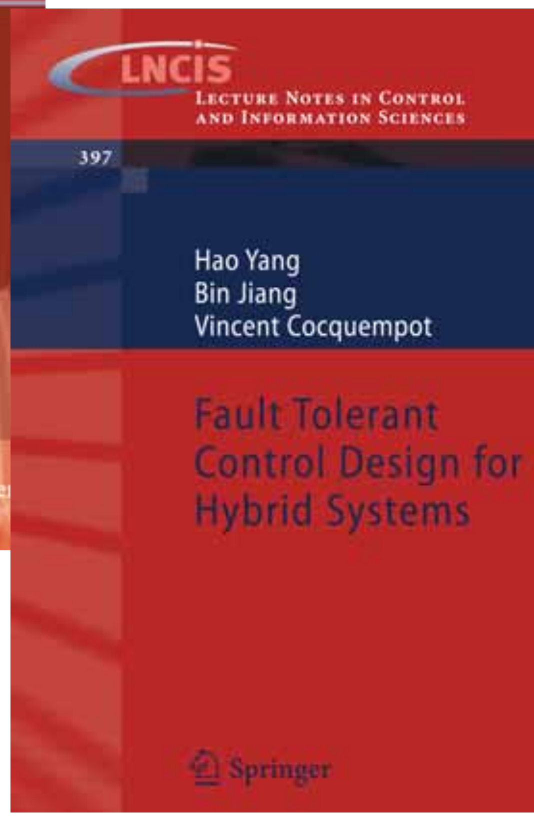
2006 **=> 2016 (3rd Edt)**



Some books …



2009



2010

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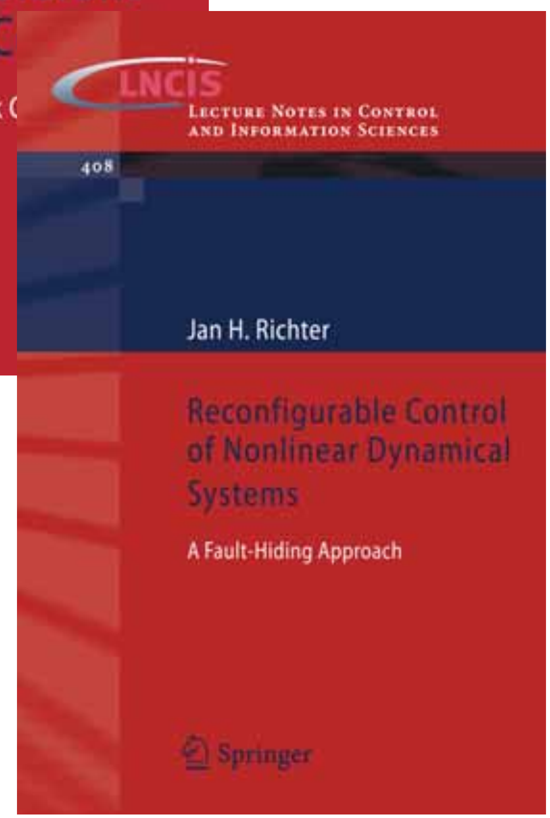
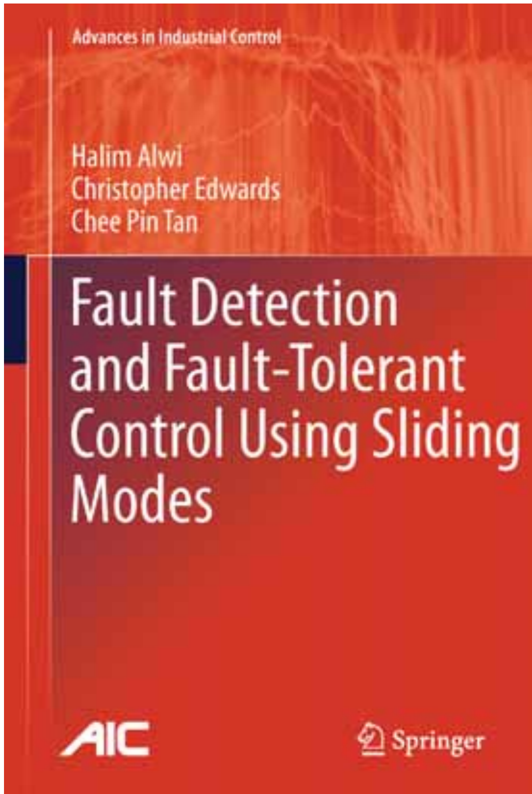


2011

Some books …



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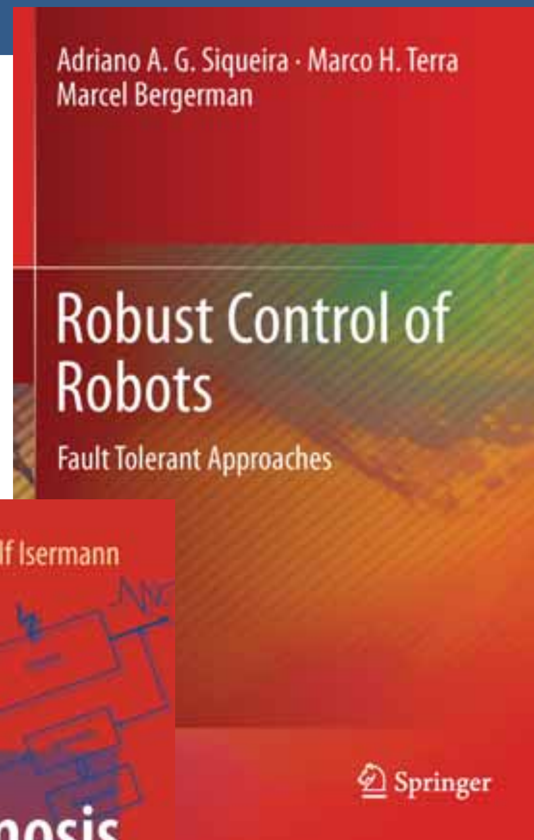
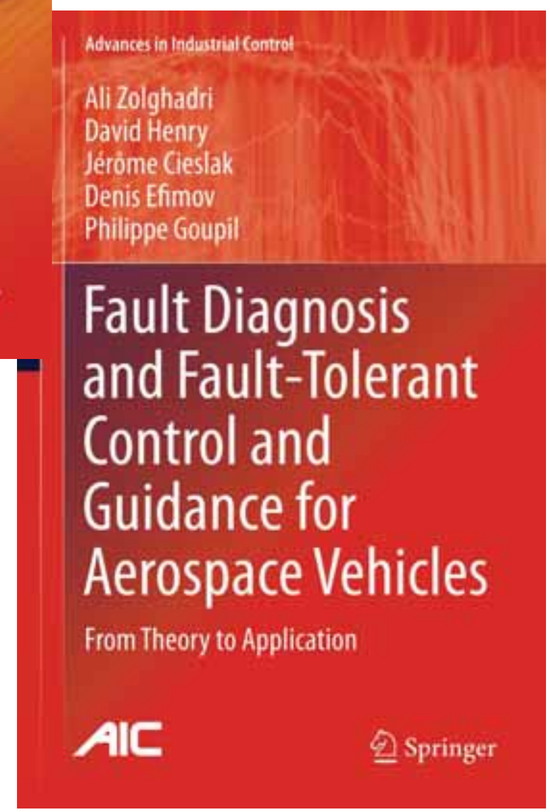


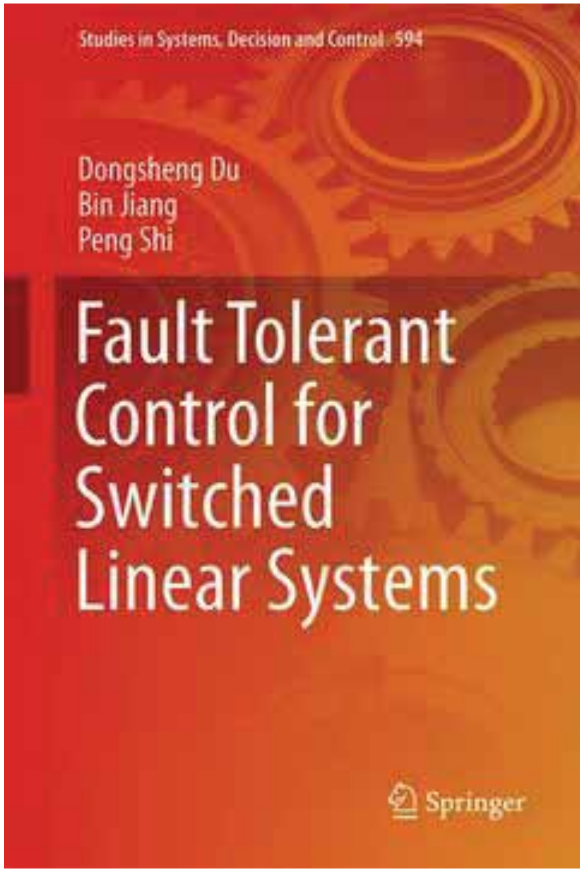
2012



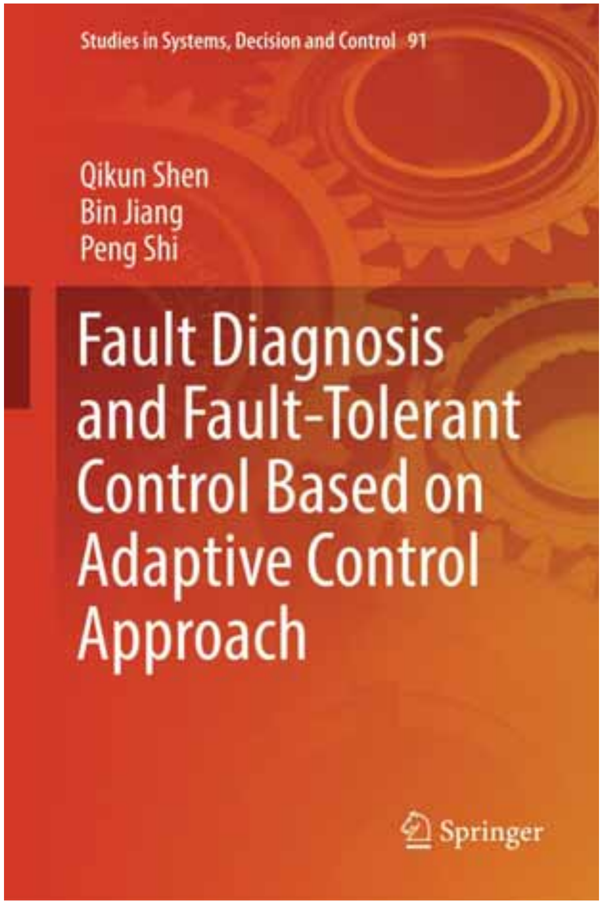
2014

Some books …

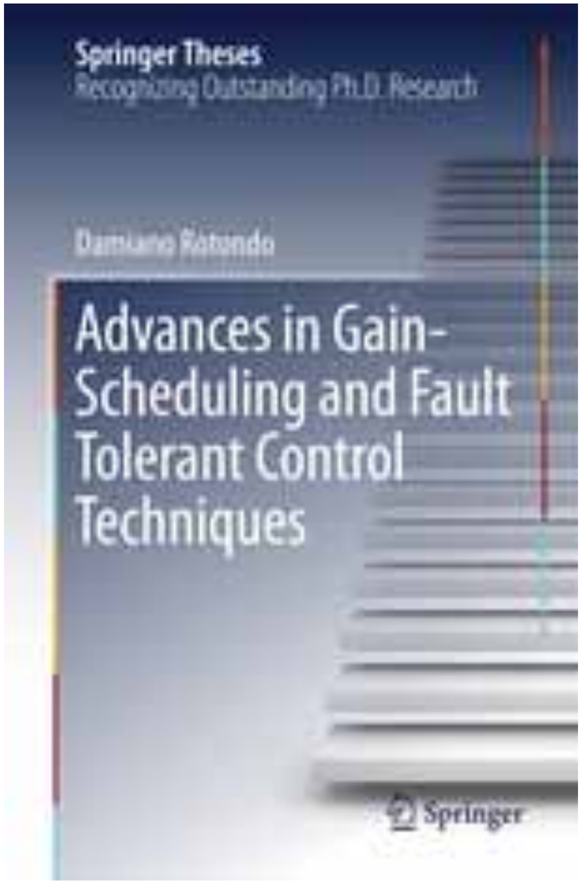
2015



2017

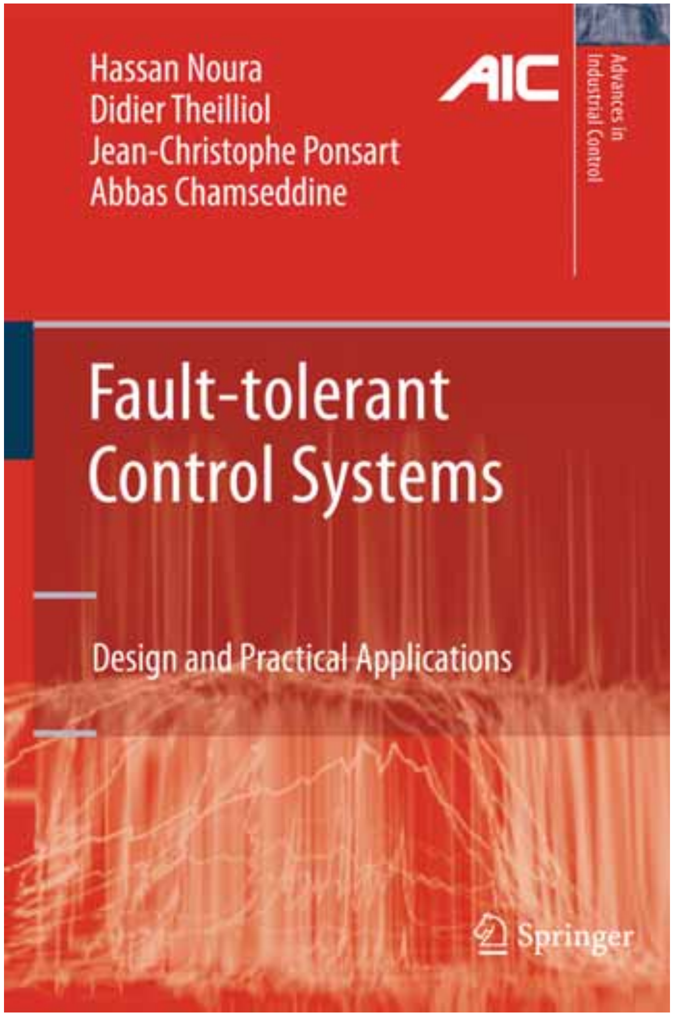


2018



An excellent book … ☺

2009



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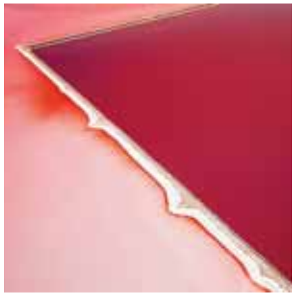

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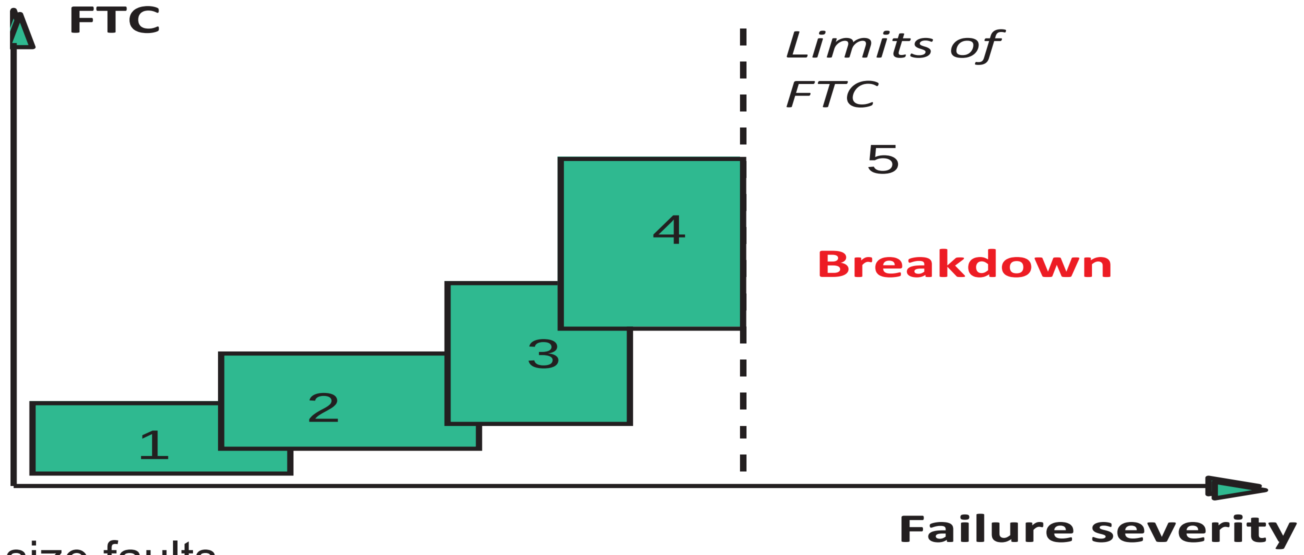

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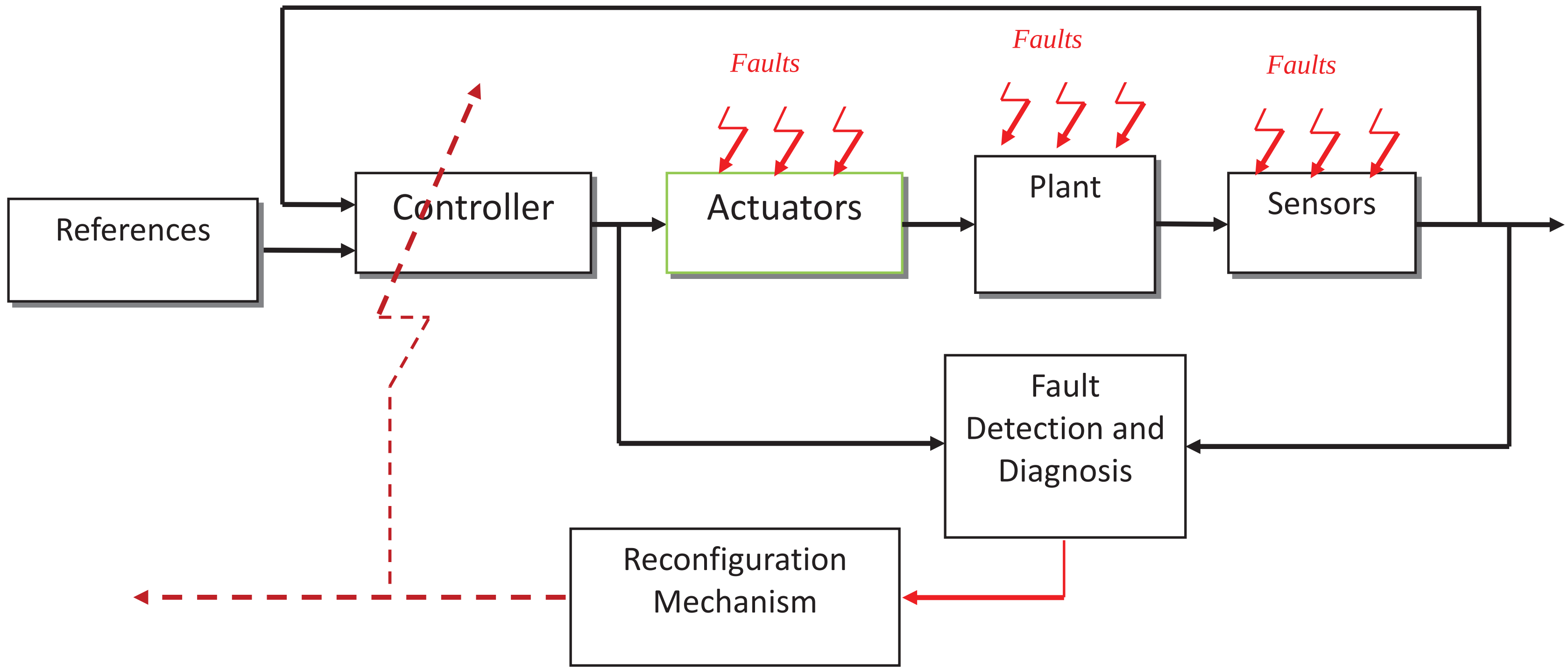
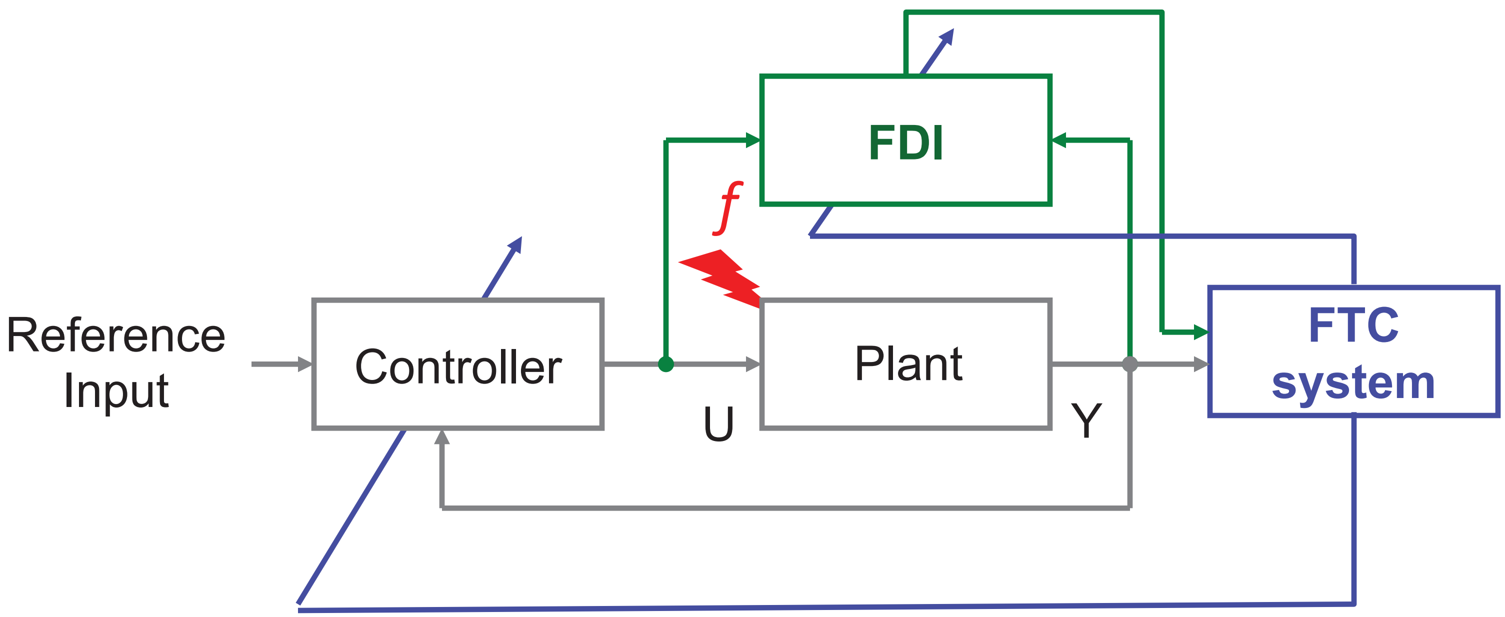
Modified objective, degraded performances

FTC - General Scheme [*]



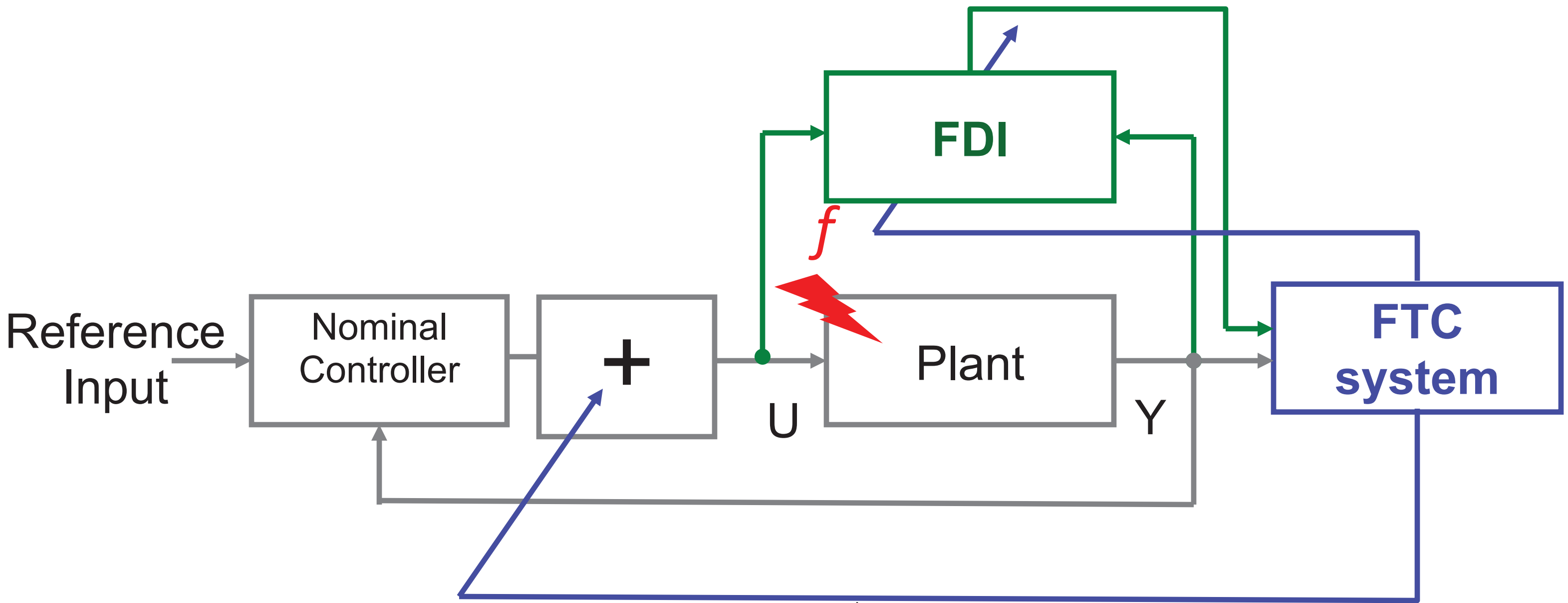
[*] FDI (or FDD) provides information to controller and synthesis is made separatly (General Scheme)

Gain Redesign



[*] Gao, Z. and P.J Antsaklis (1991). Stability of the pseudo-inverse method for reconfigurable control. International Journal of Control, vol. 53, n° 3, pp. 717-729.

Fault Compensation (FC) [*]

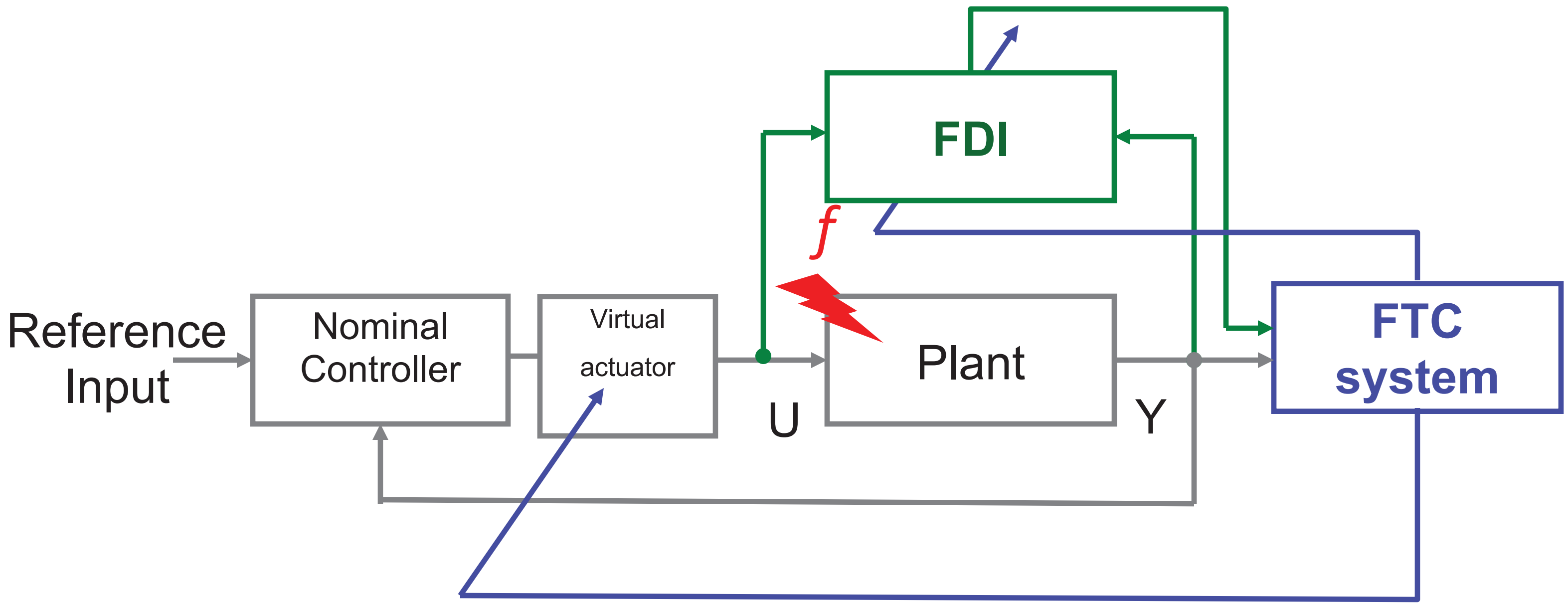


$$u_{add}(t) = -B^{+}F_{a}f^{a}(t)$$

[*] *also defined as* Fault Accommodation or Fault Handling

"Virtual Actuator" since 2007 …

- Principle **(Gain Redesign) + (FC)= Virtual Actuator**



Application to Qball X4

ELSEVIER

Journal of the Franklin Institute

Volume 350, Issue 9, November 2013, Pages 2396-2422

Development of advanced FDD and FTC techniques with application to an unmanned quadrotor helicopter testbed

Y.M. Zhang [a], A. Chamseddine [a], C.A. Rabbath [a], B.W. Gordon [a], C.-Y. Su [a], S. Rakheja [a], C. Fulford [b], J. Apkarian [b], P. Gosselin [c]

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Context
Fault Tolerant Control
- Problem statement
- Principle and some definitions
- Active FTC under fault effectiveness
  - under critical fault
  - under severe fault

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- Overactuated Systems
- Heuristic approach - Optimal reliable FTC method
- PHM for UAV (battery case)

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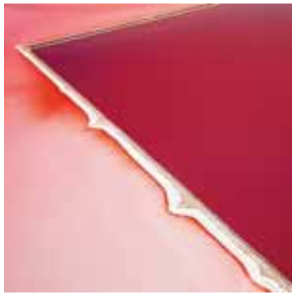
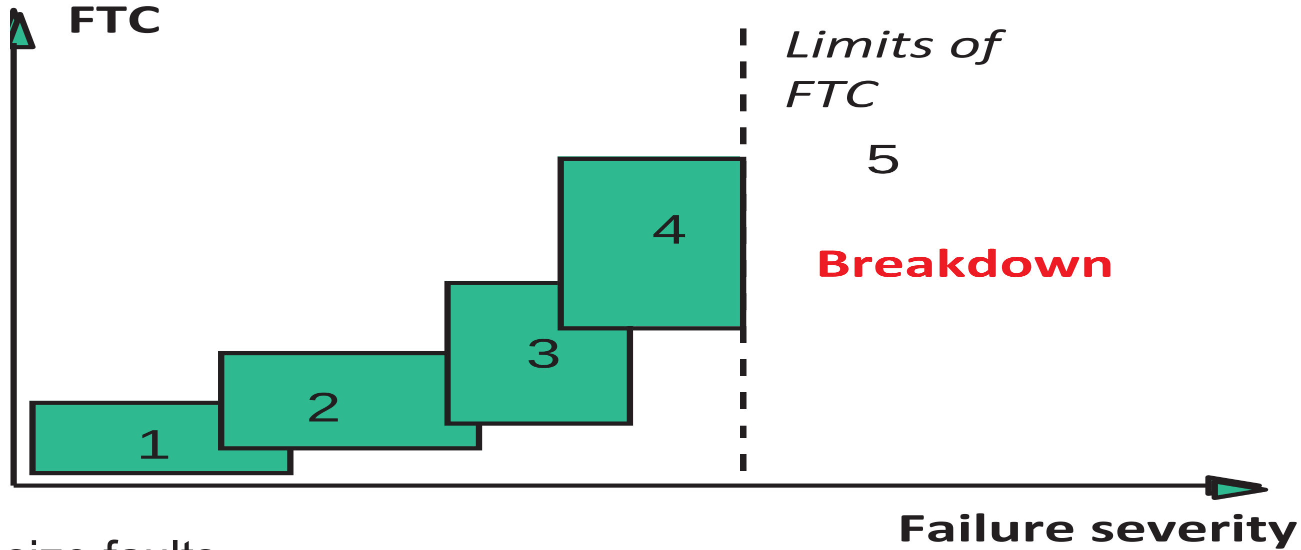
- Cooperative Control based on Multi-agent systems
- Cooperative FTC design

Conclusions and Perspectives



FTCS: What is possible to do ?



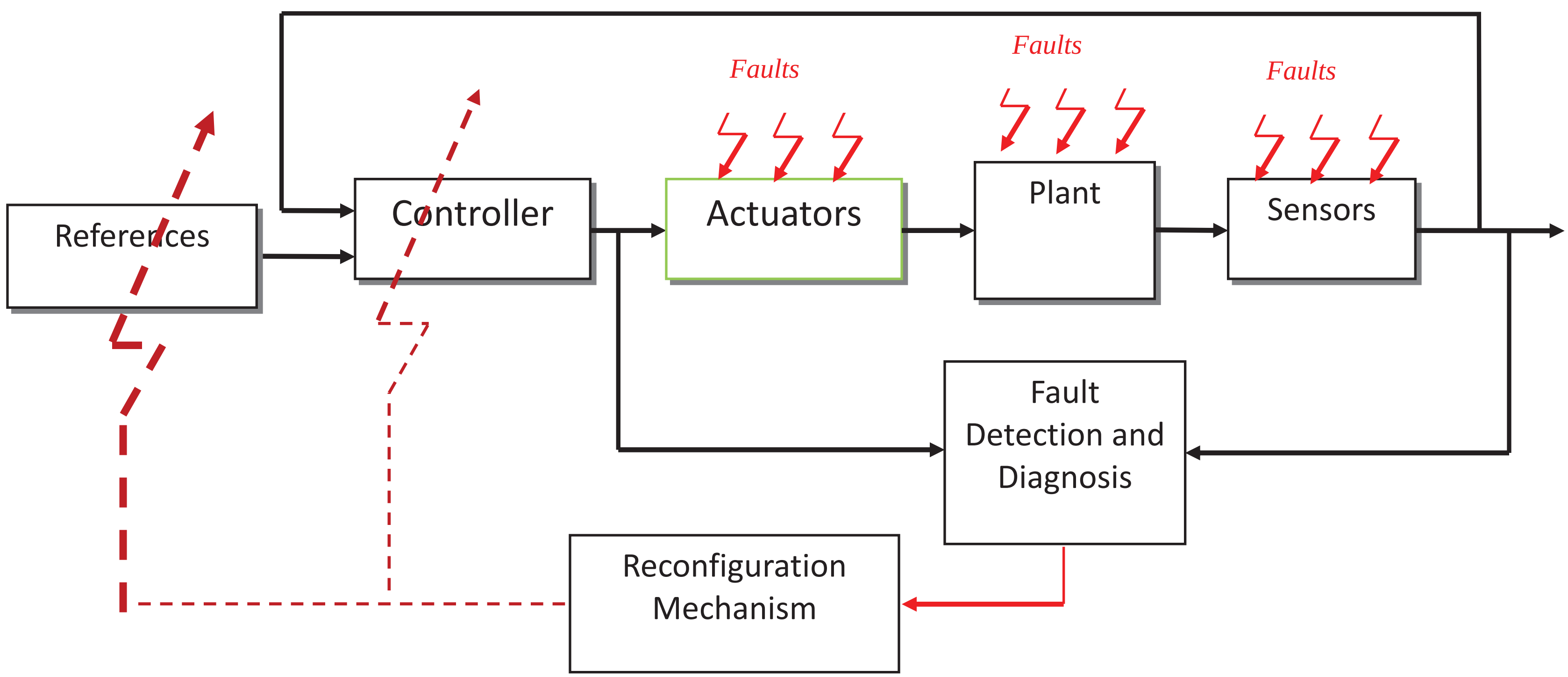
1 : Small size faults
Robust control (no FDI module)

2 : Non critical faults: biais,drifts, loss of actuating effectiveness
Disturbance rejection , adaptive control,..   *Interaction Control-FDI*

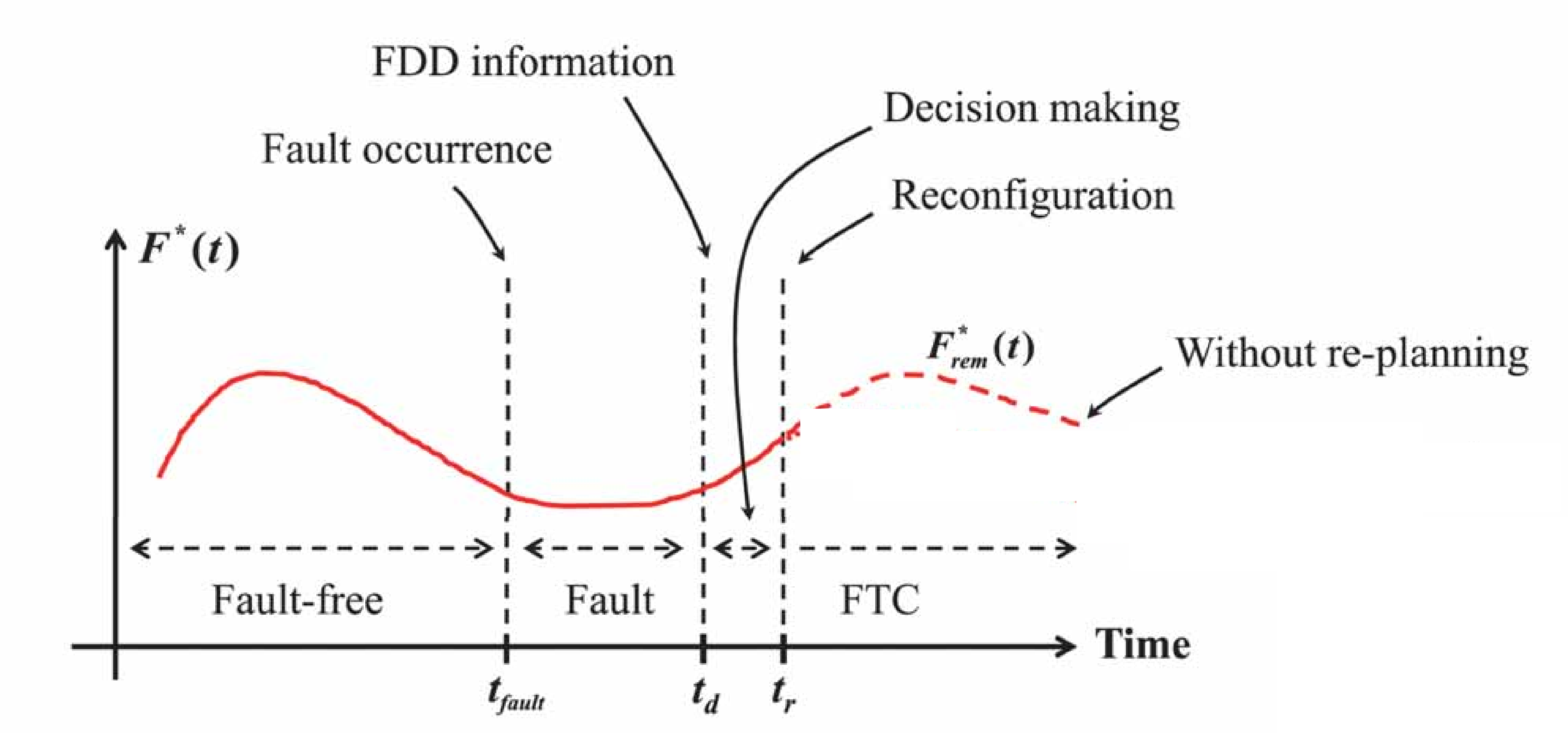
3 : Critical faults leading to saturations or unstability ;
Control reconfiguration ;   *Modified objective, still acceptable*

4 : Severe faults : inoperant actuator, loss of a sensor ;
Modified objective, degraded performances

FTC - General Scheme - Reconfiguration



Main Steps

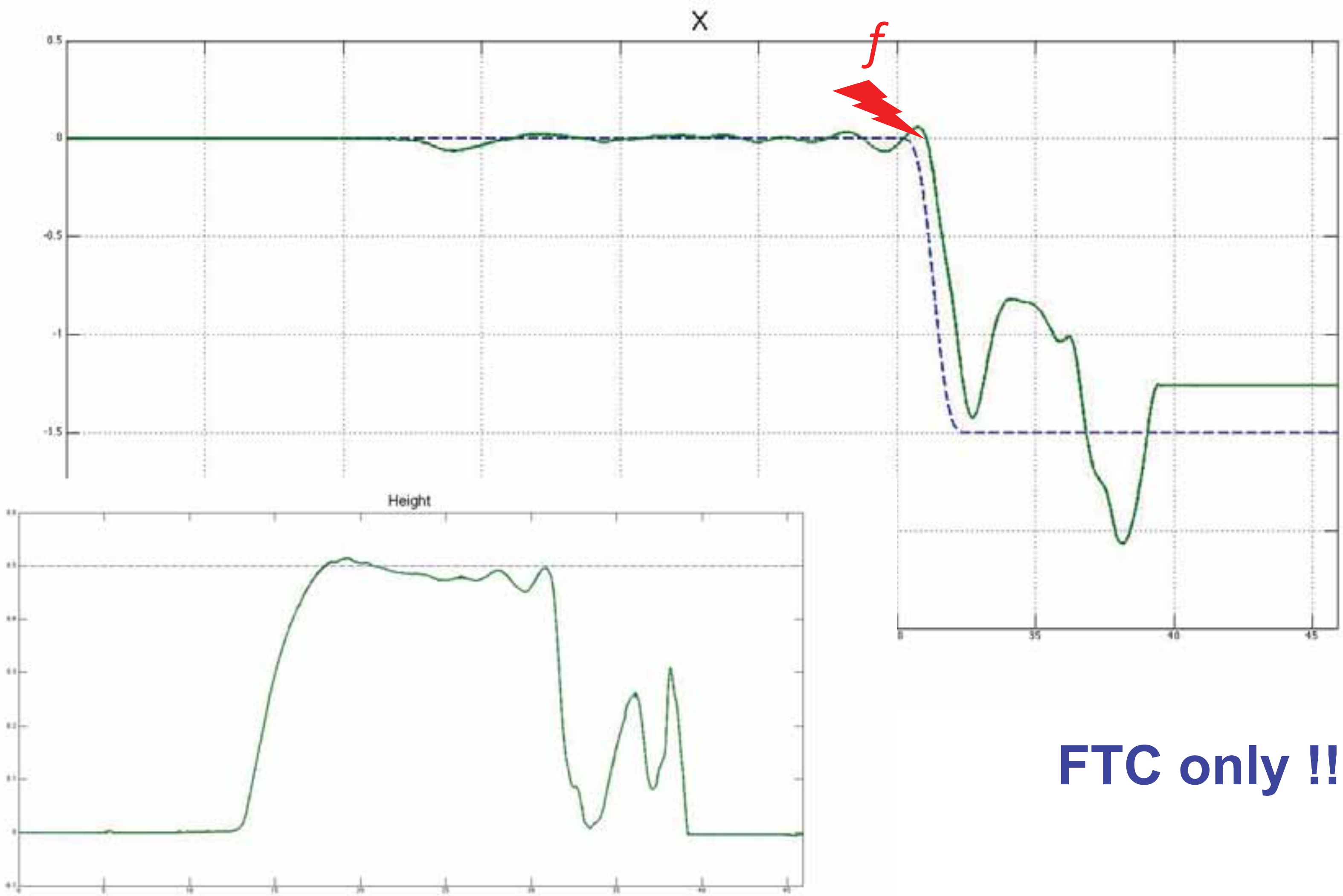


Caution: Take care about actuator saturations and stability properties under FTC approach.

Application to Qball X4

Caution: Take care a … r FTC approach.

FTC - Qball X4 with Actuator Fault = 30%

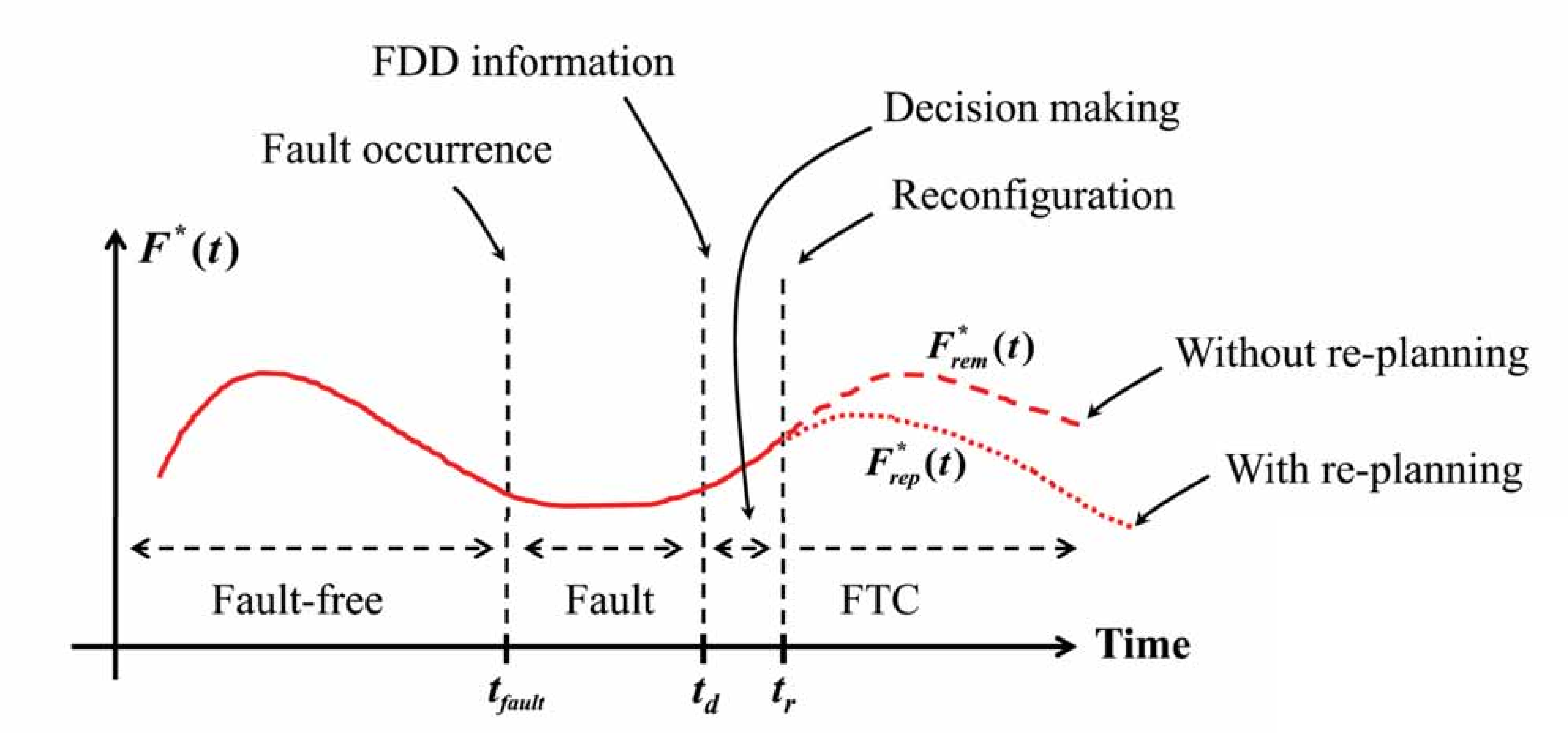


FTC only !!!

Qball X4 with Actuator Fault = 30%

Concordia University
Engineering and Computer Science
Department of Mechanical and Industrial Engineering

Main Steps

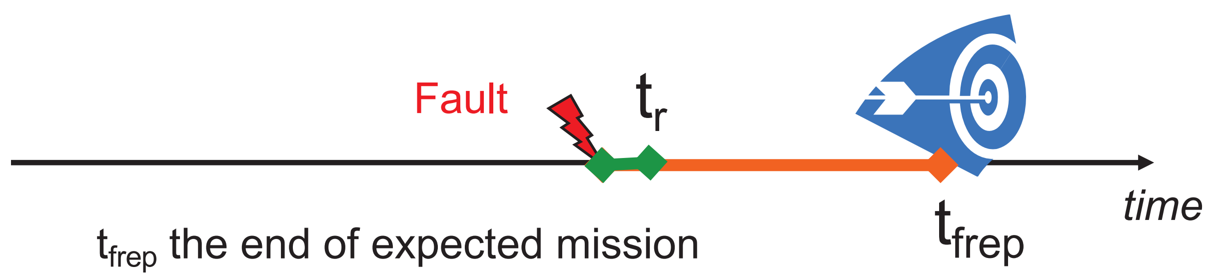

FDD information
Decision making
Fault occurrence
Reconfiguration
F*(t)
F*rem(t)
Without re-planning
F*rep(t)
With re-planning
Fault-free
Fault
FTC
Time
tfault
td
tr

Main principles

Redesign reference F_{rep} as an optimization problem such as:

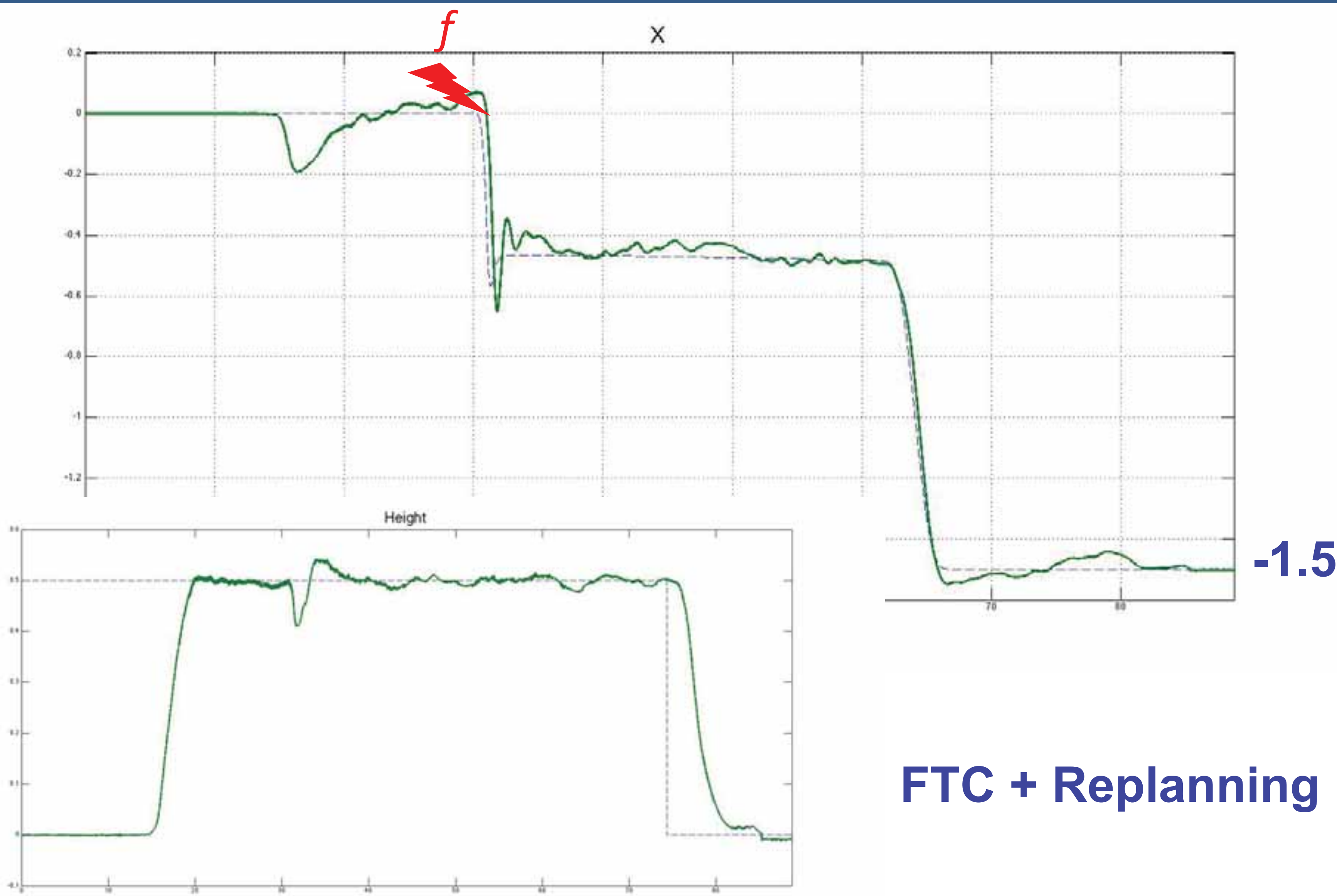
$$P^f \begin{cases} \text{Minimize} & t_{frep} - t_r \\ \text{Subject to} & \underline{\xi}^f \leqslant \phi_l^f \left(\mathcal{F}^*_{rep}, \dot{\mathcal{F}}^*_{rep}, \ddot{\mathcal{F}}^*_{rep}, \ldots, \mathcal{F}^{*(\gamma_l)}_{rep} \right) \leqslant \overline{\xi}^f \end{cases}$$

where $\underline{\xi}^f$ and $\overline{\xi}^f$ are post_fault



t_{frep} the end of expected mission

FTC+Replanning - Qball X4 with Actuator Fault = 30%



FTC + Replanning

Reference

INTERNATIONAL JOURNAL OF ADAPTIVE CONTROL AND SIGNAL PROCESSING
Int. J. Adapt. Control Signal Process. 2015; **29**:1–23
Published online 25 November 2013 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/acs.2451

Active fault-tolerant control system design with trajectory re-planning against actuator faults and saturation: Application to a quadrotor unmanned aerial vehicle

A. Chamseddine[1], D. Theilliol[2,3], Y. M. Zhang[1,*,†], C. Join[2,3] and C. A. Rabbath[1]

[1]*Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Quebec, Canada H3G 1M8*
[2]*Faculté des Sciences et Techniques, University of Lorraine, Vandoeuvre-lès-Nancy, France*
[3]*CNRS, CRAN, UMR 7039, France*

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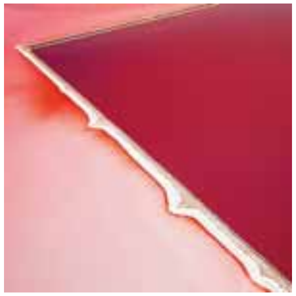

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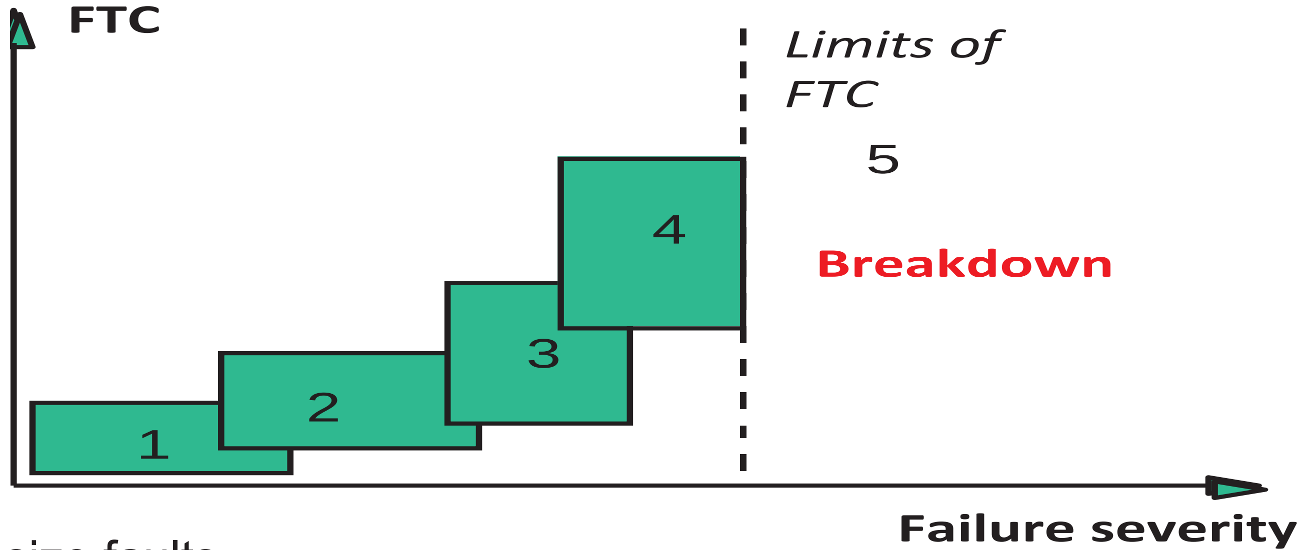

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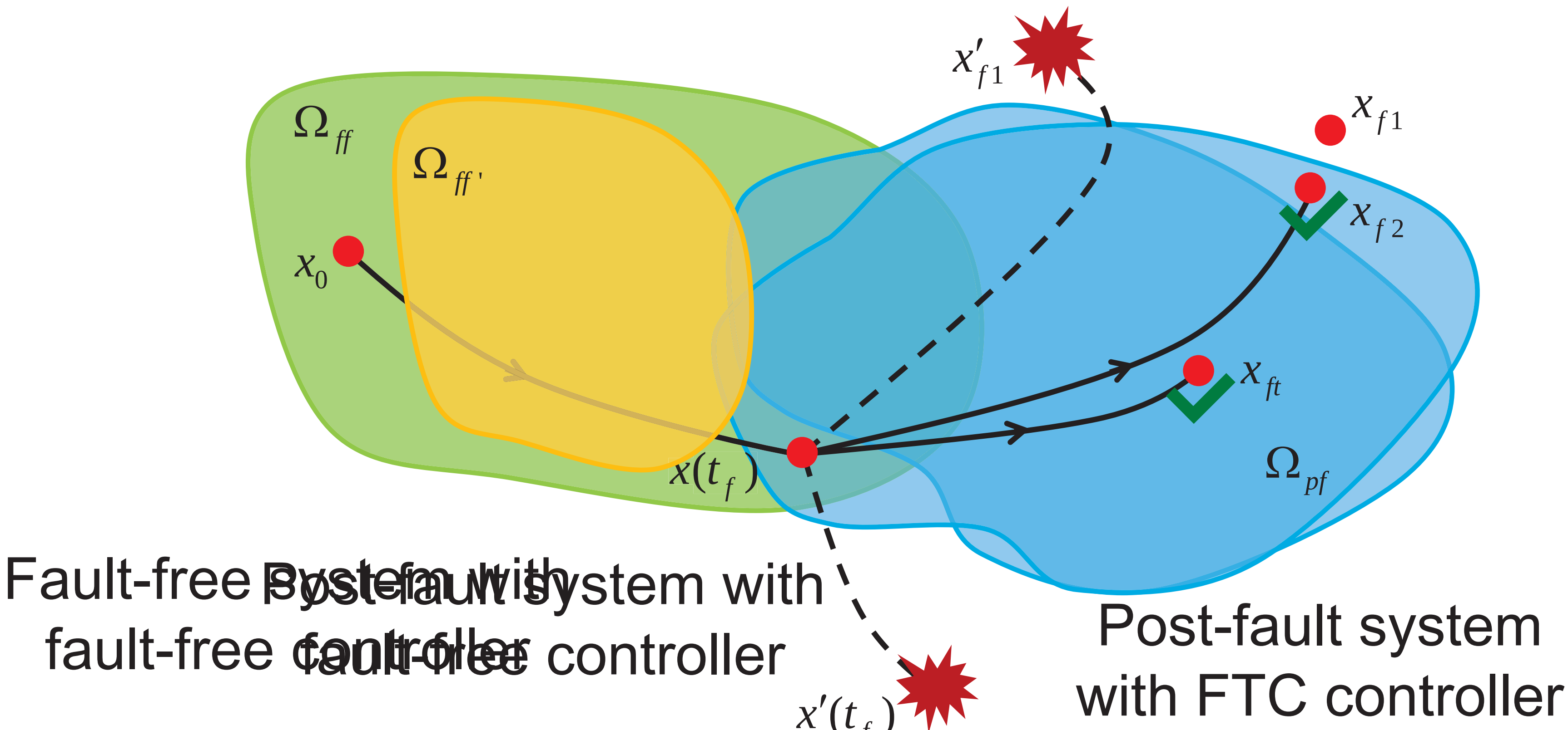
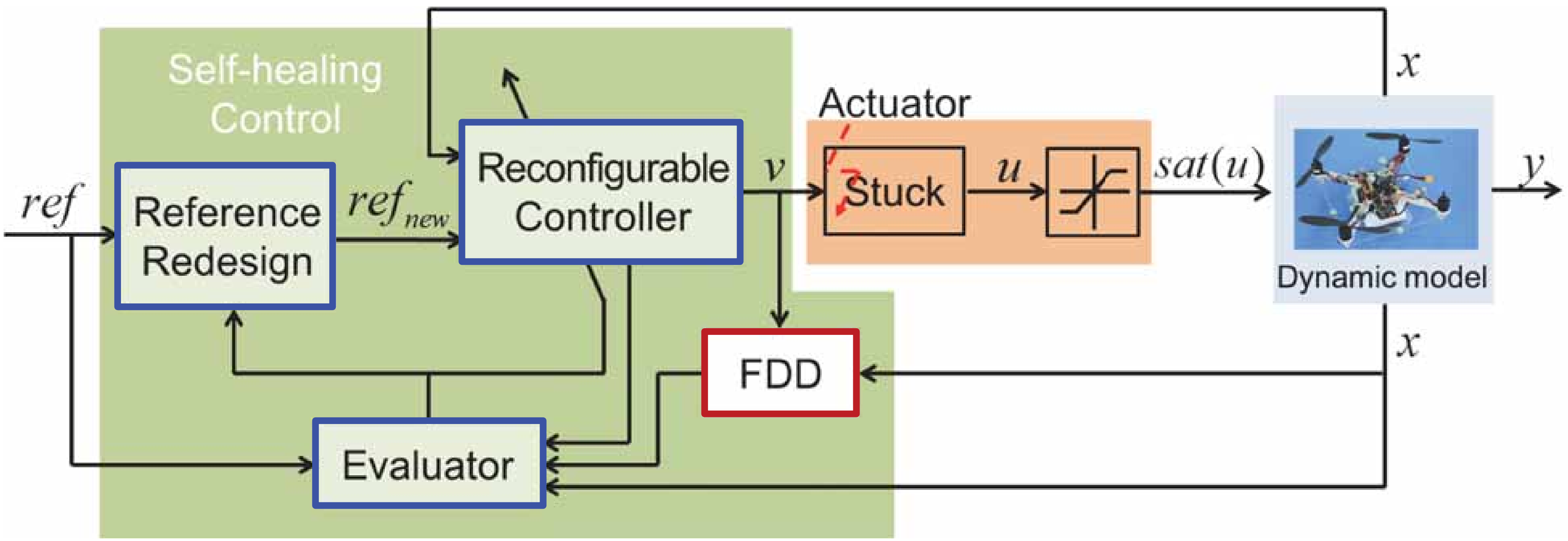
Extended FTC: Self-healing control

1. Fault-tolerant controller design
2. Fault compensation analysis
3. Reference reachability analysis
4. Reference redesign



Extended FTC: Self-healing control



Self-healing control is the extension of fault-tolerant control.

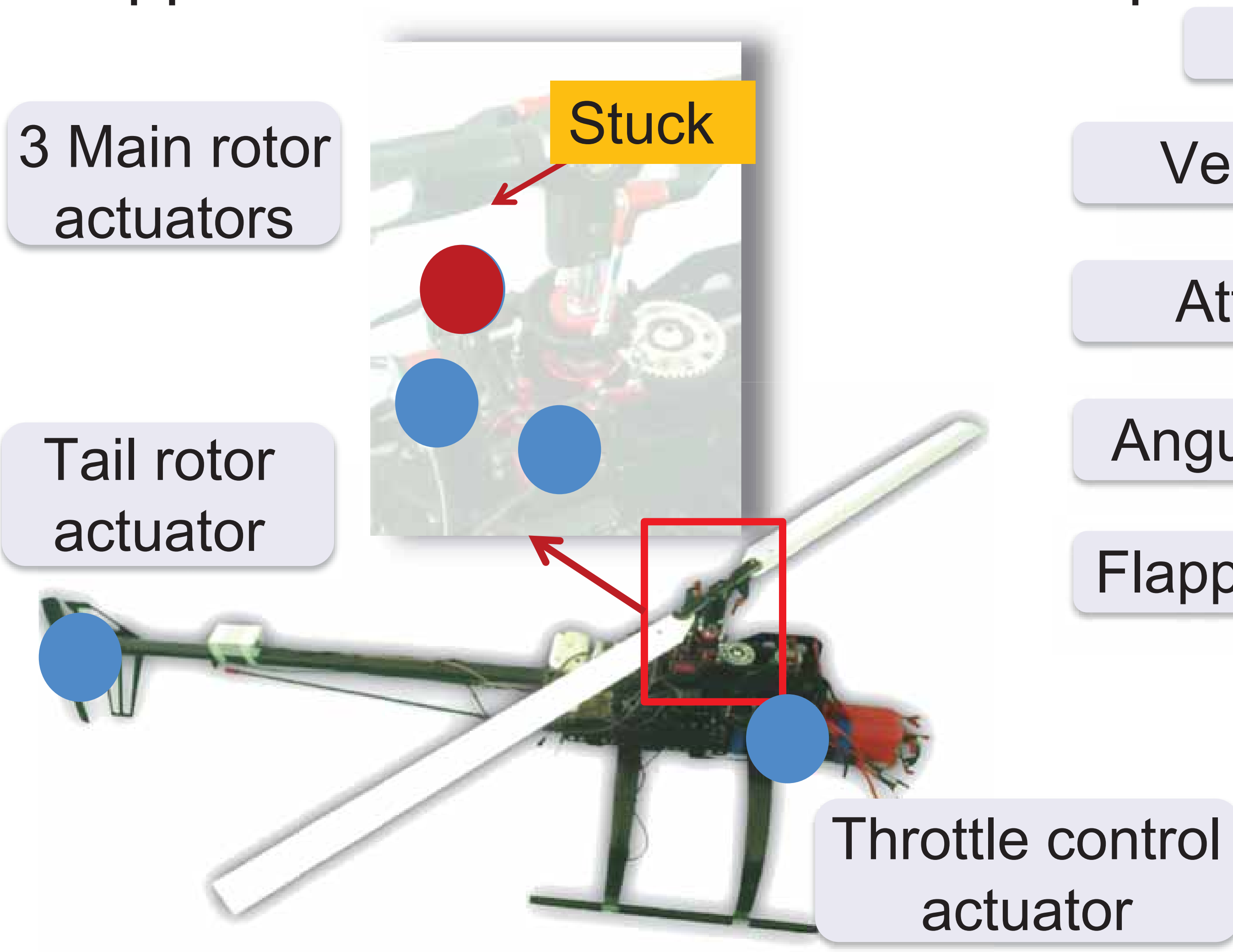
FTC - Unmanned Helicopter

Shenyang Institute
of Automation - RPC

Swashplate

FTC - Unmanned Helicopter

Application to an unmanned helicopter



11 States

- Velocities: u, v, w
- Attitudes: φ, θ, ψ
- Angular rates: p, q, r
- Flapping angles: a_{1s}, b_{1s}

Unmanned helicopter

Actuator constraints:

$$u_{\max} = -u_{\min} = \begin{bmatrix} 0.15 & 0.15 & 0.15 & 0.15 & 94.20 \end{bmatrix}$$

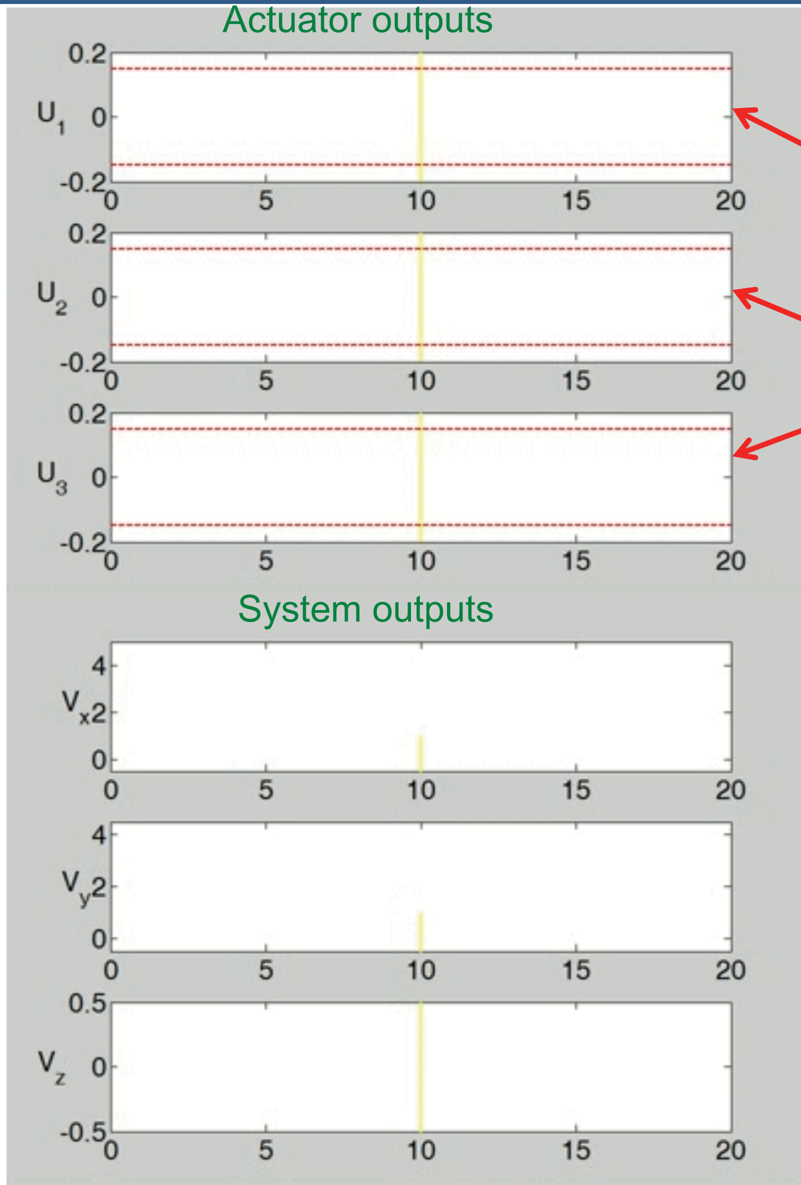
Original references:

$$ref = \begin{bmatrix} 4 & 4 & 0 & 0 \end{bmatrix}$$

Actuator stuck fault:

$$u_1 = u_f = 0.05$$

Unmanned helicopter simulation

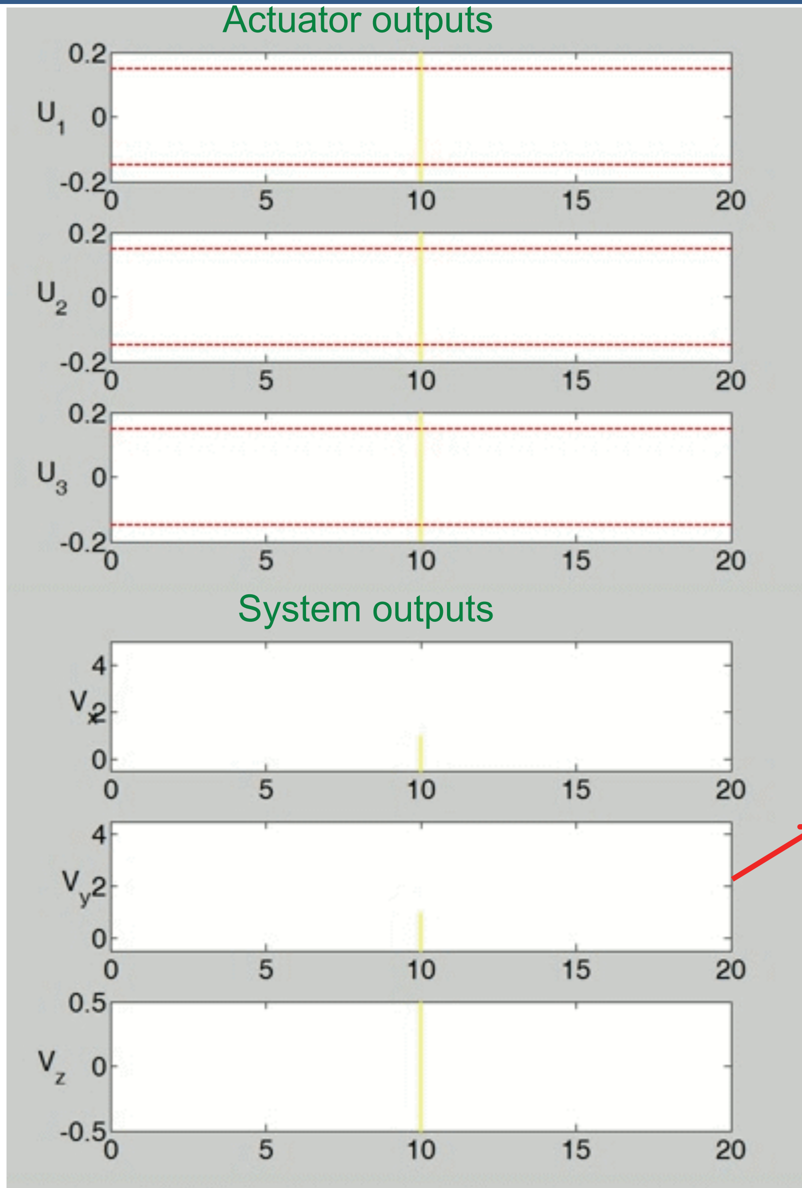


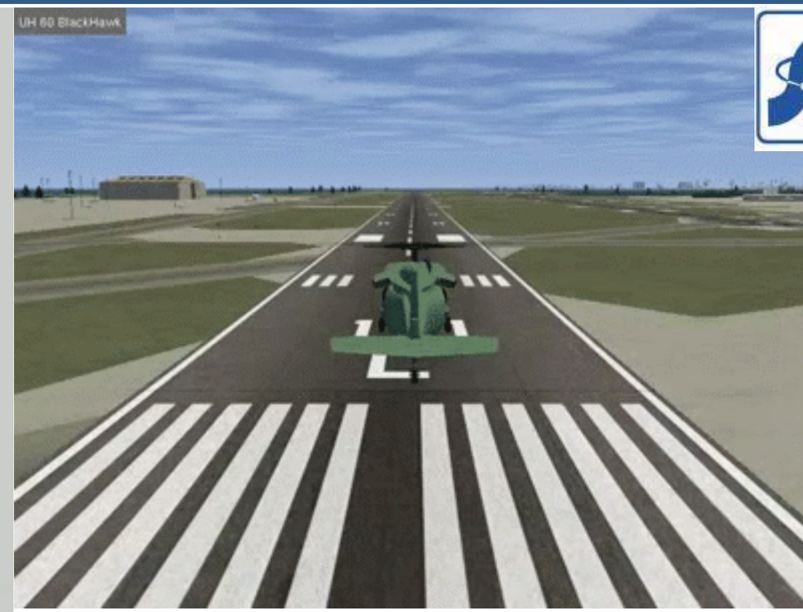
The first actuator is stuck at 10s.

Actuators are saturation.

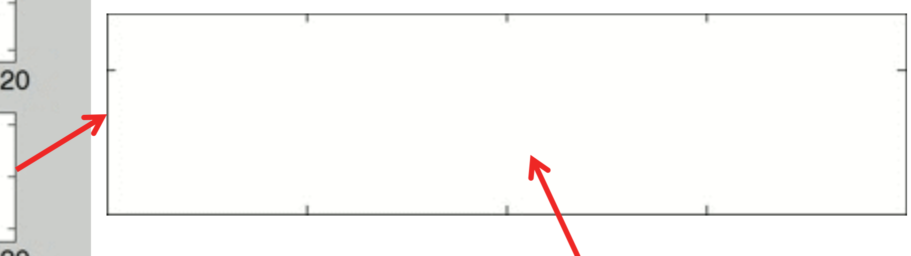
The helicopter is out of order.

Unmanned helicopter simulation



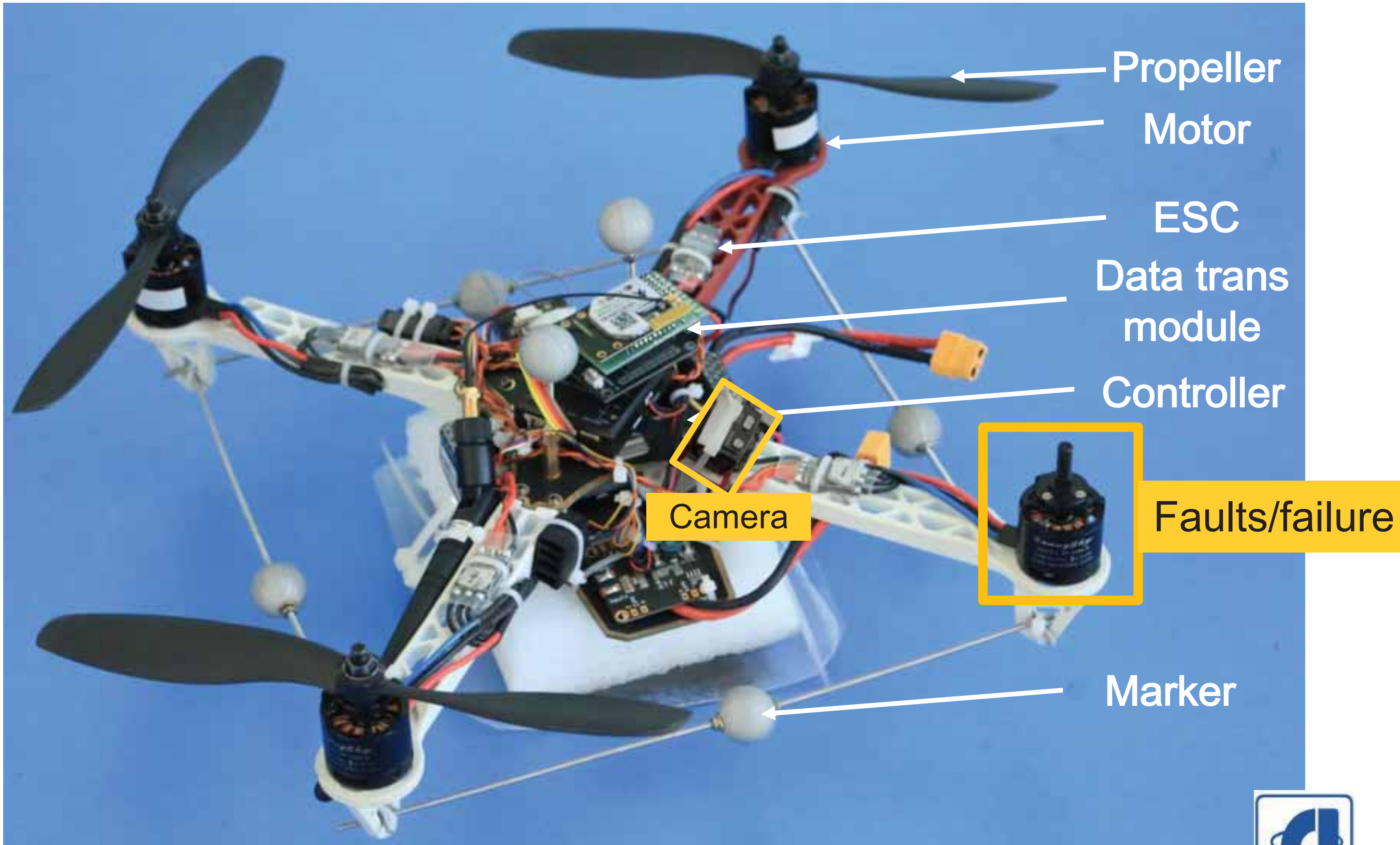


The helicopter is safe!!!



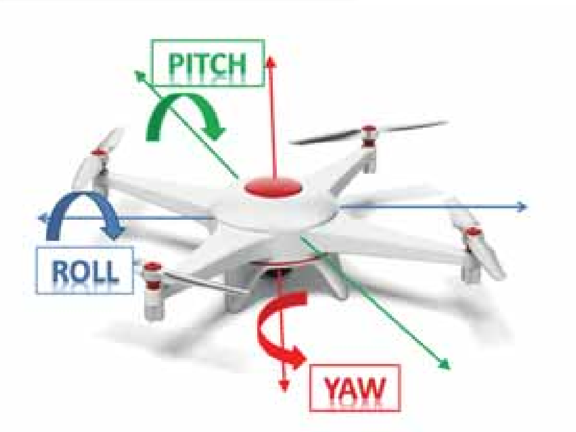
New reference

Quadrotor from SIA



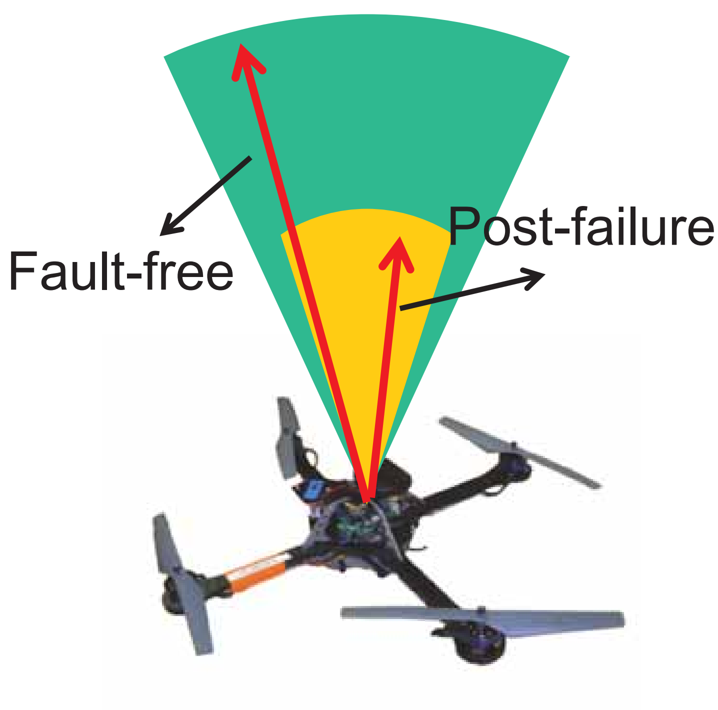
Relaxed hover solution (inspired from ETH work)

States	Hover	Relaxed Hover
Angular acceleration	0	0
Angular rates	0	*constant*
Attitudes(roll, pitch)	0	*constant*
Attitude(yaw)	*constant*	*uncontrollable*
Position	*Fixed point*	Around fixed point

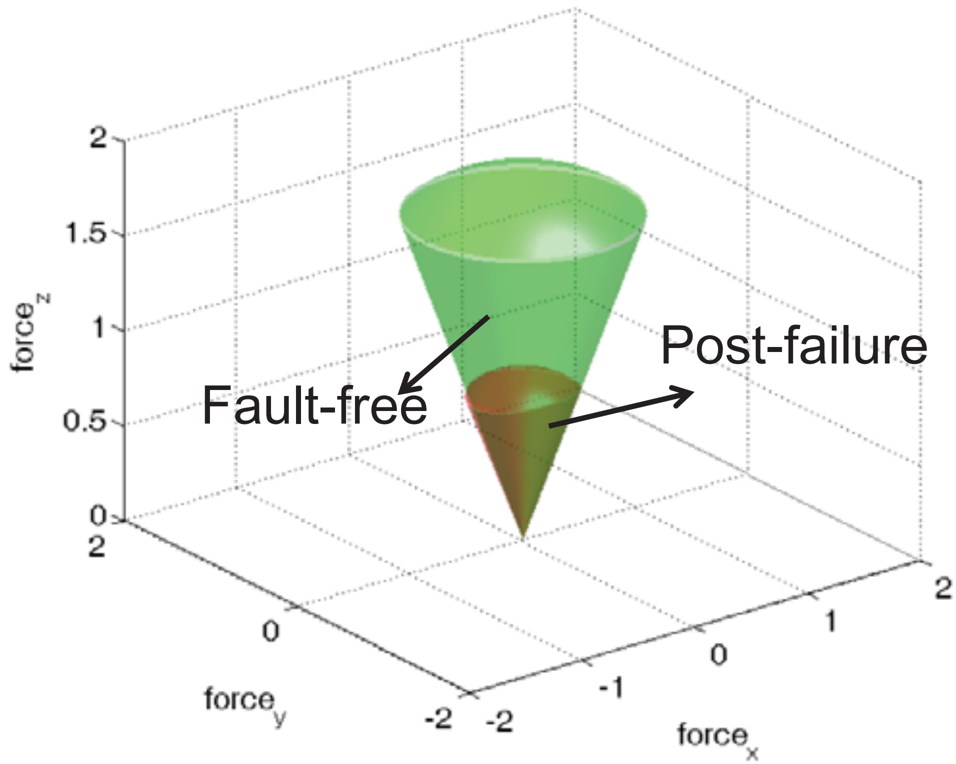


Analysis of reachable sets

Reachable sets (force vector, Propeller one 50% loss)



Force vector
(Pos & Att)



Reachable sets

Experiments on real quadrotor (indoor)

Self-Healing Control Design for Quadrotors: One motor failure case

Xin Qi, Didier Theilliol, Yuqing He and Jianda Han
Autonomous Robot Lab, Shenyang Institute of Automation, CAS
CRAN, CNRS, Université de Lorraine

中国科学院沈阳自动化研究所
SHENYANG INSTITUTE OF AUTOMATION CHINESE ACADEMY OF SCIENCES

CRAN

UNIVERSITÉ DE LORRAINE

References

X. Qi, D. Theilliol, Y. He, J. Han,
“Active fault-tolerant control framework against actuator stuck failures under input saturations",
International Journal of Applied Mathematics and Computer Science, Volume 27 – 2017

X. Qi, D. Theilliol, J. Qi, Y. Zhang, J. Han,
"Self-Healing Control Design under actuator faults occurrence on single-rotor Unmanned Helicopters",
Journal of Intelligent and Robotic Systems, volume 84, Issue 1-4, pp. 21-35, 2016

Qi X., D. Theilliol, Y. He J. Han,
“Recoverable Set Computation for Post-fault/failure Quadrotors based on Sum Of Squares“,
3rd International Conference on Control and Fault-Tolerant Systems SysTol'16, Barcelona, Spain, September 2016

X. Qi, J. Qi, D. Theilliol, J. Qi, Y. Zhang, J. Han, D. Song C. Hua
"A Review on Fault Diagnosis and Fault Tolerant Control Methods for Single-rotor AerialVehicles",
Journal of Intelligent and Robotic Systems, Vol. 73, No. 1-4, pp. 535-555, 2014

Fault-Tolerant Control ….

FTC, Reconfiguration, accommodation, recovery !!!!

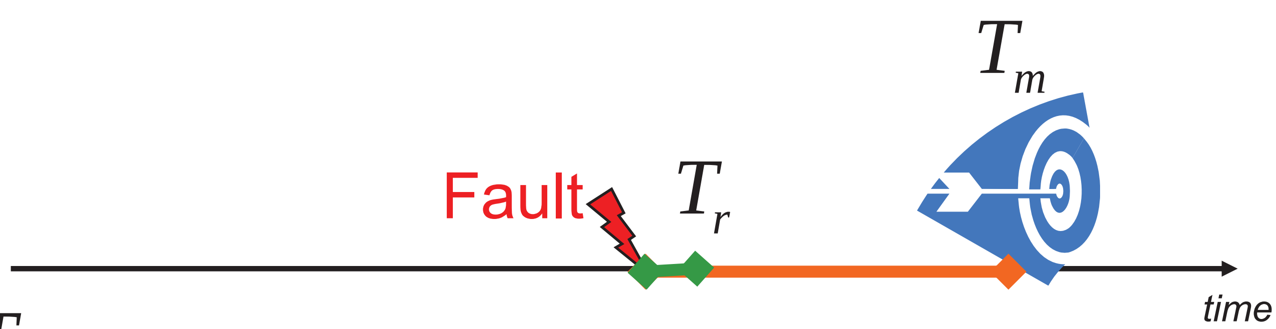
Fault-Tolerant Control ….

FTC, Reconfiguration, accommodation, recovery !!!!

some contributions to increase the safety of the system …

but not the global reliability (or health) of the system

in order to guarantee to achieve the end of the mission



T_m represents period between fault occurrence and the end of expected mission

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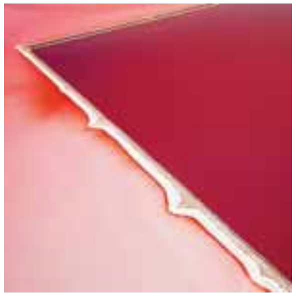

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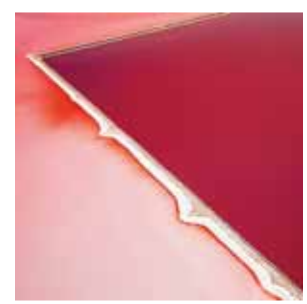
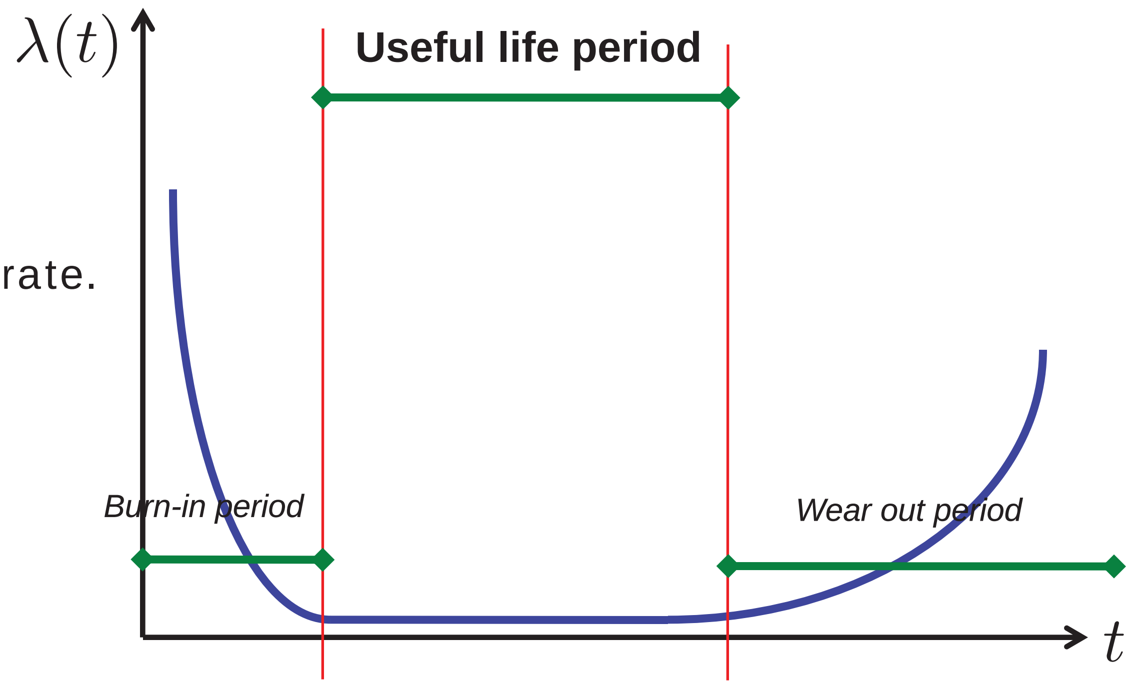


Reliability: “mathematic” definitions

Reliability R(t) is defined as the probability ***a priori*** that units, components, equipments and systems will accomplish their intended function for a specified period of time t under some operating conditions and specific environments [*].

$$R(t) = e^{-\int_0^t \lambda(t)\,\mathrm{d}t}$$

where λ(t) presents the failure rate.

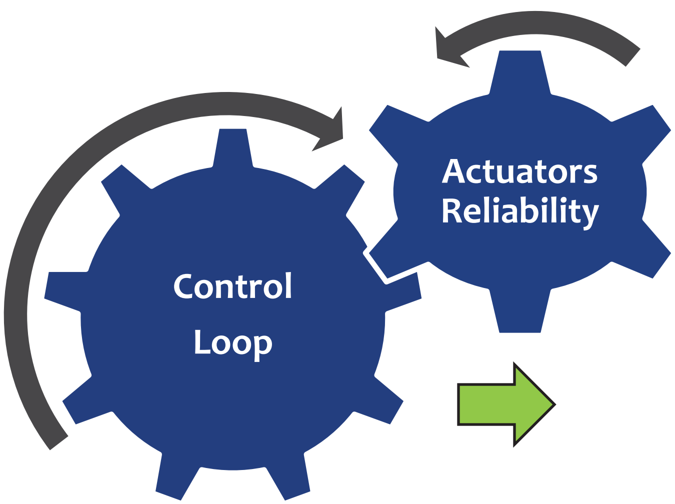


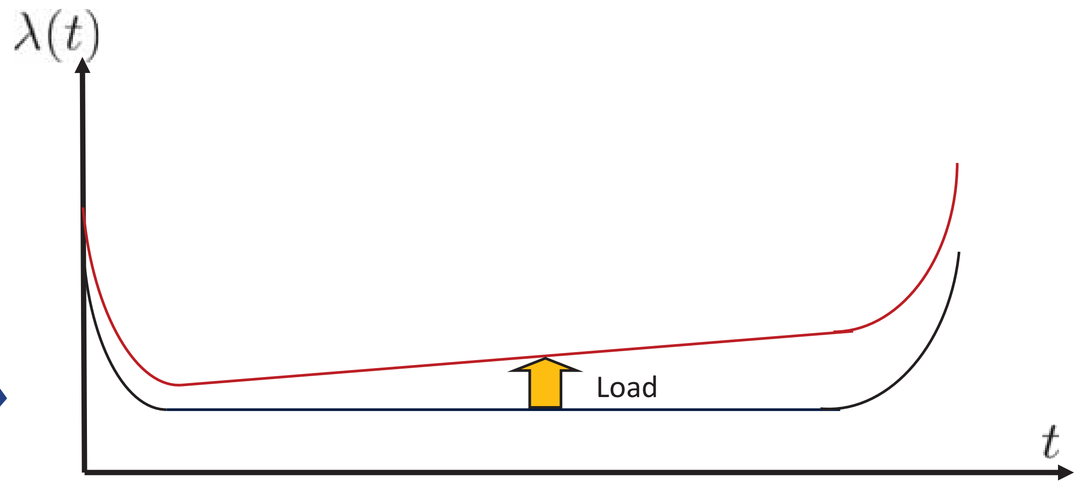
[*] *I. Gertsbakh. Reliability Theory with Applications to Preventive Maintenance. Springer, 2000.*

Reliability and Control

Reliability and Control theory

- Actuators are subject to a variable control input during their life
- Applied load modifies the characteristics of actuators reliability
- Failure rates are obtained under different load levels





Impact on reliability

Reliability analysis for actuator component

Nominal Reliability $$R_i^0(t) = \exp(-\lambda_i^0 t), \quad i = 1, \ldots, m$$

Failure rate $$\lambda_i(t) = \lambda_i^0(1 + g(\ell_i)), \quad i = 1, \ldots, m$$

Load function $$g(\ell_i) = \frac{\beta_i}{t} \int_0^t u_i^2(\tau) d\tau, \quad i = 1, \ldots, m$$

At time $t \in [t_1, t_M]$

$$R_i(t) = \exp(-\lambda_i(t_1) \times (t - t_1)), \quad i = 1, \ldots, m$$

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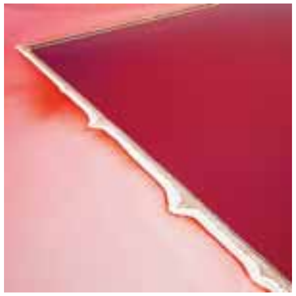


Control Method for Overactuated Systems

- Nominal system

$$\begin{cases} \dot{x}(t) = Ax(t) + B_u u(t) \\ y(t) = Cx(t) \end{cases}$$

$x(t) \in \mathbb{R}^n$ $\quad A \in \mathbb{R}^{n\times n}$

$u(t) \in \mathbb{R}^m$ $\quad B \in \mathbb{R}^{n\times m}$

$y(t) \in \mathbb{R}^r$ $\quad C \in \mathbb{R}^{p\times n}$

Overactuated system

$$rank(B_u) = l < m \quad \Rightarrow \quad B_u = B_v B$$

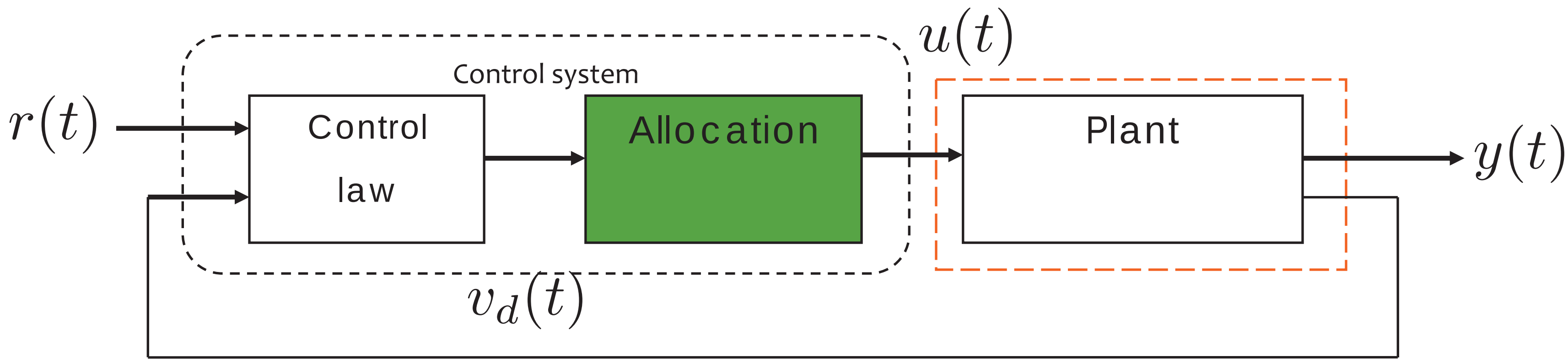
$$\begin{cases} \dot{x}(t) = Ax(t) + B_v v_d(t) \\ v_d(t) = Bu(t) \\ y(t) = Cx(t) \end{cases}$$

$v_d \in \mathbb{R}^l$

$B_v \in \mathbb{R}^{n\times l}$

$B \in \mathbb{R}^{l\times m}$

Basic concepts and properties



Problem description of Control Allocation

How to allocate and distribute the desired efforts to the set of actuators?

$$u(t) = ? \quad \Rightarrow \quad \dot{x}(t) = Ax(t) + B_v v_d(t)$$

Contents lists available at SciVerse ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Control allocation—A survey☆

Tor A. Johansen [1], Thor I. Fossen

Department of Engineering Cybernetics, Center for Autonomous Marine Operations and Systems, Norwegian University of Science and Technology, Trondheim, Norway

Control Allocation Method

Allocation problem without actuators saturations

$$u^* = \arg\min_{u \in \psi} \|W_u u\|_2$$

$$\psi = \arg\min_{u_{\min} \le u \le u_{\max}} \|Bu - v_d\|_2$$

$\Rightarrow$

$$\min_u J = \|W_u u(t)\|_2$$
$$s.t. \quad Bu(t) = v_d(t)$$

A simple control allocation method is the Pseudo-Inverse approach with the following explicit solution

$$u(t) = W_u^{-1}(BW_u^{-1})^+ v_d(t)$$

$W_u = diag([w_1, w_2, ..., w_q]^T)$ a positive definite weighting diagonal matrix

Control Allocation Method

Allocation problem WITH actuators saturations

- Mixed optimization problem $\epsilon \in [0,\ 1]$

$$u = \underset{u_{\min} \le u \le u_{\max}}{\arg\min} \quad (1-\epsilon)\|Bu - v_d\|_2 + \epsilon\|W_u u\|_2$$

- Fixed point algorithm (among 8 others)

$$u^k = \mathrm{sat}[(1-\epsilon)\eta B^T v_d + (I_m - \eta H)u^{k-1}], \quad k = 1, \ldots, N$$

with

$$H = (1-\epsilon)B^T B + \epsilon Q_2$$
$$Q_2 = W_u(t)^T W_u(t)$$
$$\eta = \|H\|_F^{-1}$$

where

$$\mathrm{sat}_i(u) = \begin{cases} \underline{u}_i, & u_i < \underline{u}_i \\ u_i, & \underline{u}_i \le u_i \le \bar{u}_i, \quad i = 1, \ldots, m \\ \bar{u}_i, & u_i > \bar{u}_i \end{cases}$$

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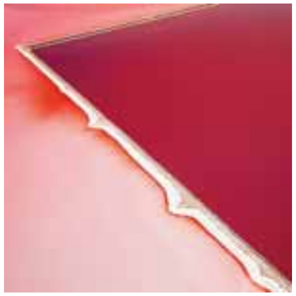


Problem statement

Optimal approaches of Control Allocation or Reallocation Method

Optimization problem $$u^* = \arg\min_{u\in\psi} \|W_u u\|_2$$

W_u gives some specific priority to the actuators

Choice of the weighting matrix

Generally, the current choice :

- Equal distribution
- Heuristic priority of the actuators
- Min and Max properties

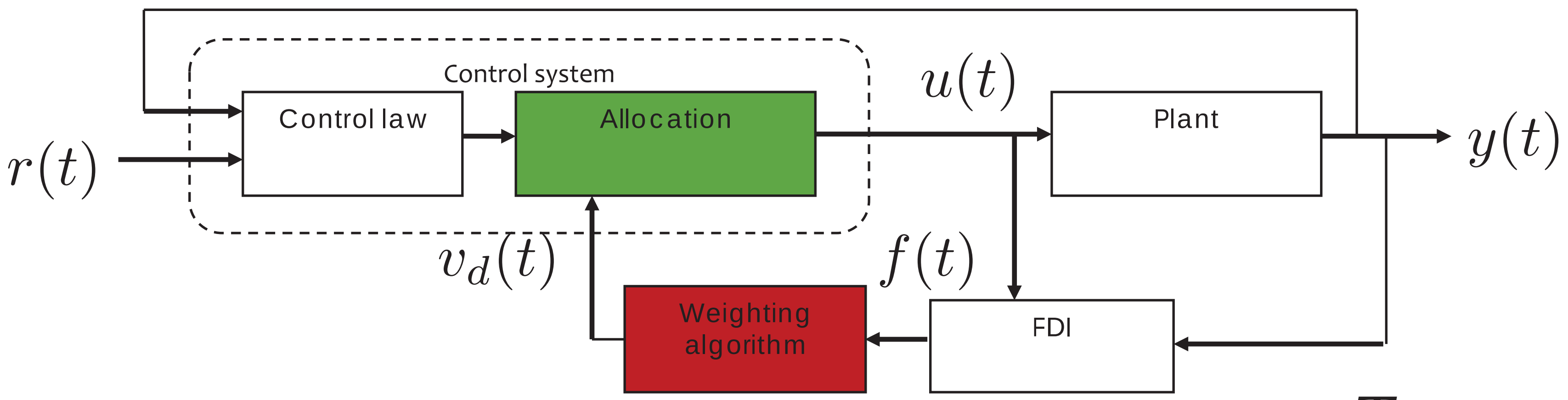
→ $W_u = I$ A useful solution

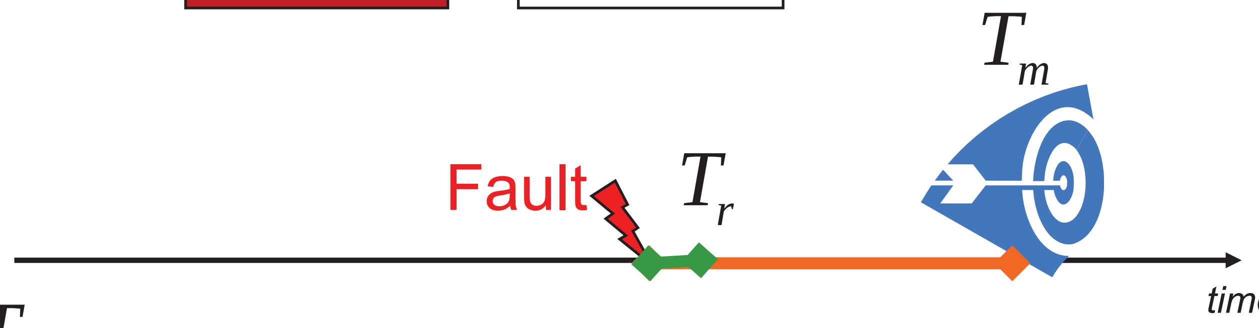
weighting matrix (Idea)!

W_u is chosen in order to improve the system dependability

Control (re) allocation method

To summarize: For overactuated systems, the reconfigurable control allocation, or called control re-allocation is to provide an admissible management of the redundant actuators throughthe re-distribution of the desired control efforts among the remaining healthy actuators.



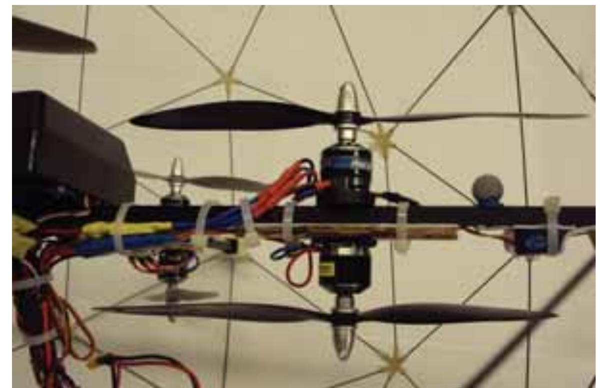


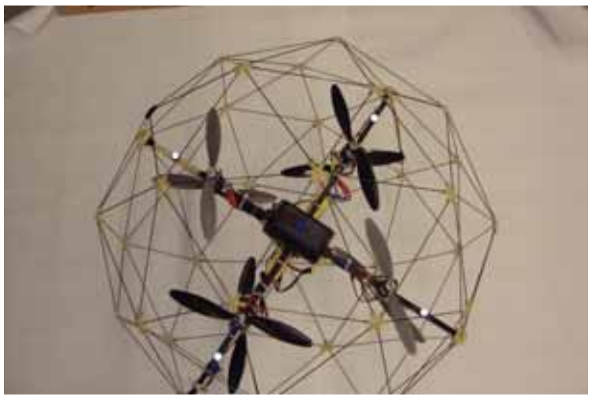
T_m represents period between fault occurrence and the end of expected mission

Application Qball-X8

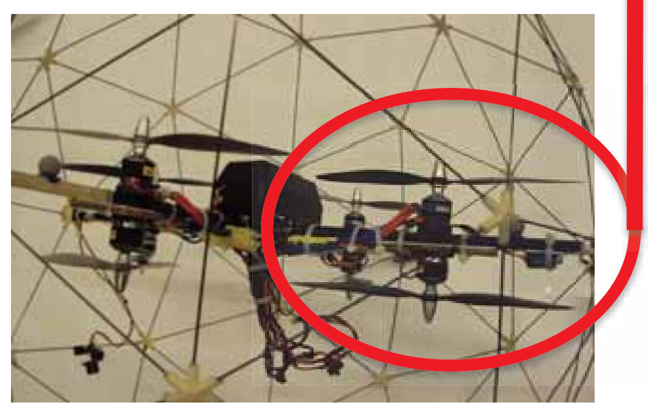
Why to modify the Qball-X4 ?

To increase system's reliability, safety and capability, four additional actuators are added.



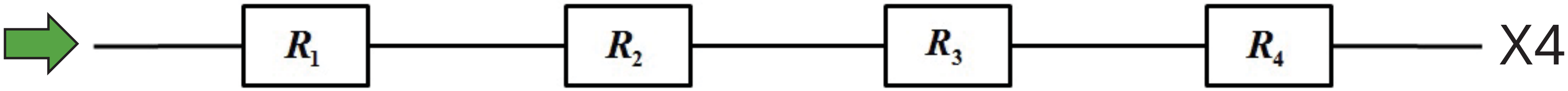


Top view



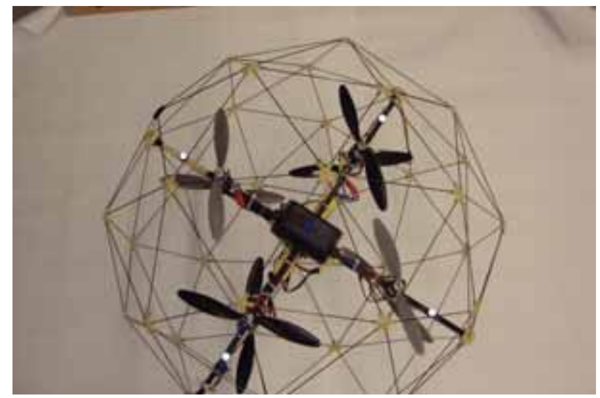
Side view

Reliability Diagram

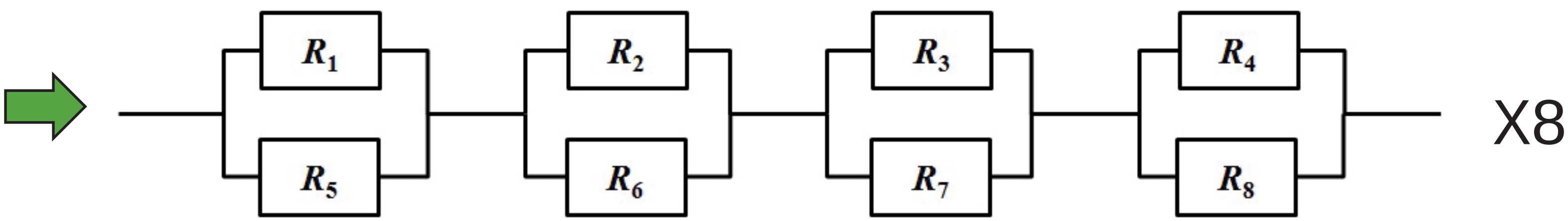


$$R_g^{X4}(t) = \prod_{i=1}^{4} R_i(t)$$

$$R_g^{X8}(t) > R_g^{X4}(t)$$



$$R_g^{X8}(t) = \prod_{i=1}^{4} [1 - (1 - R_i(t)) \times (1 - R_{i+4}(t))]$$



$$R_i(t) = e^{-\lambda_i \times t}$$

Control allocation: Weighting Functions

The objective is to increase the global reliability of the system. This is achieved by adjusting the weighting matrix W to penalize the least reliable actuators and reduce their duties, and consequently increase the duties of the most reliable actuators. To this end, the weighting matrix W is defined as:

$$W_u = \begin{pmatrix} \frac{\lambda_1}{\lambda_{max}} & \cdots & 0 \\ & \ddots & \\ \vdots & \frac{\lambda_i}{\lambda_{max}} & \vdots \\ & & \ddots \\ 0 & \cdots & \frac{\lambda_m}{\lambda_{max}} \end{pmatrix}$$

λ_{max} represents the maximal failure rate corresponding to the least reliable actuator.

Weighting Functions: Intuitive Approach

$$\Rightarrow \quad W_u = \begin{pmatrix} \frac{\lambda_1}{\lambda_{max}} & \cdots & 0 \\ & \ddots & \\ \vdots & \frac{\lambda_i}{\lambda_{max}} & \vdots \\ & & \ddots \\ 0 & \cdots & \frac{\lambda_m}{\lambda_{max}} \end{pmatrix}$$

When $\lambda_i < \lambda_{max}$ **then** $w_i < 1$ higher control input is allowed for the i-th actuator.

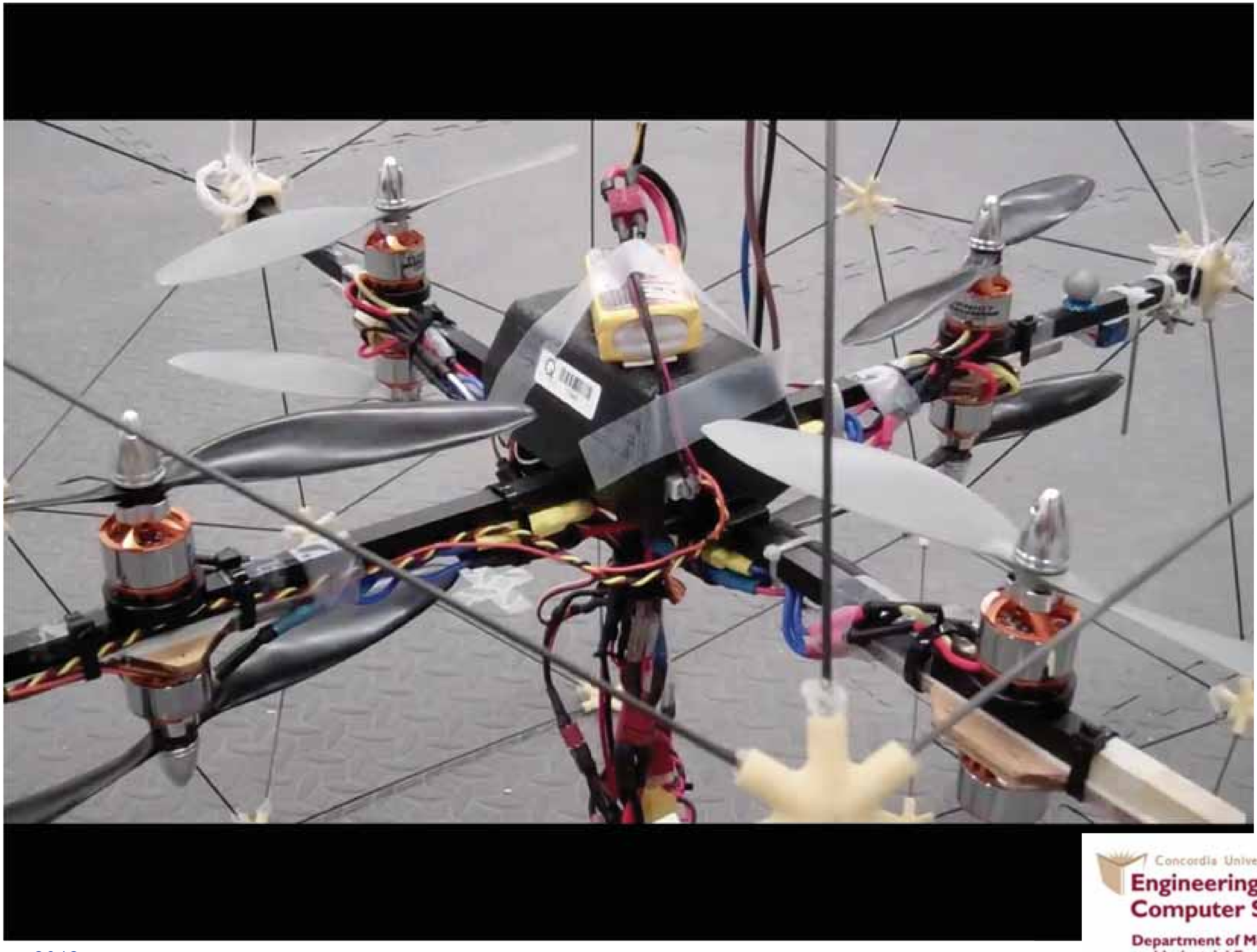
When $\lambda_i \mapsto \lambda_{max}$ **then** $w_i \mapsto 1$ and the i-th element of u(t) is more penalized compared with the previous case: a lower control input is then allowed for the i-th actuator.

Failure rates Qball-X8

	Top Motors			
	M_1	M_2	M_3	M_4
Rate λ_i	10×10^{-3}	6×10^{-3}	2×10^{-3}	5×10^{-3}

	Bottom Motors			
	M_5	M_6	M_7	M_8
Rate λ_i	1×10^{-3}	4×10^{-3}	3×10^{-3}	2×10^{-3}

Failure rates Qball-X8



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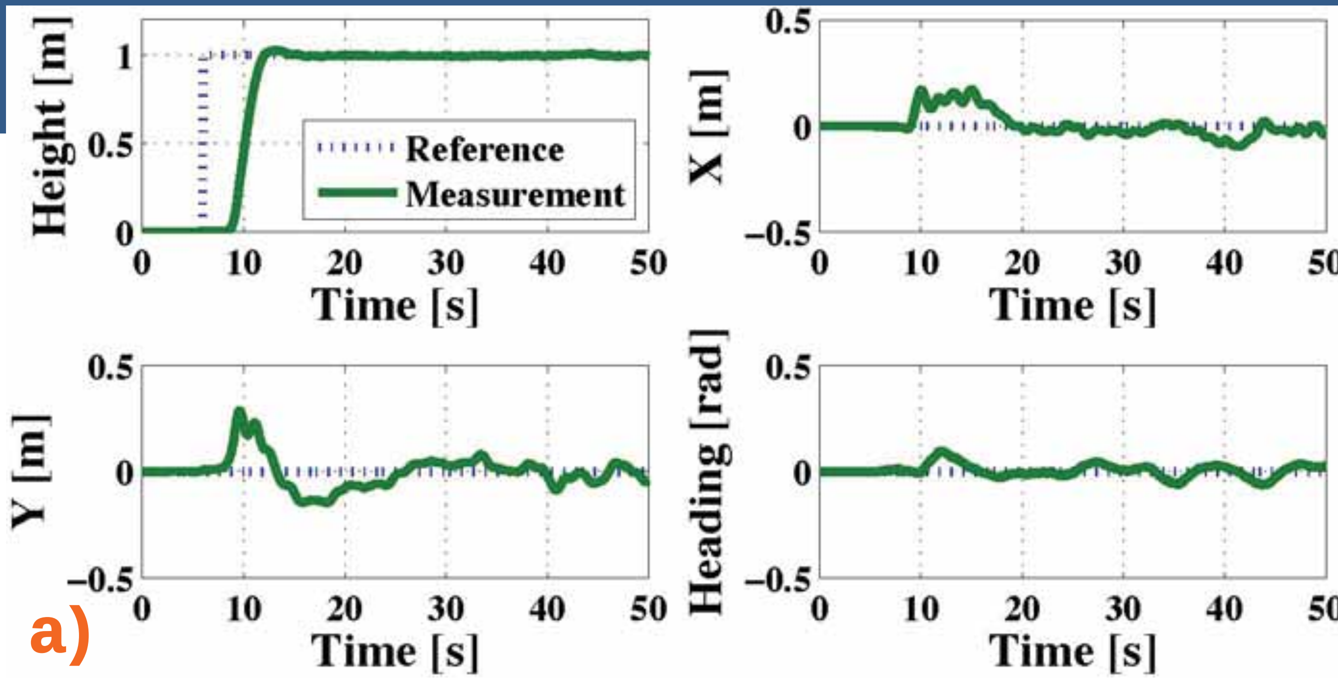
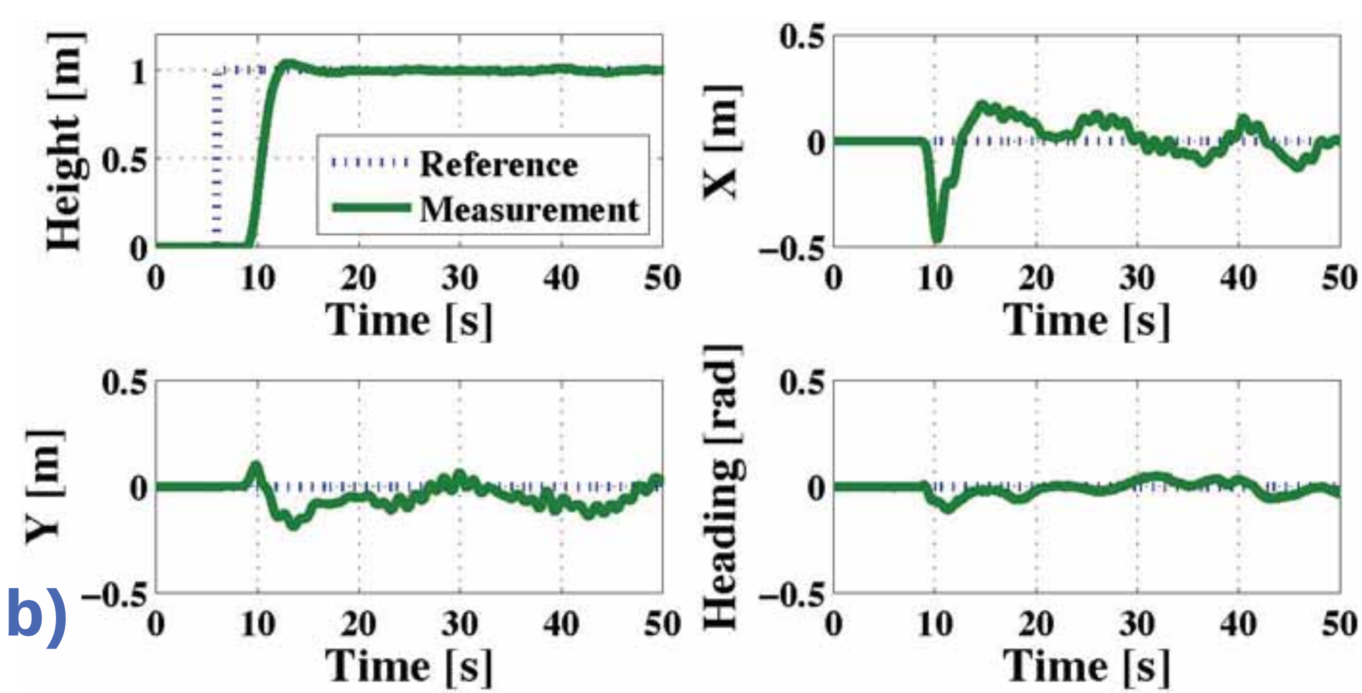
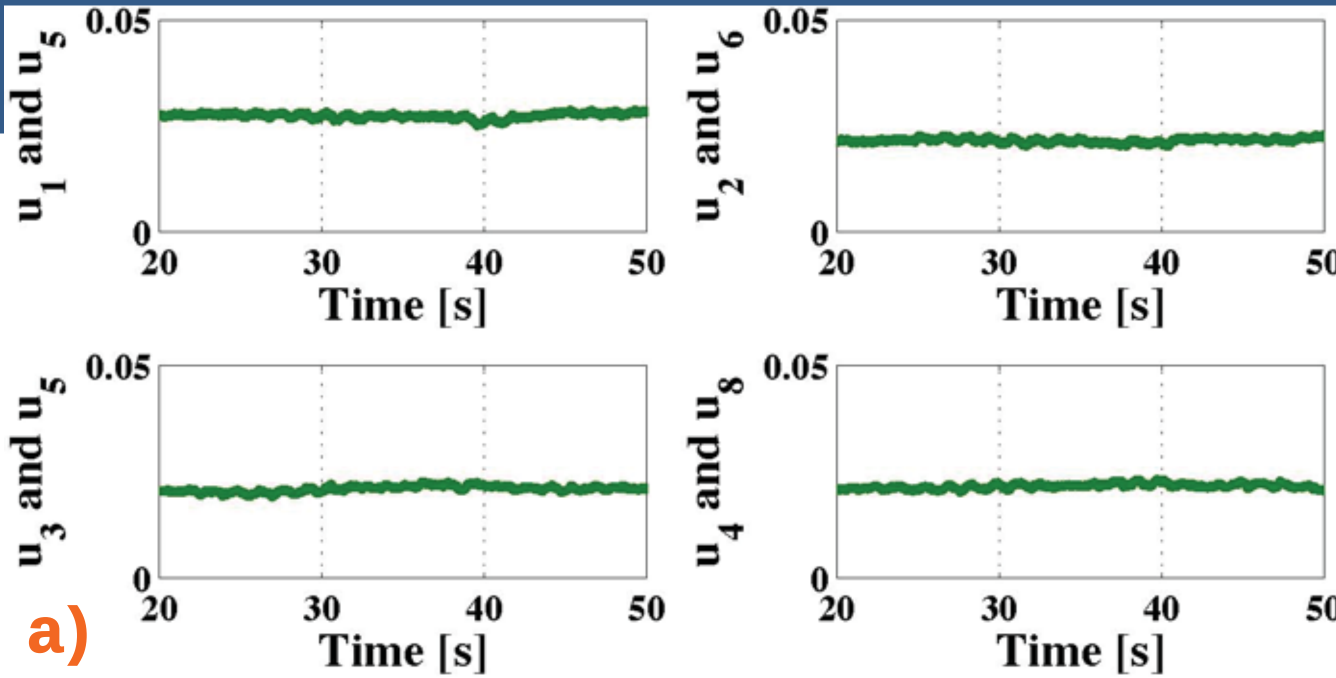
Outputs :



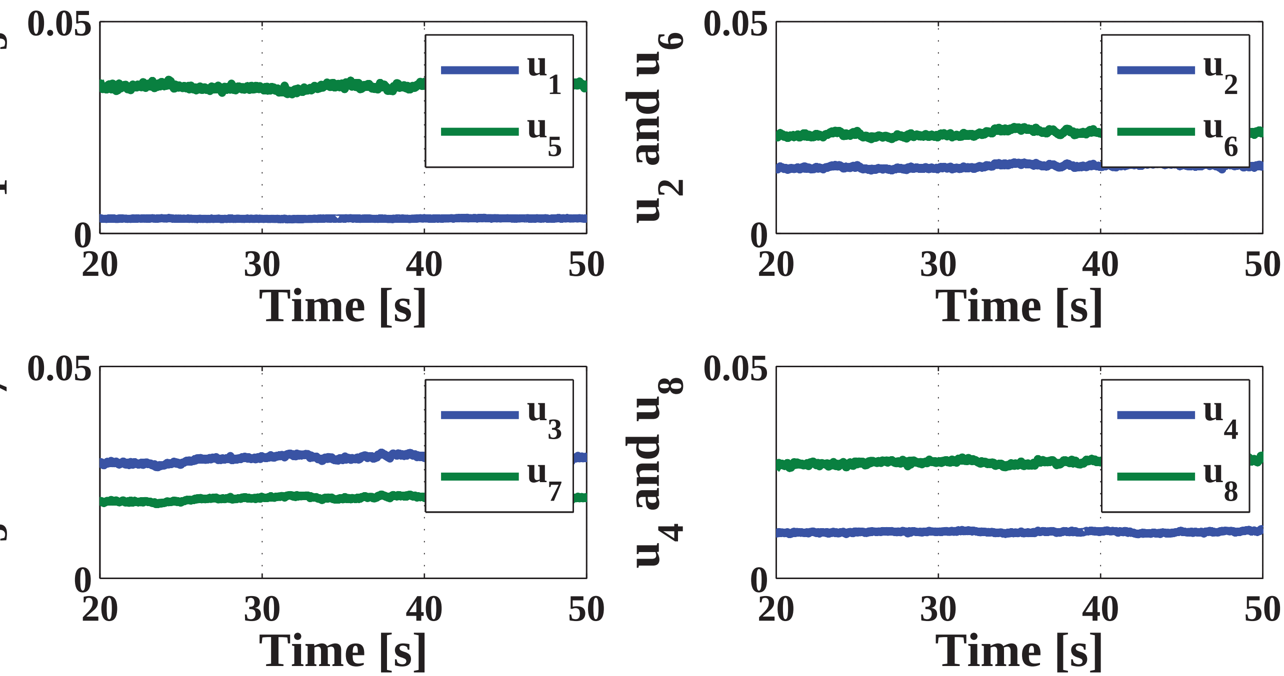
The system states remain similar in both cases **a)W=I** and **b) W=f(R)**.



Inputs :



a)



b)

The PWM control inputs are not the same **a)W=I** and **b) W=f(R)**.

Quantitative comparison

	Top Motors			
	M_1	M_2	M_3	M_4
Rate λ_i	10×10^{-3}	6×10^{-3}	2×10^{-3}	5×10^{-3}

	Top Motors			
	$\lVert u_1 \rVert$	$\lVert u_2 \rVert$	$\lVert u_3 \rVert$	$\lVert u_4 \rVert$
Without reliability	2.106	1.642	1.603	1.656
With reliability	0.2654	1.1989	2.1720	0.8331

	Bottom Motors			
	M_5	M_6	M_7	M_8
Rate λ_i	1×10^{-3}	4×10^{-3}	3×10^{-3}	2×10^{-3}

	Bottom Motors			
	$\lVert u_5 \rVert$	$\lVert u_6 \rVert$	$\lVert u_7 \rVert$	$\lVert u_8 \rVert$
Without reliability	2.106	1.642	1.603	1.656
With reliability	2.6541	1.7984	1.4480	2.0828

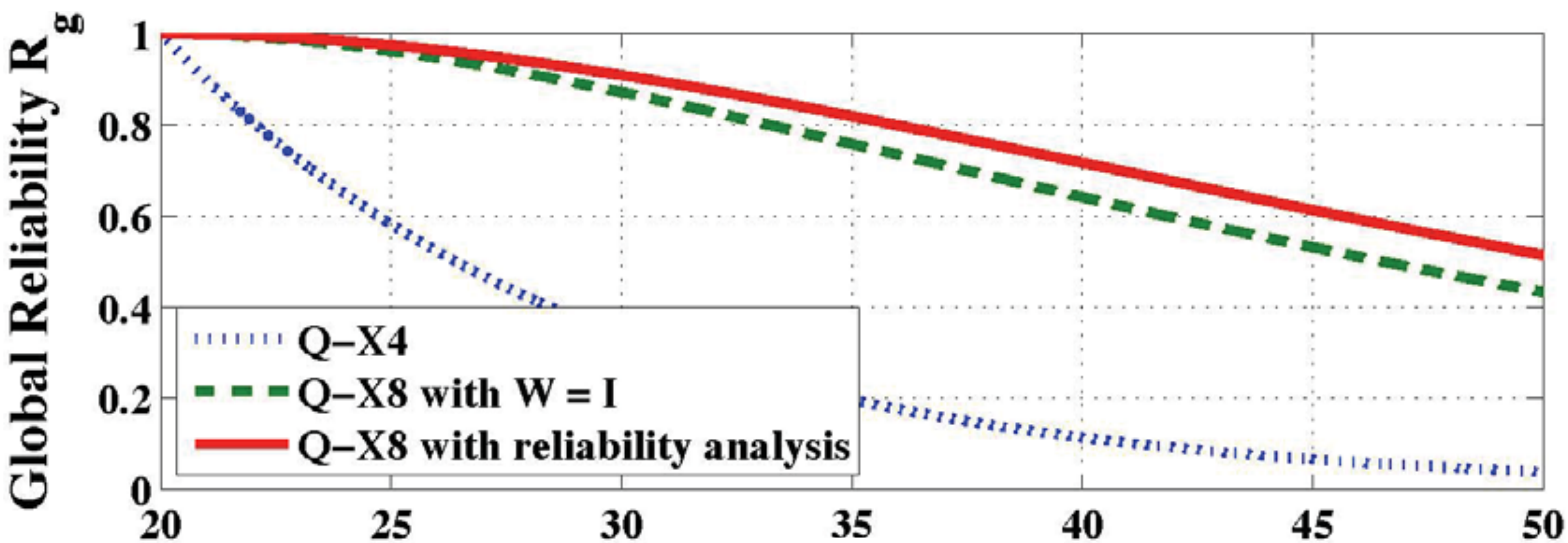
Without reliability analysis, the control inputs to the redundant motors are the same.

With reliability analysis, the control inputs to the most reliable actuators are larger than those to the least reliable actuators.

Global Reliability “a posteriori”

The reliability of the Qball-X4 dramatically drops down (**blue** line) because of the series configuration of its actuators and the lack of redundancy.

Actuator redundancy in the Qball-X8 greatly increases the overall system’s reliability (**green** line). Moreover, taking into consideration the actuator failure rates in the control allocation helps to further improve the global reliability (**red** line).



FTC: Control (re) Allocation Method

- Faulty system

$$\begin{cases} \dot{x}(t) &= Ax(t) + B_v v_d(t) \\ v_d(t) &= B_f u(t) \\ y(t) &= Cx(t) \end{cases} \quad \Rightarrow \quad B_f = B(I_m - \Gamma)$$

[*1] present an adaptive fault tolerant actuator allocation for overactuated plants using an online parameter estimator coupled with an allocation algorithm to perform on-line control reconfiguration whenever necessary.

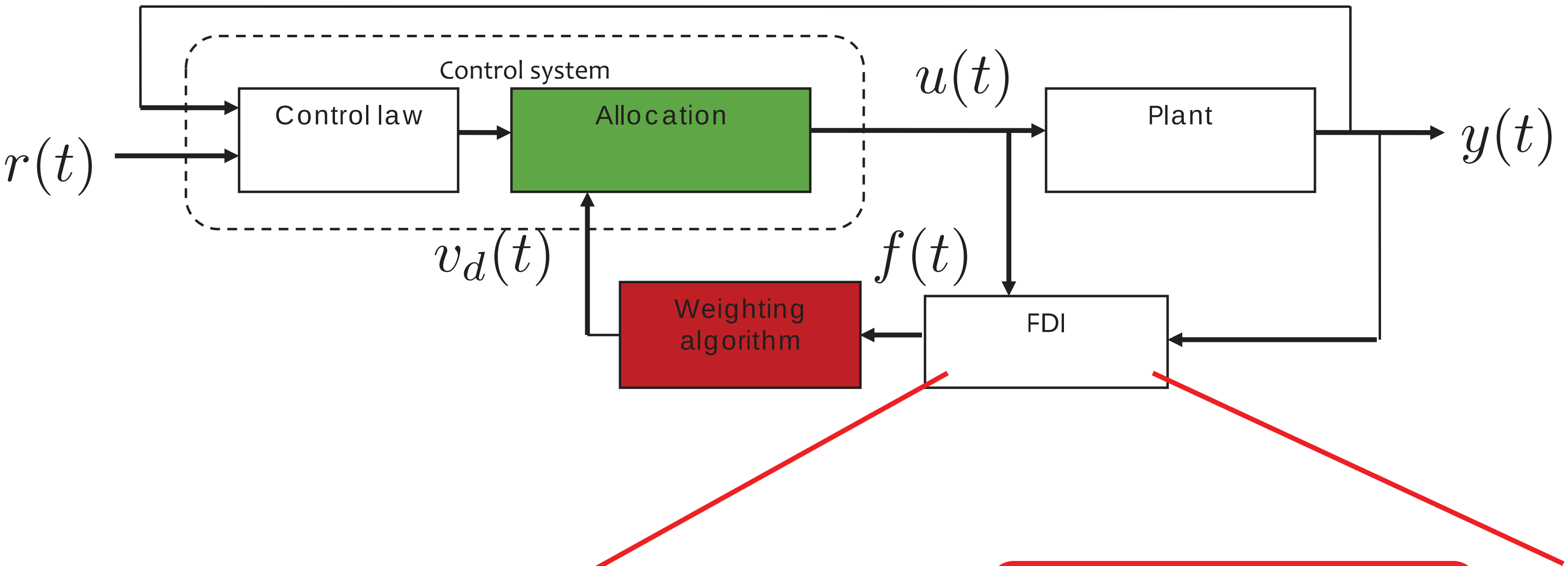
[*2] handle control effector failures based on a one-line control re-allocation method according to fault magnitude estimation .

[*3] for linear system or [*4] for nonlinear system have developed a real-time reconfigurability of the control inputs with an exact penalty functions applied on the weighting matrix **Wu** based on FDI module.

[*1] *A. Casavola and E. Gerone. Adaptive fault tolerant actuator allocation for overactuated plants. In Proceedings of the 2007 American Control Conference,New York City, USA, pp. 3985–3989, 2007.*
[*2] *Y. M. Zhang, V.S. Suresh, B. Jiang, and D. Theilliol. Reconfigurable control allocation against aircraft control effector failures. IEEE International Conference on Control Applications, Singapore, Oct., pp 1197-1202, 2007.*
[*3] *T.A. Johansen, T.I. Fossen and P. Tondel. Efficient Optimal Constrainted Control Allocation via Multiparametric Programming. Journal of Guidance,Control, and Dynamics, vol. 28, no. 3, 2005.*
[*4] *H. Alwi and C. Edwards. Fault tolerant control using sliding modes with on-line control allocation. Automatica, vol. 4, 2008, pp 1859–1866.*

Application Qball-X8 – Actuator faulty-case

Control (re) allocation method



- **Faulty system**

$$B_f = B(I_m - \Gamma)$$

Application Qball-X8 – Actuator faulty-case

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Optimal solution

(Re)Allocation Solution with explicit solution

An optimal control (re)allocation method is defined as:

$$\forall t \; W_u(t) = \max_{R_g > (R_g^{W_u = I} + \xi)} R_g(t_m, (\|u\|_2)^2)$$

with $\quad R_g(t) = f(R_1(t), R_2(t), \ldots, R_m(t))$

and $\quad \forall t \in [t, t_m] \; R_i(t) = exp(-\lambda_i(t)(t - t_m))$

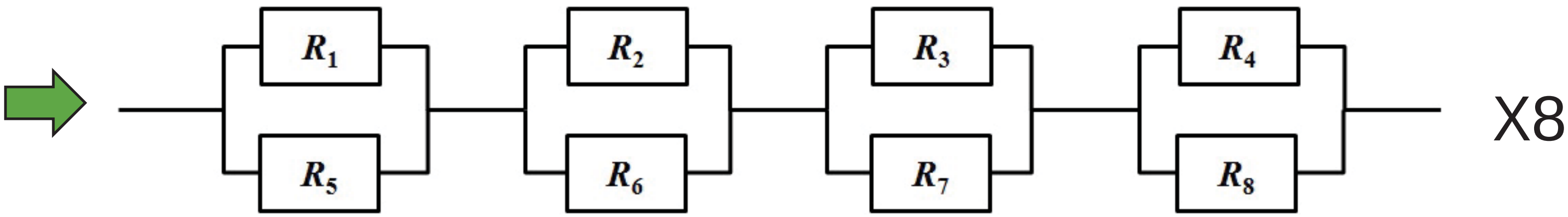
where $\quad \lambda_i(t) = \lambda_i^0(1 + \beta_i(\|u_i\|_2)^2)$

$$(\|u_i\|_2)^2 = h(W_u(t), B, (\|V_d\|_2)^2)$$

$\Rightarrow$ $u(t) = W_u^{-1}(BW_u^{-1})^+ v_d(t)$

Application to X8 - Simulation

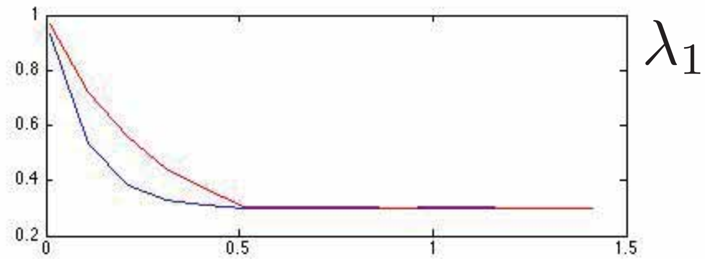
$$R_g^{X8}(t) = \prod_{i=1}^{4} [1 - (1 - R_i(t)) \times (1 - R_{i+4}(t))]$$



	Top, Bottom Motors			
	$M_1, 5$	$M_2, 6$	$M_3, 7$	$M_4, 8$
Rate λ_i	0.1×10^{-5}	0.9×10^{-5}	0.5×10^{-5}	0.5×10^{-5}

Application to X8 – Simulation - Rg

$$R_g(t_m = 300s, (\|u\|_2)^2) \text{ for } t = 40,000s$$

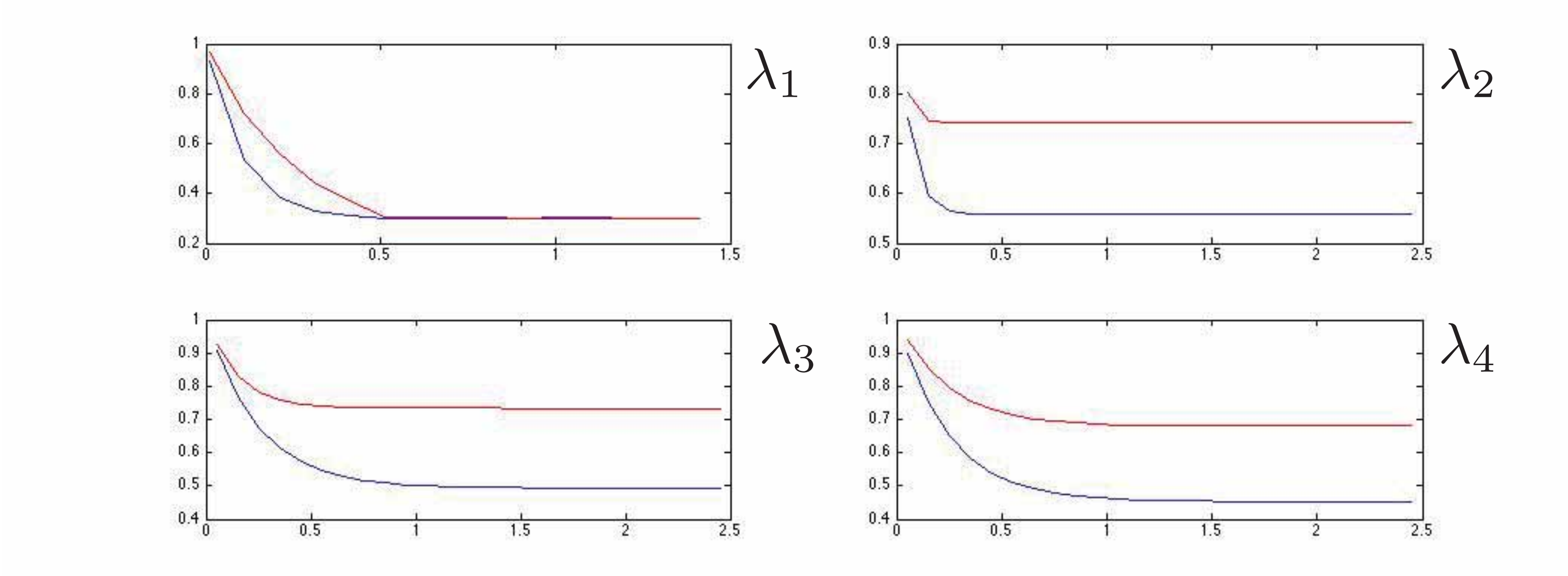


(red line) $$\forall t \; W_u(t) = \max_{R_g > (R_g^{W_u = I} + \xi)} R_g(t_m, (\|u\|_2)^2)$$

(blue line) $$u(t) = B^+ V_d(t)$$

Application to X8 – Simulation - Rg

$$R_g(t_m = 300s, (\|u\|_2)^2) \text{ for } t = 40,000s$$

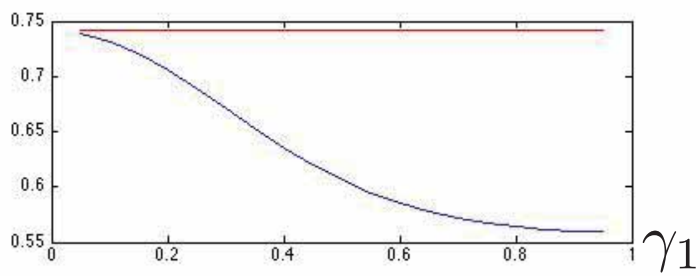


$$\forall t \; W_u(t) = \max_{R_g > (R_g^{W_u = I} + \xi)} R_g(t_m, (\|u\|_2)^2)$$

$$u(t) = B^{+} V_d(t)$$

Application to X8 – Simulation - Rg

$$R_g(t_m = 300s, (\|u\|_2)^2) \text{ for } t = 40,000s$$

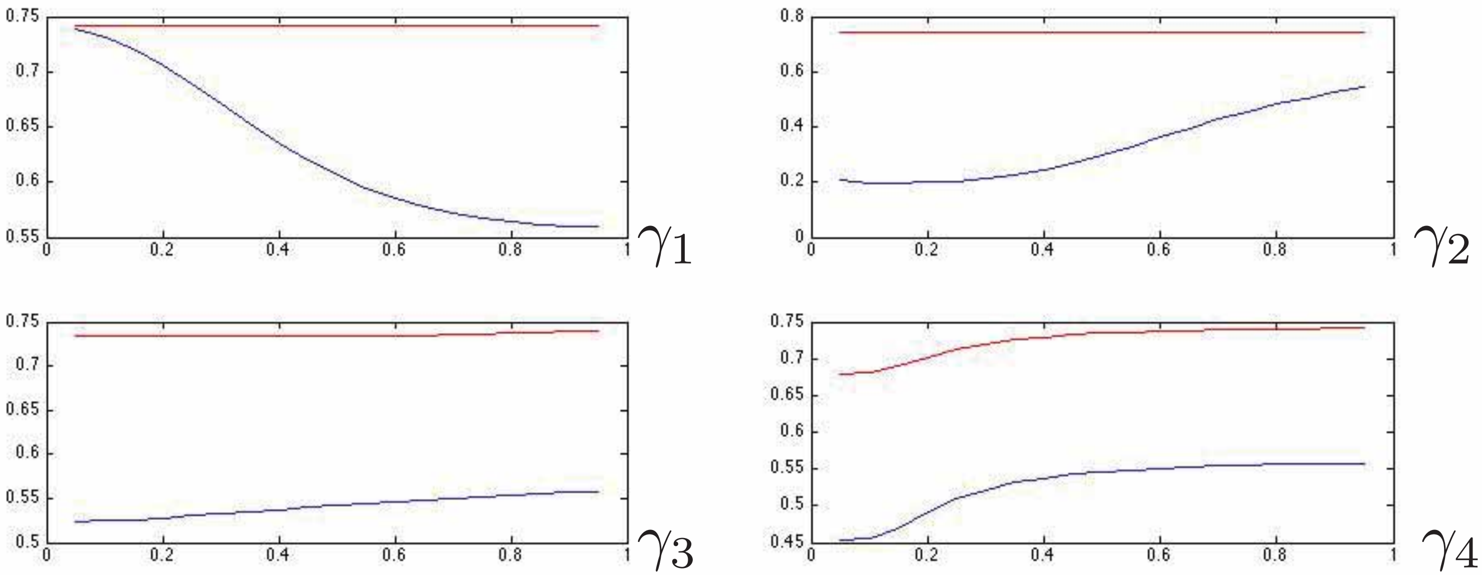


$$\forall t \; W_u(t) = \max_{R_g > (R_g^{W_u = I} + \xi)} R_g(t_m, (\|u\|_2)^2)$$

$$u(t) = B^+ V_d(t)$$

Application to X8 – Simulation - Rg

$$R_g(t_m = 300s, (\|u\|_2)^2) \text{ for } t = 40,000s$$



$$\forall t \; W_u(t) = \max_{R_g > (R_g^{W_u = I} + \xi)} R_g(t_m, (\|u\|_2)^2)$$

$$u(t) = B^{+} V_d(t)$$

Optimal Solution

(Re)Allocation Solution WITHOUT explicit solution

$$\begin{cases} u^* = \arg\min_{u \in \psi} \|W_u u\|_2 \\ \psi = \arg\min_{u_{\min} \le u \le u_{\max}} \|Bu - v_d\|_2 \end{cases}$$

$$+ \quad \forall t \; W_u(t) = \max_{R_g > (R_g^{W_u = I} + \xi)} R_g(t_m, (\|u\|_2)^2)$$

Reference

Reliability Engineering and System Safety 132 (2014) 196–206

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Optimal reliability design for over-actuated systems based on the MIT rule: Application to an octocopter helicopter testbed

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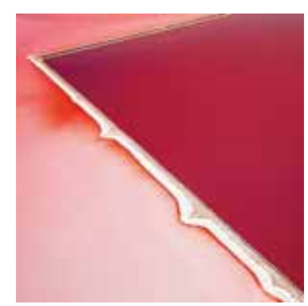
OUTLINES

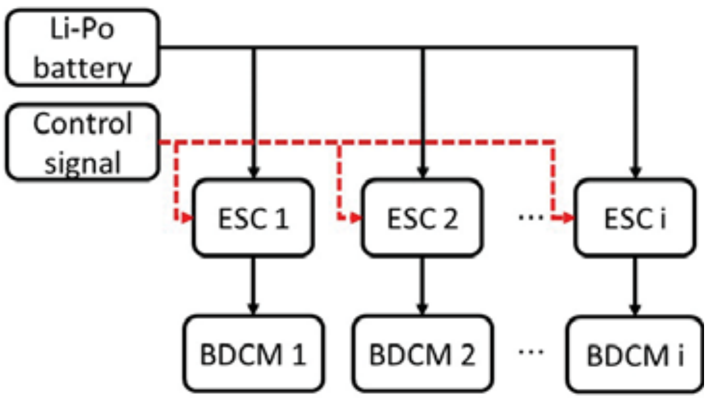
- Context
- Fault Tolerant Control
  - Problem statement
  - Principle and some definitions
  - Active FTC under fault effectiveness
    - under critical fault
    - under severe fault
- Fault Tolerant Control versus Health

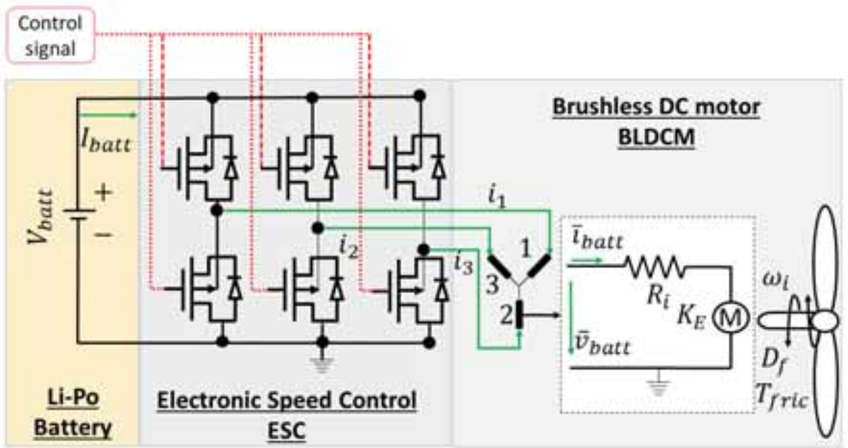
  - Definitions
  - Overactuated Systems
  - Heuristic approach - Optimal reliable FTC method
  - PHM for UAV (battery case)
- Fleet Control of UAVs
  - Cooperative Control based on Multi-agent systems
  - Cooperative FTC design
- Conclusions and Perspectives



Prognosis & Health Management for the prediction of UAV flight endurance

❑ Propulsion system of UAV multirotor

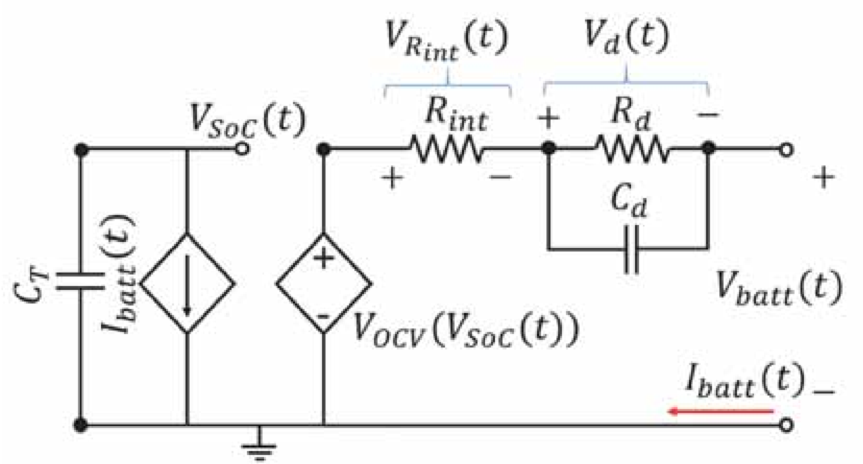




- A Lithium Polymer (Li-Po) battery supplies the power for all BrushLess DC motors (BLDCMs).
- Each motor is connected to the battery through an Electronic Speed Control (ESC).
- The ESC adjusts the angular speed of the BLDCM by a control signal generated as Pulse Width Modulation (PWM). The PWM is computed by the cascade control loop of position and orientation of the multirotor.

Prognosis & Health Management for the prediction of UAV flight endurance

❑ Lithium Polymer battery dynamics



Parameter	Meaning
C_T	Capacity of the battery
C_d	Capacity of the dynamic response
R_{int}	Internal resistance
R_d	Resistance of the dynamic response

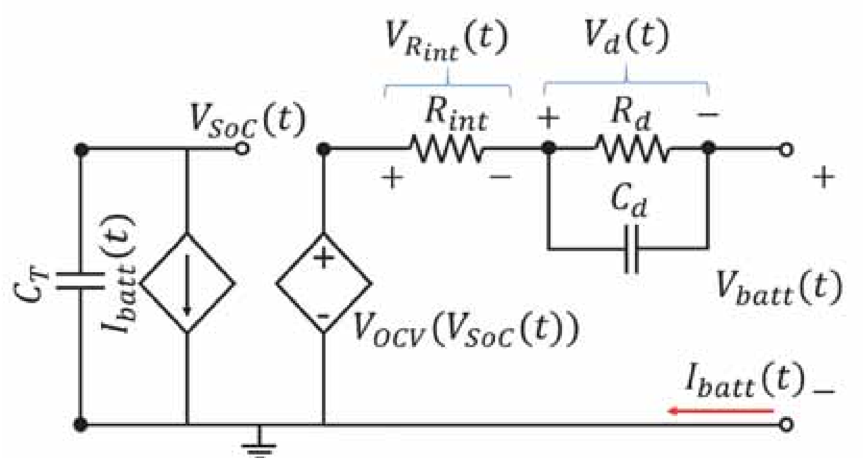
- Electrical dynamics

$$\begin{cases} \dot{V}_{SoC}(t) = \dfrac{I_{batt}(t)}{3600 \cdot C_T} \\ \dot{V}_d(t) = -\dfrac{V_d(t)}{R_d \cdot C_d} + \dfrac{I_{batt}(t)}{C_d} \\ V_{OCV}(V_{SoC}(t)) = \sum_{i=0}^{n} \lambda_i V_{SoC}{}^i + \ln(V_{SoC}(t)) V_{SoC}(t) \\ V_{batt}(t) = V_{OCV}(V_{SoC}(t)) - V_d - R_{\text{int}} I_{batt}(t) \end{cases}$$

Variable	Meaning
$V_{SOC}(t) = SoC(t)$	State of Charge of the battery SoC
V_d	Dynamic voltage
$V_{R_{int}}$	Drop voltage due to internal resistance
$V_{OC}(SoC(t))$	Open circuit voltage

Prognosis & Health Management for the prediction of UAV flight endurance

❑ Lithium Polymer battery dynamics



- Electrical dynamics

$$
\begin{cases}
\dot{V}_{SoC}(t) = \dfrac{I_{batt}(t)}{3600 \cdot C_T} \\
\dot{V}_d(t) = -\dfrac{V_d(t)}{R_d \cdot C_d} + \dfrac{I_{batt}(t)}{C_d} \\
V_{OCV}(V_{SoC}(t)) = \sum_{i=0}^{n} \lambda_i V_{SoC}{}^{i} + \ln(V_{SoC}(t)) V_{SoC}(t) \\
V_{batt}(t) = V_{OCV}(V_{SoC}(t)) - V_d - R_{int} I_{batt}(t)
\end{cases}
$$

The mathematical model, describing the dynamic behavior of the voltage in a Li-Po battery is based on this *Equivalent Circuit Representation* (ECR) presented in (Chen and Rincon-Mora (2006)).

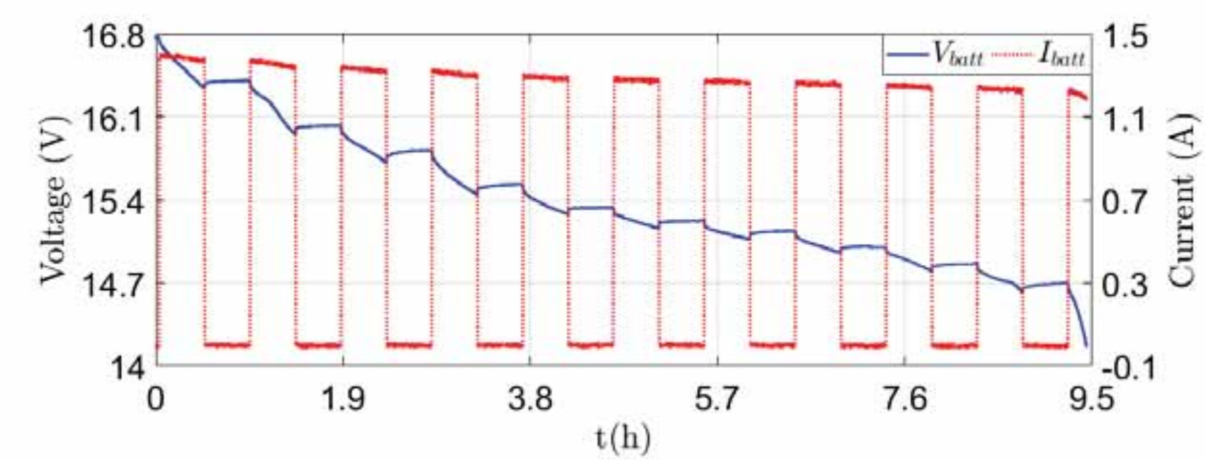
On the left-side of the circuit, the voltage $\boldsymbol{V_{SoC}}$ models the state of charge ***SoC(t)*** of the battery from the capacity $\boldsymbol{C_T}$.
The voltage $\boldsymbol{V_{OCV}(V_{SoC})}$ is the Open Circuit Voltage (OCV), i.e. it is the effective voltage in the terminals of battery, and it is modeled as a function of the state of charge of the battery.
The voltage $\boldsymbol{V_{Rint}}$ characterizes the ohmic over-potential due to the internal resistance of the battery $\mathbf{R_{int}}$.
$\mathbf{V_d}$ represents the transitory response of the voltage when a current is demanding to the battery.

Prognosis & Health Management for the prediction of UAV flight endurance

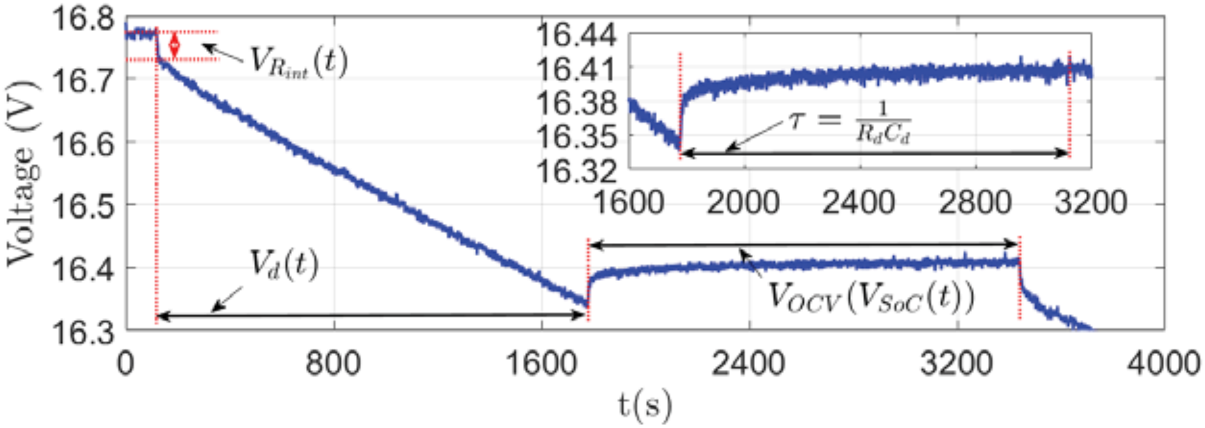
❑ Lithium Polymer battery dynamics

Parameter	Value
Cells	4
Capacity	6200 mAh
C-Rate	25 C
Min voltage per cell	3.5 V
Max voltage per cell	4.2 V
Total mínimum voltage	14 V
Total voltage max	16.8 V

Evolution of battery voltage

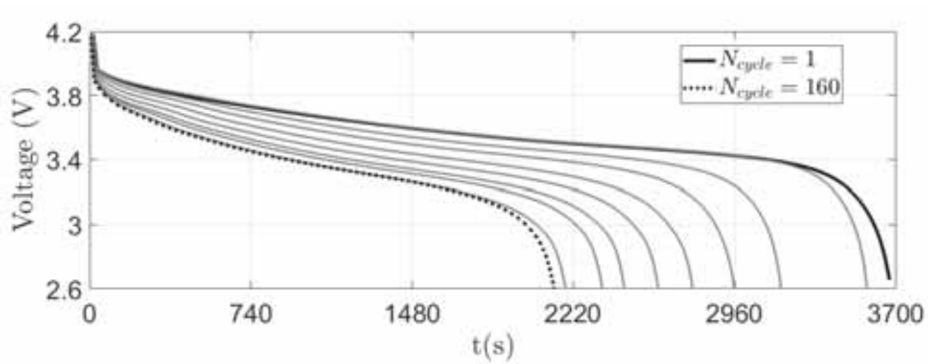


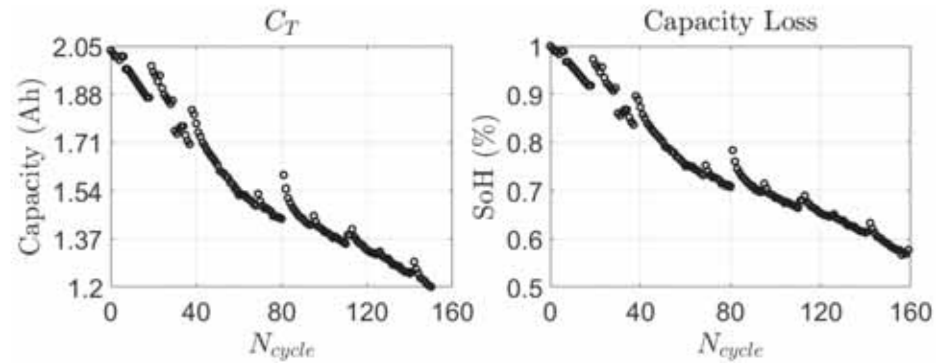
Characteristic of battery voltage



Prognosis & Health Management for the prediction of UAV flight endurance

❑ State of Health (SoH) of the battery





- The battery SoH ($\in [0 \ldots 1]$) indicates the degradation level or aging in the battery.
- The aging depends mainly on the charges/discharges number N_{cycle}.
- The main phenomenon associated with aging is the Capacity Loss caused by the decrease of the battery capacity C_T.

$$\begin{cases} SoH\left(N_{cycle}\right) = \dfrac{C_a\left(N_{cycle}\right)}{C_{init}} \\ C_T = C_0 \cdot SoH\left(N_{cycle}\right) \end{cases}$$

$C_a\left(N_{cycle}\right)$: Capacity after charge/discharge cycle.

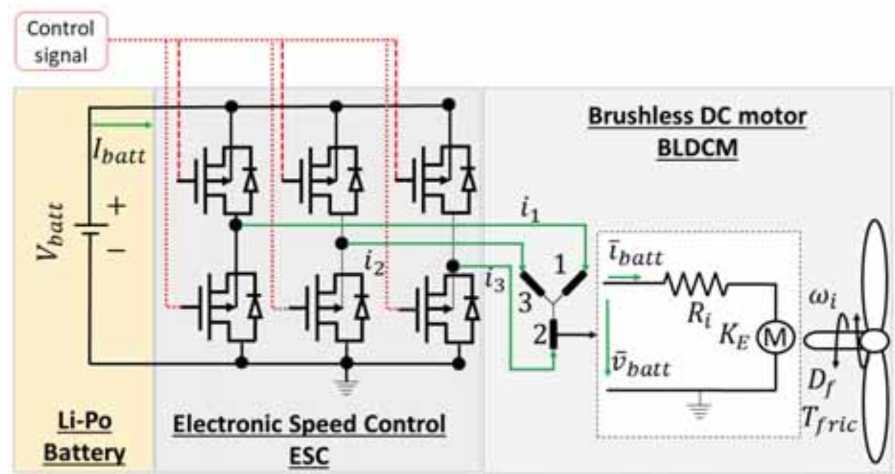
C_{init}: Initial value of the capacity.

C_0: capacity value when the battery is new.

Prognosis & Health Management for the prediction of UAV flight endurance

❑ BrushLess DC Motor (BLDCM) dynamics

$$\begin{cases} \bar{v}_{batt_i} = R\bar{i}_{batt_i} + K_E\omega_i \\ \dot{\omega}_i = \dfrac{1}{J_m}\left(K_E\bar{i}_{batt_i} - d\omega_i^2 - D_f\omega_i - T_{fric}\right) \end{cases}$$



$$\begin{cases} \bar{v}_{batt_i} = V_{batt}Dc_i \\ I_{BLDCM_i} = \bar{i}_{batt_i}Dc_i \\ I_{batt} = \sum_{i=1}^{6} I_{BLDCM_i} \\ Dc_i = f\left(\omega^2_{ref_i}\right) \end{cases}$$

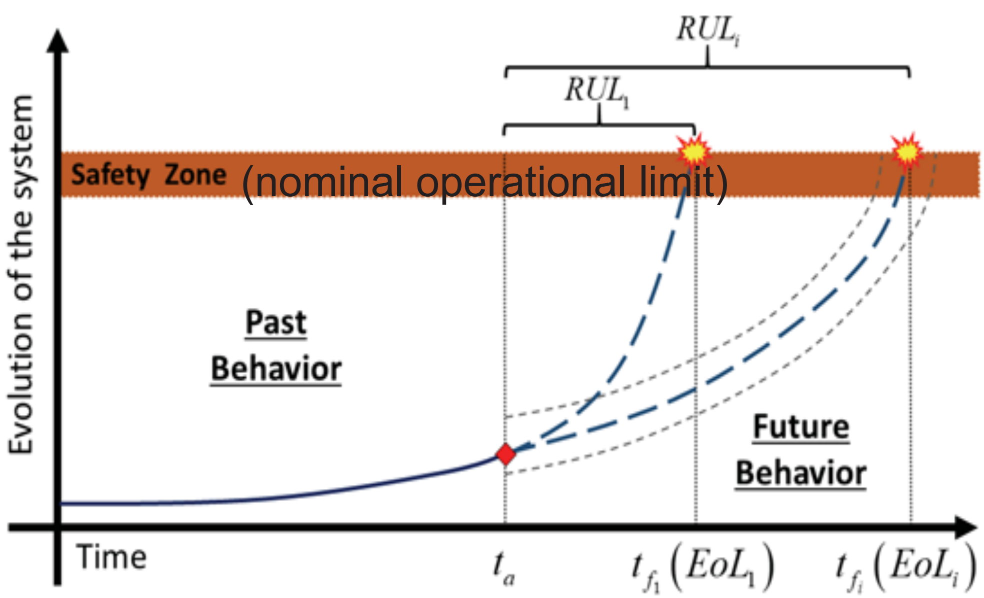
R $\left(= \frac{2}{3}\sum_{i=1}^{3} R_i\right)$: eq electric resistance of each coil
K_E: back electromotive force
J_m: inertia of the motor
d: drag constant
D_f: viscous damping coefficient of the motor
T_{fric}: motor friction torque

Dc_i: duty cycle of PWM signal for motor i

Prognosis & Health Management for the prediction of UAV flight endurance

❑ Prognosis & Health Management (PHM)

To predict how the system will behave in the future in order to know if more stress or changes in the nominal operation cause an acceleration to undesirable event and the time when such event will occurs.



Remaining Useful Life (RUL) until reach the *EoL* is:

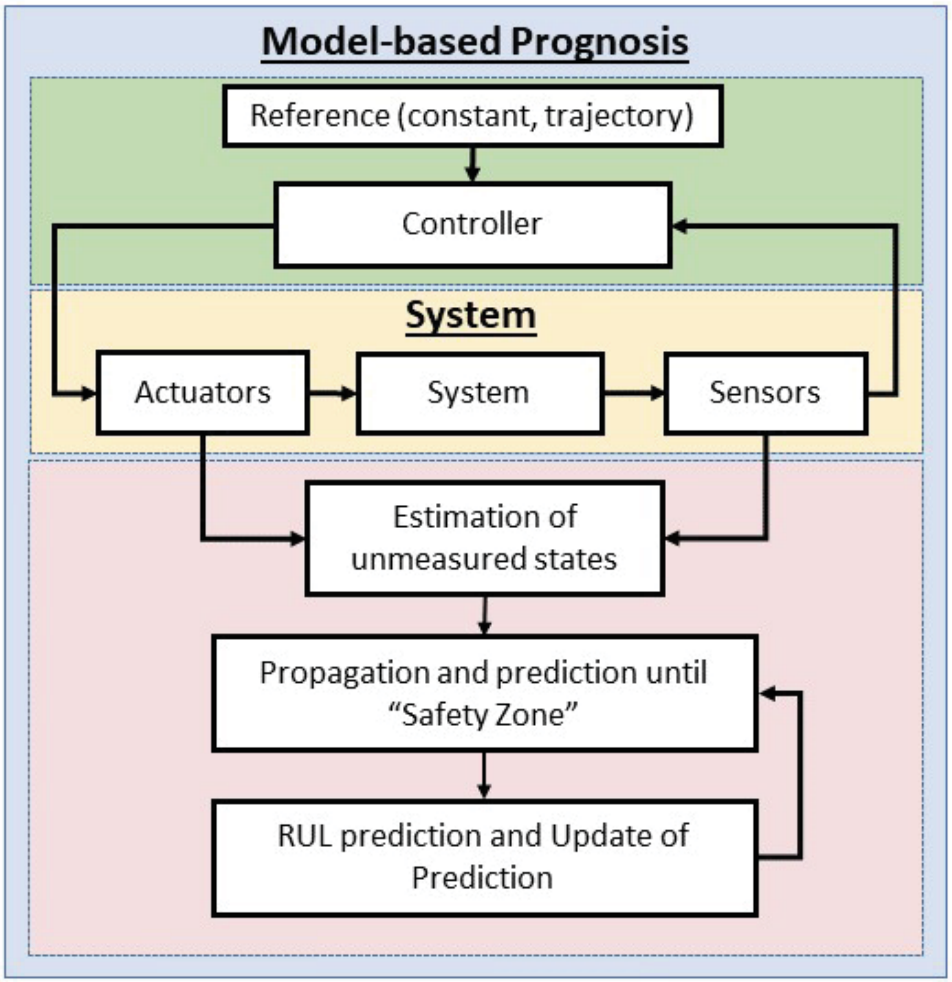
$$RUL_i = t_{f_i}\left(EoL_i\right) - t_a$$

- Flight Endurance Prediction
- Remaining Mission Time computation

Prognosis & Health Management for the prediction of UAV flight endurance

❑ Prognosis & Health Management (PHM)

The proposed model-based prognosis methodology is based on an estimation of the battery ***SoC*** in order to predict the UAV flight endurance.



Prognosis & Health Management for the prediction of UAV flight endurance

❑ Prognosis & Health Management (PHM)

$$\begin{cases} \begin{bmatrix} V_{SoC}(k+1) \\ V_d(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1-\dfrac{T_s}{R_d C_d} \end{bmatrix} \begin{bmatrix} V_{SoC}(k) \\ V_d(k) \end{bmatrix} + \begin{bmatrix} \dfrac{T_s}{C_T(N_{cycle})} \\ \dfrac{T_s}{C_d} \end{bmatrix} I_{batt}(k) + w(k) \\ V_{batt}(k) = \begin{bmatrix} V_{OCV}(V_{SoC}(k)) & -1 \end{bmatrix} \begin{bmatrix} V_{SoC}(k) \\ V_d(k) \end{bmatrix} - R_{\text{int}}(N_{cycle}) I_{batt}(k) + v(k) \end{cases}$$

Estimation-Propagation-Prediction

Due to the fact that there are no abrupt changes or discontinuities in the evolution of estimation ***SoC***, the prediction function is defined as a *polynomial function* of the time

EKF to estimate the state of the battery model

1. Initial value of $\hat{x}_{k-1}^-$ and $P_{(k-1)}$
2. To compute:
$$C_k = \left.\frac{\partial g(x_k, u_k)}{\partial x_k}\right|_{x_k = \hat{x}_{k-1}^-}$$
3. State estimate update:
$$\hat{x}_k^- = f(\hat{x}_{k-1}, u_{k-1})$$
4. Error covariance matrix:
$$P_k^- = A P_k A_k^T + Q$$
5. Kalman gain:
$$K_k = P_k^- C_k^T \left(C_k P_k^- C_k^T + R\right)^{-1}$$
6. State estimate measurement update:
$$\hat{x}_k = \hat{x}_k^- + K_k\left(y_k - g\left(x_k^-, u_k\right)\right)$$
7. Error covariance matrix update:
$$P_k = (I - K_k C_k) P_k^-$$

→

1. Delay (t_p)
2. Recollect data until $S\hat{o}C(t_a)$
3. Define H and m to
$$H = \begin{bmatrix} 1 & t & \cdots & t^m \end{bmatrix}$$
and
$$\mu(t,\delta) = \sum_{j=0}^{m} \delta_j t^j = \delta_0 + \delta_1 \cdot t + \cdots + \delta_m \cdot t^m$$
4. Estimate $\hat{\delta}$ with $Y = S\hat{o}C(t_0 : t_a)$
$$\hat{\delta} = \left[H^T R^{-1} H\right]^{-1} H^T R^{-1} Y$$
5. Verify R^2 to $Y = S\hat{o}C(t_0 : t_a)$ with $\mu(t_0 : t_a, \hat{\delta})$
6. Propagate $\mu(t_0 : t_a, \hat{\delta})$ until $t(EoD)$ to get Flight Endurance (FE)
$$FE = t(EoD)$$
7. Compute Remaining Mission Time (RMT)
$$RMT = t(EoD) - t_a$$

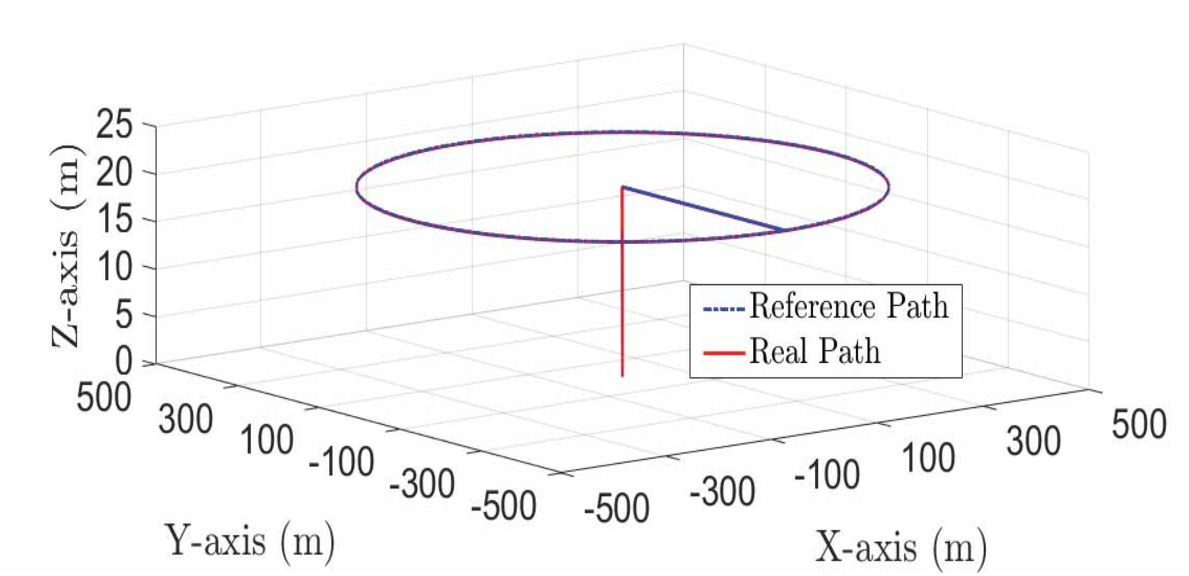
Prognosis & Health Management for the prediction of UAV flight endurance

❑ Simulation results

- An UAV hexarotor was considered.

- The battery is fully charged and new, i.e.
  $SoC = 1$, and $SoH = 1$.

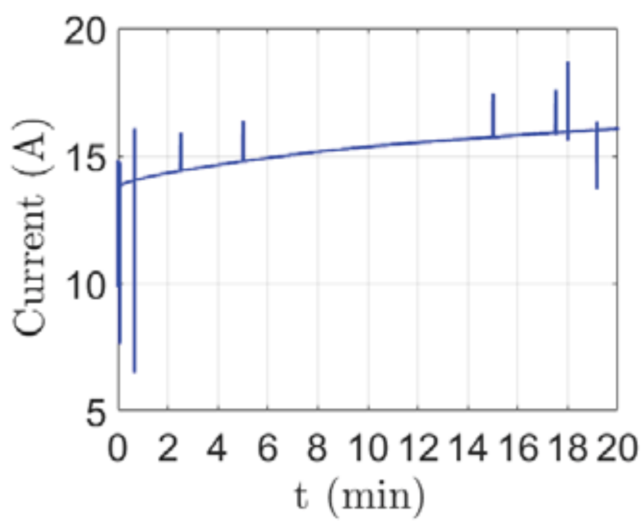
- A circular trajectory was developed: area of 785400 m^2 ; altitude of 20 m

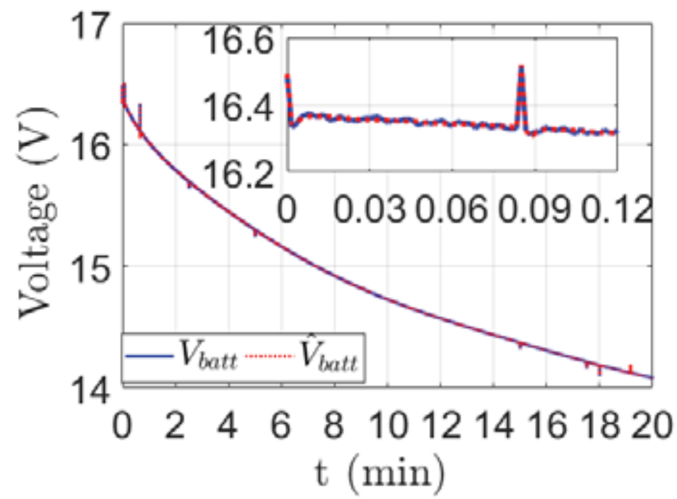


Prognosis & Health Management for the prediction of UAV flight endurance

❑ Simulation results

Battery response





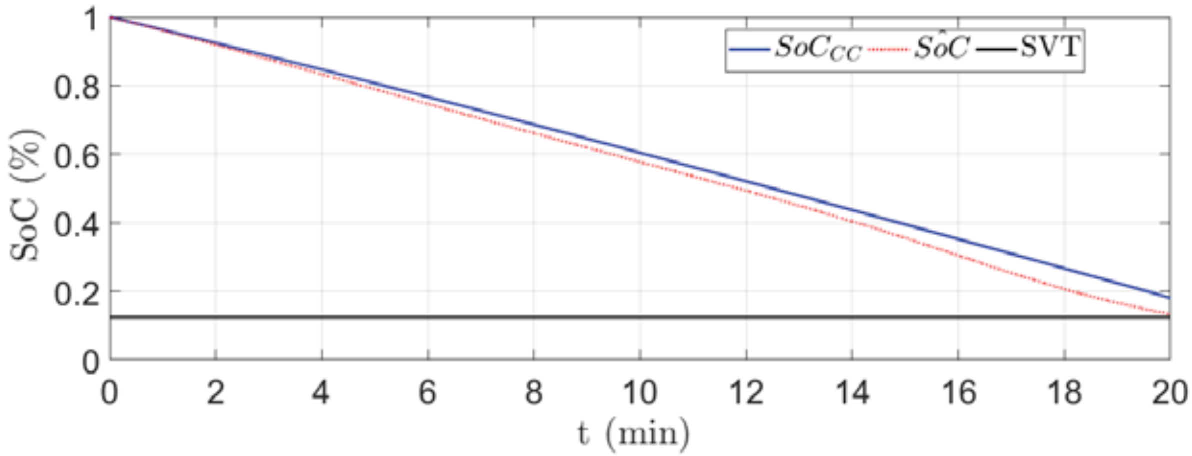
The variations in the current are due to velocity changes of the motors caused by the UAV movement.

The mission is fulfilled in 20 minutes before to reach the ***SVT***, in order to avoid an overdischarge in the battery.

Prognosis & Health Management for the prediction of UAV flight endurance

❑ Simulation results

State of Charge Estimation



comparison between the computed (by Coulomb Counted) and estimated ***SoC*** (by EKF).

The ***SoC*** estimation through the EKF relates the ***SoC*** with the dynamic of the battery discharge.

This relationship allows to predict the flight endurance from the estimated ***SoC***.

Prognosis & Health Management for the prediction of UAV flight endurance

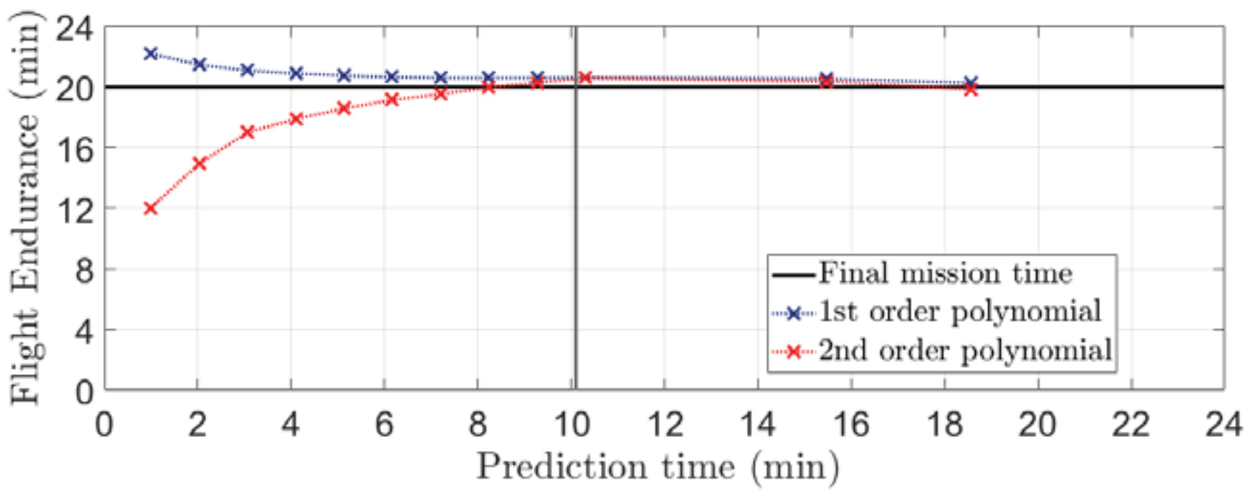
❑ Simulation results

The propagation and prediction were developed over sampling time of 1 minute, and the ***SoC*** estimation each 10 milliseconds to collect enough data to estimate the parameters of the prediction function.

Two 1st and 2nd order polynomials were considered for the prediction function.

Prognosis & Health Management for the prediction of UAV flight endurance

❑ Simulation results



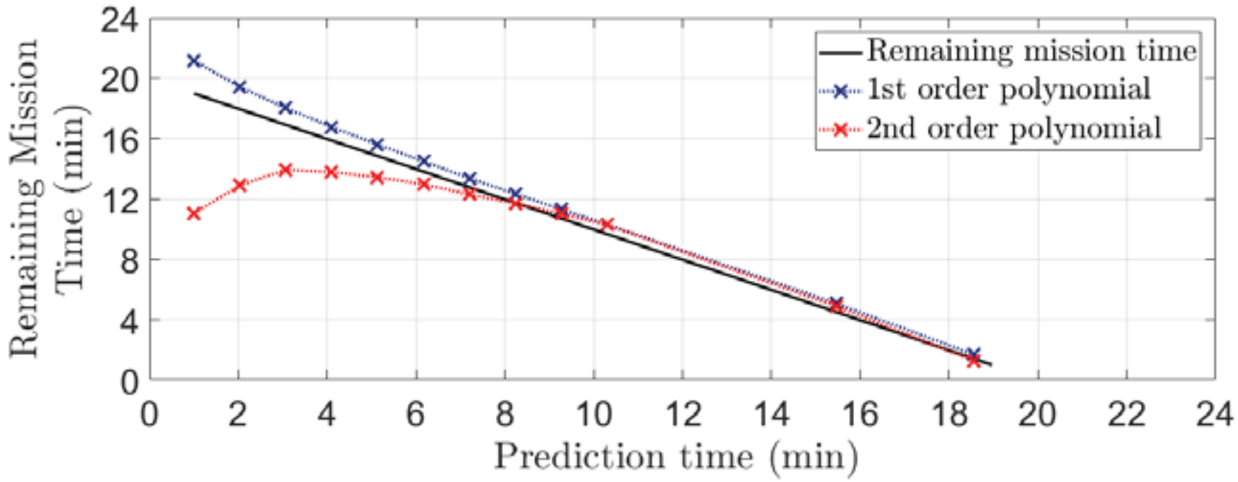
Predictions of the total flight endurance for both prediction:

The first predictions (1 − 4 min) with the 1st order polynomial are closer to the real flight endurance, whilst an approximation of the real flight endurance is displayed from 6 minute onwards with the 2nd order polynomial.

However the closest prediction of real flight endurance is obtained at time 8 min with the 2nd order polynomial.

Prognosis & Health Management for the prediction of UAV flight endurance

❑ Simulation results

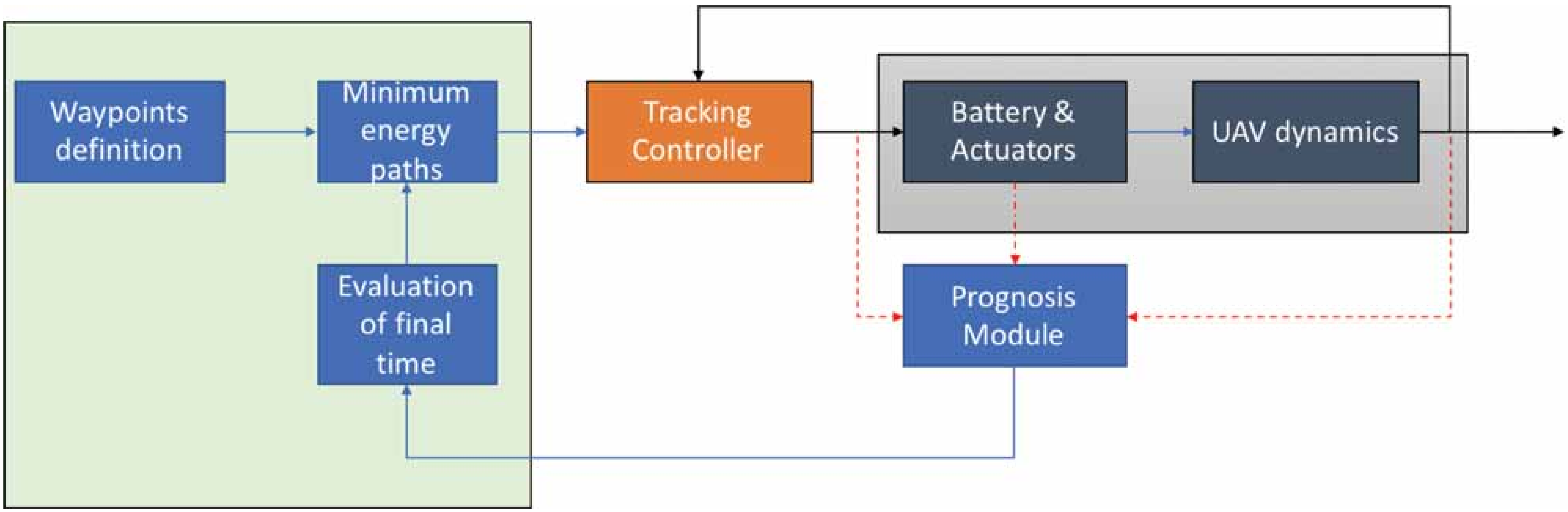


The computation of *Remaining Mission Time* (***RMS***) was made from the first prediction.

It is possible to predict the total flight endurance and the ***RMS*** from the beginning of the mission considering the defined Decision Threshold ***DT***.

Prognosis & Health Management for the prediction of UAV flight endurance

❑ Trajectory tracking



Prognosis & Health Management for the prediction of UAV flight endurance

❑ Trajectory tracking

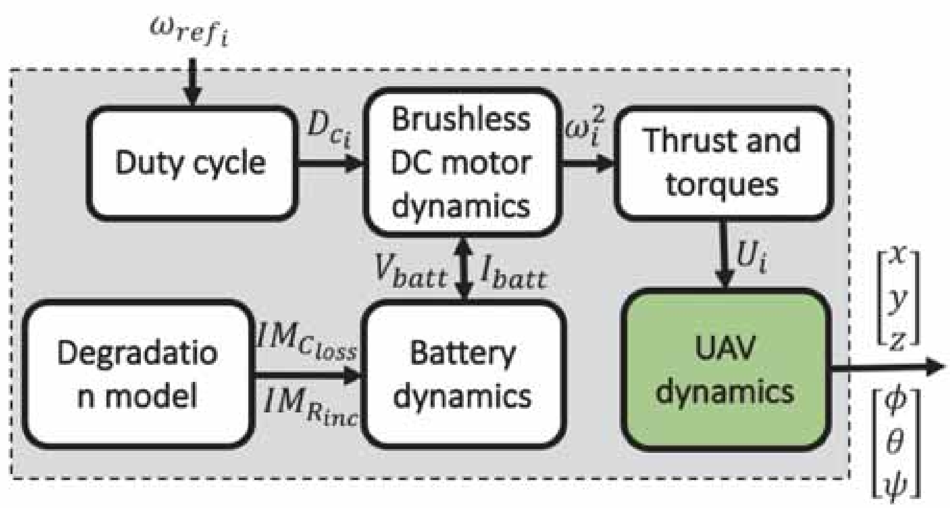
Minimal energy (E_c) and time (t_f) paths

Multi-Objective minimization problem:

$$\min_{\omega_{ref_i}} \quad E_c \;\; \&\& \;\; \left(t_f - t_0\right)$$

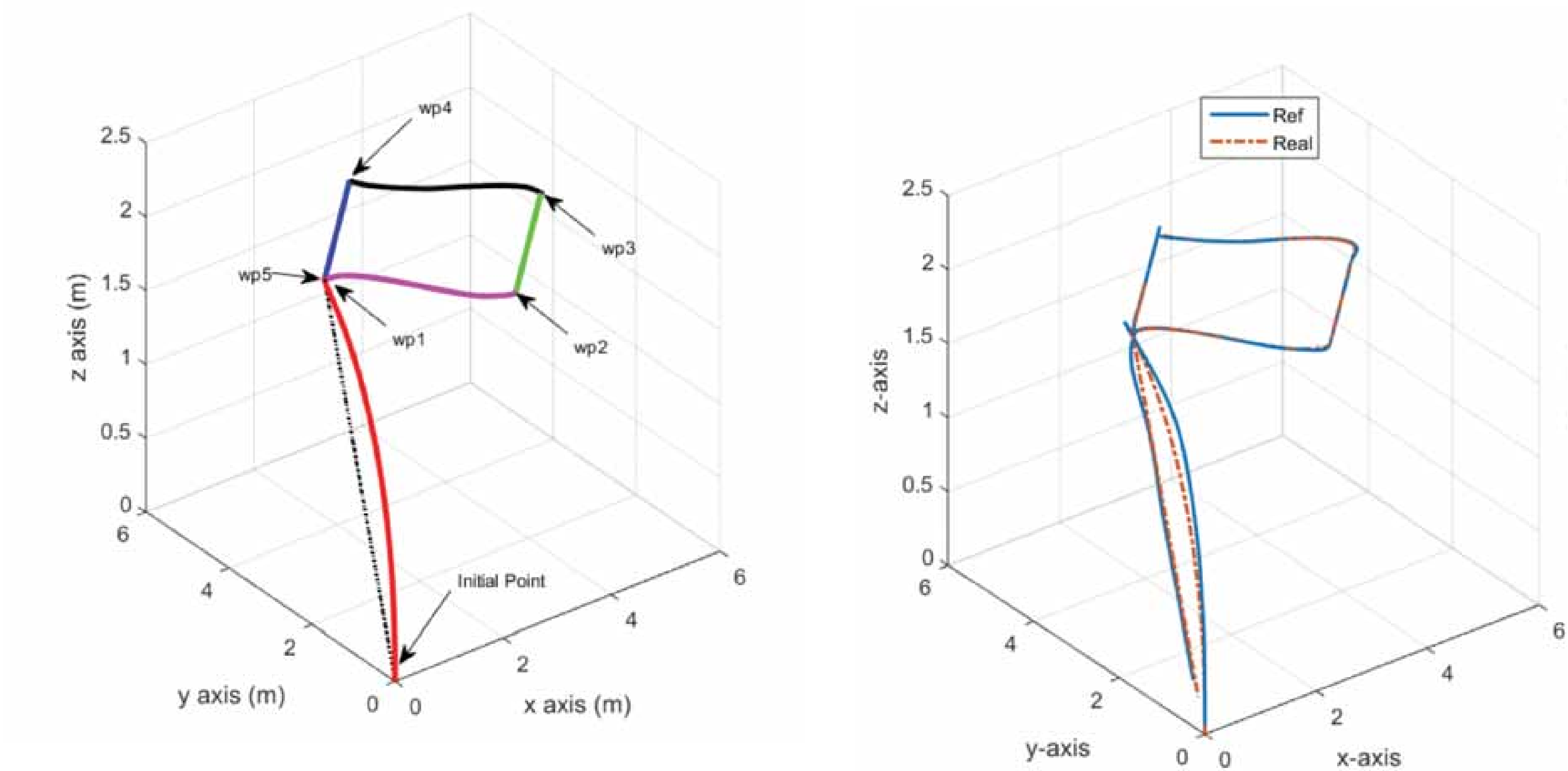
such that

$$\begin{gathered}
Hexacopter \;\; dynamics \\
BLDCM \;\; dynamics \\
Battery \;\; dynamics \\
X_a\left(t_0\right) = X_{a_{t_0}},\; X_a\left(t_f\right) = X_{a_{t_f}} \\
0 \le \omega_i \le \omega_{\max} \\
V_{batt}\left(EoD\right) \le V_{batt} \le V_{batt}\left(t_0\right) \\
SoH\left(EoL\right) \le SoH \le 1 \\
t_{\min} \le t_f \le t_{\max}
\end{gathered}$$



Prognosis & Health Management for the prediction of UAV flight endurance

❑ Trajectory tracking



Next step: disturbances + real-time reconfiguration of the trajectory

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- Context
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  - Principle and some definitions
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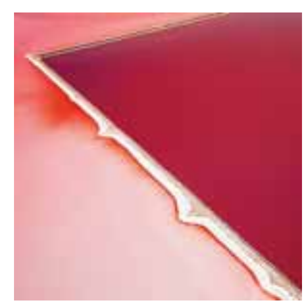
    - under critical fault
    - under severe fault
- Fault Tolerant Control versus Health
  - Definitions
  - Overactuated Systems
  - Heuristic approach - Optimal reliable FTC method
  - PHM for UAV (battery case)

- Fleet Control of UAVs
  - Cooperative Control based on Multi-agent systems
  - Cooperative FTC design
- Conclusions and Perspectives



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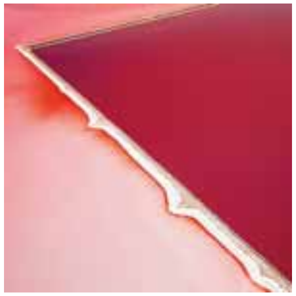


Flocking algorithms

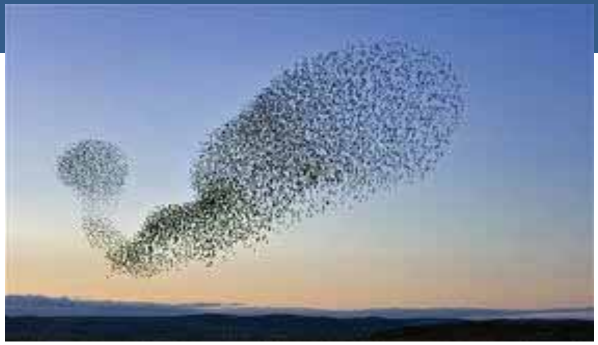
Flocking is one of the most significant research fields in coordination control of multi-agent systems, and flocking phenomena can be widely observed in nature

In the group, each agent depends on local sensing and simple rules to coordinate its behavior for the sake of keeping a common velocity while moving as a compact group

The classical flocking model was proposed by Reynold in 1987, consisting of :

- Collision avoidance
- Velocity matching : adopt a common direction
- Flocking centering : agents that are near each other

Since then, Many Variants of these three properties have been suggested, and relative control algorithms have also been proposed



Flock of starlings

Schooling of fishes

Geese flying in V-formation

Extensions of the Cucker-Smale model

Numerous studies have suggested extensions of the Cucker-Smale model to build a model able to control a fleet of mobile UAVS(2D), among them [5] have been considered:

$$\dot{x}_i(t) = v_i(t)$$

$$\dot{v}_i(t) = \sum_{j=1}^{n} a_{ij}(t)(v_j(t) - v_i(t)) + \lambda(t) \sum_{j \neq i} f(||x_i(t) - x_j(t)||^2)(x_i(t) - x_j(t))$$

with :

$$a_{ij}(t) = \frac{H}{(1 + ||x_i(t) - x_j(t)||^2)^\beta}$$

$$\lambda(t) = \left(\frac{1}{n} \sum_{i>j} ||v_i(t) - v_j(t)||^2 \right)^{1/2}$$

$$f(r) = (r - r_0)^{-\theta} \text{ and } \theta > 1$$

The first condition allows for convergence to alignment speed and the second ensures collision avoidance.

- Alignment at a common velocity is equivalent to $\lambda(t) = 0$ and the quantity $\lambda(t)$ is used to moderate the repelling force.
- The distance $r_0 > 0$ represents the safety distance and the differentiable function $f(\mathrm{r})$ satisfying the following conditions:

$$1) \int_{r_0}^{r_0+1} f(r)\,\mathrm{d}r = \infty$$

$$2) \int_{r_0+1}^{\infty} f(r)\,\mathrm{d}r < \infty$$

[5] CUCKER, Felipe et DONG, Jiu-Gang. Avoiding collisions in flocks. Automatic Control, IEEE Transactions on, 2010, vol. 55, no 5, p.1238-1243.

Main contribution

The approach consists to define an extension of the models proposed in [5], in order to build a robust and suitable flocking model for outdoor fleet control. Then, the following objectives should be achieved simultaneously:

★ 1) All of the pairwise forward speed differences asymptotically converge to zero

$$\forall i, j \in N : \lim_{t\to\infty} (v_i(t) - v_j(t)) = 0$$

★ 2) Collisions between interaction agents are avoided

$$\forall i, j \in N : d_{ij}(t) > r_0 \text{ avec } d_{ij}(t) = ||x_i(t) - x_j(t)||$$

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3) Formation-keeping is asymptotically achieved

$$\forall i, j \in N : \lim_{t \to \infty} d_{ij}(t) < R(n, r_0) \text{ avec } R(n, r_0) > r_0$$

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Formation Keeping

To ensure the cohesion of the fleet without changing the overall dynamics of flocking model proposed in [5], we propose to add a bounded attractive force on agents away from the group. Flocking algorithm can be rewritten as follows:

$$\dot{x}_i(t) = v_i(t)$$
$$\dot{v}_i(t) = \sum_{j=1}^{n} a_{ij}(t)\left(v_j(t) - v_i(t)\right) + \lambda(t)\sum_{j \neq i} f\left(\|x_i(t) - x_j(t)\|^2\right)(x_i(t) - x_j(t)) + \underbrace{\delta_i(d_i^*(t))}$$

where $d^*i\ (t)$ is the distance between agent i and the average position of virtual q^* agent defined by the point (x^*,y^*) ($x^*=1/n \sum x_i$ and $y^*=1/n \sum y_i$) and function $\delta i(d^*i\ (t))$ satisfies:

$$a) ||\delta_i(d_i^*(t))|| \approx 0 \text{ when } (d_i^*(t) - R(n, r_0)) \leq 0$$
$$b) ||\delta_i(d_i^*(t))|| \leq \delta_{max} \text{ when } (d_i^*(t) - R(n, r_0)) > 0$$

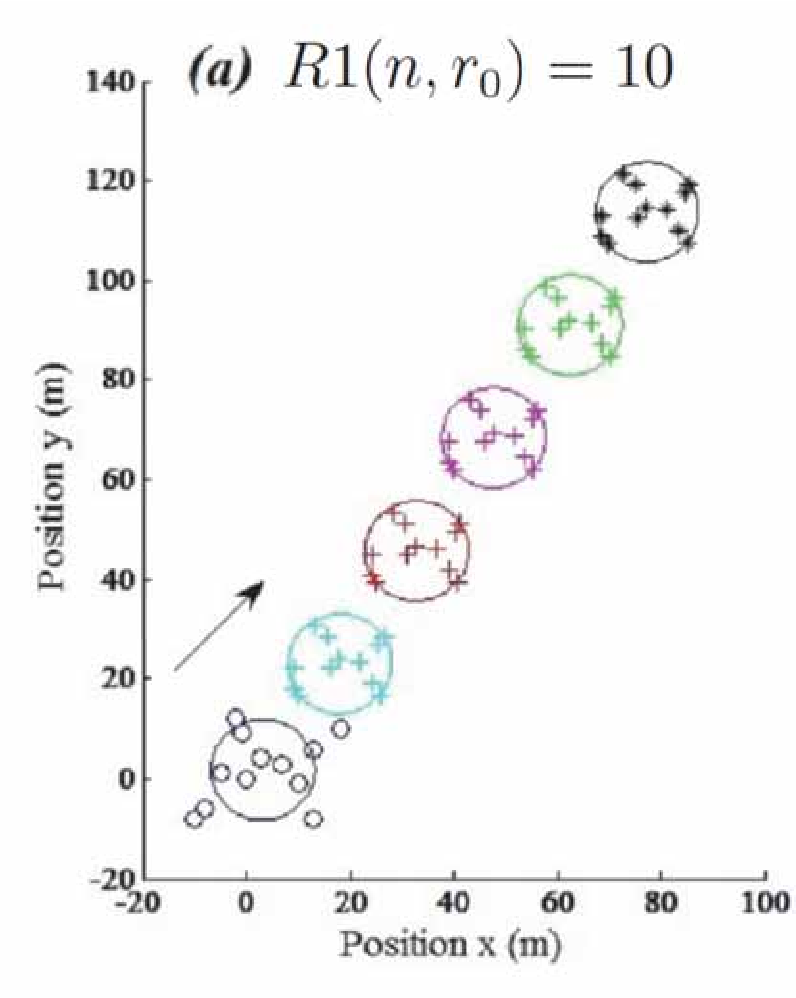
Note that the attracting force occurs on an agent when it is outside the group and vanishes after. For instance, function $\delta i(d^*i\ (t))$ can be defined as:

with $\delta_i(d_i^*(t)) = \overline{\delta_i}(d_i^*(t)) sat\left(\frac{x^*(t) - x_i(t)}{d_i^*(t)}\right)$ and $\overline{\delta_i}(d_i^*(t)) = \frac{H_c}{2}(sign(d_i^*(t) - R(n, r_0)) + 1)$

where H_c is defined as a positive constant parameter of the model.

Simulation in fault-free case

In our numerical simulation, we consider that the autonomous agents initially have different velocities, and are spread out in space. It is also assumed that the minimum distance between two agents is greater than the safety distance r0 = 1.



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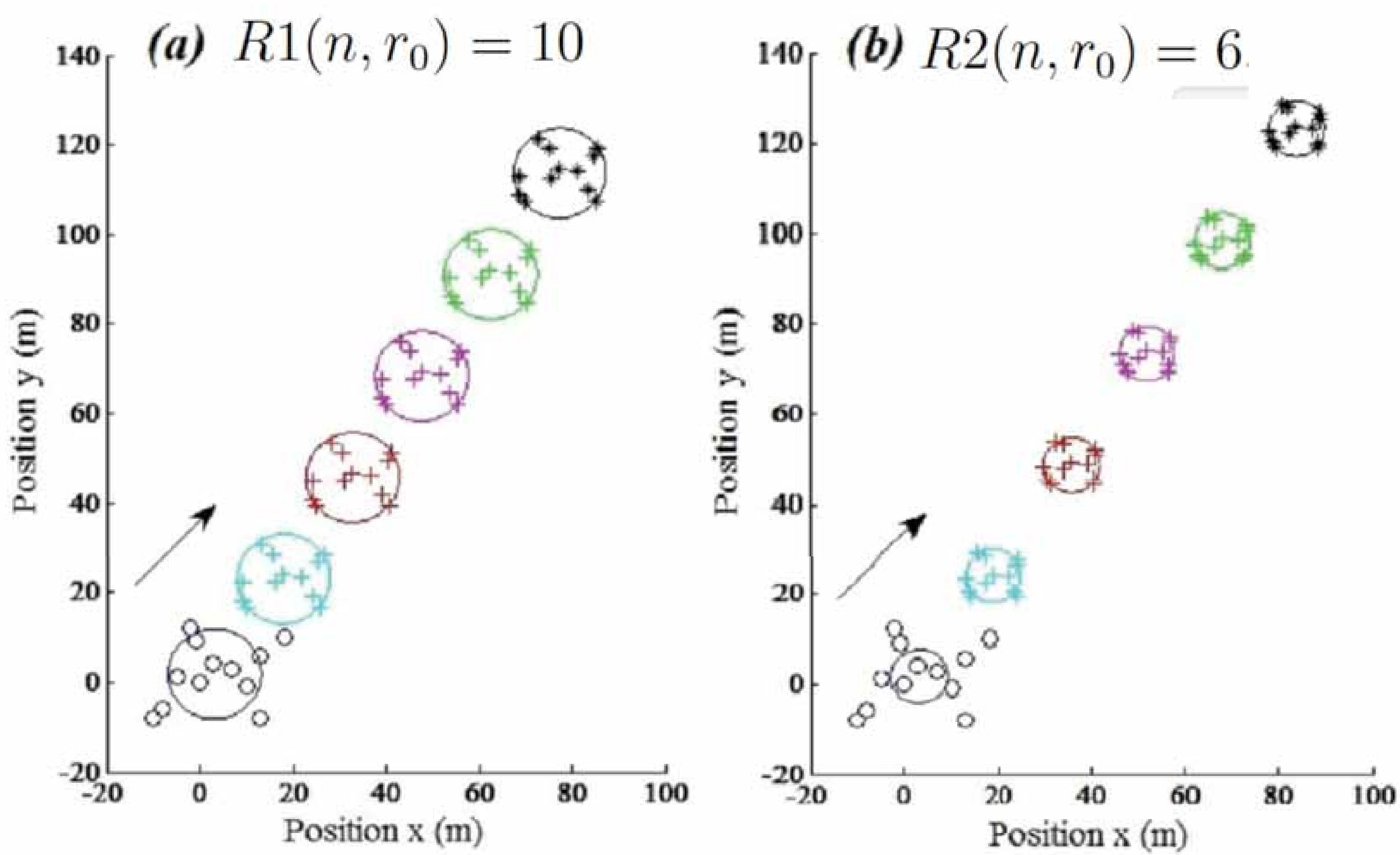
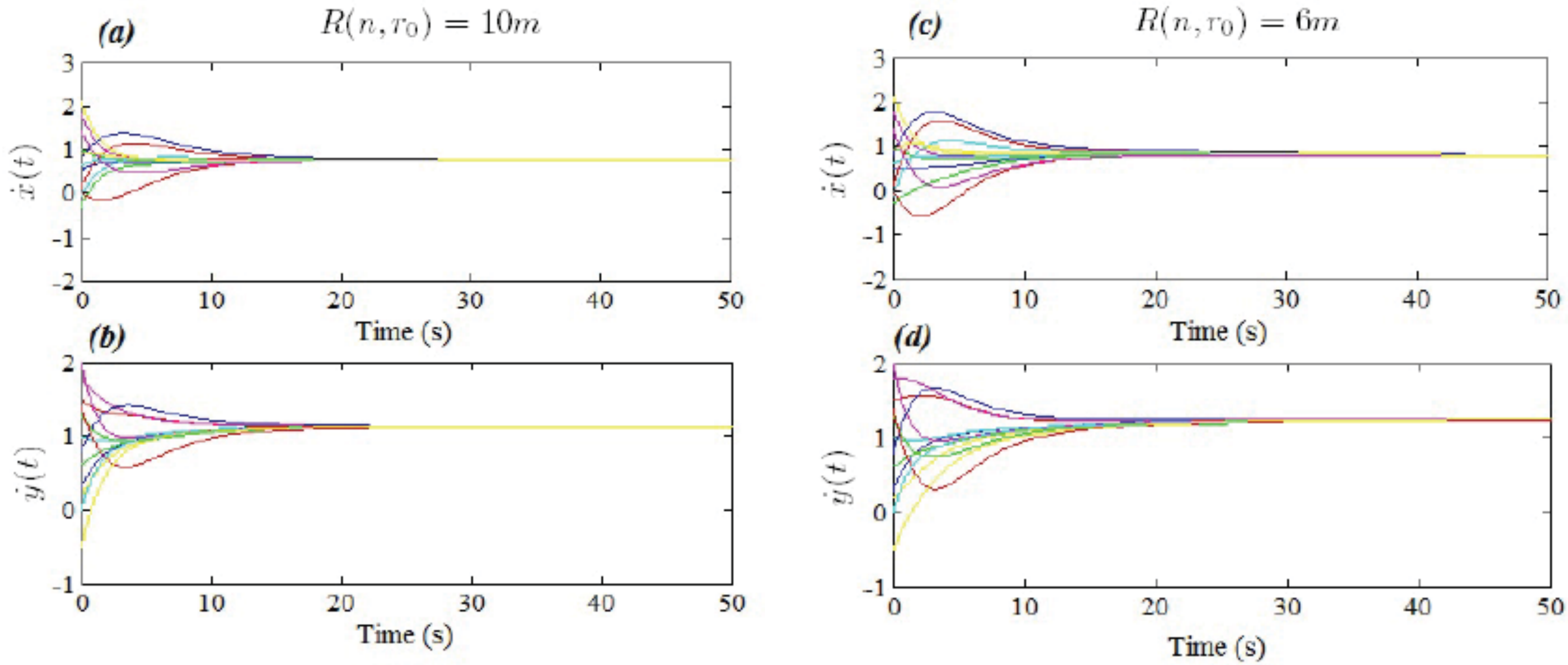


Simulation in fault-free case

To assess the flocking convergence of the fleet, Fig presents the evolution speeds *vx(t)* and *vy(t)* of all agents for the previous two cases.



The convergence time is estimated at *15s* when *R1(n,r0)=10* and at *18s* when *R1(n,r0)=6*. This result is in link with the influence of the term $\delta i(d^* i\ (t))$ which is even greater when *R(n,r0)* is smaller.

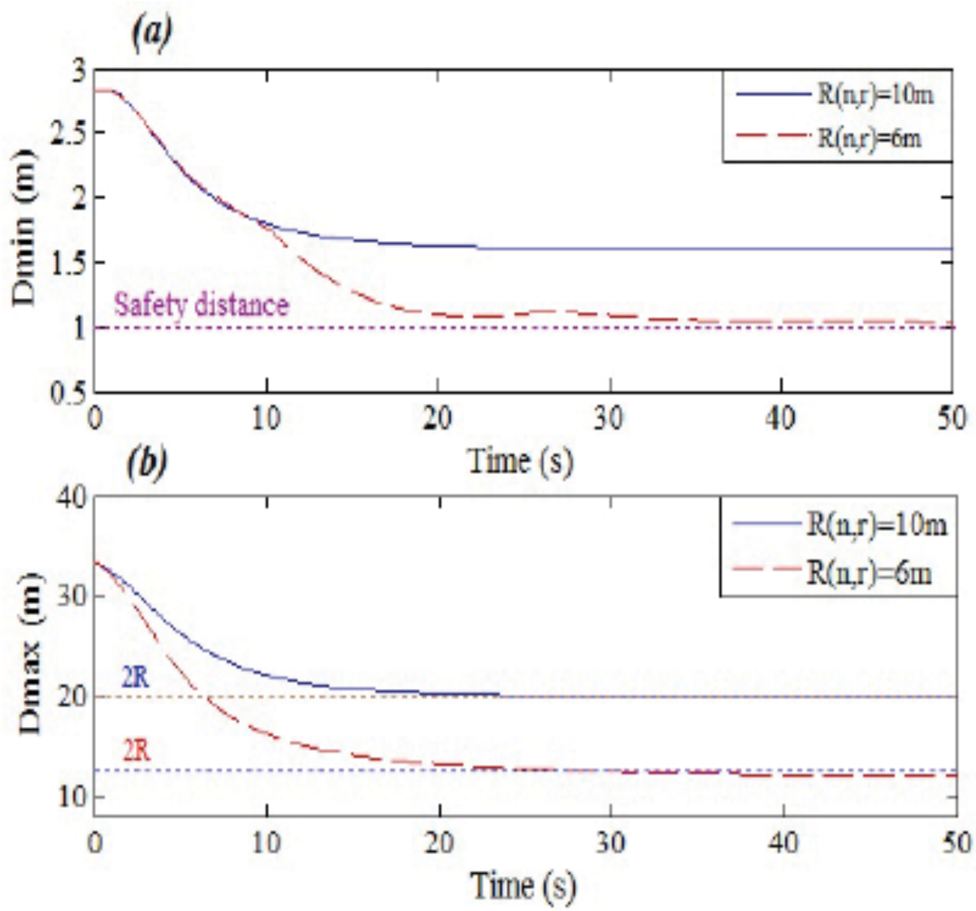
Simulation in fault-free case

Fig allows to confirm, and visualize, the minimum and the maximum distances between each two agents, such that:

$$D_{min} = \min_{i \neq j} ||x_i(t) - x_j(t)||$$

$$D_{max} = \max_{i \neq j} ||x_i(t) - x_j(t)||$$

Note that the safety distance between agents are always granted.



Rendezvous : 3 agents in fault-free case without leader

Rendezvous : 3 agents in fault-free case without leader + disturbances

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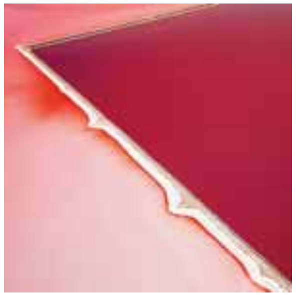

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4) Fault tolerance: two types of faults are considered ("***defective agent***")

a) an agent is out of order i.e. vi(t) = 0

b) an actuator fault i.e. *vi(t) = constant*

[5] CUCKER, Felipe et DONG, Jiu-Gang. Avoiding collisions in flocks. Automatic Control, IEEE Transactions on, 2010, vol. 55, no 5, p.1238-1243.

Fault tolerance

The presence of a fault on one or more agents in the fleet changes the behavior of all of the group. Two types of faults are addressed:

- In the case of one or more agents out of order, the fleet would be demanded to continue the mission without taking the defective agents into consideration and at the same time it will *decrease the radius of the group*

- In the case of a momentary presence of an actuator fault on one agent, the fleet would be demanded to support the defective agent until it resumes its normal behavior and at the same time it will *increase the radius of the group*

In order to tolerant faults, a vector W defined as W = $w_1,\ldots,w_n$ is considered in the design of the robust flocking control algorithm as:

$w_i = 0$ when agent i is out of order
$w_i = 1$ when agent i in fault-free case
$w_i = w^*$ when momentary presence of a fault agent i

FDI module is assumed to be perform with a neglected time delay.

Fault tolerance

To keep into consideration these three situations, the vector W will be introduced in revisited Flocking Algorithm , such as:

$$\dot{x}_i(t) = v_i(t)$$

$$\dot{v}_i(t) = \sum_{j=1}^{n} \underline{w_j} a_{ij}(t)(v_j(t) - v_i(t))$$

$$+ \lambda_i(t) \sum_{j \neq i} f(||x_i(t) - x_j(t)||^2)(x_i(t) - x_j(t))$$

$$+ sat\left(\frac{H_c}{2}\left(sign(d_i^*(t) - R(n, r_0) + \underline{R_s^i}) + 1\right)\frac{q^*(t) - q_i(t)}{d_i^*(t)}\right)$$

with :

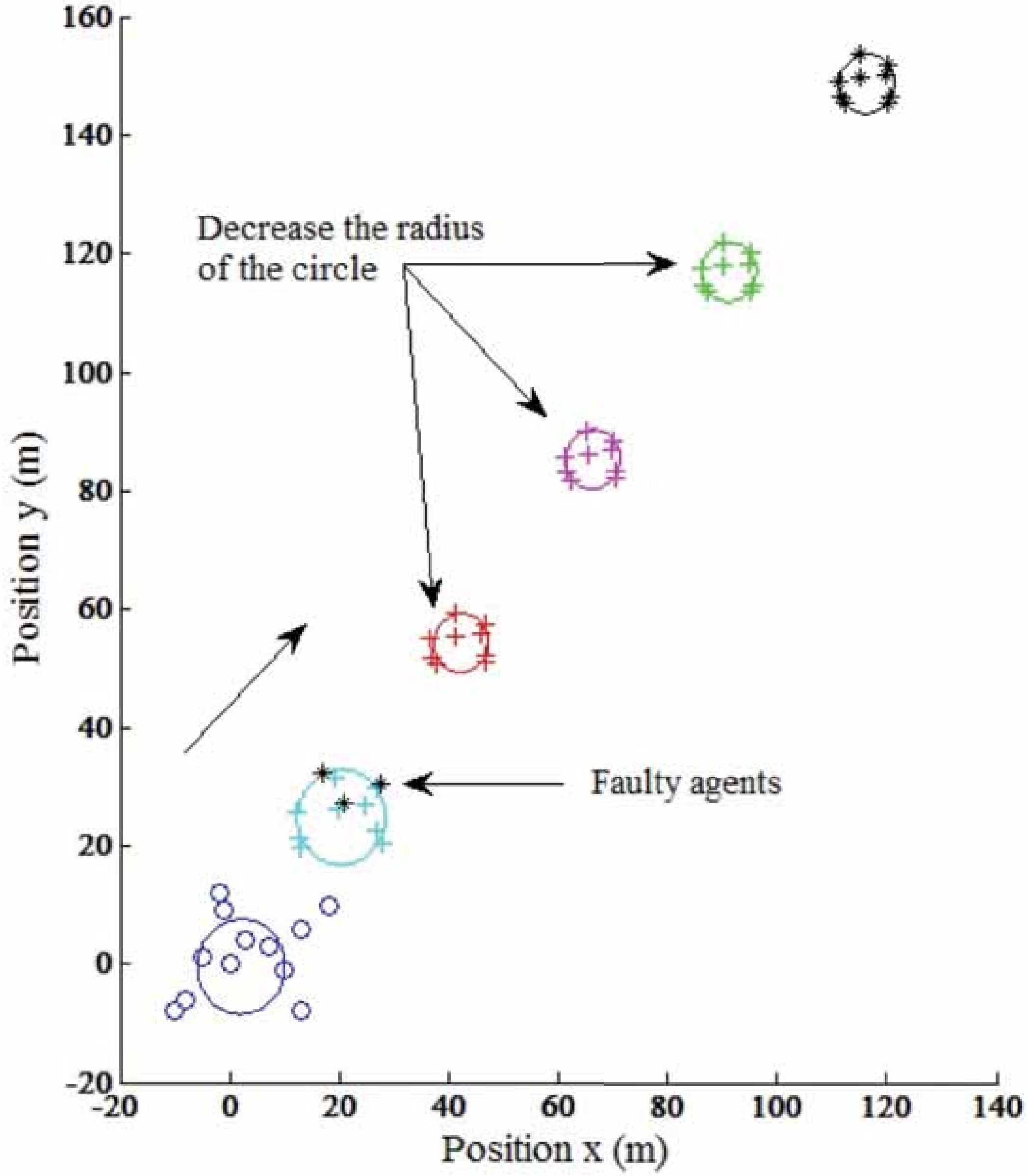
$$\lambda_i(t) = \left(\frac{1}{n_i{}^*}\sum_{i>j} \underline{w_j} ||v_i(t) - v_j(t)||^2\right)^{1/2}$$

$$x_i^*(t) = \frac{1}{n_i{}^*}\sum_{j=1}^{n} \underline{w_j} x_j(t) \text{ and } y_i^*(t) = \frac{1}{n^*}\sum_{j=1}^{n} \underline{w_j} y_j(t)$$

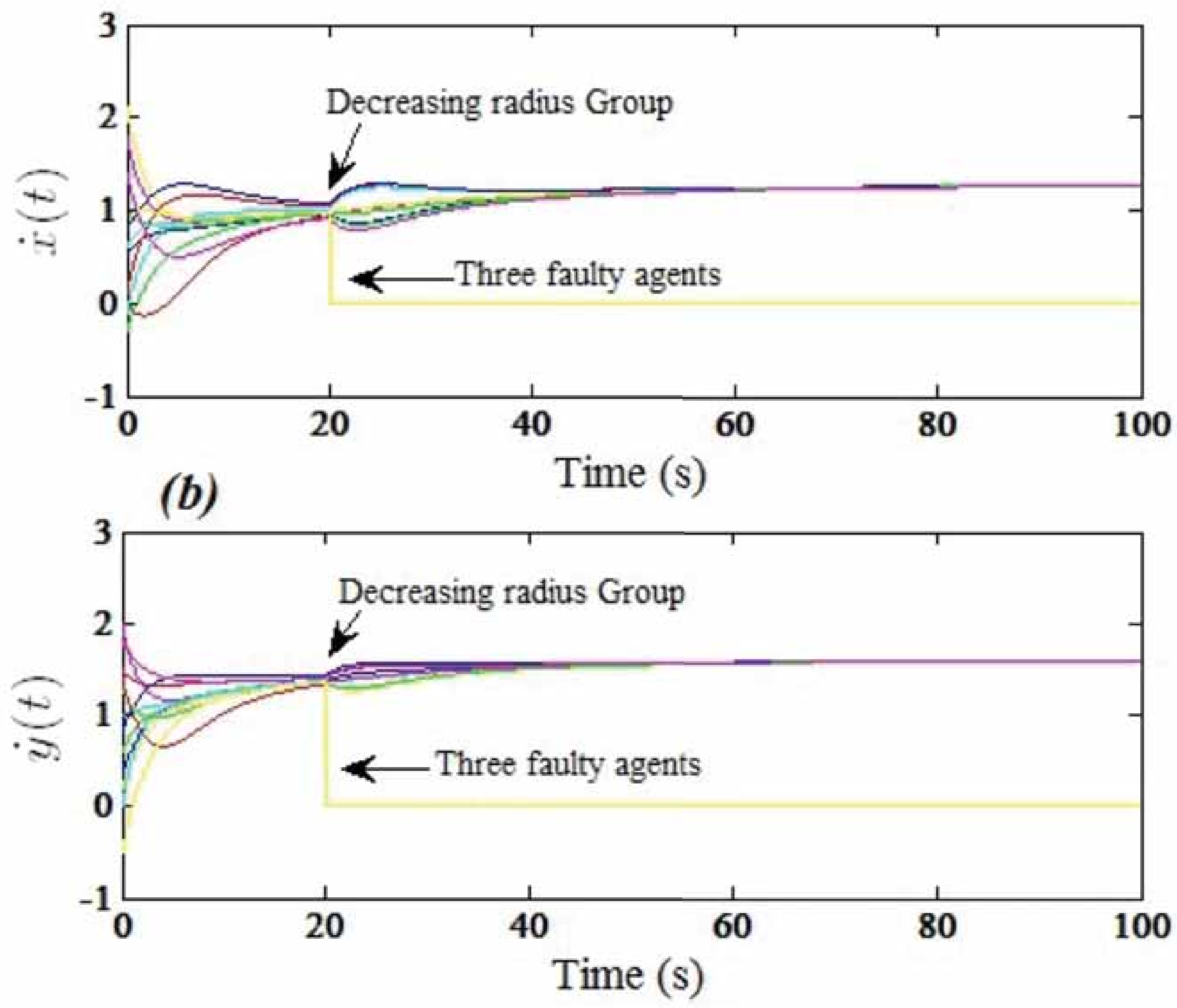
$$n_i{}^* = \sum_{j=1}^{n} \underline{w_j}$$

Fault tolerance - faulty case (out of order)

The figure show the behavior of the fleet when three agents are out of order at time $t = 20s$



Fault tolerance - faulty case (out of order)



The figure show the behavior of the fleet when three agents are out of order at time $t = 20s$

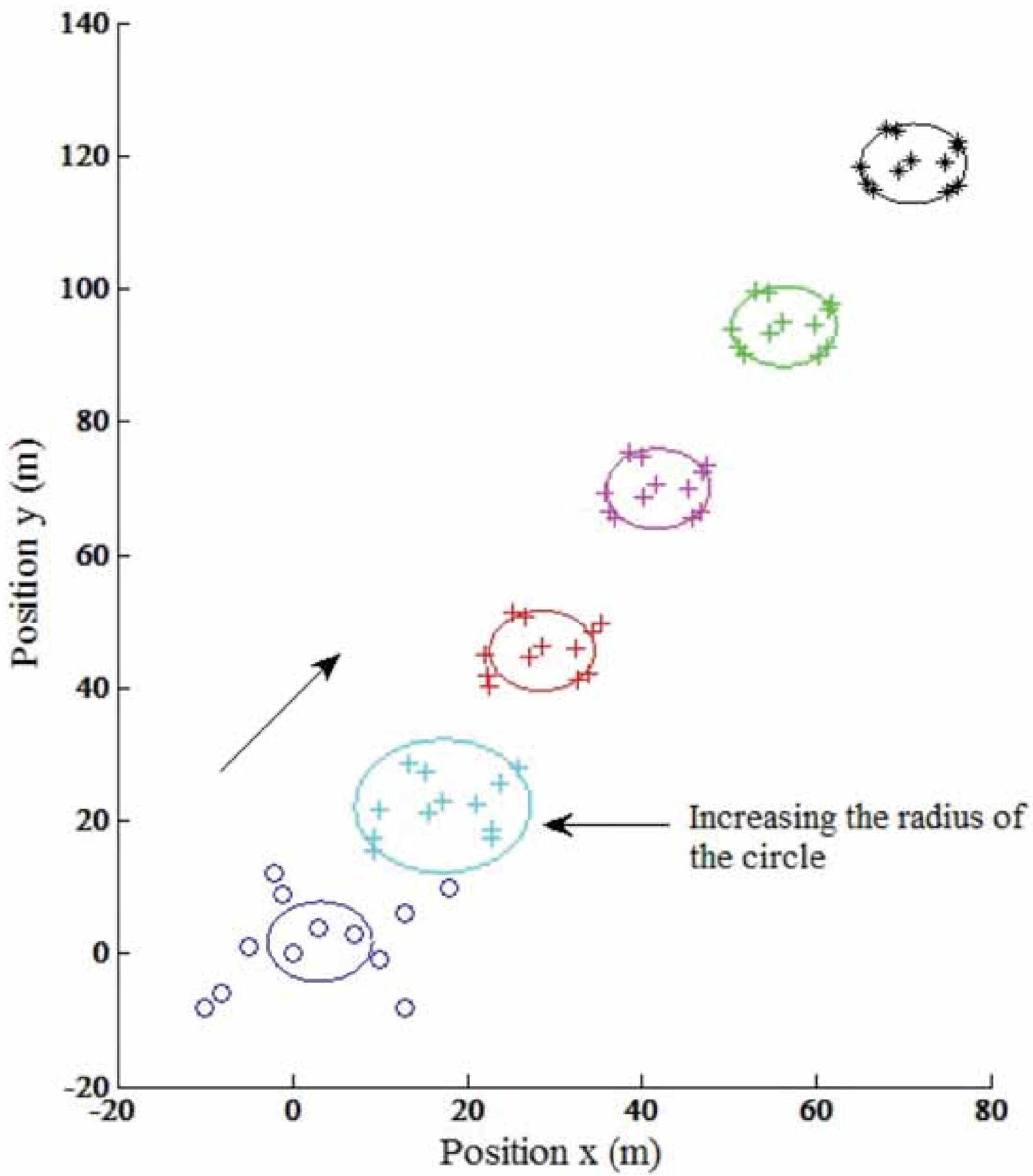
Fault tolerance - faulty case (out of order)

On agent is out of order, the fleet follows a mobile virtual agent

heudiasyc

Fault tolerance - faulty case (actuator failure)

The figure shows the behavior of the fleet at the detection of an actuator failure on one of agents between the time intervals *[8s,25s]*



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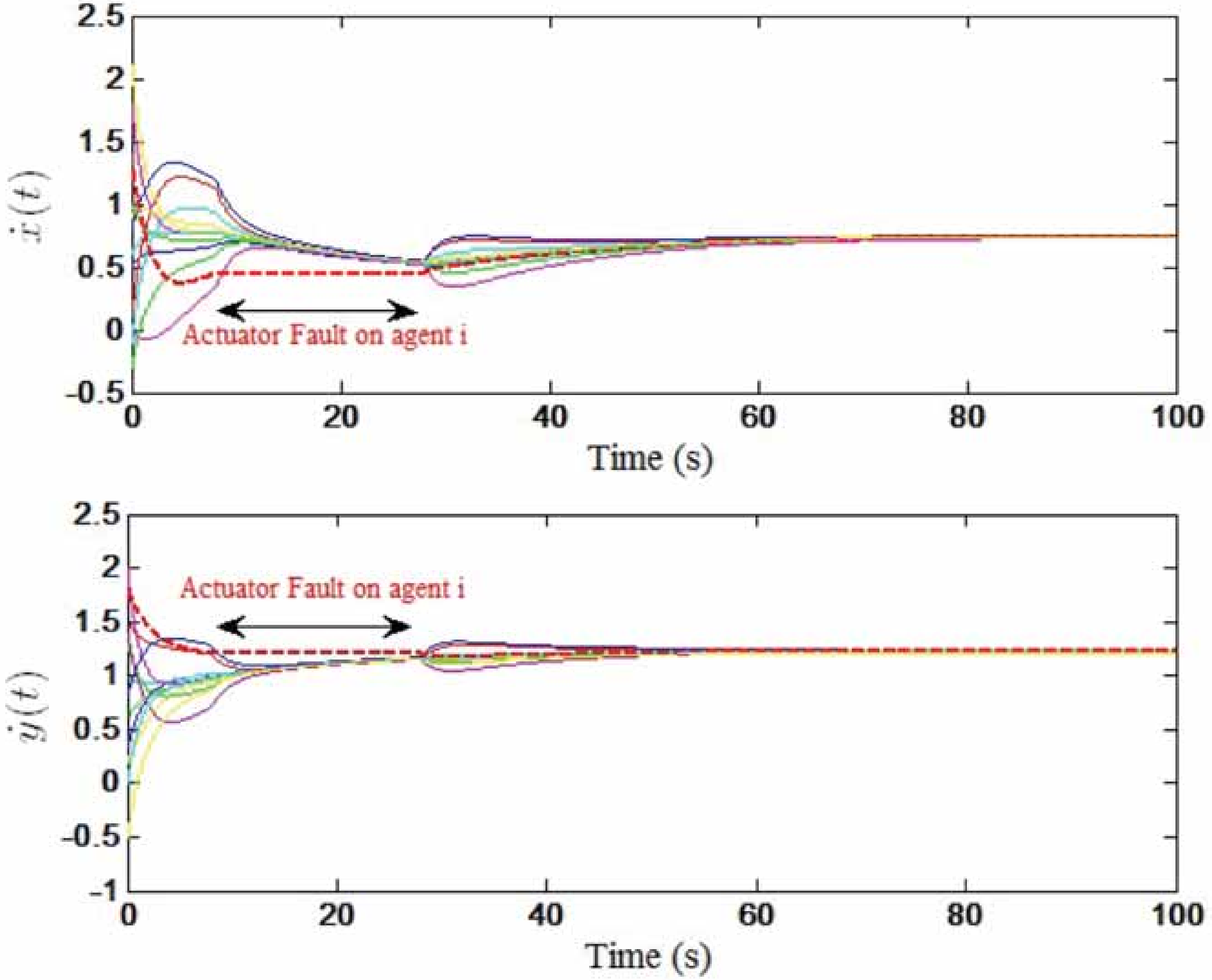

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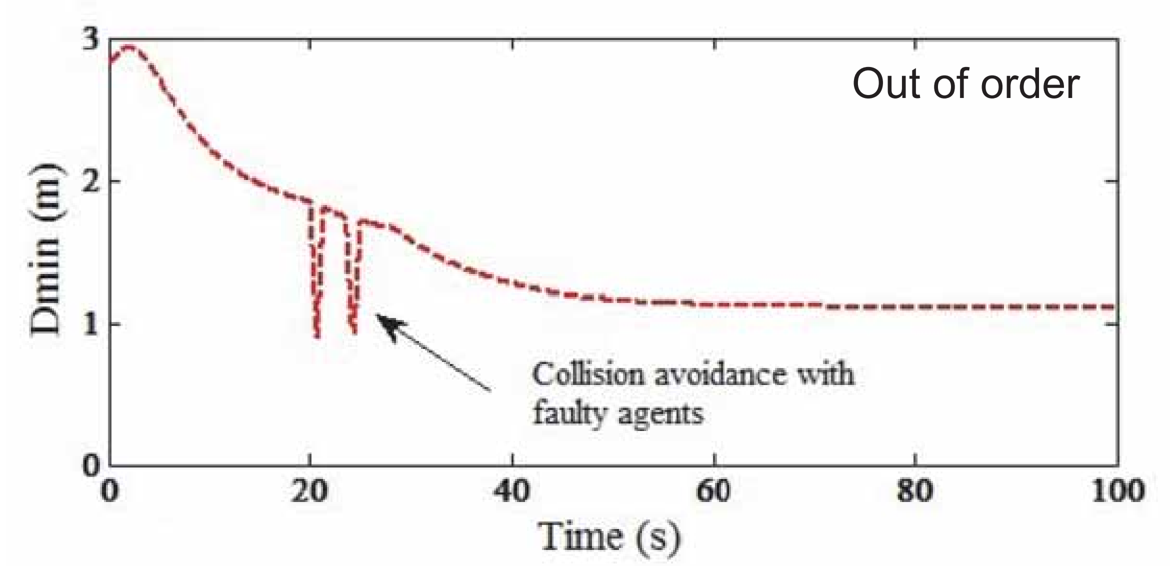
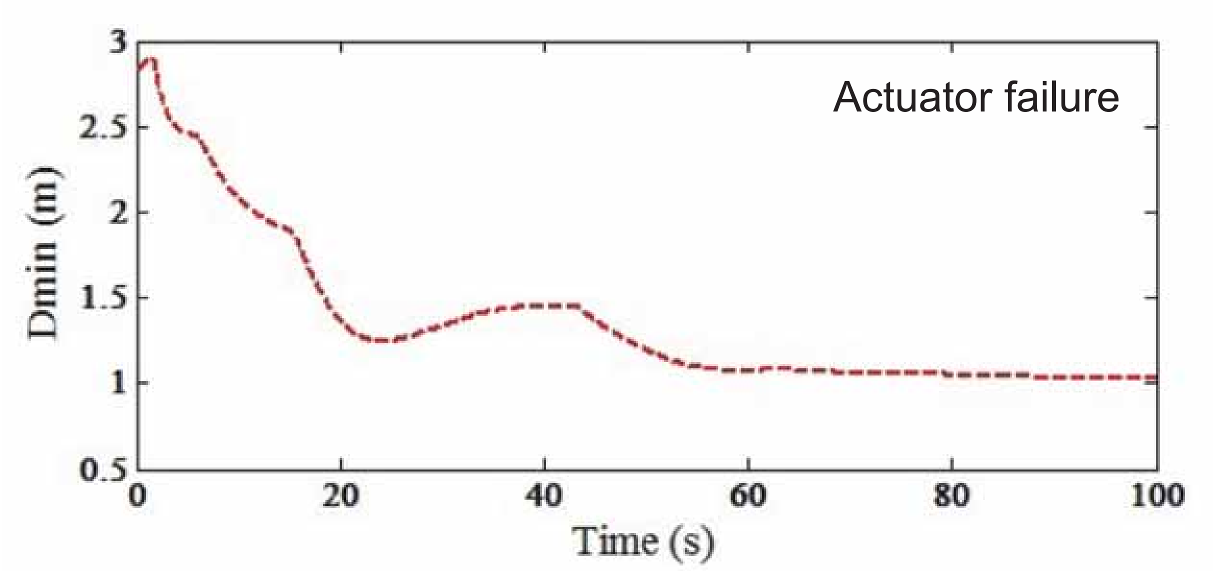
Safety distance - faulty cases





July 2017: Adel Belkadi - **PhD title** "FDI/FT methods Design to multi-agent systems: Application to Fleet Autonomous Vehicles" in collaboration with Dr. L. Ciarletta (LORIA – University of Lorraine)

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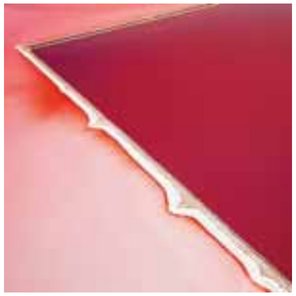
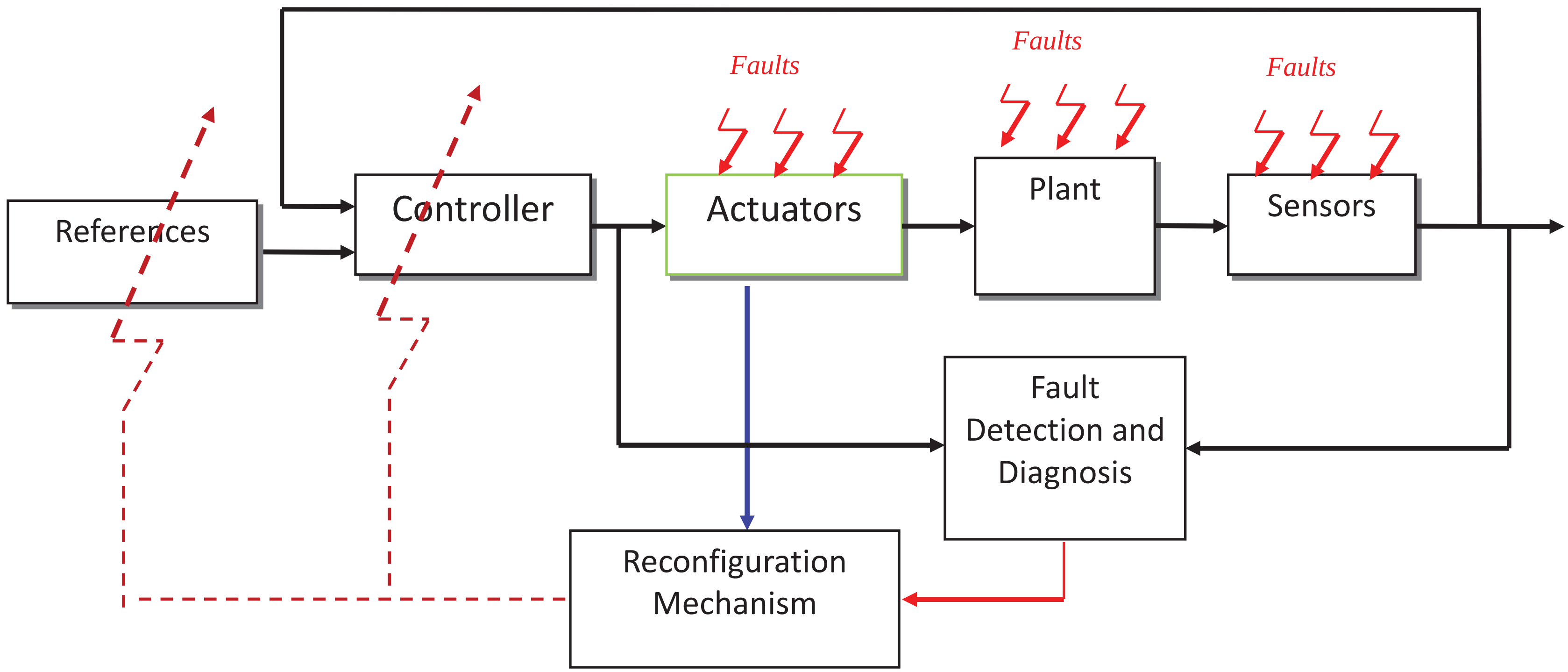


General conclusion



Other recent approaches:

- Integrated FDI/FTC (Markov Chain or Dwell-time)
- Fault Estimation and Fault Accommodation Synthesis
- FE/FTC Joint Design
- Reference redesign compensation methods
- Fault tolerant collaborative control methods

fault-tolerant controllers based on safety-related issues

[*] « A series of industrial safety standards and guidelines have been issued for the safety of industrial processes. International standard IEC 61508 (IEC, 2010) « **IEC 61508 Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems** » is a general standard for design, construction, and operation of safety related systems, from which more specific sets of safety standards are developed for various industrial fields. For instance, IEC 62061 (IEC, 2005), IEC 61513 (IEC, 2011), and IEC 62425 (IEC, 2007) are industrial standards especially for machinery systems, NPPs, and railway signaling systems, respectively. In avionics industry, a series of guidelines for the design and manufacture of airplanes has also been issued (RTCA, 1992, 2000; SAE, 1996). One needs to follow the industrial rules, regulations, and standards when designing an active FTC."

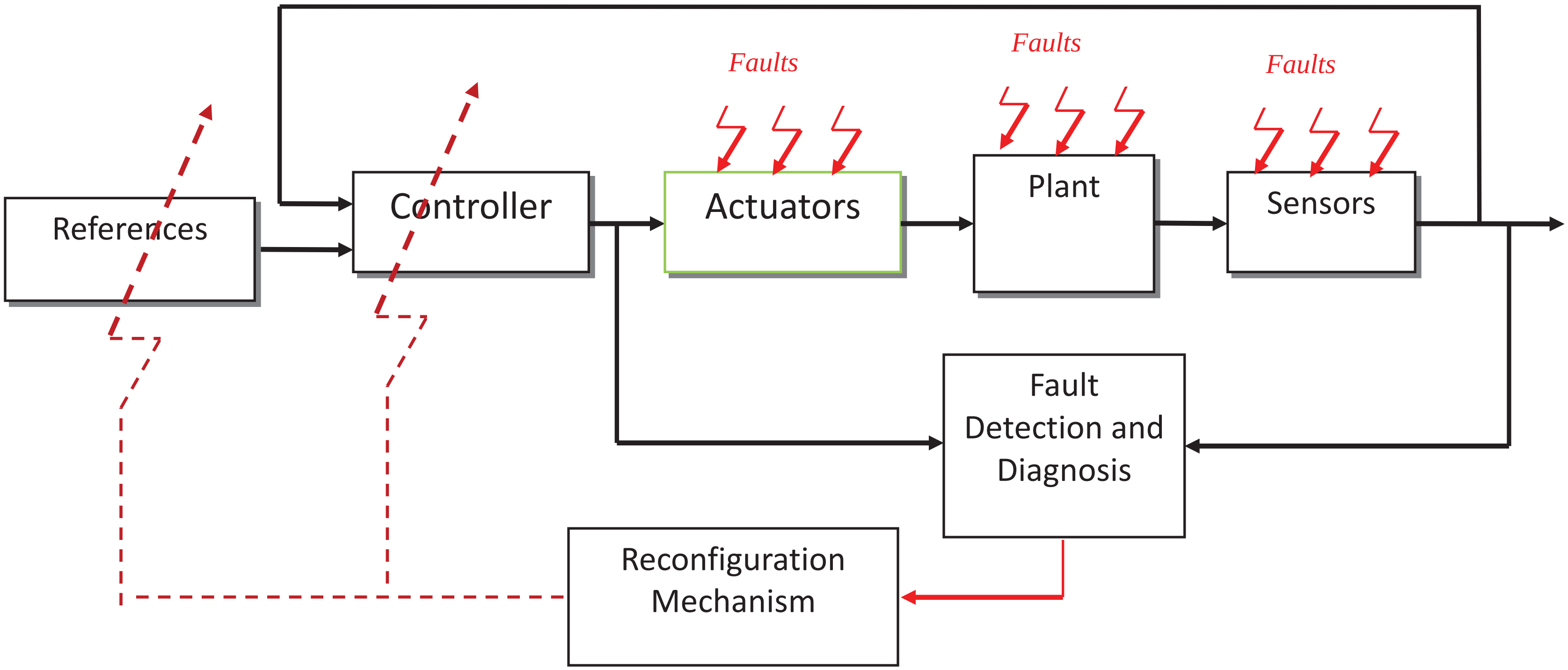
[*] X. Yu and J. Jiang A survey of fault-tolerant controllers based on safety-related issues, Annual Reviews in Control , 2016

UAV for Materials (15 tonnes) – October 2017
Neifu Aerport from Pucheng

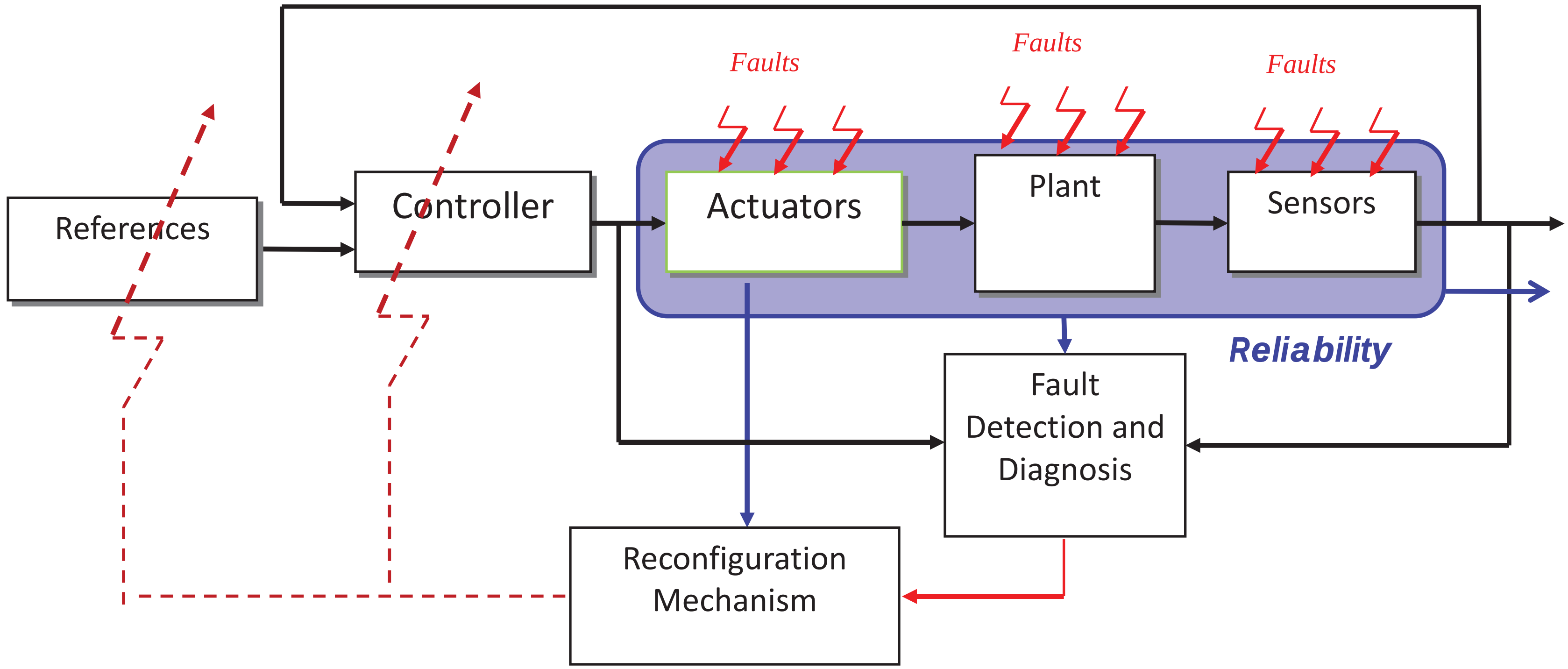
Rules, regulations and standards for UAV (Fleet of UAVS)

Pay attention to consider Active FTC

Integration of Reliability and FTC design



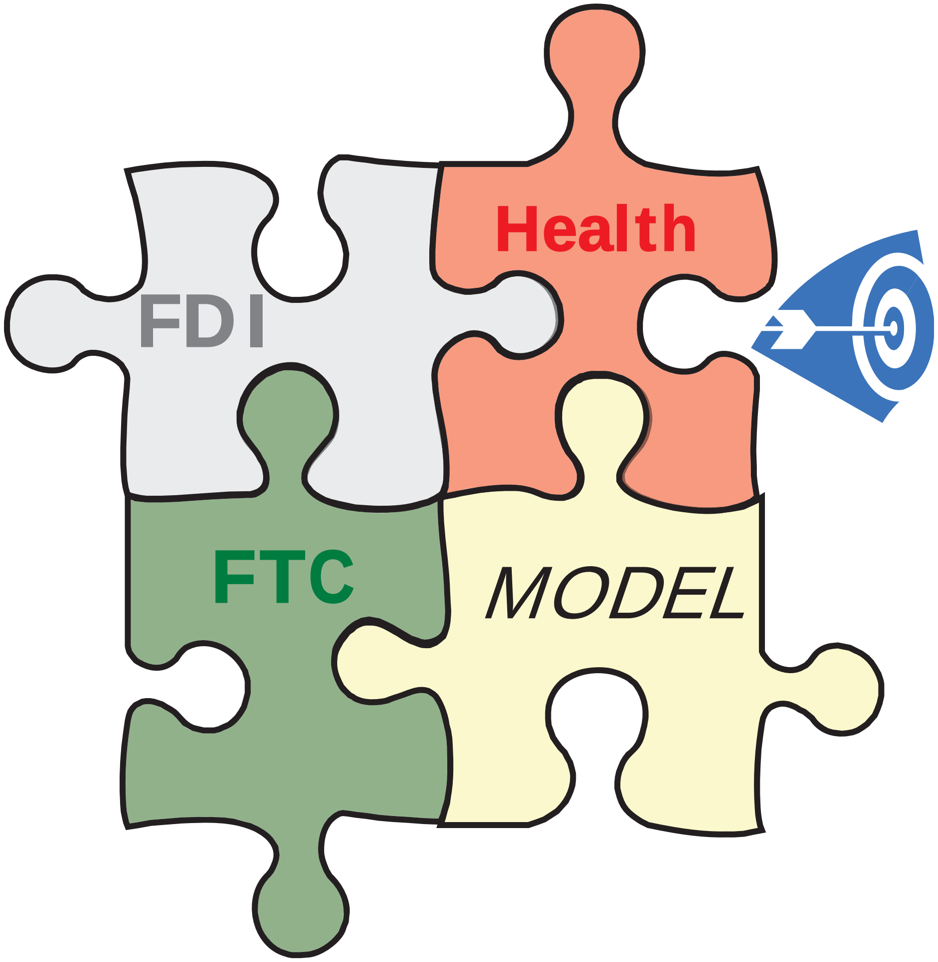
Integration of Reliability and FTC design



- Actuators/Sensors reliability estimations "on line"
- Uncertainties on failure rates
- Link with maintenance constraints
- ....

Reliability
&
Controllability

General conclusion



Health aware oriented
Control Strategy

Acknowledgment (*) to:

Dr. A. Belkadi (France)
Dr. P. Castillo (France/Mexique)
Dr. A. Chamseddine (Canada)
Dr. L. Ciarletta (France)
Dr. Y. He (China)
Dr. F. Guenab (France)
Dr. A. Khelassi (France)
Dr. X. Qin (China)
Prof. J.C. Ponsart (France)
Dr. I. Sadeghzadeh (Canada)
R. Schacht Rodríguez (France/Mexique)
Prof. P. Weber (France)
Prof. Y. Zhang (Canada)
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Experimental plateform from:

Shenyang Institute of Automation - RPC

Concordia University
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Department of Mechanical and Industrial Engineering

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Laboratoire lorrain de recherche en informatique et ses applications

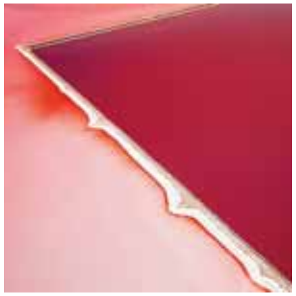
OUTLINES

Context
Fault Tolerant Control
- Problem statement
- Principle and some definitions
- Active FTC under fault effectiveness
  - under critical fault
  - under severe fault

Fault Tolerant Control versus Health
- Definitions
- Overactuated Systems
- Heuristic approach - Optimal reliable FTC method
- PHM for UAV (battery case)

Fleet Control of UAVs
- Cooperative Control based on Multi-agent systems
- Cooperative FTC design

Conclusions and Perspectives



Fault-Tolerant Control Methods Design: Applications to UAVs Testbed

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