Safe Reinforcement Learning, Resilient/Fault Tolerant and Health Aware Control Strategies for Autonomous Systems

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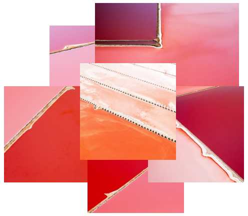

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Safe Reinforcement Learning, Resilient/Fault Tolerant and **Health Aware Control** Strategies for Autonomous Systems

Seminar on Health Aware Control !!!

Action

Groupement de recherche
MACS Modélisation, Analyse et Conduite des Systèmes dynamiques

Health Aware Control Design in Dynamic Systems

Soumis par THEILLIOL le mer 15/03/2023 - 23:43

Initiateur Didier THEILLIOL

Porteur(s) Mayank Shekhar JHA John Jairo MARTINEZ MOLINA Didier THEILLIOL Philippe Weber Christophe BERENGUER

Type d'action Création et animation d'une communauté scientifique

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Dr. A. Khelassi (France)
Dr. X. Qin (China)
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Dr. I. Sadeghzadeh (Canada)
Dr. R. Schacht Rodríguez (Mexique)
Dr. J.A. Vazquez (Mexique)
Prof. P. Weber (France)
Prof. Y. Zhang (Canada)

(*) alphabetic order

Experimental plateform from:

Shenyang Institute
of Automation - RPC

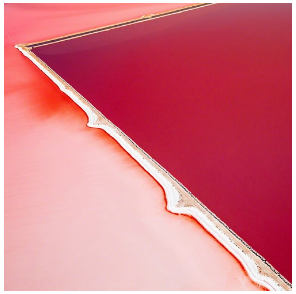
Concordia University
Engineering and Computer Science
Department of Mechanical and Industrial Engineering

heudiasyc

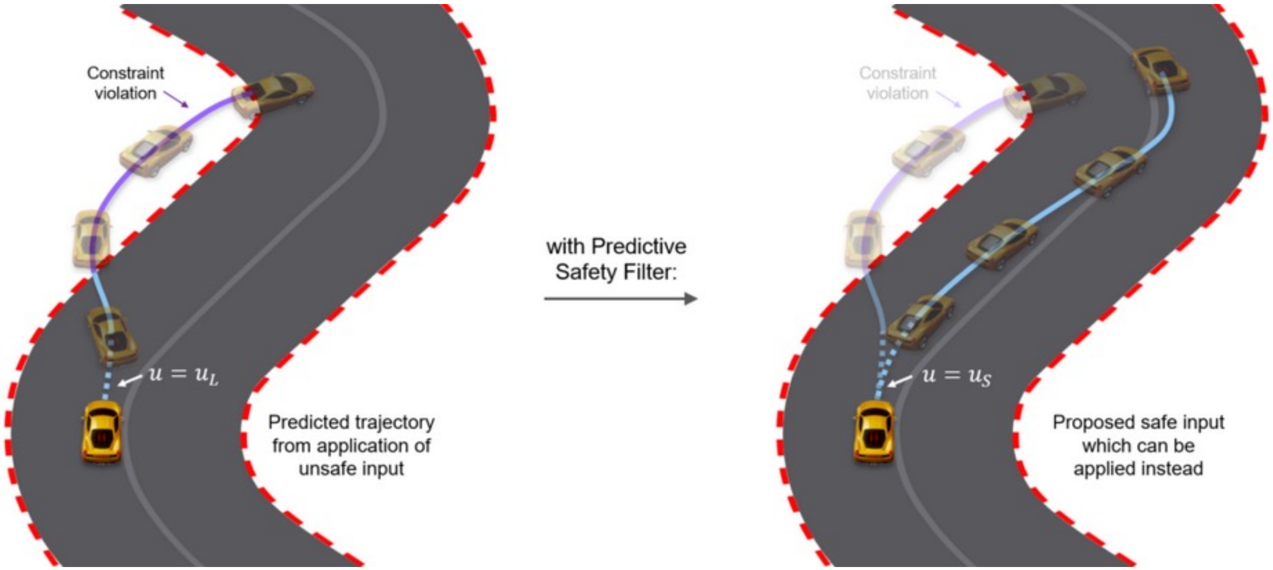
Loria
Laboratoire lorrain de recherche en informatique et ses applications

OUTLINES

Context



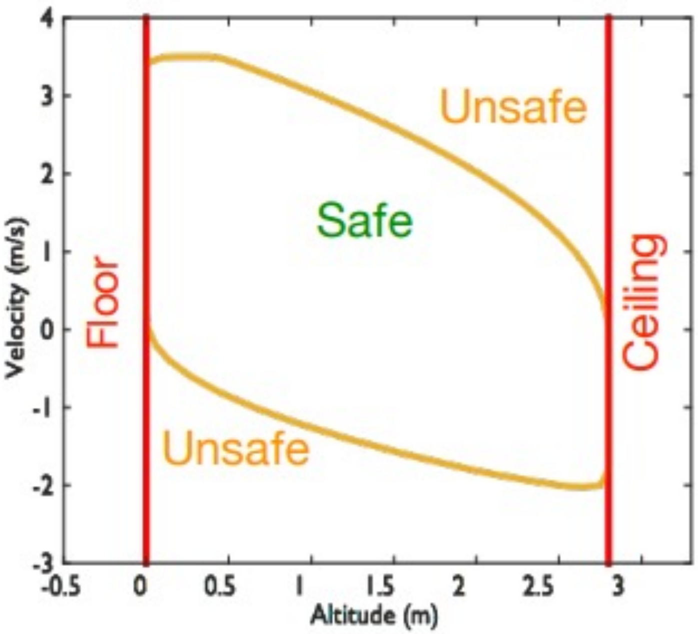
Motivations:
Ensure safety



Wabersich, K. P., & Zeilinger, M. N. (2021). A predictive safety filter for learning-based control of constrained nonlinear dynamical systems. ***Automatica***, *129*, 109597.

Motivations:
Ensure safety

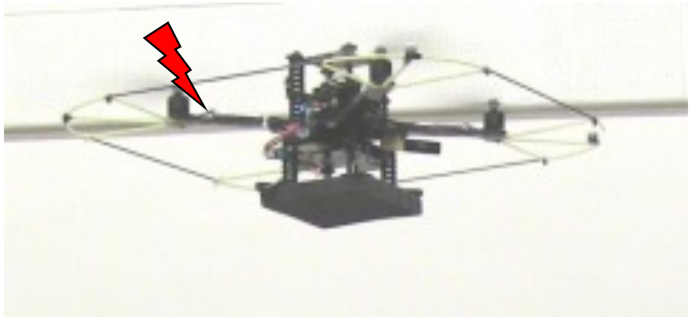
$$x_{k+1} = f(x_k, u_k) + d(\bullet)$$



Gillula, J. H., & Tomlin, C. J. (2012, May). Guaranteed safe online learning via reachability: tracking a ground target using a quadrotor. In *2012 IEEE **ICRA*** (pp. 2723-2730). IEEE.

Motivations:

Ensure operational safety



Fault / Degradation/ Failure

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…."

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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)

Dependability Norms

IEC 60812 Analysis techniques for system reliability - Procedure for failure mode and effects analysis (FMEA)
IEC 60863 Presentation of reliability, maintainability and availability predictions
IEC 61014 Programmes for reliability growth
IEC 61025 Fault tree analysis (FTA)
IEC 61070 Compliance test procedures for steady-state availability
IEC 61078 Analysis techniques for dependability - Reliability block diagram method
IEC 61123 Reliability testing - Compliance test plans for success ratio
IEC 61124 Reliability testing - Compliance tests for constant failure rate and constant failure intensity
IEC 61164 Reliability growth - Statistical test and estimation methods
IEC 61165 Application of Markov techniques
IEC 61508 Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems
IEC 61703 Mathematical expressions for reliability, availability, maintainability and maintenance support terms
IEC 61709 Electronic components - Reliability - Reference conditions for failure rates and stress models for conversion
…

Scope… IFAC TC 6.1. SAFEPROCESS

IFAC International Federation of Automatic Control

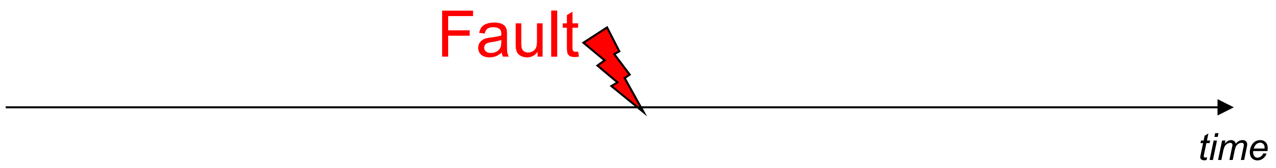
"…..
The main objective of the **Fault Detection and Isolation (FDI)** research area, widely addressed from several points of view in the last years, is to study methodologies for identifying and exactly characterizing possible incipient faults arising in predetermined parts of the plant. After accurate 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."

FTC as industrial standards and guidelines ?

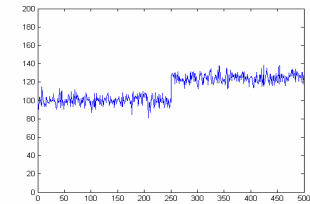
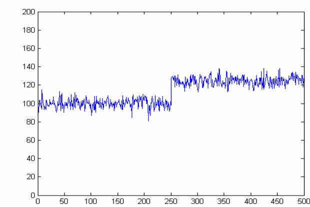
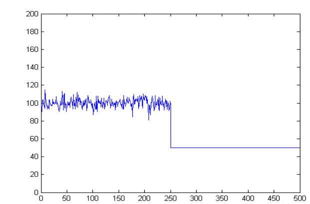
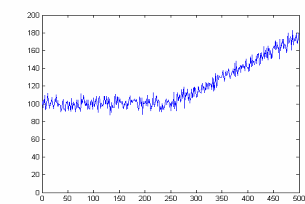
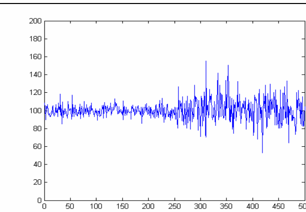
[*] « A series of industrial safety standards and guidelines have been issued for the safety of industrial processes. International standard IEC 61508 (IEC, 2010) « **IEC 61508 Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems** » is a general standard for design, 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

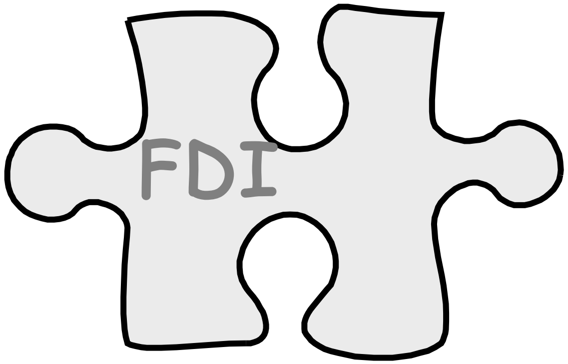
Context and aim



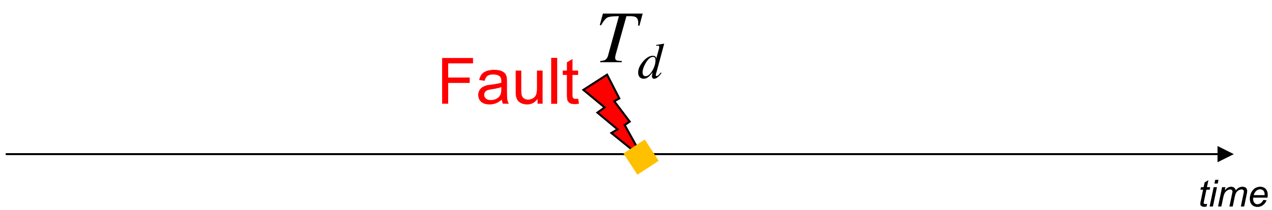
Fault/ Degradation/ Failure

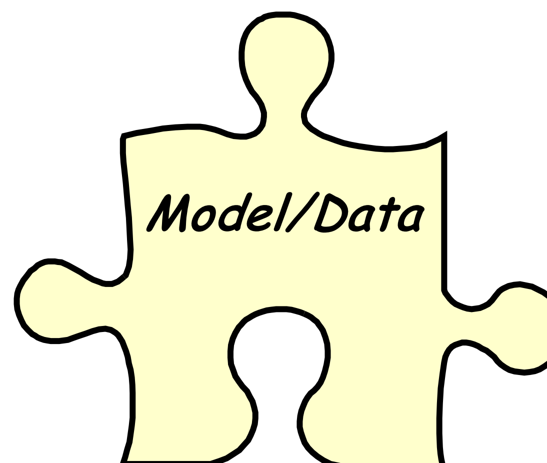
Fault	Equation	Cause	Effect	Graph
Bias	$Y_i(t)=Y_i^*(t)+\varepsilon_i(t)+\alpha\Gamma_\theta$ $\alpha = constant\ value$ $\Gamma_\theta = \begin{cases} 0, t<\theta \\ 1, t\geq\theta \end{cases}$ the Heavisides function	• Decalibration	Jump in the mean value	
Gain modification	$Y_i(t)=\alpha\Gamma_\theta Y_i^*(t)+\varepsilon_i(t)$	• Decalibration	Jump in the mean value	
Total breakdown	$Y_i(t)=(1-\Gamma_\theta)[Y_i^*(t)+\varepsilon_i(t)]+k$ $k\in\{Y_{min},0,Y_{max}\}$	•Destruction of the sensor •Disconnection of an electrical signal	Signal constant, zero or min/max	
Offset drift Bias drift	$Y_i(t)=Y_i^*(t)+\varepsilon_i(t)+\alpha\, r_{\theta,t}\,\Gamma_\theta$ $r_{\theta,t}=\begin{cases} 0 & ,t<0 \\ t-\theta & ,t\geq 0 \end{cases}$	•Ageing •Slow destruction of the sensor •Temperature drift	Signal slowly deviates from the true value	
Increased noise	$Y_i(t)=Y_i^*(t)+\varepsilon_i(t)+[\eta_i(t)-\varepsilon_i(t)]\Gamma_\theta$ η_i = increased noise standard deviation	•Electro-magnetic disturbance •Loss of screening •Disconnection of the ground signal	Small signal to noise ratio	

Context and aim

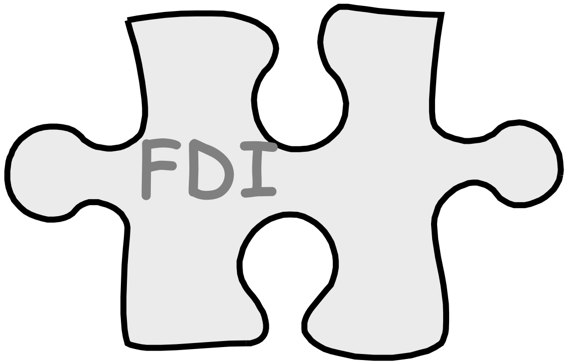


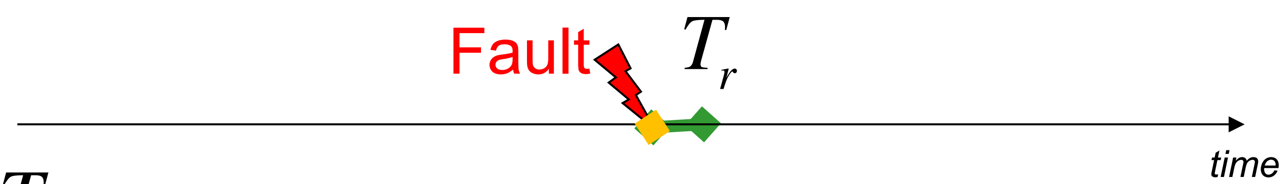
T_d represents time to detect, isolate and to estimate



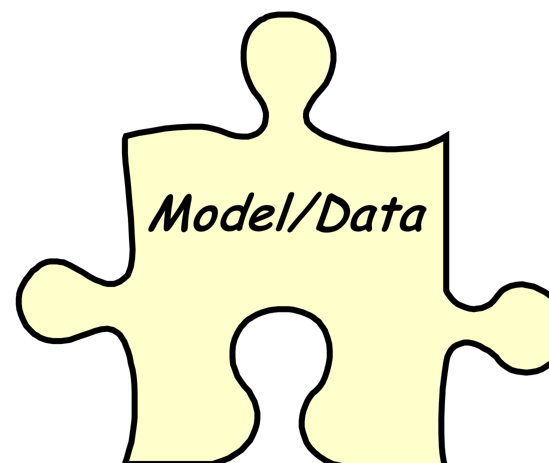


Context and aim

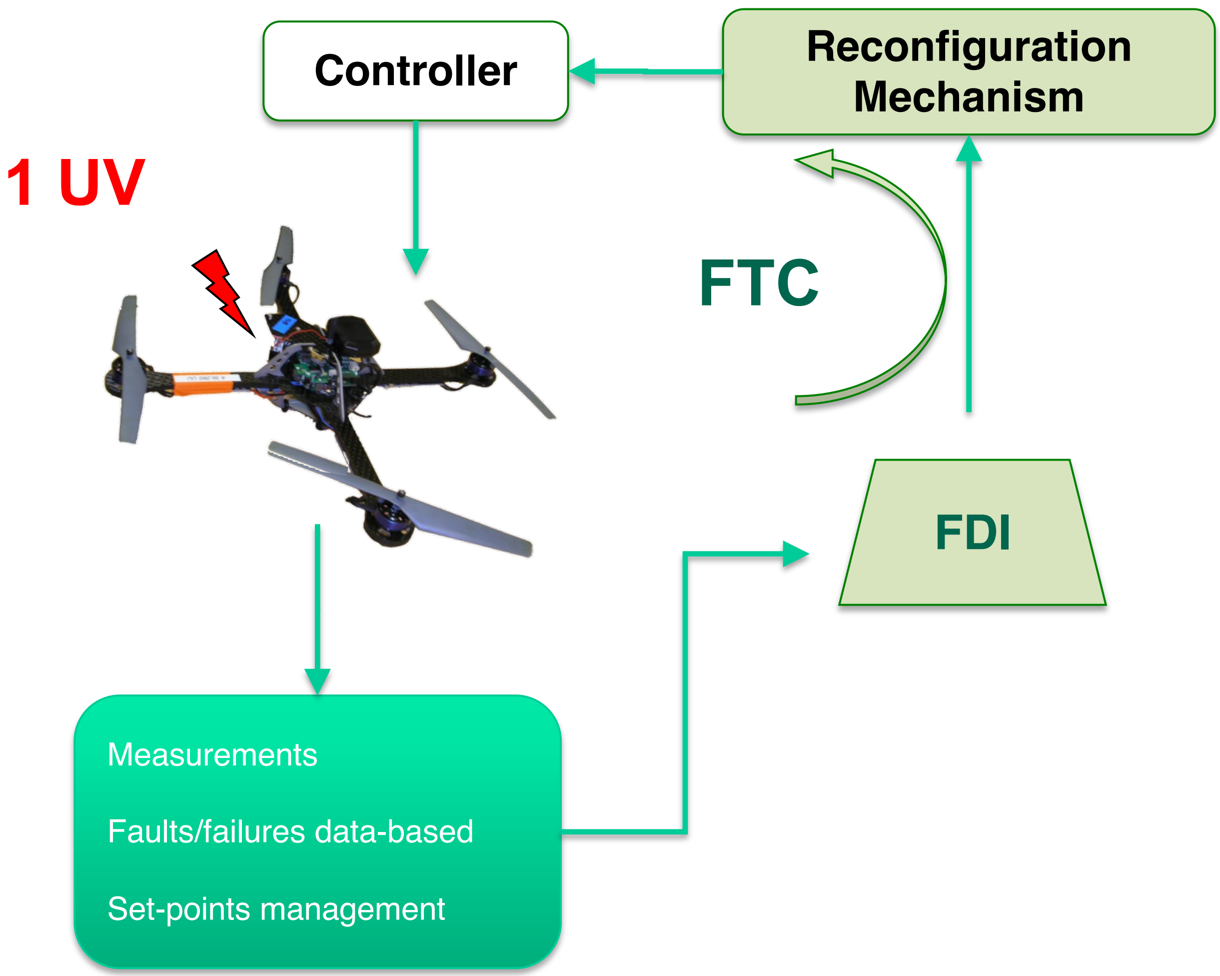




T_r represents time to reconfigure

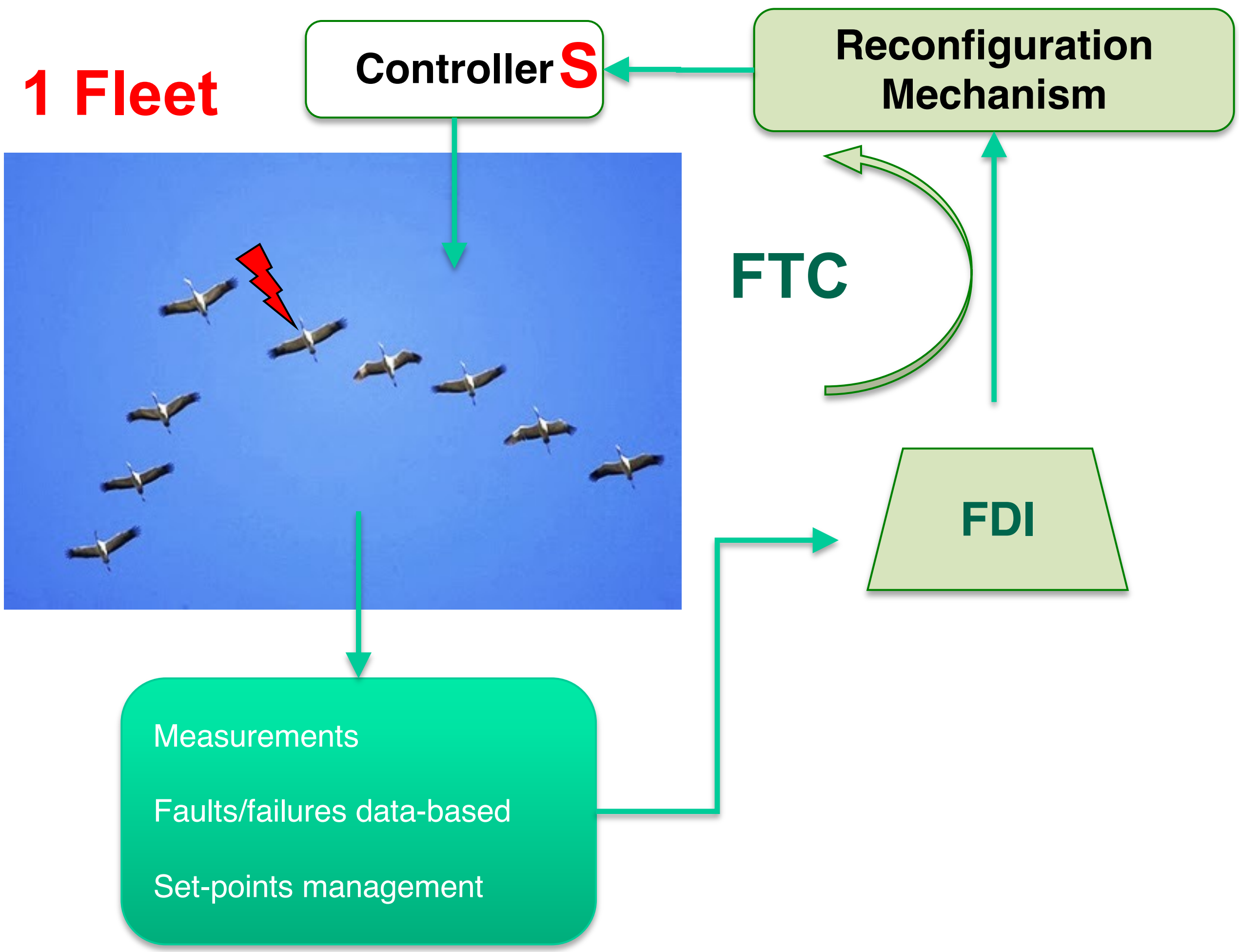


FDI / FTC & Prognosis Health Management



FDI / FTC & Prognosis Health Management

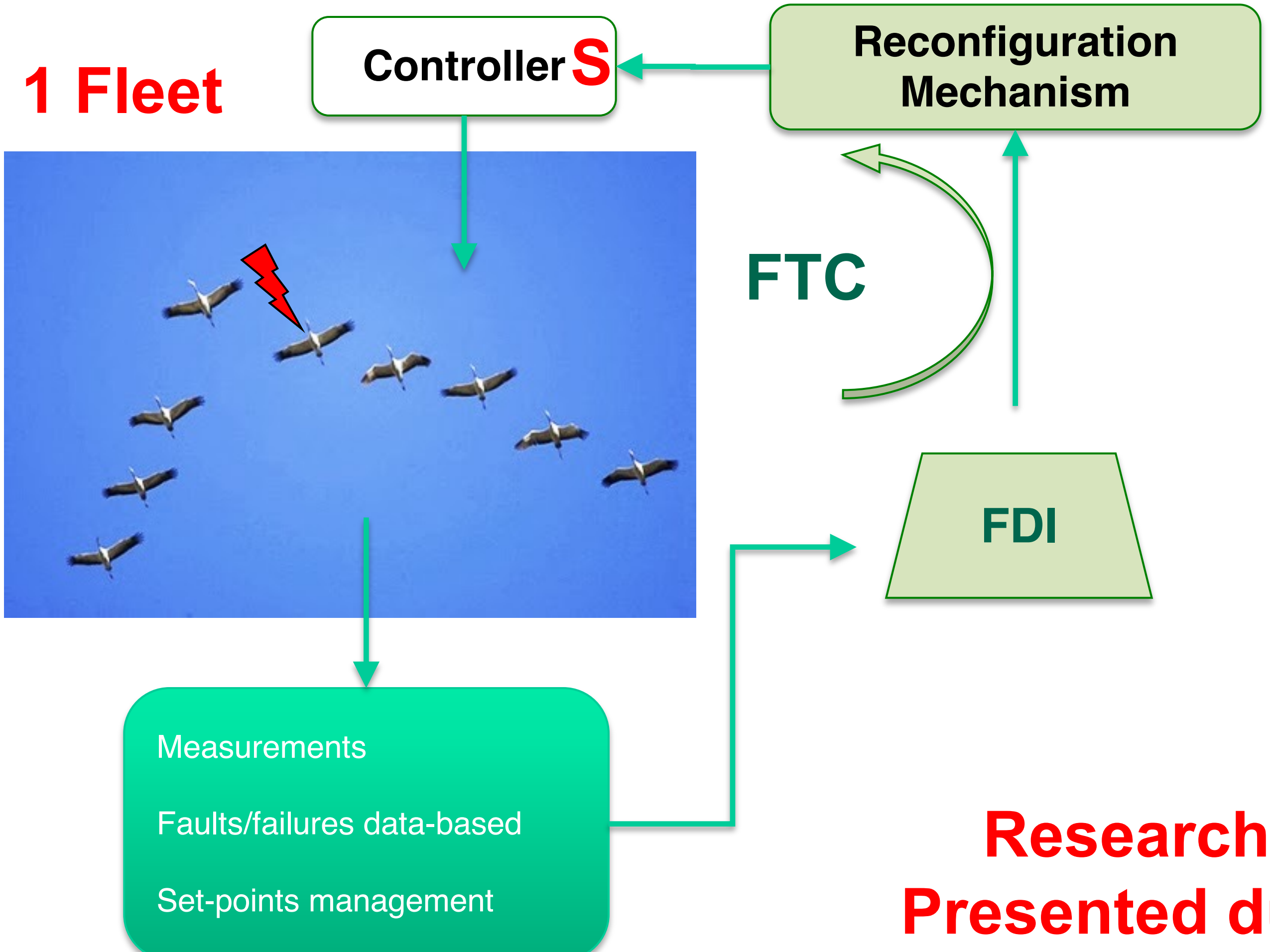
Multi Agent System (Consensus…)



FDI / FTC & Prognosis Health Management

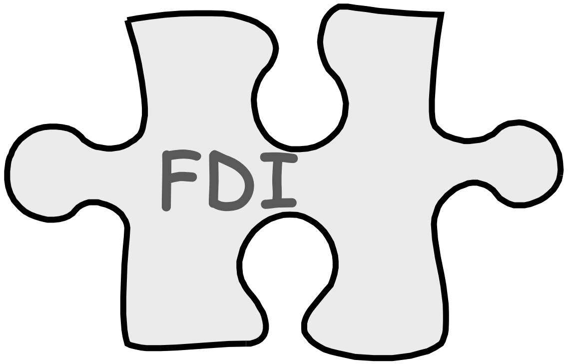
Multi Agent System (Consensus…)

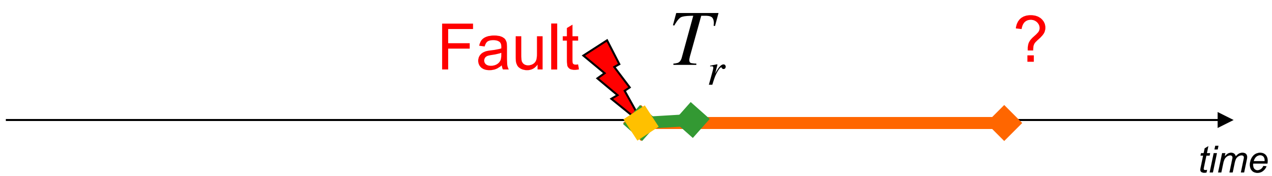
1 Fleet

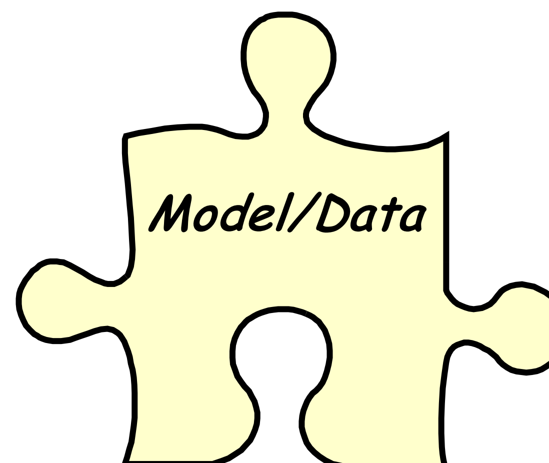


Research Activities NOT Presented during this Plenary

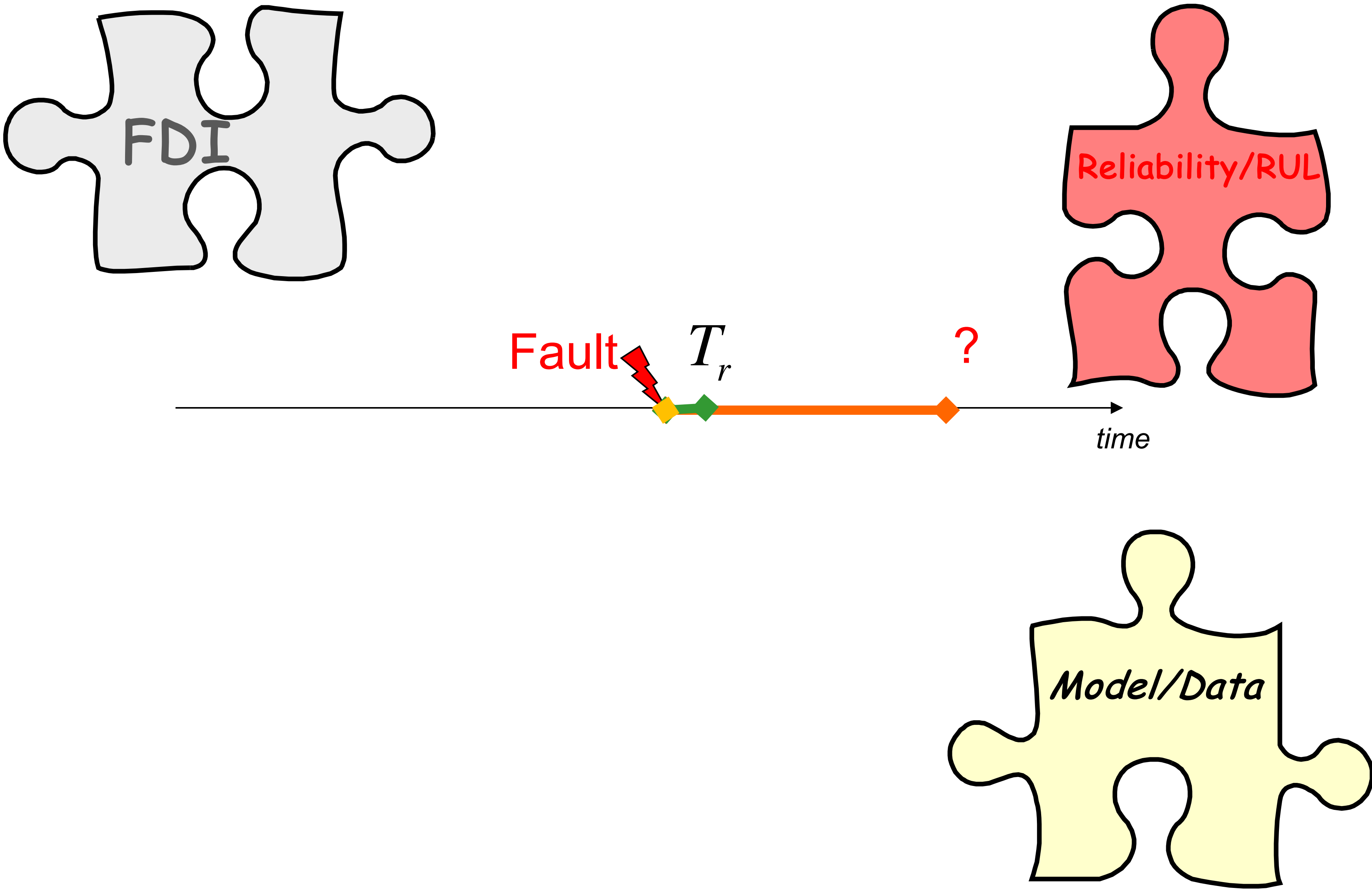
Diagnosis and ....



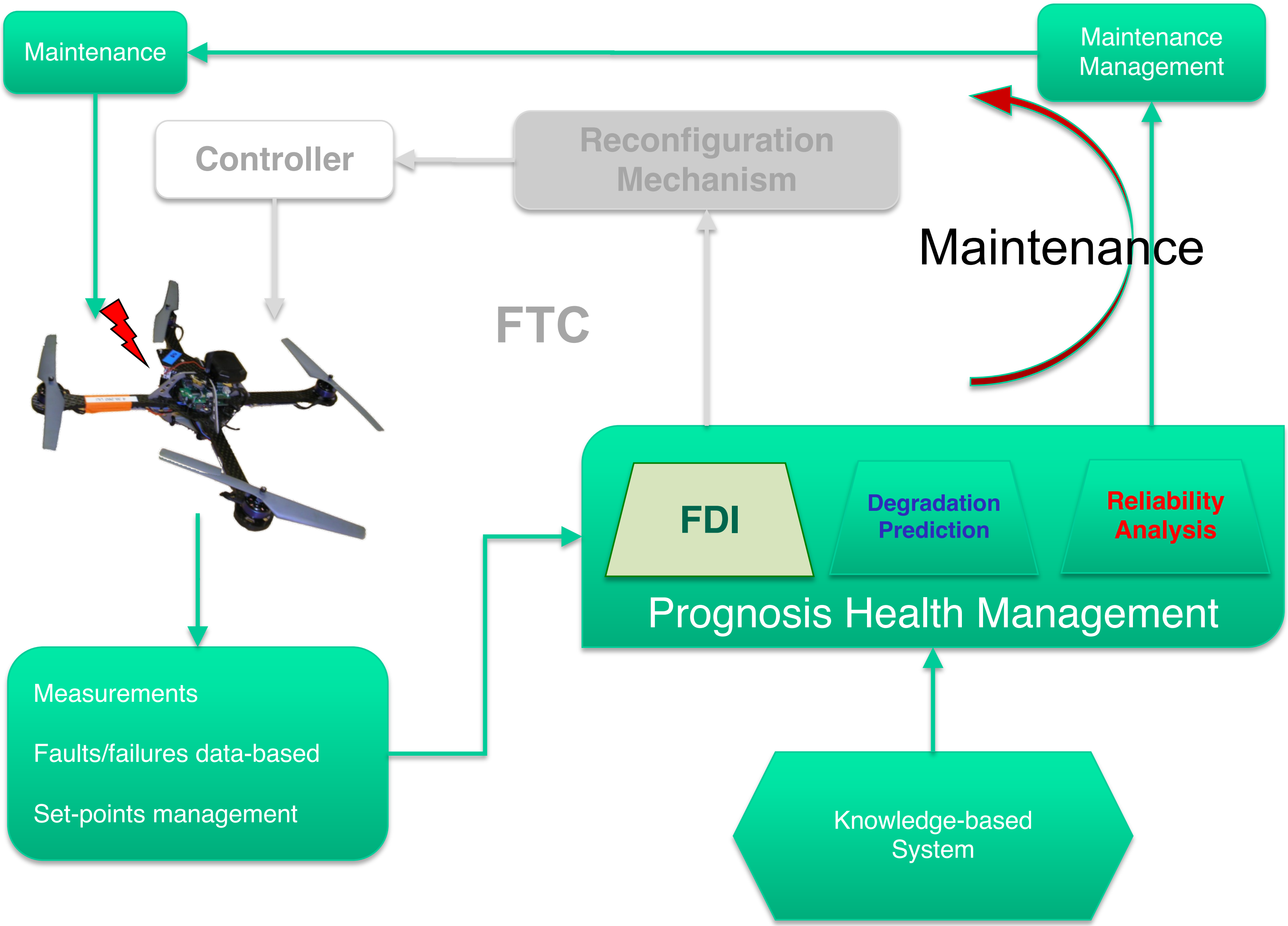




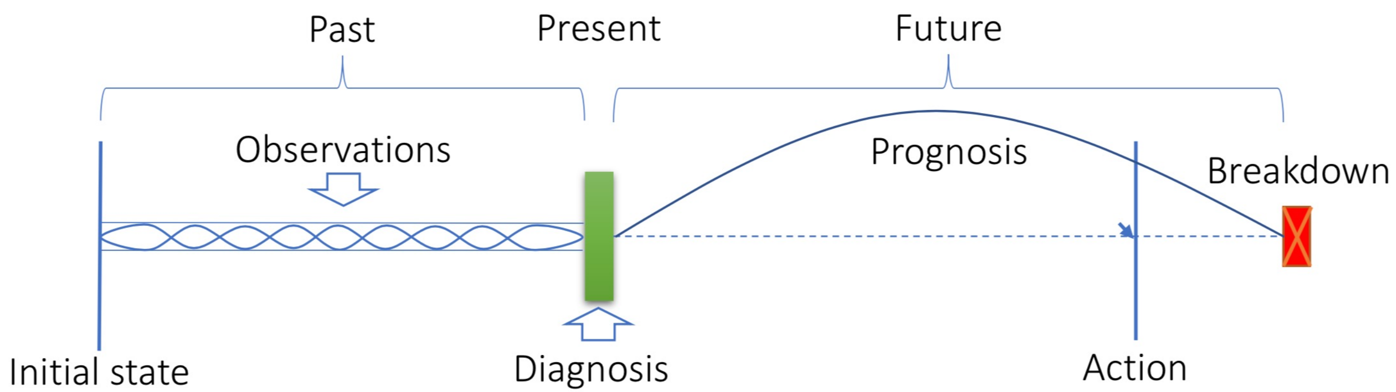
Diagnosis and Prognosis



FDI / FTC & Prognosis Health Management

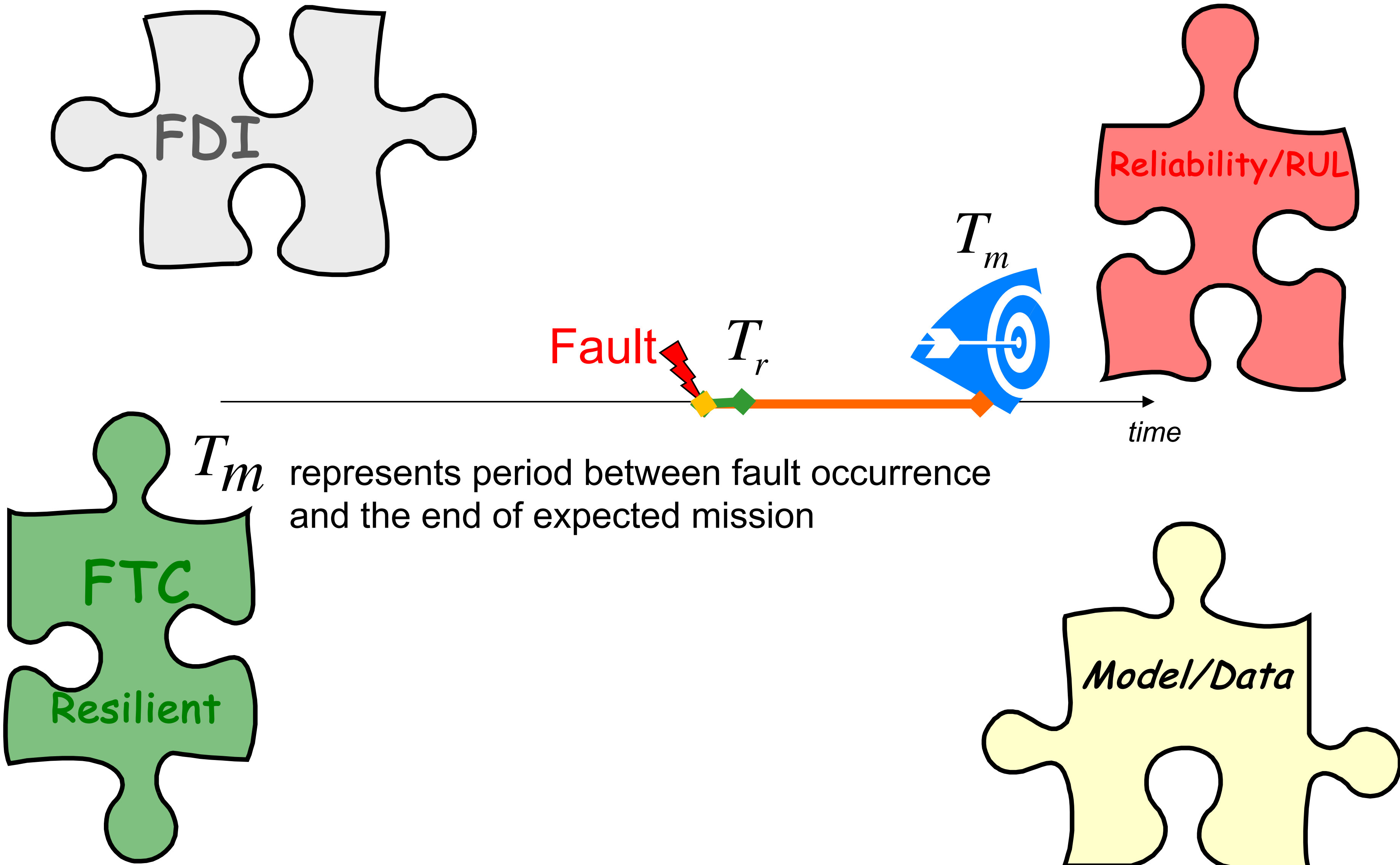


Diagnosis (FDI) & Prognosis



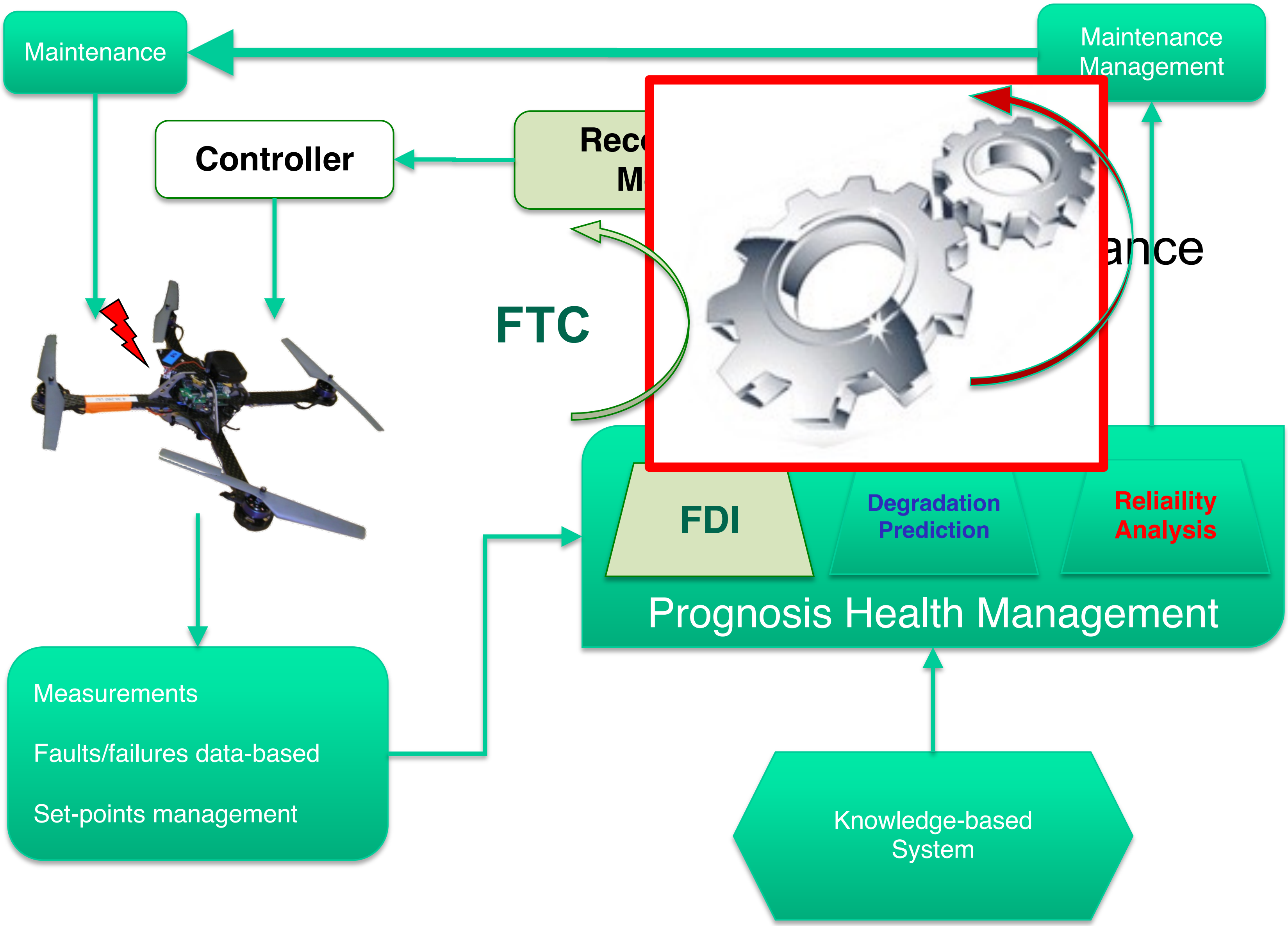
- Initial state: State distribution at the beginning.
- Observations: Extracted data from sensors on the complex system.
- Diagnosis: Identifying the current hidden health state of the system based on observations.
- Prognosis: prediction of the future health evolution of the system considering operating conditions.
- Action: Plan maintenance.
- Breakdown: System failure.

Consider prognosis in the closed-loop ... Why not !!!

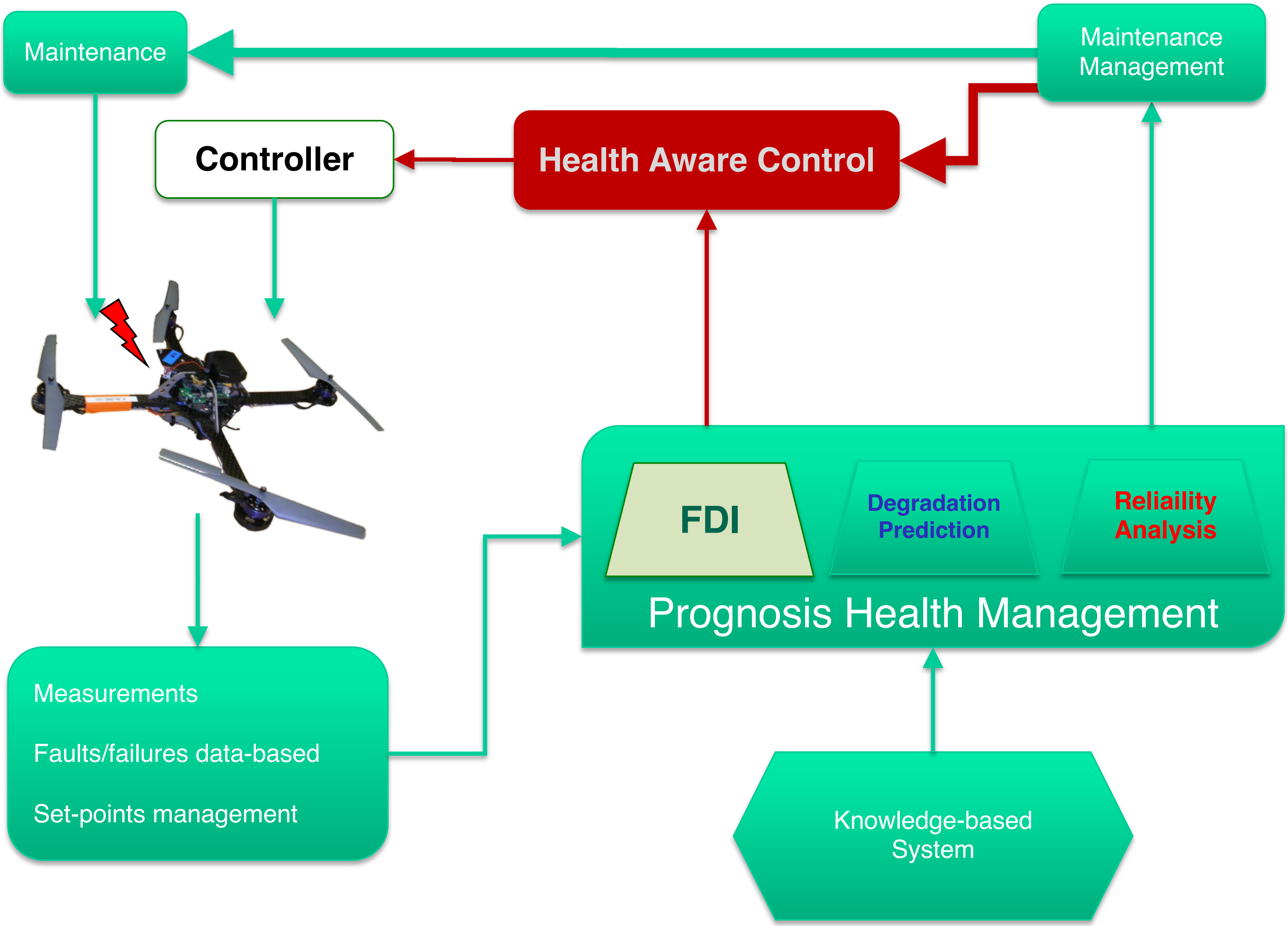


T_m represents period between fault occurrence and the end of expected mission

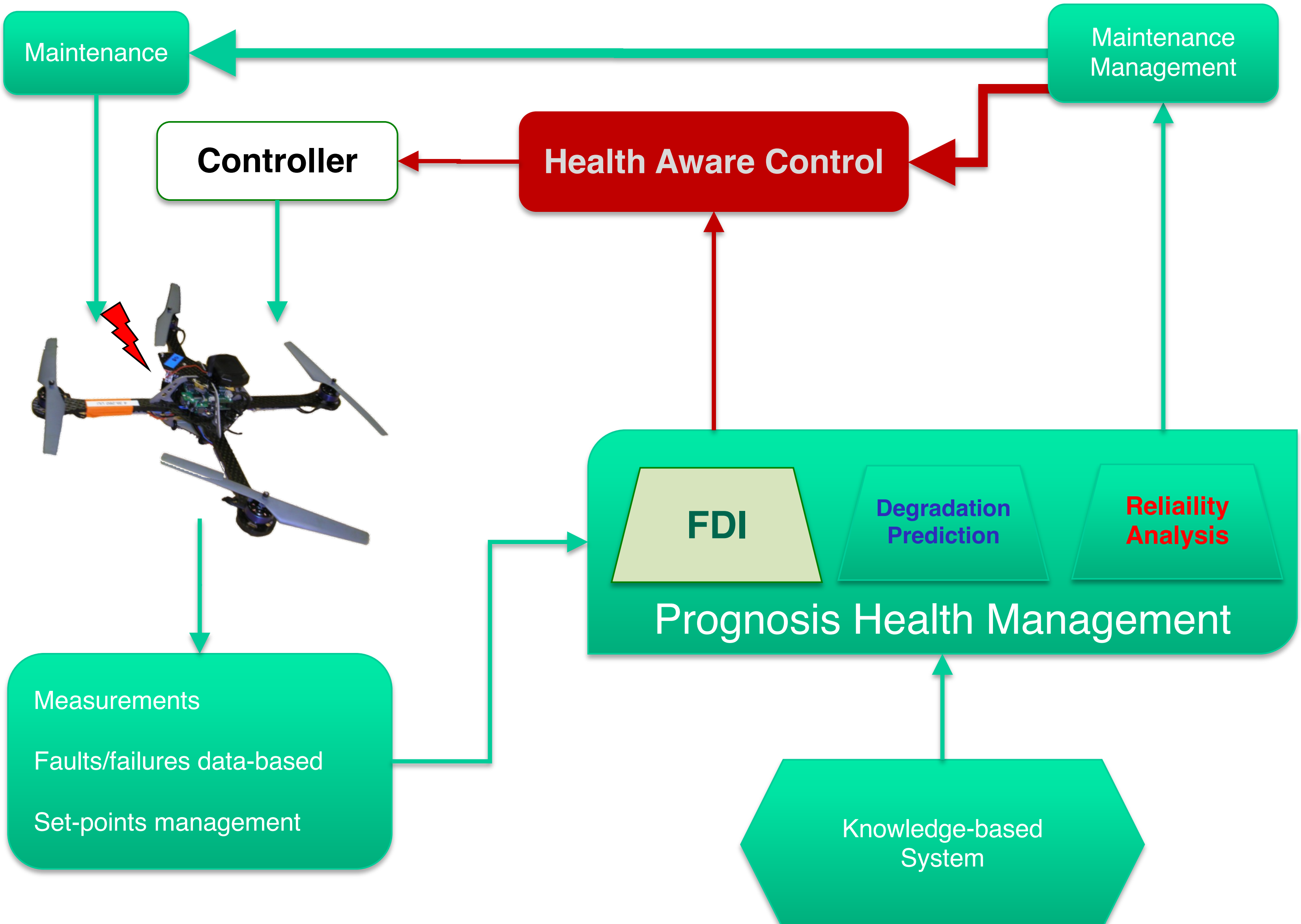
FDI / FTC & Prognosis Health Management



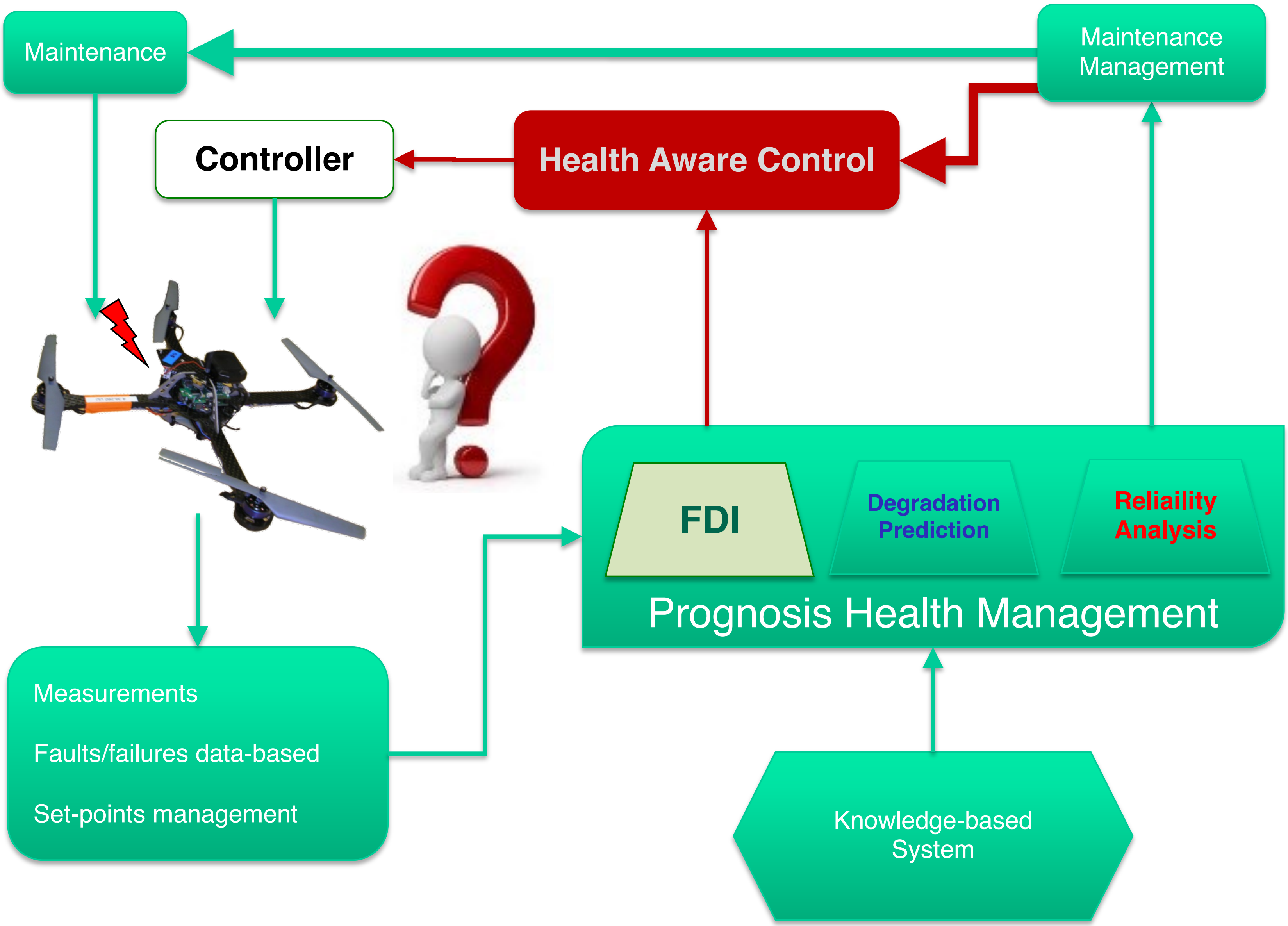
Health Aware Control Design



Health Aware Control Design – Model Based Approach



Health Aware Control Design – ~~Model Based Approach~~



Reinforcement Learning – RL

RL : Rich History

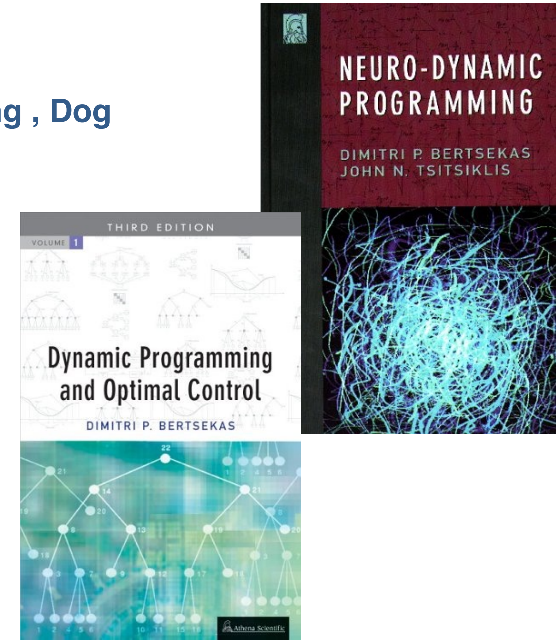
Psychology: Ivan Pavlov 1890 (Classical conditioning vs Instrumental conditioning , Dog experiments….)

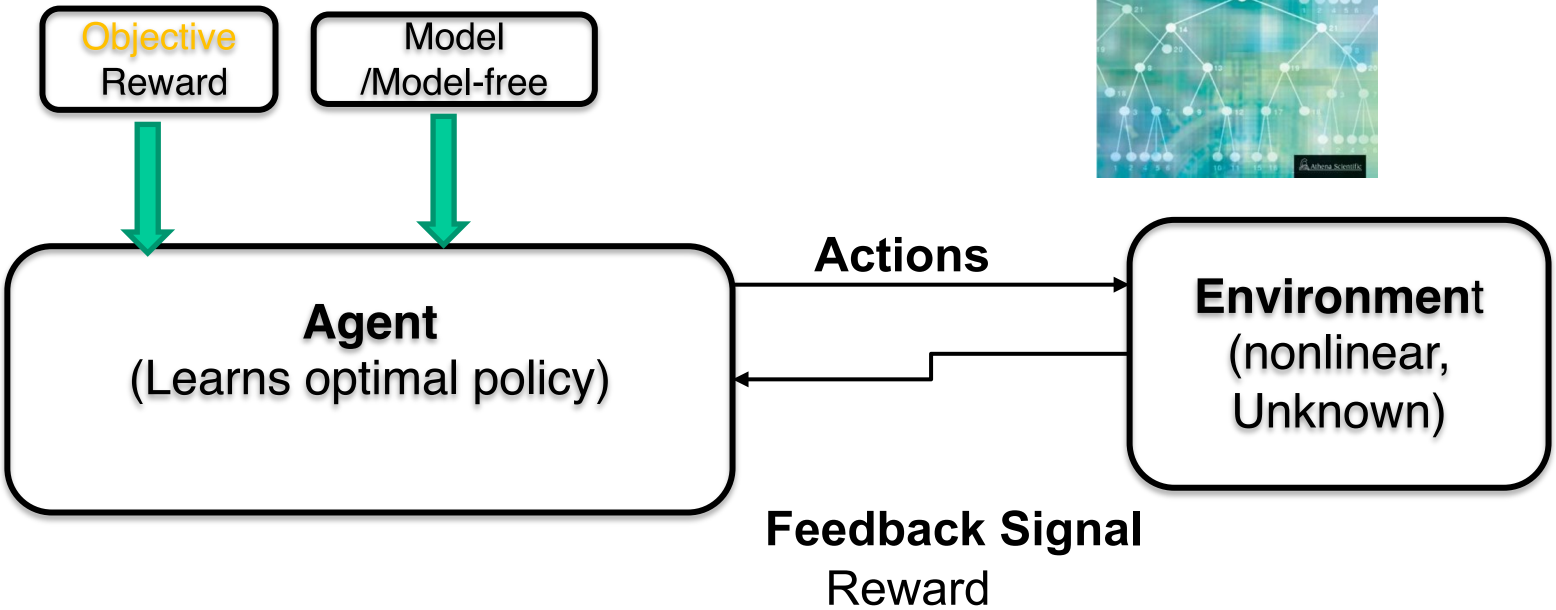
Optimal control and Dynamic programming (1950) Richard Bellman, MIT)

Dynamic programming + Neuro-dynamic programming (Neural Networks) 1980-…

RL + Deep Learning = Deep RL (2010-…)

Supervised learning --- Unsupervised Learning --- Reinforcement Learning





OUTLINES

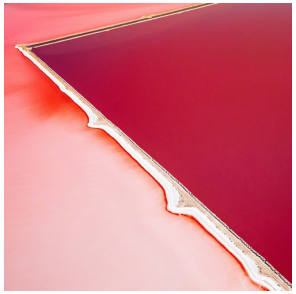
Context

Fault Tolerant Control
- Problem statement & Principle

Health Aware Control
- Reliability and RUL Definitions
- Heuristic approach - Optimal “reliable FTC” method
- HAC based on RUL estimation

Safe Reinforcement Learning (*)
- Reinforcement Learning
- Safe Reinforcement Learning

Conclusions and Perspectives

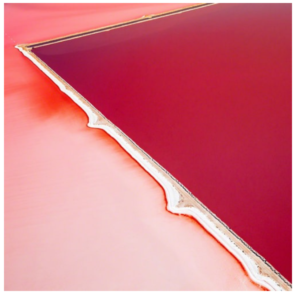


(*) *new results from main contributor Dr. MS JHA*

OUTLINES

Fault Tolerant Control

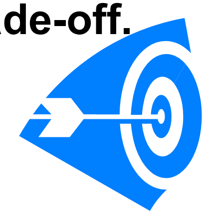
Problem statement & Principle



General Principle of FTC

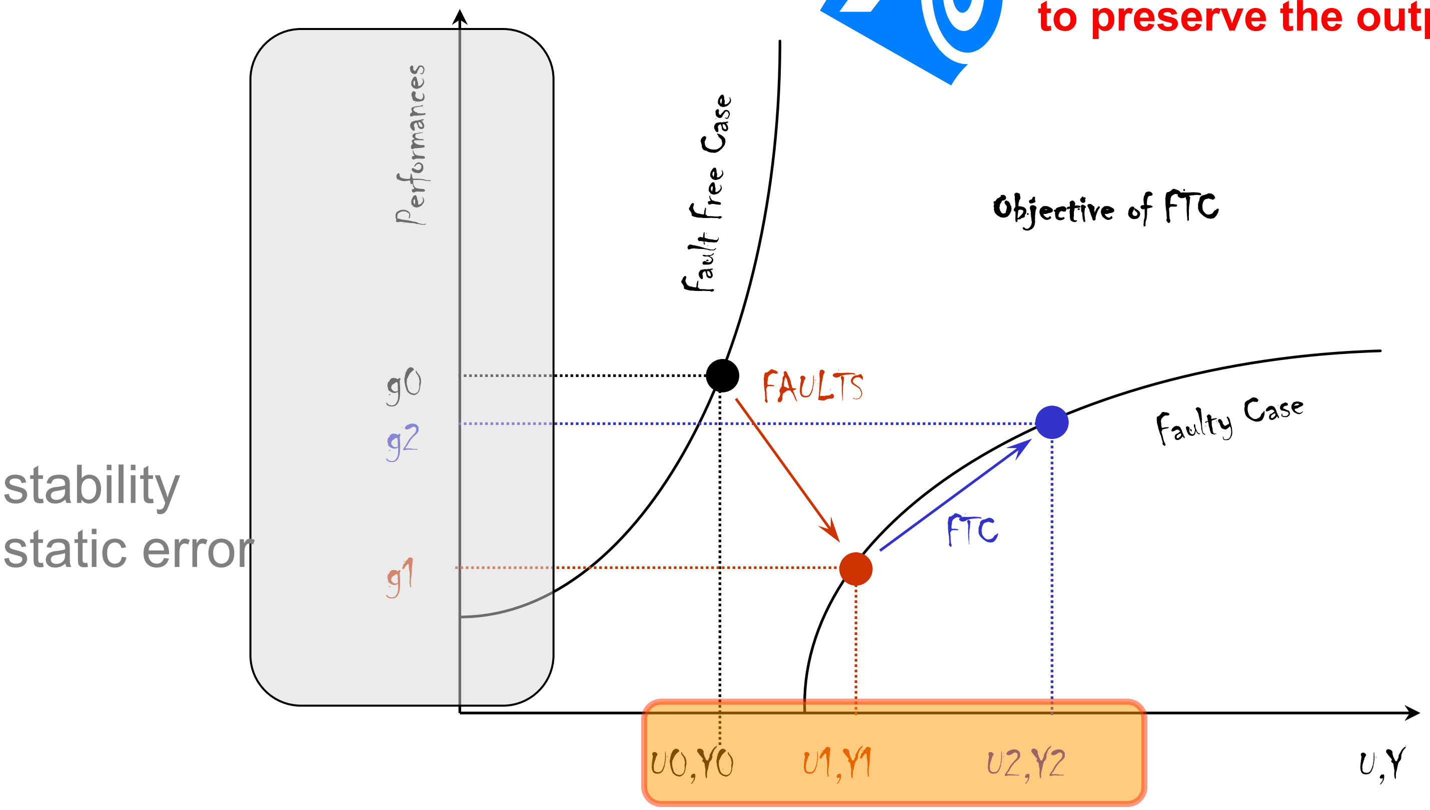
✓ *Fault Tolerant Control system* (1980)

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.



to limit the energy of control inputs

to preserve the output dynamic properties



Definition

✓ ***Fault Tolerant Control system*** (1980)

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.

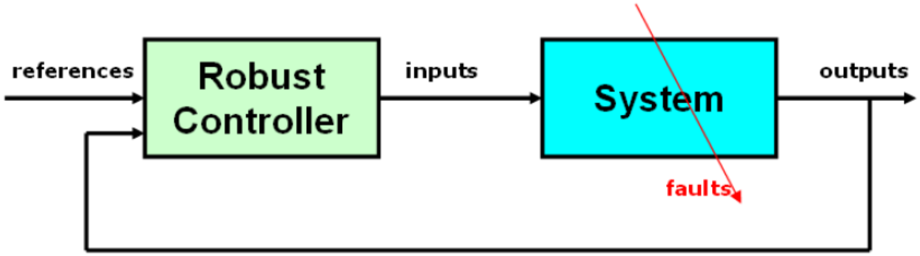
RESISTANCE ∪ RENAISSANCE

✓ ***Resilient system or resilience*** (2006)

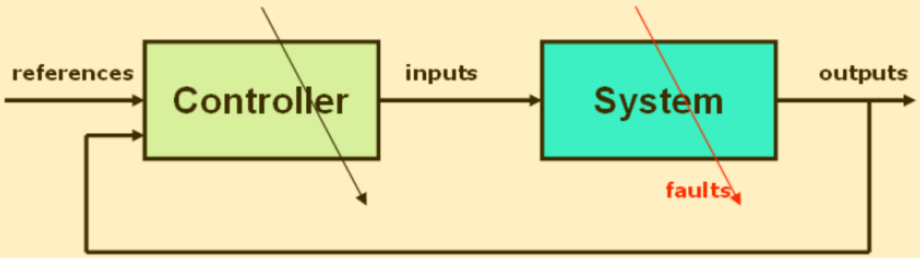
System able to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incident .

Definitions

Passive FTC:



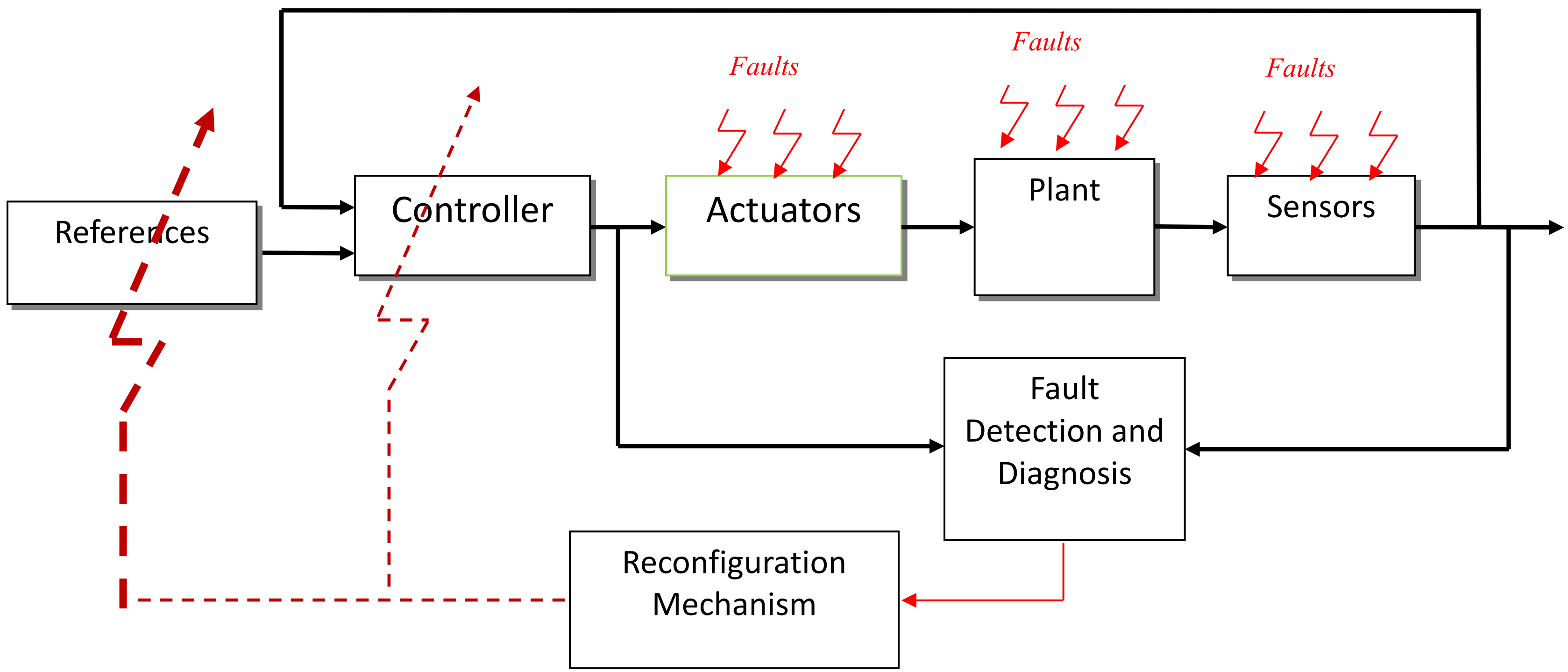
Active FTC:



- **Passive FTC** are mainly based on robust control theory. Non require on-line detection, it could be very conservative, and only for small failures.
- **Active FTC** integrates a re-configurable mechanism (adaptation) intended to preserve both *stability* and *performance*.

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

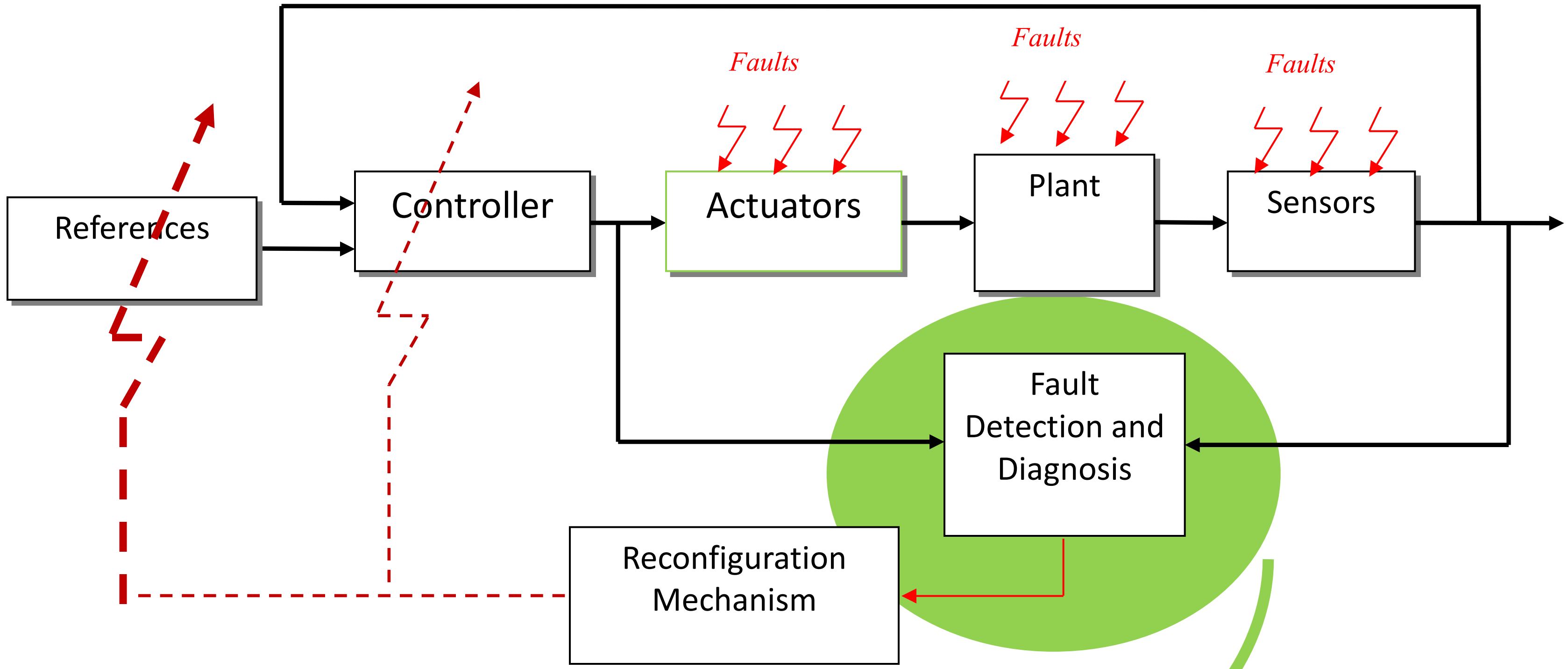
FTC - General Scheme - Reconfiguration



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

Remark 1: Adaptive methods and Predefined Faulty Multiple models Adaptive approaches(MMAE Family) have been omitted in the presentation

FTC - General Scheme - Reconfiguration



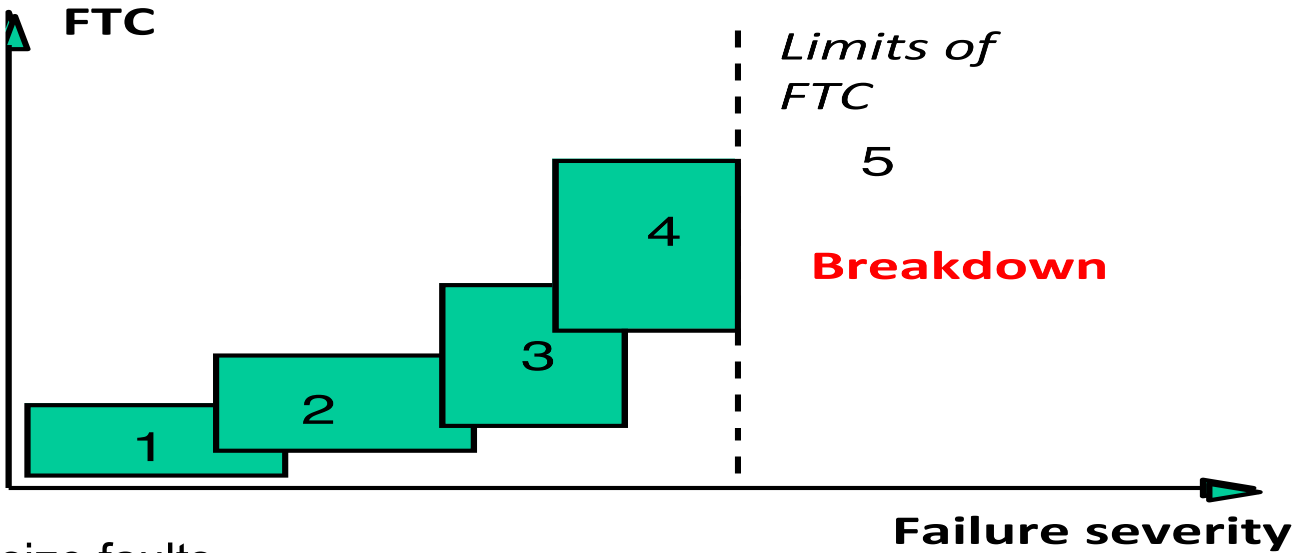
Caution: Controllability, Detectability and reconfigurability properties (Structure Analysis can be considered) should be studied before to synthesize FTC.

Remark 1: Adaptive methods and Predefined Faulty Multiple models Adaptive approaches(MMAE Family) have been omitted in the presentation

Remark 2: *Damage compensation in robotics without diagnosis* – JEAN-BAPTISTE MOURET, PhD / Inria Senior Researcher - Nancy

A. Cully, J. Clune, D. Tarapore, J.-B Mouret (2015). *Robots that can adapt like animals.* Nature. 521. (7553) 503-507. Nature Publishing Group.

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

Pseudo-Inverse Method (PIM)

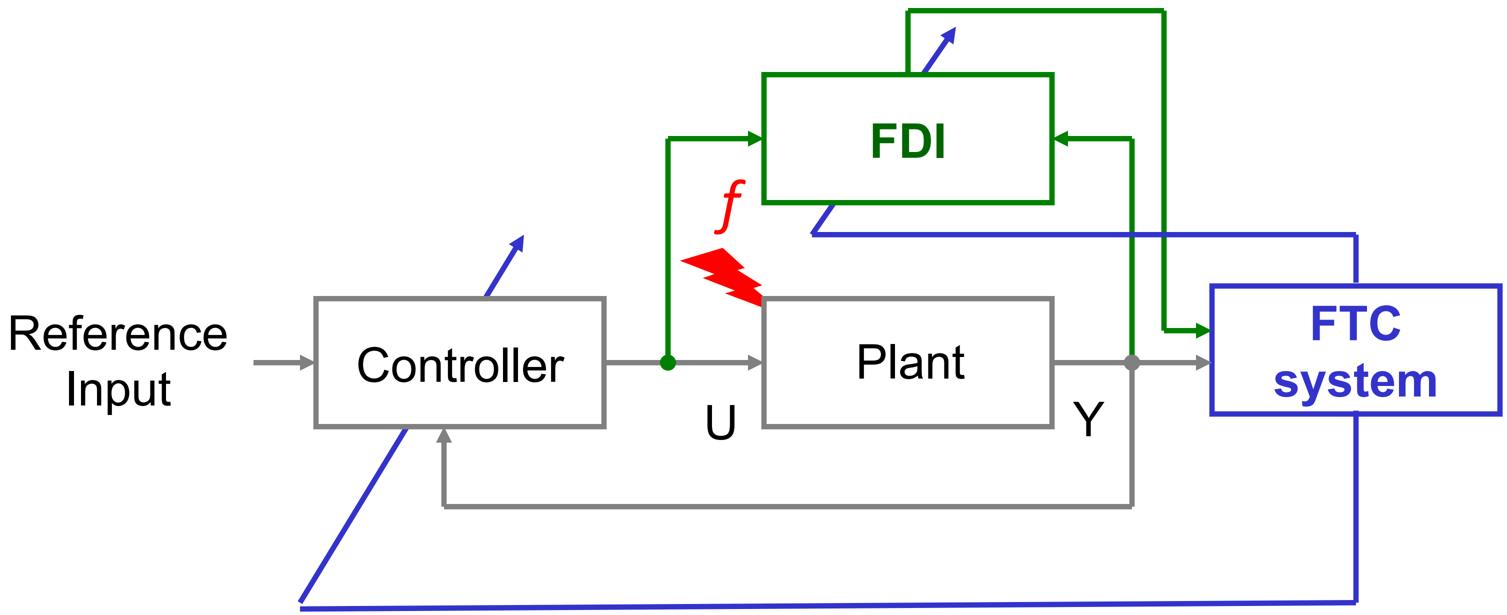
● Principle

Basic Idea: To redesign the controller so that the closed-loop system matrix of the reconfigured system as close as possible to that of the nominal system

- Advantages: Simplicity in calculating the reconfigurable control Law

- Requirement: Perfect information on FDD (fault time) and post-fault system (post-fault model)

Pseudo-Inverse Method (PIM)



Pseudo-Inverse Method (PIM)

- Method

Let the nominal system be given as:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases} \qquad \begin{cases} \dot{x}(t) = (A + BK)x(t) \\ y(t) = Cx(t) \end{cases}$$

and the multiplicative faulty mode:

$$\begin{cases} \dot{x}(t) = A_f x(t) + B_f u(t) \\ y(t) = Cx(t) \end{cases} \qquad \begin{cases} \dot{x}(t) = (A_f + B_f K_f)x(t) \\ y(t) = Cx(t) \end{cases}$$

Pseudo-Inverse Method (PIM)

- Solution: $$minJ(K_f) = \|(A_f + B_f K_f) - (A + BK)\|_F$$

$$K_f^* = (B_f)^+ (A - A_f + BK)$$

- Model matching: $$\begin{cases} \dot{x}(t) = Mx(t) + Nr(t) \\ u(t) = -Kx(t) + Gr(t) \end{cases}$$ $$G_f^* = (B_f)^+ N$$

The control reconfiguration is based on the minimization of the Frobenius norm of the difference of two system matrices

« without connection with system stability measure, e.g., eigenvalues »

– lack of a stability guarantee —

=> Overcome by a modified PIM (MPIM) ([*])

[*] 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)

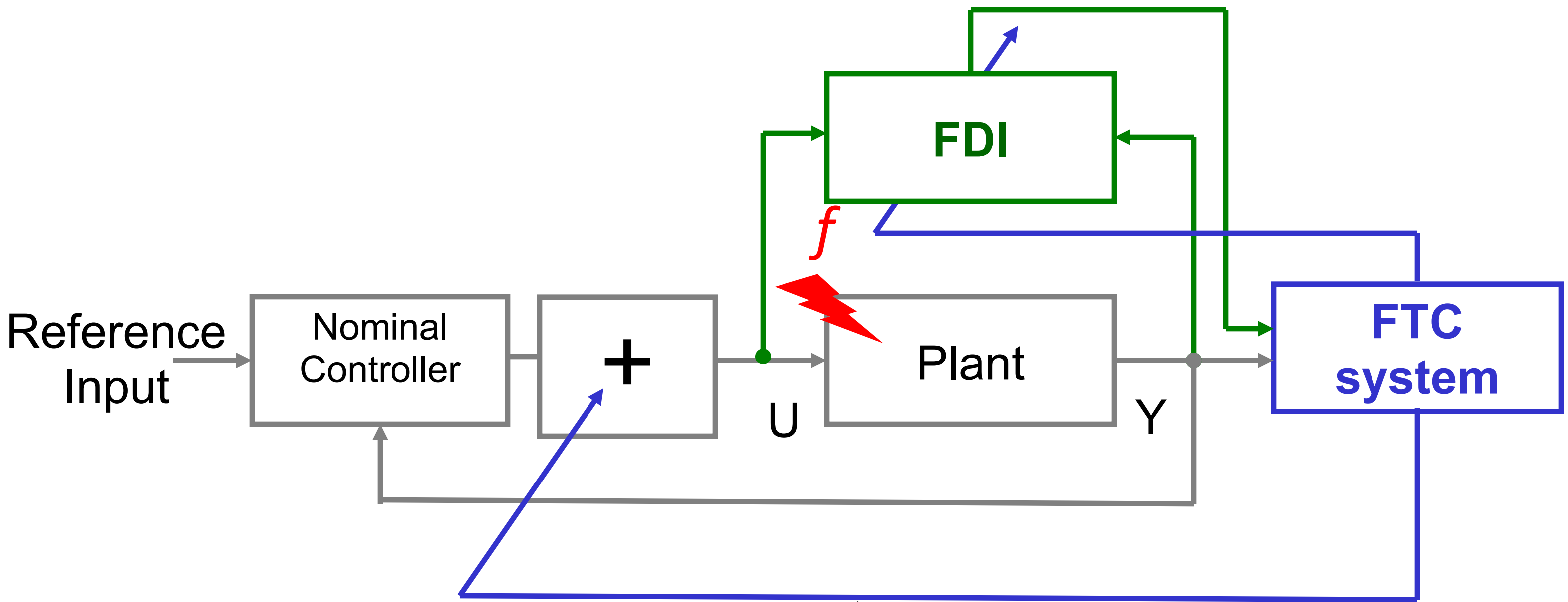
● Principle

Basic Idea: To compensate the fault effect based on an additive control law so that the reconfigured closed-loop system is closed as possible to the nominal one

- Advantages: Simplicity in calculating the reconfigurable control Law and do not modify the controller

- Requirement: Perfect information on FDD (fault time) and post-fault system (post-fault model)

Fault Compensation (FC)



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

Fault Compensation (FC)

● Method

Let the nominal open-loop system be given again as

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

and the additive faulty mode :

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + F_a f^a(t) \\ y(t) = C(t) \end{cases}$$

- Solution :

$$\begin{cases} u_{comp}(t) = u_{nom}(t) + u_{add}(t) \\ Bu_{add}(t) + F_a f^a(t) = 0 \end{cases}$$

$$\Longrightarrow \quad u_{add}(t) = -B^+ F_a f^a(t)$$

Fault Compensation (FC)

- Method

$$\Rightarrow \quad u_{add}(t) = -B^{+} F_a f^a(t)$$

Remark 1: if B is square $\quad u_{add}(t) = -B^{-1} F_a f^a(t)$

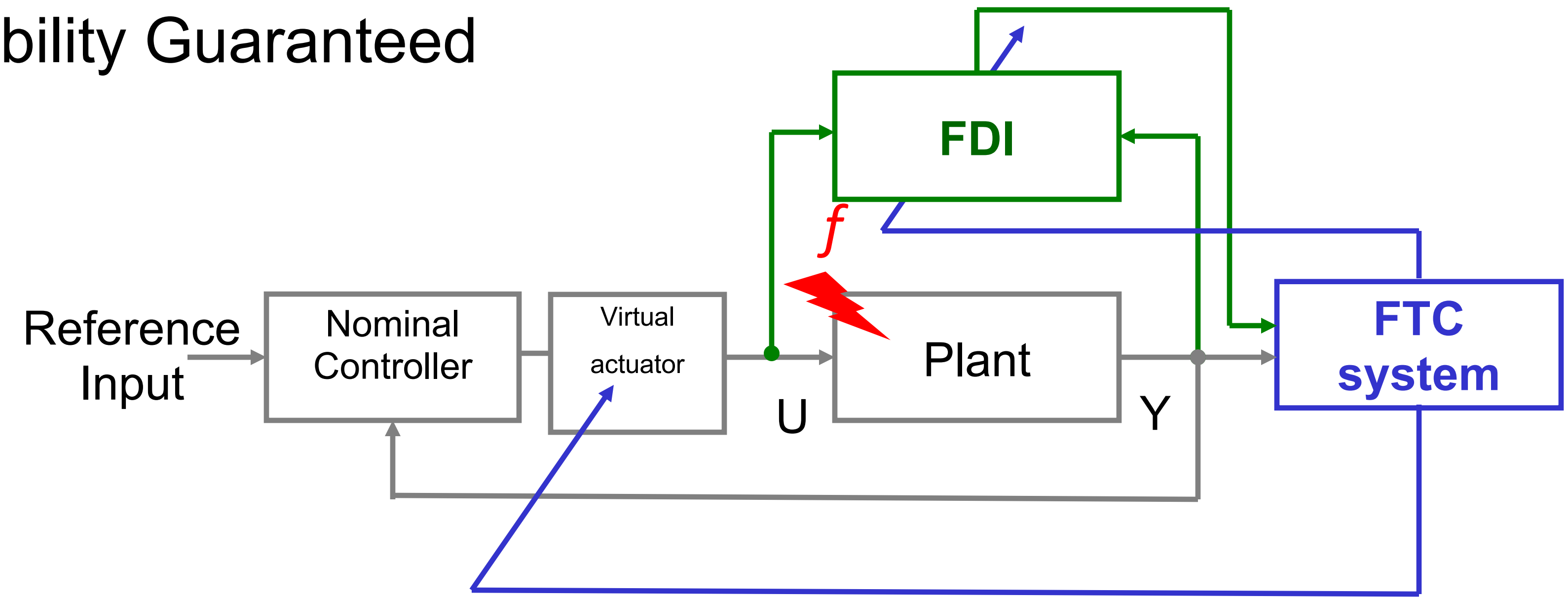
Remark 2: if B is not a full row rank matrix (nb of state less than input). A SVD can be applied to the matrix B.

The stability is not guaranted and can not studied off-line !!!

"Virtual Actuator" since 2010 …

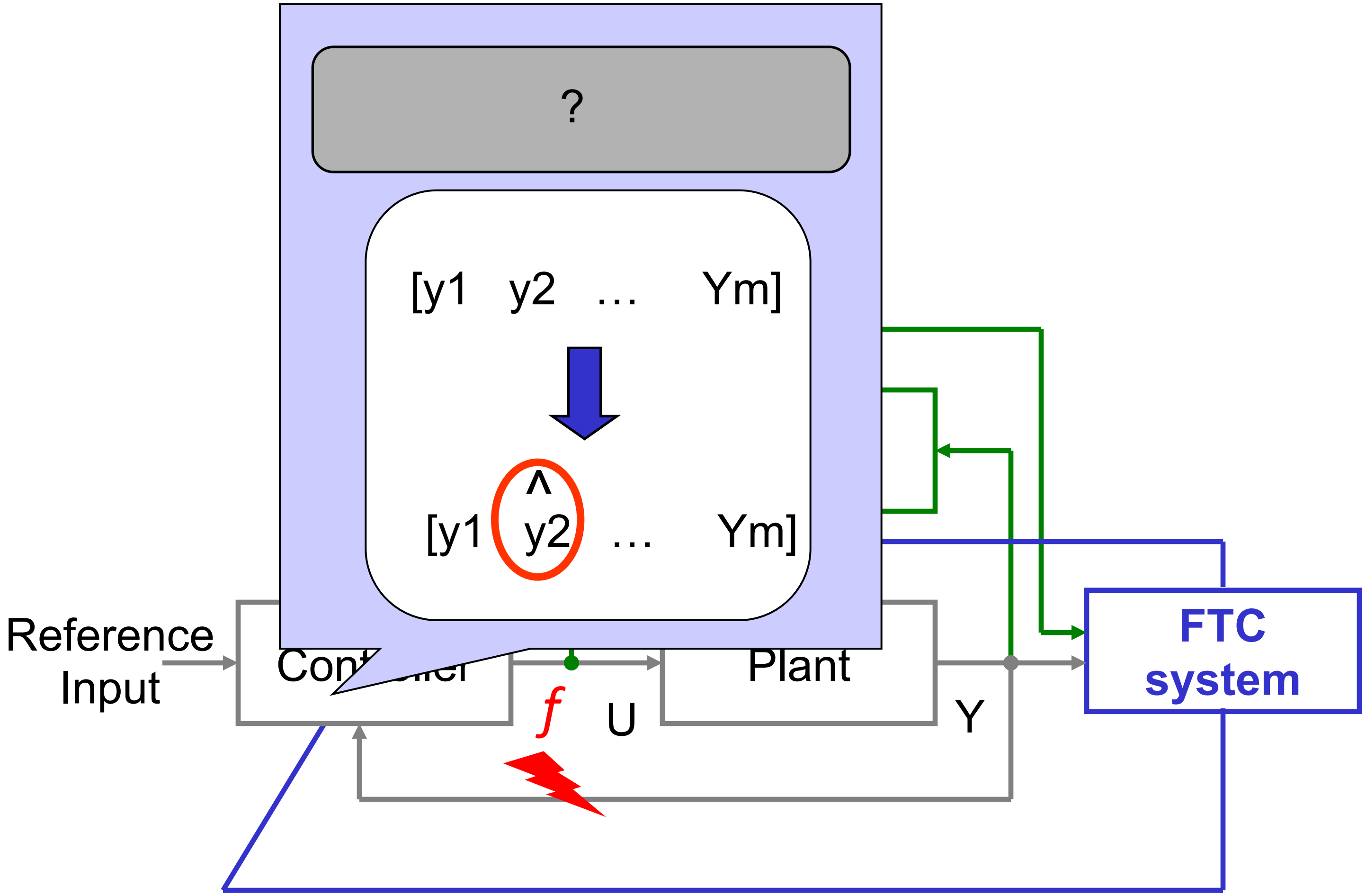
- **(Gain Redesign) + (Fault Compensation)= Virtual Actuator**

Excellent Dynamic Performance
Stability Guaranteed



Certification Valided

Sensor FTC = “ Sensor Fault Masking”



Survey

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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]

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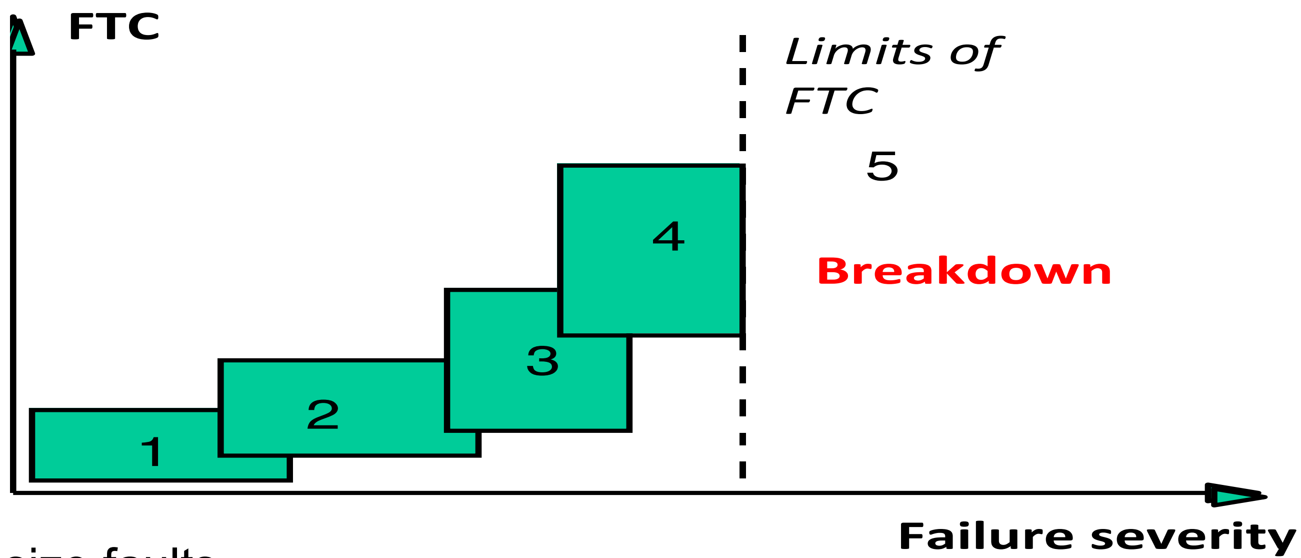
[b] *Department of Electrical and Computer Engineering, The University of Western Ontario, London, Ontario N6A 5B9, Canada*

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…)”

FTCS: What is possible to do ?

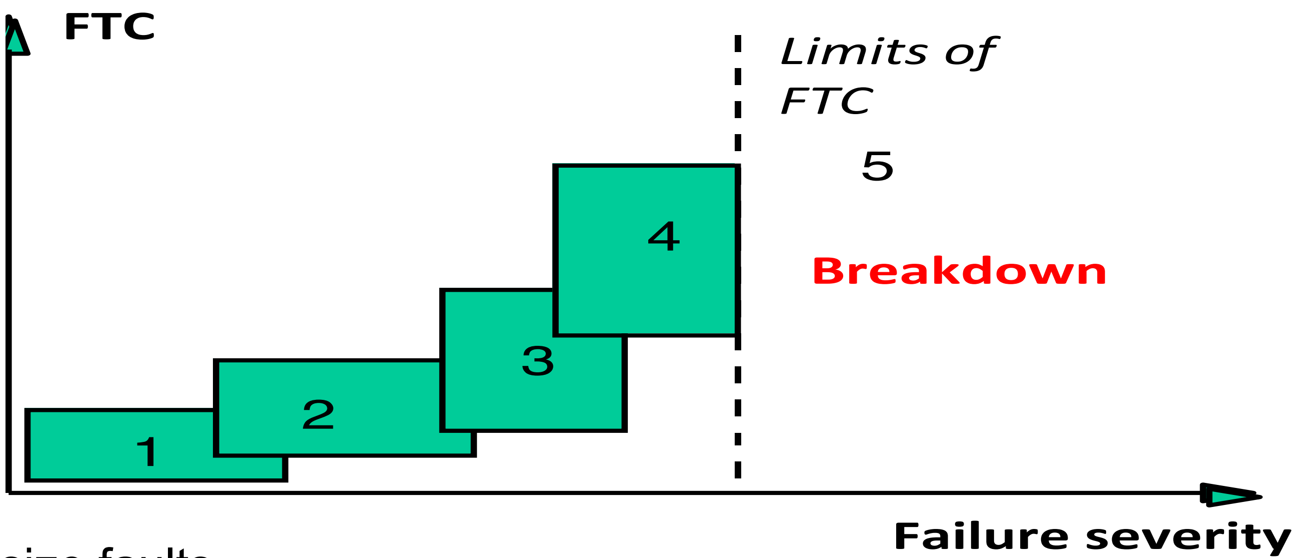


1 : Small size faults
Robust control (no FDI module)

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*

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

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

Resilient/Fault Tolerant Control ….

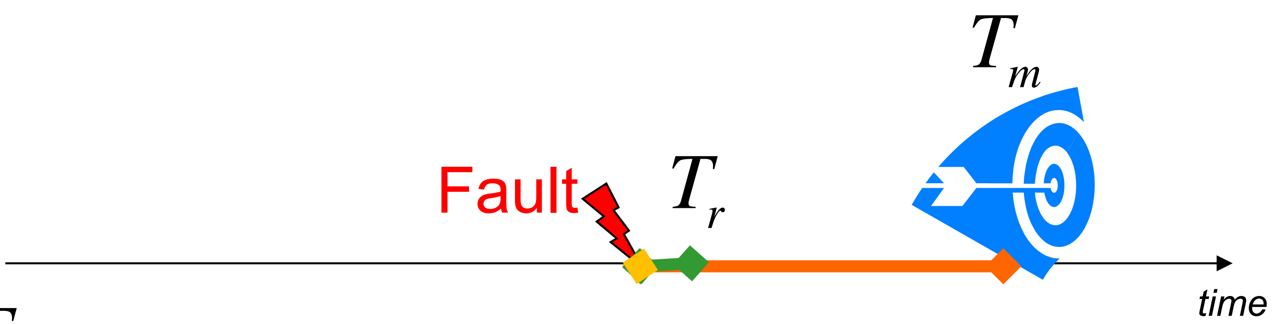
FTC, Reconfiguration, accommodation, recovery !!!!

Health Aware Control Design ….

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

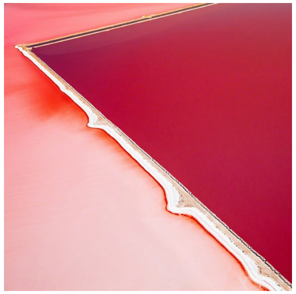


T_m represents period between fault occurrence and the end of expected mission

OUTLINES

Health Aware Control

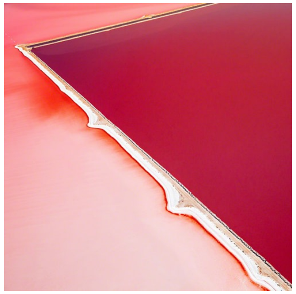
- Heuristic approach - Optimal “reliable FTC” method
- HAC based on RUL estimation



OUTLINES

Health Aware Control

Heuristic approach - Optimal “reliable FTC” method

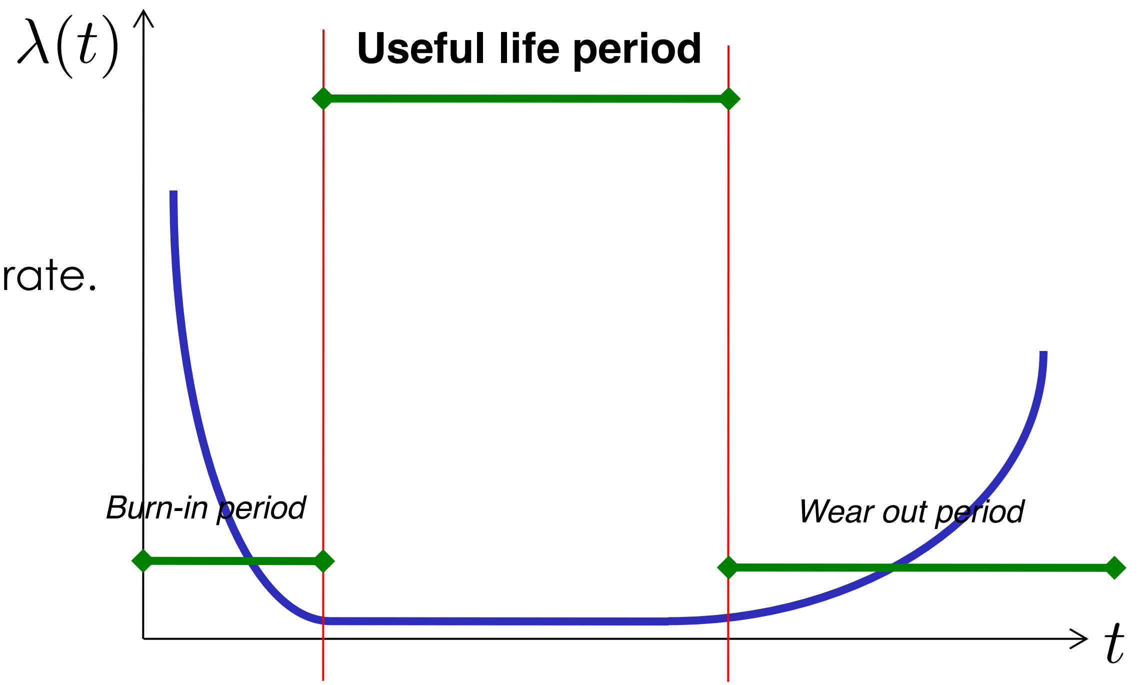


Reliability: “mathematic” definitions

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 $\lambda(t)$ presents the failure rate.



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

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

Reliability analysis for actuator component

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

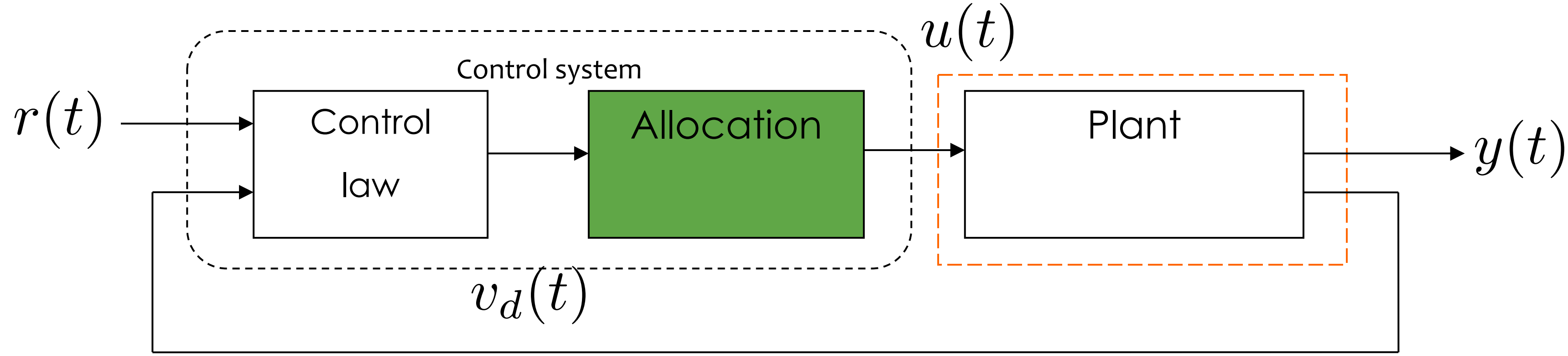
Failure rate $\lambda_i(t) = \lambda_i^0(1 + g(\ell_i)), \quad i = 1, \ldots, m$

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 $t \in [t_1, t_M]$

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

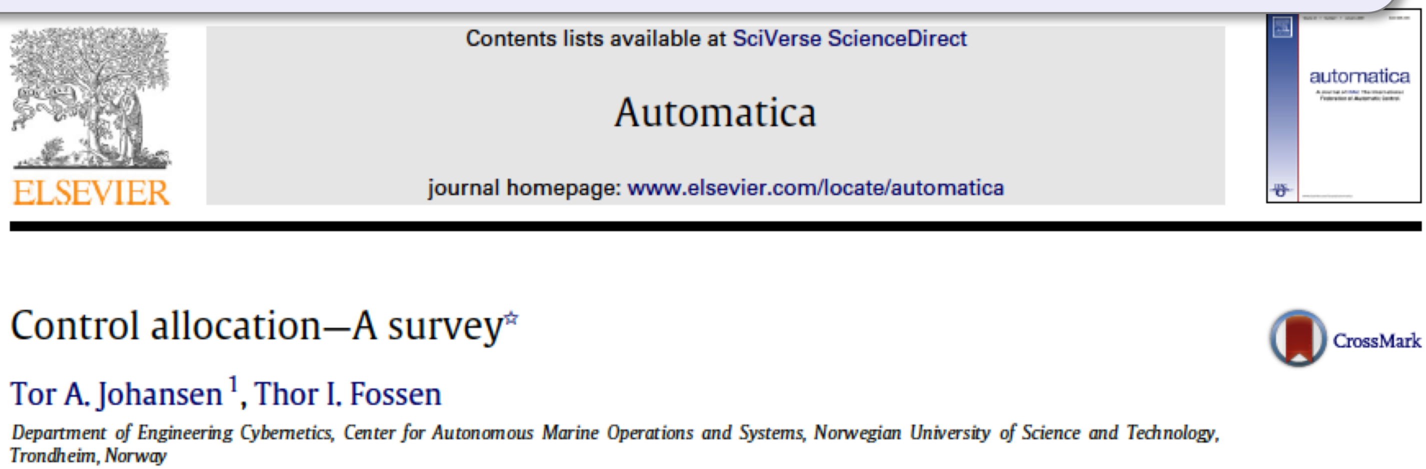
Control Method for Overactuated Systems



Problem description of Control Allocation

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

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



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Automatica

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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

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

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

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

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

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

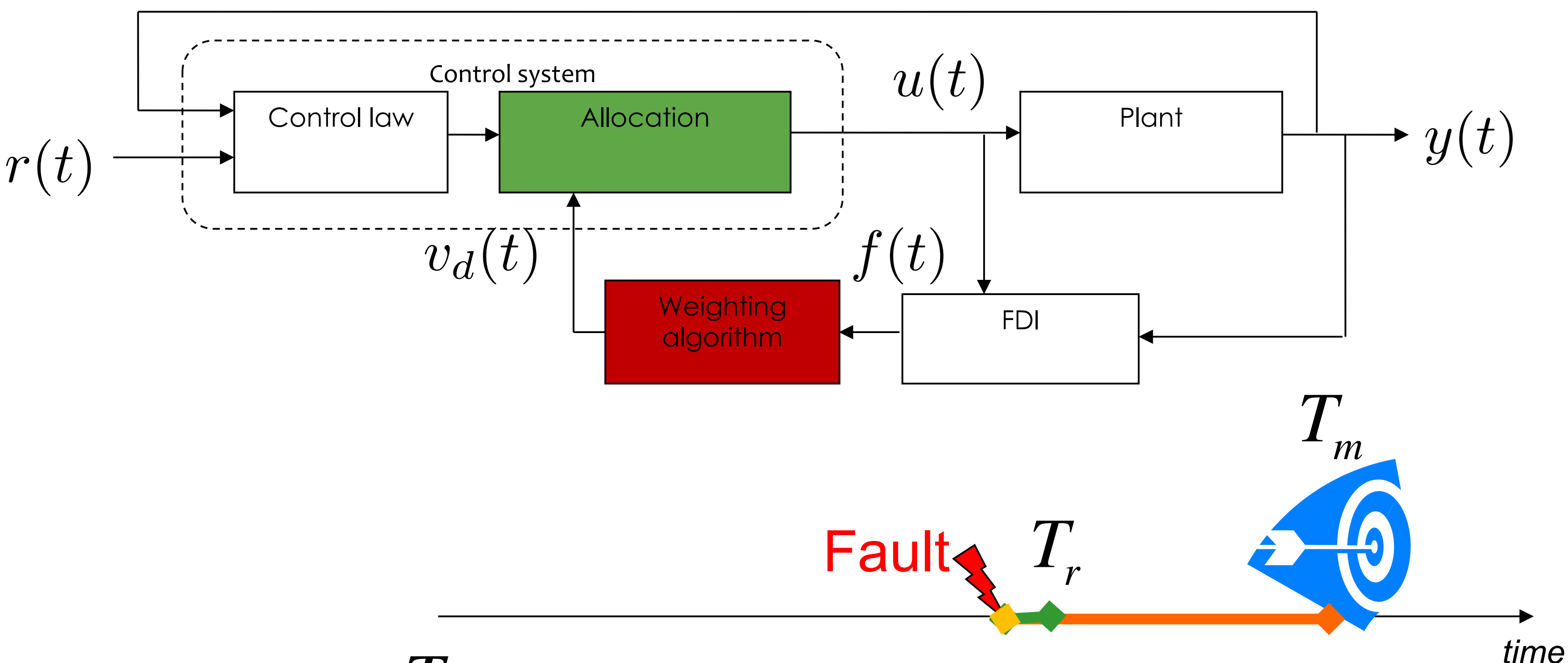
$\Rightarrow$ $W_u = I$ A useful solution

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.

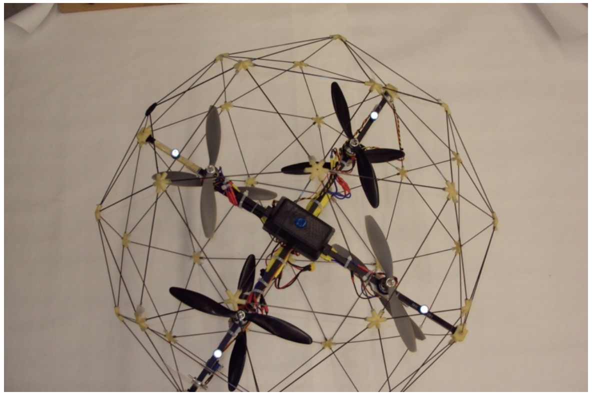


T_m represents period between fault occurrence and the end of expected mission

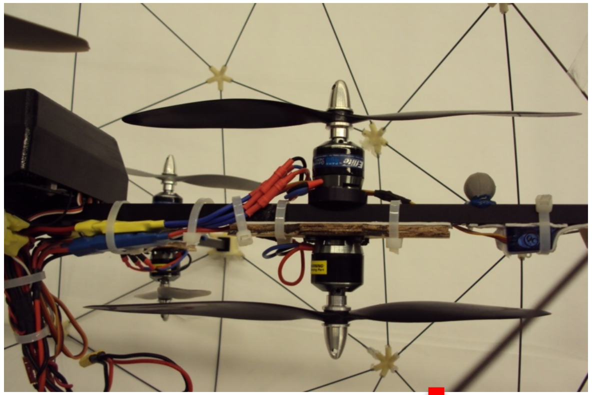
Application Qball-X8

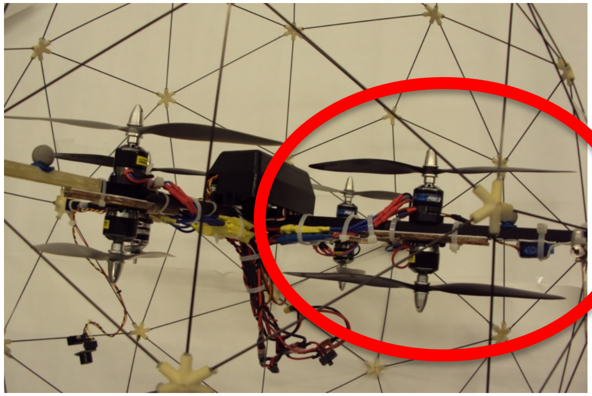
Why to modify the Qball-X4 ?

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



Top view





Side view

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:

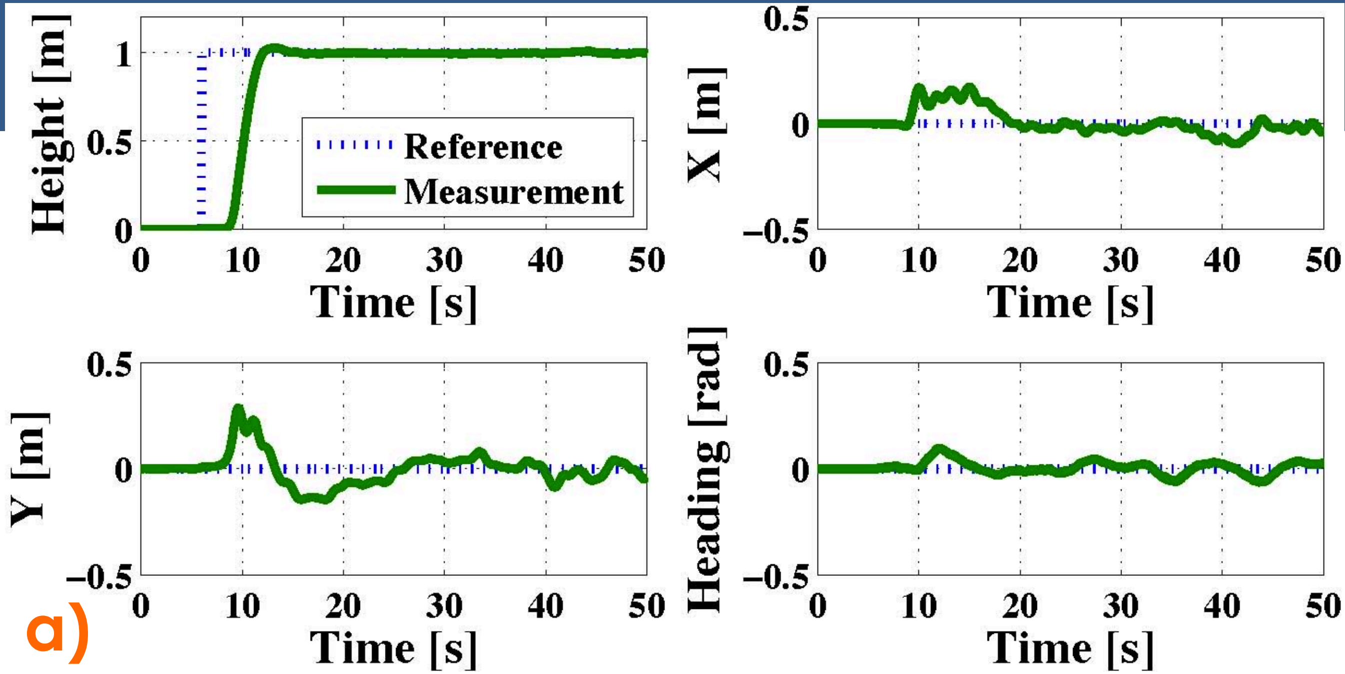
$$W_u = \begin{pmatrix} \frac{\lambda_1}{\lambda_{max}} & \cdots & 0 \\ & \ddots & \\ \vdots & \frac{\lambda_i}{\lambda_{max}} & \vdots \\ & & \ddots \\ 0 & \cdots & \frac{\lambda_m}{\lambda_{max}} \end{pmatrix}$$

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.

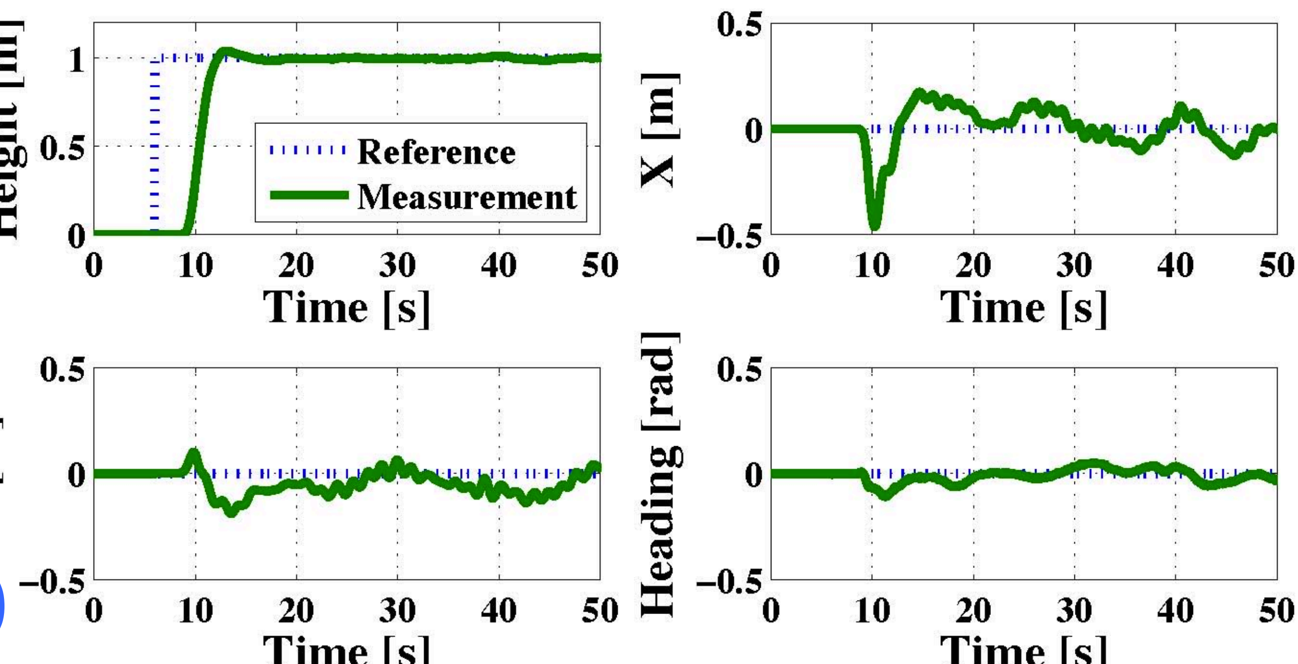
λ_{max} represents the maximal failure rate corresponding to the least reliable actuator.

Outputs :



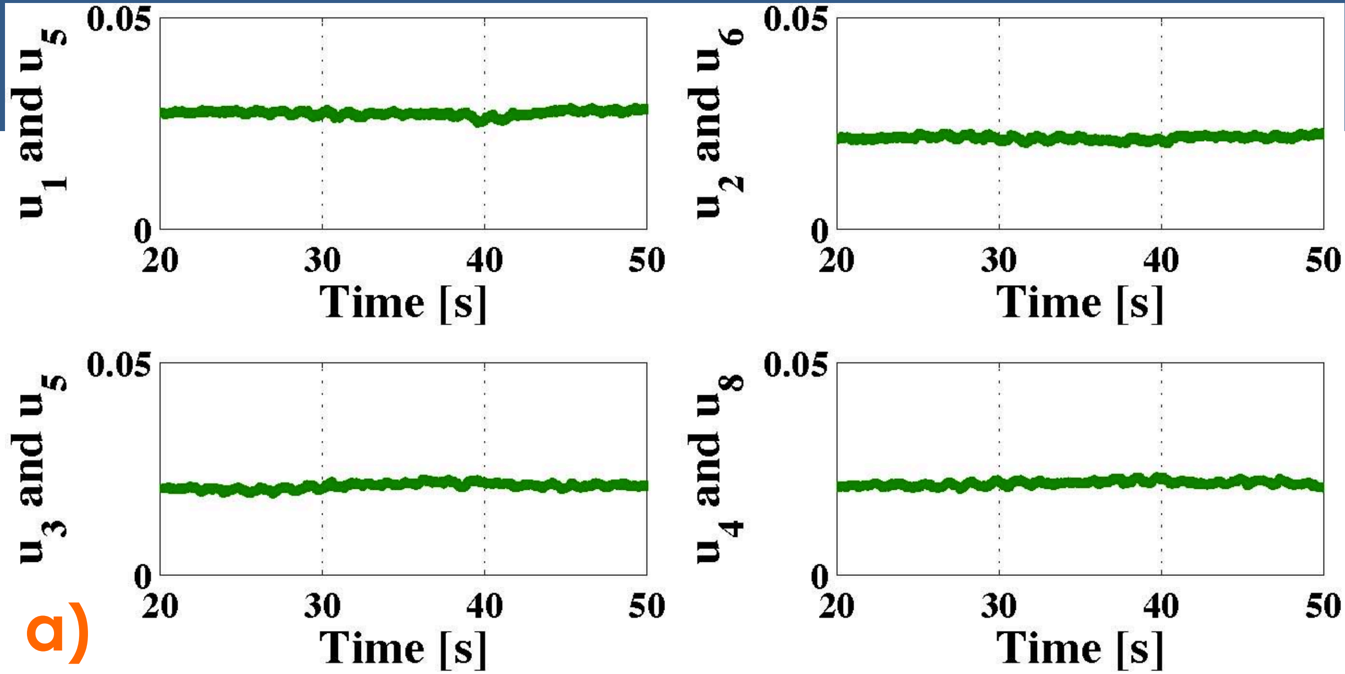
a)

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

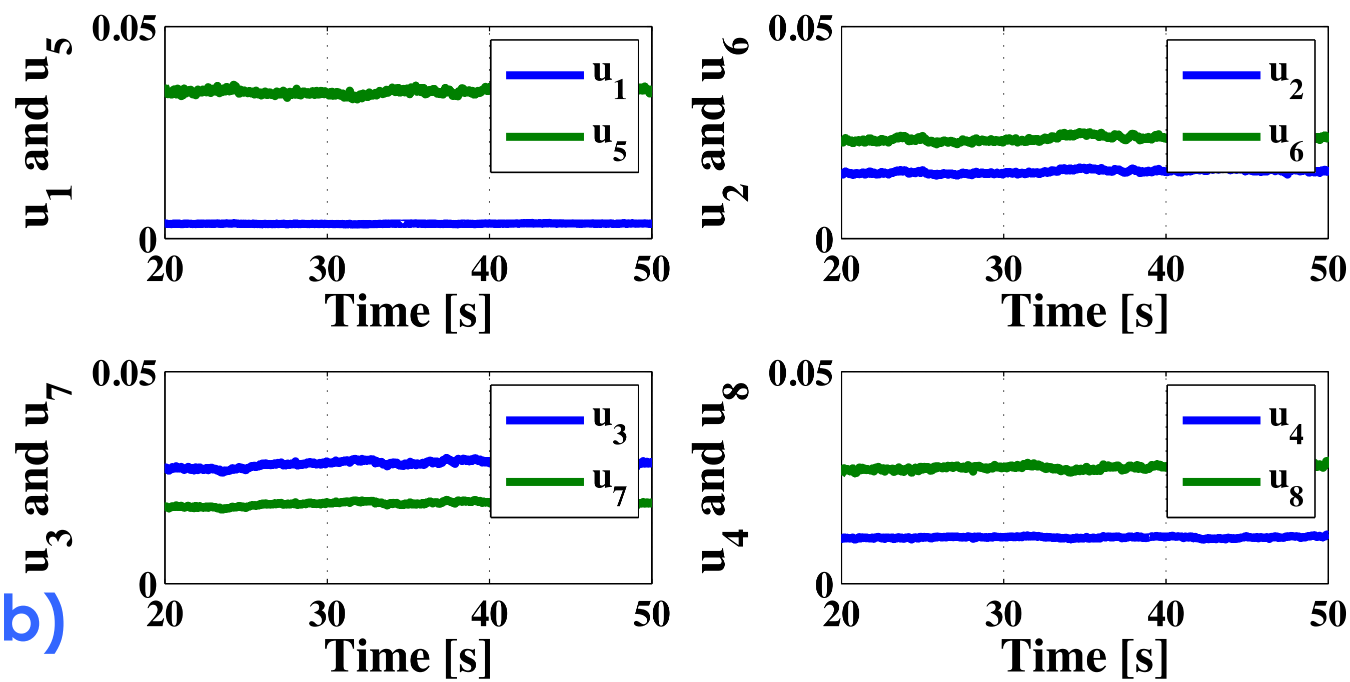


b)

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

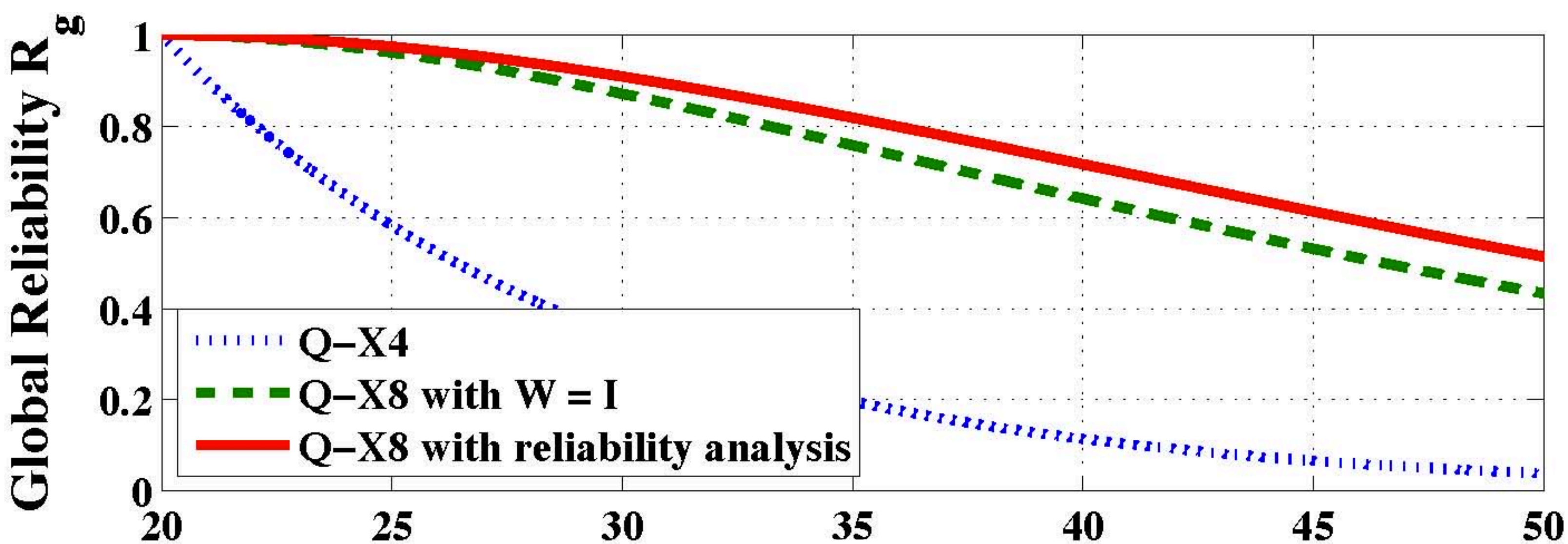
Without reliability analysis, the control inputs to the redundant motors are the same.

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

Global Reliability “a posteriori”

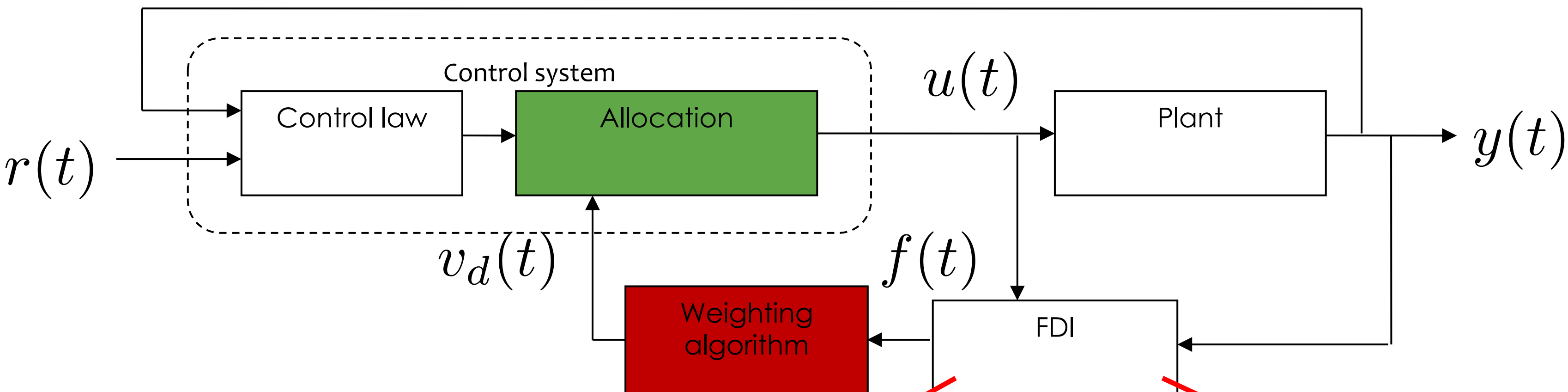
The reliability of the Qball-X4 dramatically drops down (**blue** line) because of the series configuration of its actuators and the lack of redundancy.

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).



Application Qball-X8 – Actuator faulty-case

Control (re) allocation method



- **Faulty system**

$$\boxed{B_f = B(I_m - \Gamma)}$$

- Faulty system

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

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

$\Gamma = \text{diag}(\gamma_1, \gamma_2, \ldots, \gamma_m)$

Application Qball-X8 – Actuator faulty-case

Second try:

70% of propeller damage
without
control re-allocation
(unstable)

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

Optimal Solution

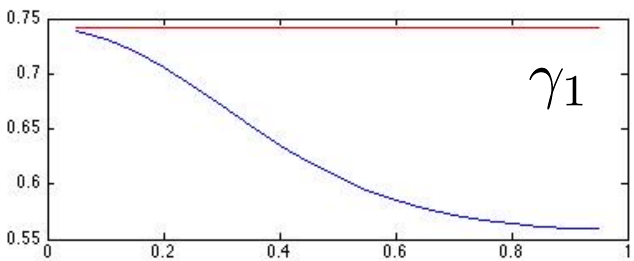
(Re)Allocation Solution WITHOUT explicit solution

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

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

Application to X8 – Simulation - Rg

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



- Faulty system

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

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

Γ=diag(γ_1, γ_2, …, γ_m)

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

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

Reference

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

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Reliability Engineering and System Safety

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RELIABILITY ENGINEERING & SYSTEM SAFETY

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

Abbas Chamseddine [a], Didier Theilliol [b,*], Iman Sadeghzadeh [a], Youmin Zhang [a], Philippe Weber [b]

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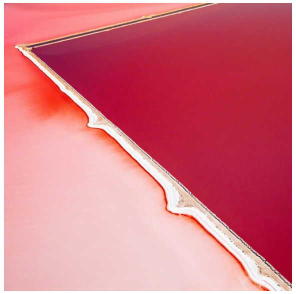
[b] Centre de Recherche en Automatique de Nancy, CRAN CNRS UMR 7039, University of Lorraine, France

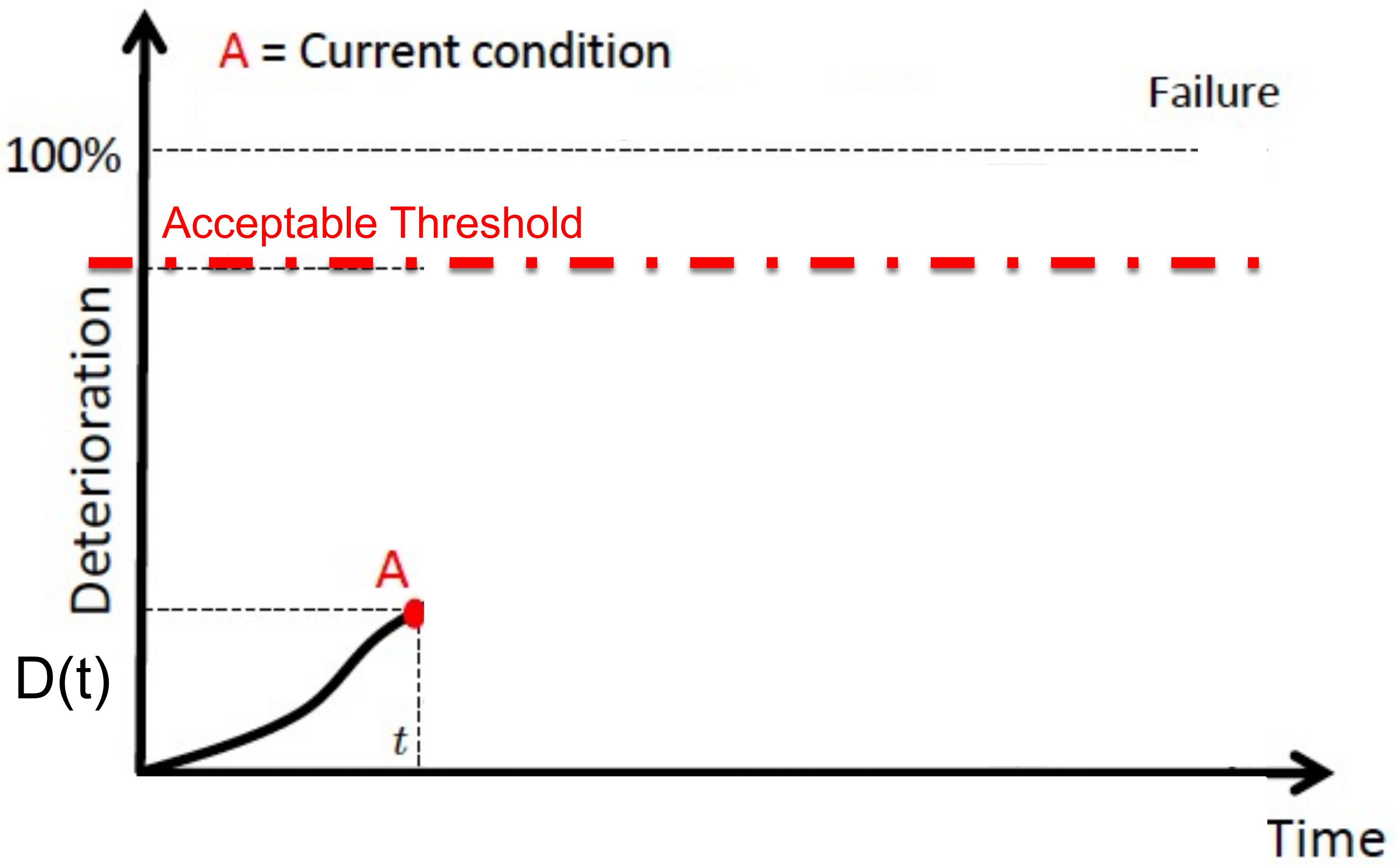
OUTLINES

Health Aware Control

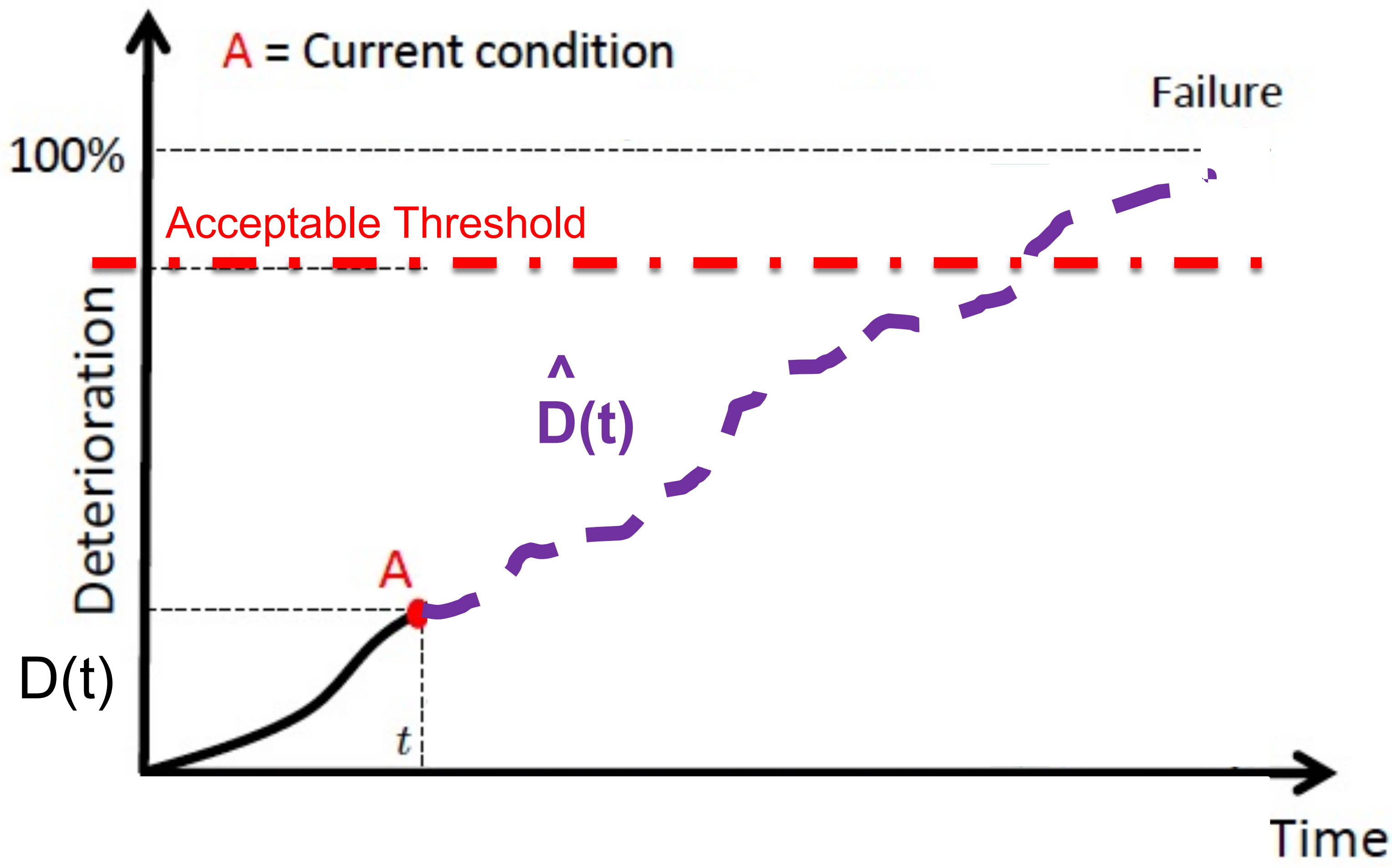
HAC based on RUL estimation



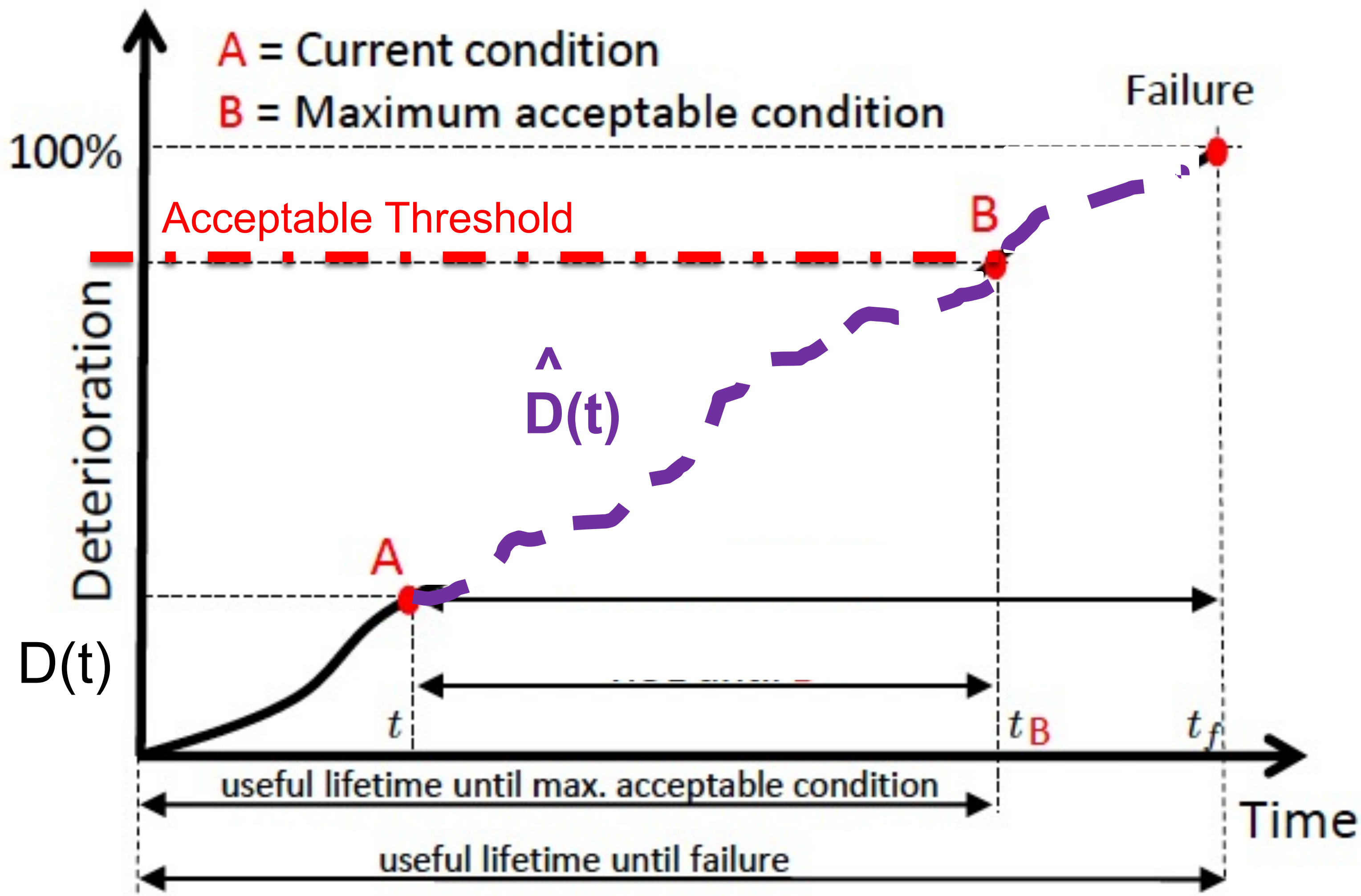
Remaining Useful Life Estimation



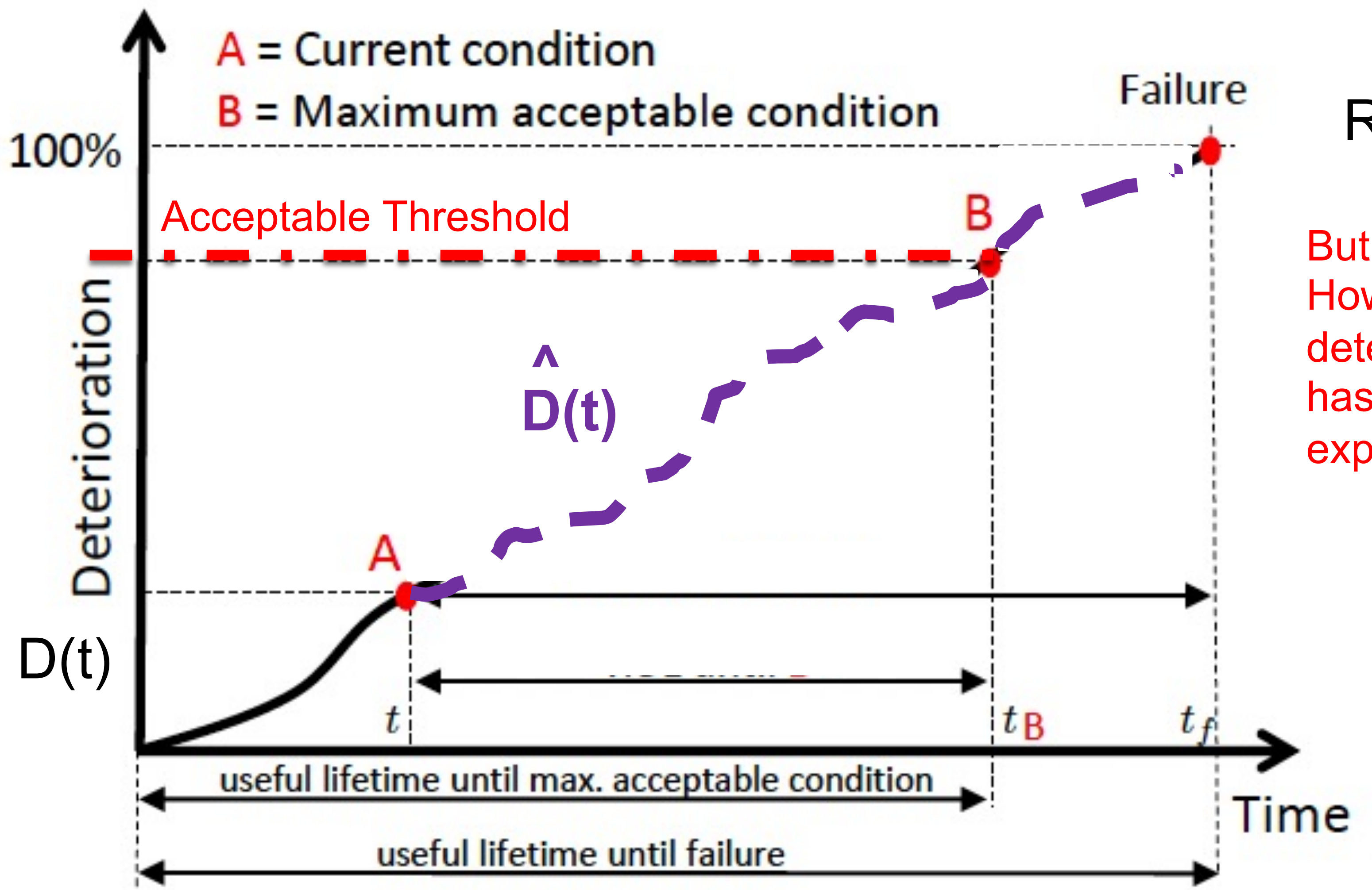
Remaining Useful Life Estimation



Remaining Useful Life Estimation



Remaining Useful Life Estimation

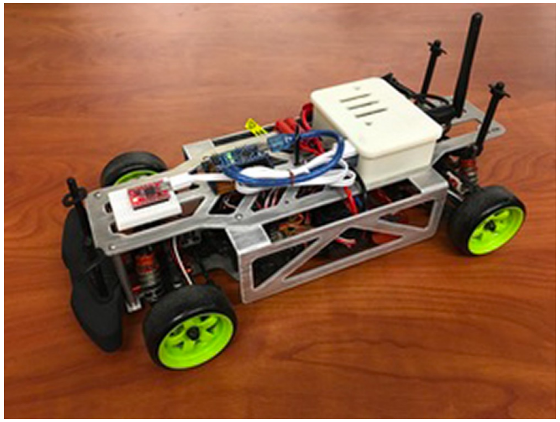


$\hat{D}(t)$

$RUL(t)=t_B-t$

But t_b is unknown
However only deterioration level has been fixed by expert

Unmanned Ground Vehicle

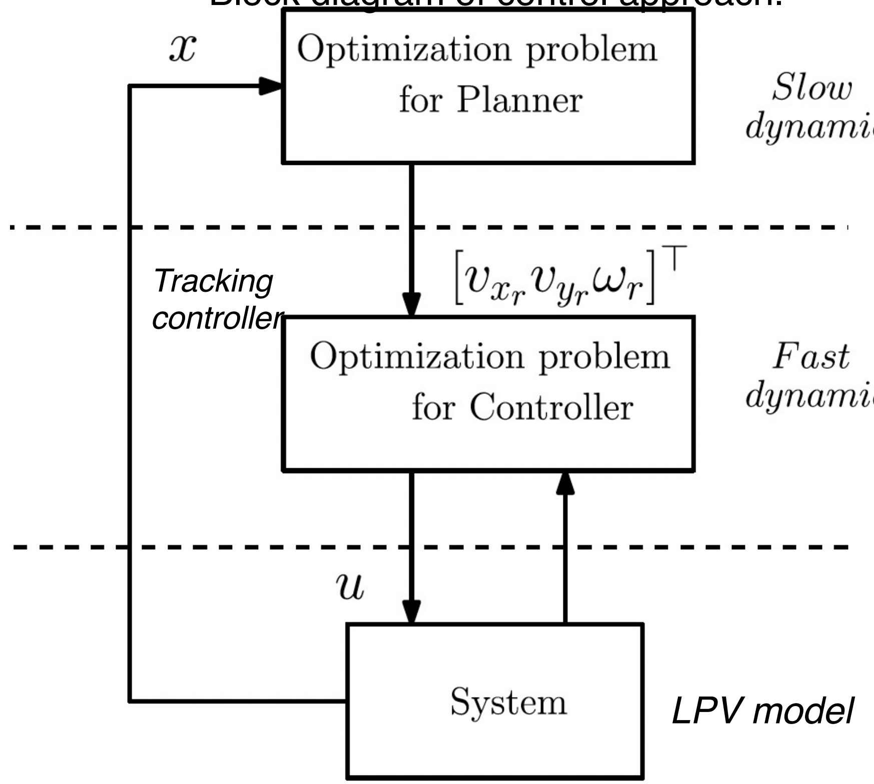


Berkeley Autonomous Vehicle

State of Charge (SoC):

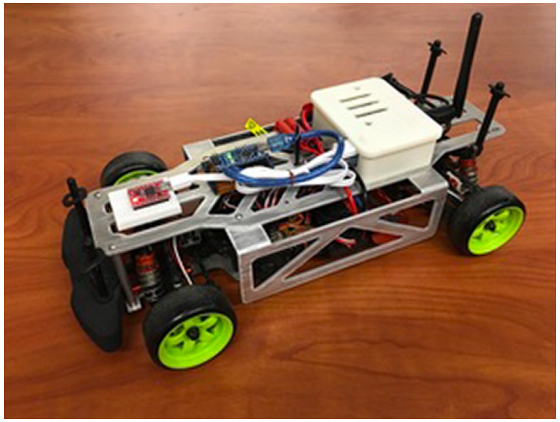
$$SoC(t) = SoC(t_0) - \; P_{batt}(t),$$
$$P_{batt}(t) = P_{move}(t) + P_{friction}(t),$$
$$P_{batt}(t) = \frac{1}{2} C_d \rho A_r v_x^2 + \mu m g v_x,$$

Block diagram of control approach.



$$RUL(k) = \frac{SoC_{thresh} - SoC(k)}{-u_b(k)},$$

Unmanned Ground Vehicle



Berkeley Autonomous Vehicle

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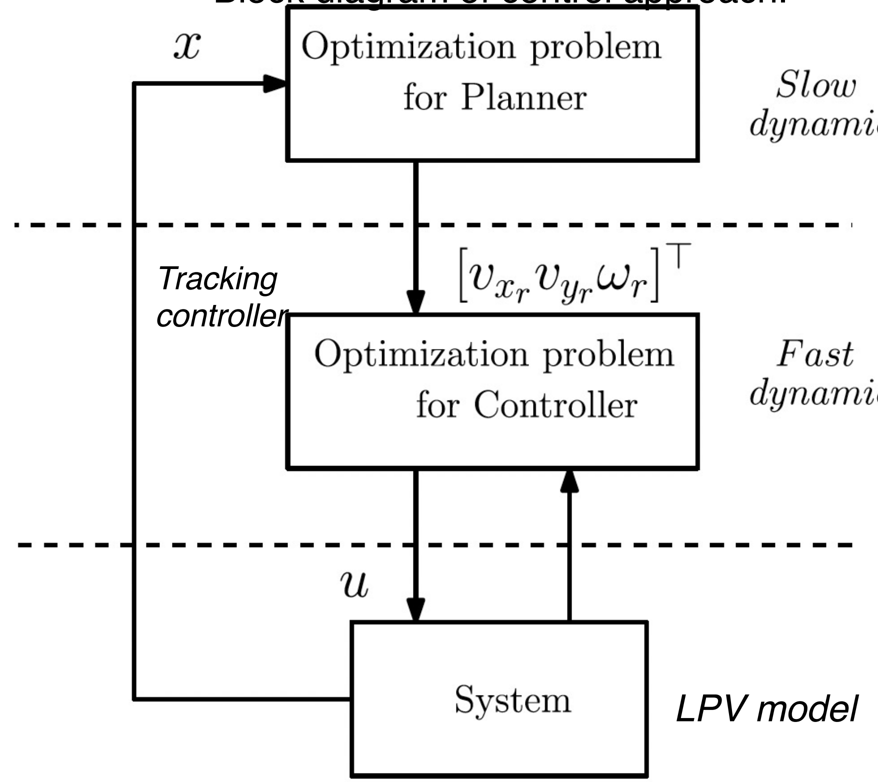
$$P_{batt}(t) = P_{move}(t) + P_{friction}(t),$$
$$P_{batt}(t) = \frac{1}{2} C_d \rho A_r v_x^2 + \mu m g v_x,$$

Block diagram of control approach.

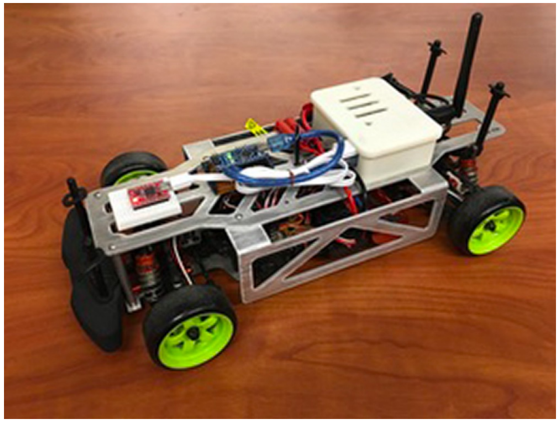


$$\dot{\tilde{x}}(t) = \tilde{f}(\tilde{x}(t), u(t), w(t), v(t)),$$

with $\tilde{x}(t) = [v_x,\ v_y,\ \omega,\ \tilde{e}_y,\ \tilde{e}_\theta,\ \underline{t,\ SoC}]^\top,$

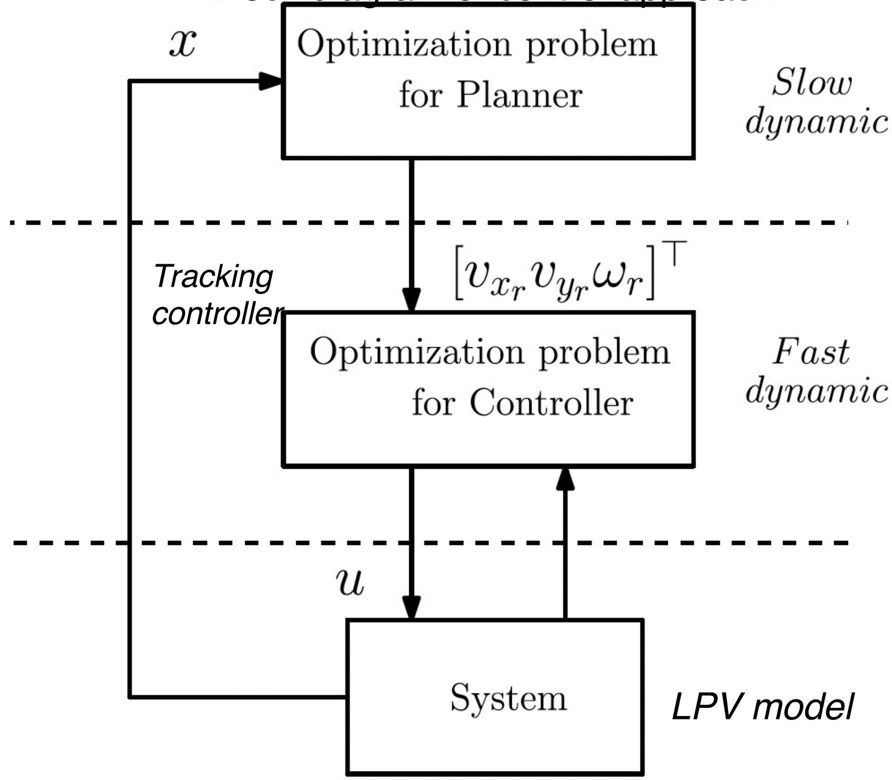
$$RUL(k) = \frac{SoC_{thresh} - SoC(k)}{-u_b(k)},$$

Unmanned Ground Vehicle



Berkeley Autonomous Vehicle

Block diagram of control approach.



State of Charge (SoC):

$$SoC(t) = SoC(t_0) - \; P_{batt}(t),$$
$$P_{batt}(t) = P_{move}(t) + P_{friction}(t),$$
$$P_{batt}(t) = \frac{1}{2} C_d \rho A_r v_x^2 + \mu m g v_x,$$

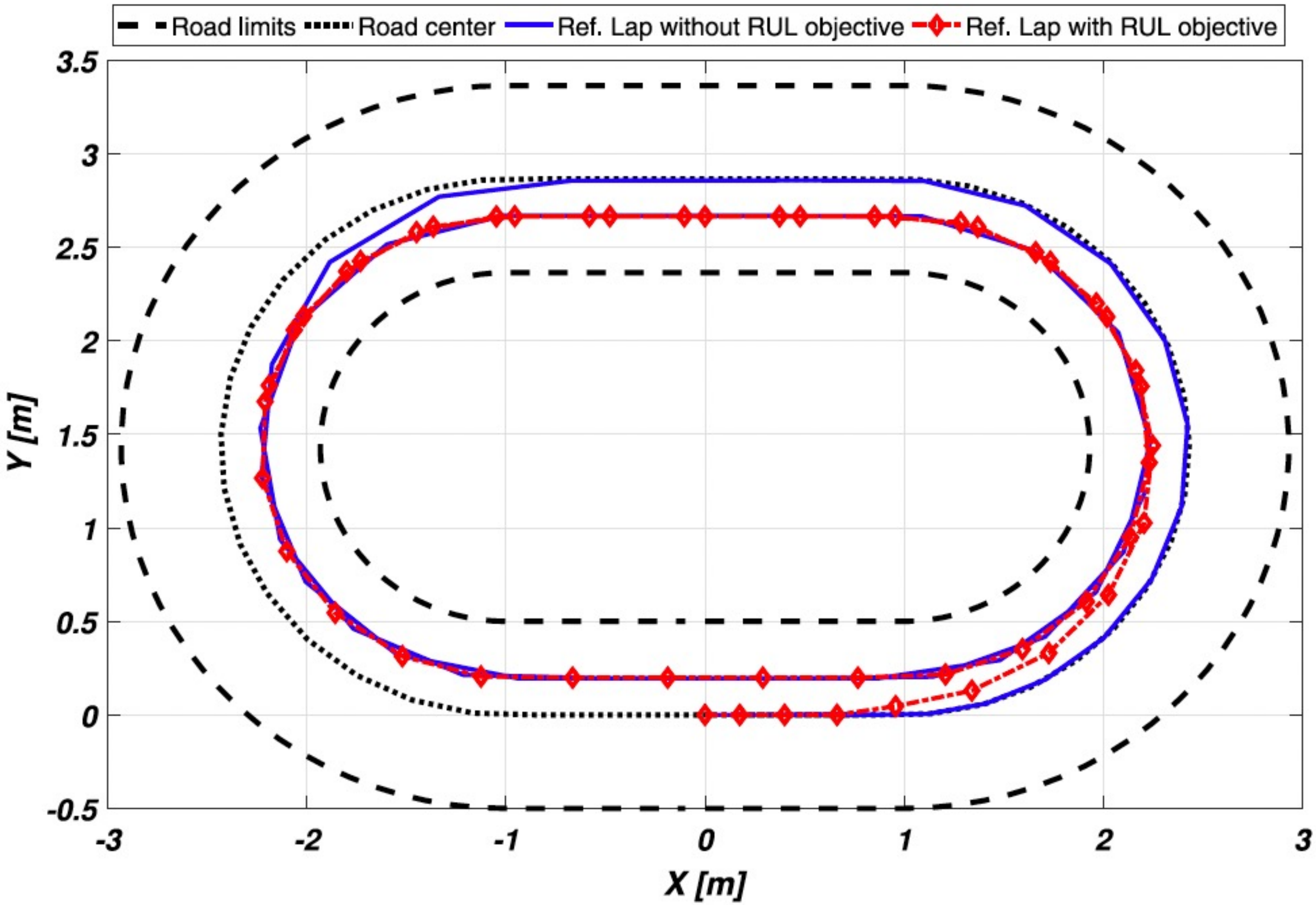
$$\dot{\tilde{x}}(t) = \tilde{f}(\tilde{x}(t), u(t), w(t), v(t)),$$

with $\tilde{x}(t) = [v_x,\ v_y,\ \omega,\ \tilde{e}_y,\ \tilde{e}_\theta,\ \underline{t,\ SoC}]^\top$,

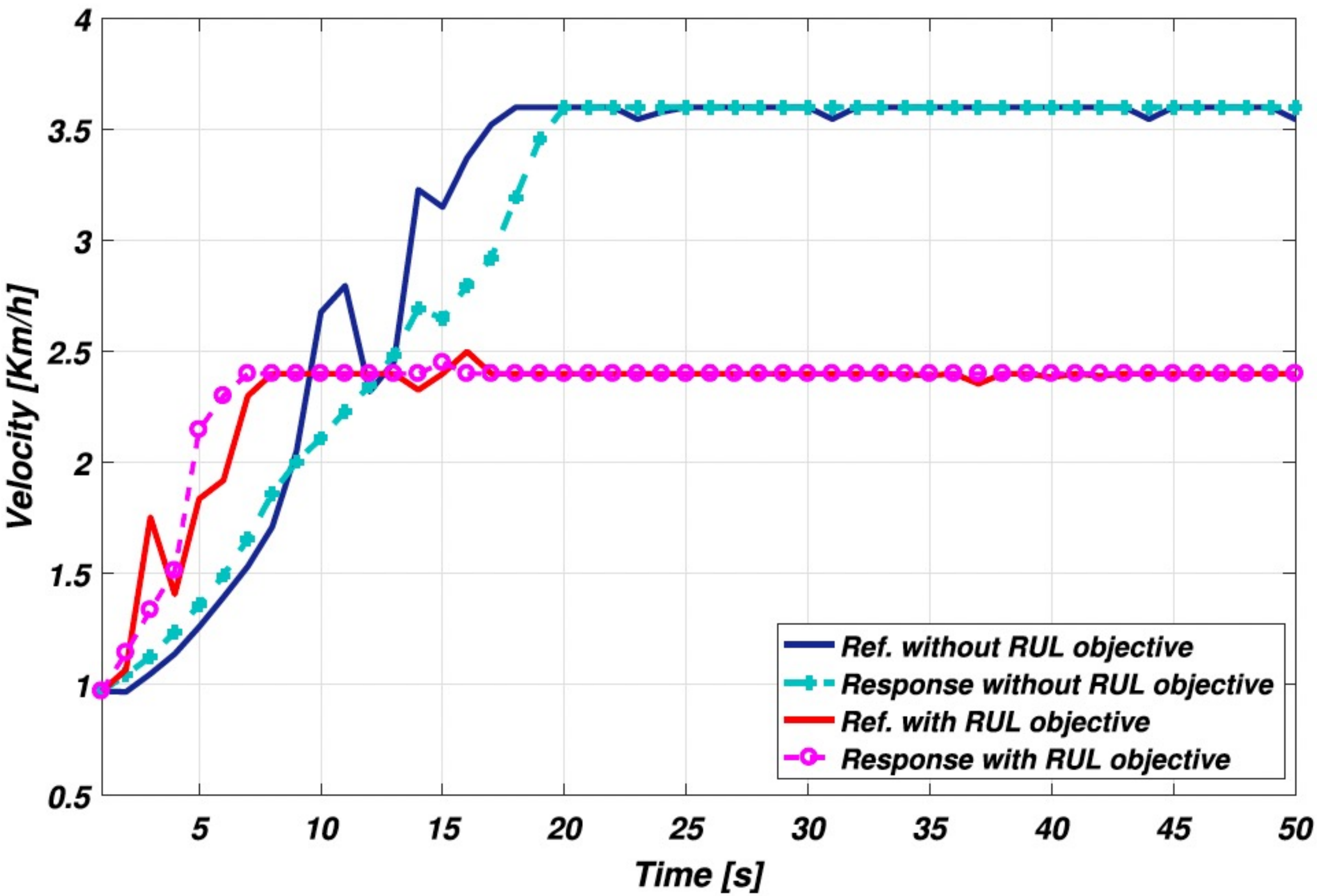
$$RUL(k) = \frac{SoC_{thresh} - SoC(k)}{-u_b(k)},$$

$$\min_{\tilde{u}(k+i|k), i \geq 0} \; \max_{[A(k+i), B(k+i)] \in \Psi, i \geq 0} J_{g,\infty}(k) = \sum_{i=0}^{\infty} (\| \, t \, \|_{\lambda_1}^2 + \| \, \frac{1}{RUL} \, \|_{\lambda_2}^2),$$

Simulation Results

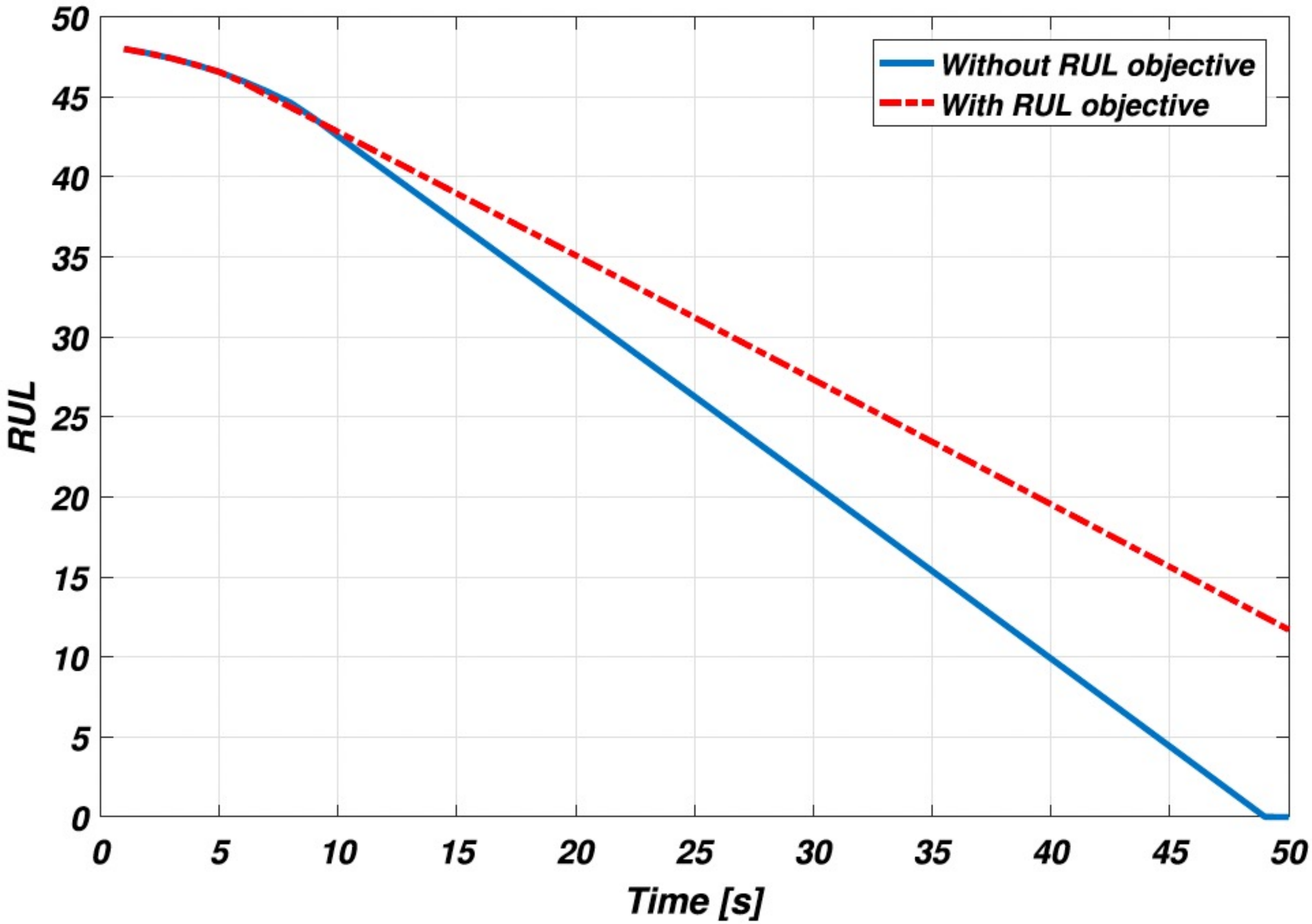


Simulation Results



Simulation Results

Reduce carbon footprint !!



Reference

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Practice article

Health-aware control design based on remaining useful life estimation for autonomous racing vehicle

Check for updates

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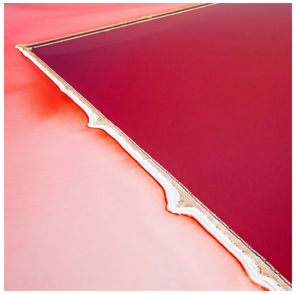
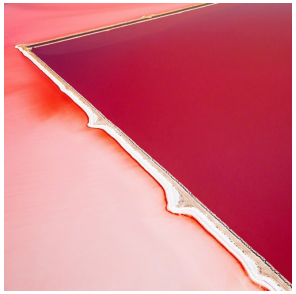
OUTLINES

Safe Reinforcement Learning (*)

- Reinforcement Learning
- Safe Reinforcement Learning

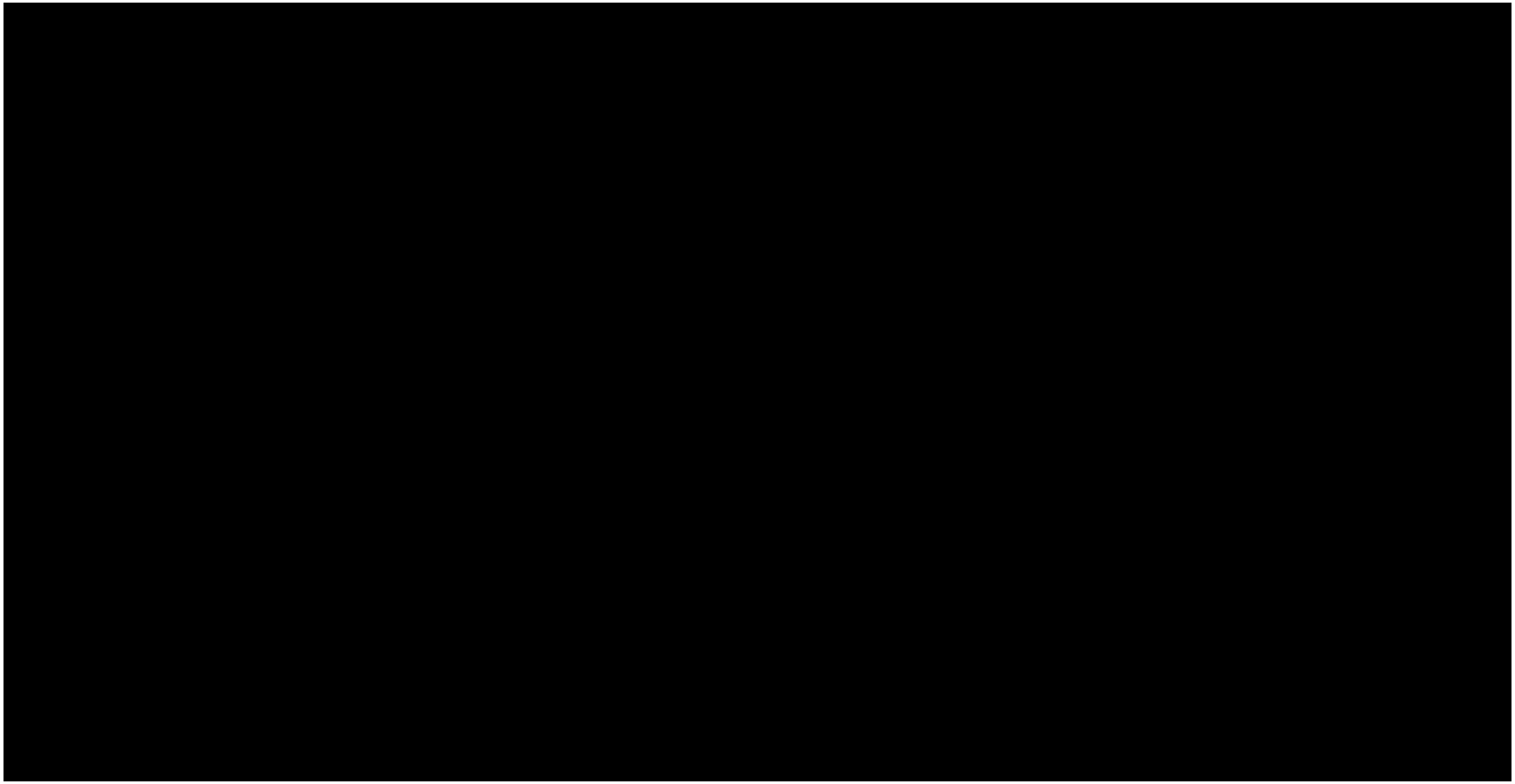


(*) new result from main contributor Dr. MS JHA



Model free control learning: Q-learning (DDPG)

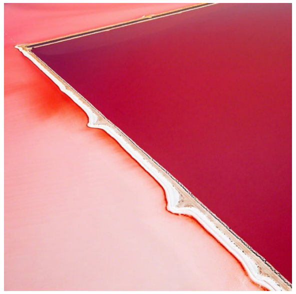
Inverted pendulum: Model free, learning of nonlinear stabilizing optimal control law



George Claudiu Andrei, Mayank Shekhar JHA*, Didier Theilliol, 2022, *Complementary reward function based learning enhancement for Deep Reinforcement learning*, 16th European Workshop on Advanced Control and Diagnosis (ACD 2022), Nancy, France

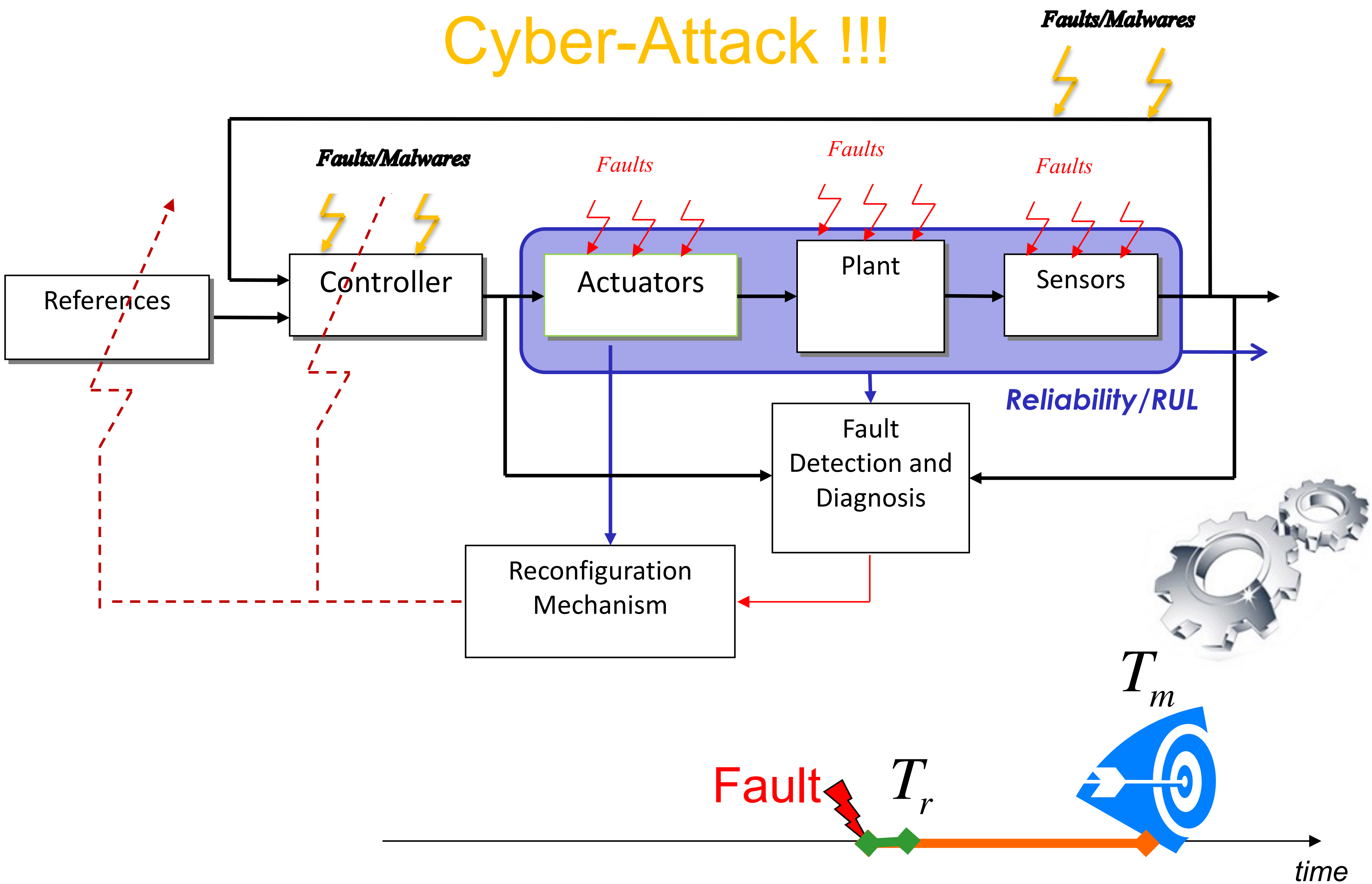
OUTLINES

Conclusions and Perspectives

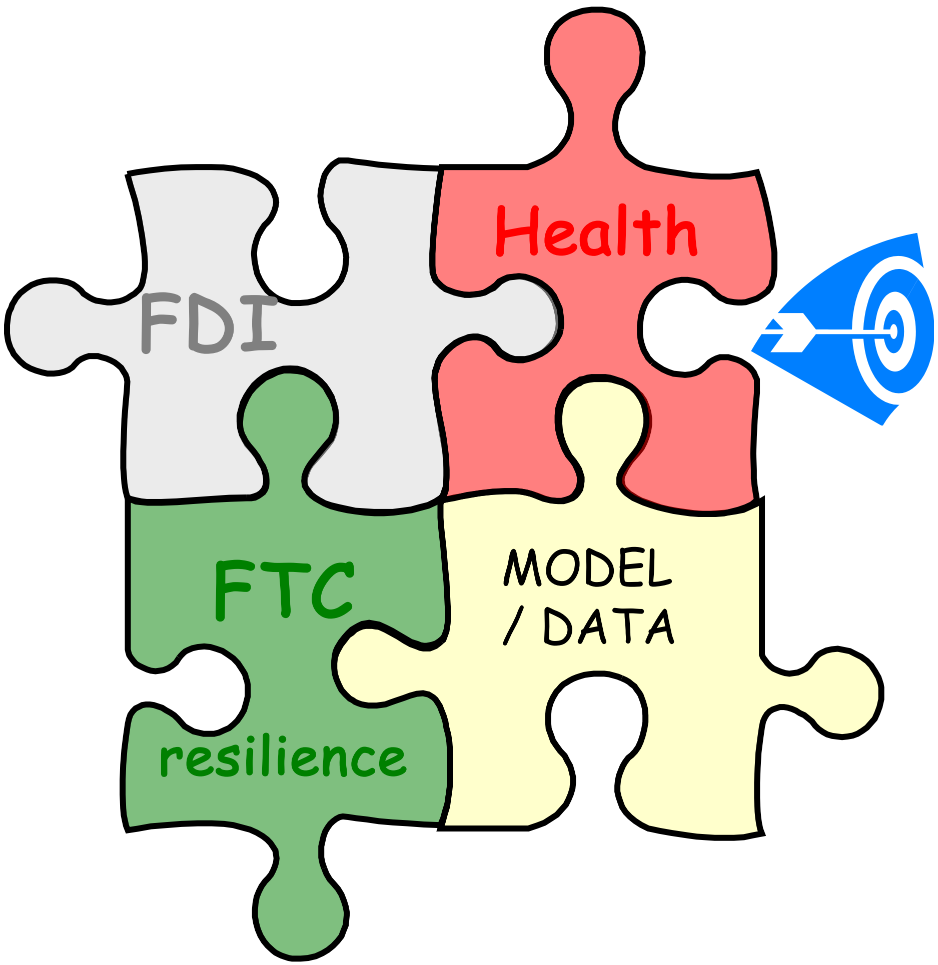


(*) *new result from main contributor Dr. MS JHA*

Heath Aware Control Design



Heath Aware Control Design

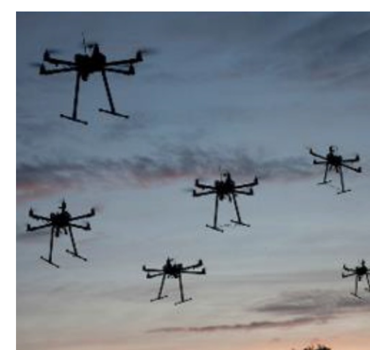


Health Aware Control Strategy

+ Safe Learning

+ Multi Agent Systems

on a fleet of Unmanned Vehicles



Safe Reinforcement Learning, Resilient/Fault Tolerant and Health Aware Control Strategies for Autonomous Systems

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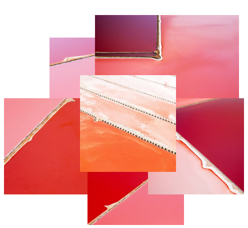

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