ACD 2010

8th European Workshop on Advanced Control and Diagnosis
Ferrara Nov. 18-19 2010

New Perspectives for Research in Fault Tolerant Control

Ron Patton

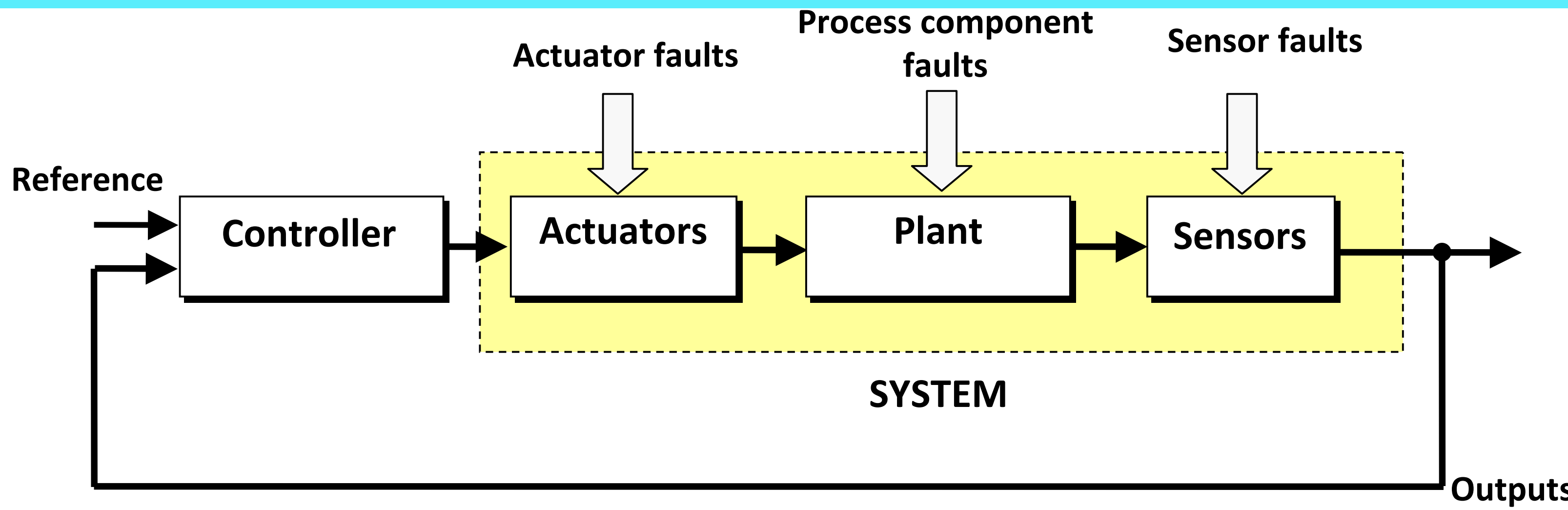
Department of Engineering, University of Hull, UK

www.hull.ac.uk/control

OUTLINE

- Introduction
- The FTC Story
- New Perspectives in FTC
- Concluding Discussion

THE FTC STORY



Objective of Fault Tolerant Control:
Joint optimization of stability and *admissible* performance
Subject to bounded faults, complexity and modelling uncertainty!

A topic with increasing interest at major international conferences of IFAC, IEEE, AIAA, etc (CDC, ACC, IFAC *Safeprocess (1991-2009), Systol (2010)*, IFAC World Congress, AIAA Guidance, Navigation and Control,….).

CLASSIFICATION OF FTC SYSTEMS

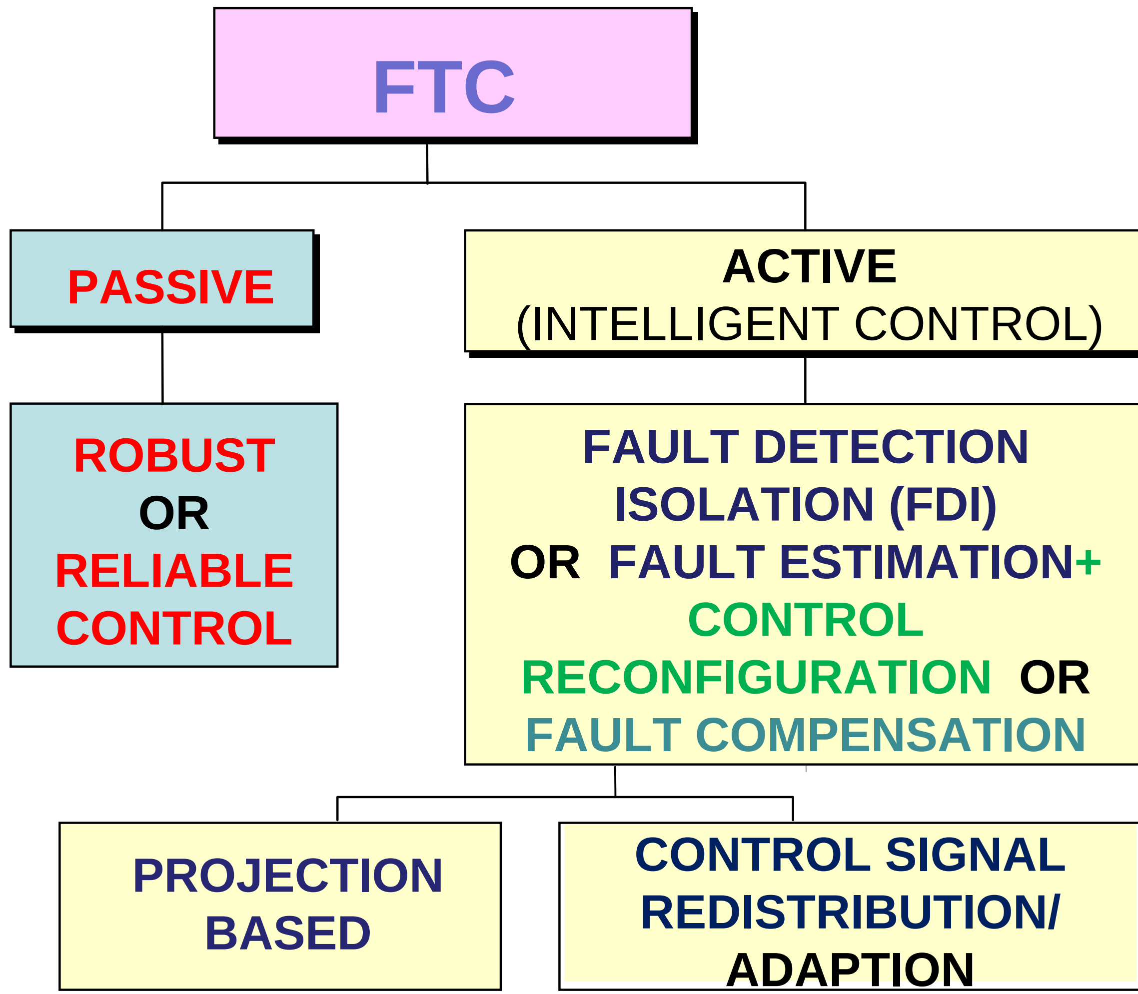
Several surveys and a good book to help…..

Patton. (2007). Fault-tolerant control: The 1997 situation

Blanke, Frei, Kraus, Patton, & Staroswiecki. (2000), What is Fault-tolerant control?

Blanke, Kinnaert, Lunze J & Staroswiecki. (2003, 2006). *"Diagnosis and Fault-Tolerant Control"*.

and numerous other papers!



THE FTC STORY

Active FTC

PROJECTION BASED	CONTROL SIGNAL REDISTRIBUTION/ ADAPTION
Mutiple-model Switching Interacting Multiple-Model (IMM) Gain-Scheduling, MPC, etc	Fault Compensation, MRAC, Control Allocation, Feedback Linearisation, LPV, Backstepping

THE FTC STORY

In the early years FTC developed as an aerospace topic, focused mainly on projects at NASA and in the USA, motivated by advanced aircraft that could be “control configured” through a high degree of flight surface redundancy.

The research led to well known flight control benchmark – the HiMAT which considers the longitudinal dynamics of an advanced fighter that was flight tested in 1970s.

Dryden Flight Research Center EC80-14281 Photographed 1980
HiMat

Model has *two* actuator inputs:

Elevons and canards flaps.

Vehicle equipped with two sensors that measure angle of attack and pitch angle.

Control objective:

To realize a vertical translation on flight. Pitch angle is maintained constant whereas the angle of attack varies. Fault scenario consists of an abnormal constant gain variation of 20% in the elevon actuator.

THE FTC STORY

Traditional Reconfigurable Flight Control

Feedback linearisation: **Lane & Stengel [1988], Ochi *et al* [1991]**

Pseudo-inverse methods: **Ostroff [1985]; Gao and Antsaklis [1990, 1991]**

Adaptive control: **Åström [1991, 1996], Ioannou, [1996],..**

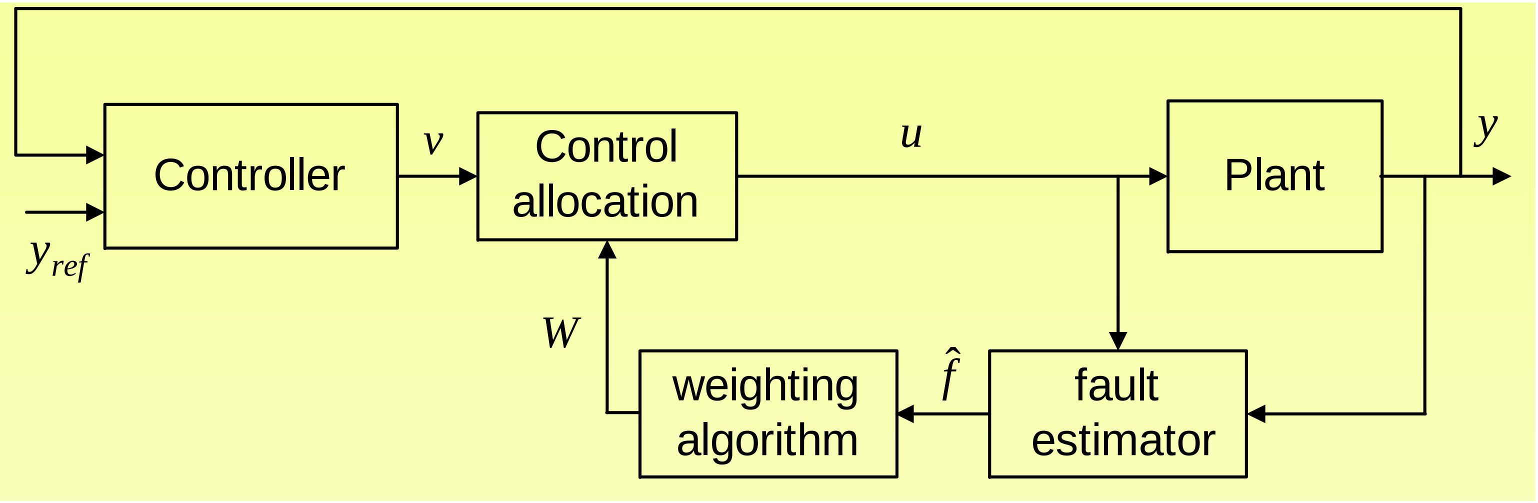
Model-following: **Huang & Stengel [1990]; Morse & Ossman [1990]; Mariton *et al*, [1990]; Jiang [1994]**

And…Restructurable Control:

Control Allocation: **Huang & Stengel [1990]; Morse & Ossman [1990]; Mariton *et al*, [1990]; Jiang [1994],…..Patton (1997)**

THE FTC STORY

The control allocation problem – also known as "Restructurable Control"



See Patton(1997)

CONTROL ALLOCATION DEPENDS ON EFFECTIVENESS OF ACTUATORS

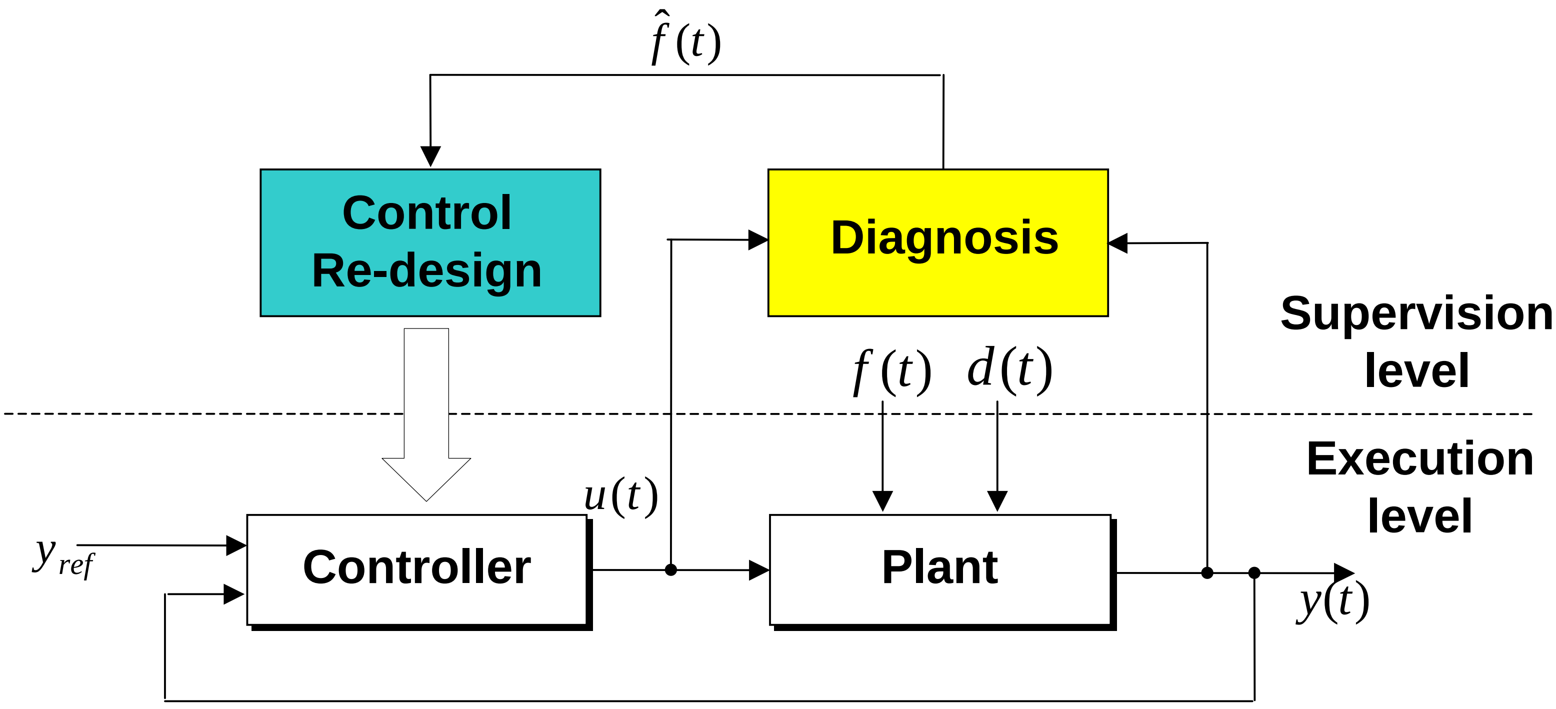
Information to compute *W* on-line comes from fault estimation/reconstruction or by using comparison of actual actuator deflection compared with demand.

In event of total failure in i^{th} actuator , *W^{-1} becomes very large and $u_i(t)$ is re-routed to other actuators, depending on available redundancy.*

Separating of control law from CA task fits well with "feedback linearisation" and "backstepping" which employ intermediate "virtual" control signals.

THE NEED FOR FTC ARCHITECTURES

In early years, architectures were not described very much.



Basic Architecture of FTC (Blanke et al, 2003, 2006)

Passive FTC

Robust control ensures closed-loop system remains insensitive to certain faults via constant controller parameters, **without on-line fault information** (Eterno *et al., 1985).*

Impaired system continues to operate with same controller and system structure.

Objective: To recover original system performance.

Effectiveness depends on robustness of nominal (fault-free) closed-loop system.

System made "robust" to faults, assuming restrictive repertoire of likely faults (usually one!) and way(s) in which they affect control function. Suitable in restricted cases, for small fault effects in the system.

Related topic: ***Reliable control*** *(Birdwell et al., 1986; Veillette et al.,* 1992).

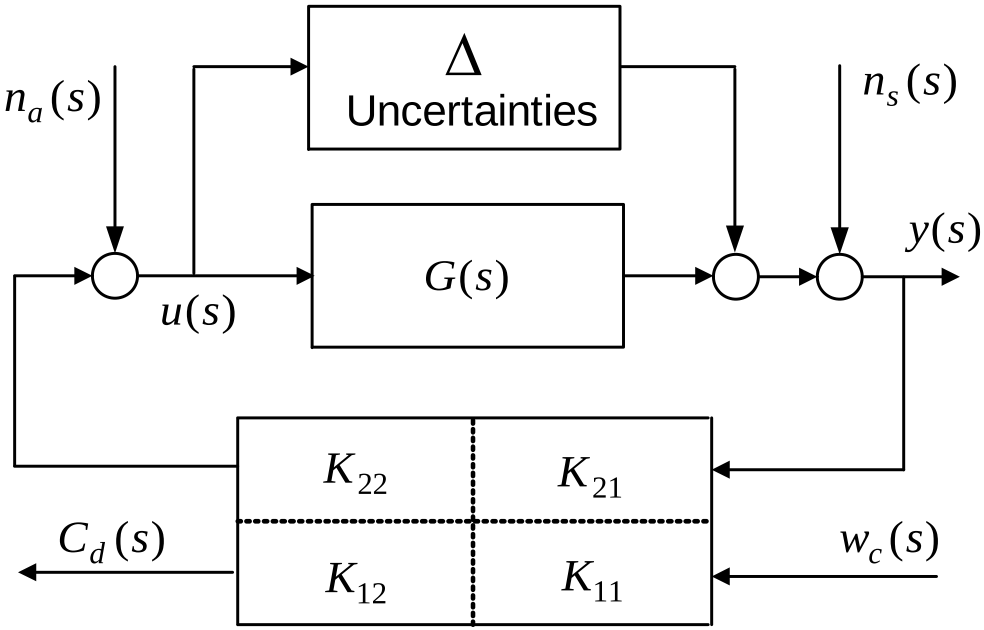
Robust design strategy that seeks to maintain constant controller design under certain "loop failures".

System over-designed, use available functional redundancy so that closed-loop behaviour is optimal when sensor signal is removed via "inferred measurements" (analytical redundancy), generating estimates of dissimilar quantities using available (healthy measurements).

THE FTC STORY

$n_a = f_a + \partial_a$

The 4-parameter controller



$n_s = f_s + \partial_{sa}$

USES "INTERNAL MODEL CONTROL" STRUCTURE

$$C_d(s) = [K_{11} \;\; K_{12}] \begin{pmatrix} \omega_c(s) \\ y(s) \end{pmatrix}$$

estimated fault/diagnosis signal

$$U(s) = [K_{21} \;\; K_{22}] \begin{pmatrix} \omega_c(s) \\ y(s) \end{pmatrix}$$

estimated control signal

The 4-parameter controller

H_∞ *used to achieve*:

1. Plant o/p signal *y(s)* tracks Ref commands & insensitive to actuator faults
2. Diagnostic o/p signal tracks actuator faults

1 & 2 hold in presence of bounded uncertainties

DISADVANTAGES:

a)Bilateral coupling between controller and fault estimation (or FDI) robustness [see Patton (1997)

b)“worst case” bounding in H_∞ gives “conservative” results
c)No guarantees for performance & stability
d)Structure only holds for actuator faults
e)No simple ways to “balance degrees of freedom”

The 4-parameter controller

Tyler *et al. (1994),* Murad *et al. (1996), Niemann et al. (1997) and* Stourstrup *et al. (1997) presented further results on robust design* approaches to integrated control and fault estimation based on *4 parameter controller.*

Tyler and Morari (1994) showed that the 4-parameter controller fits to the Youla-Bongiorno-Kucera parameterization of all stabilising controllers and this stimulated further research until 1997!

Argument against 4-parameter approach

Advantage of separate fault diagnosis and robust control designs is that their separate robustness problems can be Optimised.

Controller affects the robustness of fault detection and isolation, But "open-loop" approach to fault diagnosis does not in any way affect the controller design.

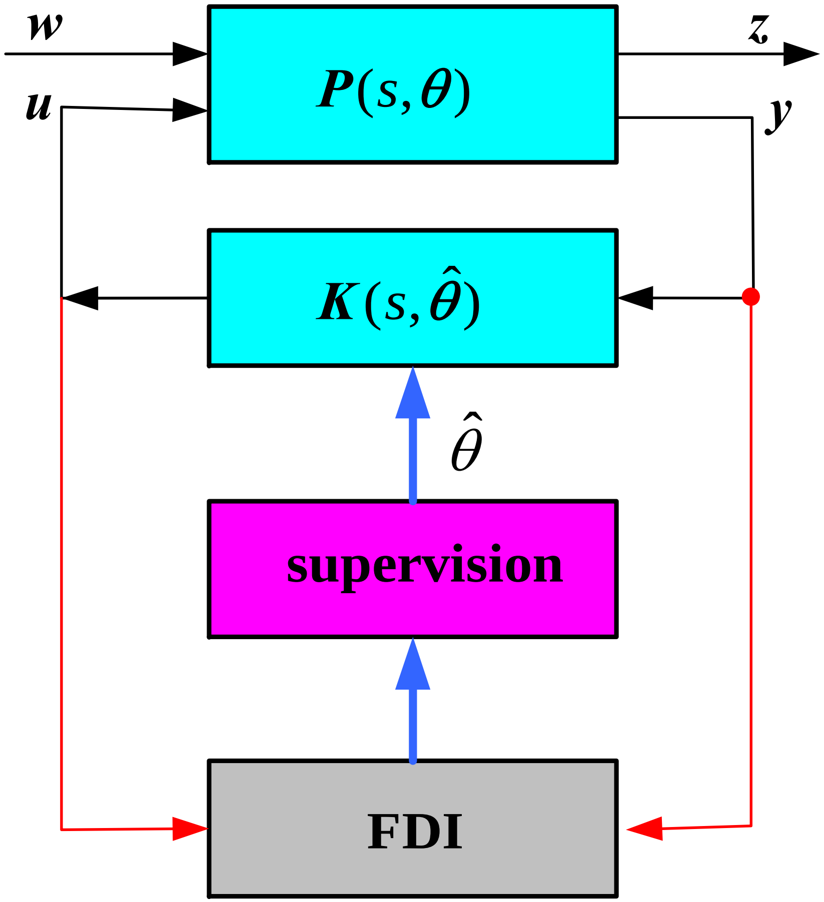
Hence, by separate designs of controller & diagnosis functions, degrees of freedom in controller design are not compromised. (Patton, 1997)

Active FTC

ESSENTIAL COMPONENTS

- **Fault Detection and Isolation (FDI) or fault estimation**
- **Robust Baseline (Nominal) Controller**
- **Reconfigurable, Restructurable or Adaptive (Accommodating) Control**
- **Supervision**

Active FTC scheme



$P(s,\theta)$ is generalized plant which includes all weighting functions

$K(s,\hat{\theta})$ is self-scheduled controller to be designed

θ is the *fault effect factors* estimated on-line using a suitable robust FDI mechanism.

Controller design must satisfy:

Bounds on uncertainties & faults, stability & admissible model-matching

NEW PERSPECTIVES

Around 2000-2003 a lot of "navel-contemplating"!

→ **Investigators wondering, where we are coming from, where we are going and really what IS FTC?**

→ **Several papers and a book giving "FTC definitions"**

Blanke, Frei, Kraus, Patton & Staroswiecki (2000),

Blanke, Staroswiecki & Wu (2001)

Stoustrup & Niemann (2001)

Zhou and Ren (2002)

Campos-Delgado & Zhou (2003)

Blanke, Kinnaert, Lunze J & Staroswiecki, (2003, 2006), "*Diagnosis and Fault-Tolerant Control*".

NEW PERSPECTIVES

In 2000s decade – Developing themes

Research on Suitable FTC Architectures

Internal Model-based FTC

Multi-objective optimization of joint control, reconfiguration and FDI/fault estimation robustness

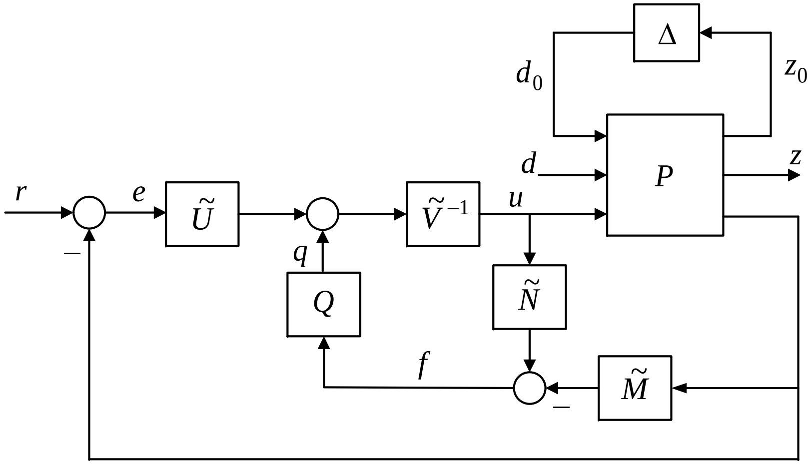
Robust Control Allocation schemes:

- Sliding mode, pseudo-inverse modelling, etc.

NEW PERSPECTIVES

Architectutres……

Gen. Internal Model Control with general uncertain plant

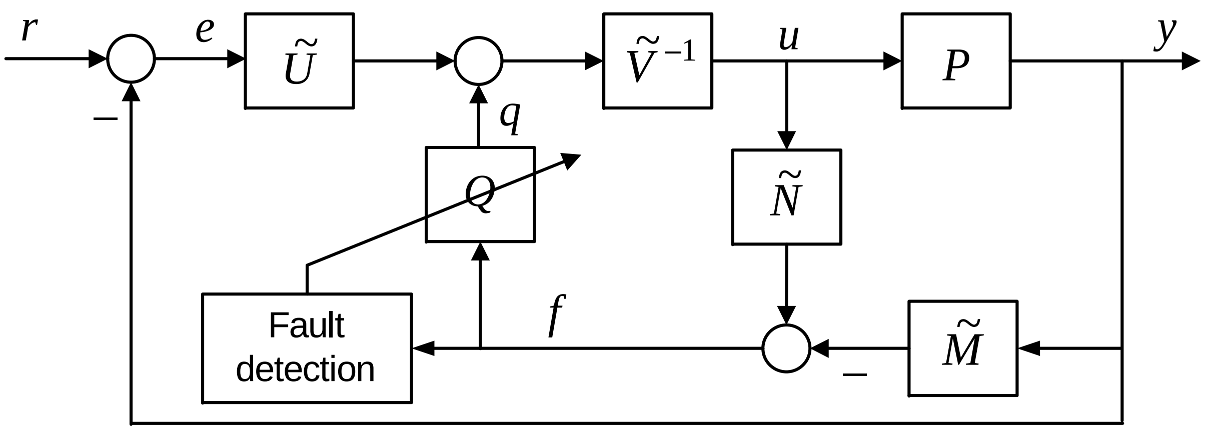


FTC in two parts: Nominal performance controller and Robustness controller, and works in such way that when a fault is detected controller structure is reconfigured by adding robustness loop to compensate the fault.

Zhou K and Ren Z, (2001), Reconfigurable control using GIMC structure, IEEE Trans. AC. 48(5), 832-838

See later papers by:

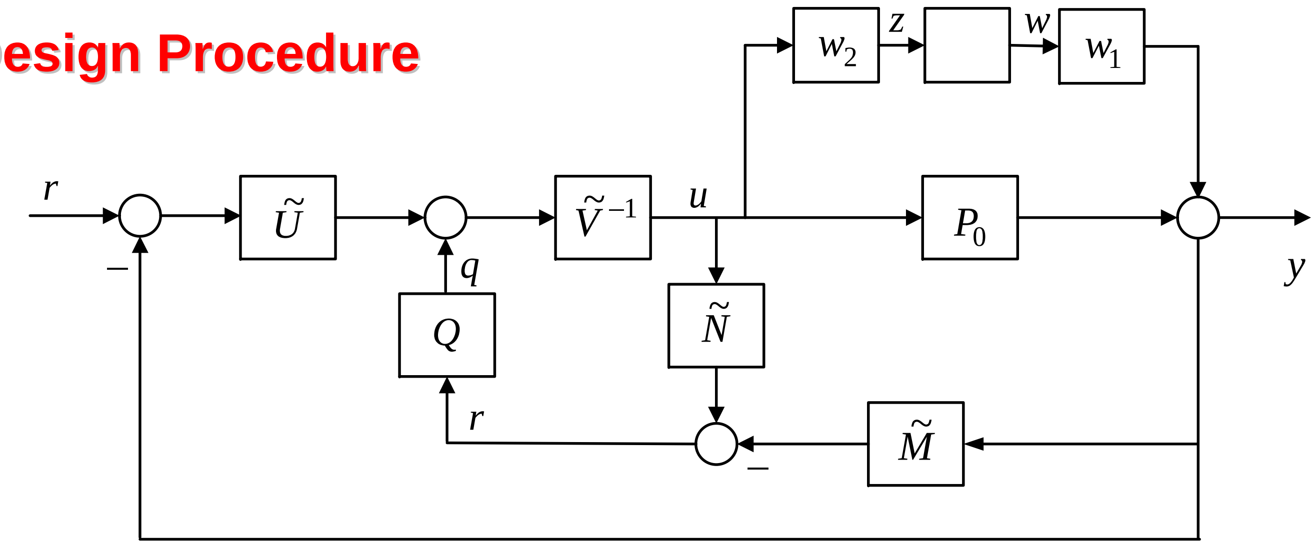
Niemann (2003, 2005, 2006, 2009, 2010)
Change from high performance to "Safe mode controller" (Systol'10)



A fault-tolerant control scheme

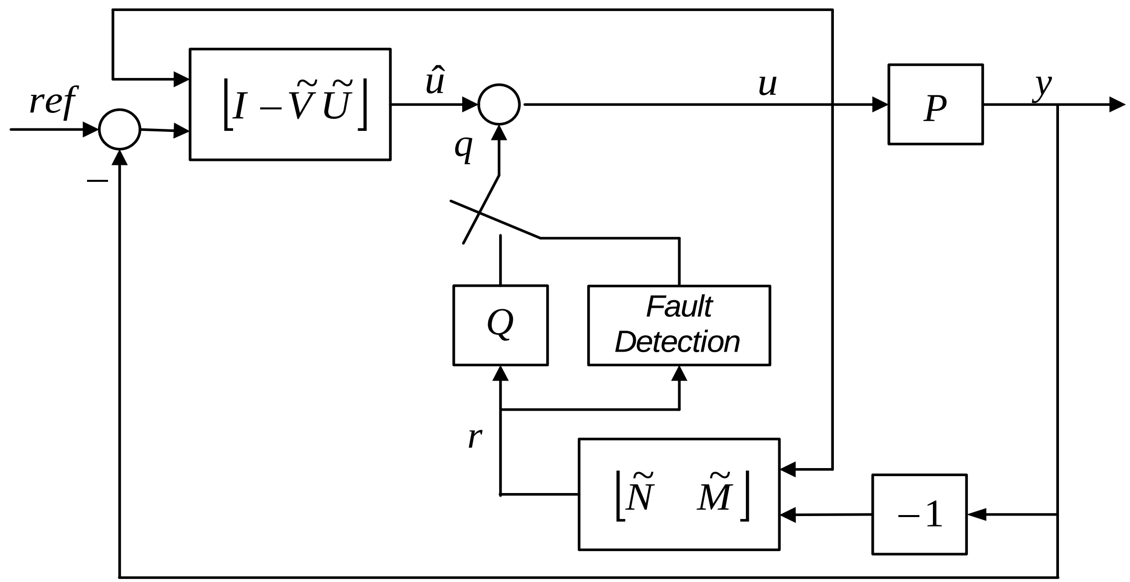
GIMC FTC Design Procedure

GIMC Architecture with Uncertain Plant



Delgado C & Zhou K, (2002), Reconfigurable control using GIMC structure, IEEE Trans. AC. 48(10), 1613-1618

GIMC structure with fault detector



Pseudo-Inverse Modelling Methods:

Caglayan, 1988; Huber, 1984; Ostroff, 1985; Rattan, 1985; Razza & Silverthorn, 1985; Gao & Antsaklis, 1990; Staroswiecki, 2005

Challenge Ostroff (1985): Minimise difference between "faulty" and "nominal" closed-loop linear systems, determining the appropriate gain: Model-matching Problem.

$$\dot{x}(t) = Ax(t) + BKx(t);\ K \in R^{mxn}$$
$$y = Cx(t)$$

Nominal model

$$\dot{x}_f(t) = Ax_f(t) + BK_f x_f(t)$$
$$y_f = C_f x_f(t)$$

Faulty model

NEW PERSPECTIVES

Aims of PIM/MPIM..model-matching

a) Maintain as much simplicity as possible in controller design,

b) Reconfigured system made to approximate nominal system {OR reference model} closely, and

c) Provide graceful performance degradation, subsequent to a fault.

Challenges, to satisfy:

Stability constraints: Gao & Antsaklis (1991)

"Admissible model-matching": Staroswiecki (2005a, 2005b)–**"family of behaviours"**

Robustness to uncertainty via so-called $\mathcal{D}_R$ *–regions via LMI constraints:* Tornil-Sin, Theilliol, Ponsart and Puig (2010)

NEW PERSPECTIVES

Minimise Frobenius norm of the difference

Between the closed-loop matrices:

$$\min J = \left\| (A + BK - A_f - B_f K_f) \right\|_F^2 \quad s.t \; Im(B_f K_f) \subseteq Im(B_f)$$

$$\rightarrow \quad K_f = B_f^{\,+} (A - A_f + BK)$$

Stability? Performance?

Staroswiecki (2005a) {MPIM} showed an **improvement** can be determined by using reference model with **"Admissible model-matching"**: $\dot{x}_r(t) = M^* x_r(t) + N^* e(t)$

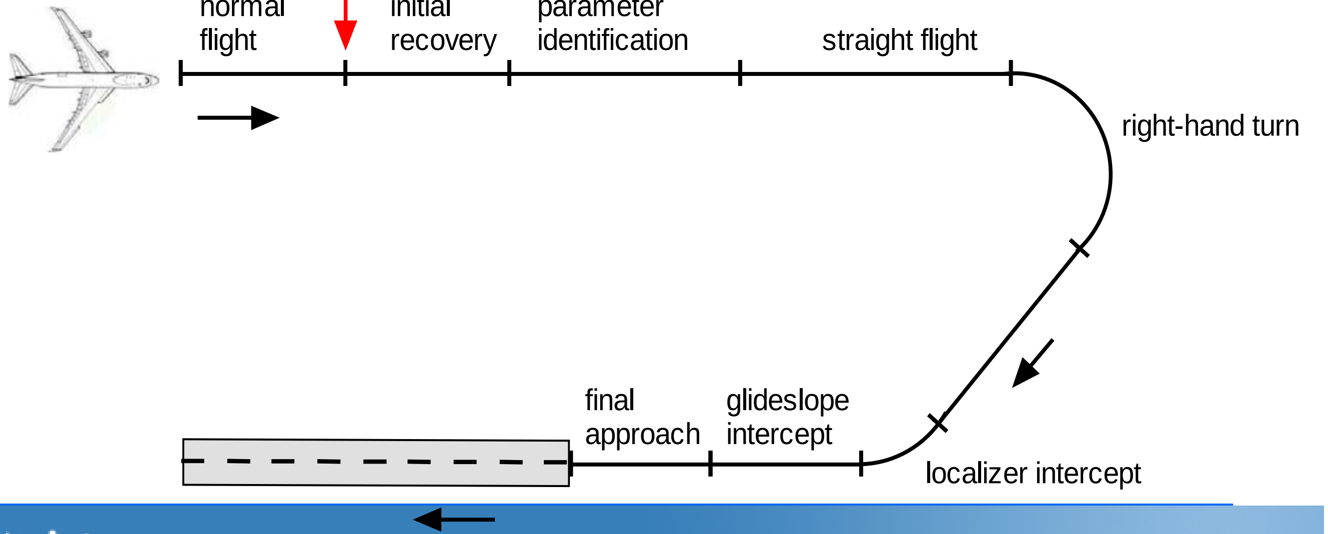
$$\min J_1 = \left\| (A_f - B_f K_f - M^*) \right\|_F^2 \quad \min J_2 = \left\| (I - B_f B_f^{+}) N^* \right\|_F^2$$

s. t. stability constraint from Gao & Antsaklis (1991)

Reconfiguration via Sliding Mode Control

Adaptive SMC - *Demirci & Kerestecioglu, 2005*:
Fault distribution matrix used to switch corrective or "equivalent control" part of SMC in adaptive way. Objective is to control MIMO system under nominal operation as well as in case of faults/

Control Allocation via SMC (Garteur AG16): *Edwards, Alwi & Tan* (Systol'10)



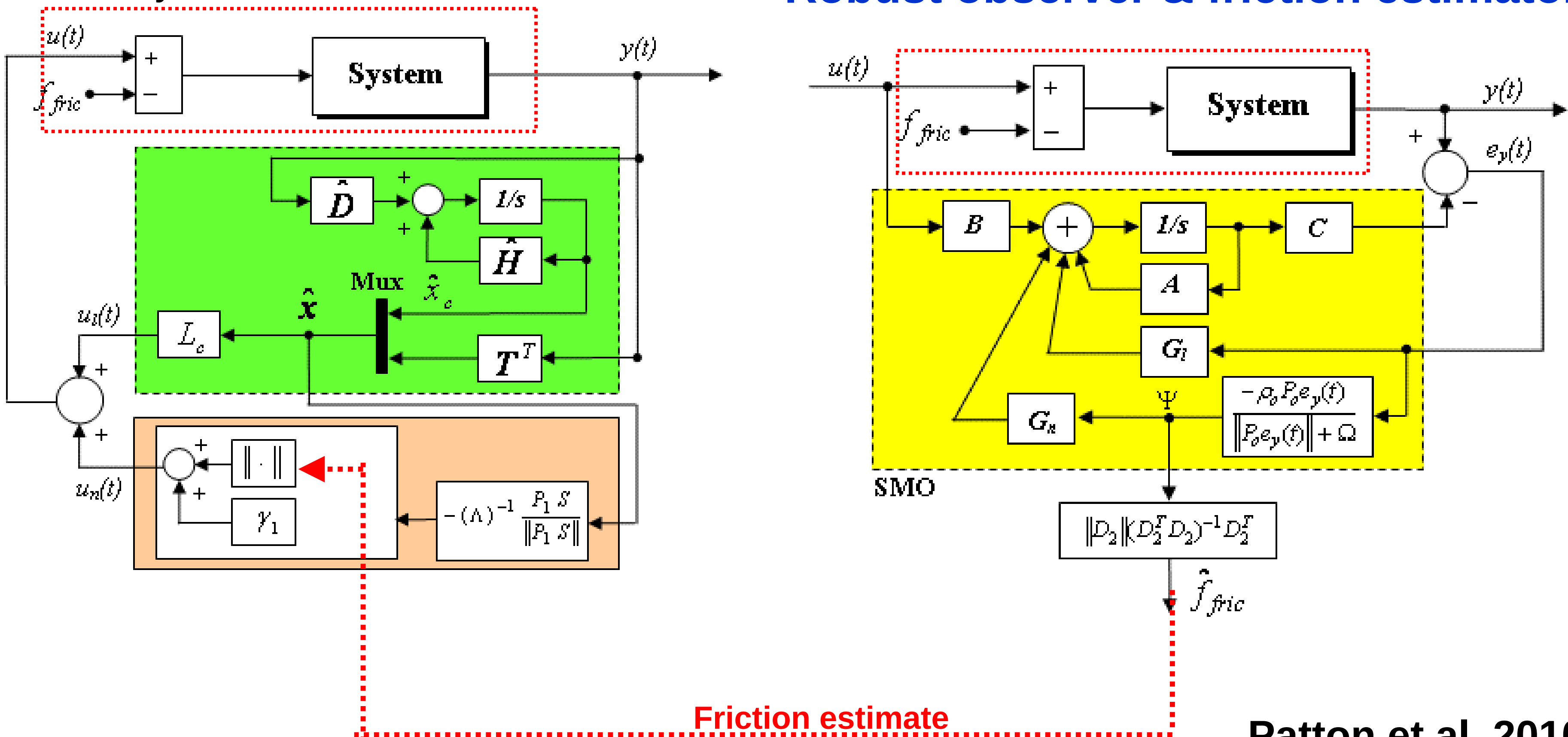
NEW PERSPECTIVES

Sliding Fault Estimation Compensation/Accommodation

Controller with friction compensation

System with Friction

Robust observer & friction estimator

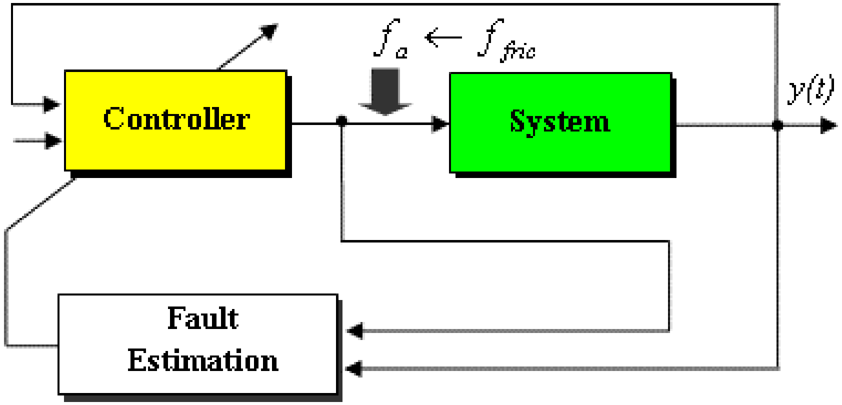


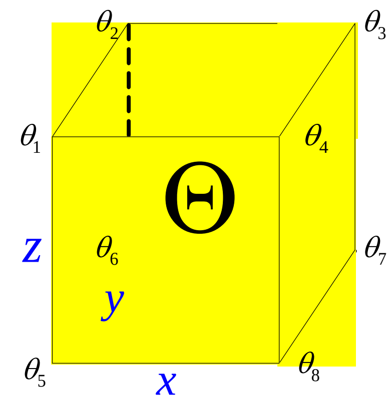
Patton et al, 2010

NEW PERSPECTIVES

Linear Parameter Varying Estimation and Control – for FTC

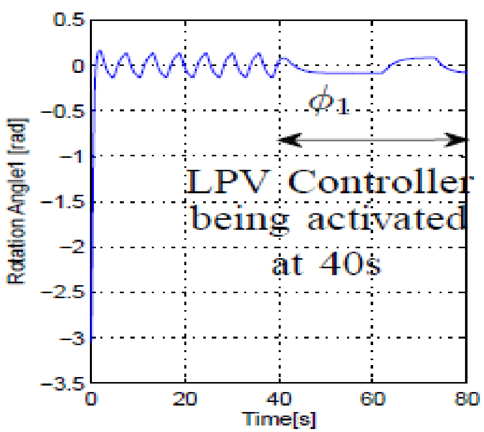
Chen L & Patton, Systol'10

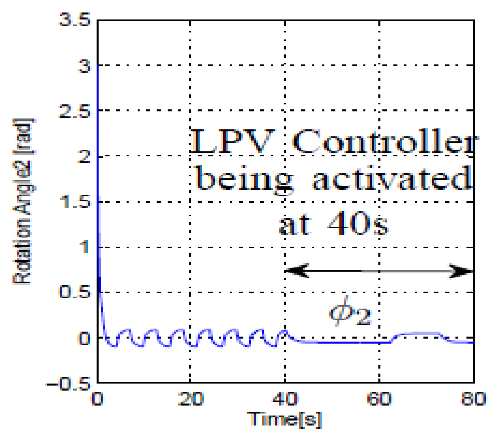




$$\theta(t) \in \Theta := Co\{\theta_1, \theta_2, \cdots, \theta_r\}$$

$$: \quad \alpha_p^i \geq 0, \quad \sum_{i=1}^{r} \alpha_o^i = 1 \Big\}$$



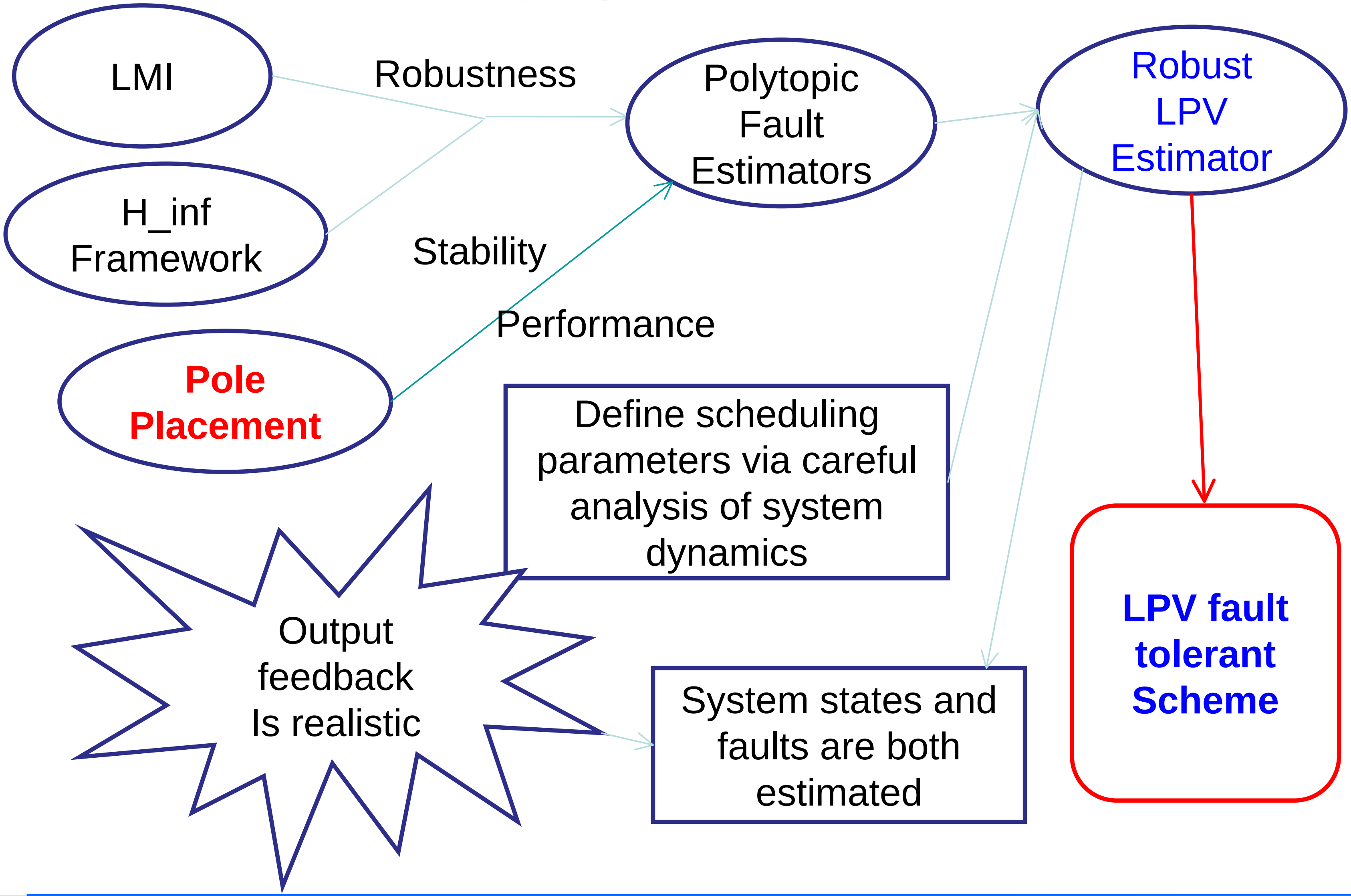


Friction compensation in robot system as an FTC problem

See also: "LPV AMM…" Oca, Puig, Theilliol & Tornil-Sin: MED'09

NEW PERSPECTIVES

Linear Parameter Varying Estimation and Control – for FTC



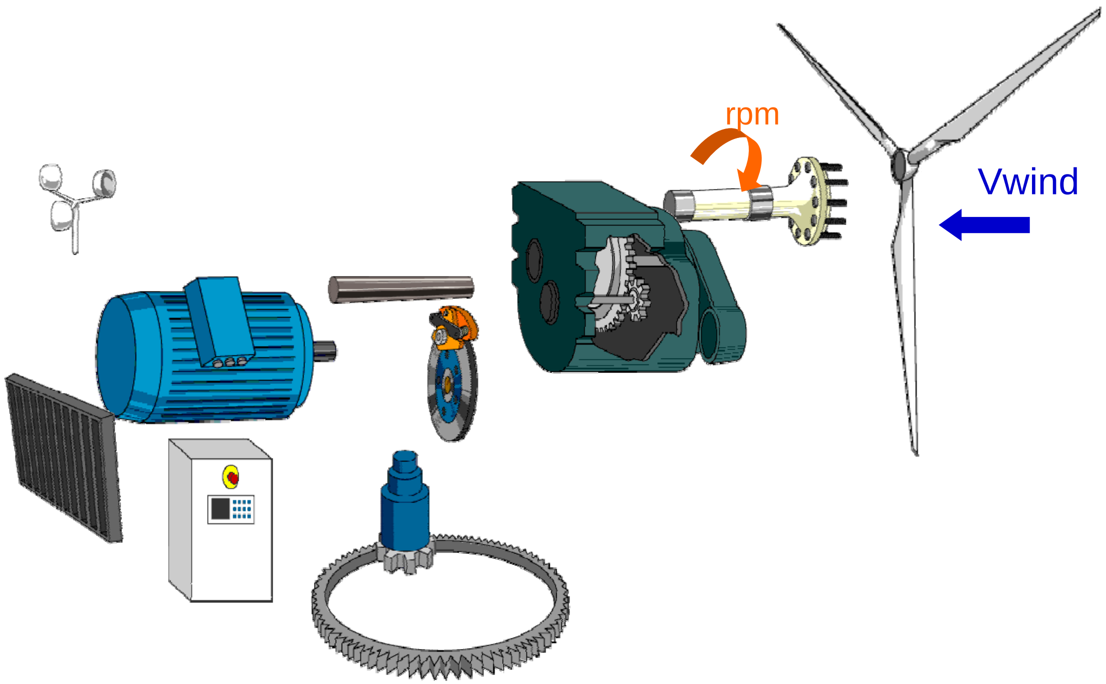
NEW PERSPECTIVES

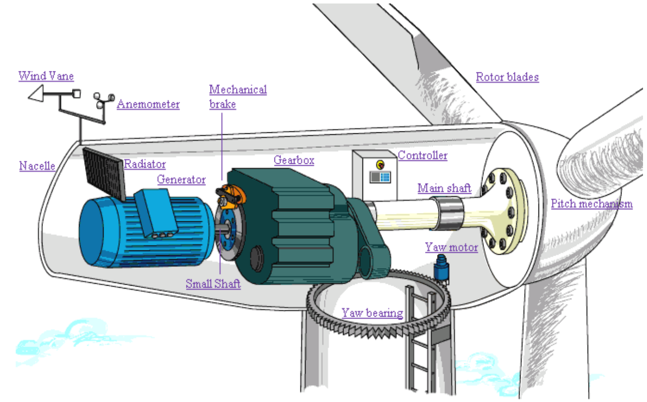
Strong Directions of New Research in FTC

- **Admissible Model Matching (AMM) (use of reference models) and LMI conditions; robustness issues**
- **Sliding Mode Control (fault estimation + control allocation); SMC fault estimation/compensation**
- **LPV Control with LPV estimation – Fault Compensation, Accommodation and AMM**
- **FTC of Distributed/Networked Systems, based on hierarchy**

NEW PERSPECTIVES

Applications of New Research in FTC, eg:





Offshore wind-turbine problem presents huge challenges to FTC…..robust estimation, robust & admissible model-matching, adaptive FTC, etc…

Thanks for your attention