Data-Driven and Model-Based Robust Fault Diagnosis and (Fault Tolerant) Control of a Wind Turbine Model

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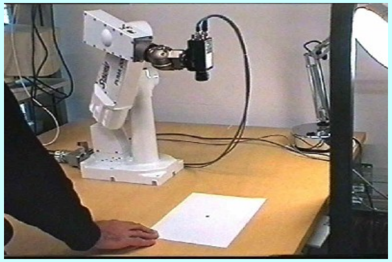
GOOGLE SCHOLAR: http://scholar.google.it/citations?user=unGaoZgAAAAJ&hl=it

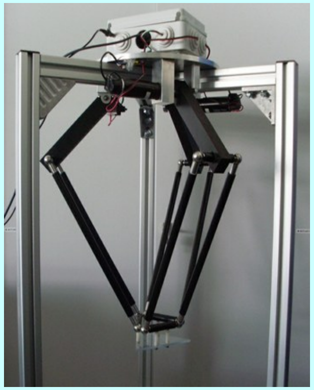
UniFE… An *Old* Story

- The University of Ferrara **founded in 1391**. The first courses inaugurated were **Arts, Theology and Law**
- The University of Ferrara (UniFE): ~ 2500 students per year
  - **3rd place in the national evaluation of the scientific research**
- **The Engineering Department of the University of Ferrara** (**EnDiF**) was founded in 1996 (before, only the first two years…)
  - ~ 250 students per year; ~ 70 academics; ~ 120 Ph.D. students
- From the National Agency for the Evaluation of Universities and Research Institutes (ANVUR, 2013, research quality): ranked **1st in our region & 11th of 137 Engineering Departments in Italy**
- **Bachelor degrees** in Civil and Environmental Engineering, Electronic and Computer Science Engineering, and Mechanical Engineering. **Master degrees** in Civil Engineering, Electronic and Telecommunication Engineering, Computer Science and Automation Engineering, Mechanical Engineering

Research Staff



- **4 senior researchers**
  - **Disciplines**: System Theory, Automatic Control, Computer Science, Mathematics, Optimization, Aerodynamics
- 2 professors under contract, 1 technician (lab.), 4 Ph.D.
- **Intelligent Robotics and Automation Lab (L.I.R.A.)**
  - Design, modelling, analysis, control, implementation and verification of embedded mechatronic systems
  - Human-computer interfaces, user-interface design and real-time simulation and control of systems
  - Various high speed computers support, virtual prototyping, computing platforms and tools for embedded implementation, hardware-in-the-loop testing
  - Powerful computer cluster containing 50 machines with Intel processors + Linux OS. A new High Performance Computing server with 2 CPUs six-core Intel Xeon X5690 at 3.46GHz, 448 cores, 6 GB GDDR5 RAM each, 188 GB DDR3 RAM, 12 TB HD



Research Issues

1) **Modelling and identification of dynamic processes**
   - Affine or piecewise linear prototypes
   - Fuzzy models and neural networks
2) **Fault diagnosis and fault tolerant control**
   - Output observers, Kalman filters, particle filters
   - Residual generators designed via polynomial methods or nonlinear geometric approach (fault sensitivity optimisation + uncertainty/disturbance effects minimisation)
   - Nonlinear adaptive filters for fault time-behaviour identification
   - **From FDD to FTC exploiting faults estimate**
   - Feedback linearization + sliding mode controller/observer
3) **Applications to:**
   - **Wind turbines and wind farms**
   - **Aircraft and spacecraft systems**
   - Power processes
   - Chemical reactors

FDI/FDD & FTC Issues

- **Fault Detection and Diagnosis (FDD) is strictly connected with process control**
  - At the controller design stage, **FDD is a 'by-product'**
  - **Fault Tolerant Control (FTC) is mainly considered**
- **Passive Fault Tolerant Control Scheme** (PFTCS) & **Active Fault Tolerant Control Scheme** (AFTCS)
  - **PFTCS**: controllers are designed to be robust against a class of presumed faults
  - **AFTCS**: reacts to the system component faults actively by reconfiguring control (also exploiting faults estimates)
- **AFTCS** can rely on *(1)* **analytic model-based** (disturbance decoupling) approaches or *(2)* **data-driven** methods

Approaches to *A*FTCS (1)

- The 2 proposed strategies implements **fault estimation schemes** used for the design of ***AFTCS***
- This **on–line** fault estimation relies on 2 types of **nonlinear dynamic filters**
- The controller ***accommodation*** methods exploits further control loops depending on the on–line estimates of the fault signals: **Active FTC**

1. The **suggested scheme with analytic disturbance decoupling** is described in detail in: [S. Simani and P. Castaldi, “Active Actuator Fault Tolerant Control of a Wind Turbine Benchmark Model,” *International Journal of Robust and Nonlinear Control*, vol. 2013, 2013, DOI: 10.1002/rnc.2993]…

Approaches to AFTCS (2)

2. … **However**, the nonlinear fault estimation is based also on nonlinear filters **directly identified from the monitored process data**, see *e.g.*:

   [S. Simani, S. Farsoni, and P. Castaldi, "Active fault tolerant control of wind turbines using disturbance decoupled nonlinear filters," Proceedings of the 2nd IEEE International Conference on Control and Fault–Tolerant Systems – SysTol'13, Nice, France. 9–11 October 2013, pp. 383–388, ISBN: 978–1–4799–2854–5]

❖ The previous approach **does not use** nonlinear filters **analytically** decoupled from disturbance and designed via **the nonlinear geometric approach (NLGA)** described in:

   [Bonfè, M. Castaldi, P. Mimmo, N. and Simani, S. "Active fault tolerant control of nonlinear systems:The cart–pole example," *International Journal of Applied Mathematics and Computer Science* – AMCS, vol. 21, no. 3, pp. 441–455, Sept. 2011]

Advantages & Comments

1. **Analytic design** when the process model is **available**
   - **Purely nonlinear method + exact** disturbance decoupling
     - fault estimator (RBF-AF) + fault reconstruction

✓ Applied to an aircraft model: [P. Castaldi, N. Mimmo, S. Simani, "Differential Geometry Based Active Fault Tolerant Control for Aircraft," *Control Engineering Practice*, Jan. 2014]

1. **Direct approach** – data from the controlled process
   - Fuzzy Modelling and IDentification (**FMID**®)
     - *i)* **Approximate** disturbance decoupling
     - *ii)* Fault estimator **fuzzy identification** + **fault reconstruction**

✓ Applied to a diesel engine *real data* [S. Simani, "Residual Generator Fuzzy Identification for Automotive Diesel Engine Fault Diagnosis," *International Journal of Applied Mathematics and Computer Science – AMCS*, vol. 23, no. 2, pp. 419–438, June 2013]

Ingredients & Recipes

1. Analytic design of nonlinear adaptive filters

- **Nonlinear geometric approach** (differential geometry tools)

sis function NN

dynamic filters

uzzy clustering

identification

lli, "Parameter identification for piecewise linear fuzzy models in models in noisy environment," *International Journal of Approximate Reasoning*, vol. 1, no. 22, pp. 149–167, September 1999]

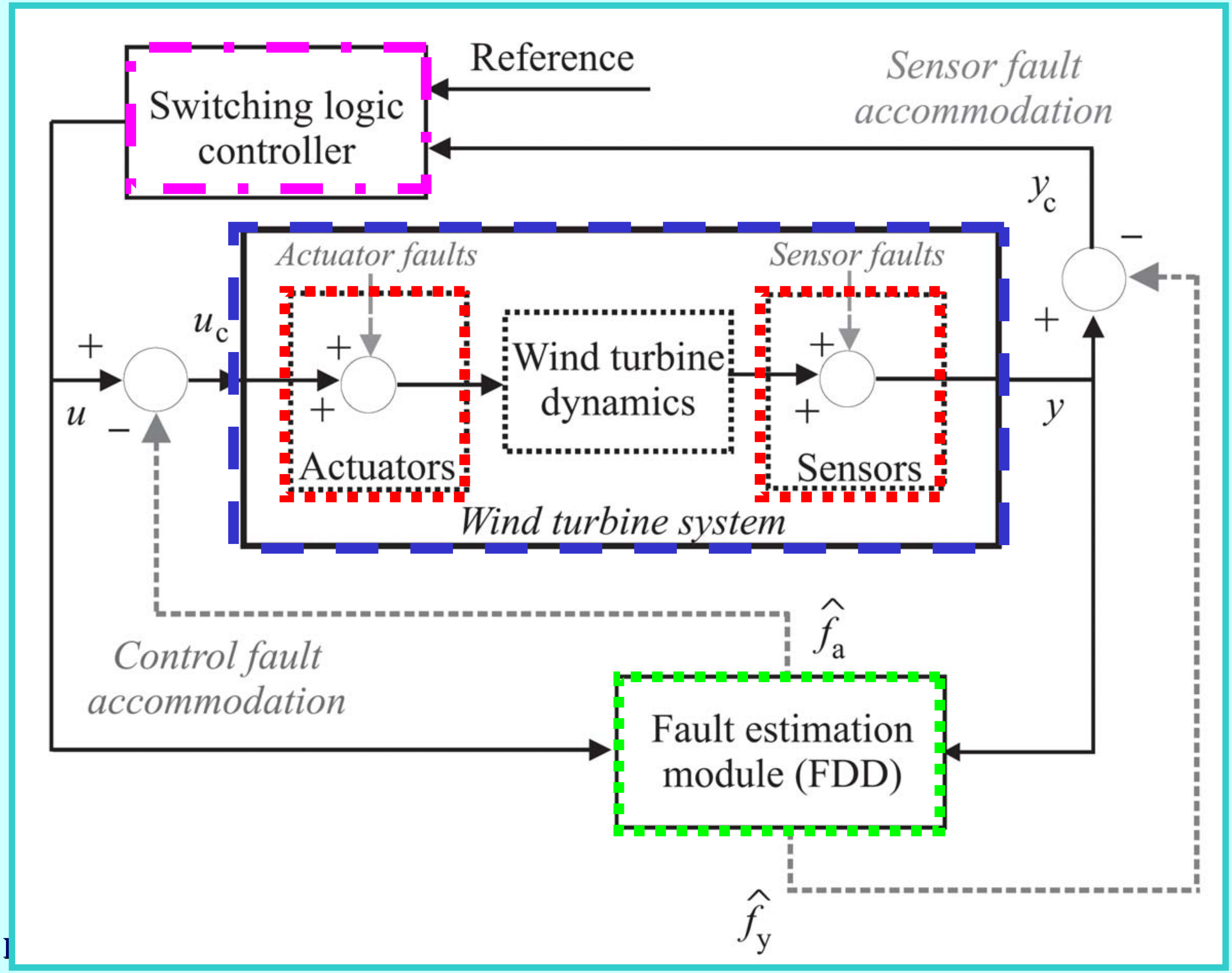
September 1999]

t accommodation

om disturbance: *(1)* exact or *(2)* approximate design

roximate design

FDD & Control Diagram



NLGA Approach to AFTCS (1)

- The NLGA approach applied to the **nonlinear affine model**:

$$\begin{cases} \dot{x} &= n(x) + g(x)\,u + \ell(x)\,f + p_d(x)\,d \\ y &= h(x) \end{cases}$$

  - $f(t) \in R^{lf}$ is the fault vector (faults to be estimated).
  - $d(t) \in R^{ld}$ the disturbance vector (including also the faults to be decoupled, for **fault isolation**)
- The system is affine w. r. t. both inputs (u, f) and disturbance (d)

➢ **To obtain a subsystem sensitive to the fault** with the **disturbance decoupling feature**

  - Determine a coordinate transformation by using **NLGA procedure** (exploits the differential geometry tools)

NLGA Approach to AFTCS (2)

- In the new (local) state and output coordinates the monitored system is transformed into:

$$\begin{cases} \dot{\bar{x}}_1 &= n_1(\bar{x}_1, \bar{x}_2) + g_1(\bar{x}_1, \bar{x}_2)\, c + \ell_1(\bar{x}_1, \bar{x}_2, \bar{x}_3)\, f \\ \dot{\bar{x}}_2 &= n_2(\bar{x}_1, \bar{x}_2, \bar{x}_3) + g_2(\bar{x}_1, \bar{x}_2, \bar{x}_3)\, c + \\ & \quad + \ell_2(\bar{x}_1, \bar{x}_2, \bar{x}_3)\, f + p_2(\bar{x}_1, \bar{x}_2, \bar{x}_3)\, d \\ \dot{\bar{x}}_3 &= n_3(\bar{x}_1, \bar{x}_2, \bar{x}_3) + g_3(\bar{x}_1, \bar{x}_2, \bar{x}_3)\, c + \\ & \quad + \ell_3(\bar{x}_1, \bar{x}_2, \bar{x}_3)\, f + p_3(\bar{x}_1, \bar{x}_2, \bar{x}_3)\, d \\ \bar{y}_1 &= h(\bar{x}_1) \\ \bar{y}_2 &= \bar{x}_2 \end{cases}$$

- $l_1(.)$ not identically zero. The **x1-subsystem is decoupled from the disturbance vector** and **affected by the fault**:

$$\begin{cases} \dot{\bar{x}}_1 &= n_1(\bar{x}_1, \bar{y}_2) + g_1(\bar{x}_1, \bar{y}_2)\, c + \ell_1(\bar{x}_1, \bar{y}_2, \bar{x}_3)\, f \\ \bar{y}_1 &= h(\bar{x}_1) \end{cases}$$

- where the variable y_2 is assumed to be measured and considered as independent input.

NLGA Approach to AFTCS (3)

- Via the x_1-subsystem, the filters can be designed if:
  - x_1 independent from x_3 (not measured state components)
  - the considered faults was step functions and recently a generic function [P. Castaldi, N. Mimmo, and S. Simani, "Nonlinear Fault Tolerant Flight Control for Generic Actuators Fault Models," in American Control Conference – ACC 2014, (Portland, OR), invited paper]
  - there exists a scalar component x_{1s} of x_1 such that the corresponding scalar component of y_1 is $y_{1s} = x_{1s}$ and the following holds ($M_1 \neq 0$ for all $t \geq 0$):

$$\dot{y}_{1s}(t) = M_1(t) \cdot f_s + M_2(t)$$

  - f_s can be a single scalar fault or a combination of single scalar faults weighted by nonlinear state functions
  - **Adaptive filter design** (generic fault estimate with RBF-NN)

Fuzzy Modelling & IDent.®

- Fuzzy nonlinear identification: **2nd alternative design**
- Fuzzy Modelling and IDentification (**FMID®**) toolbox
- Gustafson–Kessel (GK) fuzzy clustering
- Fuzzy estimator parameter identification (**EIV** scheme)

$$y(k+1) = \frac{\sum_{i=1}^{M} \mu_i \left(\mathbf{x}(k)\right)\ y_i}{\sum_{i=1}^{M} \mu_i \left(\mathbf{x}(k)\right)}$$

with

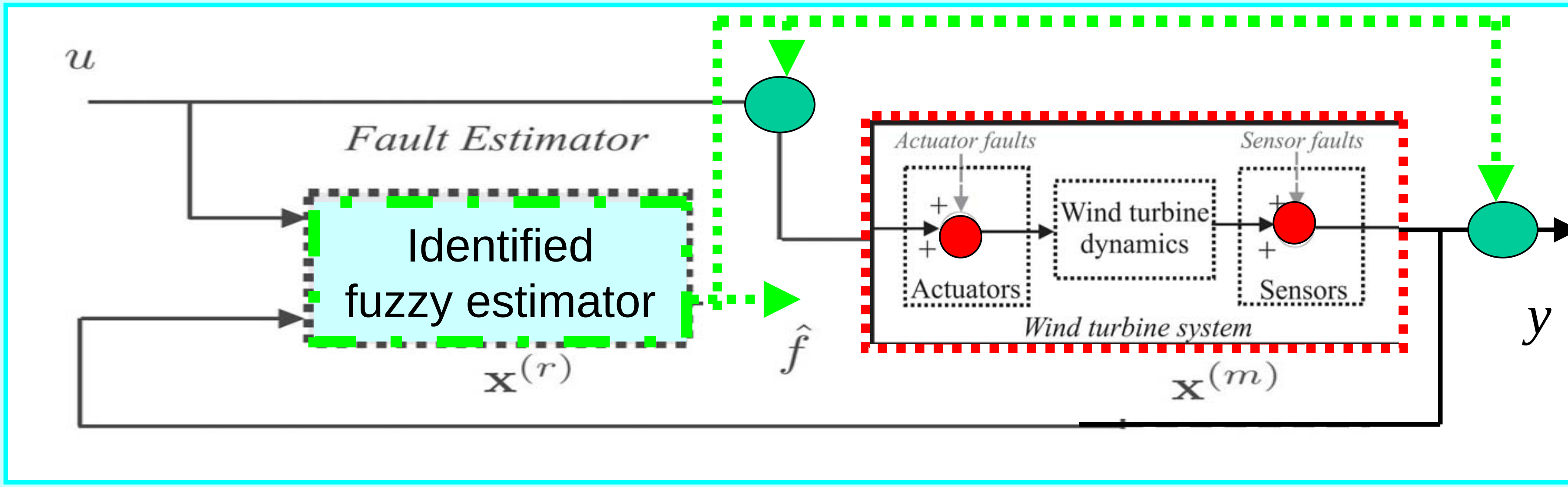
$$y_i = \mathbf{a}_i\, \mathbf{x} + b_i$$

$\mathbf{a}_i$ & $\mathbf{b}_i$ estimated parameters, μ_i from the fuzzy partition matrix; $\mathbf{x} = \mathbf{x}(k)$ the regressor vector

Unknown Input Reconstruction

- The **fault** is considered as an **unknown input**
  - Unknown input (fault) reconstruction solved within the fuzzy identification framework
- The **nonlinear estimator** for the unknown input (fault) is designed by exploiting the **fuzzy model** of the controlled wind turbine
- In ideal conditions: this estimator provides the *perfect* reconstruction of the unknown input signal
- In practice, with both modelling errors and disturbances, the fault estimation is performed with an **arbitrary degree of accuracy**
- **Dual approach** proposed for the controller identification [Simani, S. "Application of a Data–Driven Fuzzy Control Design to a Wind Turbine Benchmark Model," *Advances in Fuzzy Systems*, 2012]

Fault Estimator Identification



- Unknown input estimator

$$\hat{f}(k+1) = F^{-1}\left(\mathbf{x}(k),\, y(k)\right)$$

- Fuzzy TS model

$$\hat{f}(k+1) = \frac{\sum_{i=1}^{M} \mu_i^{(r)}\left(\mathbf{x}^{(r)}(k)\right)\left(\mathbf{a}_i^{(r)}\,\mathbf{x}^{(r)}(k) + b_i^{(r)}\right)}{\sum_{i=1}^{M} \mu_i^{(r)}\left(\mathbf{x}^{(r)}(k)\right)}$$

- Such that

$$y(k+1) = F\left(\mathbf{x}^{(m)}(k),\, \hat{f}(k)\right)$$

Model Parameter Estimation

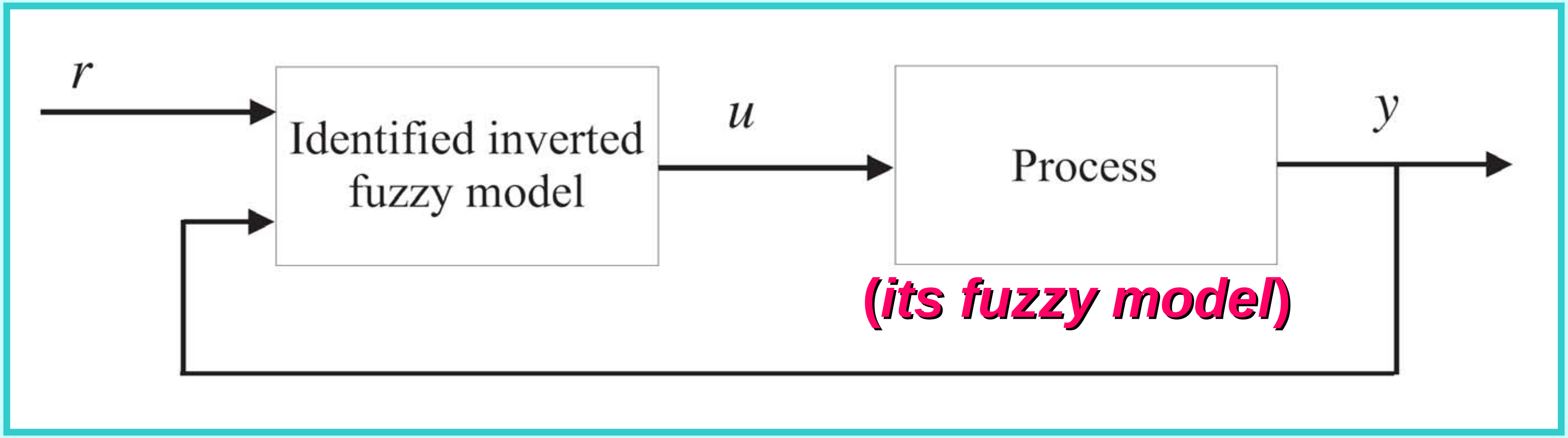
- **Parameter identification**
- Fuzzy model of the wind turbine $\mathbf{x}^{(m)}(k)$
  - membership functions $\mu^{(m)}_i$, the parameters $\mathbf{a}^{(m)}_i$, $b^{(m)}_i$
- Fuzzy model of the fault estimator $\mathbf{x}^{(r)}(k)$
  - membership functions $\mu^{(r)}_i$, the parameters $\mathbf{a}^{(r)}_i$, $b^{(r)}_i$
- Modelling errors, noise, and disturbance managed via the fuzzy identification
- The difference $|y(k+1) - F\left(\mathbf{x}(k), \hat{f}(k)\right)|$

  is made arbitrarily small with an appropriate choice of the parameters of the fuzzy models MFs, the regressands, and the number of clusters M

Passive FTC Methods

- **Controller reconfiguration: 2 schemes**
  1. Robust design
  2. Adaptive control (FDD not required)
- **1st approach (passive robustness)**
  - Input-output measurements from the fault- free system
  - Data fuzzy clustering
    1. Takagi-Sugeno prototype identification
    2. Inverse fuzzy model controller identification
  - Validation with fault-free and faulty data

Inverse Fuzzy Control Model

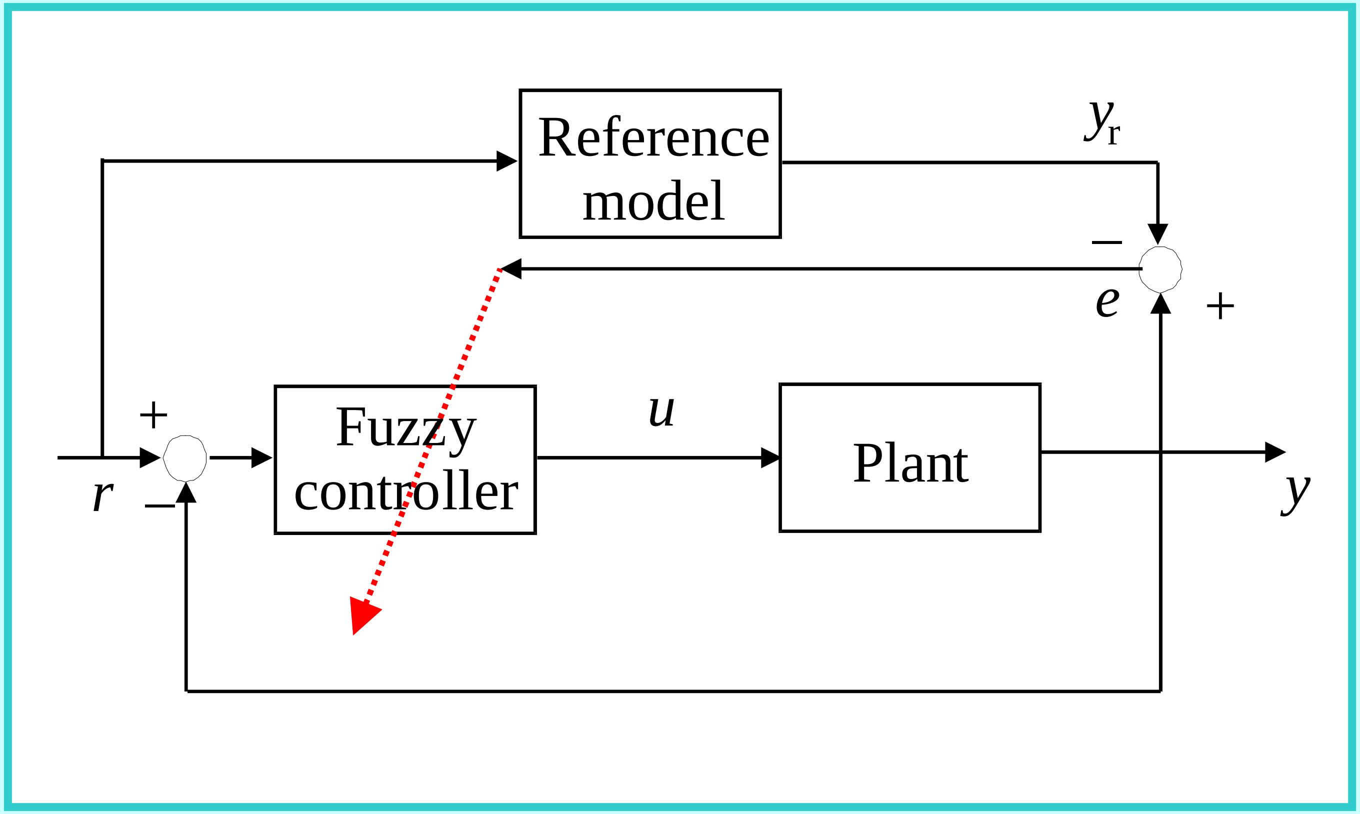


- The controller exploits the current output *y* of the process *(i.e.* its fuzzy model*)* in order to update the internal state *x(k)* of the controller
- Off-line: fast algorithm with the fuzzy model

> - Different schemes: **Reference Model Control** or **on-line adaptation** (see the the 2nd approach, *adaptive*)

Inverse Fuzzy Control Model

- Reference controller model
  - 2 step procedure
- Plant model identification



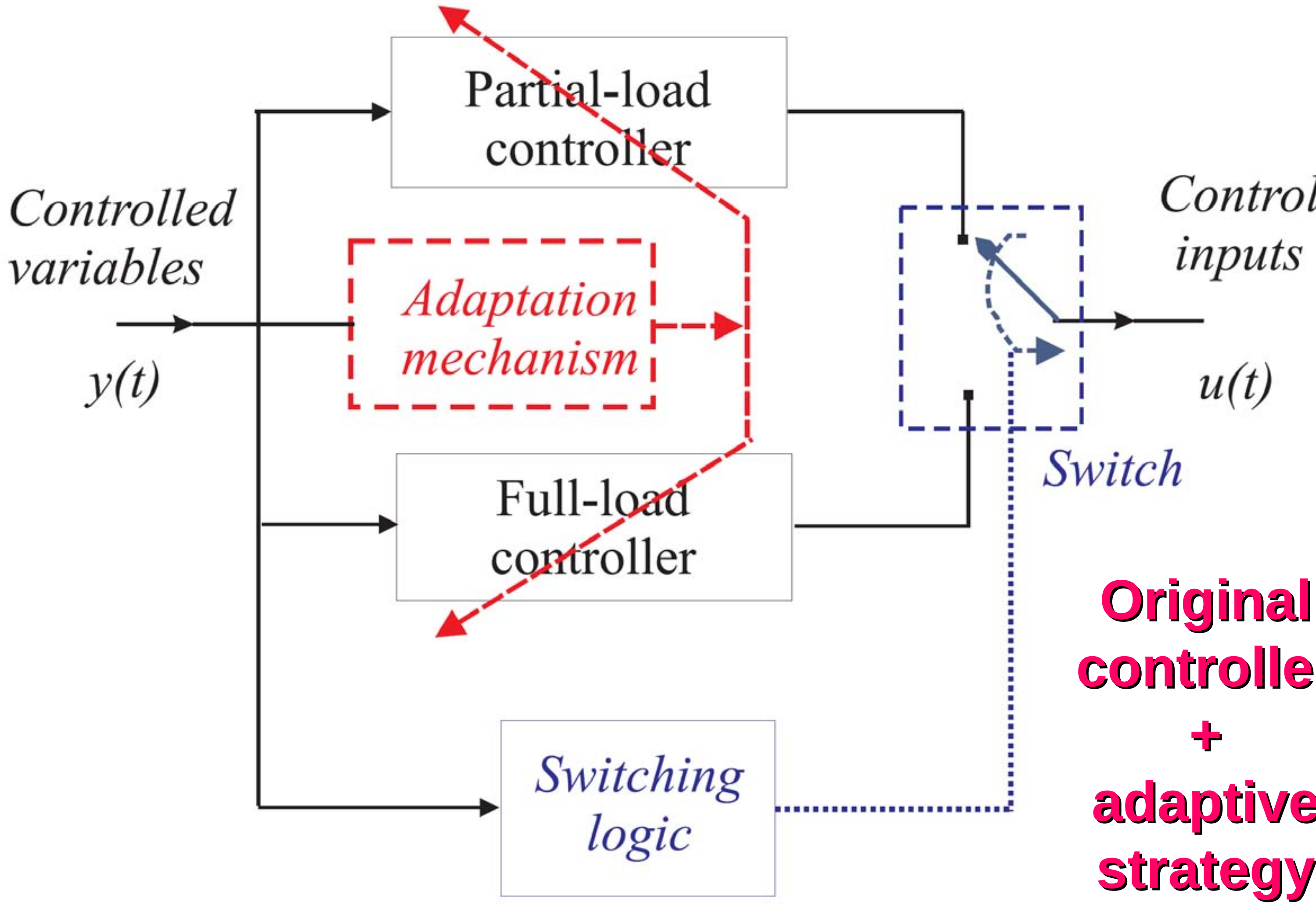
Model Reference Control

- Fuzzy controller estimation

Adaptive FTC (Passive)

- ✓ Input-output fault- free & faulty measurements
- ➢ On-line parametric model identification & model–based adaptive control design
- ✓ Fault–tolerant controller based on adaptive identification schemes
  - On–line estimation of the process, affected by uncertainty & faults
  - Time–varying controller parameters
- ➢ Required control performances maintained
- ➢ Original structure of the controller scheme already implemented can be preserved

Adaptive FTC Diagram



Original controller + adaptive strategy

On-Line Identification

- On-line identification schemes relying on
  - Classical LSM
  - LMS with exponential forgetting
  - **LSM with adaptive directional forgetting**

$$G(z) = \frac{A(z^{-1})}{B(z^{-1})} = \frac{b_1\, z^{-1} + \ldots + b_m\, z^{-m}}{1 + a_1\, z^{-1} + \ldots + a_n\, z^{-n}}\, z^{-d}$$

$$\hat{y}(k) = -\hat{a}_1\, y(k-1) - \ldots - \hat{a}_n\, y(k-n) + \\ + \hat{b}_1\, u(k-1-d) + \ldots + \hat{b}_m\, u(k-m-d)$$

Process model and predicted plant output

Adaptive Control Design

- Process under diagnosis modelled via

$$G(z) = \frac{b_1\, z^{-1} + b_2\, z^{-2}}{1 + a_1\, z^{-1} + a_2\, z^{-2}}$$

$$\Theta_k = \left[\hat{a}_1,\, \hat{a}_2,\, \hat{b}_1,\, \hat{b}_2\right]^T$$

- Discrete-time Ziegler-Nichols controller

$$u(k) = K_p \left[e(k) - e(k-1) + \frac{T_s}{T_I}\, \frac{e(k) - e(k-1)}{2} \right] + \\ +u(k-1)$$

or its feedback representation

$$u(k) = q_0\, e(k) + q_1\, e(k-1) + u(k-1)$$

- K_p & T_I computed from the LTV model parameters

Final Comparisons

- Performance index:

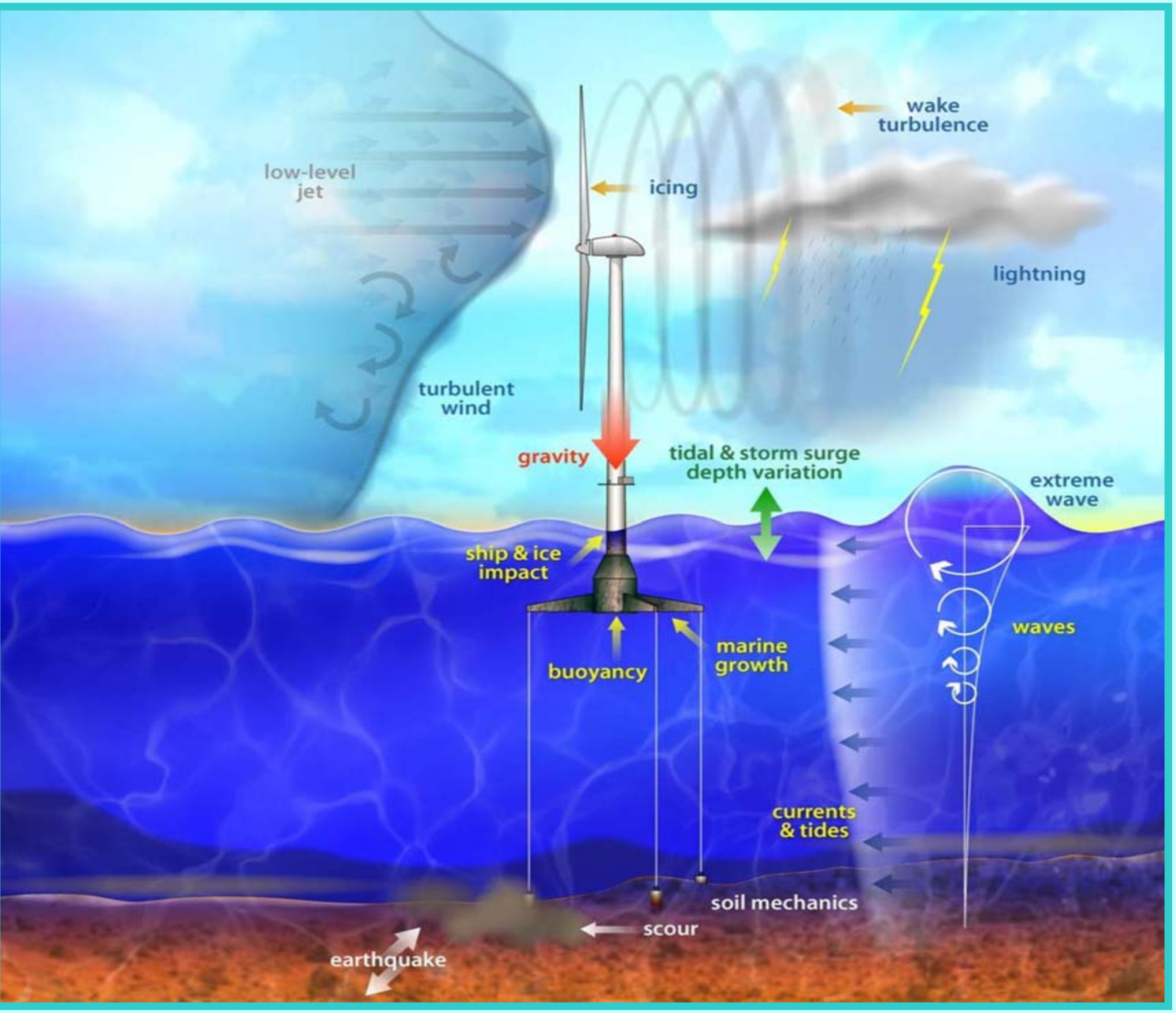
$$NSSE\% = 100 \sqrt{\frac{\sum_{k=1}^{N} \left(r(k) - y(k)\right)^2}{\sum_{k=1}^{N} r^2(k)}}$$

- Comparisons with:

FTC Scheme	Fault case 1	Fault case 2 $NSSE\%$	Fault case 3
Fuzzy identified FDD module & FTC	14.94%	14.37%	14.01%
Analytic disturbance decoupled FTC [1]	14.99%	14.86%	14.34%
PFTCS [2]	40.04%	39.93%	38.98%
Adaptive AFTCS [3]	31.83%	30.94%	29.87%

1. [Simani and P. Castaldi, “Active Actuator Fault Tolerant Control of a Wind Turbine Benchmark Model,” *International Journal of Robust and Nonlinear Control*, vol. 2013, 2013, DOI: 10.1002/rnc.2993]
2. [S. Simani and P. Castaldi, “Data–driven design of fuzzy logic fault tolerant control for a wind turbine benchmark,” in 8th IFAC SAFEPROCESS 2012, 29th – 31st Aug. 2012, pp. 108–113 DOI: 10.3182/20120829-3-MX-2028.00036]
3. [S. Simani and P. Castaldi, “Adaptive fault–tolerant control design approach for a wind turbine benchmark,” in 8th IFAC SAFEPROCESS 2012, 29th – 31st Aug. 2012, pp. 319–324, 1474–6670. DOI: 10.3182/20120829-3-MX-2028.00066]

Modelling Requirements

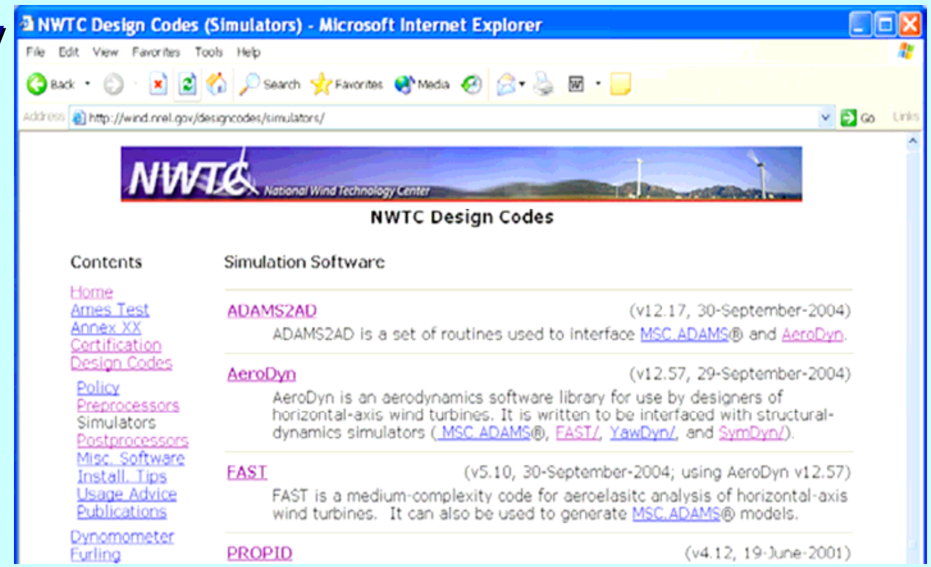


- Coupled aero-hydro-servo-elastic interaction
- Models originate from different disciplines
  - Wind-Inflow
  - Waves
  - Aerodynamics
  - Hydrodynamics
  - Structural dynamics
  - Control systems
- Multi-Physics Simulation Tools

NREL Design Codes

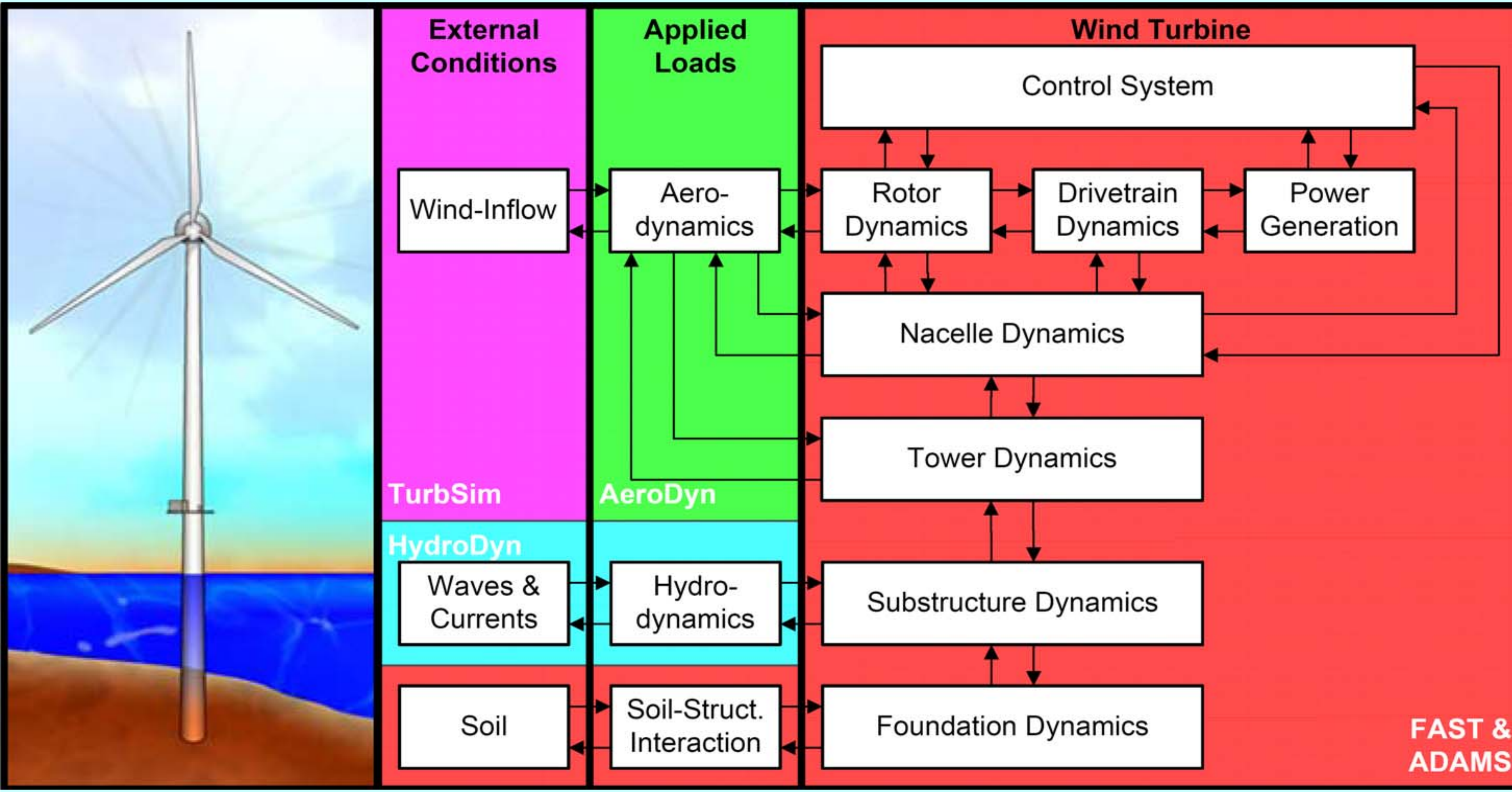
National Renewable Energy Laboratory

- ✓ **http://wind.nrel.gov/designcodes**
  - FAST (Fatigue, Aerodynamics, Structures, and Turbulence) – aeroelasticity
  - TurbSim – turbulent inflow
  - ADAMS (Automatic Dynamic Analysis of Mechanical Systems)
  - NASTRAN – flexible blade model



- ✓ Used heavily in industry, academia and other governmental research organizations
- ✓ Important for control systems design

Design Codes



Coupled Aero-Hydro-Servo-Elastic Simulation

Recent Challenges

- ✓ **Current state-of-the-art design tools**
  - Originate in separate disciplines
- ✓ **Classical modelling tools**
  - Good for turbines that are operating below rated wind speed
  - Structurally stiff
  - Very little yaw
  - Low turbulence
- ✓ **Next generation turbines**
  - Larger and more flexible
  - More accurate models
  - Closer coupling
  - Advanced control schemes

Project Call (1)

- **HORIZON2020**
  http://ec.europa.eu/programmes/horizon2020/en/
- **Call Master**
  http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/master_calls.html
- **Societal Challenges**
  - 10. Secure, clean and efficient energy
  - COMPETITIVE LOW-CARBON ECONOMY (page 40)
  - LCE 2 – 2014/2015: Developing the next generation technologies of renewable electricity and heating/cooling
- *Two stage evaluation process*

Project Call (2)

- **Important/global challenges**
  a) Technology performance needs to increase further and cost of equipment to decrease resulting in a decrease of the overall cost of renewable energy production in order for renewable energy to be attractive in the market and cover a large part of the final energy consumption by 2050.
  b) Resource efficiency and environmental impacts need to be addressed taking a life-cycle perspective.
  c) In order to increase the performance of the energy system as a whole, the particular renewable energy conversion device or renewable energy system will have to address a number of enhancements in delivering energy to the increasingly smarter grid.
  d) Renewable energy technology supply chains and manufacturing processes able to compete globally need to be developed and consolidated.

Project Call (3)

- Specific challenge
  - **Wind energy**: Develop **control strategies** and innovative substructure concepts - There is a need for ***i)* control strategies** and systems for new and/or large rotors and wind farms (on- and offshore); **ii) new innovative** substructure concepts, including floating platforms, to **reduce** production, installation and **O&M costs** for water depths of more than 50m
- Type of action: Research & Innovation Actions

Project Call (4)

- Expected impact
  - Significantly increased technology performance.
  - Improving EU energy security.
  - Making variable renewable electricity generation more predictable and grid friendly, thereby allowing larger amounts of variable output renewable sources in the grid.
  - Bringing cohesion, coherence and strategy in the development of new renewable energy technologies.
  - Increasing the reliability and lifetime while decreasing operation and maintenance costs.
  - …

Discussion Issues (1)

- **Sustainable cOntrol of ofFshore wind Turbines = SOFT?**
- **Aims**
  - Demonstration of the feasibility of novel concepts in fault tolerant control, applied through a demonstrator for very large rotor systems
  - Multi-generator concepts in combination with a FTC concept to handle total generator failure or aging or full-load control with smart blades and distributed FTC structure
  - Involves need for control strategies => FTC reduce operating costs and downtime of a turbine
  - Increasing the wind turbine availability with incorrect sensor readings, due to actual sensor faults or rare operational conditions
- **Focus**
  - Sensors readings: position, blade root bending moment in flap and edge wise directions, rotor speed, azimuth angle, wind speed and wind direction, etc.
  - Incorrect sensors readings due to sensors faults or rare operational conditions
  - Special operational situations could be icing on blades or wind turbine located at sites with very special and problematic wind conditions

Discussion Issues (2)

- **Modelling and tools**
  - Fault/failures in several sensors
  - Independent blade pitch actuation faults
  - Structural loads on the turbine, significant imbalance structural modes
  - Pneumatic and hydraulic system actuators for smart blades
  - Load control/simulation and new actuators
  - Individual pitch control: reducing dynamic loading, periodic in nature, with the dominant load frequency equal to the rotor speed
- Combination of FTC control strategies, novel mechanical/electrical/aerodynamic wind turbine design studies
- Virtual Sensor approach (no controller accommodation)
  - Provides correct measurements
  - Estimates uncertain measurements
- Optimization of the number of sensors, w.r.t. costs and reliability, with the constraints of being x-fault tolerant, shut down times, lost production, …

Discussion Issues (3)

- **Different FTC approaches on real or realistic data**
- **Application**
  - Development and use of a demonstrator of the techniques with important benchmark targets
  - Basic benchmark (kk-electronic)
  - Advanced FAST NREL high-fidelity benchmark
  - Testing of benchmarked designs on real facility

EnDiF (UniFE) General Skills

1. **System Theory/Automatic Control** – Fault diagnosis and fault tolerant control of linear and nonlinear dynamic processes; system modelling, identification and data analysis; linear and nonlinear filtering techniques; fuzzy logic and neural networks for modelling and control; as well as the interaction issues among identification, fault diagnosis, and fault tolerant control
2. **Optimization** – Numerical algorithms for large-scale nonlinear optimization problems; Numerical algorithms for specially structured nonlinear systems; modelling and simulation of mechatronic systems
3. **Aerospace/Aerodynamics** – Aircraft & spacecraft modelling and simulation, FDI, FTC; navigation, guidance & control for general aviation aircrafts, UAS and satellites; methodologies for landing in wind shear conditions

EnDiF (UniFE) Project Roles

- **Dynamic process modelling and identification**
  - Data-driven schemes (linear parametric, fuzzy, neural networks)
- **Fault Tolerant Control**
  - Data-driven approaches
  - Purely nonlinear methods
- **Integration of fault estimation schemes with the controller reconfiguration/accommodation**
  - Active, Passive and adaptive FTC methods
- **Nonlinear filters for fault estimation**
  1. Nonlinear geometric approach + (adaptive) RBF-NN
  2. Directly identified from the input–output data

Concluding Remarks

- **EU - FP7**: in general, theoretical methodologies applied to benchmarks/simulators
- For **HORIZON2020** may not be enough!
  - **Strong points**
    - Industrial partner(s) required
    - Theory applied to *real* example(s)
    - Industrial parter is the project leader
  - **Weak points**
    - Experts should give the maximum score
    - Experts will evaluate on the basis of the **criteria ‘excellence’, ‘impact’ and ‘quality & efficiency of the implementation’** (see General Annex, part H)

References

1. P. Castaldi, W. Geri, M. Bonfè, S. Simani, and M. Benini, “Design of residual generators and adaptive filters for the FDI of aircraft model sensors,” *Control Engineering Practice*, vol. 18, pp. 449–459, May 2010.DOI: 10.1016/j.conengprac.2008.11.006.
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3. S. Simani, P. Castaldi, and A. Tilli, “Data–driven Modelling of a Wind Turbine Benchmark for Fault Diagnosis Application,” *Transaction on Control and Mechanical Systems*, vol. 1, pp. 278–289, November 2012. Transaction Series on Engineering Science and Technologies. Journal Code: E220088. Available at: http://tsest.org/index.php/TCMS/article/view/107.
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5. S. Simani and P. Castaldi, “Active Actuator Fault Tolerant Control of a Wind Turbine Benchmark Model,” *International Journal of Robust and Nonlinear Control*, vol. 2013, 2013. DOI: 10.1002/rnc.2993.
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