RTFs in fusion experiments

A plasma control experts' perspective

Future Improvements in Realtime Systems and Technologies (FIRST 2019)

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Cosylab - Ljubljana, Jan, 21st 2019

UNIVERSITA' DEGLI STUDI DI NAPOLI FEDERICO II
DIETI.
DIPARTIMENTO DI INGEGNERIA ELETTRICA E DELLE TECNOLOGIE DELL'INFORMAZIONE

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- **I need to thank all the colleagues together with whom I had the honor and pleasure to work, for everything you may find useful in this presentation**

Outline

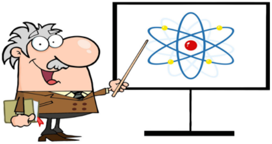
1. Development real-time systems in fusion experiments
   - The main characters
   - Automatic code generation
   - Model validation

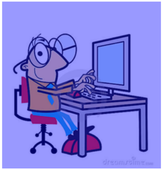
2. Standard control architecture for ITER-like machines

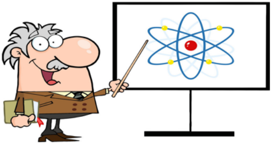
3. Conclusions & discussion points

The main characters

The CODAC expert (The Good), the Scientist (The Bad) and the Control Expert (The Ugly)







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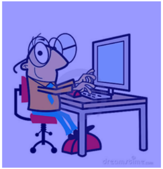

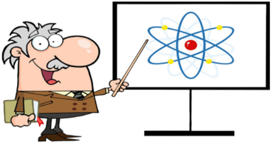

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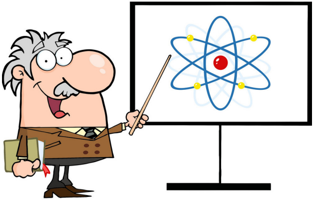
- **The Control Expert**
  - works in a research institute or university
  - sometimes he/she does not have a strong knowledge of the domain
  - many times he/she knows nothing about RTF...
  - ...but he/she claims to be **THE** expert

- The three *roles* could overlap



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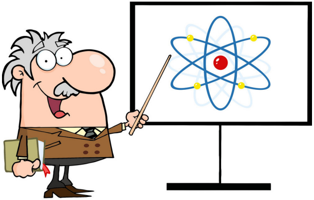

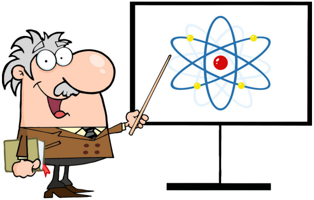

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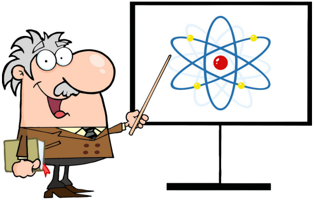

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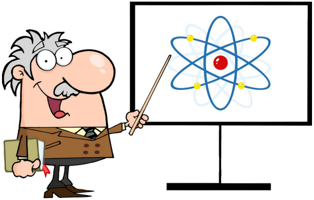

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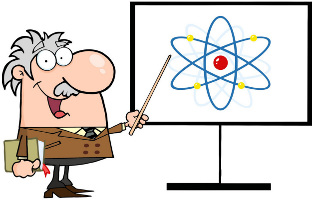

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  - does not want to *loose time* on the details of the RTF infrastructure/architecture

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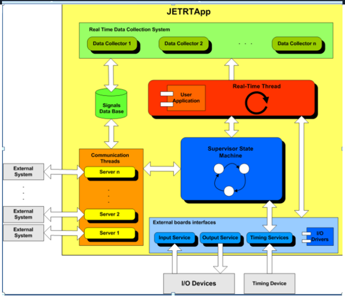
- We need to learn how to leave with The Ugly, minimising the effort needed to get his amazing control algorithm

To confine (as much as possible) the Ugly



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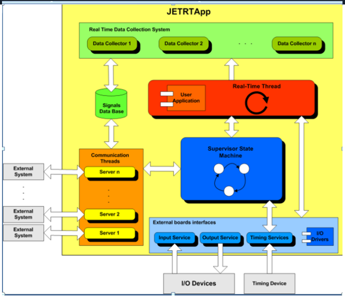

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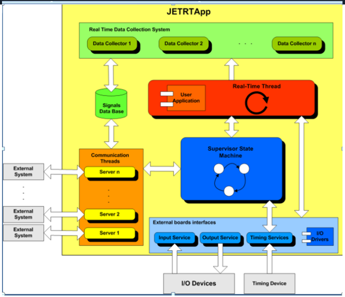

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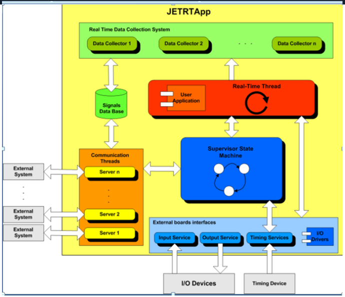

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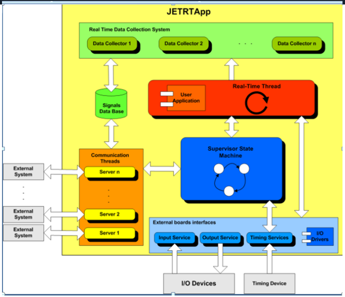

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- . . . similar concept in the ITER RTF

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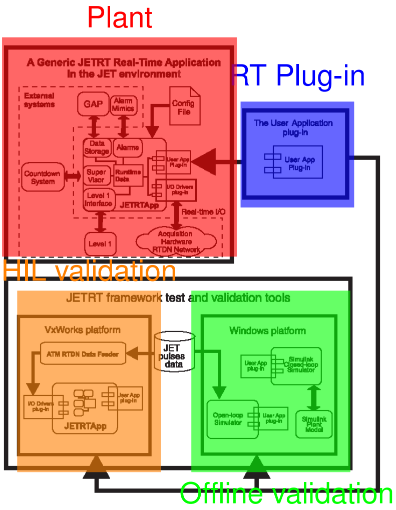
A **Real-time Application Plug-in** that can be used:

- to perform offline validation against a plat model
- to perform real-time validation with hardware-in-the-loop
- to run the real-time system on the plant



Automatic code generation

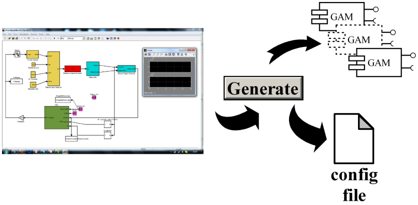


Figure: Old idea (never implemented, AFAIK).

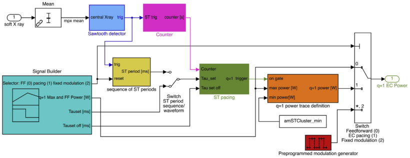


Figure: Taken from Felici et al., FED, 2014.

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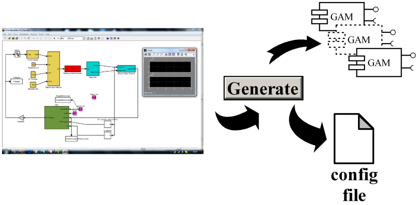

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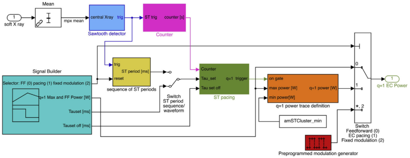

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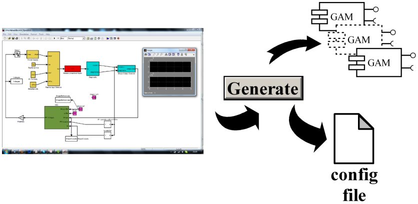

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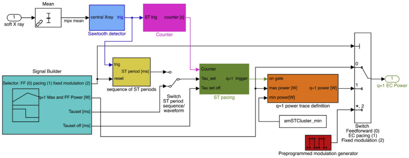

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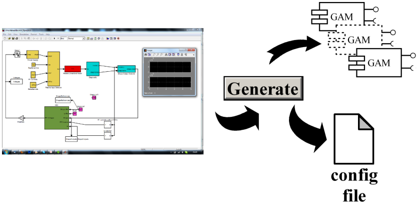

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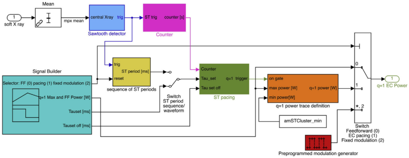

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- So far, little effort has been put **on this aspect**
- The needed effort is not negligible
- **Generally, the effort to develop a *robust* PCS simulation platform for ITER is not negligible**
- The development of such a platform should not be left only to The Ugly(ies) **(remember the disclaimer!)**

More references

F. Felici et al.
Development of real-time plasma analysis and control algorithms for the TCV tokamak using Simulink
Fus. Eng. Des., 2014

M. L. Walker et al.,
A simulation environment for ITER PCS development
Fus. Eng. Des., 2014

More on automatic code generation. . .

- It works mainly for (simple) control algorithms
  - what about control algorithms that requires online solution of optimization problems?
  - what about *support functions* (ITER jargon for diagnostic functions *et similia*)?

MPC example

S. Gerkšič et al.
Model predictive control of ITER plasma current and shape using singular value decomposition
Fus. Eng. Des., 2018

M. Perne et al.,
Soft inequality constraints in gradient method and fast gradient method for quadratic programming
Opt. Eng., 2018

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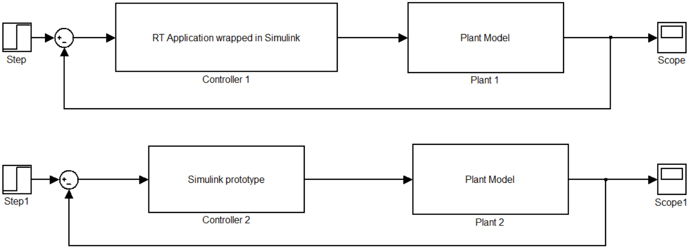
  - to trust automatic code generation, when available

The *inverse process*



Embedding RTF code into Simulink

- In most of the cases to check the real-time version of the controller it is convenient to run it against the plant model in the Simulink environment.
- The real-time version and the Simulink version of the system can be run in *parallel* in order to perform the validation

Example: commissioning of the ITER-like VS at EAST

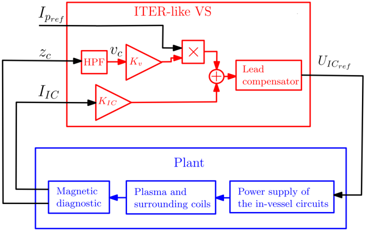


Figure: ITER-like vertical stabilization controller.

$$U_{IC_{ref}}(s) = \frac{1+s\tau_1}{1+s\tau_2} \cdot \left(K_v \cdot \bar{I}_{p_{ref}} \cdot \frac{s}{1+s\tau_z} \cdot Z_c(s) + K_{IC} \cdot I_{IC}(s) \right)$$

CREATE

3. *Commissioning procedure*

3.1 Commissioning of the voltage-driven VS system

This section describes the commissioning procedure for the voltage-driven VS system.

3.1.1 Pre-requisites for the voltage-driven VS commissioning

The following systems/services are required and must be successfully commissioned before the VS commissioning:

1. PFC current control system.
2. Plasma current control system.
3. Bang-bang voltage-driven VS controller.

Furthermore:

4. The **reference pulse 52444** should be reproduced under the current machine configuration.
5. The code that implements the control algorithm (1) should be validated against its Simulink version.

Item 5 will be performed once the CREATE team will be onsite.

Figure: Excerpts of the ITER-like VS commissioning procedure.

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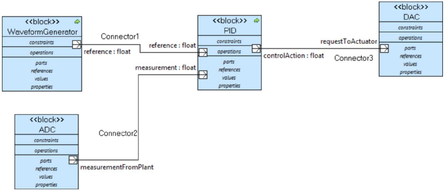
  - Example: model your system in SysML and automatically generate the RTF configuration



An incomplete example for FTU

G. De Tommasi et al.,
Modeling of MARTe-Based Real-Time Applications With SysML
IEEE Trans. Ind. Inf., 2013

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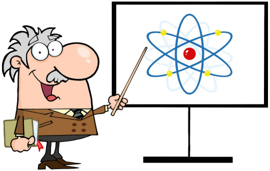

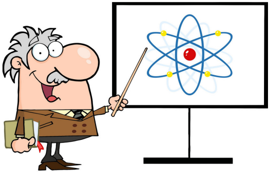

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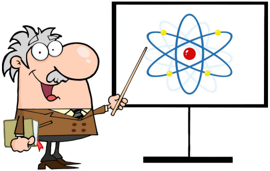

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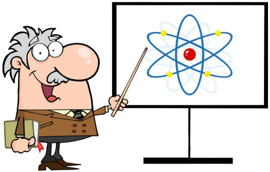
  - These models are indeed used for the design of the control algorithm
  - In order to assess (robust) performance a more complex model is desirable, which takes into account the *peculiarities* (nonlinearities) of the diagnostic and/or actuators



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- **Control-oriented models** are (simple) linear and time-invariant; the overall plant model is obtained exploiting simplifying assumptions
  - These models are indeed used for the design of the control algorithm
  - In order to assess (robust) performance a more complex model is desirable, which takes into account the *peculiarities* (nonlinearities) of the diagnostic and/or actuators
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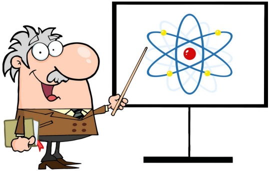

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- **The *inverse process* is useful also to validate the control-oriented models**

Embedding support functions in the Ugly's simulation suite

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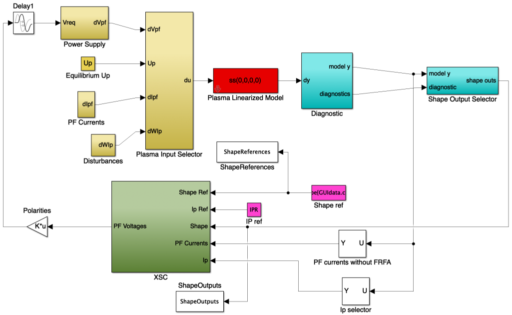
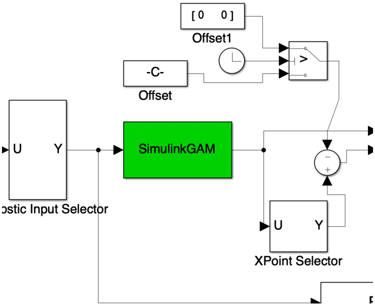
  - **Usually requires *ad hoc* coding**
  - **It would be nice to have the inverse option in the RTF**

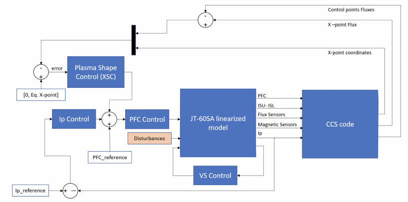
- Plasma shape controller designed on a linear approximation of the *gaps* behavior
- Validation in closed-loop using the real-time code for plasma boundary reconstruction *wrapped* into a S-function
- **Some work needed, but ok (modularity and separation of MARTe were exploited)**





The JT-60SA CCS case

- Objective: preliminary assessment of the effect of the measurement noise on plasma boundary reconstruction
- QST colleagues provided the Cauchy Condition Surface (CCS) code
- Fortran compiled as an executable that runs only on Linux and I/O with text files
- **Closed-loop simulations take ages! KO**



A2. How to run CCS

Binary of CCS: ccs_sa
Sample shell script for running binary of CCS: run.csh

[If you implement CCS with CREATE]

1. CREATE make “fort.70” in reference to inner plasma equilibrium and “fort.21” provided by QST magnetic controller
2. Run “ccs_sa”
3. CREATE read controlled variables and so on from “fort.71” which is output of binary of CCS

- Although their are simple, the linear models need to be validated and *tuned* on the experiment
- This experimental validation is an important step to be carried out before starting the design of *advanced model-based controller*

Validation of the Ugly's modelling tools

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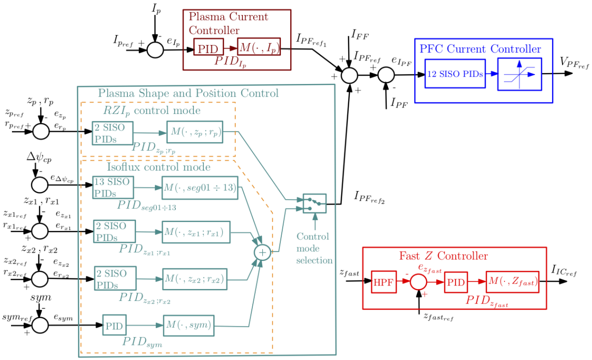
  - Advanced controller = whatever *more* than a PI experimentally tuned
- Both open-loop and closed-loop validations are needed
- **Closed-loop validation is important when dealing with unstable plants**

- In order to validate/tune the CREATE plasma/tokamak linear model a campaign of simulations was carried out

Validation of EAST magnetic model

- In order to validate/tune the CREATE plasma/tokamak linear model a campaign of simulations was carried out
- Since EAST colleagues **did not** provide a Simulink version of the existing controllers. . .
  1. Back engineering of the existing magnetic control system
     A LOT OF TIME
  2. Tuning of the model
  3. Design of new controllers
  4. Something not working because changes have been made in the EAST PCS (new control modes, new bumpless transfer, . . .)? $\rightarrow$ **go back to 1**

Back engineering the EAST magnetic control system



Q. P. Yuan et al.
Plasma current, position and shape feedback control on EAST
Nucl. Fus., 2013

A. Castaldo et al.
Simulation suite for plasma magnetic control at EAST tokamak
Fus. Eng. Des., 2018

Open-loop model validation

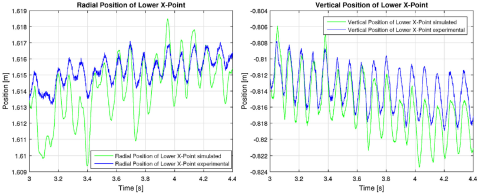


Fig. 6. Comparison between simulated (green solid line) and experimental (blue solid line) plasma Lower X-point radial (left figure) and vertical (right figure) position for pulse #69449. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

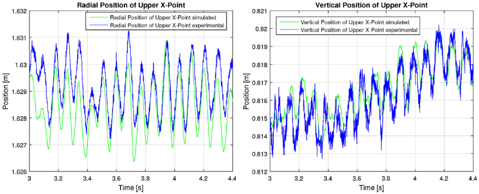


Fig. 7. Comparison between simulated (green solid line) and experimental (blue solid line) plasma Upper X-point radial (left figure) and vertical (right figure) position for pulse #69449. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

A. Castaldo et al.
Simulation suite for plasma magnetic control at EAST tokamak
Fus. Eng. Des., 2018

Open-loop EAST controller validation

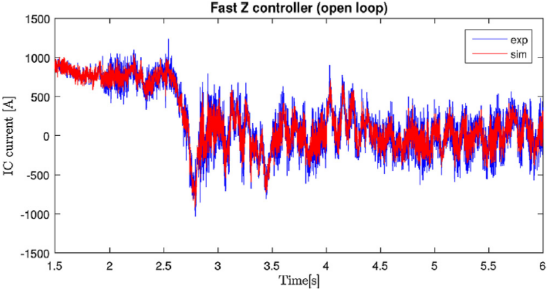


Fig. 12. Fast Z controller (including the high pass filter) output for pulse #74104. The small discrepancies are due to a subsampling of the experimental feedback signal.

A. Castaldo et al.
Simulation suite for plasma magnetic control at EAST tokamak
Fus. Eng. Des., 2018

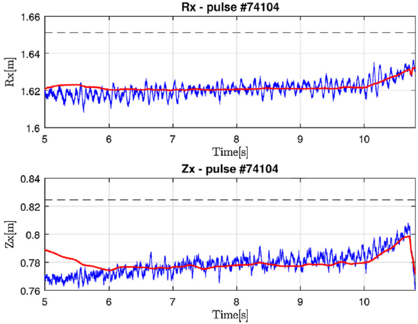
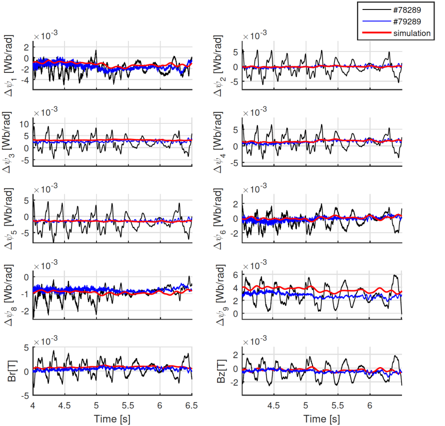


Fig. 14. Simulated and experimental X-point position for pulse #74104, obtained with the existing EAST controller. The experimental signal is shown in blue, while the simulated one is in red. The dashed black line shows the reference signal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

A. Castaldo et al.
Simulation suite for plasma magnetic control at EAST tokamak
Fus. Eng. Des., 2018

Model-based controller tuning



A. Mele et al.

MIMO shape control at EAST tokamak: simulations and experiments

30th Symposium on Fusion Technology (SOFT), 2018

Filling RTFs with control algorithms

- RTFs are one part of the whole story
- There are also control algorithms and support functions

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- **Why CODAC Experts (The Good) should leave the fun only to the Control Experts (The Ugly)?**
- **Standard control algorithms (and support functions) should come together with the RTF (GA PCS approach)**
- **The Control Expert can still play with advanced control algorithms (The Ugly becomes The Man With The Rifle)**

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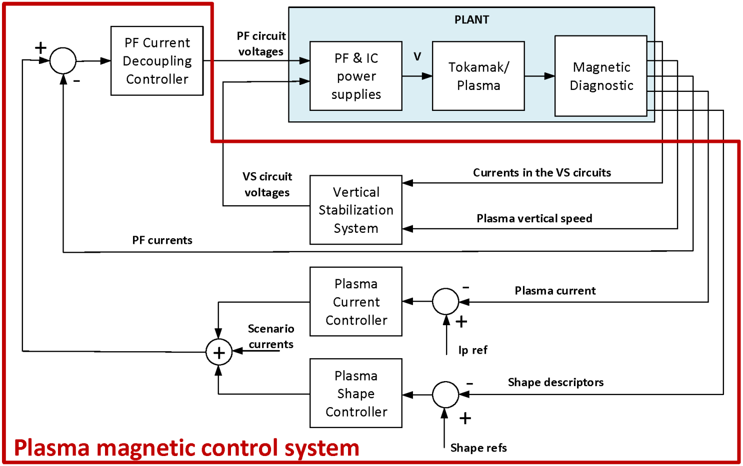
  - → the design procedures relies on (validated) control-oriented models for the response of the plasma and of the surrounding conductive structures
- The proposal is based on the JET experience
- The architecture has been proposed for ITER & JT-60SA (& DEMO) and has been partially deployed at EAST (ongoing activity)

G. De Tommasi
Plasma Magnetic Control in Tokamak Devices
J. Fus. Energy, 2018

A possible architecture - 1/2



A possible architecture - 2/2

- **Include *standard* algorithms for each controllers of the architecture**
  - Current decoupling controller
  - Vertical stabilization controller
  - Plasma current controller
  - Plasma shape controller

Conclusions - Discussion points

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  - Example: **in my view** EU contribution to JT-60SA may be affected by the lack of these (and other) features
- It may be the case to invest not only on RTFs, but also on *standard* control algorithms (as GA PCS)

. . .I hope that The Ugly will appear a little less ugly to The Good

RTFs in fusion experiments

A plasma control experts' perspective

Future Improvements in Realtime Systems and Technologies (FIRST 2019)

Gianmaria De Tommasi
Email: detommas@unina.it

Cosylab - Ljubljana, Jan, 21st 2019

Thank you!

DIETI. UNIVERSITA' DEGLI STUDI DI NAPOLI FEDERICO II
DIPARTIMENTO DI INGEGNERIA ELETTRICA E DELLE TECNOLOGIE DELL'INFORMAZIONE