Plasma Current, Position and Shape Control
Hands-on Session
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Outline

Plasma Magnetic Control Design for the JET tokamak

- Introduction
- PF Currents Controller
- Plasma Current Controller
- Plasma Current Controller

Rapid prototyping of control systems for the ITER tokamak

- Motivations
- Rapid prototyping of CSS at ITER
- Experimental setup

Material

All the material (slides + source code) can be downloaded from

http://wpage.unina.it/detommas/iiss.html

Plasma current and shape control

- This hand-on session focuses on:
  1. PF Current Control
  2. Plasma Current Control
  3. Plasma Shape Control (in an *XSC-flavor*)
- The JET tokamak will be considered
- We will assume the plasma is vertically stabilized on a faster timescale (wrt the current and shape control time scale)

Plasma linearized model of JET tokamak

The linearized plasma model used in this session is

$$\begin{aligned}\delta\dot{x} &= A\delta x + B\delta u\\ \delta y &= C\delta x\end{aligned}$$

where the state and input vectors are given by

$$\delta x = \begin{pmatrix} \delta I_{PF} \\ \delta I_p \end{pmatrix} \quad \text{and} \quad \delta u = \begin{pmatrix} \delta V_{PF} \\ \delta V_p \end{pmatrix}$$

- δI_{PF}, δV_{PF} are the PF current and voltage variations
- δI_p, δV_p are the plasma current and loop-voltage variations

Model Outputs

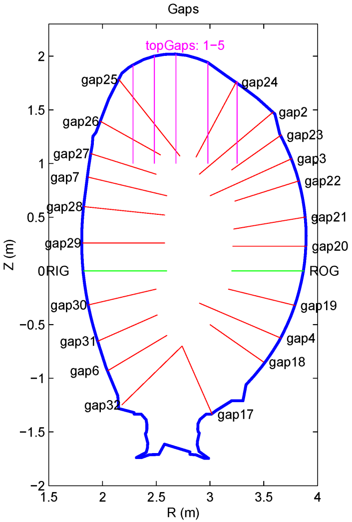
The output vector is equal to

$$\delta y = \begin{pmatrix} \delta I_{PF} \\ \delta I_p \\ \delta g \end{pmatrix}$$

where δg holds the plasma shape descriptors, i.e.

- gaps
- strike-points
- x-points

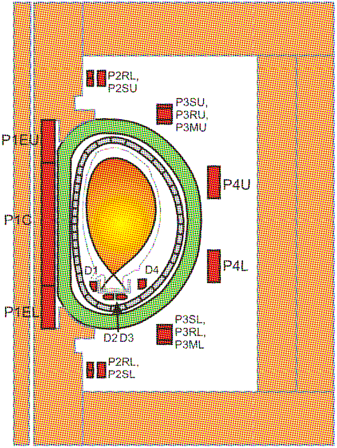
Plasma shape descriptors at JET



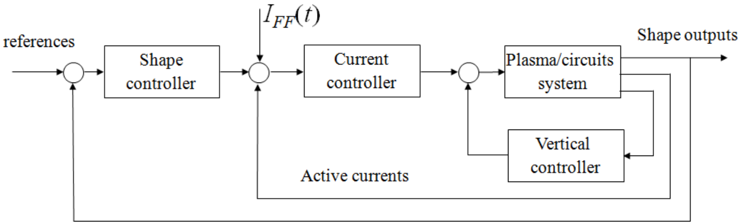
JET PF circuits

The 9 currents in the PF coils are

- I_{P1} - current in the $P1$ circuit
- I_{P4T} - current in the $P4$ circuit
- I_{IMB} - imbalance current in the $P4$ circuit
- I_{PFX} - current in the FX circuit
- I_{SHP} - current in the shaping circuit
- I_{D1} , I_{D2} , I_{D3} , I_{D4} - currents in the divertor coils



Reference Control Scheme



- SC generates current references
- A PF currents controller must be designed

JET Current Controller

Plasmaless model

$$\mathbf{V}_{PF} = \begin{bmatrix} L_1 & M_{12} & \dots & M_{1N} \\ M_{12} & L_2 & \dots & M_{2N} \\ \dots & \dots & \dots & \dots \\ M_{1N} & M_{2N} & \dots & L_N \end{bmatrix} \frac{\mathrm{d}\mathbf{I}_{PF}}{\mathrm{d}t} + \begin{bmatrix} R_1 & 0 & \dots & 0 \\ 0 & R_2 & 0 & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & R_N \end{bmatrix} \mathbf{I}_{PF}$$

Resistive compensation

$$\mathbf{V}_{PF_{ref}} = \hat{\mathbf{R}}\mathbf{I}_{PF} + \mathbf{K}(\mathbf{Y}_{ref} - \mathbf{Y})$$

Static relationship between PF coils current and controlled variables

$$\mathbf{Y} = \mathbf{T}\mathbf{I}_{PF}$$

Control Matrix

$$\mathbf{K} = \hat{\mathbf{M}}\mathbf{T}^{-1}\Lambda^{-1} \text{ with } \Lambda \text{ diagonal matrix}$$

JET Shape Controller

Closed-loop system

$$\mathbf{M}\mathbf{T}^{-1}\dot{\mathbf{Y}} + \mathbf{R}\mathbf{I}_{PF} = \mathbf{M}\mathbf{T}^{-1}\Lambda^{-1}(\mathbf{Y}_{ref} - \mathbf{Y}) + \mathbf{R}\mathbf{I}_{PF} \Rightarrow$$
$$\Rightarrow \; \dot{\mathbf{Y}} = \Lambda^{-1}(\mathbf{Y}_{ref} - \mathbf{Y})$$

By a proper choice of the **T** matrix it is possible to achieve:

- current control mode
- plasma current control mode
- gap control mode

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Plasma current model

A simplified model of the plasma current circuit is considered

- plasma resistance is neglected
- only the mutual inductance with the *P1* circuit is retained

The following broadly valid linear model can be derived

$$\dot{I}_p(t) = -c\dot{I}_{P1}(t)\,, \quad \text{with } c > 0\,.$$

eXtreme Shape Controller (XSC)

- The *eXtreme Shape Controller* (XSC) controls the whole plasma shape, specified as a set of 32 geometrical descriptors, calculating the PF coil current references.
- Let $\mathbf{I}_{PF_N}(t)$ be the PF currents normalized to the equilibrium plasma current, it is

  $$\delta\mathbf{g}(t) = \mathbf{C}\ \delta\mathbf{I}_{PF_N}(t).$$

  It follows that the plasma boundary descriptors have the same dynamic response of the PF currents.
- The XSC design has been based on the **C** matrix. Since the number of independent control variables is less than the number of outputs to regulate, it is not possible to track a generic set of references with zero steady-state error.

  $$\delta\mathbf{I}_{PF_{N_{req}}} = \mathbf{C}^{\dagger}\delta\mathbf{g}_{error}$$

eXtreme Shape Controller (XSC)

- The XSC has then been implemented introducing weight matrices both for the geometrical descriptors and for the PF coil currents.
- The determination of the controller gains is based on the Singular Value Decomposition (SVD) of the following weighted output matrix:

  $$\widetilde{\mathbf{C}} = \widetilde{\mathbf{Q}}\,\mathbf{C}\,\widetilde{\mathbf{R}}^{-1} = \widetilde{\mathbf{U}}\,\widetilde{\mathbf{S}}\,\widetilde{\mathbf{V}}^{T},$$

  where $\widetilde{\mathbf{Q}}$ and $\widetilde{\mathbf{R}}$ are two diagonal matrices.
- The XSC minimizes the cost function

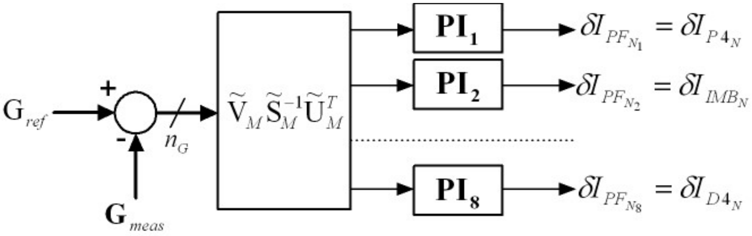
  $$\widetilde{J}_1 = \lim_{t\to+\infty} \left(\delta\mathbf{g}_{ref} - \delta\mathbf{g}(t)\right)^T \widetilde{\mathbf{Q}}^T \widetilde{\mathbf{Q}} \left(\delta\mathbf{g}_{ref} - \delta\mathbf{g}(t)\right),$$

  using $\bar{n} < 8$ degrees of freedom, while the remaining $8 - \bar{n}$ degrees of freedom are exploited to minimize

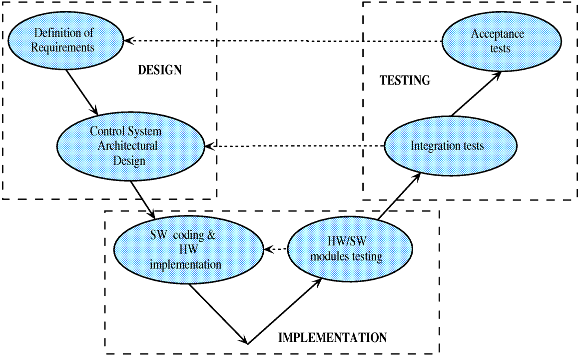
  $$\widetilde{J}_2 = \lim_{t\to+\infty} \delta\mathbf{I}_{PF_N}(t)^T \widetilde{\mathbf{R}}^T \widetilde{\mathbf{R}} \delta\mathbf{I}_{PF_N}(t).$$

  (it contributes to avoid PF current saturations)

XSC - Gap controller



Development of control systems – V Cycle 1/2



Definition of Requirements

DESIGN

Control System Architectural Design

Acceptance tests

TESTING

Integration tests

SW coding & HW implementation

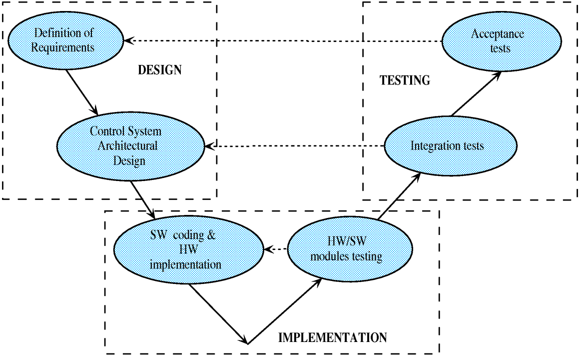
HW/SW modules testing

IMPLEMENTATION

The traditional development cycle of control systems follows the **three** phases:

- design
- implementation
- testing

Development of control systems – V Cycle 2/2



- the design phase ends with the functional requirement specification;
- the implementation phase starts with the software requirements;
- the test and validation phase is **mainly carried out on-site**.

Motivations

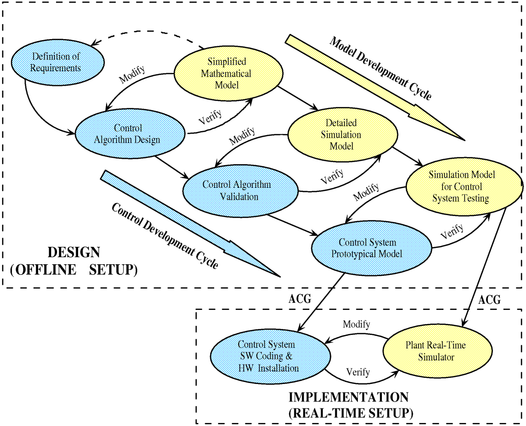
Due to the additional efforts and costs, often the architectural design is carried out without any modeling and simulation support.
However, if

- the system to be controlled is *non-conventional* or new;
- the required performances are very demanding;
- the plant is not yet available and/or the testing on-site is very risky;

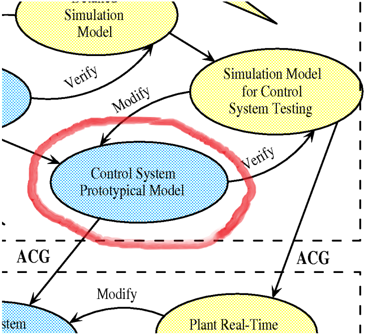
then the use of modeling and simulation tools during the design phase becomes highly recommended.

Design aided with modeling, simulation and rapid prototyping tools

For the design and development of a critical system, it is more appropriate to resort to modeling, simulation and rapid prototyping tools.

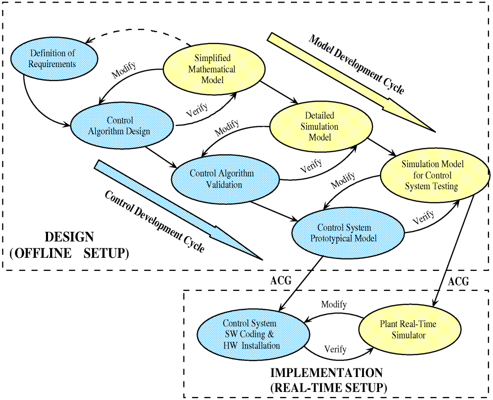


Prototype of the control system as formal description of the requirements



- The high-level description of the prototype represents an unambiguous description of the control system behavior.
- It can be used as formal specification of the requirements.

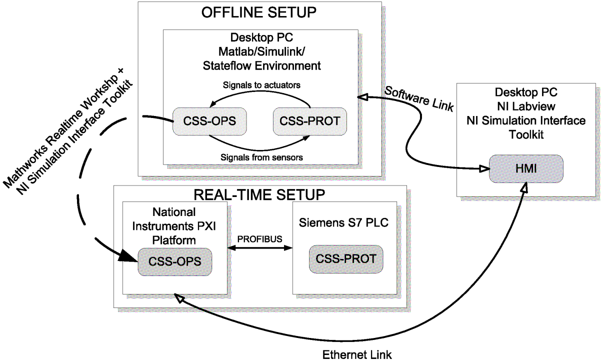
Tools



The proposed approach is based on the availability of

- several plant models (at different level of details)
- **automatic tools** for the rapid prototyping of both control systems and plant models

Setup 1/3



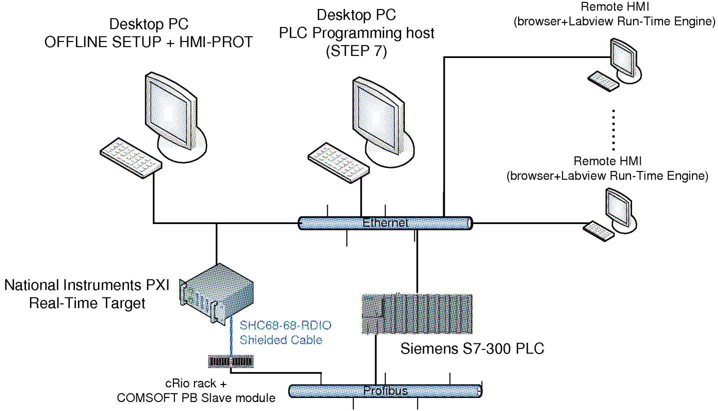
Two operational setups have been provided

- the *offline setup* to perform the design of the control system,
- the *real-time setup* whereto perform test and validation with hardware-in-the-loop (HIL) simulations.

Setup 2/3

- A simplified model of both the plant (CSS-OPS) and of the controller (CCS-PROT) have been developed in the Matlab/Simulink environment.
- Exploiting the Labview Simulation Interface Toolkit (SIT) we:
    - Develop a common Human-Machine Interface both for the *offline* and for the *real-time* (that can be accessed even remotely, thanks to a web server application)
    - Deploy the plant on a PXI Real-Time target to perform HIL simulations with a PLC-based controller

Experimental setup deployed at ITER for the rapid prototyping of the CSS



Desktop PC
OFFLINE SETUP + HMI-PROT

Desktop PC
PLC Programming host
(STEP 7)

Remote HMI
(browser+Labview Run-Time Engine)

Remote HMI
(browser+Labview Run-Time Engine)

Ethernet

National Instruments PXI
Real-Time Target

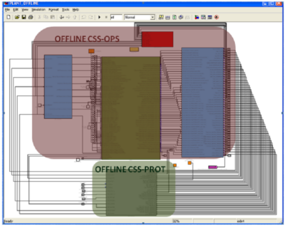
SHC68-68-RDIO
Shielded Cable

Siemens S7-300 PLC

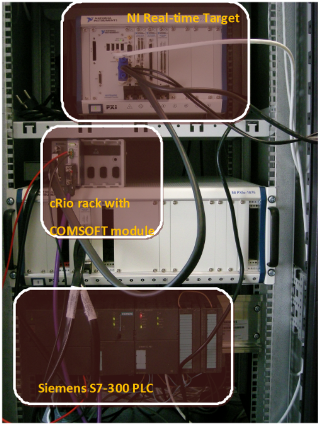
cRio rack +
COMSOFT PB Slave module

Profibus

Rapid prototyping via NI Labivew SIT



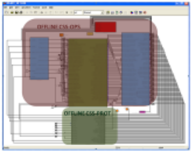
Labview SIT



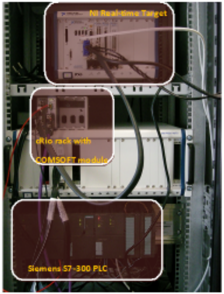
Common HMI with Labview

Local or Remote (via Labview Runtime Engine)

Offline environment



NI Real-time target



CSS Rapid prototyping - Reference

More details can be found in

G. Ambrosino et al.
Rapid Prototyping of Safety System for Nuclear Risks of the ITER Tokamak
IEEE Transactions on Plasma Science, accepted for publication, Jul. 2010.