Real-time Systems in Tokamak Devices. A case study: the JET Tokamak May 25, 2010

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Outline

Introduction

Overview of the JET Real-Time Infrastructure

- Real-Time Data Network
- The MARTe Real-Time Framework

Model-based Design and Validation of Real-Time Systems

- The eXtreme Shape Controller Experience

JET Real-Time Systems: Examples

- The new Vertical Stabilization System
- The Error Field Correction Coils Controller
- The BetaLi Diagnostic

Motivations

- Today's tokamak reactors are **experimental devices**
- The achievement of the required performance is strictly dependent on the **flexibility** and **reliability** of the real-time system that operate the plant
- There are some **common requirements** that have to be taken into account during the design of the real-time infrastructure

. . . but the main aim. . .

is to reduce the time needed for the commissioning of new real-time systems on the plant

Common requirements

Hardware side

- cope with the unavoidable hardware obsolescence and maintenance requirements (experiments last several decades)
- be as **hardware independent** as possible
- be **scalable** to manage the increase in computational requirements
- share resources between the processing nodes (e.g. to share the plant measurements and the outputs of each processing node)

Software side

- establish strict and well defined boundaries between the application algorithm and the interfaces with other plant systems $\rightarrow$ facilitate testing and validation
- support **model-based development** $\rightarrow$ software validation against plant models $\rightarrow$ minimization of the risks and of commissioning/debugging efforts
- guarantee **low latency and low jitter** in control cycle

Main plasma control systems at JET

Magnetic Control

- Plasma Position and Current Control (PPCC)

Density Control

- Plasma Density Control
- Gas Introduction plant

Additional Heating & Current Drive Control

Plant systems of:

- Neutral Beam Injection
- Ion Cyclotron Heating
- Lower Hybrid Current Drive

have been recently modified to switch from open-loop to closed-loop control of power requests.

Plant Safety Systems

System for the protection of the investments (e.g. WALLS for thermal protection of the tokamak first wall)

Distributed architecture

- The systems are large and complex
- The signal processing in many systems is itself quite complex.
- The processing is distributed among different nodes

This distribution of the calculations over separate systems has benefits for basic functionality, minimizing impact on other systems when internal changes are performed in an individual node

JET Plant Systems

Each system is designed to have:

1. **high cohesion** - it has everything it needs in its own domain and does not overlap other domains
2. **low coupling** - it has all the inputs and outputs essential for the global operation

Real-Time Data Network (RTDN)

- The present real-time network was setup about 10 years ago
- It is an ATM/AAL5 communications on 155 MHz fibre-optic
- Each system sends *application specific* datagrams into the network, known as the *Real-Time Data Network*
- Cross-platform interoperability is guaranteed
- The network switch distributes the datagrams
- The ATM network provides one-to-many connections

- **Currently there are more than 30 systems, 40 datagram types, and a total of more than 500 signals**
- **Typical latency is in the order of $100\ \mu s$, which is sufficient for JET fastest cycle time of $2\ ms$**

A new framework for RT applications

Motivation

- In 2001/2002 the revamping of the SC was planned in order to add the eXtreme Shape Controller algorithm (XSC)
- Within the PPCC group, it was decided to move to a common framework for the development of real-time applications

Aims

- Standardize the development of real-time applications
- Increase the code reusability
- Give the possibility to separate the user application from the software required to interface with the plant infrastructure
- Reduce the time needed for commissioning.

Requirements

The new framework would have been:

- portable (multi-OS and multi-platform)
- modular – the user application would have been easily *plugged* into an executor of real-time application
- written in C++ (at that time C++ was not a JET *standard*)

MARTe framework

The **MARTe** framework is:

- Multi-platform C++ middleware
- Modular
  - Clear boundary between algorithms, hardware interaction and system configuration
  - Reusability and maintainability
  - Simulation
- Minimize constraints with the operational environments (portability)
- Data driven
- Provide live introspection tools
  - Without sacrificing RT

A. C. Neto et al.,
MARTe: a Multi-Platform Real-Time Framework,
IEEE Transactions on Nuclear Science, vol. 57(2), Apr. 2010

Modeling in real-time system design and validation

Modeling helps you ...

- to define control system requirements
- to design the control algorithms
- to make performance analyses
- to validate real-time implementation of the control systems
- to perform offline analyses to forecast experimental behaviour

Plasma Shape Control

- The problem of controlling the plasma shape is probably the most understood and mature of all the control problems in a tokamak
- The actuators are the Poloidal Field coils, that produce the magnetic field acting on the plasma
- The controlled variables are a finite number of geometrical descriptors chosen to describe the plasma shape

Objectives

- Precise control of plasma boundary
- Counteract the effect of disturbances (β_p and l_i variations)
- Manage saturation of the actuators (currents in the PF coils)

XSC "philosophy"

- To control the plasma shape in JET, in principle 8 *knobs* are available, namely the currents in the PF circuits except $P1$ which is used only to control the plasma current
- As a matter of fact, these 8 knobs do not practically guarantee 8 degrees of freedom to change the plasma shape
- Indeed there are 2 or 3 current combinations that cause small effects on the shape (depending on the considered equilibrium).
- **The design of the XSC is model-based. Different controller gains must be designed for each different plasma equilibrium, in order to achieve the desired performances**

XSC vs standard JET SC

SC

- A few geometric parameters are controlled, usually one gap (Radial Outer Gap, ROG) and two strike points
- The desired shape is achieved precalculating the needed currents and putting these currents as references to the SC
- This gives a good tracking of the references on ROG and on the strike points but the shape cannot be guaranteed precisely
- Shape modifications due to variations of β_p and l_i cannot be counteracted

XSC

- The shape to be achieved can be chosen
- The XSC receives the errors on 36 descriptors of the plasma shape and calculates the "smallest" currents needed to minimize the error on the "overall" shape
- The controller manages to keep the shape more or less constant even in the presence of large variations of β_p and l_i

Model-based approach: the XSC example

- XSC design is based on a plasma linearized model
- the XSC is **optimized** for each given scenario $\rightarrow$ the controller parameters are different for different operative scenarios
- Thanks to the model-based design approach, XSC functionalities have been easily extended in order to include **strike-points sweeping** and **plasma boundary flux control**

G. Ambrosino et al.
Design and Implementation of an Output Regulation Controller for the JET Tokamak
IEEE Transactions on Control Systems Technology, vol. 16(6), November 2008

G. De Tommasi et al.
XSC Tools: a software suite for tokamak plasma shape control design and validation
IEEE Transactions on Plasma Science, vol. 35(3), June 2007

M. Ariola et al.
Integrated plasma shape and boundary flux control on JET tokamak
Fusion Science and Technology, vol. 53(3) April 2008

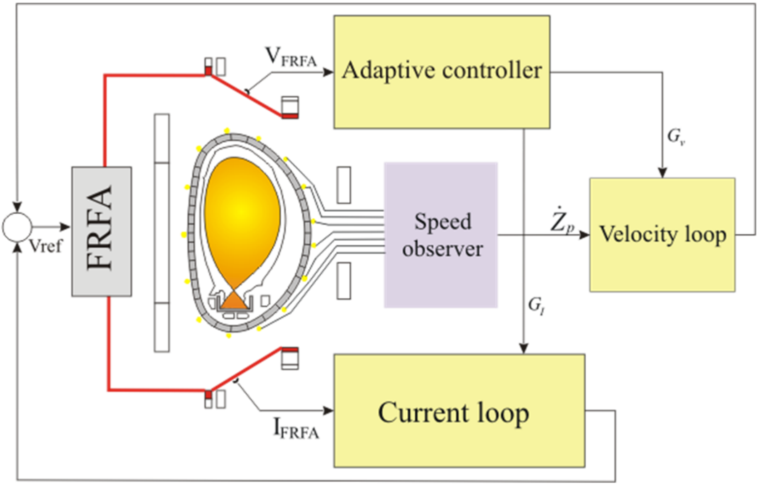
G. Ambrosino et al.
Plasma strike-point sweeping on JET tokamak with the eXtreme Shape Controller
IEEE Transactions on Plasma Science, vol. 36(3), June 2008

Vertical Stabilization Problem

Objectives

- Vertically stabilize elongated plasmas in order to avoid disruptions
- Counteract the effect of disturbances (ELMs, fast disturbances modelled as VDEs,...)
- It does not control vertical position but it *simply* stabilizes the plasma
- The VS is the essential magnetic control system!

JET VS Control Scheme



VS & JET PCU Project - 1

The **Plasma Control Upgrade (PCU)** project has increased the capabilities of the JET **Vertical Stabilization (VS)** system so as to meet the requirements for future operations at JET (ITER-like wall, tritium campaign, . . .).

The PCU project aims to enhance the ability of the VS system to recover from large perturbation.

This is especially true for future operation at JET with the beryllium ITER-like wall.

VS & JET PCU Project - 2

Within the PCU project, the design of the new VS system has included

1. the design of the new power supply for the RFA circuit
2. the assessment of the best choice for the number of turns for the coils of the RFA circuit
3. **the design of the new VS software, so as to deliver to the operator an high flexible architecture**

Why a new software architecture?

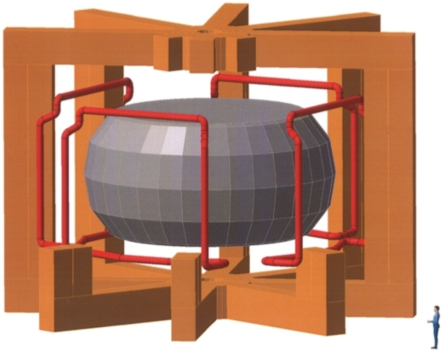
- Better fusion performance in tokamaks are achieved with highly elongated plasmas in presence of large perturbations
- In these **extreme scenarios** a *general purpose controller* cannot guarantee the requirements
- To push the performance up to the desired level, it is usual to rely on a model based design approach which assures the needed control performance (e.g. XSC)
- **To optimize the system behavior in each advanced plasma scenario, it should be possible to choose**
  - **different estimations of the plasma vertical velocity**
  - **different adaptive algorithms for the controller gains**

The new Vertical Stabilization

- It is a MARTe-based system
- 192 signals acquired by ADCs and transferred at each cycle
- 50 μs control loop cycle time with jitter $< 1 \;\; \mu s$
- Always in real-time (24 hours per day)
  - 1.728×10^9 50 μs cycles/day
  - Crucial for ITER very long pulses

EFCC Voltage Controller - Introduction

- EFCCs, what do they do?
  - They change magnetic field topology at the plasma boundary
- Why is it important?
  - Instability mitigation and ELM control
- How?
  - By controlling the current in the EFCCs we can control the magnetic field
- Who?
  - The session leader sets the required current waveforms



New EFCC Controller

Motivation

- Performance limitations of the amplifiers restrict the effective system bandwidth
- A new controller with the ability to improve the amplifiers response has been designed and implemented using the MARTe framework

Design Approach

- The new control algorithm exploits the amplifier model
- It is based on an *anticipation* approach of the current reference waveform. This anticipation is adapted during the experiment in order to maximize the performance

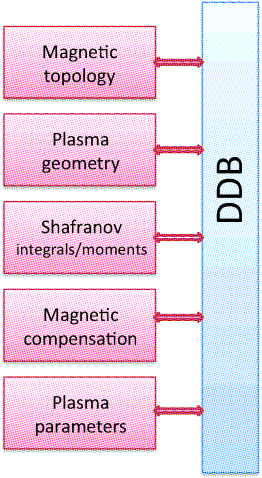
Implementation

The controller has been implemented using:

- a **FeedForward** module which incorporates the amplifier model and implements the adaptation logic generating the feedforward signal for the amplifier
- a **PID** module which implements the standard PID controller

The BetaLi diagnostic

- The **BetaLi** real-time code provides a large set of plasma parameters
  - plasma poloidal β
  - plasma internal inductance l_i
  - ...
- It is routinely used for many different real-time feedback controls
- Its software architecture has been recently redesigned exploiting the **MARTe framework**, in order to improve its performance and precision



BetaLi

- Thanks to its new flexible architecture new diagnostics can be easily included to extend the set of plasma parameters computed by the system
- The system is presently running with a time resolution of 2 ms on a standard PC

Conclusions

THE END

Thank you!