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The PCU JET Plasma Vertical Stabilization control system

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ABSTRACT

The Plasma Control Upgrade (PCU) enhancement project was setup with the aim of effectively increasing the JET operating space by both improving the Vertical Stabilization System Controller and by procuring a more powerful Radial Field Amplifier. The hardware and software technological advancements that have been used allowed to implement a 200 channel, 20 kHz control system with less than 2 μs jitter and over 2*Gops* of processing capability. The software design, driven by an object oriented analysis, enabled a good compromise between real-time performances and reliability–maintainability objectives. The first operational experience of the system will be presented.

1. Introduction

Modern tokamak machines are designed to run elongated X-point configurations for which the plasma is vertically unstable. To enable plasma operation beyond the vessel time the introduction of a Vertical Stabilization (VS) System is required. Furthermore, in presence of top–bottom asymmetric passive structures, fast perturbation to the internal pressure (ELMs, H-L transitions) can perturb the unstable vertical mode. This is the case for JET where H mode is restricted by the risk that an ELM could trigger a vertical displacement event (VDE) leading to a disruption.

The Plasma Control Upgrade (PCU) project aimed at increasing the capabilities of the JET VS system [1]. The main objective was to enhance the ability to recover from large edge localised mode (ELM) perturbations, in particular for the case of plasmas with high elongation, i.e. plasmas with large growth rate parameters. The project implements changes to the three major components of the VS system: a new amplifier (ERFA), a new controller (the subject of this paper), and the ability to change the number of turns in the radial field circuit.

The VS is one of the most critical systems of the JET tokamak. It is responsible for guaranteeing a zero vertical velocity of the plasma while at the same time trying to keep the average radial field to zero [2]. The stabilization is obtained by using a velocity and a current control loop: the former is a proportional control which stabilizes the vertical velocity of the plasma, while the latter has a proportional-integral action and tracks a current reference, usually zero, in order to prevent drifts in the vertical position and to avoid exceeding the limits of the power supply.

As it is not possible to directly measure the vertical velocity of the plasma, an observer is required, which is capable of translating the magnetic signals from the vessel pickup coils and saddle loops to an estimation of the vertical velocity.

Along with these two components, the VS system also provides a collection of features that enable the scientific exploitation of the system during experiments. In particular it is able to apply desired perturbations to the radial field, named kicks [3], using either the vertical stabilization amplifier or any combination of the four divertors amplifiers (driving four internal coils near the divertor), at a certain frequency or as response to a particular event, e.g. ELMs.

Eventually, in order to test, commission and diagnose problems, the VS system also provides a way of simulating a full JET pulse in closed loop using a model of the plasma [4]. Due to the complexity of the requirements, instead of building monolithic and unmanageable software, it has been decided to divide the controller in smaller and independent blocks, thus facilitating its debug and development, resulting in a higher level of flexibility, as each module can be easily substituted or modified without requiring a complete re-testing of the code.

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[1] See the appendix of F. Romanelli et al., Proceedings 22nd IAEA Fusion Energy Conference, Geneva, Switzerland, 2008.

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This paper presents first operational experience of the system, especially focusing on the first five months when the system has been operating in parallel to the old VS, and the controller has been progressively commissioned.

2. Model based approach and software support

The design and implementation of the new system has been carried out following a model based approach [5,6]. Such a methodology is very helpful when high performance and robustness are required. In particular, it has been essential for the correct specification of the new VS power supply characteristics (maximum voltage, current and delay), and for the optimization of the controller parameters in different plasma operation scenarios.

Thanks to the development of reliable linear models for the plasma magnetic behaviour [4], it was possible to validate and tune each design step, from the conceptual to the final implementation.

The control algorithms were at first implemented and tested against the models in the Matlab/Simulink environment. Then, using the new real-time framework recently developed at JET [7], both control algorithms and simulation models have been implemented as plug-ins modules of the real-time application. The modularity and platform independence of the framework architecture was used to prepare an appropriate mix of test environments for the real-time control software.

Initially the software modules have been validated offline on different targets (Linux, Windows) both in closed-loop against the models, and in open-loop with recorded or designed inputs. Finally, they have been commissioned on the real plant, operating in parallel with the old system. In particular, the new system has been used to control the plasma vertical velocity for progressively longer time windows, during the experiment.

3. Hardware architecture

The VS controller hardware and data acquisition system are based on the PICMG 3.0 Advanced Telecommunication Computing Architecture (ATCA [8]).

The system comprises six data acquisition cards, an ×86 based controller and a rear transition module (RTM). Each acquisition board provides 32 galvanically isolated, 18-bit resolution, 2 MSPS A/D converters.

The RTM contains 8 analog output channels, a RS-485 based external clock, and trigger input and an optical digital link output.

The controller board accommodates a uATX motherboard and 3 PCIe switches that provide the bridge to the PCIe lanes in the ATCA backplane. The motherboard contains an Intel Quad-core CPU, 2 GB of DIMM DDR2 DRAM and a Gigabit Ethernet interface.

The acquired signals, thanks to the ATCA full-mesh topology (where every card is connected to every other card), can be exchanged among the boards using a protocol named Aurora [9]. Once the signals are available at the same time in the six boards it becomes possible to develop distributed signal processing algorithms directly inside the board FPGAs and with that potentially close the VS control loop. While it has not been necessary to use this feature in the present version of the PCU controller, its availability offers a powerful upgrade path whenever more processing power was necessary.

The data acquisition cards contain a powerful FPGA that is not just handling the interfaces, but implements algorithms for digitally filtering and decimation to 20 kHz of the acquired data. The data are then sent directly to the processor memory via bus master DMA transfers. This mechanism allows the efficient implementation of a control loop with a cycle time of 50 μs (Fig. 1).

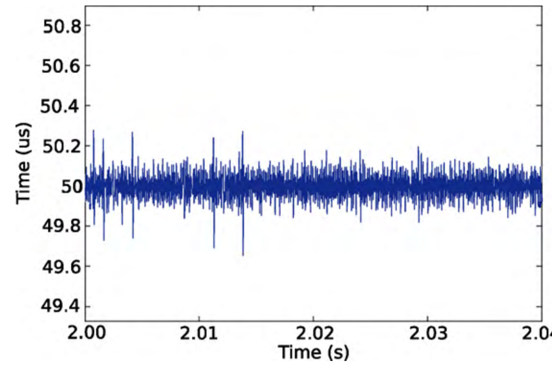

Fig. 1. Jitter values in the start time for a new control loop cycle. Each cycle is started every 50 μs and synchronisation is achieved within a jitter in the order of the hundreds of ns.

Exploiting the multi-core technology, an interrupt-less communication scheme between the operating system and the boards was implemented. A driver continuously (1 μs interval) polls a memory region that is updated by one of the boards, using DMA, as soon as new samples are available in all boards. This synchronization mechanism allows jitters in the order of the hundreds of ns [10]. Using this scheme, the system runs continuously, performing low jitter and low latency real-time data acquisition at this frequency for 24 h a day, while at the same time it responds to a number of non real-time communication requests (Fig. 1).

Although the new PCU Enhanced Radial Field Amplifier (ERFA [1]) can still be controlled using analogue references, a bidirectional optical digital link has been designed and implemented connecting the amplifier directly to the ATCA control hardware. The usage of this digital interface provides the following advantages: (i) no delays introduced by the otherwise necessary anti-aliasing filters; (ii) one link providing both reference delivery and read-back of output voltage and current; (iii) access to information about the internal state of the amplifier (faults). A special interface module linked optically to the RTM optical port has been developed for the purpose. The module interfaces to the power amplifier using a bidirectional parallel link and transfers information to/from the RTM using the Aurora protocol at a 5 MHz rate.

4. Software architecture

In order to meet the requirements of the new VS control system the entire real-time software framework was redesigned. Although driven by VS, the new framework has been designed to address a wider set of specifications. High level of flexibility and improved debugging and testing without compromising the real-time performance were among the root design choices.

4.1. MARTe: the real-time framework

The real-time framework is built upon a C++ library named *BaseLib2*, which implements a light weight multi-platform support and is optimised for real-time applications. The library supports multi threaded or multi processor applications thanks to a fully re-entrant API, to the provision of garbage collection (reference counting), to the implementation of shareable object containers and inter-thread messaging services that allow exchanging of objects. BaseLib2 encourages data driven programming by providing automatic instantiation of classes based on a database (XML like file). A typical application is assembled by defining the objects and their interaction in the database and, whenever necessary, by implementing missing functionalities as extensions to the basic framework (typically in the form of shared libraries). *MARTe* (Multiplatform Application Real-Time executor [7]) is a BaseLib2 extension library that implements a real-time framework for developing and executing generic real-time applications.

Any generic real time application can be implemented as the collaboration among a number of atomic elements called Generic Application Modules (GAMs). GAMs are either data sources, sinks or elaborators. Each has a number of inputs and outputs. The framework provides the binding (dynamic data buffer) and scheduling mechanisms (real time thread).

Data driven programming is supported by the underlying Baselib2 ability to instantiate and initialise classes based on database information. A generic real-time application is therefore implemented by combining the framework libraries (BaseLib2 and MARTe), a set of custom or reused extension modules, and a database describing the application structure.

MARTe also provides generic mechanisms to handle communication with the plant and experiment central management systems. Interface to the JET Control Data Acquisition Systems (CODAS) is implemented on a separate library containing modules that operate as communication brokers.

This extreme modularity and the platform independence provides a significant advantage during the debugging and testing phases. The application could be assembled with the opportune selection of components to support each specific testing needs: test of single module, run the application using collected data, close the loop on a model. Debug and commissioning also took advantage of the object introspection functionality offered by BaseLib2. While the application is operating, and without impact on the real-time performances, it is possible to inspect the C++ variables of an object using a simple web interface.

Neither MARTe nor BaseLib2 provides tools for the editing of the application configuration database. In JET this facility is supplied by as part of the generic experiment user-interface: the pulse schedule editor *xpsedit*. This editor assembles the final database to be used by MARTe by using the information input by the operators on two set of user interface pages. The first set of pages is available only for the initial commissioning or for special applications and allows the full editing of the application breakdown into GAMs. The second, designed for normal operation, only allows changes to the standard GAMs input parameters.

4.2. The real-time infrastructure

The high real-time performance requirements of the PCU VS control algorithm could only be implemented by running the code kernel mode using RTAI [10] and by isolating the execution of the real-time functions from any unwanted interrupt. Linux on a multi processor hardware supports this requirement providing a mechanism to manage the interrupt routing. On a quad core machine, one core was dedicated to user mode LINUX tasks and general handling of interrupts, a second to RTAI to handle communication to/from LINUX, and the remaining two are used to run the real-time tasks within RTAI/MARTe.

During the design process an additional problem had to be addressed: due to the large amount of data acquired, large memory allocations were required in order to store information from a full experiment at maximum frequency. As the 32 bits RTAI (Linux kernel) only permits allocations of up to 1 Gbytes of data, an UDP message based streaming mechanism [11] was developed. A continuous data streaming between the real-time thread and an external server (again running MARTe) is able to sustain up to 56 MB/s without compromising the real-time performance.

5. Software implementation and simulation support

Fig. 2 shows the architecture of the PCU VS controller. The boxes in pink are modules of the controller while those in yellow are optional modules to operate on a simulated plasma. A large collection of software modules (GAMs) are used to implement the VS control functions. After transferring the data from the acquisition boards (ATCA-ATC GAM) a signal processing module is invoked (SPGAM). At this stage rotating toroidal modes $n = 1, 2$ noise is removed from the magnetics and ELMs are detected.

The filtered magnetic data are then processed by the “Observer GAM”, which is responsible for providing a set of vertical velocity measurements or vertical instability mode estimations using either static or dynamic observers.

The “Controller GAM” implements the two main control loops: vertical stabilization and radial field control. The controller produces a voltage reference that is processed by the Vertical Amplifier Manager (VAM GAM). This module manages the link to the amplifier, allowing the choice between analogue and digital link while minimizing the difference in the amplifier behaviour in either case. The amplifier is a series of four H-bridges each controllable to produce 0, MAX or -MAX voltage. In order to avoid oscillation between the levels a mechanism of threshold with hysteresis is implemented on the analogue link. A similar hysteresis mechanism needs to be implemented in software for the digital link. This module also contains the vertical kick generation logic (to stimulate vertical instability) and some other experimental features.

The Divertor Amplifier Manager (DAM GAM) allows the VS to share the divertor (four internal coils near JET divertor plates) amplifiers with JET Shape Controller. Its primary function is to provide an alternative kick mechanism to that provided by the VAM. Using the divertors it is possible to apply a perturbation to the plasma vertical stability that is independent to the parameters of the radial field circuit: new/old amplifier, number of radial field coil turns. Thus, the PCU project has chosen this mechanism as one of the tools to compare between the old and the new systems: perturb the vertical stability and compare the responses.

The DAM also allows the clipping, reducing, or filtering of the Shape Controller divertor references. During large an slowly evolving ELM perturbations the Shape Controller attempt to keep the plasma shape interferes with the VS task. It does that by requiring rapid variations of the divertor currents with a sign that is destabilizing. The DAM has been designed to act by suppressing/moderating the Shape Controller request during an ELM.

Exploiting the potentialities of MARTe, a collection of modules were specifically developed to simulate the environment and a complete close loop test-bench implemented. The plasma behaviour was simulated with a state-space model (StateSpace GAM) that receives as input the requested voltages to the actuators and produces the estimation of the plasma vertical velocity. The state space has been provided by using CREATE code [4]. Additional inputs for the controller are the plasma current and optionally H-alpha and divertor voltages. These signals are not modified by the closed loop and are simulated with a waveform generator (WaveGen GAM). A third module simulates the hysteresis and noise in order to recreate the hysteretic characteristic of the amplifier and add some white noise to simulate a real acquired signal (Amplifier Model GAMS).

This is one of the possible simulation schemes, one that can operate in the presence of the target hardware, runs in real-time and allows plasmaless testing of the full VS system.

6. Experimental results

During the early 2009 JET experimental campaign the system ran in parallel to the old VS controller: in different phases of a dis-

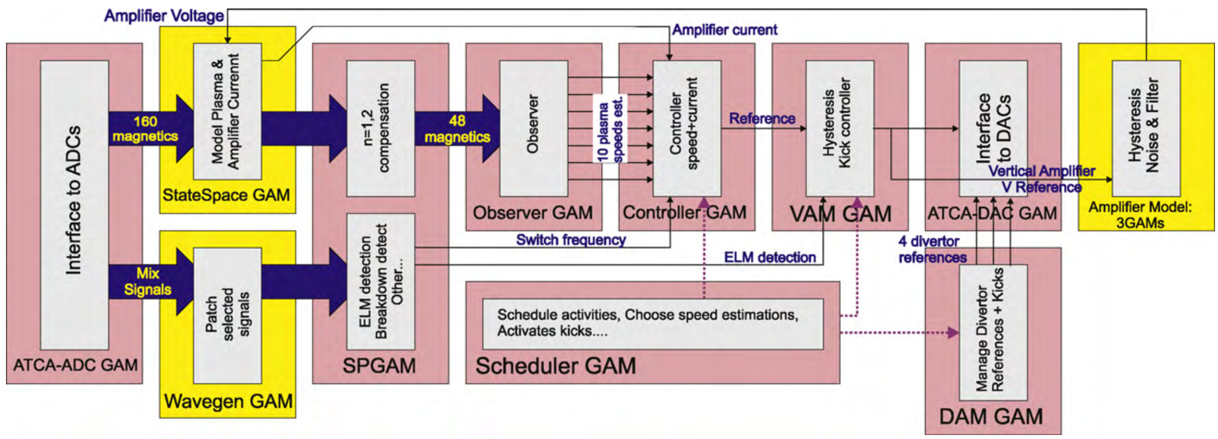

Fig. 2. Controller scheme. The physics and control requirements have a direct correspondence in the software organization. Each functional requirement was implemented in a different software module, enabling the replacement of some of the modules with simulators in a completely transparent way. In this figure a model of the amplifier of the input data is being used to replace the actual hardware.

charge one of the systems was driving the amplifier. The switch was performed by a time driven hardware signal switch.

The initial tests consisted in verifying that the output requested by the new VS controller was comparable to that of the old VS. The task was complicated by the fact that in some cases differences could be explained both by errors in the new system and by the drift that naturally occurs in control systems operating in open loop. In this phase all the new controller features were activated and the resulting controller behaviour verified against specifications.

While this open loop commissioning phase provides a good indication of the quality of the system under test it cannot replace the final closed loop tests.

Given the harsh consequences of even the smallest mistake, a disruption, the initial closed loop tests were performed on the very end of a discharge, where the impact of a failure is minimal. Many tests were performed, where the new controller was demonstrated progressively on a larger set of scenarios. Eventually the first ELMy plasmas was controlled and the first breakdown was performed using the new controller.

The slow and prudent progress is not an indication of failures or of difficulties. JET was in the middle of a standard experimental campaign, its resources were primarily directed to scientific exploitation. In fact, it was the almost perfect record of the PCU tests that allowed obtaining experimental time and therefore completing the test schedule.

7. Conclusions

The PCU project is especially remarkable because it sponsored a large set of innovative developments, where different associations were able to collaborate effectively to develop a modern and reliable plasma control system.

The ATCA based hardware development provided access to state of the art technology and processing power. This enabled the design of a low latency, low jitter, 20 kHz closed loop control systems with almost 200 input channels driven by modern multi-core CPU technology.

Driven by the need for highly reliable and at the same time flexible software MARTe modular real-time framework was developed. Its multi-platform design provided a good environment where to integrated model based design and test efforts.

The combination of these two developments resulted into a low jitter, highly modular system which was able to control a JET plasma for several seconds.

Following a very important design decision, the system is always running, acquiring data at 20 kHz and executing the software modules. Synchronisation and real-time is always guaranteed at 50 μs even outside the experiment. The system has been running, 24 h per day, for weeks without ever loosing real-time. This concept is particularly relevant for long pulse duration machines, like ITER.

No software failures were ever observed during the execution of an experiment. This is due to the design choice of validating all the parameters and performing the majority of the operations before the experiment. The number of software validations that is performed in run time is kept to the absolute minimum and must be thoroughly justified. This result is especially important since it indicates that the adopted design and implementation methods lead to systems that minimize risk during runtime.

The last phase of the project has now just begun. ERFA has been delivered and is now under test. JET radial field coil set has been updated to allow flexible choice of turns. In the second part of 2009 the three new PCU elements will be commissioned together to perform vertical stabilization at JET. It is in this final set of tests, where the work of more than two years will come together and hopefully demonstrate an improved plasma control capability.

The new VS controller main objectives will be to operate reliably and to provide the specified new control features. If the initial experimental results can be used as indication, then the new controller will be very successful.

Acknowledgments

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