Proceedings of the 3rd International Conference on the Frontiers of Plasma Physics and Technology (PC/5099)

ADVANCED REAL-TIME CONTROL SYSTEMS FOR MAGNETICALLY CONFINED FUSION PLASMAS

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Abstract

Real-time control of magnetically confined plasmas is a critical issue for the safety, operation and high performance scientific exploitation of the experimental devices on regimes beyond the current operation frontiers. The number of parameters and the data volumes used for the plasma properties identification scale normally not only with the machine size but also with the technology improvements, leading to a great complexity of the plant system. A strong computational power and fast communication infrastructure are needed to handle in real-time this information, allowing just-in-time decisions to achieve the fusion critical plasma conditions. These advanced control systems require a tiered infrastructure including the hardware layer, the signal-processing middleware, real-time timing and data transport, the real-time operating system tools and drivers, the framework for code development, simulation, deployment and experiment parameterization and the human real-time plasma condition monitoring and management. This approach is being implemented at CFN by offering a vertical solution for the forthcoming challenges, including ITER, the first experimental fusion reactor. A given set of tools and systems are described on this paper, namely: (i) an ATCA based hardware multiple-input-multiple-output (MIMO) platform, PCI and PCIe acquisition and control modules; (ii) FPGA and DSP parallelized signal processing algorithms; (iii) a signal data and event distribution system over a 2.5/10Gb optical network with sub-microsecond latencies; (iv) RTAI and Linux drivers; and (v) the FireSignal, FusionTalk, SDAS FireCalc application tools.

1. Introduction

Real Time Measurement and Control of magnetically confined plasmas is a critical issue for safe operation and high performance scientific exploitation of experimental devices on regimes beyond the current operation frontiers and it is essential for achieving the goals of the ITER experimental programme. This is a broad task undertaken by most relevant devices and involving a large number of competencies: plasma physics, control, machine operations, systems, machine safety, software, hardware, communications engineering, computational mathematics, etc. Presently, the ITER CODAC conceptual design is advancing towards peer review. At the moment, technical solutions are not being proposed yet once that they would most likely be obsolete some years from now. However, prototyping ideas is desirable and all concepts must be fully functional and exhaustively tested, well before it is essential for ITER. Therefore, all CODAC functions/RT control systems must be proven on advanced facilities like the existing tokamaks and/or ITER test stands. In addition, near-term needs for RT control on existing devices represent an opportunity to address issues of relevance for ITER-CODAC.

This important and increasing role that Real-time control is playing in the operation of fusion experiments is mainly due to the following facts: (i) the optimisation of the plasma performance which demands adequate feedback control processes based on an increasing number of plasma parameters [1]; (ii) the operation close to unstable regimes and on not yet explored parameter ranges that requires more demanding safety procedures [2]; and (iii) the enlargement of the discharge duration forces the implementation of new philosophies of control and data acquisition [3, 4], in which sometimes data from several specialised diagnostics is only acquired when a particular phenomena occurs.

These features are considerably hard to implement with existing control systems. The successful development of advanced operational regimes depends strongly on the architecture and processing capacity of the installed control system. A modern real-time control system for plasma control must be rather fast and demands a large computation power; besides it needs an intelligent strategy for real-time decision making, which is only made possible by a digitally programmable system. The data acquisition and control tasks in the first feed-back control systems have been carried out by separate digital hardware platforms, while the signal processing algorithms ran in the host CPU and data was exchanged using the instrumentation bus. Aiming at decreasing the control cycle, increasing the computing power and dealing with large amounts of raw data, the new generation of real-time control systems are based on intelligent modules that can perform with high efficiency the data acquisition, signal processing and control tasks.

This paper presents our view on the development of advanced real-time systems with particular emphasis for the solutions being pursued by "Centro de Fusão Nuclear" (CFN), in the frame of the Contract of Association Euratom/IST. The first section of the paper describes the hardware layer which provides an unified and distributed control and data acquisition hardware platform able to perform real-time signal processing at the signal acquisition level; Section 3 discusses the signal-processing middleware; Real-time timing and data processing is addressed in section 4 and the real-time data operating systems tools and drivers on section 5; Finally in section 6 the Human Real-time plasma condition monitoring and management is also discussed.

2. Hardware layer

Plasma control systems may require hundreds of input signals, which are frequently shared among the output control variables (for plasma vertical position, shape control, etc). Multiple-input-multiple-output (MIMO) plasma controllers are more efficient in this scenario since resources are efficiently shared between control tasks on the same unit. Also control loop delays as low as 10 μs may be necessary, thus requiring fast real-time interconnect data transport both internally on the MIMO controller and externally linking several controller units.

To attain the requirements of the MIMO architecture the support hardware shall comply with the following technical aspects:

- Reduction of loop delay on the signal acquisition/generation endpoints, on the data interconnect links from and to the processing unit and on the analogue signal path (analogue filters).
- High processing power both on the acquisition/generator endpoints and on the system controller.
- Synchronization of all digitizer/generator endpoints.
- Architecture designed for maintainability, upgradeability and scalability.
- Target the specificities of the plasma controllers and low cost per channel.
- Low risk of implementation and testing.

An hardware platform for MIMO controller implementation is being developed at IST, based on the PICMG 3.0 Advanced Telecommunications Computing Architecture (ATCA), which was designed for high availability and scalability. The ATCA standard defines a backplane with a full mesh of serial gigabit communication links.

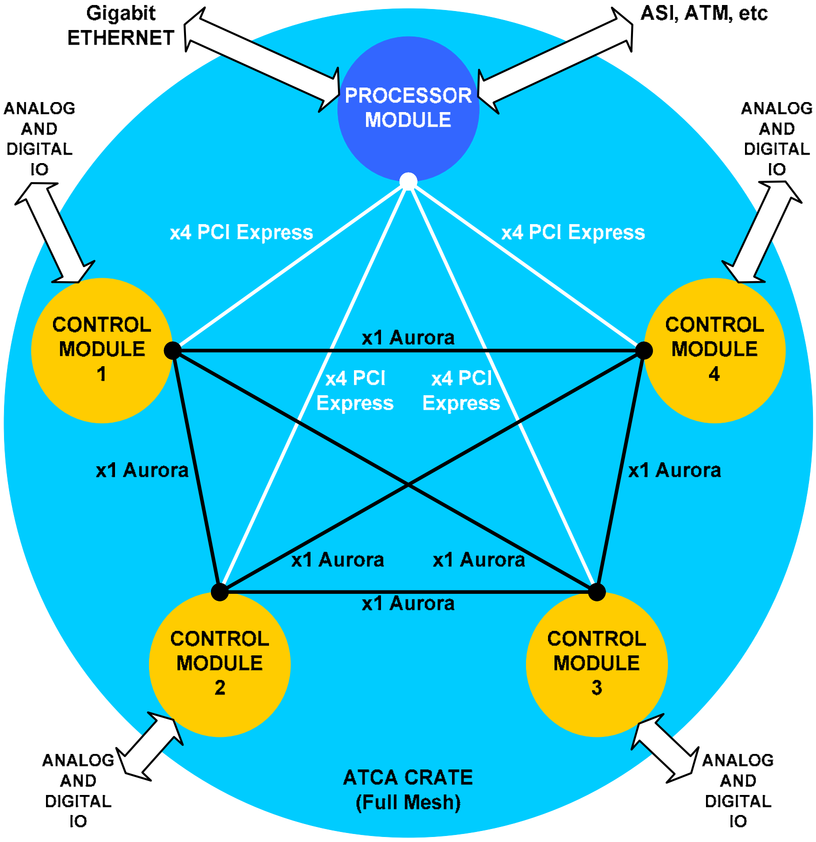

Figure 1: Interconnections between processor nodes.

The controller prototype contains one x86-based ATCA controller and up to 12 ATCA Digitizer / Generator / Processor (DGP) cards. The controller is connected to the DGP cards by PCIe links through the ATCA full mesh backplane (Figure 1).

The DGP cards can also be connected through a full mesh of links using the Xilinx Aurora standard, allowing the parallel execution on the FPGAs for MIMO signal processing. Tasks can be performed on only one, a set of or on all processors since all input channels acquired data will be available at all processors simultaneously. One possible scenario is each FPGA calculating one of the output voltages. Sub-microsecond delays can be attained on the Aurora links and under 2 μs on PCIe.

This solution is being pursued in the development of the Vertical Stabilisation Controller hardware for the Plasma Control Upgrade Project at JET.

3. Signal-processing middleware

Forthcoming fusion devices like ITER will benefit from the most advanced plasma diagnostics, the above mentioned increase in number of channel compared to present experimental devices and from the state-of art data conversion devices in which will potentially generate huge quantities of raw experimental data and it is not convenient to acquire all data provided by all diagnostics. Therefore, diagnostics are divided in two groups:

(i) Technical diagnostics are in continuous operation, connected to the data acquisition system (DAS) running in real-time algorithms for data analysis and control;

(ii) Scientific diagnostics driven by detection of an event. The DAS generates a signal that is distributed to all transient recorders to adequate their operation to study the detected event. For that to be possible, the transient recorders must have pre-trigger capabilities, aiming at not to loose any information.

The aim of this strategy is to achieve high rates of data compression/reduction. However, the computational effort to process this amount of data using conventional workstation PC or computer clusters will grow exponentially. Moreover, this usual offline processing paradigm also inhibits real-time control.

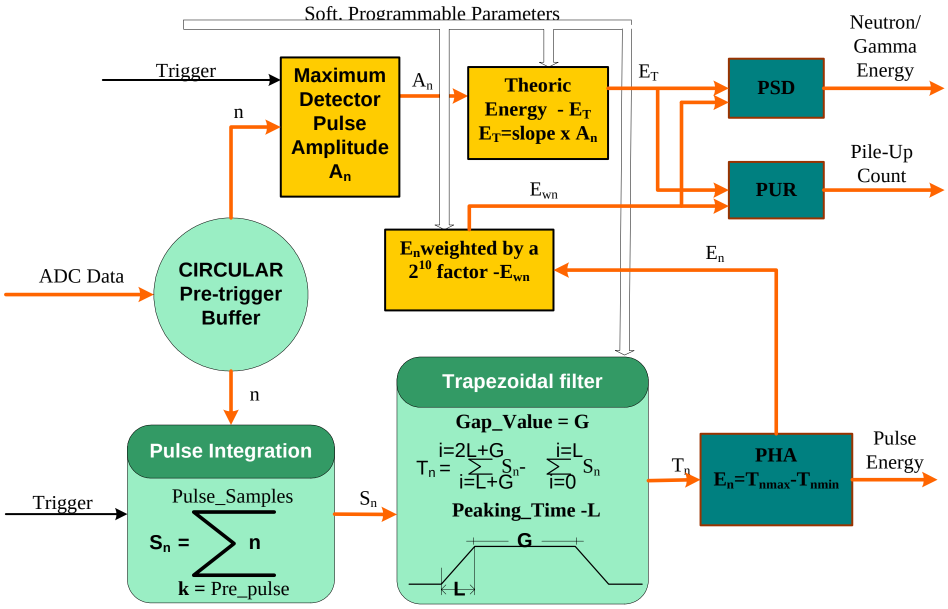

Figure 2: FPGA architecture block diagram for neutrons and gamma rays real-time pulse analysis.

The approach proposed by IST to overcome these restrictions is to bring into play the parallelized data processing power presently available in commercially available in modern Field Programmable Logic Devices (FPGA) and Data Signal Processors (DSP).

Two different systems following this approach are being developed: The first one, which is being developed for tokamak ISTTOK, ETE and CASTOR, implements data reduction by multi-rate real time decimation, using either FIR or cascaded-integrator-comb CIC digital filters in the FPGA (XILINX Spartan 3- XC3S2000) included in the locally developed PCI acquisition board with 8 galvanic isolated 14bit resolution channels and 2 Msamples/sec acquisition rate; The second is a new data acquisition system, developed in the frame of the JET enhancements projects, for real-time pulse analysis for neutrons and gamma rays spectrometry. This system is based on ATCA containing four channels at 400 MSamples/sec, where the Pulse Height Analysis (PHA), Pulse Shape discrimination (PSD) and Pile-Up Rejection (PUR) parallelized algorithms are fully implemented in FPGA[5]. Figure 2 depicts the FPGA internal configuration.

These developments are very versatile and can be easily adapted to be used in different diagnostic systems.

4. Real-time timing and data transport

Long-discharges or even steady state machine operation requires the implementation of dynamic experiment scheduling, event-driven discharge control with failure counteraction and dynamic data acquisition [6, 7]. The control and data acquisition tasks, running on multiple nodes, share plasma state variables propagated through the interconnections of a low time latency network, which provides support for management and transmission of prioritised signals, alarms, events and other objects as well as trigger scheduling and synchronism distribution.

Actual network links are oriented for bulk transfer of data having time latencies of no less than tens of microseconds and provide no-deterministic propagation of triggers and synchronism. These restrictions limit real-time operation since results may not be attained with acceptable optimality and predictability of timeliness.

A distributed Trigger and Timing System (TTS) has been developed at IST for MAST in order to fill this gap by providing sub-microsecond transport time latencies and accurate simultaneous triggers and synchronism on all nodes in a large experiment campus where previous timing systems were unsuitable [8, 9]. The Trigger and Timing system has been designed in a tree-type topology, with a central unit providing time synchronisation and event distribution between all satellite nodes (Figure 3). The interconnections allow bi-directional communication from one to all other nodes permitting them to synchronously share small data objects.

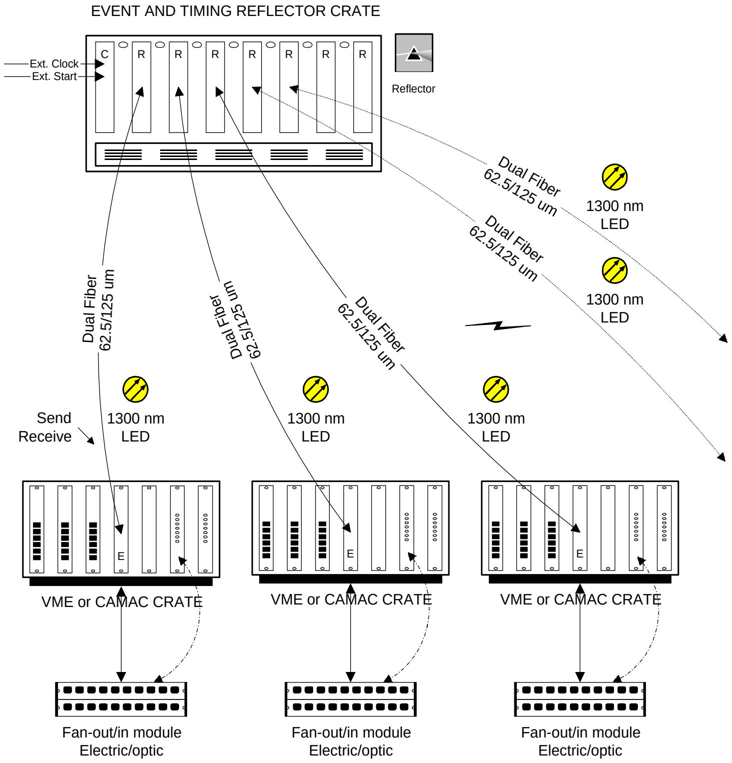

Figure 3: The topology of the trigger and timing system.

The Central Unit contains at least one Reflector Unit holding a maximum of 16 Event and Synchronism Reflector modules (ESR). A 2.5 Gbit optical network connects each ESR to an Event and Pulse Node (EPN) module with sub-microsecond latencies. Pre-defined and event dependent timing actions are performed in each of the EPN inserted in host crates scattered all over the experiment campus.

5. Real-time operating system tools and drivers

The functionality and capabilities of all hardware modules and systems developed for fusion devices above described must rely on computers running real-time operating systems (RTOS) when the goal is feedback active plasma control.

Presently, IST is developing applications based on open source solutions, (i) the first is the RealTime Application Interface for Linux (RTAI) project as the RTOS and; (ii) Linux device drivers specially developed for the hardware modules, using the Control and Measurement Device Interface API (www.comedi.org) interface, tools, and libraries. These applications and drivers are integrated in the framework described in the following sections and normally hide the specific hardware details of each module or subsystem and provide abstract common functions utilizable in streaming acquisition and real-time control

6. Human Real-time plasma condition monitoring and management.

The FireSignal [10] software platform is a complete modular system which allows to configure and operate physics experiments or to be embedded in existent experiments where it behaves as a hardware controlling unit. It can be divided in five distinct modules: *Central Server*, which acts as a bridge between all the other modules; *Database Manager*, responsible for data storage and retrieval; *Security Manager*, validates user's and hardware authentications and authorizations; *Hardware Nodes*, drives, configures and reads data from hardware; *User Clients*, the interfaces that allow to interact with the system. All the modules are connected through the Common Object Request Broker Architecture (CORBA) protocol. Figure 2 shows how the described components are connected.

In large fusion experiments a significant number of different diagnostics must coexist in order to fulfil the requirements of machine's operation and physics studies. Connected to each of these usually one can find a great variety of hardware devices that have different configurations and retrieve data in different formats. From the end-user's (engineer or physicist) point of view the user-interfaces for the configuration of diagnostics and hardware devices parameters should be as uniform and non-ambiguous as possible. FireSignal uses the concept of meta-data and self-description to guarantee the coherence of all devices interfaces: each hardware that is connected to the machine must provide an eXtensible Markup Language (XML) file with all the information about its configuration capabilities (what can be changed and how) and the type of data it produces. Using this file, FireSignal's user-interface automatically creates a form with all the required fields and provides auto-validation for data introduced by the user.

It is common that hardware provided by the industry only works with a specific platform, computer architecture or operating system. Since the communication protocol used in FireSignal is CORBA, different hardware controller nodes might be running in different computer architectures and written in different languages, without causing any interference to the system. This solution is completely transparent to the diagnostic operators and physicists.

FireSignal supports any database through the *Database Controller*, a software layer which provides the same communication functions to all the other modules; any changes in the database solution will not be noticed by the other components of the system. FireSignal provides remote connections to the experiments, allowing authorized users to change diagnostic's configuration and to follow-up experiments. Through a plug-in based system different data viewers, specific for each data type, are also available to the users. They are also allowed to exchange messages between them through a built-in implementation of the open protocol for instant messaging called XMPP (also known as Jabber).

Each laboratory stores data using proprietary schemes, usually developed by the research unit or using third party software; however the international collaboration requires the access of data from different experiments. A common software layer among end-users and laboratories is implemented in Firesignal. With this approach [11] all the complexity is hidden from end-users, allowing them to use the same analysis code in different laboratories and to concentrate in data analysis without having to spend time and effort learning new data access techniques.

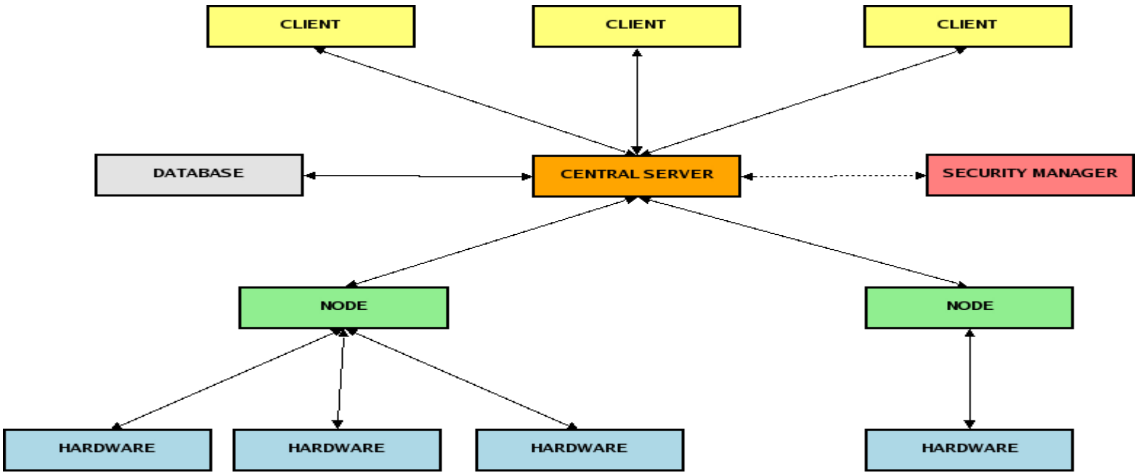

Figure 4: Connection between the several components of FireSignal. Since CORBA is used as the communication protocol, different components might be running in different computers and written in different languages.

7. Summary

CFN recent developments of advanced real-time systems offer a vertical solution for the forthcoming challenges of plasma control, and in particular the challenges posed by ITER requirements. The new generation of real-time control systems are based on intelligent modules that can perform the data acquisition, signal processing and control tasks very efficiently. This data acquisition hardware platform implements locally real-time signal processing, provides low latency serial gigabit interconnection between modules and simultaneously performs the synchronisation of all digitizer and generator endpoints.

The real-time processing capabilities of these intelligent modules will allow decreasing the huge quantities of raw experimental data that will be generated by the forthcoming fusion experiments. The modules will be capable of parallelized data processing executed on modern Field Programmable Logic Devices (FPGA) and Data Signal Processors (DSP) which are built in the data acquisition modules. The developed distributed Trigger and Timing System provides the support for management and transmission of prioritised signals, alarms, events and other objects as well as trigger scheduling and synchronism distribution as required by these experiments. All these developments are complemented by a modular software platform (FireSignal), which allows to configure and operate physics experiments or to be embedded in existent experiments where it behaves as a hardware controlling unit.

Acknowledgements

This work has been carried out within the framework of the Contract of Association between the European Atomic Energy Community and "Instituto Superior Técnico". Financial support was also received from "Fundação para a Ciência e Tecnologia" and "Programa Operacional Ciência, Tecnologia, Inovação do Quadro Comunitário de Apoio III".

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