ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-TUPDP042

CONTROL AND DATA ACQUISITION SYSTEM UPGRADE IN RFX-MOD2

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Abstract

RFX-mod2, currently under construction at Consorzio RFX, is an evolution of the former RFX-mod experiment, with an improved shell and a larger set of electromagnetic sensors. The extended set of sensors allows for exploring a wide range of plasma control schemes but also poses a challenge to its Control and Data Acquisition System (CODAS). RFX-mod2 CODAS is required to provide the high-speed acquisition of a large set of signals and their processing in the Plasma Control System (PCS). The PCS must provide a sub-millisecond response to plasma instabilities. While brand-new solutions provide for the acquisition of electromagnetic signals, involving Zynq-based ADC devices, other parts of the CODAS system have been retained from the former RFX-mod CODAS.

INTRODUCTION

RFX-mod2 is an upgrade of RFX-mod [1, 2] with a modified shell and mechanical structure to enhance plasma-shell proximity and improve plasma control. The main goal of RFX-mod2 is an improved plasma that will be achieved thanks to a much larger number of electromagnetic (EM) probes (1500) than that (800) used in RFX-mod. The higher number of signals to be acquired and possibly used for real-time plasma control significantly impacts the requirements of the Control and Data Acquisition System (CODAS), consequently requiring new extensions and improvements.

Moreover, even if the new CODAS inherits the overall architecture of the previous one, it must cope with the obsolescence of several hardware and software components. Luckily, several architectural choices in software and hardware made almost 20 years ago for RFX-mod, are still valid. Hence, the new system will maintain them. Indeed, the use of Linux is now even more widespread than at the time of initial CODAS development, and the software frameworks MDSplus [3] and MARTe [4], used for data acquisition and real-time control, respectively, are currently in use in many fusion experiments and actively maintained.

As for the hardware, the new system will maintain the CompactPCI (CPCI) technology, adopted for a large part of the data acquisition system, since it is still widely used. However, some legacy systems still using CAMAC will be replaced by more modern hardware. Similar considerations hold for plant control, where Siemens S7 400 PLCs used in some plant systems will be retained, while legacy S5 PLCs used in other subsystems will be replaced.

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ELECTROMAGNETIC SIGNALS

Acquisition of signals from EM probes represents an important CODAS function in fusion because it allows the reconstruction of the plasma equilibrium profiles that represent the first step in the analysis of plasma performance and in the plasma control itself. While the former is usually performed offline, relying on the signal database built by CODAS (called pulse file in the Fusion research jargon), the latter requires real-time data acquisition and control computation to meet the strict temporal requirements of the Plasma Control System (PCS), which require a sub-millisecond system response.

Two independent systems performed the corresponding functions in RFX-mod: CPCI-based solution for non-real-time data acquisition and VME for real-time data acquisition. It involved costly hardware duplication, complicating data acquisition management and hardware maintenance.

Moreover, most signals derived from EM probes must be integrated over time to derive the measured magnetic field. In RFX-mod, signal integration was performed before acquisition via hardware.

However, Plasma Control often requires the time derivative of the input signals (e.g. to perform PID control), which can be achieved either by (1) digitally differentiating the integrated original signal or (2) duplicating acquisition by additionally acquiring the original EM signal. The second solution is preferable for control as it avoids any error derived from a digital differentiation, but requires duplication of the acquisition channels.

FPGA-Based Architecture

The new FPGA-based architecture currently under development for RFX-mod2 provides the definitive solution:

1. The ADC board hosting the FPGA will be used for (1) high-speed data acquisition (up to 1 MHz) with DMA transfer to local memory and (2) low-speed (10 kHz) data sampling and streaming for plasma control.
2. The same FPGA will also perform digital integration to provide real-time integrated signals, avoiding the need for an additional front end for analog integration.

Long-lasting experiments require sustained streaming for data acquisition; conversely, due to the foreseen pulse duration of RFX-mod (up to 1 s), it is possible to use local ADC board memory in the Transient Recorder configuration, i.e. storing signals in local memory during the pulse and reading the memory content afterwards.

Moreover, thanks to the short plasma discharge duration, it is possible to achieve the desired precision in integration

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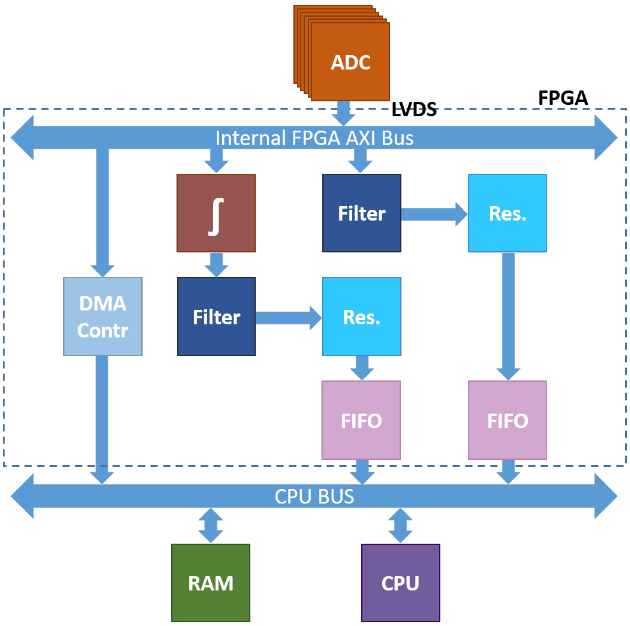

Figure 1: The FPGA architecture. DMA Controllers and FIFOs are implemented by XILINX IPs AXI-DMA and AXI4-FIFO, respectively.

by performing offset correction before the discharge, thus avoiding special techniques such as chopping as performed in ITER [5].

Thanks to the availability of the FPGA for real-time computation, it is possible to implement numeric integration of EM signals for real-time control, thus avoiding analog integration and ADC channel duplication. Each channel performs fast acquisition of a direct signal (usually the derivative of a magnetic field) and streams acquisition of a sub-sampled and integrated one for plasma control. Data acquisition of integrated signals is not needed at high frequency, even if they are available in the FPGA, because it is possible to compute them offline, thus avoiding a useless duplication of the DMA channels and memory.

Architecture Details

In a preliminary investigation of the feasibility of numerical integration, it turned out that the quality of the ADC stage and especially the noise spectrum were critical. In particular, the $1/f$ dependency of the noise spectrum can generate an unacceptable drift in integration [6], which makes using the ADC stage initially considered and used in other experiments unfeasible [7].

A new ADC stage is being developed using the ADS8900B chip with an improved Signal-To-Noise Ratio (SNR) to solve the problem. Galvanic insulation of the input signals, performed after their digitization, is another crucial function carried out by the ADC board. It is essential in the EM probe acquisition because the strong electromagnetic fields can induce over-voltage up to 1 kV or more. The insulated ADC stages are connected to a SOM Board PicoZed 7020 [8]. Every board will serve 12 ADC carrying out temporary storage, filtering, sub-sampling, integration and streaming.

Figure 1 shows the hardware elements implemented in the FPGA. Acquired 20-bit channels at 1 MHz from the 12 ADCs are provided in a single internal bus (AXI bus) and passed to the other components. The first data path flows data via a DMA controller to RAM, whereas the second internal AXI bus receives integrated data, which is re-sampled (after low pass CIC filtering) down to 10 kHz and sent to the CPU via an interface FIFO.

The Linux IP stack of the ARM processor embedded in the Zynq FPGA provides the software interface between the board and the network. The MARTe2 framework [9, 10] installed in the processor will supervise the whole data flow for offline data acquisition and real-time streaming. A prototype board has already been developed and is currently under test.

CODAS REFURBISHMENT

Except for the acquisition of EM, the data acquisition system of RFX-mod2 will implement a distributed architecture as in RFX-mod, based on Linux computers and CPCI. Due to their obsolescence, the embedded Linux CPUs hosted in the CPCI crates, in operation since 2004, cannot be used any more. Since replacing the embedded CPUs would be very expensive, we have adopted a more cost-effective solution. It consists of low-cost industrial PCs connected to the CPCI crates via bus extenders. Every industrial PC can now host up to two CPCI crates.

From the software point of view, thanks to the flexible configuration of the MDSplus data acquisition framework, moving from embedded systems to bus extenders is almost transparent, requiring only a reconfiguration in the assignment of tasks to processes and no change at all in any user or system program. Information stored in the MDSplus experiment database also includes the data acquisition tasks configuration.

The Dispatcher MDSplus tool [11] implements the activation and the orchestration of the distributed software components for data acquisition based on the current content of the experiment database. Therefore, changing the topology of the data acquisition tasks (e.g. moving from one computer to another) requires only changing the content of the experiment database, which can be achieved by using the graphical tools of MDSplus for browsing the experiment database.

The same approach is adopted to replace some VME-based diagnostic control systems, which use embedded CPUs running VxWorks, introducing VME bus extenders and porting the code written for VxWorks to Linux. Some other legacy systems implemented in CAMAC will require ad hoc solutions, which are being implemented using the RedPitaya devices with custom FPGA configuration.

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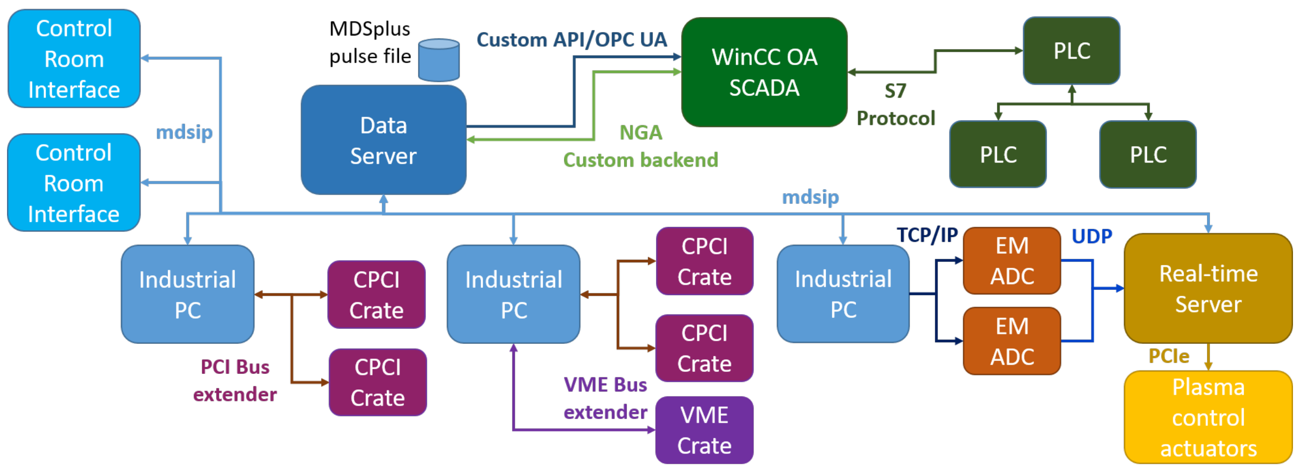

Figure 2: The new CODAS architecture of RFX-mod 2.

NETWORK

The RFXMod2 network infrastructure presents a star architecture, which remains based on Ethernet technology, as it has become the de facto standard.

The introduction of significant topological changes allowed the extension of the network to new experimental areas, such as onboard the machine to acquire proximity sensors and fast diagnostic systems. New redundant 10 Gbit/s fiber optic technologies for the backbone connections guarantee wide bandwidth for massive data transfer and reduced latency for real-time acquisition.

All peripheral uplinks have been increased to 1 Gbit/s, usually using optical fiber, to reduce the effects of electromagnetic disturbances and the risk of loops.

The network infrastructure has also introduced VLAN technology to functionally separate the different traffic flows, for example, plant operation from PLC plant and real-time SDN traffic. The physical and logical segmentation has also been implemented concerning the modern concepts of system functional safety, to ensure by design access regulation in a controlled and authorized manner for remote assistance or management activities.

The introduction of Network Monitoring systems using the SNMP protocol allows for controlling the status of individual uplinks and switch ports and intervening promptly in the event of anomalies. All these activities use a separate management VLAN.

PLANT CONTROL

The Plant Control of RFX-mod2 will retain the hierarchical distributed architecture it had for RFX-mod. When possible, the choice is to maintain hardware and software at the plant and supervisory levels to reduce costs and development time. However, several changes are necessary due to technological obsolescence and new requirements.

Some plant systems date back to the former RFX experiment, not having been renewed for RFX-mod, and use legacy technology such as Siemens SIMATIC S5 PLCs. Maintaining these plant systems, namely the vacuum and gas injection system, the cooling system, and the high voltage step-down substation, is not feasible: they will be re-implemented from scratch using modern SIMATIC S7-1500 PLCs. The remaining plant systems use SIMATIC Siemens S7 400 PLCs, which will be kept in service since they are in good condition and replacing them would require excessive resources. Similar considerations hold for plant control coordination.

Despite replacing some components, its architecture, defining a hierarchical state machine synchronizing all subsystems, will be retained. Regarding hardware, S7 1500 PLCs will replace all legacy S5 ones. When possible, a single S7 1500 PLC will substitute more than one S5, thus reducing hardware costs and simplifying the architecture.

PLC Software

Consequently, a new implementation of the PLC software (called Scheduler) is ongoing for the new S7 1500 PLCs, comprehensive of a hierarchical state machine, alarm management and communication. The new Scheduler will keep the former message exchange structure to maintain communication compatibility with the retained PLCs. At the protocol level, the previous Scheduler software uses proprietary Siemens S7 Protocol routines (AGLSEND, AGLRECV) to communicate with partner PLCs.

However, these routines are no longer available in S7 1500 PLCs, as the TCP/IP-based Open User Communication (OUC) is now the standard in non-real-time communication with SIMATIC S7 CPUs. Therefore, minor modifications are necessary in the previous Scheduler version to handle OUC communication with S7 1500 PLCs.

SCADA System

The SCADA system used for RFX-mod (FactoryLink) has long been obsolete and will be replaced by WinCC OA, using native S7 communication between the SCADA and plant system PLCs for process variable setting and readout.

Communication between WinCC OA and MDSplus is also needed for data acquisition, configuration and control

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reasons. Tests are still necessary to decide whether to implement communication for configuration and control through an OPC UA server (integrated into WinCC OA) or by developing a custom C++ API. If the API solution proves better, it will allow access to the MDSplus pulse files directly for configuration purposes.

We are currently developing a new C++ database backend for WinCC OA to store in MDSplus the time evolution of the process variables monitored by the SCADA. The New Generation Archiver (NGA) of WinCC OA provides communication between the SCADA and the backend, while the latter can natively access the MDSplus pulse files. Process variables can be stored as a continuous trend, using an absolute time reference, or in correspondence with an experimental pulse, using relative pulse time. This solution permits to rely on a single data system for all the experiment-related information.

CODAS Overall Architecture

Figure 2 illustrates the overall architecture. A central data server hosts the MDSplus pulse file, which is exported for remote data access via the mdsip protocol to the computers in the control room and the industrial PCs used for data acquisition.

The industrial PCs replace the old embedded CPCI CPUs and use bus extenders to connect to the CPCI and VME crates. The CPU hosted by the EM data acquisition boards will also get configuration information and store data acquired in the local RAM. These boards will also stream acquired samples in real-time for plasma control, supervised by MARTe2 on the real-time server. The latter will use PCIe to send reference waveforms to the actuators for plasma control. Plant data will also be stored in MDSplus, using the MDSplus data backend for WinCC OA. WinCC OA will read configuration parameters from the MDSplus pulse file via OPC UA or a custom C++ API.

DISCUSSION

The new RFX-mod2 CODAS must adhere to a set of fresh requirements while being affected by several constraints. The primary requirements include the need to support a significantly larger number of electromagnetic (EM) signals and the replacement of outdated components relying on obsolete technology. A major constraint faced in this endeavour is the limitation imposed by the available budget.

Consequently, the development of the new CODAS has entailed numerous trade-offs, with innovations introduced only when deemed essential. These circumstances justified new developments in cases where the previous system could not meet the enhanced requirements, such as those related to EM signals, or when obsolete components, like CAMAC, S5 PLCs, and FactoryLink, could no longer be sustained.

Nevertheless, certain architectural decisions made nearly two decades ago have stood the test of time and greatly facilitated the CODAS upgrade process. Critical design choices that have proven exceptionally successful at RFX-mod include:

1. **Utilization of MDSplus and MARTe Frameworks:** The adoption of the MDSplus and MARTe frameworks, widely used and actively maintained across various laboratories, has shielded the system from obsolescence.
2. **CPCI Technology for Hardware Modules:** The selection of CompactPCI (CPCI) technology for a substantial portion of the hardware modules has proven advantageous. CPCI remains prevalent, and the availability of CPCI bridges in the market has facilitated the replacement of ageing embedded systems.
3. **Deployment of Linux MRG and Multicore Servers:** An upgrade dating back to 2012, the implementation of Linux MRG and multicore servers for hosting the plasma control system represents a contemporary and state-of-the-art choice in the realm of real-time control.
4. **Adoption of UDP for Real-Time Communication in Plasma Control:** The strategic use of User Datagram Protocol (UDP) for real-time communication in plasma control has emerged as a resilient choice. While alternative technologies like reflective memories are still employed in some experiments, Ethernet, as a mainstream technology, assures an extended life-cycle and a continuously improving performance. This approach aligns with the technology selection at ITER, further validating its robustness.
5. **Hierarchical and distributed architecture of Plant Control:** The modular replacement of obsolete hardware and related software allowed for the saving of resources by retaining several components.

In light of these strategic decisions and adaptations, the evolution of the RFX-mod2 CODAS successfully addresses the challenges posed by the new requirements and budget constraints, ensuring a modern and sustainable system for years to come.

REFERENCES

[1] O. Barana *et al.*, "Data acquisition upgrade in the RFX experiment", *Fusion Eng. Des.*, vol. 74, no. 1-4, pp. 841-845, Nov. 2005. doi:10.1016/j.fusengdes.2005.06.250

[2] O. Barana *et al.*, "Real-time control environment for the RFX experiment", *Fusion Eng. Des.*, vol. 74, no. 1-4, pp. 617-621, Nov. 2005. doi:10.1016/j.fusengdes.2005.06.146

[3] T. Fredian *et al.*, "MDSplus extensions for long pulse experiments", *Fusion Eng. Des.*, vol. 83, no. 1-3, pp. 317-320, Apr. 2008. doi:10.1016/j.fusengdes.2007.08.022

[4] A. C. Neto *et al.*, "MARTe: A Multiplatform Real-Time Framework", *IEEE Trans. Nucl. Sci.*, vol. 57, no. 2, pp. 479-486, Apr. 2010. doi:10.1109/TNS.2009.2037815

[5] A. J. N. Batista *et al.*, "F4E prototype of a chopper digital integrator for the ITER magnetics", *Fusion Eng. Des.*, vol. 123, pp. 1025-1028, Nov. 2017. doi:10.1016/j.fusengdes.2017.02.024

ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-TUPDP042

[6] N. Marconato *et al.*, "Accurate Magnetic Sensor System Integrated Design", *Sensors*, vol. 20, no. 10, p. 2929, May 2020. doi:10.3390/s20102929

[7] A. J. N. Batista *et al.*, "ATCA control system hardware for the plasma vertical stabilization in the JET tokamak", *in Proc. 2009 16th IEEE-NPSS Real Time Conference*, Beijing, China, Nov. 2009, pp. 308-313. doi:10.1109/RTC.2009.5321967

[8] PicoZed board, https://www.avnet.com/wps/portal/us/products/avnet-boards/avnet-board-families/picozed/

[9] G. Manduchi *et al.*, "The New Feedback Control System of RFX-mod Based on the MARTe Real-Time Framework", *IEEE Trans. Nucl. Sci.*, vol. 61, no. 3, pp. 1219-1221, Jun. 2014. doi:10.1109/TNS.2014.2321185

[10] G. Manduchi *et al.*, "MARTe2 and MDSplus integration for a comprehensive Fast Control and Data Acquisition System", *Fusion Eng. Des.*, vol. 161, p. 111892, Dec. 2020. doi:10.1016/j.fusengdes.2020.111892

[11] O. Barana *et al.*, "A general-purpose Java tool for action dispatching and supervision in nuclear fusion experiments", *IEEE Trans. Nucl. Sci.*, vol. 49, no. 2, pp. 469-473, Apr. 2002. doi:10.1109/TNS.2002.1003777