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FINAL DESIGN OF CONTROL AND DATA ACQUISITION SYSTEM FOR THE ITER HEATING NEUTRAL BEAM INJECTOR TEST BED

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Abstract

Tokamaks use heating neutral beam (HNB) injectors to reach fusion conditions and drive plasma current. ITER, the large international tokamak, will have three high-energy, high-power (1MeV, 16.5MW) HNBs. MITICA, the ITER HNB test bed, is being built at the ITER Neutral Beam Test Facility, Italy, to develop and test the ITER HNB, whose requirements are far beyond the current HNB technology. MITICA operates in a pulsed way with pulse duration up to 3600s and 25% duty cycle. It requires a complex control and data acquisition system (CODAS) to provide supervisory and plant control, monitoring, fast real-time control, data acquisition and archiving, data access, and operator interface. The control infrastructure consists of two parts: central and plant system CODAS. The former provides high-level resources such as servers and a central archive for experimental data. The latter manages the MITICA plant units, i.e., components that generally execute a specific function, such as power supply, vacuum pumping, or scientific parameter measurements. CODAS integrates various technologies to implement the required functions and meet the associated requirements. Our paper presents the CODAS requirements and architecture based on the experience gained with SPIDER, the ITER full-size beam synchronization, fast real-time control, software development for long-lasting experiments, system commissioning and integration.

INTRODUCTION

MITICA (Megavolt ITER Injector and Concept Advancement) is an experimental device located at the Neutral Beam Test Facilities (NBTF) in Padova, Italy [1]. Its primary purpose is to develop and test high-energy heating neutral beam injectors (HNB) for ITER, the International Thermonuclear Experimental Reactor [2]. Table 1 reports the MITICA requirements.

The MITICA experiment [3] consists of various components, including the beam source to generate the ionized gas, the accelerator to accelerate the ions through an electrostatic voltage gap of up to 1MV, the neutralizer to make the beam neutral, the residual ion dump to deflect the residual ionized particles from the neutral beam, and the calorimeter, which serves as a target for the neutralized beam.

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Table 1: MITICA Key Requirements

	Unit	H	D
Beam Energy	keV	870	1000
Acceleration ion current	A	46	40
Max beam source filling pressure	Pa	0.3	0.3
Max deviation from uniformity	%	±10	±10
Beamlet divergence	mrad	≤ 7	≤ 7
Beam on time	s	3600	3600
Duty cycle on/off		25%	25%
Co-extracted electron fraction		< 5%	< 1%

Various power supply systems provide the necessary electrical power. A series of power supply units known as the Ion Source and Extraction Power Supply (ISEPS) power the beam source. The Acceleration Grids Power Supply (AGPS) and the Ground Related Power Supply (GRPS) energize the acceleration grids and the residual ion dump, respectively.

In MITICA, there are other components: the Cooling System to remove heat from all heated components, the Gas and Vacuum System to create the high-vacuum conditions in the MITICA vessels and provide the gas feed for beam creation and neutralization, and the Cryogenic System to feed the cryogenic pumps with cryogenic coolant. These components are referred to as auxiliary plant systems because they are needed for the HNB operation in the NBTF but are not part of the HNB system itself.

This paper reports the design of the MITICA Control and Data Acquisition System (CODAS) that monitors and controls the other plant systems and acquires and manages the experimental data. After a brief overview of the CODAS architecture, we will present its integration with the other plant systems. Then, we will introduce the strategies adopted to develop CODAS in a long-lasting experiment framework. Finally, we will discuss the advantages of the synchronization network already implemented in MITICA.

MITICA CODAS ARCHITECTURE

Functions

MITICA CODAS consists of two main parts: Central and Plant System CODAS. The former provides central functions, such as long-term data storage, supervisory control,

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and top-level graphical user interface, while the latter implements the interface with plant components (plant units), including plant unit control, data acquisition, and Human-Machine Interface (HMI). We grouped the plant units in three plant systems: the HNB, the auxiliary, and the diagnostic plant systems. The first one includes all the plant units that are part of the ITER HNB itself (power supply, thermal monitoring, and Caesium diffusion), the second one manages the services, such as the cooling, gas and vacuum, and the cryogenic systems, and the third one deals with the MITICA diagnostic systems for scientific measurements, such as beam tomography, emission and absorption spectroscopy, neutron monitor, and langmuir probe diagnostic systems.

Requirements

Table 2 reports the overall MITICA CODAS requirements.

Table 2: MITICA CODAS Requirements

	Unit	Figure
Plant Units	No.	20
Process variables	No.	20000
Real time cycle time	ms	1
Diagnostic measurements	No.	1000
Max sampling frequency	MS/s	2
Image frame rate (4800 px)	FPS	25/50
Image frame rate (1920x1200 px)	FPS	10
Max diagnostic data throughput	MB/s	200
Expected daily data amount	TB	< 1
Expected annual data amount	TB	< 100

Software Environment

MITICA CODAS is built on three software frameworks: ITER CODAC Core System (CCS) for monitoring, supervisory functions, and timing synchronization [4]; MDSplus for data management (data acquisition, storage, and access) [5]; and MARTe2 for real-time operations [6]. Figure 1 shows the interaction among the software frameworks, where data exchange is provided through EPICS channel access, which conveys information between each other. CCS is naturally based on EPICS channel access, while we developed the needed channel access interface for MDSplus and MARTe2.

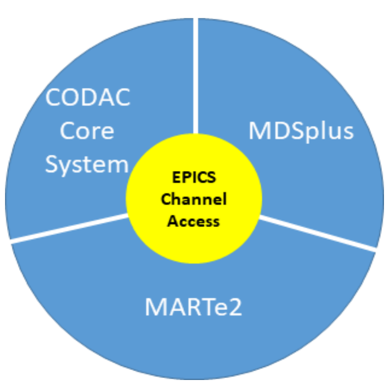

Figure 1: Integration of software frameworks.

Control and Data Acquisition

The integration of plant unit slow control with CODAC is achieved through EPICS Input Output Controllers (IOCs) [7]. An IOC has been implemented for each plant unit slow controller. The slow controllers are Siemens PLCs, as for ITER CODAC requirements [8], and the communication between IOCs and PLCs is accomplished via the S7 protocol. The plant system IOCs publish plant variables as EPICS Process Variables (PVs). The MDSplus pulse files records all the PVs produced by the plant units for long-term data storage. PVs are acquired on variation, and the maximum sample rate can reach up to 20–30 S/s.

CODAS implements fast real-time control by running MARTe2 applications on Linux servers. Fast control provides real-time driving of power supply and management of breakdown events, which are electrical discharges on the acceleration grids due to applied high-voltage and narrow vacuum insulated gaps. Breakdowns are common during normal operation. They are not faults but must be promptly handled to avoid damage to the acceleration grids and power supply systems. When a breakdown event is detected, the fast control must promptly turn off the power supply units (hardware command in less than 1 µs) and, after a predefined time window required to restore insulation (20 ms), must gradually restore power to the grids and ion source.

Data acquisition in the power supply systems must be implemented in both continuous and event-driven modes. In event-driven mode, signals are sampled at high sampling rate (2 MS/s) in a predefined time-window (typically 1 ms) centered on a given event (typically a breakdown). This acquisition is performed using National Instruments ADC PXIe-6368 (16 channels, up to 2 MSps) modules for ISEPS, AGPS, and GRPS plant units. For AGPS, an acquisition system based on compactRIO technology has also been implemented. Table 3 reports the number of the power supply signals and their acquisition mode.

Table 3: Power Supply Signals

	I/O	Sample rate	Mode
AGPS & ISEPS	15	10 kS/s	Continuous
		2 MS/s	Event-driven
AGPS	88	20 kS/s	Continuous
ISEPS	44	20 kS/s	Continuous

As an example, Fig. 2 illustrates the HNB plant control system, with industrial procurement components shown in white and CODAS components in green. The blue rectangle represents the HNB control system, which will interface with the ITER CODAC control system at the ITER site through various networks: Data Archive Network (DAN), Timing Communication Network (TCN), Synchronous Data Network (SDN), and Plant Operation Network (PON) [9]. Components outside the blue rectangle show the CODAS components necessary to manage the MITICA experiment at the NBTF.

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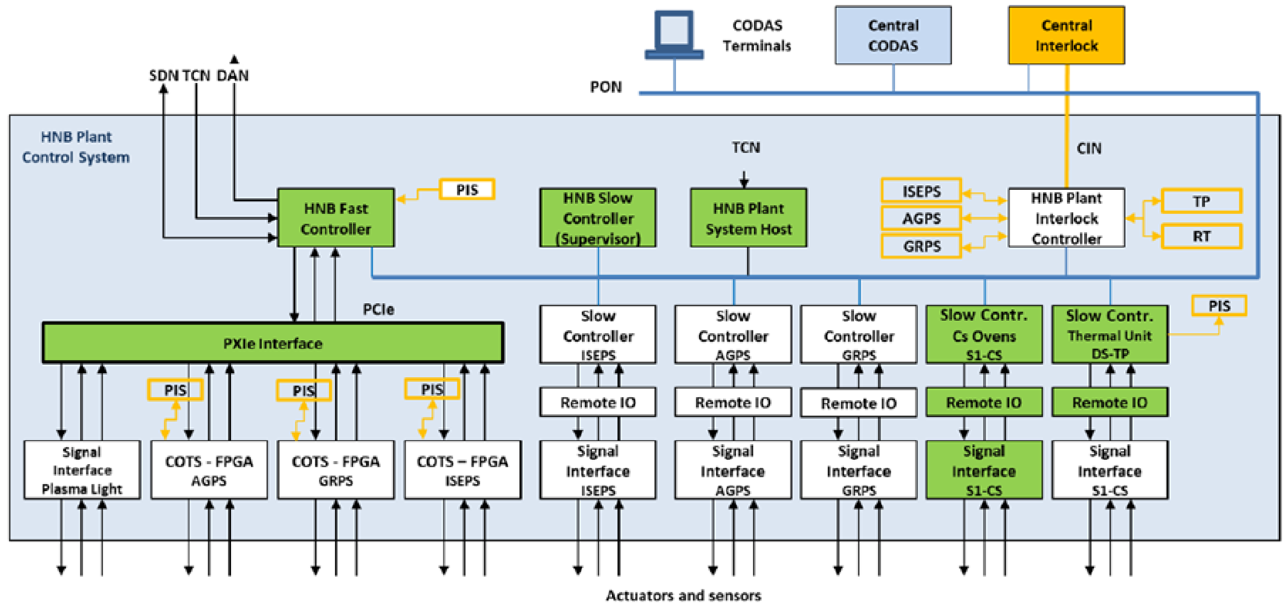

Figure 2: HNB plant system.

SYSTEM ACCEPTANCE AND COMMISSIONING

The approval process for plant supplies consists of multiple sequential phases. The first one is the FAT (Factory Acceptance Test), during which the supplier verifies the main functions of the system. Typically, it is not always possible to test the entire plant unit at this stage, often only some of its parts can be tested. After the installation in the NBTF, the acceptance tests follow, during which the entire system is tested under the supervision of the company that developed it. These campaigns are conducted utilizing the local HMI, aimed at identifying critical issues and swiftly addressing them. Hence, based on the experience gained in SPIDER, it has been noticed that even during the final phase, it is useful to test the interface with CODAS to identify any communication issues with the system. It has been observed that, in many cases, more emphasis is placed on the plant field aspects than on the interface with CODAS, which can lead to longer integration times in subsequent phases.

Once the SATs (Site Acceptance Tests) are completed and the formal authorizations are obtained to operate the system without the supervision of the supplier company, the actual commissioning phase begins. Now CODAS remotely controls completely all the systems involved in the experimental sessions. In the initial 'one2one' phase, each system is exclusively connected to CODAS. All operational scenarios are tested accurately, including error signal verification by using forcing or simulation procedures, and ensuring the correct signaling of states and commands through the system's HMI. In the SPIDER project, it proved beneficial to design the CODAS HMI to closely resemble the HMI on the local panel, providing plant experts with a unified view of the plant through the HMI.

INTEGRATION

After the completion of the one2one commissioning phase, the system needs to be integrated with other commissioned plant units. During the integration phase, the system interacts with the other ones, making the presence of an Interlock system of paramount importance. The Interlock system serves the critical function of safeguarding against the propagation of faults from one subsystem to others, thus preventing potential damage. To carry out this phase effectively, the Interlock system must be sufficiently flexible to facilitate the monitoring of the other plant units and the testing of all the fault signals. SPIDER's experience highlighted that the design solutions of the Interlock system were flexible enough to simplify the systems integration phase [10].

DATA ACQUISITION

MITICA posed several challenges for data acquisition, on line analysis management and data storage. The long duration of the experiment, that may last up to one hour, requires indeed a change in paradigm with respect to the data acquisition functions formerly handled in short duration experiments. In typical short plasma sessions, it's customary to store collected data in local device memory and subsequently transfer it to the central database after the experiment. However, in the case of MITICA, a continuous data streaming solution is crucial, encompassing all components of data acquisition, from sensor inputs to data communication and storage in the central database. At any time, the data acquired must be available to be accessed to allow the execution of online analysis software that otherwise would need to be deferred until the end of the experiment. The underlying data system must therefore be able to withstand the sustained data flow from a distributed set of sensors to the database as well as to provide readily data access at

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any time. As the system is inherently distributed, data flow in both directions (data storage and data access) possibly involves TCP/IP communication that must be handled by the data systems themselves. Moreover, a multi writer and multi reader configuration must be supported because of the several actors that are involved both in data acquisition (i.e. the data acquisition tasks and the analysis tasks producing new elaborated data to be stored in the central database) and data readout (i.e. data access for online visualization and analysis). All the presented functions are provided by the MDSplus data acquisition system adopted in many lasting applications in fusion research. The requirements derived from such experiments, as well as from other long lasting projects such as EAST in China and the Gyrotron test Facility in Switzerland, drove the evolution of the MDSplus systems in the last ten years to fully support the new requirements. Even if the required functions are provided by MDSplus, the proper configuration of the whole system is not an easy task because of the bottlenecks in the data transfers that can affect the overall system performance. From our experience, the following guidelines should be followed to tune the system to achieve the best data throughput.

Parallelize Data Acquisition

Distributing data acquisition in different plant systems avoids creating bottlenecks due to the management of an excessive number of data acquisition channels by means of a single system. In our distributed topology, the most critical component is the central data server hosting the experiment database. Such a server must equip fast SSD disks for data storage, and provides an enough large number of processors and redundant network boards to parallelize as far as possible the data flow from different clients. The centralized data server solution has been preferred to a distributed one, even if the latter is also supported by MDSplus. However, distributed data storage presents several problems, mainly due to (a) the increased difficulty in the management of data spread around several databases (even if synchronized with each other) and (b) the need to equip plant systems with more expensive solutions for local data storage.

Optimize Data Throughput

As a general rule of thumb, larger buffers in data streaming produce better throughput. In our distributed data acquisition architectures, buffer sizes affect both network communication and storage in the database. MDSplus provides an important concept related to buffering: segment size. Data streaming is achieved in MDSplus by handling chunks of new data samples and appending them into existing signal representations in the database. All the segments for a given signal stored in the MDplus database can at any time be retrieved as a whole signal (or only a subset of segments if a Region of Interest (ROI) is defined). The size of the data segments has a dual impact, influencing both network communication, managed by MDSplus in remote data access, and the efficiency of data storage. In general, larger

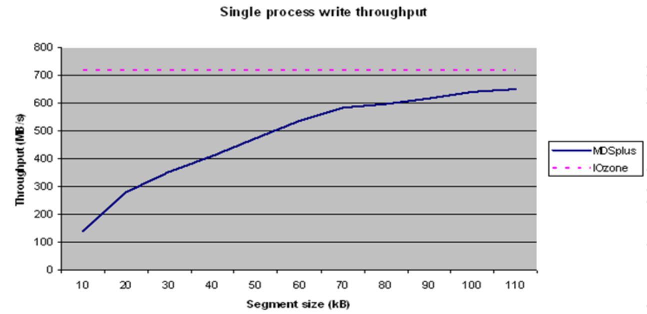

Figure 3: Impact of MDSplus segment size on data exchange throughput.

segments enhance data throughput improving overall system performance, as shown in Fig. 3. However, using larger segment sizes results into reducing the frequency at which new data is made available for access in the database since the segment must be filled before being transferred into the database. A trade-off must be therefore defined between larger segment sizes and readiness in data availability. As a practical rule, ensuring a maximum delay of about one second between data acquisition and their availability is a reasonable approach. This means that the choice of segment size should be tailored to the specific sampling speed to meet this time-frame effectively.

Provide Diagnostic Tools

Identifying bottlenecks in data streaming is a challenging task, often leading to a pervasive decline in the overall system's performance. This decline can be caused by various factors, including sub-optimal configuration settings (such as using small segment sizes), communication disruptions, and unexpected spikes in system loads. Hence, a prompt identification of the faulty or misconfigured components is crucial, especially when degradation is observed during experimental sessions.

PLANT SYSTEMS SYNCHRONIZATION

In MITICA, extended experiment sessions may rise synchronization issues. When a pulse lasts a few milliseconds, all the plant systems involved are triggered at the same time to execute the desired actions in a very small time frame. Over the course of milliseconds, synchronization becomes less critical as the pulse is so fast to minimize the impact of any clock drift in the devices. Instead, in the long lasting experiments scenario the absence of a good synchronization among the plant systems can potentially result in data loss or even in critical situations. A breakdown event, very common in fusion science experiments, is the perfect example to explain the aforementioned issues. It is evident that the response time to such events in each plant system must be minimized, and this objective can only be realized when all devices operate simultaneously with a very small delay.

MITICA Time Communication Network

MITICA, as part of the ITER project, is required to fulfill synchronization requirements. More specifically, the

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Root Mean Square (RMS) of the delay between the various plant units has to be less that 50ns. To ensure such a precise synchronization, MITICA implements the TCN that, based on the Precision Time Protocol (PTP) IEEE1588, ensures the asked synchronization between the connected devices. PTP is a network communication protocol used for precise synchronization of clocks in distributed systems. It achieves microsecond-level accuracy, critical in applications like industrial automation and telecommunications. PTP relies on timestamping packets, compensating for network delays, and adjusting clock rates to ensure synchronized time across devices. Above the other features that make this protocol widely used, it operates on standard Ethernet networks, making it compatible and easy to implement.
The TCN network together with its APIs developed by ITER have been tested and already built in Consorzio RFX in Padua. Since the network involves tens of devices, to validate the project we performed diverse small test campaigns in the initial phases to understand if the selected hardware was in line with the ITER requirements. Successively, we simulated the whole topology with an open-source software named Omnet++ and verified the correctness of our choices.

Lazy Trigger

The Lazy trigger is a widely used trigger mechanism adopted in NBTF. In conventional timing infrastructures, triggers are conventionally encoded within the reference clock signal, subsequently distributed to synchronize all timing devices. Nevertheless, in scenarios where this established link is absent, the Ethernet connection emerges as the sole viable medium for facilitating trigger communication. To compensate for the latency and variability of the trigger, the event is tagged with its precise absolute timestamp denoting its occurrence. This necessitates that the device responsible for event detection possesses knowledge of the absolute time. In the context of NBTF, this capability is achieved by the PXI-6683H, an advanced timing device with PTP awareness. The lazy trigger is adopted, for example, for multi-speed acquisition [11] that allows to increase the sampling rate when a certain event is detected on the network. In this way, critical events as breakdowns can be acquired at very high sampling rates only when they occur, without impacting the storage capabilities.

CONCLUSION

This paper enlightens the evolution of the MITICA experiment control system, emphasizing the strategies addressed to fulfill the requirements of long-lasting experiments. From the design phase to the integration one, the SPIDER experience guided the definition of MITICA CODAS in each of its aspects. This is true not only for the macroscopic tasks handling the interface of each plant unit with the control system, but also for the microscopic ones that deepen the data acquisition design to maximize the efficiency of our acquisition system. Then, the importance of a good synchronization between all the MITICA components is presented to highlight how the performance of the control system is enhanced both from a software point of view and a hardware one.

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