Preparation of W7-X CoDaC for OP2

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***Abstract*— The superconducting stellarator Wendelstein 7-X has successfully concluded its third operation phase in October 2018. The machine will see substantial changes during the next two years, when an actively cooled divertor will be installed, as well as many new diagnostic systems. The W7-X Control, Data Acquisition and Communication (CoDaC) group is responsible for the integration of all new diagnostics into the W7-X control ecosystem (around 10 systems) as well as carrying out significant upgrades to the I&C and data acquisition of another 15 systems.**

This paper will present an overview of the integration challenges for Operation Phase 2 (OP2) both from a technical perspective as well as highlight the strategy employed by the W7-X CoDaC group to meet those challenges within the time and resource budget. The cornerstone for this strategy is standardization as far as possible to minimize individual integration effort.

Siemens PLCs already handle general slow control throughout the project. However, up to now the integration work is still predominantly done fully in-house. In order to handle the large scope of work within the time budget, CoDaC will have to be in a position to outsource a significant part of the work. In addition, efforts are under way to make validation and commissioning of the central systems as efficient as possible using modelling and simulation environments as well as industry standard requirements management.

***Index Terms*— Nuclear Fusion, Control Systems, Systems Integration**

I. Introduction

THE superconducting fusion experiment Wendelstein 7-X (W7-X) is a stellarator with capability for steady state plasma operation. Since the original commissioning of W7-X in December 2015, three extremely successful operation phases were carried out [1], comprising a total number of 4067 plasma discharges during 117 experiment operation days. The high availability and performance of the W7-X systems were the basis for the outstanding experimental physics results obtained [2]. The machine is currently shut down while major modifications are carried out. The main focus is on the installation of actively cooled plasma-facing components together with a high heatflux divertor. Apart from the mechanical modifications to the machine, a number of other machine components will be integrated ranging from 10 new and 15 significantly expanded diagnostics to new heating systems, notably the Ion Cyclotron Heating. Some of those have been operating autonomously with only minimum integration into the central infrastructure up to now. This was due to time and resource constraints during the previous operating phases. In addition, significant changes and enhancements are foreseen to the Central Safety System (cSS) and Central Operations Management (cOPM) as well as a number of other machine systems, e.g. the integration of 10 cryogenic pumps.

The amount of work can only be accomplished in time and on budget, when relying heavily on standardization in order to minimize individual integration effort. One example for the video diagnostics is the development of a generic, flexible and scalable camera acquisition framework based on µTCA hardware for cameralink, camerlink HS and GigEVision. This will enable CoDaC to compartmentalize the specifics of any individual camera - provided it is compliant with the aforementioned standards – and treat all cameras virtually identically for integration purposes.

In addition to standardization, the CoDaC group is focusing its efforts to be in a position to utilize external companies to implement a lot of the work. This requires a testing and simulation infrastructure such that external partners can develop and test according to the W7-X needs and deliver fully functional and fully tested systems limiting the risk of major refactoring work after delivery.

An overview of the W7-X control system and the modifications of the central components is presented in section II, followed by the standardization strategy for both hard- and software in sections III to VI.

II. Overview of the W7-X Control System

A general overview about the structure of W7-X control system is given in Figure 1. The structure of the control system follows the standard two-tier approach with safety and fast interlock isolated from the standard control components. Tasks are delegated to the local level wherever feasible to avoid overcrowding the central components. The central group includes the central Operational Management (cOPM), the central Safety System (cSS), the central Fast Interlock System (cFIS), and the central Segment Control System. The cSS is currently undergoing significant enhancement to cope with the numerous additional systems requiring an interface to the cSS. A new requirements analysis was conducted to limit the amount of safety functions and to streamline the architecture. This

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pertains in particular to the implementation of a standardized interface to all plant systems. More details can be found in [4].

The technical systems (e.g. vacuum systems, plasma heating systems, gas supply and gas inlet systems, power supplies for the magnet systems) and diagnostic systems (operational diagnostics, plasma diagnostics) form the lower layer of the control structure. All sensors and actuators are part of the technical and diagnostic components. The segment control system is used to start and execute an experiment program and perform all tasks pertaining to real-time control. Further information can be found in [3].

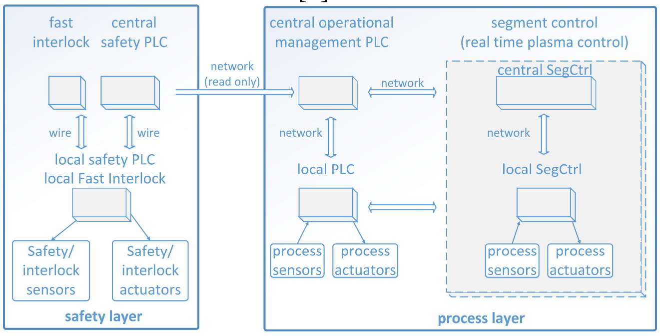

Figure 1: Overview of the W7-X Control System [4]

III. STANDARDIZATION OF CAMERA INTEGRATION – HARDWARE

A large number of camera systems will be installed in W7-X during the shutdown, most notably for divertor monitoring and protection. The physics requirements for the camera systems are rather diverse and mandate a number of different camera types ranging from visible to infrared with various data rates. While industry has made efforts to standardize the data interface of the cameras, at least 4 types are currently in use at W7-X, namely Camera Link, Camera Link HS, FireWire and GigE Vision. The cameras are typically delivered with their own framegrabber and driver, making each camera a bespoke system and hence the conglomerate almost unmaintainable.

A. Framegrabber and chassis standard

To address this challenge, IPP and the Department of Microelectronics and Computer Science of Lodz University are collaborating on a common hardware platform, which allows integration of all those types with minimal hardware changes and no software modifications at the driver level [5]. A typical setup is shown in Figure 2. It is based on the µTCA platform which was already in use as a standard in W7-X for other data acquisition purposes. This relatively recent platform makes use of the PCI Express (PCIe) backplane and can be considered future proof as more and more cards for the use in large-scale physics experiments are being developed. The default implementation of the Intelligent Platform Monitoring Interface (IPMI) for all cards allows for easy central monitoring and maintenance of a large number of crates and boards [6]. A CPU is typically added as an Advanced Mezzanine Card (AMC) module, but high-performance PCIe extenders are also available which enable the use of common industry PCs for processing, treating the µTCA crate effectively as external PCIe periphery.

Lodz University has developed a custom framegrabber consisting of a FPGA carrier board with two FPGA Mezzanine Cards (FMC) slots [7]. Adapter cards have been developed for the Camera Link [8] and COAXpress [9] interface, mapping the FPGA pins to the connector. Similar boards will be developed for the other standards in use at W7-X. This makes it possible to use one carrier board for all types of cameras.

B. Timing

In the current configuration, an IEEE 1588-2008 compatible timing module delivers precise time to the FPGA of the framegrabber. This allows for the exact generation of triggers and timestamps. It simplifies the triggering architecture as external components are not needed and triggers can be sent via the standardized pins of the cable. In case an external trigger is necessary, an FMC module exists which delivers the appropriate digital output for the FPGA generated triggers. A significant advantage of this approach is that timestamps with 50 ns accuracy can be attached to the raw images in the FPGA directly after they have been acquired [10].

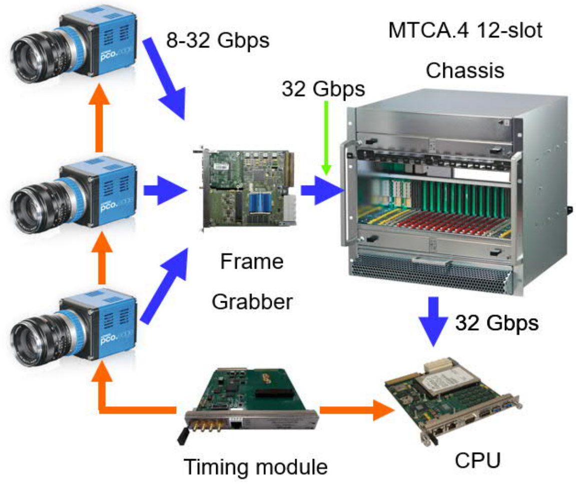

Figure 2: Typical configuration of a camera DAQ system

IV. STANDARDIZATION OF CAMERA INTEGRATION – SOFTWARE

While the firmware has to be adapted for each type of camera interface, there is still a high degree of modularity. Hence, necessary changes to accommodate a different camera interface can be well contained (see Figure 3). The firmware architecture separates three paths, one for video data from camera to PCIe interface, a control path to the camera serial interface and a separate timing and trigger module. The FPGA has resources to spare, so that additional bespoke algorithms may be included in the processing chain. Further details on the firmware and software architecture can be found in [11].

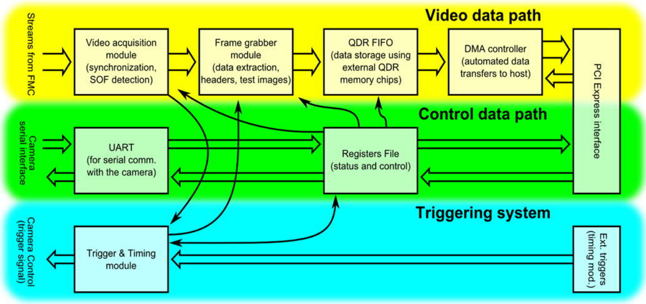

Figure 3: Image Acquisition and Processing Firmware Structure

A typical headache in dealing with bespoke framegrabbers is the lack of abstraction for higher-level software, which requires the implementer to deal with a specific API per system. If on top of that the drivers are only available for one operating system, it makes managing the infrastructure a challenge and requires significant additional resources. The driver framework of our generic framegrabber addresses this issue by employing a high degree of abstraction. It presents an identical API for all camera types to the user (or a high-level orchestration framework such as EPICS [12] or DOOCS [13]). As serial control is not fully standardized in the Camera Link industry standard, it an additional library is required between user and the linux driver, which maps the generic API call to the specific implementation of each camera. This has to be implemented for any new camera, but is a very small effort.

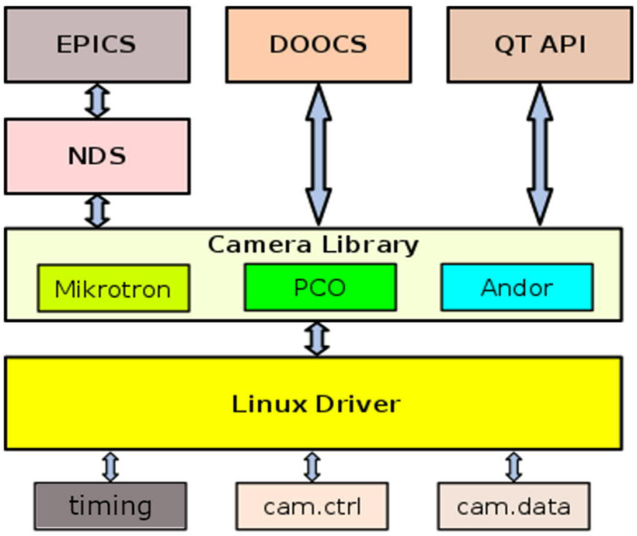

Figure 4: Software Stack

V. Standardization of Interfaces – Generic Resource Interface

Due to resource constraints towards the end of the initial W7-X construction phase, not all diagnostics could be fully integrated into W7-X CoDaC. This led to the use of a parallel infrastructure based on MDS+ [14] to enable the rapid deployment of additional diagnostic systems. It was clear and accepted that this would be a temporary solution, which would eventually be replaced. During operation, it became clear that this setup has significant limitations, notably the delayed and slow upload of data to the W7-X central archive for non-integrated diagnostics and the lack of state machine integration of the diagnostics. The interface to the central W7-X data acquisition infrastructure was limited to a start trigger. The result of this was that no automatic status query was possible for non-integrated diagnostics. System readiness had to be ensured by verbal communication between Responsible Officer and experiment leader.

In order to improve the situation, the CoDaC section developed a well-defined, language-agnostic API (**Ge**neric **R**esource **I**nterface) to the central services (segment control, archive and automation) which can be implemented on the diagnostic side using a number of different programming languages (stub compilers are available for C/C++, Java, Python and many more). This was a novel approach for W7-X, where the initial philosophy had been to either fully integrate a system or only provide existential support (trigger and network).

This interface has been developed, tested and initial results are presented in [15]. It will be deployed for practically all MDS+ based diagnostics for the upcoming operation phase. The interface is quite performant and an existing MDS+ based diagnostic can be adapted very quickly. This will allow keeping existing hardware and parts of already developed bespoke configuration/operation software in place but still achieve the following main objectives:

a) *All systems are orchestrated by the central operational management*

b) *All systems stream directly to the W7-X archive*

c) *All systems can -if necessary- interface to W7-X segment control.*

d) *All systems can use the central W7-X live monitoring system*

MDS+ will still have its place in the W7-X control ecosystem, as it is very well suited for rapid prototyping of diagnostics especially if external collaborators are involved who may not be familiar with the W7-X CoDaC infrastructure. However, any permanent installations at W7-X will eventually either be fully integrated into CoDaC (for operationally relevant systems) or use the GeRi interface.

VI. Conclusion

The W7-X CoDaC team faces a set of very challenging tasks during the currently ongoing shut down phase of W7-X. Many new systems need to be integrated or existing systems significantly enhanced. Standardization is the only possible avenue, which allows addressing all tasks within the given time and resource profile. An overview of the upgrades to the central CoDaC systems was presented, as well as an example of such standardization in both hard- and software for one of the most complex diagnostic systems at W7-X, the divertor monitoring and protection system. A new interface was described, which opens the CoDaC infrastructure to externally provided systems with minimal integration effort. We are confident, that the CoDaC team will be able to deliver a comprehensive and fully integrated control environment for the next operation phase of Wendelstein 7-X.

VII. ACKNOWLEDGMENTS

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