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Overview of the COMPASS CODAC system

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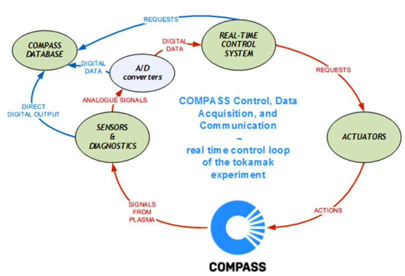
HIGHLIGHTS

- Overview of the Control, Data Acquisition, and Communication system (CODAC) on the COMPASS tokamak.
- Set-up of CODAC hardware, software implementation, and communication tools.
- Feedback control of COMPASS plasma using the MARTe framework.
- Actuators, data sources, and data acquisition systems employed on COMPASS.
- Communication links and protocols used within the COMPASS CODAC.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents an overview of the Control, Data Acquisition, and Communication system (CODAC) at the COMPASS tokamak: the hardware set-up, software implementation, and communication tools are described.

The diagnostics and the data acquisition are tailored for high spatial and temporal resolution required by the COMPASS physics programme, which aims namely at studies of the plasma edge, pedestal, and Scrape-off-Layer (SOL). Studies of instabilities and turbulence are also an integral part of the programme. Therefore, the data acquisition consists of more than 1000 channels, sampled at rates from 500 kS/s up to 2 GS/s.

Presently, the feedback system controls the plasma position and shape, plasma current, and density and it includes 32 analogue input channels as well as 1 digital input/output channel and 8 analogue outputs. The feedback control runs within the Multi-threaded Application Real-Time executor (MARTe) framework with two threads, a 500 μs cycle to control slow systems and a 50 μs cycle to control the fast feedback power supplies for plasma position control.

In this paper, special attention is paid to the links between the systems, to the hardware and software connections, and to the communication. The hardware part is described, the software framework is addressed, and the particular implementation – the dedicated software modules, communication protocols, and links to the database are described.

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1. Introduction

COMPASS is a tokamak with $R = 0.56$ m, $a = 0.18 \div 0.23$ m, $I_{pl} < 300$ kA, $B_T = 0.9 \div 2.1$ T operated by the Institute of Plasma Physics ASCR in Prague, Czech Republic [1]. The COMPASS tokamak is equipped with a comprehensive set of diagnostics [2] which have outputs either in the form of analogue signals (magnetic sensors, Langmuir probes etc.) or in digital form (e.g. cameras observing plasma in visible as well as infra-red spectra). Moreover, the actuators available on COMPASS are characterized by different characteristic response times and communication interfaces. The different characteristics of the sensors and diagnostics systems as well as capabilities of the actuators set complex requirements on the Control, Data Acquisition, and Communication (CODAC), which results in a heterogeneous system.

This paper gives an overview of the COMPASS CODAC hardware and software elements, data flow, and communication links. The key parts of the system are depicted in Fig. 1 which shows the data flow from the sensors and diagnostic systems through the real-time control loop to the actuators, and to the database. The data post-processing is also marked there. Individual elements shown in the scheme are addressed in more detail further in the text. Section 2 describes the elements and tools used for the experiment set-up and control, including timing, triggering, the digital real-time feedback, and the actuators. Section 3 gives an overview of the existing data sources, available A/D (analogue to digital) converters, and their link to the database. Section 4 presents the links involved in the communication among individual nodes.

2. Control

The overall COMPASS operation is managed by several systems. Each of these systems is responsible for a particular part of the control, data acquisition, and/or communication. Typically, the system runs on a dedicated server and has its own user/operator interface. Individual components of the control system are depicted schematically in Fig. 2 and detailed in the following sections.

2.1. Experiment control – FireSignal

The top level control of the experiment uses the control and data acquisition software FireSignal [3], developed by IST Lisbon. FireSignal is a modular system, whose core is based on XML, Java, and CORBA technologies; several different modules provide the functionality of the whole system.

FireSignal central server manages connections to individual nodes and set-up of data acquisition systems (sampling rate, record length, etc.) as well as of other nodes. The software nodes, usually written in C++, control particular subsystems (data acquisition, timing, real-time system) and their links to the central server. Three additional modules are a part of FireSignal: database controller, security manager (authentication), and optionally user clients, i.e. graphical user interfaces.

All software components are connected through CORBA that allows them to run in different operating systems and to be written in different languages (Java, C++, and Python are used on COMPASS).

Particular features of the FireSignal system were adopted to COMPASS special needs by IPP Prague. The database controller and client GUI (Graphical User Interface) were modified to use the COMPASS DataBase (CDB, [4]) instead of the integrated PostgreSQL database. Data acquisition nodes were enabled to write directly to the CDB so that the data traffic through the central server can be substantially reduced; this feature is presently used for newly implemented nodes. Few changes were also implemented within the client GUI in order to help operators with the configuration of nodes and checks during the shot launching [5].

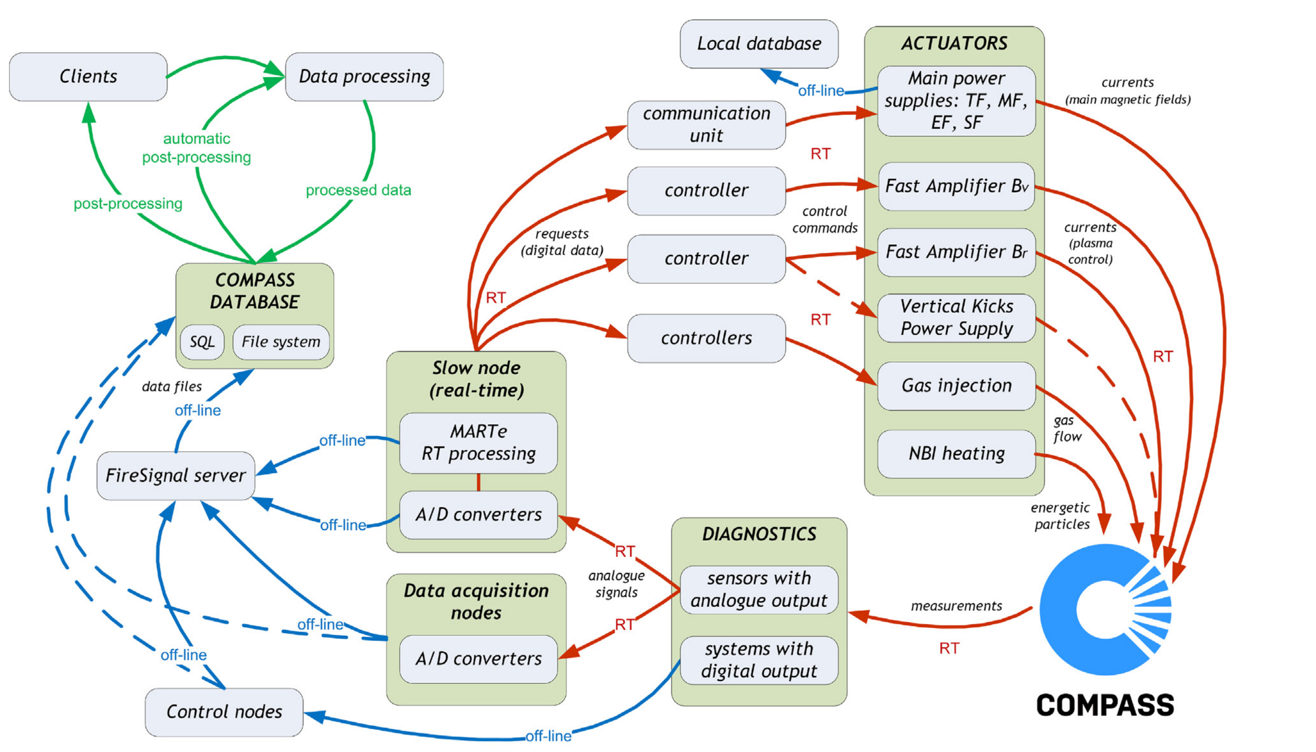

Fig. 1. Scheme of data flow in the COMPASS CODAC: feedback control from the COMPASS diagnostics through the digital real-time control loop to the actuators ("RT", marked by red arrows); data storage ("off-line", blue); post-processing of the data ("post-processing" and "processed data", green). Full lines denote the standard data flow, dashed lines show the options that are being implemented currently. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

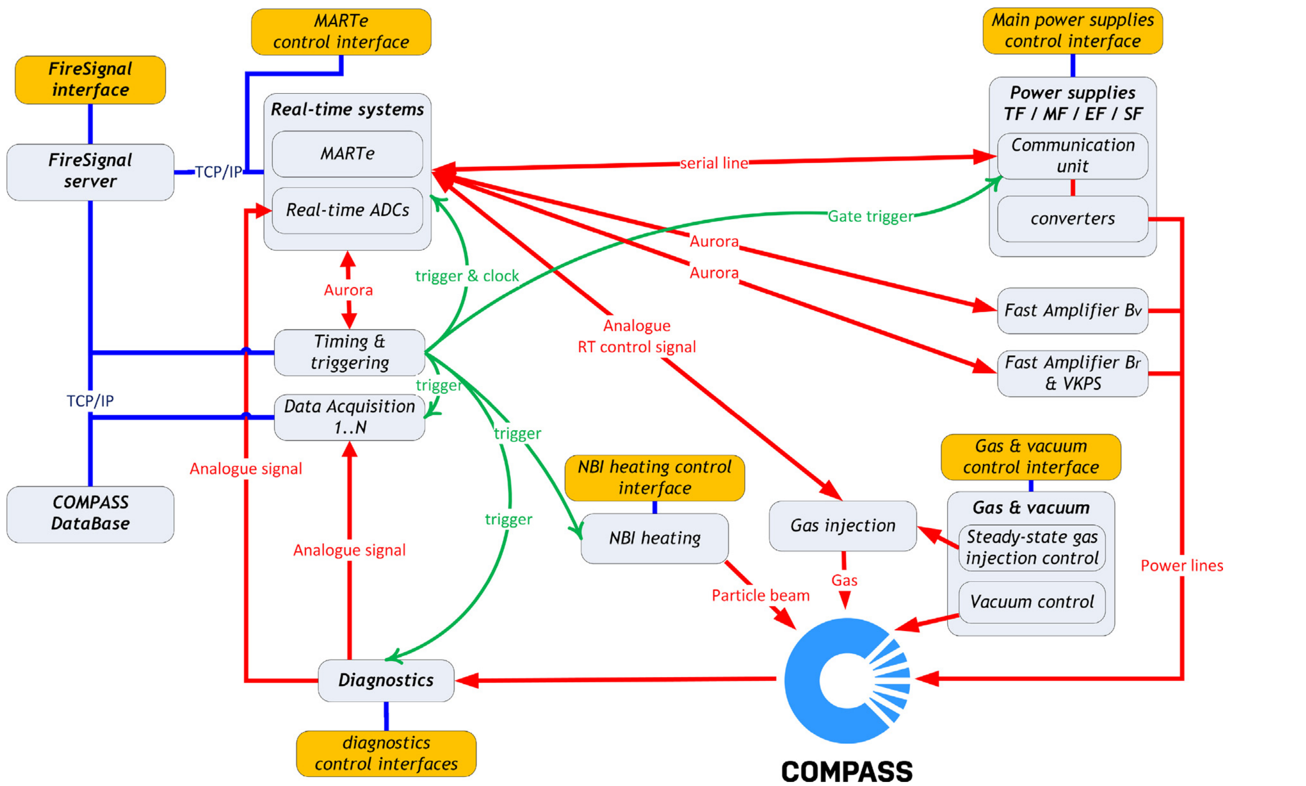

Fig. 2. Control and communication: grey boxes represent the elements of the COMPASS CODAC system (central FireSignal server, ATCA data acquisition and real-time system, other ADCs, timing and triggering node) and actuators (power supplies, gas injection, and auxiliary NBI heating). Yellow boxes denote the operator's interfaces; for completeness, it should be noted here that FABV, FABR and VKPS, and gas injection control set-up is done using configuration files uploaded to MARTe through its control interface before the shot. Ethernet (marked "TCP/IP", blue lines) is used to set-up the systems before the discharge, trigger and clock are distributed via optical links ("trigger", green lines). Real-time loop including signals from the tokamak, communication links from the real-time system to the actuators, and action links from the actuators to the tokamak are marked in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2.2. Real-time framework

The COMPASS real-time (RT) system is based on the Multi-threaded Application Real-Time executor (MARTe [6]), a multi-platform library framework which assures real-time performance within a defined duration of the control loop. MARTe uses blocks of software, called Generic Application Modules (GAMs), which contain the implemented algorithms. Each GAM can be configured, the GAMs can be chained, and they are executed by the real-time scheduler.

COMPASS is one of the first devices where MARTe has been implemented [7,8]. Presently, MARTe is used to control several real-time systems at JET [9] as well as on some other fusion experiments [10]. MARTe on COMPASS runs on two of the ATCA systems (Advanced Telecommunications Computing Architecture, see Section 3.1.1). The real-time system capable to control fully the experiment runs on a 4-core PC in the ATCA1 and it uses one board, i.e. 32 input channels. MARTe on ATCA2 runs as a slave system and is used for test purposes at present. Communication between both RT systems is based on UDP protocol (see also Section 4.3).

The ATCA1 provides an operator web interface for control and detailed monitoring of the status of individual RT system elements and for their configuration. The details of recent MARTe enhancements on COMPASS are presented in [5].

2.3. Feedback control

The COMPASS real-time framework MARTe runs in two threads: a 500 μs cycle is used to control slow systems and a 50 μs cycle to control the fast amplifiers [7].

2.3.1. Slow feedback

Slow control loop controls the plasma current and shape by the poloidal coils currents, created using the power supplies described briefly in Section 2.4.1. Furthermore, it controls also the plasma density by gas injection through a piezoelectric valve as noted in Section 2.4.2; for this purpose, the plasma density is measured by an interferometer.

2.3.2. Fast feedback

The fast control loop is used to control the plasma position using the Fast Amplifiers and the Vertical Kicks Power Supply [11]. The real-time plasma position reconstruction algorithms developed for COMPASS are presented in [12] together with the implementation in MARTe.

The set-up of the feedback parameters, i.e. constants of the PID regulator, requested values of the set-points, etc. is done in configuration files of MARTe. Recent modifications and improvements of the MARTe framework on COMPASS are presented in [5].

At present, MARTe with the implemented algorithms successfully controls the COMPASS discharges in all operational scenarios that were planned for physics exploitation: the circular, elliptic, and diverted plasmas; the ohmic as well as NBI heated discharges; both the L-mode and H-mode (incl. ELMy H-mode) discharges [13].

2.4. Actuators

Presently, COMPASS uses three kinds of actuators: power supplies connected to different tokamak circuits, gas injection valves, and auxiliary heating provided by two Neutral Beam Injection (NBI) systems.

2.4.1. Power supplies

2.4.1.1. AC/DC converters for COMPASS main magnetic fields. As noted above, the slow thread in MARTe controls the thyristor power supplies [14] creating the main magnetic fields in COMPASS: Toroidal Field, Magnetizing Field, Equilibrium Field, and Shaping Field, marked as TF, MF, EF, and SF respectively in Figs. 1 and 2.

The overall power supply system has an autonomous control, fault protection, and communication system running on the Siemens Simatic platform and including e.g. its own local database for operation data, a server and clients based on the Control Web [15], etc. The control from the CODAC side is limited to the exchange of triggers and current set-point requests (see also Section 4.1).

2.4.1.2. Power supplies for fast plasma position control. Two transistor power supplies, named Fast Amplifiers (FAs), are used to control the radial and vertical position of the plasma column by creating corresponding vertical (B_v) and radial (B_r) magnetic fields, by the power supplies FABV and FABR, respectively [11].

Moreover, a dedicated IGBT power supply, called Vertical Kicks Power Supply (VKPS), was built for the ELM control by generation of the vertical kicks, i.e. ELM triggering by fast vertical movements of the plasma column. The VKPS has been built recently and will be connected in series with the FABR to the circuits controlling the vertical plasma position. Both the FABR and VKPS will have a common controller securing the co-ordinated operation of both power supplies [11].

2.4.2. Vacuum and gas handling system

The COMPASS vacuum system consists of several kinds of vacuum pumps, number of valves, shutters, and pressure gauges. The gas injection system uses piezoelectric valves to fill the tokamak vessel with the working gas. In principle, we can distinguish two modes of operation of the vacuum and gas handling system.

First, in the standby mode and during the shot preparation (e.g. standard pumping, vacuum vessel baking, and wall conditioning by glow discharge), the control runs in 24/7 mode and is based on a micro-controller which is located on an electronic board with dedicated input/output circuits. The micro-controller is connected to a server which allows to monitor and control whole system (incl. individual valves, flow-meters, vacuum pumps, shutters etc.) using an operator interface in Java [16].

Second, the gas injection during the experiment is controlled directly from MARTe using one of the analogue outputs on the ATCA RTM (see also Section 3.1.1). During the shot, MARTe switches between pre-programmed waveforms (e.g. for plasma breakdown) and feedback controlled periods (in steady-state) to achieve requested plasma density and optimum behaviour.

2.4.3. Neutral beam heating

Two NBI systems, each with the power of 300 kW, operating at 40 kV [17] are available for heating of the COMPASS plasma. These systems have their own autonomous control with dedicated operator interface as marked also in Fig. 2. A simple pre-programmed feed-forward mode of operation is launched by trigger received from the timing unit noted in Section 2.5. The machine protection uses direct input from diagnostics and can terminate the NBI operation at any time so that the beam can enter the vacuum vessel only when stable plasma column with a given minimum parameters is established.

2.5. Timing and triggering scheme

The central COMPASS timing and triggering system is based on the principles and hardware described in [18].

The so called timing unit is a PC equipped by 24 optical outputs (8× trigger, 8× clock, 8× configurable) and 8 optical inputs for communication. The clock and trigger are distributed by the timing unit via optical cables to the RTMs, start and reset signals via the Aurora link. Moreover, one pair of Aurora links is used to communicate with MARTe on the ATCA1 system in real time.

The timing and triggering system has its own node in FireSignal which allows to set the trigger length and delay on individual channels, the clock rate etc. The inputs are used for communication and synchronization with other subsystems, like e.g. the AC/DC converters (see Section 2.4.1).

In addition, a new synchronization and event triggering unit for the COMPASS Thomson scattering diagnostics [19] has been developed recently. The unit is based on a FPGA (Field Programmable Gate Array) and allows to develop complex timing and triggering schemes for the high-power lasers [20], incl. event-driven triggering. Since the lasers belong to systems which require several minutes of preparation before the discharge, a dedicated GAM for the real-time framework was developed and implemented in MARTe, corresponding hardware was modified and FireSignal was upgraded to deliver triggers before the start of the toroidal magnetic field ramp-up.

3. Data sources and data acquisition

The COMPASS diagnostics [2] deliver two kinds of outputs: analogue signals and/or digital data as marked in Fig. 1. The links between the A/D converters (ADCs), central system, and database are managed by dedicated data acquisition nodes, usually installed on the control PC of the ADCs. The analogue signals are brought to ADCs, digitized, and processed or stored in digital form. Digital data are streamed straight via digital links. Each of the A/D converters and diagnostic systems with digital outputs has its own control node responsible for communication within the CODAC system.

3.1. Analogue signals and A/D converters

There are many diagnostics on COMPASS, which have an analogue output – either in the form of a voltage or current signal. Since the COMPASS physics programme aims namely at the edge plasma, turbulence and flows in plasma, plasma instabilities, and L-H transition, the demands on the sampling rate are relatively high. The duration of ELMs (Edge Localized Modes) is typically 1 ms in COMPASS. However, the plasma turbulence has a broad frequency spectrum up to about 500 kHz. Thus, we are generally interested in structures in the plasma with frequencies up to several hundreds of kHz. Moreover, there are diagnostics that actively probe the plasma with even shorter events (Thomson scattering, radiometer). Table 1 gives an overview of the existing diagnostics, including duration of typical events which have to be sampled, required sampling rate, and the maximum level of signal.

The used types of A/D converters cover a broad range of HW and SW solutions. This altogether creates a heterogeneous system which addresses particular needs of individual diagnostic systems but also places higher demands on the CODAC management.

The individual systems are briefly described in the following sections; Table 2 then summarizes the existing A/D converters, incl. information on sampling rate, input range, bit resolution, noise, and input impedance. Simultaneous sampling of all channels in each of the systems is a key common feature of all data acquisition systems on COMPASS.

3.1.1. ATCA

The ATCA ADCs are based on Advanced Telecommunications Computing Architecture [21]. Dedicated data acquisition (DAQ) boards were developed for use in fusion research by IPFN IST Lisbon, Portugal [22,23], which are presently employed also for e.g. Gamma-ray cameras at JET [24]. A PC motherboard is installed on

Table 1
List of COMPASS diagnostics with analogue outputs: the event duration denotes the typical lifetime of structures in plasmas (like ELMs, turbulent structures, or blobs) or the duration of the diagnostic tools actions (laser pulse duration, frequency step of the reflectometer), depending on which of them sets more strict requirements on the data acquisition. Output range represents the maximum level of signal to be digitized.

Diagnostics	Characteristic events and their duration	Output range	Number of signals	Required sampling rate
Magnetics	Turbulence: $\sim 2 \div 5$ µs ELMs: ~ 1 ms	± 1 V $\div \pm 10$ V	440	Several MS/s
Divertor Langmuir probes		± 10 V	60	
Electrostatic and magnetic probes on reciprocating drives		± 10 V	26	
Spectroscopy		$0 \div -10$ V	10	
AXUV bolometry		$0 \div +5$ V	120	
SXR tomography		$0 \div +5$ V	70	
Radiometer		$0 \div +10$ V	16	
Interferometer		$0 \div +5$ V	4	
Li beam diagnostics		$0 \div +5$ V	96	
Neutral particle analyzer		$0 \div +10$ V	24	
Thomson scattering – background		10 mV $\div$ 1 V	240	
Thomson scattering – laser pulse	Laser pulse ~ 10 ns	10 mV $\div$ 1 V	240	~ 1 GS/s
Reflectometry	Frequency step ~ 4 ns	$0 \div +1$ V	16	> 100 MS/s

Table 2
List of ADC systems on COMPASS and their parameters. It should be noted that (a) the ATCA 2 MS/s ADCs input impedance is given for the 110 kHz filter; (b) for D-tAcq, 50 MS/s is a maximum rate which can be used for 4 channels/board; to use all 16 channels/board, the maximum rate is reduced to 16 MS/s; moreover, oversampling can be still used to reduce the noise; (c) the NI 2 GS/s ADCs have two options for input impedance.

ADC	Sampling rate	Input range	Bit resolution	RMS	Input impedance	Number of channels
ATCA	2 MS/s	±10 V	18 bit	406 µV	100 kΩ	608
	250 MS/s	±1.1 V	13 bit	370 µV	50 Ω	16
D-tAcq	50 MS/s	±1.6 V to ±10 V	14 bit	490 µV to 1.46 mV	5 kΩ	128
	500 kS/s	±10 V	16 bit	310 µV	20 kΩ	384
NI	2 GS/s	±50 mV to ±5 V	8 bit	240 µV to 24 mV	50 Ω or 1 MΩ	120
	2 MS/s	±1 V to ±10 V	16 bit	61 µV to 252 µV	>10 GΩ	256
APDCAM	2 MS/s	±5 V	12 bit	5×10^7 photon/s	N/A	96

a special carrier which interfaces the ATCA system and the control PC.

3.1.1.1. Basic 2 MS/s converters. The 2 MS/s DAQ boards represent the core of the COMPASS data acquisition system and the whole CODAC in general. In total, 19 DAQ boards are installed in two ATCA crates; each module has 32 analogue inputs connected to 18-bit A/D converters. The input modules are equipped by 3rd order Butterworth filters, filtering the input signal at frequencies of 110, 300, or 850 kHz.

Next, on-board data processing is made possible thanks to a FPGA installed on each DAQ board. Acquired data (received via the FPGA) are then stored to an on-board memory. Communication is assured by Aurora fast serial links [25], 4 RS-232 slow serial links, and one optical transceiver for the real-time event network connection. FPGA firmware for control of DAQ boards is stored on a Compact Flash card.

3.1.1.2. Real-time system. The real-time system uses identical modules equipped by the 2 MS/s ADCs; however, the firmware in the FPGA is adapted to down-sample the data to 20 kS/s used in the real-time loop. These data are then transferred through the PCIe to the control PC where the real-time calculations are performed.

Fig. 3 shows the connection of the COMPASS real-time system: the analogue signals are brought to the ADCs, digitized, down-sampled by the on-board FPGA, and transferred via the PCIe bus to the processor in the PC, within the ATCA.

Here, MARTe performs the real-time data processing on the processor and transfers the digital data straight through the RTM (Rear Transition Module) to one of the available outputs.

Set-up of the ATCA ADCs, real-time system, and timing is done through Ethernet connection, using corresponding nodes connected to the FireSignal central server and accessed by the operator interface.

3.1.1.3. Fast data acquisition for reflectometry. Third application of the ATCA system is the reflectometry system for fast plasma density measurements: special DAQ boards are used for digitization of the reflectometry data. Since the reflectometry data include frequencies up to 20–30 MHz, the sampling rate of 250 MS/s was chosen (configurable from 50 MS/s to 250 MS/s). Two dedicated DAQ boards were designed and constructed in IST Lisbon for this purpose [24,26,27]. Each of the DAQ boards has 8 channels and is equipped with a FPGA for on-board data processing. The input range is ±1.1 V at 50 Ω, the ADC resolution 13 bits.

3.1.2. D-tAcq

3.1.2.1. Turbulence measurements. Proper sampling of turbulent structures in the frequency range of several hundreds of kHz as well as measurements of current–voltage characteristics using electrostatic probes require high sampling rates. Therefore, an ADC system with sampling rate up to 60 MS/s [28] was installed to ensure measurements using the probe diagnostics (divertor Langmuir probes, probes on reciprocating drives). Maximum bandwidth of the system is 20 MHz, resolution 14 bits. Typically, the sampling rate 5–10 MS/s is used which is sufficient even for fast temperature measurements using swept Langmuir probes. The signals are filtered before connection to ADC inputs to remove high frequencies and avoid aliasing.

3.1.2.2. Discharge and machine monitoring. Two systems with the sampling rate of 500 kS/s [29], maximum bandwidth 250 kHz, and resolution of 16 bit are dedicated to the monitoring of tokamak operation systems (e.g. hydraulic pre-load system, power supply protection system /crowbar/ outputs, connection of tokamak

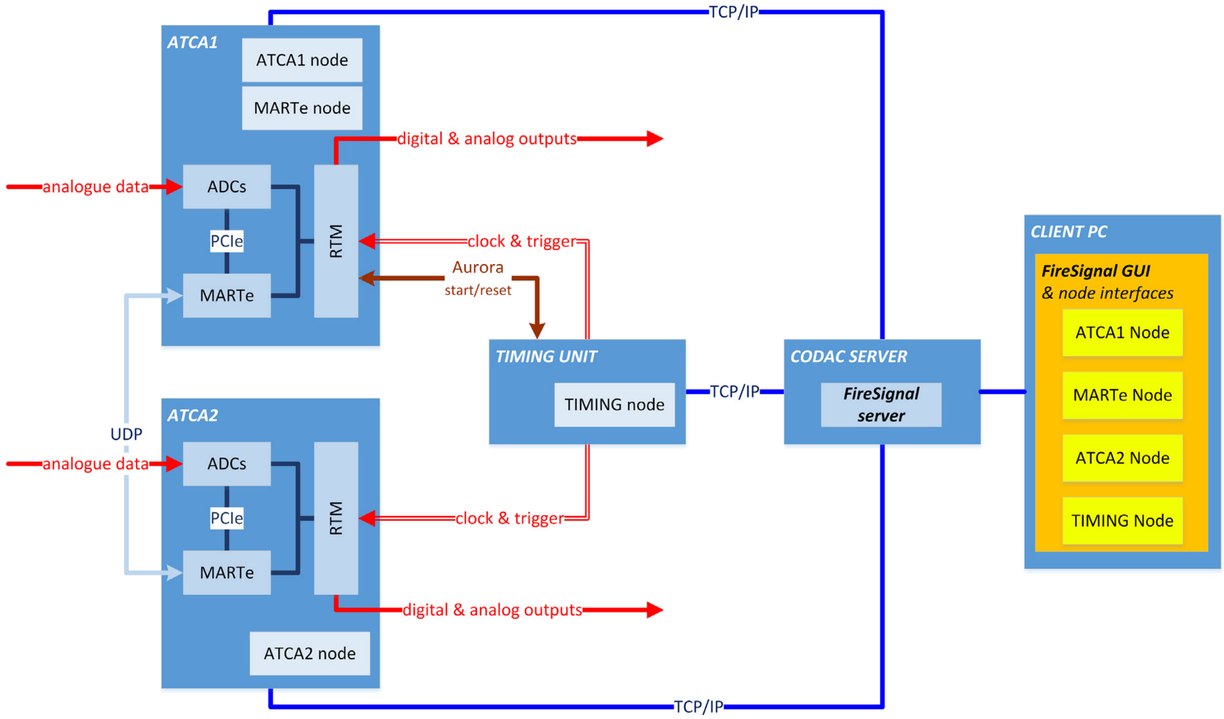

Fig. 3. Real-time system: connection between the ATCA systems, timing unit, CODAC server, and client PC with operator interface. The ATCAs host the DAQ boards with ADCs (used either for the real-time control or as the 2 MS/s converters). MARTe can be run on both ATCAs and handles the inputs and outputs via the front panel and RTM. Further, the ATCAs host nodes which manage the system; the MARTe node controls the real-time system, ATCA1 and ATCA2 nodes control the non-real-time 2 MS/s ADCs. The timing unit is a dedicated PC on which a corresponding node is running. The CODAC server is a hardware server hosting the virtual FireSignal server. FireSignal GUI, i.e. the operator interface is a Java application that can be run on any client PC and allows to set-up the nodes using their interfaces.

circuits) and to monitoring of the triggers and measurement of the background light for the Thomson scattering diagnostics.

3.1.3. National Instruments (NI) systems

Two NI systems are used for data acquisition on COMPASS: fast ADCs for Thomson scattering diagnostics and low noise ADCs for magnetic diagnostics. Both the systems are controlled by LabView running under Windows OS on an embedded computer within the chassis which houses the ADCs.

3.1.3.1. Fast ADCs for Thomson scattering diagnostics. The TS laser pulse has a duration of approximately 10 ns and the time evolution of the scattered light intensity has to be measured in order to be able to fit the experimental data and to derive the electron density and temperature. Therefore, two ADCs had to be employed: a slow one monitoring the background light (see Section 3.1.2) and a fast one with 1 GS/s sampling rate, described here.

Signals from 120 spectral channels (30 polychromators with 4 spectral channels each) are synchronously digitized by fast ADCs (PXI-5152 [30]). The system has 4 chassis: first one – master chassis, includes the embedded computer (Quad-Core) and triggering and timing cards (PXI-6653) to synchronize remaining 3 chassis (slave chassis). Maximum bandwidth of the system is 300 MHz, resolution 8 bit. The sampling rate can be increased up to 2 GS/s for half of the existing ADC channels.

3.1.3.2. Low noise ADC system for magnetic diagnostics. For selected magnetic sensor coils, a low noise 2 MS/s system (root-mean-square value /RMS/ of the noise is approximately 2× lower than that of the ATCA ADCs with the same sampling rate) based on NI 6368 [31] was employed. Maximum Bandwidth of the system is 1 MHz, resolution is 16 bits.

3.1.4. Data acquisition for Li-beam diagnostics

Accelerated Lithium beam based Beam Emission Spectroscopy (BES) diagnostic is used to determine the electron density profiles [32]. On COMPASS, the emitted photons are observed by fast Avalanche Photo Diode (APD) detector with 18 channels [33] connected to APDCAM - a dedicated system of ADCs, designed and constructed for this purpose [34,35].

It should also be noted that the slow density profile variations are detected using a CCD camera at 50 fps in full frame (640 × 480).

3.2. Sources of digital data

Digital output is directly delivered by more complex systems, like the CCD camera mentioned above, cameras observing the plasma in visible and infra-red spectral range, and spectrometers.

3.2.1. Fast cameras in visible range

Two fast cameras [36] are installed on COMPASS to monitor the plasma both tangentially and from the top, observing the divertor area.

The maximum frame rate is up to 400 Hz, spatial resolution is adjustable up to maximum 992 × 900 pixels. The size of the region of interest in pixels, the frame exposure time and a total number of images is configured by FireSignal control nodes. The camera control nodes are implemented in Java language using Jython binding to pyCDB. Images are stored in HDF5 files in the COMPASS DataBase. The individual frames are added to this file one by one as soon as they are read out from the camera control PC memory. Thus, we have the access to the record almost immediately after the discharge.

3.2.2. Infra-red camera

An infra-red camera (MICRO-EPSILON ThermoIMAGER TIM 160 [37]) is used to observe heat loads on the COMPASS inner walls.

The temperature range is from −20 °C to 1500 °C. The frame rate is 120 Hz, resolution 160 × 120 pixels. The camera is controlled by its own software TIM Connect running under Windows OS which enables external data acquisition control using interprocess communication via Dynamic Link Library (DLL). The data acquisition itself is provided by python GUI script running on the same PC as TIM Connect. This script controls external trigger, acquires data, calibrates them and writes them to the local HDF5 file as well as to the COMPASS database (CDB). The typical data size is 160 × 120 (image resolution) × 60 (number of frames) × 16 bit.

3.2.3. Spectrometers

The plasma radiation in the visible spectra (460–663 nm), in the near ultraviolet range (248–472 nm), and in the range of 630–680 nm, i.e. around H_α line, is measured by the three identical high-resolution (2048 points on wavelength axis) spectrometers HR2000+(Ocean Optics [38]). Time exposition is typically set around 10 ms for our purposes. The exact value of the exposition time and a number of requested spectra are set via FireSignal control nodes. The spectrometer nodes are written in Java. Control nodes run under Windows OS. Data from spectrometers are saved into the CDB database in the form of three different generic signals, signal level and both time and wavelength axis.

3.3. Database

A new database and a complex data handling system has been recently developed and deployed to address particular needs of the COMPASS experiments, namely fast data access, links to the sources of large amount of data (e.g. fast cameras), and interfaces to particular software codes [4]. The total amount of data to be accommodated can be up to 4 GB/shot (presently typically about 2 GB excluding the fast cameras). It integrates the data from all the sources described above in Sections 3.1 and 3.2.

The system is called COMPASS DataBase (CDB), although it is perfectly appropriate for any other tokamak or a pulsed experiment in general. CDB is based on open source technologies wherever possible, it is platform-independent and it can be easily scaled and distributed. The database structure enables to include multi-dimensional data signals in multiple revisions (no data is overwritten).

The clients directly access files on a local or remote file system (Gluster [39] in our case) using a standardized API. The native language is Python, bindings for Java, C/C++, Fortran, IDL and MATLAB are provided. Rich meta-data are stored on an SQL server, which is not heavily loaded.

The FireSignal database controller as well as the individual nodes can write directly to this system. However, Gluster (as many other remote/distributed file systems) suffers from a long response when writing a large number of data files. For this reason, a caching data storage for fresh incoming experimental data was employed to accelerate the first data writing into the database.

An automated data processing server is a part of CDB. Based on dependency rules, this server executes, in parallel if possible, prescribed jobs, either locally or distributed (e.g. on a cluster).

Backup of experimental data is done to remote data repository of the national academic network provider CESNET [40].

4. Communication

Although the topic of communication is mentioned several times in the previous text, we would like to highlight some points in this dedicated section. As already noted, Fig. 2 shows the key communication links between the individual systems.

Here, it should also be noted that COMPASS, contrary to e.g. ITER sets much more stringent requirements on the control cycle. Even though the amount of transferred data is low in case of COMPASS, the latencies play an important role. While the ITER fast systems control loop cycle time is of about 1 ms [41] and 1 Gb and/or 10 Gb Ethernet with the latencies of 50–125 μs and 5–10 μs [42] respectively can be used, the COMPASS control loop cycle time has to be kept at 50 μs.

The COMPASS vacuum vessel time constant for vertical field penetration is less than 0.5 ms [43]. This time constant corresponds also to the stabilization effect of the vacuum vessel and as COMPASS does not have any additional passive stabilization elements, all frequencies below 2 kHz have to be stabilized actively. Moreover, to achieve reasonably robust control, a safety margin must be included. Therefore, the fast feedback is operated at 20 kHz bringing thus COMPASS control close to hard real-time applications, for which Ethernet is not suitable because its communication is not deterministic [44,45].

Since the demands on communication speed and reliability are very high, the Ethernet connection, running with a TCP/IP protocol can be used solely for the set-up of the systems before the experiment. Therefore, several other communication links have to be used during the experiment.

4.1. Serial communication

Presently, the serial links are used to communicate with the controllers of the actuators: serial links secure the communication from the real-time system MARTe running on the ATCA crates to the power supplies, incl. the fast amplifiers. Typically, the serial link from a serial card within ATCA is connected to a micro-controller at the side of the subsystem.

4.1.1. Control of the AC/DC converters for main magnetic fields

The COMPASS CODAC and the power supplies are linked with one pair of optical gate triggers and a 9 bit, 921.6 kb/s optical RS-232 serial line over which the requested set-point values are transmitted. The interface on the side of the power supplies is represented by a communication unit which translates the communication further and, in addition, exchanges the information with the power supplies control system running on Simatic.

The interface on the MARTe side is represented by one of the ATCA1 serial links. The message is send each 500 μs; it contains 3 bytes of information per each of the 4 converters and the transition takes approximately 140 μs. The communication unit transmits these requests further using other serial lines to the rectifiers supplying the COMPASS circuits. The return message from the communication unit to the ATCA contains information on previous request from MARTe (echo), status of flywheel generators and AC/DC converters, and type of communication.

However, it should be noted that this communication part is related solely to the requested/measured values exchange between the COMPASS CODAC and the power rectifiers.

4.1.2. Gas handling

The gas handling is controlled by a micro-controller which communicates to dedicated control PC via an optical serial link at 115 200 b/s. This way, non-stop control of gas handling can be ensured during e.g. glow discharge, boronization etc.

It should be noted that the real-time control comes directly from MARTe via one of the digital-analogue outputs on the Rear Transition Module on ATCA (RTM DAC).

4.2. Aurora link

The Aurora links are used for the real-time communication between the timing unit and the ATCAs, as mentioned in Section 2.5 and marked in Fig. 3.

The native ATCA Aurora links are also going to be used for other most demanding tasks. This is also the case of the existing serial communication between MARTe and Fast Amplifiers. Presently, a common controller for the FABR and VKPS is being developed and new communication based on Aurora link was tested for this purpose. The FPGA was used on the FABR & VKPS controller to communicate directly with the real-time system (via the RTM). The performed tests show that significantly shorter time is needed for the communication [5] as the necessary 2 bytes of information can be transferred via Aurora in 1 μs.

4.3. UDP protocol

UDP (User Datagram Protocol) is a simple message-based protocol that belongs to the set of communication protocols used for the Internet (Internet protocol suite). The use of UDP is planned for communication between the two ATCA systems on which MARTe is running [5].

5. Conclusion

In this paper, the COMPASS control tools are presented, the capabilities of the data acquisition system are described, and the communication tools are shown. More detailed descriptions of the individual systems are cited in references, if available.

The COMPASS CODAC system allows to manage full tokamak control in all requested operation scenarios, including the ELMy H-mode [13]. Plasma current, plasma shape, and electron density are controlled within a 500 μs control loop in the slow thread of the real-time system, the plasma position is controlled using the fast, 50 μs thread in MARTe.

Nevertheless, there are several upgrades planned in the near future in order to improve the behaviour of the whole system and to broaden the operational limits.

5.1. Test and development system

An ATCA test system, identical to ATCA1 and ATCA2, was designed and is under construction at present (to be commissioned by the end of 2013). This will allow to separate the regular COMPASS operation from the development and tests of the CODAC and its subsystems. Moreover, the ATCA2 MARTe can then extend the RT capabilities to additional diagnostic systems.

5.2. Upgrades to the existing control

Integration of several autonomous systems into the central control system managed by FireSignal is ongoing and will be finished in the near future.

Simplified web interface of the real-time framework MARTe is planned to present to the operator only parameters which are needed for the standard routine operation.

5.3. Modifications to the communication links

The communication between MARTe and power supplies used for position control (FABV, FABR & VKPS – Section 2.4.1) running over a serial link will be replaced by Aurora (Section 4.2), as already marked in Fig. 2. The communication will be based on FPGAs in order to shorten the reaction time and thus make the control more robust and broaden the operational limits. Moreover, common control of the VKPS and FABR will be addressed this way.

Similarly, power supply for resonant magnetic perturbations (RMP) which is presently under commissioning will be controlled from MARTe via another Aurora link.

Direct connections from MARTe to the individual AC/DC power converters (described in Section 4.1) via serial links are planned to bypass the communication unit and to control the converters more efficiently.

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References

[1] R. Panek, O. Bilykova, V. Fuchs, M. Hron, P. Chraska, P. Pavlo, J. Stockel, J. Urban, V. Weinzettl, J. Zajac, F. Zacek, Reinstallation of the COMPASS-D tokamak in IPP ASCR, Czechoslovak Journal of Physics 56 (2006) B125–B137.

[2] V. Weinzettl, R. Panek, M. Hron, J. Stockel, F. Zacek, J. Havlicek, P. Bilkova, D.I. Naydenkova, P. Hacek, J. Zajac, R. Dejarnac, J. Horacek, J. Adamek, J. Mlynar, F. Janky, M. Aftanas, P. Bohm, J. Brotankova, D. Sestak, I. Duran, R. Melich, D. Jares, J. Ghosh, G. Anda, G. Veres, A. Szappanos, S. Zoletnik, M. Berta, V.F. Shevchenko, R. Scannell, M. Walsh, H.W. Mueller, V. Igochine, A. Silva, M. Manso, R. Gomes, T. Popov, D. Sarychev, V.K. Kiselov, S. Nanobashvili, Overview of the COMPASS diagnostics, Fusion Engineering and Design 86 (2011) 1227–1231.

[3] A. Neto, H. Fernandes, A. Duarte, B.B. Carvalho, J. Sousa, D.F. Varcarcel, M. Hron, C.A.F. Varandas, FireSignal – data acquisition and control, Fusion Engineering and Design 82 (2007) 1359–1364.

[4] J. Urban, J. Pipek, M. Hron, F. Janky, R. Paprok, M. Peterka, A. Duarte, Integrated data acquisition, storage, retrieval and processing using the COMPASS database (CDB), Fusion Engineering and Design 2013, Submitted to SI on IAEA TM on Control, Data Acquisition, and Remote Participation for Fusion Research, 6–10 May 2013, Hefei, China.

[5] F. Janky, J. Havlicek, A.J.N. Batista, O. Kudlacek, A.C. Neto, J. Pipek, O. Mikulin, A.S. Duarte, B.B. Carvalho, M. Hron, J. Seidl, Upgrade of the COMPASS tokamak real-time control system, Fusion Engineering and Design (2013), Submitted to SI on design and implementation of real-time systems for magnetic confined fusion.

[6] A.C. Neto, F. Sartori, F. Piccolo, R. Vitelli, G. De Tommasi, L. Zabeo, A. Barbalace, H. Fernandes, D.F. Valcarcel, A.J.N. Batista, JET-EFDA Contributors, MARTe: a multiplatform real-time framework, IEEE Transactions on Nuclear Science 57 (2010) 479–486.

[7] D.F. Valcarcel, A.S. Duarte, A. Neto, I.S. Carvalho, B.B. Carvalho, H. Fernandes, J. Sousa, F. Sartori, F. Janky, P. Cahyna, M. Hron, R. Panek, Real-time software for the COMPASS tokamak plasma control, Fusion Engineering and Design 85 (2010) 470–473.

[8] D.F. Valcárcel, A. Neto, I.S. Carvalho, B.B. Carvalho, H. Fernandes, J. Sousa, F. Janky, J. Havlicek, R. Beno, J. Horacek, M. Hron, R. Pánek, The COMPASS tokamak plasma control software performance, IEEE Transactions on Nuclear Science 58 (2011) 1490–1496.

[9] D. Alves, A.C. Neto, D.F. Valcarcel, R. Felton, J.M. Lopez, A. Barbalace, L. Boncagni, P. Card, G. De Tommasi, A. Goodyear, S. Jachmich, P.J. Lomas, F. Maviglia, P. McCullen, A. Murari, M. Rainford, C. Reux, F. Rimini, F. Sartori, A.V. Stephen, J. Vega, R. Vitelli, L. Zabeo, K. Zastrow, A new generation of real-time systems in the JET tokamak, in: 2012 18th IEEE-NPSS Real Time Conference, RT, 2012, pp. 1–9.

[10] A. Neto, D. Alves, L. Boncagni, P. Carvalho, D. Valcarcel, A. Barbalace, G. De Tommasi, H. Fernandes, F. Sartori, E. Vitale, R. Vitelli, L. Zabeo, A survey of recent MARTe based systems, IEEE Transactions on Nuclear Science 58 (2011) 1482–1489.

[11] J. Havlicek, R. Hauptmann, O. Peroutka, M. Tadros, M. Hron, F. Janky, P. Vondracek, P. Cahyna, O. Mikulin, D. Sestak, P. Junek, R. Panek, Power supplies for plasma column control in the COMPASS tokamak, Fusion Engineering and Design (2013), http://dx.doi.org/10.1016/j.fusengdes.2013.02.040.

[12] F. Janky, J. Havlicek, D. Valcarcel, M. Hron, J. Horacek, O. Kudlacek, R. Panek, B.B. Carvalho, Determination of the plasma position for its real-time control in the COMPASS tokamak, Fusion Engineering and Design 86 (2011) 1120–1124.
[13] R. Panek, J. Stockel, J. Havlicek, F. Janky, M. Hron, V. Weinzettl, P. Bilkova, M. Dimitrova, P. Hacek, R. Dejarnac, M. Aftanas, P. Bohm, P. Cahyna, M. Imrisek, E. Stefanikova, J. Varju, COMPASS team, Characterization of ohmic and NBI heated H-mode in the COMPASS tokamak, in: EPS Conference on Plasma Physics (Papers), 2013, pp. 1–4, P4.103.
[14] J. Zajac, R. Panek, F. Zacek, J. Vlcek, M. Hron, A. Krivska, R. Hauptmann, M. Danek, J. Simek, J. Prosek, Power supply system for the COMPASS tokamak re-installed at the IPP, Prague, Fusion Engineering and Design 84 (2009) 2020–2024.
[15] Moravian Instruments, Control web software system, http://www.mii.cz/cat?id=146&lang=409, 2013.
[16] A.S. Duarte, B. Santos, T. Pereira, B.B. Carvalho, H. Fernandes, A. Neto, F. Janky, P. Cahyna, J. Pisacka, M. Hron, FireSignal application node for subsystem control, Fusion Engineering and Design 85 (2010) 496–499.
[17] P. Deichuli, V. Davydenko, V. Belov, A. Gorbovsky, A. Dranichnikov, A. Ivanov, A. Sorokin, V. Mishagin, A. Abdrashitov, V. Kolmogorov, A. Kondakov, Commissioning of heating neutral beams for COMPASS-D tokamak, Review of Scientific Instruments 83 (2012).
[18] J.C. Fortunato, A. Batista, J. Sousa, H. Fernandes, C.A.F. Varandas, Event and pulse node hardware design for nuclear fusion experiments, IEEE Transactions on Nuclear Science 55 (2008) 679–682.
[19] M. Aftanas, P. Bohm, P. Bilkova, V. Weinzettl, J. Zajac, F. Zacek, J. Stockel, M. Hron, R. Panek, R. Scannell, M.J. Walsh, High-resolution Thomson scattering system on the COMPASS tokamak: evaluation of plasma parameters and error analysis, Review of Scientific Instruments 83 (2012).
[20] O. Mikulin, M. Hron, P. Bohm, G. Naylor, P. Bilkova, F. Janky, Timing and triggering of the Thomson scattering diagnostics on COMPASS, Fusion Engineering and Design 2013, Submitted to SI on IAEA TM on Control, Data Acquisition, and Remote Participation for Fusion Research, 6–10 May 2013, Hefei, China.
[21] PICMG, AdvancedTCA Specifications for Next Generation Telecommunications Equipment, http://www.advancedtca.org/, 2013.
[22] D.F. Valcarcel, A. Neto, J. Sousa, B.B. Carvalho, H. Fernandes, J.C. Fortunato, A.S. Gouveia, A.J.N. Batista, A.G. Fernandes, M. Correia, T. Pereira, I.S. Carvalho, A.S. Duarte, C.A.F. Varandas, M. Hron, F. Janky, J. Pisacka, An ATCA embedded data acquisition and control system for the COMPASS tokamak, Fusion Engineering and Design 84 (2009) 1901–1904.
[23] A.J.N. Batista, A. Neto, M. Correia, A.M. Fernandes, B.B. Carvalho, J.C. Fortunato, J. Sousa, C.A.F. Varandas, F. Sartori, M. Jennison, JET-EFDA Contributors, 2009 16TH IEEE-NPSS Real Time Conference, IEEE; NPSS, 2009, pp. 308–313.
[24] R.C. Pereira, A.M. Fernandes, A.C. Neto, J. Sousa, A.J. Batista, B.B. Carvalho, C.M.B.A. Correia, C.A.F. Varandas, JET-EFDA Contributors, ATCA fast data acquisition and processing system for JET gamma-ray cameras upgrade diagnostic, IEEE Transactions on Nuclear Science 57 (2010) 683–687.
[25] Xilinx, Aurora, http://www.xilinx.com/aurora, 2013.
[26] R. Pereira, A. Combo, M. Correia, A. Rodrigues, A. Fernandes, J. Sousa, C. Correia, B. Goncalves, C. Varandas, Ultra high-frequency data acquisition AMC module for high performance applications, Fusion Engineering and Design (2012), http://dx.doi.org/10.1016/j.fusengdes.2012.11.013.
[27] R. Pereira, A. Combo, M. Correia, A. Fernandes, P. Carvalho, A. Rodrigues, J. Sousa, C. Correia, B. Goncalves, ATCA/μTCA data acquisition system for spectroscopy and reflectometry microwave applications in nuclear fusion experiments, in: Poster Presentation on IAEA TM on Control, Data Acquisition, and Remote Participation for Fusion Research, 6–10 May, Hefei, China, 2013.
[28] D-tAcq, 16 Channel Simultaneous High Speed Digitizer ACQ216CPCI, http://www.d-tacq.com/pdfs/d-tacq/d-tacq-acq216cpci-ds.pdf, 2013.
[29] D-tAcq, 96 Channel Simultaneous Low Cost Digitizer ACQ196CPCI, http://www.d-tacq.com/pdfs/d-tacq/d-tacq-acq196cpci-ds.pdf, 2013.
[30] National Instruments, NI PXI-5152 Specifications, http://www.ni.com/pdf/manuals/374443b.pdf, 2013.
[31] National Instruments, NI 6366/6368 Specifications, http://www.ni.com/pdf/manuals/370084c.pdf, 2013.
[32] G. Anda, G. Petravich, S. Zoletnik, S. Bato, Li-beam developments for high-energy plasma diagnostics, Fusion Engineering and Design 74 (2005) 715–719.
[33] D. Dunai, S. Zoletnik, J. Sarkoezi, A.R. Field, Avalanche photodiode based detector for beam emission spectroscopy, Review of Scientific Instruments 81 (2010).
[34] AdimTech, APDCAM, An avalanche photodiode camera from Adimtech Kft., http://www.adimtech.com/downloads/products/apdcam/APDCAM_overview_v2.pdf, 2013.
[35] AdimTech, APDCAM Digital Avalanche Photodiode Camera, User's Guide Version 1.01, http://www.adimtech.com/downloads/products/apdcam/APDCAM_users_guide_v101.pdf, 2013.
[36] A. Szappanos, M. Berta, M. Hron, R. Panek, J. Stockel, S. Tulipan, G. Veres, V. Weinzettl, S. Zoletnik, EDICAM fast video diagnostic installation on the COMPASS tokamak, Fusion Engineering and Design 85 (2010) 370–373.
[37] Micro-Epsilon, Infrared camera thermoIMAGER TIM – operators manual thermoIMAGER TIM 160/200/400/450, http://www.micro-epsilon.cz/download/manuals/man-thermoIMAGER-TIM-en.pdf, 2013.
[38] Ocean Optics, Inc., HR2000+Data Sheet, http://www.oceanoptics.com/technical/engineering/OEM%20Data%20Sheet%20–%20HR2000+.pdf, 2013.
[39] J. Písačka, M. Hron, F. Janky, R. Pánek, Cluster storage for COMPASS tokamak, Fusion Engineering and Design 87 (2012) 2238–2241.
[40] CESNET, CESNET large infrastructure project, http://www.ces.net/project/large-infrastructure.html, 2013.
[41] B. Gonçalves, J. Sousa, B. Carvalho, A. Rodrigues, M. Correia, A. Batista, J. Vega, M. Ruiz, J. López, R. Castro, A. Wallander, N. Utzel, P. Makijarvi, S. Simrock, A. Neto, D. Alves, D. Valcárcel, P. Lousa, F. Piedade, L. Fernandes, ITER prototype fast plant system controller, Fusion Engineering and Design 86 (2011) 556–560.
[42] Qlogic corporation, Introduction to ethernet latency: an explanation of latency and latency measurement, http://www.qlogic.com/Resources/Documents/TechnologyBriefs/Adapters/Tech_Brief_Introduction_to_Ethernet_Latency.pdf, 2013.
[43] P. Vyas, D. Mustafa, A. Morris, Vertical position control on COMPASS-D, Fusion Technology 33 (1998) 97–105.
[44] Industrial Ethernet University, Real Time Ethernet I: Introduction to Real-Time Electronic Control Systems, http://www.industrialethernetu.com/courses/401_2.htm, 2013.
[45] P. Doyle, Introduction to Real-Time Ethernet I, The Extension: A Technical Supplement to Control Network 5 (2004).