Progress on the development of the ITER Control System

Dhiraj Bora, WD Klotz. A Wallander, L Scibile, I Yonekawa, J-Y Journeaux, F Di Maio, J. A. Snipes, T. Casper, A. Winter

ITER Organization, Route de Vinon sur Verdon, 13115 St. Paul Lez Durance, France

E-mail contact of main author: Dhiraj.bora@iter.org

Abstract. The development of the ITER control system has accelerated. A successful conceptual design [1] review of the Control Data Access and Communication (CODAC) system was concluded in November, 2007, and confirmed the clearly defined three vertical tiers and two horizontal layers of the system. The vertical tiers distinguish the control, interlock and safety functions. The horizontal layers separate the central control and the plant system control. The central control is under the responsibility of IO, while most of the plant system control is under the responsibility of the seven ITER member parties. This responsibility sharing poses a major challenge for realization and integration of the complete ITER instrumentation and control (I & C) system. In order to mitigate this risk, IO now enlarged the original scope of CODAC group by introducing the responsibility of supporting the plant systems to define their I & C specifications and help follow them through production and different acceptance tests and commissioning. Prerequisite to this activity is standardization in terms of hardware, software and methodology to be accepted by the ITER member parties. Initial progress has been made in this area of standardization. The aim of this paper is to provide a status update of the ITER control system after inclusion of changes during the conceptual design review of 2007 and the increased functional capabilities.

1. Introduction

CODAC is the central control system [2] and it is responsible for operating the ITER device. CODAC interfaces to more than 160 plant systems containing actuators, sensors and local control. CODAC is also responsible for coordinating and orchestrating the operation of these plant systems including plasma feedback control. CODAC is developed by ITER Organization, while plant systems are developed by the seven ITER partners (China, Europe, India, Japan, Korea, Russia and United States). As mentioned above, this procurement model poses enormous challenges, has a big impact on architecture design and requires a strong standardization for better integration and future maintenance. We describe here the CODAC conceptual design and elaborate on the actions taken by the CODAC team to move from conceptual to engineering design during the last year and outline the plans ahead.

As mentioned in the beginning, plant system I&C is under the responsibility of the seven ITER parties. Therefore, it is necessary to establish standards and rules to the maximum possible extent to achieve the required integration. These standards are documented in the Plant Control Design Handbook (PCDH) [3] released on a yearly basis. PCDH defines a development life cycle with clearly defined inputs and deliverables for each life cycle phase as well as check-points in the form of reviews and tests between the phases. It also defines the hardware and software standards in the form of catalogues of components, design rules and the interfaces between plant system I&C and central I&C. Obsolescence management is of particular importance due to long life time of ITER construction and operation.

CODAC Core System version 1 implements the standards and is released at the same time as PCDH. Using this software package during the development of the plant system I&C will ensure compliance with interfaces and standards and enable a seamless integration later on site. CODAC Core System includes the software running on PSH as well as a scaled down version of the central CODAC system called Mini-CODAC. In addition Mini-CODAC provides functionality to execute factory and site acceptance tests. An important feature of both PSH and Mini-CODAC software is promotion of a data driven approach. The goal of “self description” is to standardize all configurations and avoid plant system specific codes as much as possible. This will allow capturing all configuration data in a central database further simplifying integration. CODAC Core System is based on the widely used open source software EPICS and provides SCADA functionality and support, like device drivers, for the components listed in the PCDH catalogues. The CODAC team has selected a strategy to release this software very fast with initially limited functionality. This will allow early feedback and adjustments as the project goes along. New major releases will be produced on a yearly basis.

During normal operation, CODAC controls transitions of the entire ITER plant state, and provides high level commands to plant systems, achieving integrated control of the entire plant. CODAC also monitors the operational state of each plant system to ensure it is operating within its proper condition limits.

To achieve integrated hierarchical control of the ITER plant, CODAC provides general software functions for the benefit of the individual plant systems, a synchronization system, and large bandwidth backbone communication networks with gateways which allow real time participation from remote ITER work sites. In addition, CODAC coordinates data

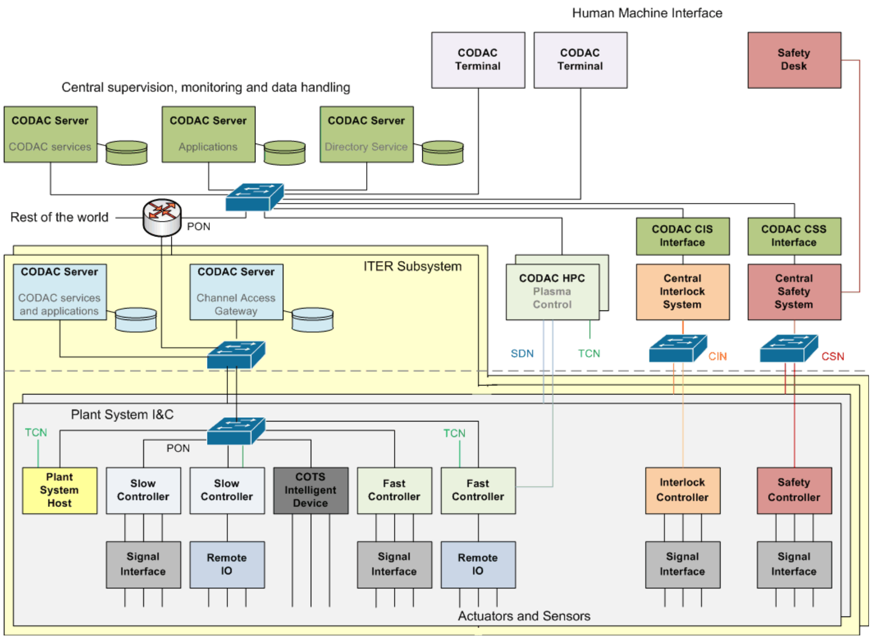

Fig. 1. Baseline physical architecture of ITER control system

acquisition & processing of data from the plant systems and manages the experimental database.

2. Technical Design

To achieve proper integration of all these functions and establish a common interface to all plant systems, it is essential that ITER uses one common software framework, communication middleware and SCADA (Supervisory Control and Dat Acquisition) system. With this in mind, in the beginning of the year, the CODAC group released the first version of the CODAC Core system based on EPICS (Experimental Physics and Industrial Control System) addressing the requirements. EPICS imply the use of the communication middleware channel access (CA).

2.1 Physical Architecture

The baseline physical architecture is shown in fig.1 [4]. It is a classical hierarchical distributed system with Human Machine Interface (HMI) at top and sensors and actuators at bottom. The system is composed of standard components with specific characteristics and interconnected by networks. The components can be selected and connected according to required functionality. Although the design of CODAC system is in an early phase it is useful to define standard components and characterize them. It would be useful at this point to identify and characterize the components with as much technical details as currently available. However, it should be emphasized that this is the "baseline" and as design progresses, there would be changes to this.

A central CODAC server is an IT standard server running CODAC applications like plant wide monitoring, supervision, scheduling system, directory services, databases, archives etc. CODAC Server runs Red Hat Enterprise Linux (RHEL).

A CODAC High Performance Computer (HPC) is a computer dedicated to real-time plasma control.

The Central Interlock System (CIS) [5] provides investment protection. It also provides status information to CODAC through a dedicated CODAC CIS interface.

The Central Safety System (CSS) provides intra plant system logic for safety. It provides status information to CODAC through a dedicated CODAC CSS interface.

The Plant systems with their local control systems are grouped together under ITER subsystems. Each of these subsystems has their own subsystem supervision and coordination using CODAC Servers. All the components of the local control systems are connected together by the plant operation network (PON), which is a general purpose switched Ethernet.

A plant system I&C (instrumentation and control) is a set of tightly coupled components implementing plant system instrumentation and control. Plant system I&C interface to actuators and sensors.

All the plant I&C system interface to the central I&C system through a computer known as the plant system host (PSH). The Plant System Host (PSH) is an IO supplied hardware and software component installed in a plant system I&C cubicle. There is only one PSH in a plant system I&C. The PSH runs RHEL and has an EPICS soft IOC (Input Output Controller). It provides standard CODAC services such as common operation state management, health monitoring, maintenance functions and time source. The PSH is fully data driven, i.e. it is customized for a particular plant system I&C configured by Self-Description Data (SDD). A PSH has no I/O. The PSH is connected to the Plant Operation Network (PON), which is the general purpose network connecting all plant I & C systems and CODAC.

A fast controller is a dedicated industrial controller implemented in PCI family form factor with PCIe and Ethernet communication fabric installed in a plant system I&C cubicle. There may be zero, one or many fast controllers in a plant system I&C. A fast controller runs RHEL and uses EPICS IOC.

A slow controller is a Siemens Simatic S7 industrial programmable logic controller (PLC) installed in a plant system I&C cubicle. There may be zero, one or many slow controllers in a plant system I&C. A slow controller runs software and plant-specific logic programmed with STEP 7 and interfaces to either the PSH or a fast controller using an IO-furnished interface (EPICS driver and configuration). A slow controller normally has I/O and IO supports a set of standard I/O modules. A slow controller can synchronize its time using NTP (network time protocol) over PON. A slow controller can act as supervisor for other slow controllers.

An interlock controller is a Siemens Simatic S7 FH industrial programmable logic controller (PLC) installed in a plant system I&C cubicle, possibly with hardwired logic for high performance protection functions. There may be zero, one or many interlock controllers in a plant system I&C. An interlock controller normally has I/O and IO supports a set of standard I/O modules. An interlock controller can act as supervisor for other interlock controllers.

A COTS intelligent device is a commercial off-the-shelf controller, which implements an integrated control function, e.g. a building management system or a power supply controller (such as intelligent electronic devices as defined by IEC 61850).

A signal interface is the mechanics, cabling and signal conditioning electronics between the actuators/sensors and the controllers. The plant system I&C hardware components are embedded within cubicles defined in an IO catalogue of products.

Besides the Plant operation Network (PON), there are five other networks dedicated to separate functions. These are Central Interlock Network (CIN), Central Safety Network (CSN), Synchronous Databus Network (SDN), Time Communication Network (TCN) and Audio/Video Network (AVN). CIN and CSN implement connections between central I&C and plant system I&C related to investment protection and human safety. The other three networks relate to High Performance Network (HPN) required for accurate time synchronization, real-time plasma control and video streaming. The PSH and networks provide the basic infrastructure for ITER I&C system being an integrated control system. On top of this infrastructure the applications are implemented such as pulse preparation, scheduling and execution system, real-time plasma control, supervision, data acquisition, archiving and analysis, human machine interface etc.

Mini-CODAC, which is a scaled down version of the CODAC System, is provided by IO to all plant system I&C developers as a software package. Mini-CODAC provides all the tools necessary to configure the plant system I&C, to implement the HMI, to monitor and supervise the plant system I&C, to configure and manage the network and to perform the factory acceptance test. The early use of Mini-CODAC in the development process will make later on-site integration seamless. Future versions of Mini-CODAC will support HPN, CIS and CSS. Other I & C components in Fig.1 are used with similar functionalities like other large central plant control systems.

2.2 Functional Architecture

The plant system I&C components defined above can be selected and connected in different ways according to the functional requirements of the plant system. To illustrate this we give two examples below. These figures show the data
flow, not the physical connections. The first example (Fig 2) is an industrial plant system I&C consisting of many slow controllers, one COTS intelligent device, one remote I/O and one fast controller dedicated to fast acquisition. In addition, the plant system I&C implements interlock functions.

The CODAC System / Mini-CODAC sends commands and, if required, publishes data from other plant system I&C to the PSH using the channel access protocol (1). This interface is also used to set runtime configuration properties. It may also send

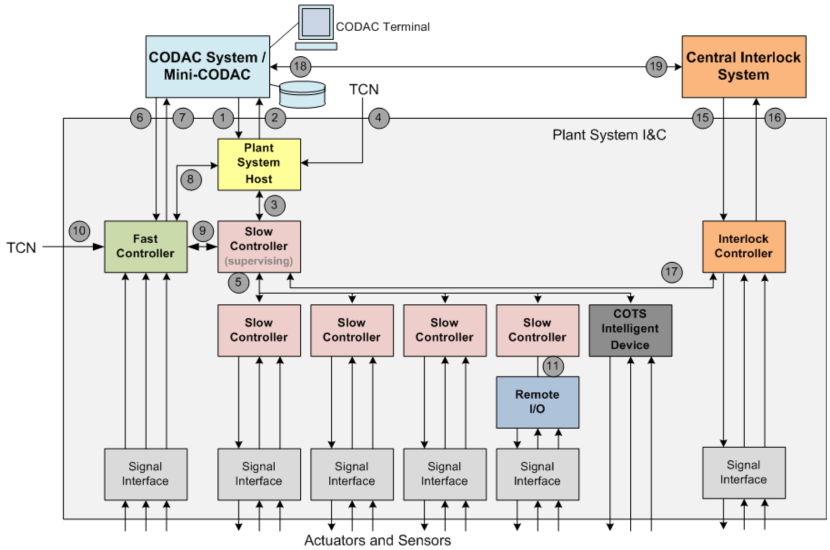

Fig. 2. Functional architecture and data flow of an industrial plant system I&C with fast acquisition

commands and, if required, publish data from other plant system I&C to the fast controller using the channel access protocol (6). The PSH publishes data, alarms and logs to the CODAC System / Mini-CODAC using the channel access protocol (2). This interface is also used to retrieve configuration properties. The fast controller may also publish data, alarms and logs to CODAC System / Mini-CODAC using the channel access protocol (7).
The second example (Fig 3) is a diagnostics plant system I&C participating in plasma control and consisting of many fast controllers and one slow controller.

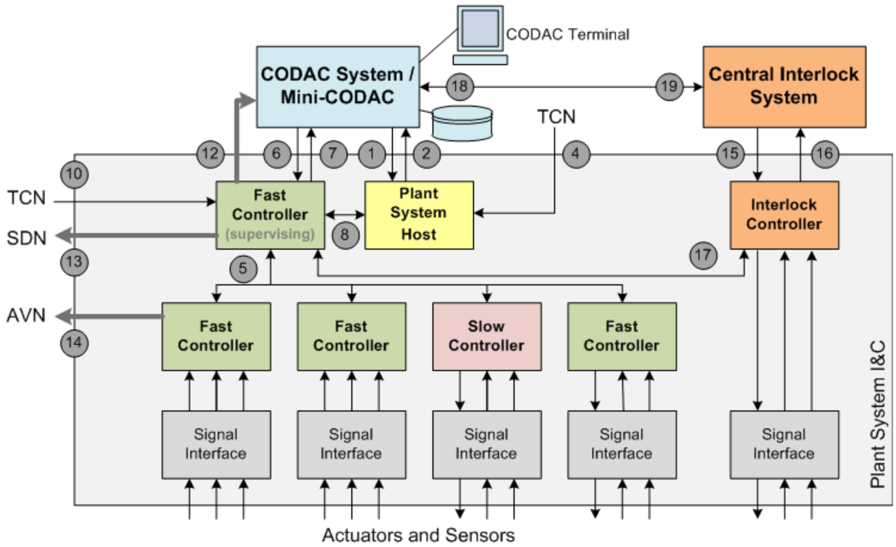

Fig. 3. Functional architecture and data flow of a diagnostic plant system I&C participating in real-time plasma control

The PSH supervises the fast controller (8) to manage the COS. The supervising fast controller implements plant specific coordination logic in EPICS. It also implements realtime logic using a real-time operating system on a different core or CPU. The supervising fast controller interfaces to three other fast controllers and one slow controller (5). The supervising fast controller and slow controller exchange data using the standard interface provided by the IO (8). The fast controllers run EPICS.

3. System size

The ITER project is organized in a plant breakdown structure (PBS) comprising of 31 products at present. It is important to identify the plant system I&C to identify the interfaces. From our analysis of the different plant systems, it is estimated that there are about 167 plant I&C systems. Like in any other large project, the instrumentation and control aspects for many plant systems are yet to be formulated. An integrated product team (IPT) for I&C has been setup to support various plant systems to identify their I&C needs and interfaces. It is foreseen that the I&C IPT will be instrumental in rationalizing the collection of plant I&C system data, producing I&C specifications required by the procurement arrangements and to follow up the design and implementation process in the member parties.

The estimate has been broken down in ITER subsystems and the central system. In total we estimate there will be around 1000 components (PSH, fast controllers, slow controllers, CODAC servers and CODAC terminals). This is a large system, but in the same order of magnitude as the largest existing operating EPICS based experimental facilities.

4. Real time Plasma control

Ultimately the performance of ITER will be determined by the capability of the real-time plasma control system. The overall requirements for such a system are performance, robustness and flexibility. These requirements are contradictory and can only be addressed by having a sound architecture allowing the right trade-offs to be made.

The ITER Plasma Control System (PCS) [6] is a fundamental part of CODAC that uses a number of actuators and input data from the pulse scheduler and diagnostic measurements to setup plasma operation, produce plasma, and control the plasma evolution throughout all phases of the discharge, including plasma termination. Unlike existing devices, because of the large stored thermal and magnetic energies in high performance ITER plasmas, the ITER PCS must be exceptionally reliable and will require pre-pulse validation through integrated plasma transport and control simulations and operational scenario and sequence changes in real-time. In addition to standard pre-programmed sequences and segment switching, adaptive control algorithms will be required to change operational sequences in response to faults or plasma events that require a change in program to maintain the experimental objective or to switch to a back-up experiment to make the best use of valuable plasma operation time.

The ITER PCS is composed of the following five coupled subsystems based on the physical parameters being controlled: 1) wall conditioning and tritium removal, 2) plasma axisymmetric magnetic control, 3) plasma kinetic control, 4) non-axisymmetric control, and 5) event handling. Unlike existing devices, the ITER PCS will control between pulse wall conditioning and tritium removal techniques, particularly those that require vertical field programming such as ion cyclotron wall conditioning [7]. For plasma axisymmetric magnetic control, the PCS will control the currents in the poloidal field (PF), central solenoid (CS), and in-vessel vertical stability (VS) coils during plasma operation, but will not control the current in the toroidal field (TF) coils, since they will be charged typically at the beginning of an experimental campaign to provide a fixed toroidal field for the campaign. Plasma kinetic control includes fuelling, power and particle flux to the first wall and divertor, non-inductive plasma current, plasma pressure and fusion burn control. The non-axisymmetric control subsystem of the PCS controls all MHD instabilities including sawteeth, neoclassical tearing modes (NTMs), edge localized modes (ELMs), Alfvén eigenmodes (AEs), and resistive wall modes (RWMs) as well as error field control. The event handling subsystem of the PCS, will be responsible for analyzing in real-time any plasma and plant system events that could require a change in plasma operation. This PCS subsystem is the first level of machine protection that will use plasma control to attempt to avoid triggering the Central Interlock System (CIS). If the PCS fails to control the plasma within prescribed operational limits and conditions, then the CIS will trigger its interlocks to ensure machine protection.

The control timescales of the PCS vary from milliseconds, in the breakdown phase and for certain instabilities, to minutes and hours or longer, for monitoring wall conditions. The PCS requires detailed measurements of plasma, machine, and plant system parameters and a number of actuators to carry out its control functions. There will be about 50 large scale diagnostic systems required for plasma control and machine protection [8]. The measurements will cover a radiation spectrum from DC to γ-rays as well as electrons, neutrons, α-particles, plasma ions and neutral atoms in the boundary. The required actuators include multiple gas and pellet fuelling and impurity injection locations, real-time variable pumping systems, in-vessel vertical stability (VS) and ELM suppression coils and external poloidal magnetic field and error field correction coil systems, electron cyclotron (EC), ion cyclotron (IC), and neutral beam injection (NBI) heating and current drive systems, and specially designed high pressure gas or pellet impurity injection systems for disruption and runaway electron mitigation.

It is common practice by existing tokamak machines as well as other large experimental facilities to use home-made custom timing systems. It is believed that the emerging standard IEEE 1588, also called precision time protocol (PTP),
provides an alternative and have baselined this for TCN. In addition this baseline provides a migration path to White Rabbit [9], being developed at CERN, should it become available in COTS products. We are setting up a test-bed to evaluate more closely commercial IEEE 1588 products.

5. Conclusions

The schedule and procurement model of the ITER project have forced the CODAC team to take a bottom up approach. All effort has concentrated in defining standards and interfaces. Nevertheless, if successful, the common infrastructure being implemented now will easily allow the implementation of the applications seen by operation and physicists. Further, the control system will be a much more integrated system, with all associated advantages in flexibility and maintenance, compared to existing tokamaks.

6. Acknowledgement

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