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Development of real-time plasma analysis and control algorithms for the TCV tokamak using SIMULINK

F. Felici [a,b,*], H.B. Le [a], J.I. Paley [a], B.P. Duval [a], S. Coda [a], J.-M. Moret [a], A. Bortolon [a], L. Federspiel [a], T.P. Goodman [a], G. Hommen [e,b], A. Karpushov [a], F. Piras [a], A. Pitzschke [a], J. Romero [c], G. Sevillano [d], O. Sauter [a], W. Vijvers [a], the TCV Team

[a] *École Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association EURATOM-Suisse, 1015 Lausanne, Switzerland*
[b] *Eindhoven University of Technology, Department of Mechanical Engineering, Control Systems Technology Group, P.O. Box 513, 5600MB Eindhoven, The Netherlands*
[c] *National Laboratory of Fusion, EURATOM-CIEMAT, Madrid, Spain*
[d] *Department of Automatic Control and Systems Engineering, Bilbao University of the Basque Country, Bilbao, Spain*
[e] *FOM-Institute DIFFER, Association EURATOM-FOM, Nieuwegein, The Netherlands*

HIGHLIGHTS

- A new digital control system for the TCV tokamak has been commissioned.
- The system is entirely programmable by SIMULINK, allowing rapid algorithm development.
- Different control system nodes can run different algorithms at varying sampling times.
- The previous control system functions have been emulated and improved.
- New capabilities include MHD control, profile control, equilibrium reconstruction.

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ABSTRACT

One of the key features of the new digital plasma control system installed on the TCV tokamak is the possibility to rapidly design, test and deploy real-time algorithms. With this flexibility the new control system has been used for a large number of new experiments which exploit TCV's powerful actuators consisting of 16 individually controllable poloidal field coils and 7 real-time steerable electron cyclotron (EC) launchers. The system has been used for various applications, ranging from event-based real-time MHD control to real-time current diffusion simulations. These advances have propelled real-time control to one of the cornerstones of the TCV experimental program. Use of the SIMULINK graphical programming language to directly program the control system has greatly facilitated algorithm development and allowed a multitude of different algorithms to be deployed in a short time. This paper will give an overview of the developed algorithms and their application in physics experiments.

1. Introduction

With the continuing increase of computing power and reduction of costs of digital control hardware, most fusion devices have migrated to fully digital technologies for their plasma control systems. This has greatly resulted in increased capabilities and flexibility of such systems and hence the possible applications. Plasma control is now at the forefront of many tokamaks' research priorities in view of ITER, which will heavily rely on advanced control for safe operation. In 2008, it was decided to develop a new digital control system in the TCV tokamak [1] (major and minor radii 0.88 m and 0.25 m, plasma current up to 1 MA, toroidal magnetic field up to 1.5 T, up to 4.5 MW auxiliary heating and current drive from second and third harmonic electron cyclotron system). Starting from initial tests in 2008–2009 and continuing after being commissioned in July 2010, the new control system has seen a large number of successful

* Corresponding author at: Eindhoven University of Technology, Department of Mechanical Engineering, Control Systems Technology Group, P.O. Box 513, 5600MB Eindhoven, The Netherlands. Tel.: +31 402472839.
E-mail address: f.felici@tue.nl (F. Felici).

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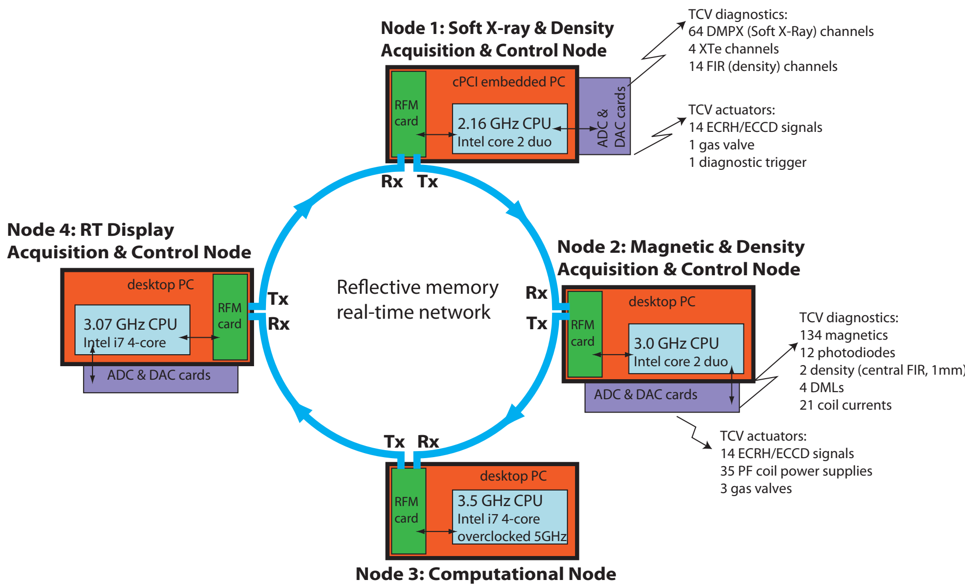

Fig. 1. SCD system nodes and connections to diagnostics and actuators. Diagnostics include DMPX (soft X-rays), XTe (ratios of filtered X-ray measurements for estimating temperatures), FIR (far infrared interferometer), photodiodes (H_α light), 1 mm (interferometer), DML (diamagnetic loop) and standard magnetic diagnostics. Actuators include PF + Ohmic coils and fast internal coils for vertical stability, as well as ECRH powers and launchers.
From [2,3].

applications. The hardware/software architecture of this system, known as SCD (*Système de Contrôle Distribué*) was previously outlined in [2] and is described in detail in the companion paper [3]. The present paper will exclusively treat the implemented control algorithms, and we refer the reader to the companion paper for details on the hardware, software, and real-time capability issues.

It was possible to develop many different algorithms with very limited manpower in a short time, using the possibility of programming algorithms entirely using the SIMULINK block programming language, i.e. without a single line of C-code. Most of the algorithms described in this paper have been used in plasma experiments that have yielded valuable insights and explored new avenues for plasma control. Details can be found in the cited references for each application.

The rest of this paper is structured as follows. Section 2 presents a brief overview of the digital control system, its architecture and programming methods. Next, Section 3 shows how the system was used to emulate the existing TCV control system, allowing backward compatibility with TCV shot preparation software. Section 4 discusses some real-time MHD detection and control algorithms. Section 5 explains how information from high-precision profile diagnostics are extracted in real-time. Section 6 briefly outlines some other applications which have been discussed elsewhere in more detail. Finally, Section 7 discusses some recent developments and plans for further use of the system's potential.

2. Overview of SCD control system and developed algorithms

2.1. Overview of the SCD control system

For completeness, we will very briefly review the architecture of the SCD control system and its interaction with other TCV control hardware. A more detailed description can be found in the companion paper [3]. The SCD is composed of a set of independent nodes (presently 4) linked via shared (reflective) memory. Each node has its own Linux-based PC, and may be equipped with ADC and/or DAC cards hosted in a Compact-PCI crate, which are in turn connected to diagnostics and/or actuators. A list of each node's characteristics and connected actuators/diagnostics is given in Fig. 1.

The SCD can entirely control a TCV discharge, apart from the fast control loop of the in-vessel vertical stability coil (which is still handled by the analog system) and the toroidal field coils (which are driven in feedforward by a separate waveform generator). Alternatively, discharges may still be controlled by the pre-existing "hybrid" control system hardware [4]. This increases the operational flexibility of TCV so that the digital system can be run in parallel to the existing system for debugging/development.

2.2. Using SIMULINK for algorithm design

Algorithms to be run in the SCD control system are programmed entirely in SIMULINKˆ® [5]. All the nodes are included in a single, main SIMULINK model, in which each SCD node is represented as a separate subsystem. An algorithm which has to run on a specific node is programmed inside the corresponding block using standard SIMULINK library blocks, allowing one to use existing advanced signal processing blocks. Simple models of the process to-be-controlled are used occasionally for closed-loop simulations during algorithm development. Once the algorithm development is complete, the ensemble of nodes can then be simulated in open-loop by running the model, and data acquired from previous shots is loaded to substitute for the ADC inputs in the simulations. Controllers and data from previous shots are stored in the TCV shot database (MDSplus [6]) and can be reloaded for later use in debugging or development. This method of programming massively speeds up development, as control algorithms can be developed with continuous testing using previous shot data. During experimental operation, algorithm behavior can be simulated in open-loop just after each shot with the freshly acquired data, modified or corrected, and re-compiled between two shots. For an experienced user, this was easily possible within the 10–15 min time between two TCV shots. Compilation takes approximately 1 min and does not delay the TCV shot cycle. Compiled control algorithms are sent to each node in the form of shared object libraries, where they are executed by pre-compiled executables on each