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Tokamak Magnetic Control Simulation: Applications for JT60-SA and ISTTOK Operation.

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ABSTRACT

Abstract en ingles

Keywords:Real-time control, plasma current, centroid position, state-space

RESUMO

Abstract em tuga

Palavras-chave:

SOMMARIO

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Parole chiave:

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LIST OF ABBREVIATIONS

@TODO: Review variable lists as writing the thesis

- AC - Alternating Current
- ADC - Analog to Digital Converter
- ATCA - Advanced Telecommunications Computing Architecture
- CREATE - Consorzio di Ricerca per l'Energia, l'Automazione e le Tecnologie dell'Elettromagnetismo
- DAC - Digital to Analog Converter
- EO - Electronic Offset
- IST - Instituto Superior Técnico
- LQR - Linear Quadratic Regulator
- MARTe - Multi-threaded Application Real-Time executor
- MIMO - Multiple-Input Multiple-Output
- PCS - Plasma Control System
- PF - Poloidal Field
- PID - Proportional - Integrative - Derivative
- RFM - Reflective Memory
- SCD - Systéme de Contrôle Distribué
- XSC - eXtreme Shape Controller
- WO - Wiring Offset

LIST OF VARIABLES

@TODO: Review variable lists as writing the thesis

VARIABLES:

- I_p - Plasma current
- B_p - Poloidal magnetic field
- μ_0 - Vacuum permeability

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INTRODUCTION

1.1 TOKAMAK PLASMA CONTROL

1.2 BEHIND THE PLASMA CURRENT

1.3 THESIS OUTLINE

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PLASMA CONTROL SYSTEMS

2.1 OVERVIEW OF CONTROL SYSTEMS

The control of plasma position, shape and current among other parameters is one of the crucial engineering problems for present and future magnetic confinement devices. The Plasma Control Systems (PCS) lead with the overall control of fusion devices being responsible also for the plasma configuration and scenarios algorithms [1, Chapter 8]. Currently different PCS's are use in the tokamaks around the world. In this chapter the "DIII-D-like" PCS, the Systéme de Contrôle Distribué (SCD) and the Multi-threaded Application Real-Time executor (MARTe) will be approach, this last one being of special interest due to its extensive utilization in this work.

2.1.1 *DIII-D Plasma Control System*

The DIII-D-like PCS is use in various fusion research facilities such as EAST(China), K-STAR (South Korea) and MAST (UK). Early documentation regarding the PCS in DIII-D[1] reefers to digitalization of analog signals transmitted to a high speed processor executing a shape control algorithm and then writing the result to a digital to analog converter for driving the controlled systems . The real-time computer used allowed to performed operations with vectors and matrices required for the plasma shape control algorithm [2]. Figure 2.1 shows the block diagram of the DIII-D PCS 30 years ago.

In recent years the DIII-D PCS had extensive software and hardware upgrades. The PCS actual software consists of an infrastructure library core which provides all the routines that are necessary for implementing a basic and generic control system. The current PCS hardware configuration uses a collection of Intel Linux based multi-processor computers running in parallel to perform the real-time analysis and feedback control [3]. New digitizers have been added to the real-time network to increase the number of signals acquired an to control hardware on real-time, several real-time control algorithms were added and real-time data was added to external entities such as web server. [4]. In the current ver-

1 DIII-D is a D-shape tokamak operated by General Atomics in San Diego, California.

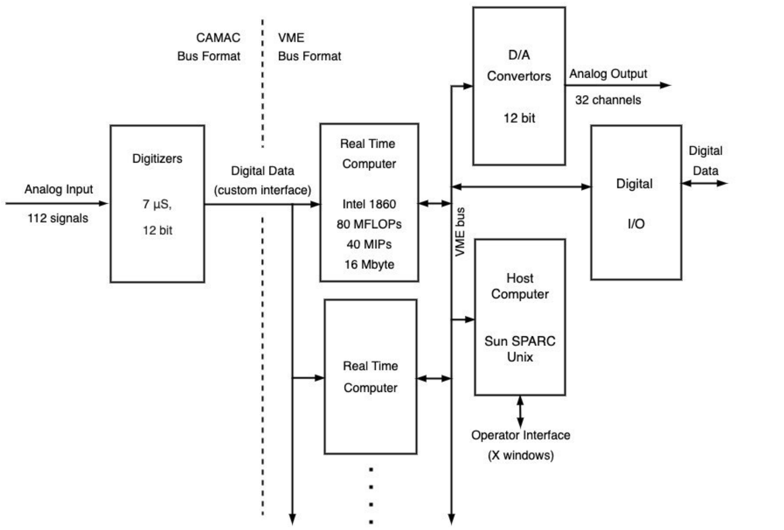

Figure 2.1.: DIII-D digital PCS in 1991 [2].

sion of the PCS, a Myricom[2] network has been replaced with a 40 Gb/sec InfiniBand[3] network based on the Mellanox Connect-X 3[4] hardware set. Figure 2.2 shows the currently overall networking diagram of DIII-D PCS .

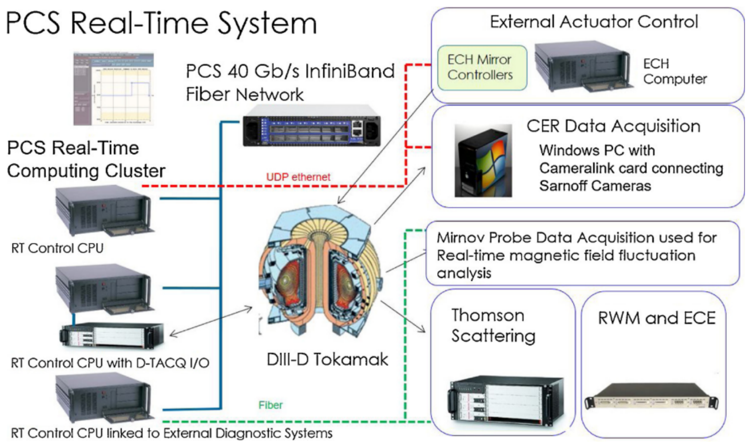

Figure 2.2.: Actual DIII-D PCS real-time systems [4].

2 Myricom networks also called Myrnet are high speed networking systems used to interconnect machines to form computer clusters.
3 Is a network architecture from Mellanox designed to support I/O connectivity and reliability, availability, and serviceability Internet requirements [5].
4 The Connect-X from the Mellanox company are Ethernet network interface cards with PCI Express.

2.1.2 *Systéme de Contrôle Distribué*

The TCV[5] distributed control system uses a modular network of real time PC nodes liken by a real time network to provide feedback control over all of the actuator systems. Each node consists of a Linux PC either embedded on a Compact-PCI module or as a desktop computer with Intel CPU. A fiber optic ring network links the reflective memory (RFM) network cards in each node [6]. The design of the diagnostic signal processing and control algorithms is performed in Matlab-Simulink software. During the real-time execution C/C++ code is generated from the Simulink and compiled into a Linux shared library and distributed to target nodes providing the input/output interface to the control algorithm code [7]. Figure 2.3 depicts the TCV SCD layout with the connectivity to diagnostics and actuators.

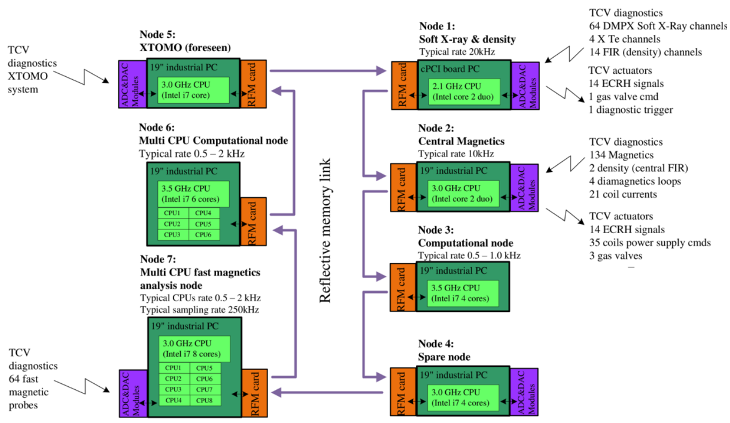

Figure 2.3.: TCV SCD. Real-time network nodes connection. The nodes configurations are shown together with the typical diagnostic and actuator systems to which they are connected [7].

2.2 MARTE FRAMEWORK

Regardless the nature of a real-time system the design of it is usually related to the specific requirements it has, commonly this implies to have customized hardware and software which causes a lack in modularity and portability. When systems become bigger is convenient to provide a common library containing shareable functionalities and which also allows for modular implementations. In order to deal with this the MARTe framework was designed about a decade ago. MARTe was developed in order to standardize general real-time control systems for the execution of control algorithms and is based on a multiplatform C^{++} library [8]. Previous implementations for a software framework similar to MARTe were developed some years before for the JET tokamak. JETRT was a software framework used to develop real-time control and data acquisition systems which laid the foundation for the current MARTe framework [9].

5 The Tokamak á configuration variable (TCV) is a medium size tokamak localized in Lausanne,Switzerland. It is characterized by a highly elongated, rectangular vacuum vessel.

2.2.1 *MARTe architecture*

[10]

2.2.2 *Hardware containers*

2.2.3 *MARTe 2.0*

Software Quality Assurance (QA) processes are being applied to the development of a new version of the MARTe framework also called MARTe 2.0.

[11]

2.3 EQUILIBRIUM AND CONTROL ALGORITHMS

The RAPTOR (RApid Plasma Transport simulatOR) code is a model-based control-oriented code that predicts tokamak plasma profile evolution on real-time. [12]

2.3.1 *PID control*

2.3.2 *Multiple-Input Multiple-Output control*

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JT60-SA CONTROL DESIGN

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4.4 PLASMA CURRENT MAGNETIC FIELD

Retrieving the contribution of the plasma current in tokamaks ...

The methods of correction of the magnetic error fields due to inaccuracies of tokamak manufacturing and assembly are considered. The problems of the plasma position and shape reconstruction based on magnetic field measurements are discussed.

4.5 PLASMA CENTROID POSITION DETERMINATION

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ISTTOK RESULTS

5.1 IMPLEMENTATION OF THE GENERAL APPLICATION MODULES

5.1.1 *PID control implementation*

5.1.2 *Multiple-Input Multiple-Output control implementation*

5.2 RESULTS

5.2.1 *PID control and LQR control results*

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CONCLUSIONS

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BIBLIOGRAPHY

[1] Andrej A. Kavin Valerij A. Belyakov. *Fundamentals of Magnetic Thermonuclear Reactor Design*. Elsevier, 2018.

[2] J. R. Ferron, A. Kellman, E. McKee, T. Osborne, P. Petrach, T. S. Taylor, J. Wight, and E. Lazarus. An advanced plasma control system for the diii-d tokamak. In *[Proceedings] The 14th IEEE/NPSS Symposium Fusion Engineering*, pages 761–764 vol.2, Sep. 1991.

[3] B. G. Penaflor, J. R. Ferron, A. W. Hyatt, M. L. Walker, R. D. Johnson, D. A. Piglowski, E. Kolemen, A. S. Welander, and M. J. Lanctot. Latest advancements in DIII-D Plasma Control software and hardware. *2013 IEEE 25th Symposium on Fusion Engineering, SOFE 2013*, pages 1–4, 2013.

[4] M. Margo, B. Penaflor, H. Shen, J. Ferron, D. Piglowski, P. Nguyen, J. Rauch, M. Clement, A. Battey, and C. Rea. Current State of DIII-D Plasma Control System. *Fusion Engineering and Design*, 150(October 2019), 2020.

[5] Mellanox Technologies. Introduction to InfiniBand. Technical report, 2003.

[6] J. I. Paley, S. Coda, B. Duval, F. Felici, and J. M. Moret. Architecture and commissioning of the TCV distributed feedback control system. *Conference Record - 2010 17th IEEE-NPSS Real Time Conference, RT10*, pages 1–6, 2010.

[7] H. Anand, C. Galperti, S. Coda, B. P. Duval, F. Felici, T. Blanken, E. Maljaars, J. M. Moret, O. Sauter, T. P. Goodman, and D. Kim. Distributed digital real-time control system for the TCV tokamak and its applications. *Nuclear Fusion*, 57(5), 2017.

[8] A. C. Neto, F. Sartori, F. Piccolo, R. Vitelli, G. De Tommasi, L. Zabeo, A. Barbalace, H. Fernandes, D. F. Valcarcel, and A. J. N. Batista. Marte: A multiplatform real-time framework. *IEEE Transactions on Nuclear Science*, 57(2):479–486, April 2010.

[9] G. De Tommasi, F. Piccolo, A. Pironti, and F. Sartori. A flexible software for real-time control in nuclear fusion experiments. *Control Engineering Practice*, 14(11):1387–1393, 2006.

[10] André C. Neto, Diogo Alves, Luca Boncagni, Pedro J. Carvalho, Daniel F. Valcárcel, Antonio Barbalace, Gianmaria De Tommasi, Horácio Fernandes, Filippo Sartori, Enzo Vitale, Riccardo Vitelli, and Luca Zabeo. A survey of recent MARTe based systems. In *IEEE Transactions on Nuclear Science*, volume 58, pages 1482–1489, 2011.

[11] Andre C. Neto, Filippo Sartori, Riccardo Vitelli, Llorenc Capella, Giuseppe Ferro, Ivan Herrero, and Hector Novella. An agile quality assurance framework for the development of fusion real-Time applications. In *2016 IEEE-NPSS Real Time Conference, RT 2016*, 2016.

[12] Chiara Piron, Gabriele Manduchi, Paolo Bettini, Federico Felici, Claudio Finotti, Paolo Franz, Ondrej Kudlacek, Giuseppe Marchiori, Lionello Marrelli, J. M. Moret, Paolo Piovesan, Olivier Sauter, and Cesare Taliercio. Integration of the state observer RAPTOR in the real-time MARTe framework at RFX-mod. *Fusion Engineering and Design*, 123:616–619, 2017.

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DEMONSTRATIONS