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Abstract. This paper presents the latest status of the DIII–D Real-Time Digital Plasma Control System (PCS). The primary focus will be on the new computing and data acquisition hardware recently incorporated into the PCS and the added features provided by the new hardware. The upgrade of the PCS real-time computing and data acquisition hardware has been in progress for the past three and a half years. Since the initial proposal to migrate off the old VME i860 based system to more modern computing hardware, the PCS has seen a number of changes and improvements occurring in several planned phases. The final phase of the upgrade was successfully completed earlier this year. This phase included the complete removal of the i860 computers and Traq digitizer hardware and the incorporation of high performance Intel PCI based computers fitted with 32 Channel PCI digitizers from D-TACQ corporation. Distinguishing features of the completed PCS upgrade include a custom real-time data acquisition and control solution based on the Linux Intel computing platform and a scaleable multi CPU parallel processing architecture connected by a 2 gigabit per second Myrinet network. Among the many improvements resulting from the upgrade are the higher computing performance (factor 20 over the previous system), connectivity to remote DIII–D diagnostics through Myrinet fiber optic links and plasma diagnostic data displayed in real-time on digital oscilloscopes.

Keywords: Tokamak, Plasma Control, Real-Time Control, Linux, PCI Data Acquisition

1. Introduction

Planning for the upgrade to the original PCS [1] Intel VME based i860 real-time computing hardware [2] began in 1999. Since that time, steady progress was made in identifying and implementing a replacement system which would provide more computing power in addition to providing a longer term solution for supporting the ever increasing needs of the DIII–D research program. The PCS upgrade work has occurred in several carefully planned phases over the course of the past three and a half years in order to minimize the impact on the physics program which relies heavily on the PCS during plasma operations.

An important decision made at the beginning of the upgrade process was to migrate from the VME platform to PCI based systems in which computing performance was significantly higher and pricing more competitive. The first phases of the PCS upgrade [3] focused on incorporating and testing the new PCI computing hardware in the existing VME based system. This was accomplished through Myrinet high speed networking components connecting the new PCI upgrade computers fitted with Myrinet PCI Network Interface Cards and a special Intel VME computer fitted with a Myrinet PMC card. As more confidence was gained in the new computing hardware more PCS software was migrated from the old computers to the new.

The necessary real-time performance requirements for controlling DIII–D plasma discharges from the new computer systems were met through special in-house customizations of the free and open source Linux operating system kernel. The standard Linux operating system is not suitable for meeting the needs of PCS real-time control. It is based on a time sharing interrupt driven scheduler which divides CPU time to various competing user and system level processes. This results in "gaps" in the PCS control cycles in which some control commands do not reach the tokamak at the expected times. These gaps occur whenever the operating system schedules the PCS process out of the processor in favor of another competing process, such as a system routine or an interrupt handler code. The fundamental method for eliminating these gaps and achieving real-time under Linux is based on a set of routines developed at DIII–D to disable and re-enable all system and hardware interrupts. The disabling of interrupts during the period of time in which the PCS real-time processes are performing active feedback control of the DIII–D plasma discharge allows the PCS real-time process to obtain steady access to the processor thus eliminating performance control gaps.

While the fundamental upgrade approach has remained mostly intact since the initial upgrade proposal was made, a few important changes have occurred in the selection of the upgrade hardware components. The computing hardware initially chosen for the upgrade was based on the 64 bit Alpha 21264 processor [3]. At the time, the Alpha chips were still supported and far outperformed other similar processors including the Intels. The first upgrade computers incorporated into the initial PCS upgrade phases were Alpha based. Performance gains in the Intel CPUs coupled with questions over the long term support and viability of the Alpha processor led to a revision to incorporate Intel Xeon processors instead.

Another significant change made to the original PCS upgrade proposal was in the selection of a new digitizer solution for replacing the old CAMAC form Traq based digitizers. The initial plans were to use Front Panel Data Port digitizers similar to those used by Princeton's NSTX program [4] in place of the old Traq digitizers. Instead a solution was found in the form of a 32 channel 200 kHz simultaneous sampling PCI digitizer from D-TACQ Solutions of Scotland (www.d-tacq.com). With much helpful assistance from D-TACQ, the digitizer was successfully modified in order to meet the low latency real-time acquisition needs of the PCS and incorporated into the upgrade computer systems.

The final phase of the PCS upgrade was successfully completed early this year and made available for use during the course of the 2003 plasma physics campaign. During this phase the i860 computing hardware was officially retired from the PCS and the old Traq digitizers were removed and completely replaced with the PCI D-TACQ based digitizers.

2. Organization of the DIII–D Plasma Control System

The computing hardware (Fig. 1) for the DIII–D PCS upgrade system consists of a set of eight rack mounted 2.4 GHz Xeon based computers connected together in a local 2.1 Gigabit per second Myrinet network. These computers, in addition to a special Intel VME based computer connected to the local Myrinet network with a PMC network card constitute the PCS real-time computing core. The real-time computer systems are only accessible from a single host computer known as the PCS "gateway" (or bridge acting) computer. The gateway computer is connected to both the local Myrinet network and the general DIII–D network via ethernet. This computer provides the interface to users for setting up the real-time computers before each plasma discharge. It is responsible for running (1) the PCS user interface applications, (2) a "waveform" server process which manages the user inputs for programming each plasma discharge, (3) a "lock" server process which synchronizes the PCS with the DIII–D discharge cycle, and (4) a set of "host real-time" processes which load the desired set up information onto each real-time computer at the beginning of each discharge cycle. In addition to this, the gateway computer is also responsible for archiving the data collected by the real-time computers after a discharge into the DIII–D archive system.

The Xeon real-time computers acquire and share tokamak diagnostic data with one another and execute the PCS control routines in real-time. Each Xeon computer may be fitted with anywhere from zero to four PCI D-TACQ digitizers. The Xeon computers are spread throughout various locations within the DIII–D facility based in part on the acquisition needs of the individual computer. Each computer which is responsible for collecting data is placed in closest proximity to its required diagnostic signals. The Xeon computers connect to a single Myrinet switch box with either short distance Myrinet SAN (short distance copper) cables or longer distance fiber optic cables. A special Xeon computer is located in the DIII–D control room to drive a set of LCD monitors and provide real-time oscilloscope plot displays of signals which are acquired or computed by the PCS.

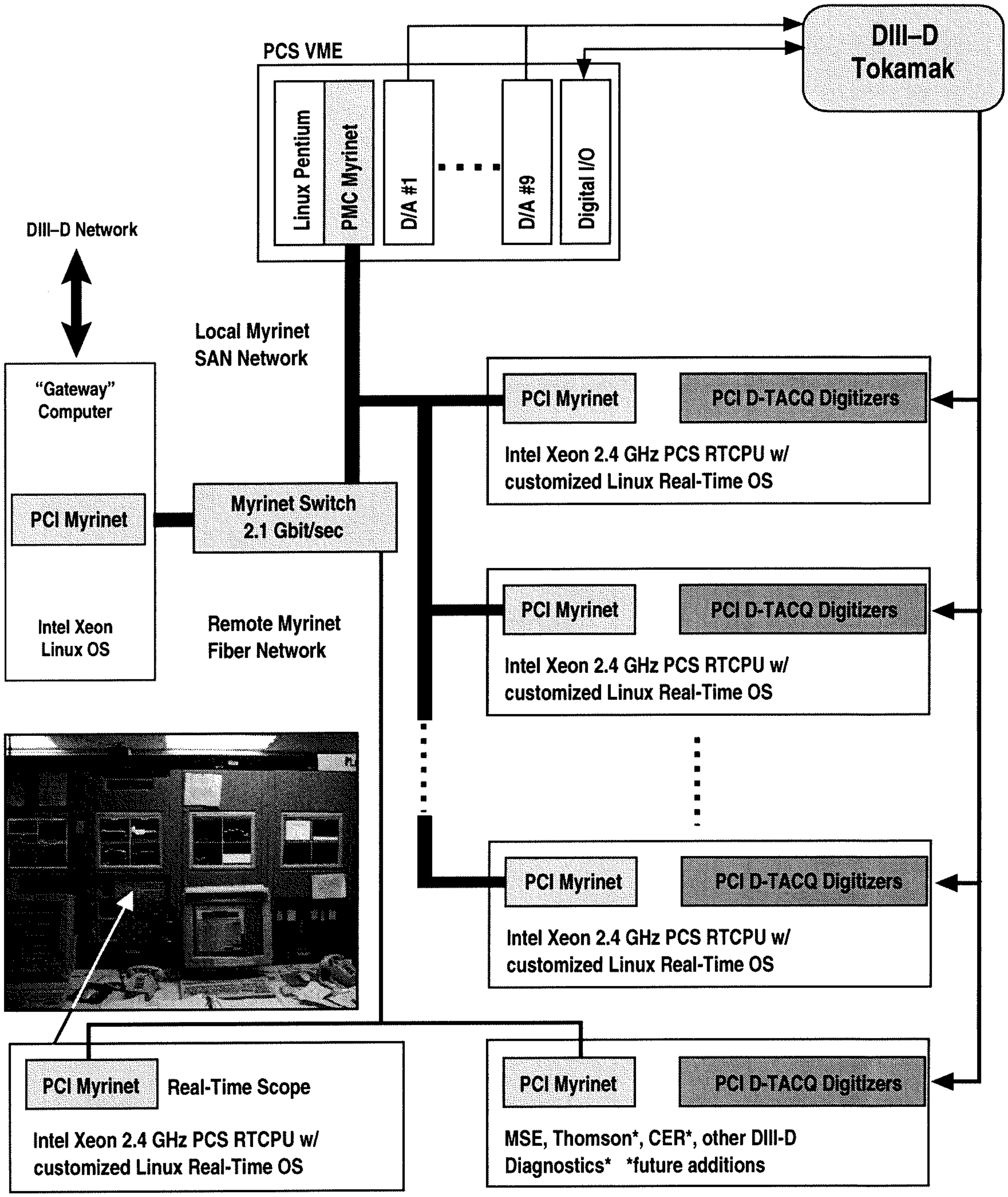

Fig. 1. Layout of new plasma control computer systems.

The Intel VME computer provides access to a VME based input/output system for sending commands to and receiving information back from the tokamak. The VME system includes nine 8 channel Datel D/A converter modules providing up to 72 analog command outputs. In addition to this are a pair of 128 bit digital input/output modules.

PCS data acquisition and control functionality is distributed amongst the nine real-time computers as follows.

CPU 1: Runs 250 μs control cycles. Acquires data from up to 32 diagnostic input signals. Controls and monitors density, gas, beams, lithium pellet injection, ICRF, and ECH, NTM (neoclassical tearing mode) suppression algorithm.

CPU 2: Runs 50 μs control cycles. Acquires data from up to 96 diagnostic input signals. Controls poloidal field power supplies, plasma vertical position, and chopper voltages.

CPU 3: Runs 250 μs control cycles. Acquires data from up to 128 diagnostic input signals. Performs plasma shape control. Executes the fast-loop real-time equilibrium reconstruction/fitting (RTEFIT) codes [5].

CPU 4: Runs 50 μs control cycles. Acquires data from up to 32 diagnostic input signals. Controls C-coil and I-coil systems for error field correction and RWM (resistive wall mode) feedback.

CPU 5: Runs 3.5 ms control cycles. Executes the slow-loop RTEFIT codes.

CPU 6: Runs 50 μs control cycles. Acquires data from up to 32 input diagnostic signals. Performs specialized RWM calculations.

CPU 7: Runs 7 ms control cycles. Acquires data from up to 32 diagnostics input signals. Runs Motional Stark Effect (MSE) RTEFIT using MSE data to compute the current profile and the Safety factor (q) profile.

CPU 8: Runs 1 ms control cycles. Drives the real-time digital oscilloscope displays of computed and acquired signals from the PCS.

CPU 9: Runs 50 μs control cycles. The VME computer which interfaces the rest of the real-time computers to the VME based input/output modules. Sends digital and analog outputs to the tokamak from the PCS. Acquires digital input signals to pass back to the other real-time processes.

A special data passing scheme has been implemented in order to account for the differing cycle times of the real-time computers and to insure the efficient transfer of information. Each of the PCS real-time computers is capable of passing and receiving data to and from any of the other real-time computers connected via the Myrinet. The data passed consists primarily of digitized raw data, and also includes computations specific to a given real-time computer. Data passing occurs in a single direction only. A "sending" computer passes data and an associated "timestamp" to a "receiving" computer. The "timestamp" can be used by a "receiving" computer to insure the information obtained is current. The rate at which data is transferred depends on the cycle time of the slower of the two computers involved. The cycle times of each of the real-time computers are purposefully set to be multiples of one another in order to provide a common time base for passing data between any two computers.

3. Improvements to Hardware, Software and Overall Capabilities

The recently completed PCS upgrade has resulted in a number of improvements to the DIII–D plasma control capabilities which have had a number of positive impacts on the DIII–D experimental program. The most noticeable improvement has been the significant performance increases provided by the new real-time computer systems. The old VME based i860s ran at 40 MHz with 16 megabytes of RAM. The new Xeon computers are running at 2.4 GHz and have 512 megabytes of RAM. The increased performance has allowed plasma control programmers to run more calculations and control codes on the real-time computers while at the same time reducing the control cycle times compared to the previous VME based hardware. Feedback of the plasma shape control and position parameters which required up to 1.5 ms per each cycle on the old systems now take only 250 μs per each cycle on the new systems.

Another benefit of the upgrade has been the ability to connect remote diagnostic systems to the PCS. The old VME system was restricted to incorporating only diagnostic information which could be connected directly to its VME rack based components. This excluded such important diagnostics such as MSE, CER and Thomson data located elsewhere in the DIII–D facility. With the new PCS utilizing the Myrinet Networking technology, real-time computers with digitizers can be placed anywhere within the DIII–D facility and connected to one another via long length fiber optic lines going into a central Myrinet switch. The MSE diagnostic has been successfully integrated into the current PCS and plans are in place for integrating Thomson and CER data in the near future.

The PCS upgrade system now provides a new and highly relied upon capability for displaying real-time digitized oscilloscope traces which was not possible with the older systems. A set of four flat panel LCD displays in the control room, connected to a single PCS real-time computer has been dedicated to plotting PCS acquired or calculated signals. The new display capability is providing DIII–D researchers with immediate feedback on the performance of the PCS and plasmas for each discharge. Information shown in real-time for each discharge includes plasma current, neutral beam power, gas fueling, total ECH power, plasma density and more. In the time between plasma discharges, users have the ability to easily select and change the signals to be displayed on the real-time scopes.

As a result of the recent hardware improvements in the PCS, software for a number of new capabilities have been added to the PCS. This has included the incorporation of electron cyclotron heating (ECH) monitoring and control, the development of codes to locate and suppress neoclassical tearing modes (NTM) in the plasmas, enhancements to RWM Control, improvements to multiple input multiple output (MIMO) [6] control development and integration, incorporation of "DUD" detection codes to cleanly terminate plasma discharges when off-normal conditions are detected, and general improvements to PCS offline simulation capabilities.

The new upgrade system has also provided a clearer upgrade path for the future of DIII–D plasma control. As a result of migrating to readily available and widely used components, particularly the PCI based Intel computing platform, the addition of new computing capability has become as simple as plugging in a new computer to the local real-time Myrinet network. With the continual gains in performance of PCI based computing systems, more CPU power can also be easily obtained by swapping out existing real-time computers with newer ones.

4. Conclusions

The upgrade of the DIII–D plasma control system has successfully achieved its objectives for replacing the older VME based computing and acquisition hardware. A flexible and well defined software and hardware architecture based on a customized Linux operating system and readily available and easily upgradeable computing components provides a simple and easy means for improving the PCS performance in the years to come. The new Myrinet provides connectivity to remote DIII–D diagnostics not possible with the old vme based i860 systems. The new D-TACQ PCI digitizers provide a straight forward, reliable means for performing the necessary real-time acquisition. The PCS upgrade system significantly improves the ability for new control codes and diagnostics to be quickly and easily implemented and provides a solid foundation for keeping up with future needs of the DIII–D experimental research program.

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