A Survey of Recent MARTe Based Systems

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, Luca Zabeo and JET EFDA CONTRIBUTORS

***Abstract*—The Multithreaded Application Real-Time executor (MARTe) is a data driven framework environment for the development and deployment of real-time control algorithms. The main ideas which led to the present version of the framework were to standardise the development of real-time control systems, while providing a set of strictly bounded standard interfaces to the outside world and also accommodating a collection of facilities which promote the speed and ease of development, commissioning and deployment of such systems. At the core of every MARTe based application, is a set of independent inter-communicating software blocks, named Generic Application Modules (GAM), orchestrated by a real-time scheduler. The platform independence of its core library provides MARTe the necessary robustness and flexibility for conveniently testing applications in different environments including non-real-time operating systems. MARTe is already being used in several machines, each with its own peculiarities regarding hardware interfacing, supervisory control configuration, operating system and target control application. This paper presents and compares the most recent results of systems using MARTe: the JET Vertical Stabilisation system, which uses the Real Time Application Interface (RTAI) operating system on Intel multi-core processors; the COMPASS plasma control system, driven by Linux RT also on Intel multi-core processors; ISTTOK real-time tomography equilibrium reconstruction which shares the same support configuration of COMPASS; JET error field correction coils based on VME, PowerPC and VxWorks; FTU LH reflected power system running on VME, Intel with RTAI.**

***Index Terms*—MARTe, real-time, nuclear fusion control, tokamak**

This work was supported by the European Communities under the contract of Association between EURATOM/IST and was carried out within the framework of the European Fusion Development Agreement. See the Appendix of F. Romanelli et al., Fusion Energy Conference 2008 (Proc. 22nd Int. Conf. Geneva, 2008) IAEA, (2008). The views and opinions expressed herein do not necessarily reflect those of the European Commission.

A. Neto, D. Alves, P. J. Carvalho, D. F. Valcárcel and H. Fernandes are with Associação EURATOM/IST, Instituto de Plasmas e Fusão Nuclear – Laboratório Associado, 1049-001 Lisboa, Portugal (e-mail: andre.neto@ipfn.ist.utl.pt; dalves@ipfn.ist.utl.pt, pedro.carvalho@ipfn.ist.utl.pt; daniel.valcarcel@ ipfn.ist.utl.pt; hf@ipfn.ist.utl.pt).

L. Boncagni and E. Vitale are with Associazione EURATOM/ENEA, 00040 Frascati, Italy (e-mail: luca.boncagni@enea.it).

A. Barbalace is with the Associazione EURATOM/ENEA, Consorzio RFX, 35127 Padova, Italy (e-mail: barbalace@igi.cnr.it).

G. De Tommasi is with Associazione EURATOM/ENEA/CREATE, Università di Napoli Federico II, 80138 Napoli, Italy (e-mail: detommas@unina.it).

F. Sartori is with Fusion for Energy, 08019 Barcelona, Spain (e-mail: Filippo.Sartori@f4e.europa.eu).

R. Vitelli is with the Dipartimento di Informatica, Sistemi e Produzione, Università di Roma "Tor Vergata," 00133 Rome, Italy (e-mail: ricardo.vitelli@uniroma2.it).

L. Zabeo is with ITER-IO, St. Paul-Lez-Durance, 13108, France (e-mail: Luca.Zabeo@iter.org).

978-1-4244-7110-2/10/$26.00 ©2010 IEEE

I. Introduction

MARTE is a C++ multi-platform framework for the development and execution of real-time control systems [1]. Its main goals are to provide a clear boundary between algorithms, hardware interaction and system configuration, leveraging reusability and maintainability. This functional division also enables control systems simulation [2] and phased commissioning, by replacing some of its components by models and synthetic data producers.

Being multi-platform it minimises the constraints with the operational environments, so that the target application can be easily run on a different operating system. A feature which allows the development and execution of code in non real-time environments and to proceed to the final deployment on the real-time target, only when the overall functionality of the control system is asserted. MARTe was already ported and tested in the following operating systems: Wind River® VxWorks^{tm}, Linux®, Linux®/RTAI, Solaris®, and MS® Windows^{tm}.

MARTe and its components are data driven using a textual language with a specific format and syntax, validated during the configuration phase. The framework does not impose a way on how the configuration data should be produced, but it does provide a standard for sending new configuration requests, using TCP/IP, allowing its integration in different experiments and human machine interfaces.

The core component of a MARTe is the Generic Application Module (GAM). A MARTe application is built by connecting a collection of specialized GAMs, using a memory data bus named Dynamic Data Buffer (DDB). Each GAM can produce and receive data using DDB named channels. These are requested by the GAM upon configuration and the framework guarantees that all the required sources are present on the system. Usually each GAM is associated with a functional requirement of the control system (e.g. PID or data conversion), enabling the reusage of the component itself, or the replacement of part of the control system, particularly useful for simulation purposes.

The interface with the hardware and synchronization is performed using a special module named IOGAM. It provides a standard hardware interface to MARTe, which expects the real hardware interaction to be implemented at the driver level (e.g. configuration and data transferring). MARTe supports two types of synchronization mechanisms, one based on continuous polling of a resource and the other as a response to an external interrupt. The framework can also have asynchronously triggered elements on the control chain, which collect the latest data available and verifying if the latency is acceptable.

Each control loop is executed by an entity named real-time thread. A MARTe application can have one or more real-time threads, running at different frequencies and with different priorities. If the underlying hardware and operating system supports it, the threads can run in different CPU sets. These threads can also be connected and exchange information between their DDBs. As a real-time executor, MARTe measures the execution time of its components, the total overall cycle time and jitter, and is capable of taking protective actions if problems are found during the control loop cycle. A series of auxiliary components are also built around the framework, enabling among other things: component introspection and browsing using a built-in HTTP server, an advanced real-time logging mechanism and a data achiever.

MARTe is currently being used in several fusion experiments, to solve different control problems, each with its own singularities regarding supervisory control and configuration, data collection and hardware. This paper describes some of the systems, comparing architectures and recent results.

II. JET VERTICAL STABILIZATION

A. Description

Tokamak plasmas are confined inside a vessel using strong magnetic fields. Vertically elongated plasmas experience a vertical instability that has to be actively controlled, by means of a radial magnetic field [3], created by a set of poloidal field coils. The controller tries to maintain the plasma vertical velocity and current on the circuit around zero. Erroneous control of the system can have serious consequences, as a sudden loss of thermal and magnetic energy can lead to the induction of large currents and forces on the machine vessel. Recently at JET [4], the largest tokamak in the world, the Vertical Stabilization (VS) system was upgraded [5], in order to enable the exploitation of the machine at high plasma current with ITER [6] relevant plasma shapes.

The power radial field amplifier (RFA) was enhanced to a newer version, ERFA [7] capable of providing ± 5 kA of output current and± 12 kV at maximum rate of change of 800 V/μs. The controller hardware was upgraded from a version running on TMS32C40™ processors [8] to an ATCA® and PCIe based system [9] acquiring 192 ADC channels at 2 MHz, with microsecond figure latencies in data transportation to the main core. Finally, all the modules and controllers were partially redesigned and improved to take advantage of the greater flexibility of the new control system, in particular the larger number of inputs and processing power available. Acquired data is filtered down to 20 kHz in the acquisition cards FPGAs and transferred at this rate to the central processing unit, providing the 50 μs cycle time of the control system. The system runs on an Intel®Core™2 Quad processor and uses the Linux operating system with the real-time extension RTAI.

The VS is also used as an experimental tool. In order to increase performance and confinement times, it is required to push plasma parameters towards high pressure and plasma current. Unfortunately this triggers a set of instabilities which can work against the system. Of particular importance is an instability named Edge Localized Mode (ELM), occurring in the outer part of the radius, which can deliver high heat loads to the plasma facing components. One of the ideas to mitigate its impact, is to try to generate the ELMs at a predefined frequency, in order to have some control over the instability size. The VS system achieves this using a technique called ELM pacing [10], which consists in applying for a given period of time a constant voltage to the amplifier (ignoring what was requested by the controller), called vertical kick, and causing an abrupt vertical movement of the plasma.

B. Software architecture

A series of 18 GAMs are used in the JET VS system. The role of the first GAM is to provide synchronization with the time source and transfer data from 192 ADC modules. This data is converted into the correct physical units, prior to placing it in the DDB. The next module to be executed provides some synthetic data and event detection mechanisms (e.g. ELMs). An IOGAM connected to the JET Asynchronous Transfer Mode (ATM) [11] network subsequently checks if a stop was requested by the real-time protection system. With all the required data in the DDB, an observer GAM combines some of the input magnetic signals in order to provide up to 10 estimations of the plasma vertical velocity. A scheduler module follows and decides, from the available controllers, what should close the loop and what velocity estimation to use. Immediately after, two GAMs are allowed to provide several experimental features (e.g. vertical kicks and delays) by overriding the controller request. Finally, the voltage request is sent to the amplifier and data is stored in memory for collection upon pulse completion.

One of the most important MARTe features used during the development and deployment of the VS system was the ability to interchange GAMs, without impacting on the remaining part of the control system. One GAM which implements a state space model was used to simulate the plasma and amplifier currents [12] . The radial field amplifier was also modelled using a GAM, enabling to simulate its hysteretic characteristics and natural noise. These permitted to have a full closed-loop simulation of the system and to test several observers and controller schemes, against different type of perturbations, before testing on the real plant. It should be noticed that these simulations were usually run in a non real-time operating system, using exactly the same algorithmic code which was running in the plant.

The configuration of the plant is performed using the JET *Level-1* pulse scheduler and editor, while data downloading and archiving is achieved through the JET *GAP* data archive system. These are the standard tools and protocols for any system deployed at JET. A module which translates these protocols into MARTe language was developed, enabling any MARTe based system to be easily integrated in the JET environment.

C. Discussion

The new Vertical Stabilization system is successfully running since July 2009. As an essential system for the operation of the machine, its first requirement was reliability. Figure 1

978-1-4244-7110-2/10/$26.00 ©2010 IEEE

depicts the cycle time which is well bounded within 1 μs of the required 50 μs, proving the resilience of the real-time system against external disturbances (e.g. interrupts).

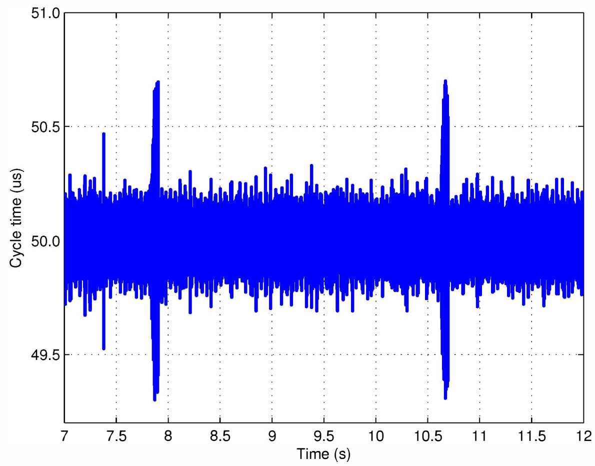

Fig. 1. Cycle time of the VS system. The synchronization of the control loop is performed within 1 μs of the configured 50 μs value.

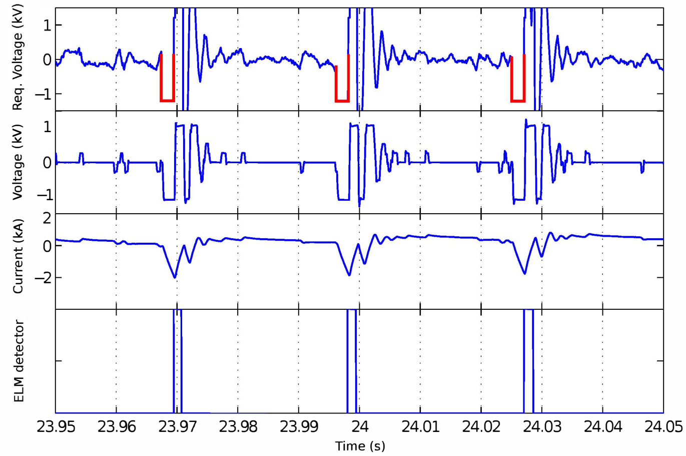

Fig. 2. The first two plots show the requested and applied voltage by the amplifier, followed by the current on the circuit. On the first plot the negative kicks are highlighted and as it can be seen from the last plot, three ELMs were successfully triggered.

An advanced configuration editor enables experts to specify up to 25 time windows, where the references, type of controller and its parameters, observers and experimental features can be enabled. Upon data collection more than 250 signals are transferred to the JET archiving system. Besides the 192 signals related to the data acquisition, several debug and controller related signals are also collected, with an average of 600 MBytes of total data per pulse.

The new VS was already used in some experiments regarding ELM pacing and against a wide spectrum of plasma scenarios. Figure 2 is an example, from JET pulse 78443, where ELM pacing was tested. The first plot shows the requested voltage, where the constant voltage for the kick is highlighted. The actual voltage and current provided by the amplifier is shown in the two following plots. As it can be seen in the last plot, three ELMs were successfully triggered against the applied negative kicks. The positive kick which normally follows, is a natural response of the controller to the original kick. When no kicks are applied it can be seen that the controller is trying to maintain the current in the circuit around zero.

III. JET EFCC

A. Description

In a tokamak, the presence of asymmetries in the magnetic fields can drive the formation of instabilities which degrade plasma confinement and eventually lead to its abrupt termination. These error fields are inevitable and are due to factors such as imperfections in the construction and alignment of the magnetic field coils and the presence of different magnetic materials. The Error Field Correction Coils (EFCC) system [13] provides a way of changing the magnetic field topology at the plasma boundary, allowing the compensation of the errors fields. More recent results have also showed that the EFCCs can be used for ELM mitigation [14]. The JET system can drive either one or two amplifiers, depending on the required EFCC magnetic configuration. In the former case the two amplifier sets are controlled by independent feedback controllers.

The JET EFCC controller and power supplies were recently upgraded. The new system is based on the VME architecture hosting a Motorola®MVME5100tm PowerPC processor module. Analog signals are acquired using the Pentland®MPV956tm board, which provides up to 32 multiplexed ADC channels with a maximum sampling rate of 330 kHz and 8 DAC channels, while digital I/O is performed using the Pentland®MPV922tm board , both interfaced to VME. The operating system is the real-time Wind River® VxWorkstm.

The control algorithm and the synchronization scheme were also upgraded, in order to add new functionality and to have better performances in higher frequency current references. The new controller scheme, still to be tested on the plant, contains a contribution from an adaptive feed-forward and a feedback system. The target cycle for the system is set to 200 μs.

B. Software Architecture

The EFCC system comprises a collection of 13 GAMs. The first module uses a VxWorkstm timer as its input. As soon as this time is a multiple of the cycle time, it enables a new control cycle to start. At this stage, a time correction GAM is executed, providing a fine adjustment of the time against the one provided by the JET central timing system, available at a lower, 1 ms, resolution. Data is then acquired from the MPV956tm board and transferred to the DDB. The waveform generator is responsible for providing the current references previously designed by the expert user. This GAM and the feedback modules are executed before the voltage requests are written to the DACs. Finally, data is stored in memory for later collection.

978-1-4244-7110-2/10/$26.00 ©2010 IEEE

The system uses the same JET interfaces of VS, both for configuration and data retrieval. The only difference relies on the configuration data itself and on the signals that are acquired.

C. Results

Figure 3 shows the cycle for the system during JET pulse 78949, where the worst case jitter for the 200 µs cycle is of 15 µs, a value which is still acceptable for the controller.

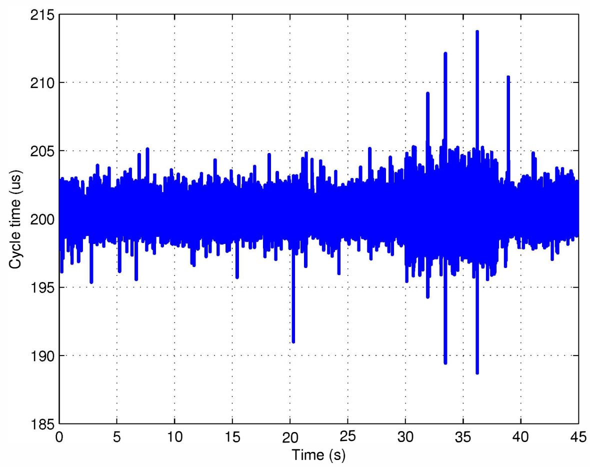

Fig. 3. Cycle time for the EFCC system. The synchronization is achieved within the required 200 µs with a worst case jitter of 15 µs.

Figure 4 depicts the controller successfully following a current reference previously setup by the expert. One of the key features that greatly enhanced the development process was the ability to run the same software modules both in online and offline environments. It not only enabled the validation of the control algorithms, by allowing the use of data from previous experiments, but also drastically reduced the debugging effort by permitting testing in non real-time systems. The time adjustment permits an improved time tagging precision of the acquired samples but is not essential to the system. It can be reused in other JET systems, based on different primary synchronization mechanisms, that also require this extra functionality. As referred before, the system can drive one or two amplifiers, each with its own feedback data. In the later case, a copy of the same set of control GAMs is used for both amplifiers, although driven by different data.

IV. COMPASS Control System

A. Description

COMPASS is a compact tokamak that has recently restarted its operation in Prague [15]. It is a machine of particular interest to the fusion community due to its ITER-relevant geometry and the possibility to perform ITER-edge plasma physics relevant experiments.

The plasma control system is also being upgraded. The architecture is divided in two control loops, one running at 50 µs and a second at 500 µs. The former is responsible for the control of horizontal and vertical position, while the later handles equilibrium, shaping and plasma current.

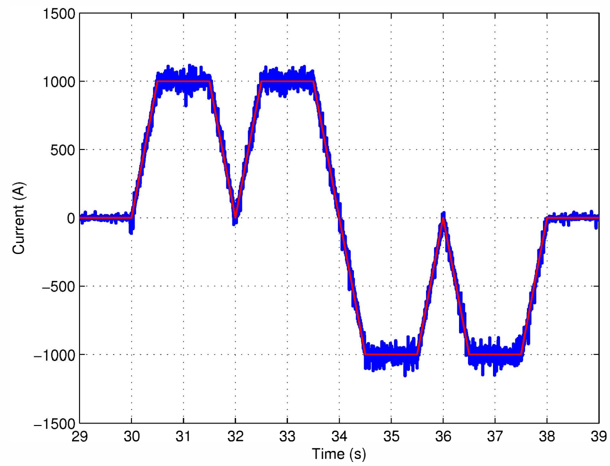

Fig. 4. The current reference is highlighted in red. The controller successfully follows the reference during the period where the EFCC system was enabled in the experiment.

The hardware data acquisition and processor solution [16] is similar to the one used for the JET VS. The interface to both the slow power supplies system and fast amplifiers is performed using a serial protocol over fiber optics.

B. Software Architecture

As referred before the system is divided in two loops [17]. This is accomplished in MARTe using two real-time threads, that in the case of COMPASS are running in two different cores of the CPU. The faster 50 µs loop, reads the data from the ADCs and synchronizes with the trigger and timing system. An offset and drift removal GAM is then used to remove the drift caused by the analog integration of the magnetic signals. Before proceeding with its main execution, the thread sends the acquired data to the 500 µs loop. The control algorithms for the fast loop are at that point executed and the references sent to the power supplies. Finally data is collected for later retrieval.

When the slower loop is executed it already has 10 samples for each signal transferred from the faster loop. These samples are filtered before being fed to the DDB. After synchronizing with the timing source, it runs a GAM that calculates the plasma current, followed by the plasma position and shaping calculator modules. As on the faster loop, data is sent to the amplifiers using the serial link and stored in memory for later collection, when the experiment terminates.

The possibility of having the conceptual division of the two control loops directly mapped into MARTe was an advantage for the design of the system, as it allowed to have one single source for data processing and acquisition, before propagating it to the different algorithms. Since part of the hardware was already being used at JET, some of the GAMs did not have to be developed and could be used without any modifications.

The integration with COMPASS supervisory control and configuration system was performed using the framework

HTTP server and introspection system. A series of components that translate between an HTTP request and a MARTe internal message, both for GAM configuration and experimental data collection, were also developed.

C. Results

Figures 5 and 6 show the cycle time for the two threads. Even running on Linux, very good jitter figures can be obtained. These are mainly due to the Linux *isolcpus* feature [18], which forces the operating system to assign its tasks to a default set of CPUs, allowing MARTe real-time tasks to run on CPUs free from any Linux activity.

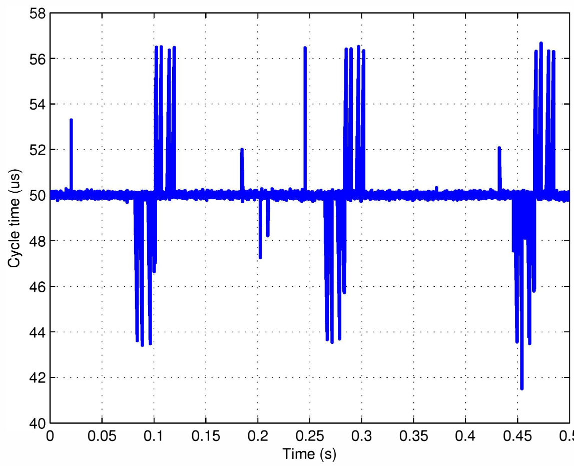

Fig. 5. Cycle time for the 50 µs loop, responsible for the communication with the fast amplifiers.

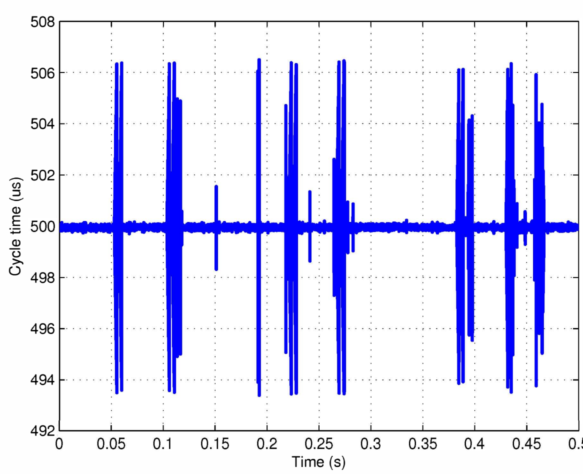

Fig. 6. Cycle time for the slower 500 µs loop. The worst jitter is less than 2% of the total time.

Figure 7 depicts the system successfully following the current reference for the magnetizing field power supply. COMPASS is already using MARTe as its real-time controller for all the coil current control systems. In the near future, with the algorithms for the plasma shape reconstruction already implemented and tested, new controller schemes and variables can be implemented.

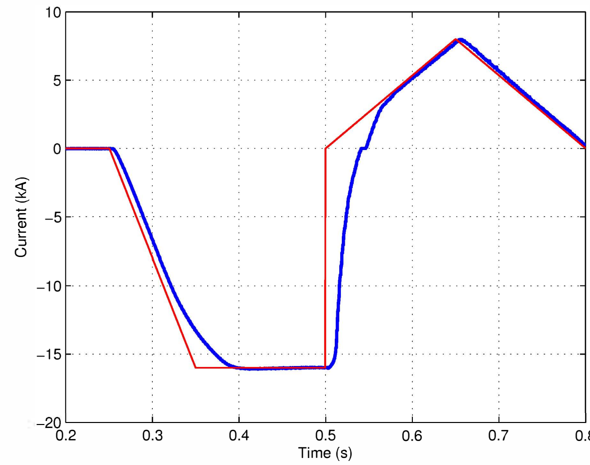

Fig. 7. Current control for the magnetizing field. This circuit is responsible for inducing the plasma current.

V. ISTTOK Tomography

A. Description

In the last two decades, some tokamaks have tested Alternating plasma Current (AC) discharges [19][20]. These type of experiments allow for longer pulses and to test the interaction of plasma with materials from both sides, without moving the sample. One of the problems which arise in AC discharges is that during the reversing of the plasma current, the magnetic diagnostics fail to provide an accurate measurement of the plasma position. Tomography, being a diagnostic that only depends in the emitted radiation from the plasma and that does not rely on magnetic measurements, is a strong candidate to provide this measurement.

A new real-time plasma position controller, based on tomography, was recently developed at ISTTOK [21]. The hardware is again based on the same ATCA® solution used for the JET VS and COMPASS. The system uses 30 ADC inputs, from one acquisition board, acquired at 2 MHz and later downsampled to 20 kHz inside the board FPGAs. The communication with the horizontal and vertical field power supplies is performed using a serial link over fiber optics, sharing the same protocol used in COMPASS. Due to the amount of calculations which have to be performed in the real-time tomography algorithm, the cycle time was set to 100 µs.

B. Software Architecture

A collection of 10 GAMs is executed for each control loop. After acquiring the data from the ATCA® IOGAM, the ISTTOK tomography reconstruction and PID algorithms are executed and the system synchronized to the timing system. Subsequently to the module which generate the references, the next step is the execution of the GAMs responsible for the communication with the power supplies, followed by a set of utility and collection GAMs.

Sharing the same hardware interface with the JET VS system and the same power supplies protocol with the COMPASS architecture, enabled the developer to focus in the development of the core tomographic and control algorithms.

C. Results

Figure 8 shows the plasma position being successfully controlled in real-time, using the tomographic reconstruction of the plasma emissivity, for ISTTOK pulse number 23330. As referred before, this is extremely useful during the inversion stage of AC tokamak discharges (happening at around 27 ms in this pulse), where magnetic measurements, are less reliable due to low plasma current.

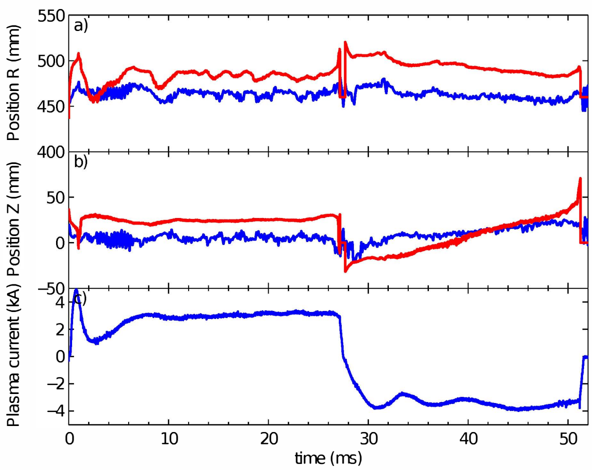

Fig. 8. The first two plots show the R and Z plasma position coordinates, as calculated by the tomographic reconstruction (blue) and by the magnetics (in red). In the third plot the plasma current is depicted. During the inversion of the plasma current (~27ms), the magnetics fail to provide an accurate value of the plasma position.

The cycle time is depicted in figure 9 and the target value of 100 μs with a maximum jitter of about 6 μs, even with a complex tomographic algorithm in the control loop.

VI. FTU Lower Hybrid Reflected Power

A. Description

In a fusion device, additional heating systems provide a way of complementing the ohmic heating attained through Joule effect. The Lower Hybrid (LH) system provides a way of delivering power to the plasma using electromagnetic waves and can also work as a current drive system [22]. The system works in the 1-10 GHz range with high power (several hundreds of kW) RF sources. This source is usually a high vacuum electronic tube working as an amplifier, named klystron, or an open resonant cavity, named gyrotron. In the case of the FTU tokamak, the 8GHz LH system [23] uses gyrotrons with an output RF power of 1MW.

The main feedback control system of FTU tokamak is going to be upgraded to receive the ratio between LH reflected and transmitted power from the plasma. The controller will use this value to change the plasma position in order to

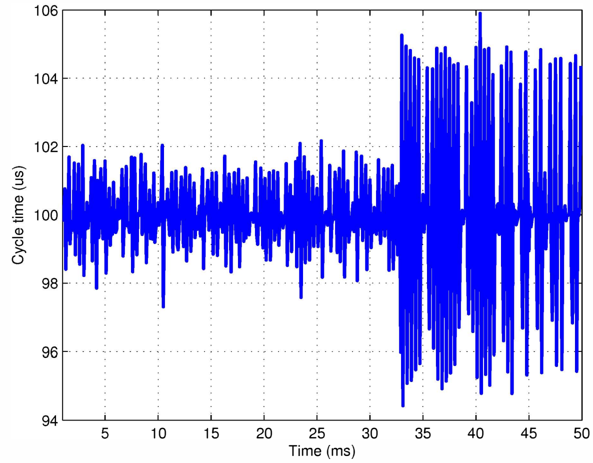

Fig. 9. Cycle time for the real-time position control of the ISTTOK plasma, using tomography. After 32 ms the cycle time worst jitter is larger by 2 μs, likely due to a larger latency in the communication with the power supplies.

optimize the coupling with the LH source antenna [24]. The power ratio is going to be computed by a MARTe based system, running on a VME crate with a XVME-6200 VMEbus Intel®Core^{tm}2 Duo T7400 processor, one acquisition board from from CAEN® with 16, 12 bits, ADC channels and two Acromag® outputs boards with 8 DAC channels each. The operating system is RTAI and the requested cycle time for the feedback system is 250 μs.

B. Software Architecture

MARTe waits for the beginning of a new control cycle using an IOGAM triggered by the acquisition board. After converting the acquired signals from the ADC channels into physical units, the module that computes the power ratio is executed. An IOGAM ultimately writes the calculated data to the DAC channels and a collection GAM stores the signals in memory for later archiving.

During the commissioning of the system, a waveform generation module was introduced in the control chain, providing simulated values of the inputs. In order to test the system and the hardware as accurately as possible, data produced by the waveform generator is sent through the DACs and digitized back using the acquisition board. This module will be removed when the system is connected to the diagnostic.

C. Discussion

As depicted in figure 10, the target 250 μs cycle time has been met with a worst case jitter of less than 2 μs. Figure 11 shows the power ratio for the LH antenna in FTU pulse number 32682.

The LH system required the development of new modules both for hardware interaction and algorithm execution. It was also the first system to use MARTe and RTAI in a VME based environment.

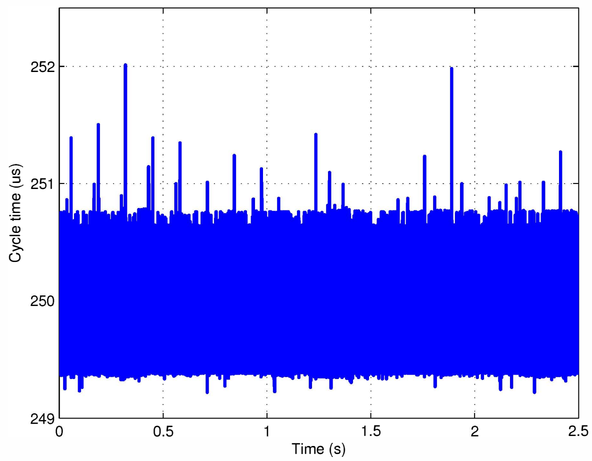

Fig. 10. Cycle time of the LH system. The jitter is under 1% of the total time.

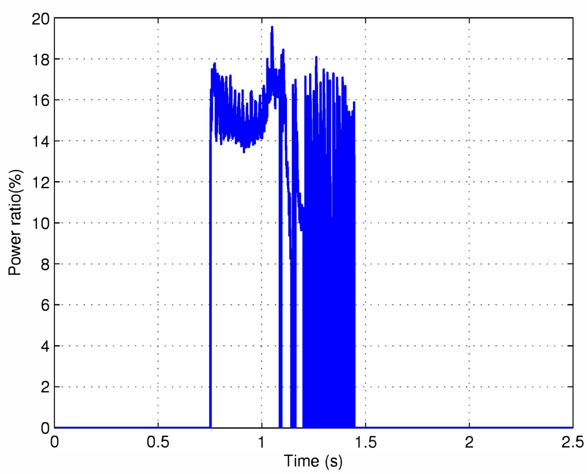

Fig. 11. Ratio between reflected and transmitted power from the LH antenna. This value is going to be send to the feedback system in order to improve the coupling.

VII. Discussion

Table I compares the different MARTe systems regarding hardware, operating system and cycle time. All have very good results in what concerns worst case jitter, proving that the operating system is protecting the controllers execution from external interrupts and correctly prioritizing the real-time tasks. It should be noticed that the development of MARTe applications is completely transparent in what concerns low level interactions with the underlying operating system, since these are delegated to the framework libraries.

The VS system was the first MARTe based application to be deployed. It delivered very high performances and allowed part of the system to be modelled and tested offline, taking advantage of the GAM structures. The EFCC application proved that the framework could also run, delivering high performances, in a completely different hardware and operating system. COMPASS used for the first time the multi-thread support to run two control loops, each with its own frequency, in the same processor set. Both COMPASS and ISTTOK took advantage of some of the already developed modules for the ATCA® based hardware and focused their effort on the development on new algorithmic modules. The FTU LH system was the first to run using Intel® dual core processors on VME.

The most important feature which seems to be transversal to all systems is the ability to easily change GAMs. It is widely used to simulate the algorithms in an offline system without hardware (model based design), or to test the hardware using simulated data. The modularity provided by the GAMs has also allowed the different projects to interchange some modules, without having to rewrite any code. Examples are the IOGAMs sharing the same low level hardware and utility GAMs (e.g. data collection).

Making no assumptions on how data is produced and what underlying protocols are used, allowed MARTe to be easily integrated in experiments with their own methodology for configuration and experimental data retrieval. More important, as the boundary is very well defined, there was no impact on existing code and allowed to develop and integrate new modules, without making any assumptions about who were the input data sources and output consumers.

The framework proved to be portable enough to be already in use in 4 different experimental devices, running important controllers and diagnostics which are in some cases essential to the operation of the machine. Although the examples presented on this paper are all related to the fusion experimental world, there is no reason why MARTe could not be used in different kinds of experiments.

References

[1] A. C. Neto, F. Sartori, F. Piccolo, R. Vitelli, G. De Tommasi, L. Zabeo *et al.*, "Marte: A multiplatform real-time framework," *Nuclear Science, IEEE Transactions on*, vol. 57, no. 2, pp. 479 –486, april 2010.

[2] G. D. Tommasi, F. Piccolo, A. Pironti, and F. Sartori, "A flexible software for real-time control in nuclear fusion experiments," *Control Engineering Practice*, vol. 14, no. 11, pp. 1387 – 1393, 2006.

[3] R. Albanese, E. Cocorrese, and G. Rubinacci, "Plasma modeling for the control of vertical instabilities in tokamaks," *Nuclear Fusion*, vol. 29, no. 6, pp. 1013 – 1023, 1989.

[4] F. Romanelli, JET-EFDA Contributors, and R. Kamendje, "Overview of JET results," *Nuclear Fusion*, vol. 49, no. 10, pp. 104 006–+, Oct. 2009.

[5] F. Sartori, F. Crisanti, R. Albanese, G. Ambrosino, V. Toigo, J. Hay *et al.*, "The JET PCU project: An international plasma control project," *Fusion Engineering and Design*, vol. 83, no. 2-3, pp. 202 – 206, 2008, proceedings of the 6th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research.

[6] R. Aymar, P. Barabaschi, and Y. Shimomura, "The iter design," *Plasma Physics and Controlled Fusion*, vol. 44, no. 5, p. 519, 2002. [Online]. Available: http://stacks.iop.org/0741-3335/44/i=5/a=304

[7] D. Ganuza, D. Rendell, B. Arenal, J. de la Fuente, S. Shaw, V. Toigo *et al.*, "The design and manufacture of the enhanced radial field amplifier (erfa) for the jet project," *Fusion Engineering and Design*, vol. 84, no. 2-6, pp. 810 – 814, 2009, proceeding of the 25th Symposium on Fusion Technology - (SOFT-25). [Online]. Available: http://www.sciencedirect.com/science/article/B6V3C-4W3P06D-1/2/9104d5bfc786818df2b89b2c45d3f117

[8] F. Sartori, S. Dorling, A. Horton, P. J. Lomas, M. E. U. Smith, and R. C. Stephen, "n=2 compensation and variable gains for jet vertical stabilisation," *Fusion Engineering and Design*, vol. 66-68, pp. 727 – 734, 2003, 22nd Symposium on Fusion Technology. [Online]. Available: http://www.sciencedirect.com/science/article/B6V3C-48XSGCJ-4/2/23a287e110e8a355499d5089dc11a693

[9] A. Batista, A. Neto, M. Correia, A. Fernandes, B. Carvalho, J. Fortunato *et al.*, "Atca control system hardware for the plasma vertical stabilization in the jet tokamak," *Nuclear Science, IEEE Transactions on*, vol. 57, no. 2, pp. 583 –588, april 2010.

TABLE I
MARTE BASED SYSTEMS CYCLE TIME COMPARISON.

System	Bus	CPU	O.S.	Cycle time (μs)
VS	ATCA and PCIe	Intel®Core™2 Quad	RTAI	50.0 ± 0.8
EFCC	VME	Motorola®MVME5100™	VxWorks™	200 ± 15
COMPASS	ATCA and PCIe	Intel®Core™2 Quad	Linux®	50.0 ± 6.5 and 500.0 ± 6.0
ISTTOK	ATCA and PCIe	Intel®Core™2 Quad	Linux®	100±5
FTU	VME	Intel®Core™2 Duo	RTAI	250 ± 2

[10] F. Sartori, P. Lomas, F. Piccolo, M. Zedda, and JET-EFDA Contributors, "Synchronous elm pacing at jet using the vertical stabilisation controller," *Proceedings of the 35th EPS Conference on Plasma Physics*, pp. P–5.045, Junel 2008.

[11] R. Felton, K. Blackler, S. Dorling, A. Goodyear, O. Hemming, P. Knight *et al.*, "Real-time plasma control at jet using an atm network," in *Real Time Conference, 1999. Santa Fe 1999. 11th IEEE NPSS*, 1999, pp. 175 –181.

[12] R. Albanese and F. Villone, "The linearized create-l plasma response model for the control of current, position and shape in tokamaks," *Nuclear Fusion*, vol. 38, no. 5, p. 723, 1998. [Online]. Available: http://stacks.iop.org/0029-5515/38/i=5/a=307

[13] I. Chapman, T. Hender, D. Howell, S. Erents, M. P. Gryaznevich, S. Shibaev *et al.*, "Perturbation of tokamak magnetic surfaces by applied toroidally asymmetric magnetic fields," *Nuclear Fusion*, vol. 47, no. 11, p. L36, 2007. [Online]. Available: http://stacks.iop.org/0029-5515/47/i=11/a=L02

[14] Y. Liang, H. R. Koslowski, P. R. Thomas, E. Nardon, B. Alper, P. Andrew *et al.*, "Active control of type-i edge-localized modes with $n = 1$ perturbation fields in the jet tokamak," *Phys. Rev. Lett.*, vol. 98, no. 26, p. 265004, Jun 2007.

[15] R. Panek, O. Bilykova, V. Fuchs, M. Hron, P. Chraska, P. Pavlo *et al.*, "Reinstallation of the compass-d tokamak in ipp ascr," *Czechoslovak Journal of Physics*, vol. 56, no. 2, pp. B125–B137, 2006.

[16] D. Valcárcel, A. Neto, J. Sousa, B. Carvalho, H. Fernandes, J. Fortunato *et al.*, "An atca embedded data acquisition and control system for the compass tokamak," *Fusion Engineering and Design*, vol. 84, no. 7-11, pp. 1901 – 1904, 2009, proceeding of the 25th Symposium on Fusion Technology - (SOFT-25). [Online]. Available: http://www.sciencedirect.com/science/article/B6V3C-4VDSD1R-N/2/3bc517a94893b910da789966a3e4d4bf

[17] D. Valcárcel, A. Duarte, A. Neto, I. Carvalho, B. Carvalho, H. Fernandes *et al.*, "Real-time software for the compass tokamak plasma control," *Fusion Engineering and Design*, vol. In Press, Corrected Proof, pp. –, 2010. [Online]. Available: http://www.sciencedirect.com/science/article/B6V3C-4YXMP1Y-3/2/b4918a83fec0d894ea31927c51ea1c9b

[18] A. Neto, F. Sartori, F. Piccolo, A. Barbalace, R. Vitelli, and H. Fernandes, "Linux real-time framework for fusion devices," *Fusion Engineering and Design*, vol. 84, no. 7-11, pp. 1408 – 1411, 2009, proceeding of the 25th Symposium on Fusion Technology - (SOFT-25). [Online]. Available: http://www.sciencedirect.com/science/article/B6V3C-4VJS6VR-C/2/b34a4ea37c455a155dd7a321334227ac

[19] J. Cabral, H. Fernandes, H. Figueiredo, and C. Varandas, "Operation of the tokamak ISTTOK in a multicycle alternating flat-top plasma current regime," *Nuclear Fusion*, vol. 37, no. 11, pp. 1575–81, 1997. [Online]. Available: http://stacks.iop.org/0029-5515/37/1575

[20] O. Mitarai, C. Xiao, L. Zhang, D. McColl, W. Zhang, G. Conway *et al.*, "Alternating current plasma operation in the stor-m tokamak," *Nuclear Fusion*, vol. 36, no. 10, pp. 1335–43, 1996. [Online]. Available: http://stacks.iop.org/0029-5515/36/1335

[21] P. Carvalho, H. Thomsen, R. Coelho, P. Duarte, C. Silva, and H. Fernandes, "Isttok plasma control with the tomography diagnostic," *Fusion Engineering and Design*, vol. 85, pp. 266–271, 2010.

[22] G. Hoang, A. Bécoulet, J. Jacquinot, J. Artaud, Y. Bae, B. Beaumont *et al.*, "A lower hybrid current drive system for iter," *Nuclear Fusion*, vol. 49, no. 7, p. 075001, 2009. [Online]. Available: http://stacks.iop.org/0029-5515/49/i=7/a=075001

[23] F. Mirizzi, P. Bibet, A. Marra, P. Petrolini, and A. A. Tuccillo, "The pam launcher for ftu: results of the preliminary tests," *Fusion Engineering and Design*, vol. 66-68, pp. 621 – 625, 2003, 22nd Symposium on Fusion Technology. [Online]. Available: http://www.sciencedirect.com/science/article/B6V3C-495VKP7-1/2/e66b1d33e850daeac2cf92fd1d717778

[24] D. Carnevale, A. Astolfi, C. Centioli, S. V. Vitale, and L. Zaccarian, "A new extremum seeking technique and its application to maximize rf heating on ftu," *Fusion Engineering and Design*, vol. 84, no. 2, pp. 554–558, 2009.