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Progress in the migration towards the real-time framework MARTe at the FTU tokamak

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ABSTRACT

Keeping in mind the proposed FAST experiment and aiming to meet basic requirements such as a modular and distributed architecture, where different control subsystems can be easily integrated at different times, and can operate either independently or in cooperation with other subsystems, at the end of last year we planned to upgrade the architecture of the FTU real-time system, improving in such a way its flexibility and modularity. We decided to adopt an available packages to reach our goal: MARTe. We report on the state of the art of the MARTe migration process, the difficulties dealt with, the benefits and advantages achieved, the progress made from our last report and, in particular, we describe the integration of the ODIN equilibrium reconstruction system in the real-time environment. The ODIN algorithm was already coded in previous works, but its integration in the real-time system has never been carried out at FTU. We illustrate how the MARTe architecture and the RTNet level allows for a first level of parallelization, distributing the data and/or time among nodes.

1. Introduction

Fusion advanced studies torus (FAST) experiment is being proposed by the Italian laboratories as an European satellite tokamak for ITER. Its real-time control system will have to meet basic requirements such as a modular and distributed architecture. The adoption of a framework that is candidate to be a standard in the fusion world, like MARTe, enables the exchange of components among different experiments (JET, COMPASS and ISTTOK). In this scenario, as a test bed, we are planning to port the current real-time system of the Frascati tokamak upgrade (FTU) under a MARTe architecture. The idea behind the project is to slice the currently monolithic code into smaller, more manageable chunks, each one with its own limited scope, in order to facilitate the experimentation of new controls, hiding all the hardware level and realtime details to those who have to implement the specific control. In Section 1 we describe the current feedback control system. In the Section 2 we report on the new feedback project, then in the following sections we show the already implemented parts and their relative test or simulation. Most of this work will be used in the final MARTe architecture with little effort.

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2. FTU feedback system

A block diagram of the current FTU feedback system is shown in Fig. 1. Roughly speaking, the system actuates (2 kHz frequency) three controls: gas density, plasma current and position.

A brief description of each block follows but interested readers can refer to [1] for more details.

The Density controller used at FTU is an On/Off control that drives the gas injection actuating on the valves a fixed voltage for a variable time duration, knowing the flow of each valve. The Controller generates the control signals using three inputs: a preprogrammed waveform which represents the mean density required by the experiment, the measured density obtained from interferometric measurements and hard X-Ray signal to take into account runaway electrons. The FTU feedback system controls four coils, two (named F and V) for the horizontal position control, one for the vertical position (named H) and the last for the plasma current (named T). The toroidal field is not under the control of the feedback system, a dedicated camac module feeds the reference directly to the amplifier. In Fig. 1 the H and F controllers are two PIDs, the latter being equipped with an anti-windup system developed in order to avoid current oscillations at low currents [2]; The V controller has recently been enhanced with an allocator module. The allocator is a control system which, using the theory developed in [3], permits an elongation control in FTU; if the allocator module is disabled, the V controller works like the toroidal one, in feedforward (the preprogrammed waveform is sent directly to

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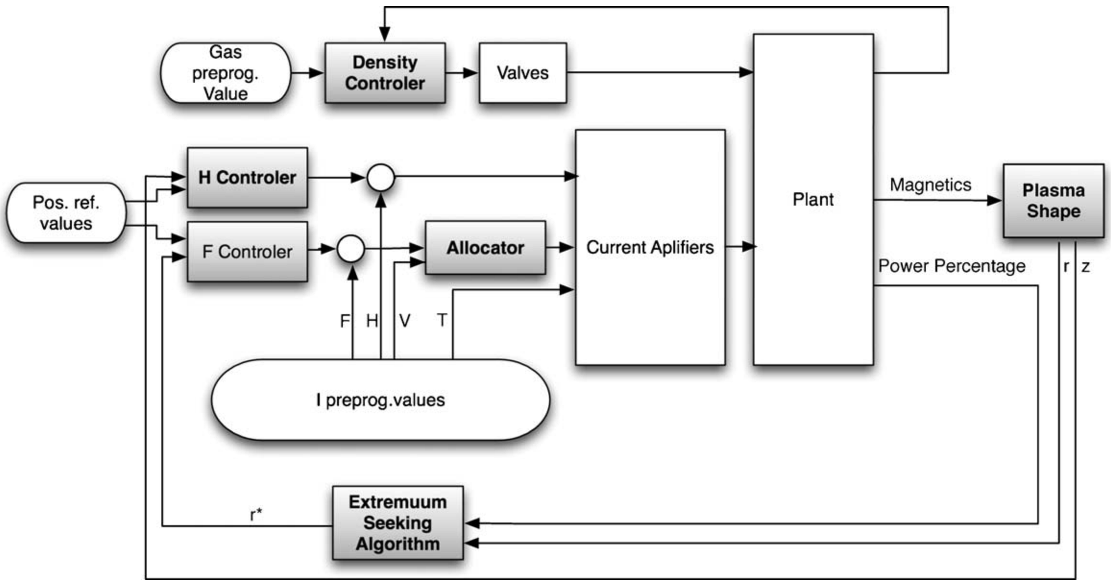

Fig. 1. Block diagram of the current FTU feedback systems.

the amplifier). The plasma shape block currently performs the vertical and horizontal position control using only 4 points on the LCMS (last closed magnetic surface), even though a fast LCMS algorithm reconstructs the boundary over 20 points, performing the multipolar moments expansion in the vacuum from the magnetic measurements [4]. The extremum seeking algorithm optimizes the horizontal position of the plasma in order to maximize the efficiency of the LH antenna [5], currently the power percentage ratio is calculated in parallel on a different VME satellite station that sends the analogical wave via DAC.

3. The new feedback system

The porting of the whole FTU feedback system in the new MARTe architecture is still in its early stage of development, even if in the last part of this section some plant test results will be shown. However, the current system has undergone an in-depth study from which a detailed project for the new feedback emerged.

MARTe is a framework for realtime control system development, it is implemented on top of the BaseLib2 library [6]. Basically a MARTe system consists of several objects whose interconnections realize the main architecture of the system. The real control system is made by a set of small independent components called GAMs (generic application modules) executed by one or more real-time threads. The GAMs are the building blocks of a control algorithm, and are able to communicate by reading and writing signals into the DDB (dynamic data buffer), a memory area shared by all GAMs. Others important components of the MARTe framework are the GenericAcqModule class and the time input, input and output GAMs. Each of the last three GAMs has to be configured to use a specific GenericAcqModule to perform the synchronization[1] and data input or output with respect to the hardware devices.

The main elements of the feedback have been sliced in a large number of GAMs (Fig. 2) each one with a very limited scope in order to simplify the debugging and commissioning procedure, and to open up to possible future improvements of the control algorithms. The blocks shown in Fig. 1 are easily recognizable, with the exception of a few “utility” GAMs in Fig. 2. The heart of the system is the scheduler GAM, which will turn on and off the various controllers following the decisions made in the planning phase of the experiment, and in case switch to a “safety mode” in order to terminate the experiment if the plasma state and security checks GAM signals a critical condition (like high temperature on the lithium limiter, or runaway plasma). The signal processing GAM, instead, calculates the offset in the magnetics due to the radial field, and subtracts it from the measures in order to correct them.

On the main feedback and on the LH node the acquisition and the output of signals is performed using respectively a time input GAM and an output GAM. Those GAMs are linked to the VMEDrv (not visible on the picture) thats implements the GenericAcqModule for the ADC and DAC Hardware. The same happens for the RTNetOut and RTNetIn but in this case the GenericAcqModule is implemented by the RTNetDrv. The RTNetDrv can be used in conjunction with a time input GAM to perform also the time synchronization respect a specific host, like in the RTODIN node that uses the RTNet time input GAM.

The lithium limiter temperature controller GAM is not yet implemented in the current feedback system and an additional density controller project is in progress (flux voltage gas control GAM in Fig. 2) in order to drive the valves using variable voltage signals.

The equilibrium reconstruction will be performed by the ODIN realtime implementation [7], as a dedicated MARTe system that runs in parallel and that could be useful for the new ECRH project [8] or for other applications. The parallel system will be triggered by the main feedback station at lower frequency (100 Hz) through the realtime network (using the RTNet output GAM on the main feedback side and the RTNet time input GAM on RTODIN system). As soon as the algorithm will be parallelized via GPUs, it will be possible to produce data at higher frequency. However, since there exist parallel efforts to study and implement these systems, they have been already inserted in the new feedback project in order to create placeholders for future developments.

During the development phase the new main feedback system will run on the backup station[2], as soon as the signals of the new software are equal to the online one for several scenarios, we can proceed with a real test. For the validation of the RTODIN results, they will be compared with the offline version shot bye shot, while

[1] Only one time input GAM per real-time thread is allowed.

[2] A VME crate that is on the same rack of the main one and has the same inputs but unplugged outputs.

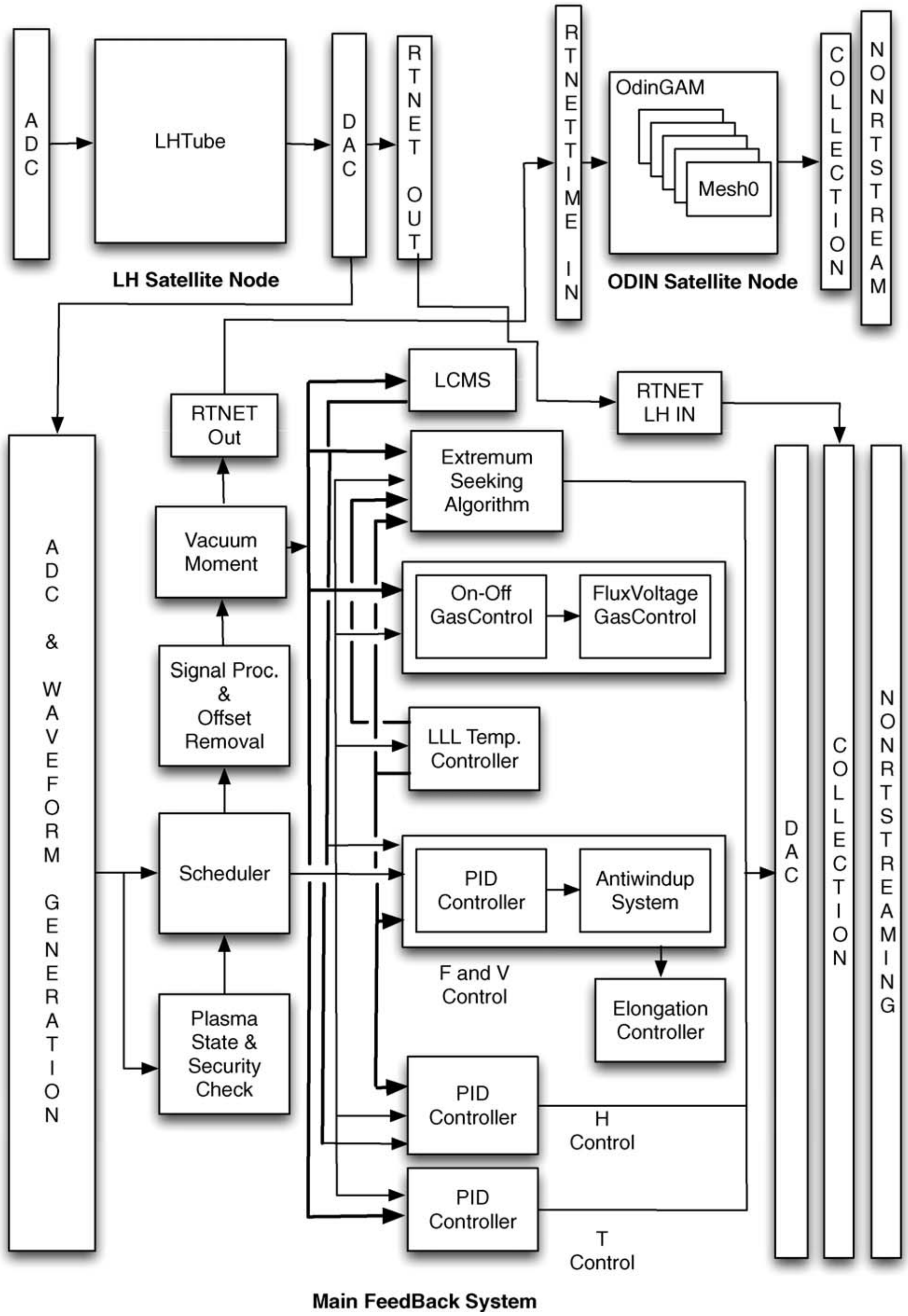

Fig. 2. GAMs that will be developed to port the current feedback to the MARTe architecture.

for the LH Node tabled data will be used instead of the real one to make a comparison with the old system.

4. The LH satellite station

On FTU the control of the LH heating maximization is achieved thanks to a VME satellite system [9] which computes the percentage of LH reflected power at the same frequency of the main feedback. The LH satellite output is sent to the feedback system, in charge of adjusting the plasma horizontal position according to the results obtained by an extremum seeking algorithm.

The extremum seeking algorithm [5] requires as input the percentage of power reflected by the plasma. The power percentage is computed as the ratio between the emitted power and the reflected power measured, and averaged, on the eight central cells of the antenna (the antenna is made by a grill of 48 cells arranged in four rows of 12 cells each).

The software architecture of the LH satellite station has been migrated towards the MARTe architecture [10], the LH tube GAM module first calculates the percentage of the reflected power and then the result of the computation is forwarded to the new feedback system using two different and redundant ways: through a DAC (DAC output GAM) and the real-time network (RTNet output GAM).

5. The new gas control system

The proposed density controller [10], is a feedback control system that uses an anti-windup scheme by taking into account the

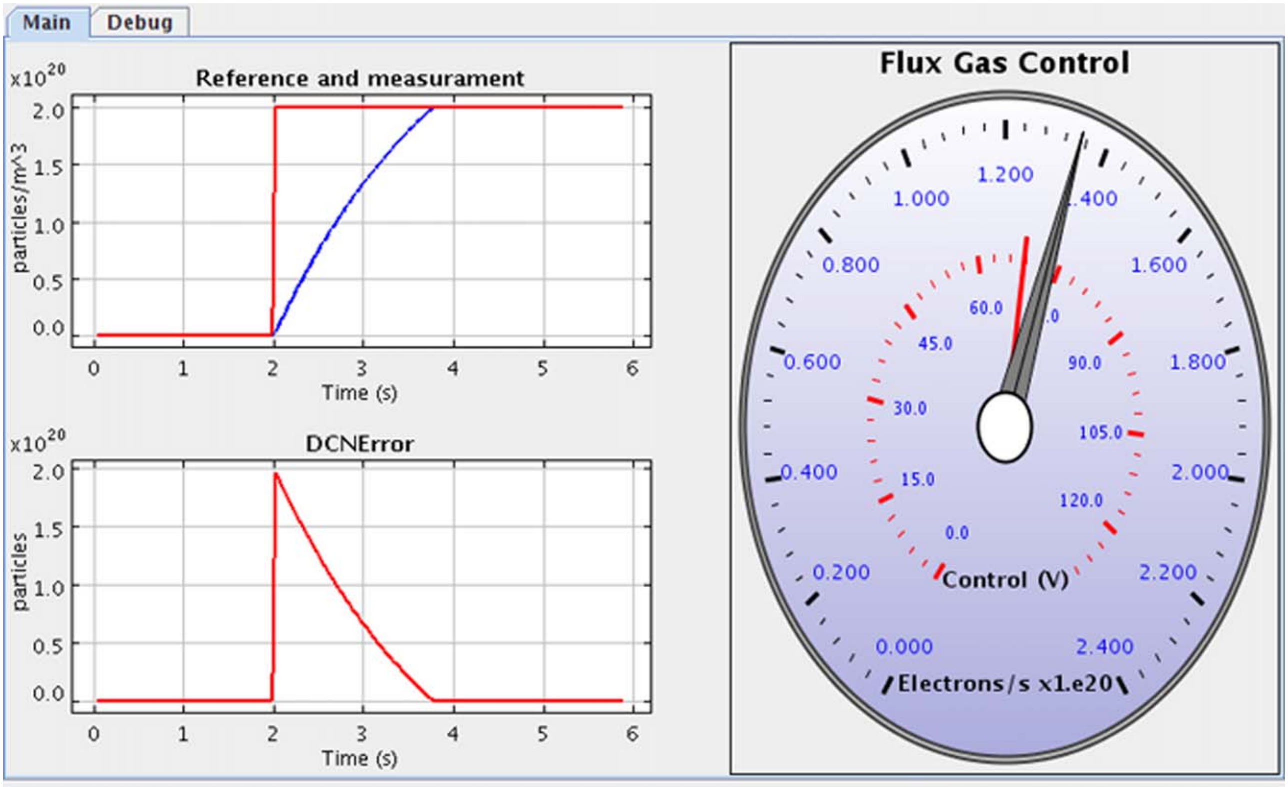

Fig. 3. Real-time density control viewer.

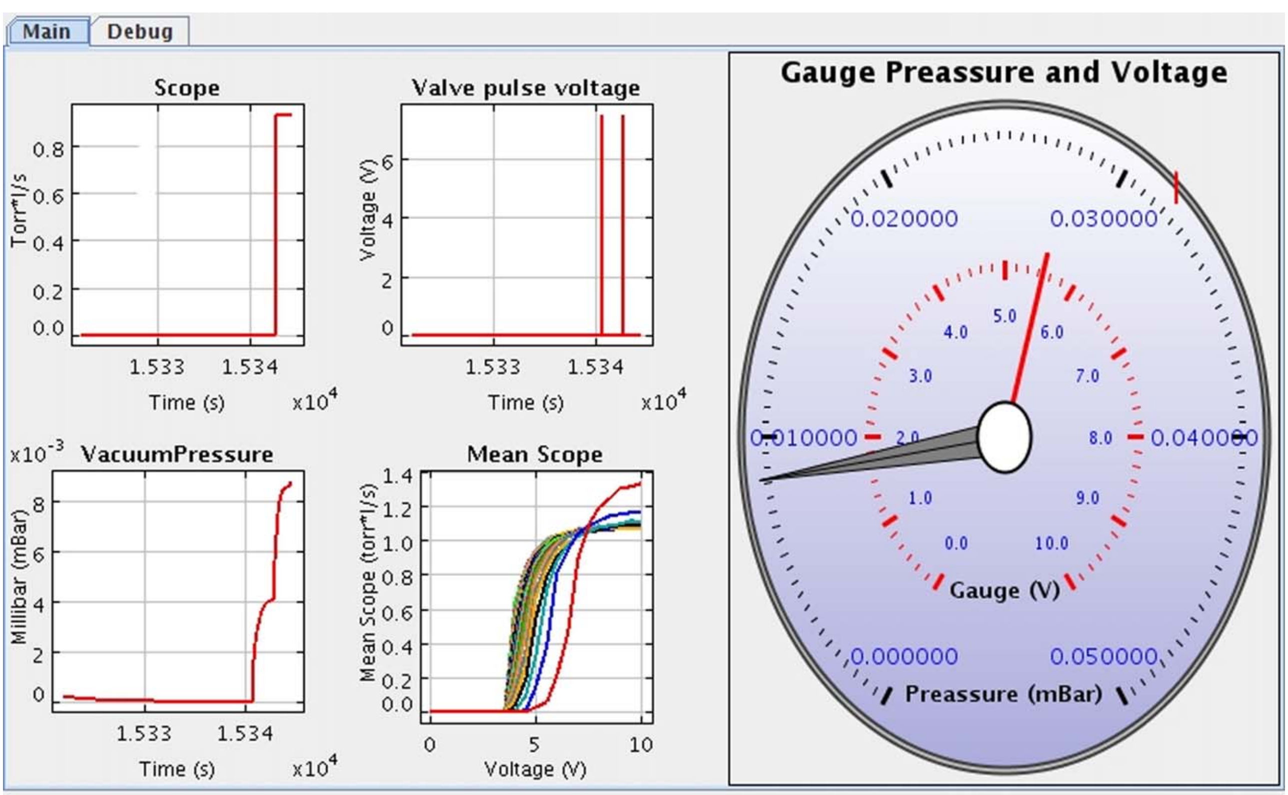

Fig. 4. Valves calibration software Gui.

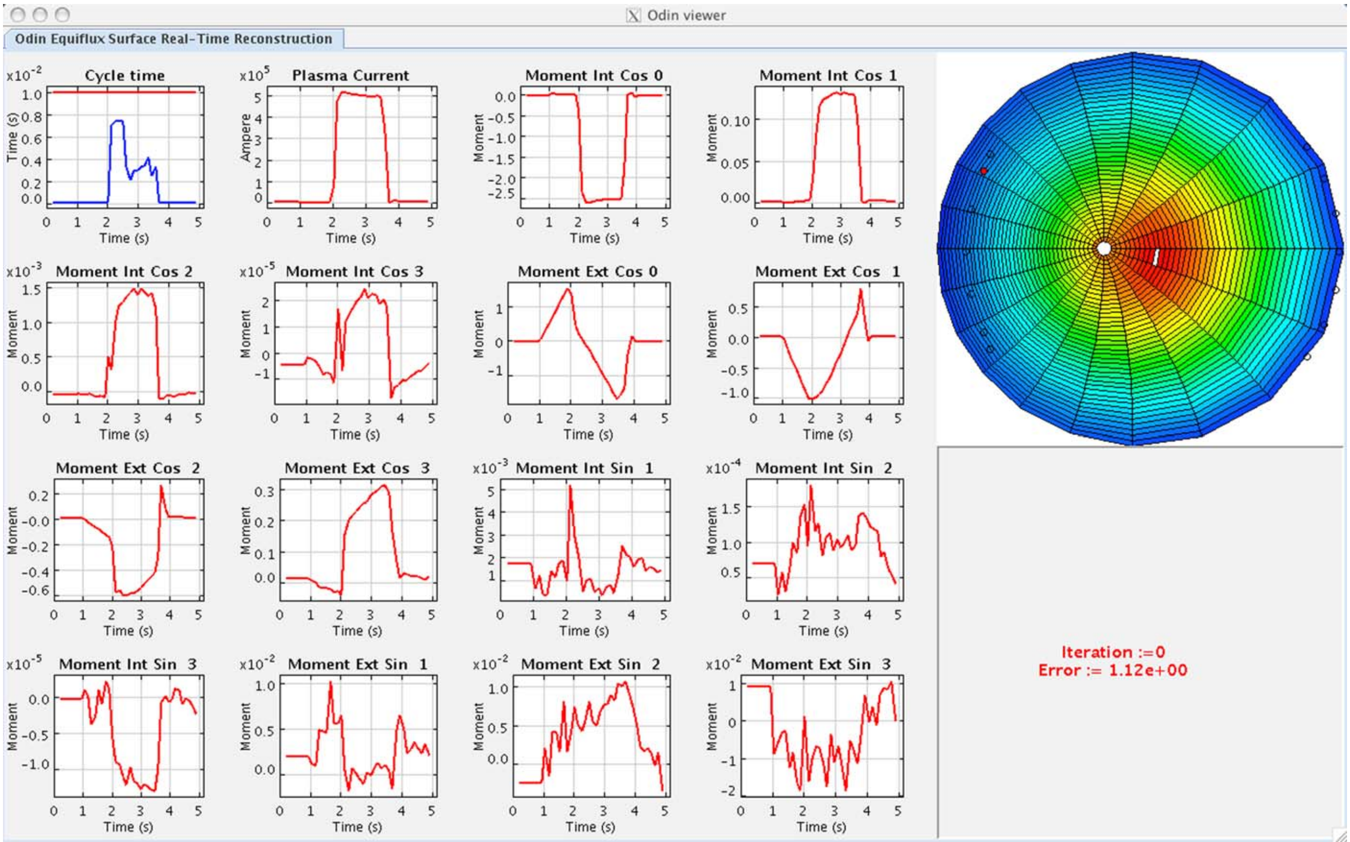

Fig. 5. ODIN real-time reconstruction viewer.

non-linearity caused by the saturation of the valve. Despite the On/Off control (On/Off gas control GAM in Fig. 2), the new algorithm drives the valve through a variable voltage signal giving in such a way a more accurate control degree.

In order to design, develop and test the control law, a set of mathematical models reproducing the behavior of the actuator and the plasma density evolution have been coded as GAMs and put together into a MARTe based test system. In our simulations only one valve is considered, but in the near future the work will be extended to more valves (the actual control can use up to 6 valves).

The flux voltage gas control GAM estimates the next requested scope for the valve using the error between the reference signal and the real one given in feedback by the plasma model during simulation (Fig. 3) or by the plant during the real experiments (Fig. 2).

The conversion from requested flux to desired voltage is performed by the Flux Voltage Gas Control GAM using interpolated data given by the Calibration Tool depicted in Fig. 4 (also based on a MARTe architecture). The calibration procedure should be executed once for each valve before the experimental campaign in order to estimate the static characteristics flux–voltage[3].

6. Equilibrium reconstruction, RTODIN

The equation arising from magneto hydro dynamics theory that describes the plasma force balance is the Grad–Shafranov equation [11].

$$\Delta^*\psi = -\mu_0 R^2 p'(\psi) - {\mu_0}^2 f(\psi) f'(\psi) \tag{1}$$

The evaluation of multi-polar expansion of moments inside the plasma is calculated in order to solve the above equation and find the internal distribution of the ψ function. The explicit expression for the internal and external multi-polar moments is estimated as an integral of the current density $J_\phi(\theta_0, \tilde{\omega}_0)$ that flows inside the torus with coordinate θ [4]. Starting from the work described in [10], the ODIN implementation has been coded as the ODIN GAM and tested using a simple test MARTe System. During the test, the probe signals are cyclically produced using a waveform GAM generator. In the next future we have planned to use a “GAMified” version of the CREATE NL plasma model [12] which will simulate the magnetic measurements. This will give us the possibility to perform closed–loop simulations which can be then exploited for the design of control systems.

In the ODIN GAM, one or more mesh objects can be configured and so instanced during the system startup. A mesh object provides the set of geometrical data[4] for the contact point to which it is referred. During the evolution of the plasma, when the contact point changes, the associated mesh pointer is used to perform the realtime computation.

The moments in the vacuum are computed using the probe signals elaboration done by the vacuum moments GAM. This GAM – as shown in Fig. 2- will be deployed on the main feedback station in the final MARTe architecture and its output forwarded to the ODIN MARTe using RTNet. During the ODIN GAM execution the moments distribution inside the plasma is adjusted using a least squares approximation which fits the internal moments in the vac-

[3] The calibration procedure will be used also for the On/Off control to setup the optimal scope parameter for the valves.

[4] Fock functions and some combination of them over the mesh, $sinh\theta$, $cosh\theta$, $sin\tilde{\omega}$, $cos\tilde{\omega}$.

uum. Then a new guess for ψ is computed[5] until the difference between two subsequent iterations is less than a specified tolerance ε over the whole mesh. Finally important quantities associated with the equilibrium are computed, such as the poloidal beta β_p and the internal inductance $l_i/2$.

In Fig. 5 The real-time ODIN viewer is shown, in this specific reconstruction[6], using 20 ω and 40 θ. Each ODIN GAM iteration lasts about 0.8 ms. Since the *maxIteationNo* parameter is fixed to 12, with a tolerance ε equal to 1^{-4}, the time cycle of the whole system is less than 10ms.

7. Conclusions

In this work we have reported a snapshot of the whole MARTe at FTU project. During the reported activities, the MARTe framework has proven to provide various advantages. The high modularity and reusability of the architecture enables a considerable rate of exchange among users at several fusion experiments, down to the component level; at the same time, it makes it easier to set up a simulation environment to test new algorithms and to switch almost seamlessly, when the test phase is completed, to the implementation. Another obvious advantage is its hardware independence, while the use of real-time networks enables communication among a variety of systems, thus not requiring the installation of dedicated cables.

On the other hand, we would like to stress that the MARTe community is still comparatively small, and the effort to generalize and to export the framework to other experiments is still under way.

Future works at FTU will include: the use of GPUs to realize a parallel version of ODIN; exploiting CREATE's NL model and the MARTe's flexibility to develop an XSC-like shape controller [13]; and finally a new level 1 interface that, using a simple java interface as a viewer of pseudo-realtime signals, will enable the physicists to configure the experiment using GUI.

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[5] The initial guess for the ψ function is a conic surface centered in R_0, monotonically decreasing or increasing along θ and constant along $\tilde{\omega}$. This guess is used by the algorithm whenever time the contact points change.

[6] The viewer reads the data from the non-real-time network as UDP packets.