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INTEGRATED REAL TIME CONTROL ON THE MAST UPGRADE TOKAMAK

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Abstract

The real time plasma control system for the MAST Upgrade tokamak has been substantially redeveloped from its original MAST incarnation with a new architecture that aims to manage complexity whilst maximising flexibility. It provides modular layers of functionality and supports the implementation of virtual actuators to aggregate, arbitrate and route requests from multiple upstream controller functions to finite downstream actuator commands. Initial experience of this design and its exploitation during the commissioning and initial operation of MAST Upgrade to first plasmas is reported. We present here the current hardware and software architecture of the control system, highlighting how the layered architecture enabled the gradual commissioning of new functionality in step with the commissioning of the plant and the tokamak system, and later paved the way to allow new functionality such as position, shape and divertor strike point control to be added with minimal impact on already commissioned critical functions. Finally, we show how the next steps of the development roadmap for MAST-U plasma control will support more advanced capabilities in future scenarios.

1. INTRODUCTION

The plasma control system for MAST-U [1] has been an essential part of the initial commissioning and operations campaigns. It is based on an extensible and flexible software framework running on mostly commercial off-the-shelf (COTS) hardware, with substantially re-written tokamak control algorithms to support the complex aims of MAST-U. This provides flexible control of many new coils to explore alternative divertor configurations. The gas system was also substantially extended to support multiple injection locations being exploited concurrently for different purposes, e.g. for fuelling, detachment control and impurity seeding.

2. HARDWARE ARCHITECTURE

Fig. 1 shows the current hardware architecture of the plasma control system, much of which has been retained from MAST. It comprises of the main control computer in a computer room that is outside the electrical isolation boundary of the tokamak, the primary I/O racks that are within the main tokamak instrumentation area, some remote output devices in the power supply buildings and miscellaneous other supporting components and services.

The real time computer is a COTS multicore server with optical PCIe link crossing the electrical isolation boundary to the main IO hardware near the magnetic measurement instrumentation racks. The link leads to an expansion case that then connects to the host cards of 2 CompactPCI subracks to provide a total I/O capacity of 352 analogue inputs, 64 analogue outputs and 4 sets of 32 configurable digital input or digital output ports. Most of the analogue inputs are taken up by measurements of magnetic fields, fluxes and currents from the tokamak but we also use fibre optic analogue links to receive voltage representations of real time measurements of line-integrated density from the CO_2 interferometer and detachment front location from the divertor Multi Wavelength Imaging (MWI) system [2]. Most of the analogue output capacity is used for driving the amplifiers that are connected to the piezo actuators for the gas injection system. The coil power supplies, being in their own remote buildings, are controlled via a command packet broadcasted by PCS through an optical Ethernet switch to remote analogue output devices (UDP DACs) installed in the power supply buildings. Each UDP DAC has a settable offset address, allowing it to define which fragment of the broadcast command packet contains the 4 analogue outputs channels that it will drive. The device was developed in house mostly from COTS field-programmable gate array (FPGA) technology including an implementation of the network stack in firmware, so that it responds deterministically to incoming packets on a segregated private Ethernet segment.

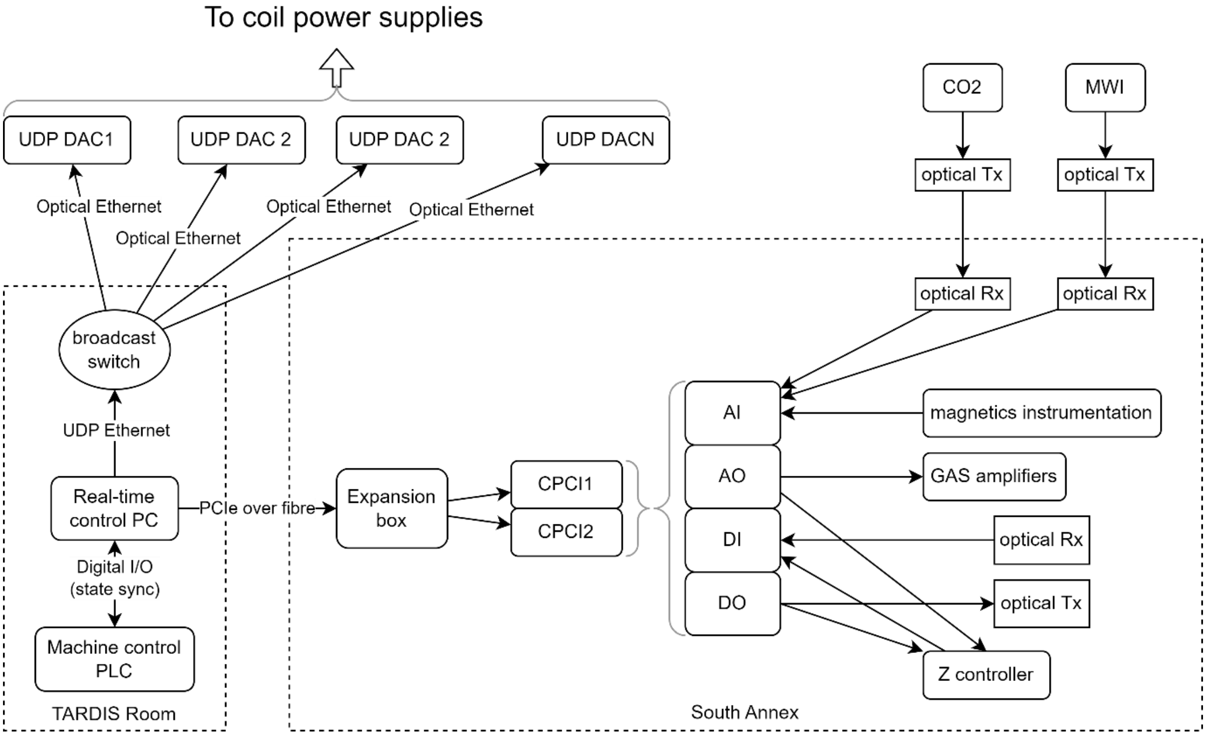

FIG. 1. PCS hardware architecture.

To achieve real-time performance, the Linux operating system is configured with core isolation and process pinning so that each real-time process runs on a dedicated CPU core that is isolated from the OS. By design, the PCS software framework has minimal need for OS services during the real-time phase. The I/O cards can act as PCI bus masters and have read/write access to a PCS-allocated memory buffer via DMA. The only part of PCS that still depends on the OS is the sending of one broadcast UDP packet per I/O cycle, but planned future work also includes removal of this remaining dependency on the OS network stack.

Vertical stabilisation and position control is performed by a dedicated FPGA device with a fast response time to directly control the fast-switching radial field power supply for the radial field coils. This device exchanges a small number of analogue and digital signals with PCS, which also manages the waveforms and settings for the vertical controller, uploading them to it each time the pulse starts.

3. SOFTWARE FRAMEWORK

The software architecture is based on the PCS framework from General Atomics as used for DIII-D [3]. It provides a set of processes and software framework that is generic to any experiment, to which one only needs to add the tokamak-specific algorithms and hardware platform-specific device interfaces. The infrastructure takes care of managing and editing the pulse schedule, dispatching real-time processes during the pulse, message logging and post-pulse data archiving. There is also a standalone build that allows the PCS code to be built and tested on a standard workstation and a simulation mode where the device I/O can be substituted by a simulation server that provides a virtual plant and tokamak interface. Fig. 2 shows the main processes and interactions.

The infrastructure framework defines the concept of categories, which contain sequences of phases, to which algorithms relevant to that category can be attached. The top level of scenario design is the category. Therefore, the timing of what is being executed in each category is independent of others. Each category can be used as a placeholder for execution of interchangeable functions, where the choice of phase to execute at any time defines (via the attached algorithm) what functions will be executed. The category acts as a unit of concurrency, since only one algorithm can be active at any time, therefore multiple categories are required to be able to execute multiple tasks concurrently. Since the PCS framework supports the implementation of all aspects of plasma control in multiple concurrent categories with easy access to each other's data, it inherently supports the concept of holistic integrated plasma control. It is also possible to implement alternative execution sequences on a per-category basis, which can be triggered in response to specific off-normal events.

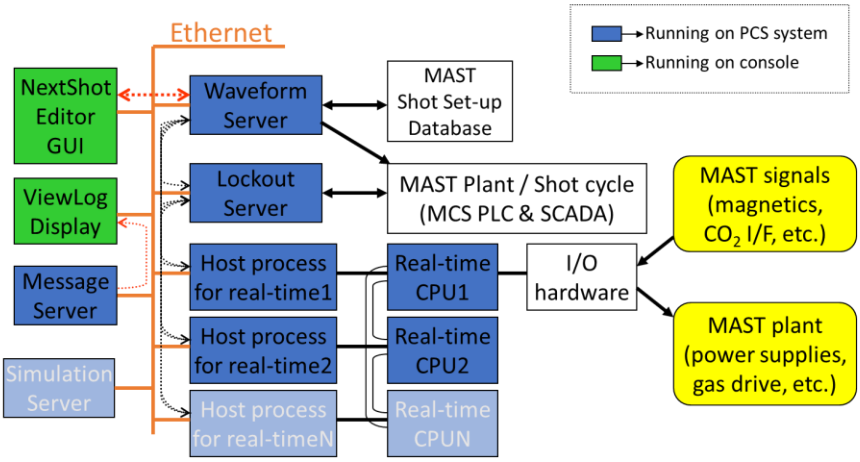

FIG. 2. PCS software process architecture: (blue boxes are PCS system processes, green boxes are user interface tasks)

The waveform server is at the heart of the PCS configuration. It embeds knowledge of all available categories and algorithms in the PCS build, including how many and which CPUs are allocated to each of them. It presents a network interface for the graphical editing software to access the pulse schedule to define the sequence of execution within each category and the corresponding setup data (waveforms and parameters) for the assigned algorithms in each execution phase. Previous pulses can be fully or partially restored, or a separate free-standing instance of the waveform server can be used to prepare a full pulse scenario for future use. Since this C program has no specific hardware dependencies it runs as a container in the MAST-U virtual machine infrastructure, as does the message server, a simple log message aggregator that receives copies of log messages generated by other PCS processes and extracts relevant information on overall system health status. A secondary panel of the user interface can be used to view log messages as they come in and to alert the operator to status problems or any detected misconfiguration of the pulse schedule.

The lockout server runs as a finite state machine that synchronises certain PCS states with those of the tokamak operations cycle. To facilitate this, it runs on the PCS computer to be able to access a USB Digital I/O device that provides direct hardware handshaking with the Machine Control System (MCS) PLC on which the tokamak pulse state machine runs as part of the plant control.

The plasma control algorithms are deployed on a set of per-CPU host and real-time processes. When a shot starts, each CPU host function asks the waveform server for the setup data needed by the tasks on its CPU and it initialises the real-time process memory map. The real-time process runs a sequence of function calls belonging to the categories in PCS. Note that instead of relying on the OS task scheduler to run the various control functions, the PCS software configuration statically schedules exactly which function from which category runs on each CPU at a given point in every control cycle, thus ensuring deterministic execution of all control functions with regular cadence.

4. IMPLEMENTATION ARCHITECTURE

Table 1 summarises the various categories of control currently included in PCS. Note that, as described in [1], some categories are assigned to be the exclusive "owners" of specific sets of plant actuators, e.g. poloidal field (PF) coils or gas valves, whilst others only provide data for consumption by other categories including the actuator managers. The latter can be identified from the use of italics in the "Outputs to" column of the table.

4.1. Supporting framework

All typical PCS implementations would be expected to have system and data acquisition categories. By convention the system category should only run one phase for the whole shot with only one choice of algorithm. This way it can be used to hold global parameters such as plant settings and calibration tables. It also provides utility functions that are always available, including limit-checking functions and other machine-protection features.

TABLE 1. PCS CONTROL CATEGORIES

Category name	Purpose	Outputs to
System	Support functions and global data	Interlocks
Acquisition	Data acquisition and processing	*All categories*
Reconstruction	Estimate plasma shape and strike points	*Shape and divertor categories*
Plasma	Control Vloop / plasma current	*Circuit category*
Shape	Control plasma shape properties	*Circuit category*
Divertor	Control divertor leg properties	*Circuit category*
IcoilPert	Add biasing waveforms for PF coils	*Circuit category*
Circuits	Map virtual actuators to PF coil currents	*PF category (via system)*
PF	Specify PF coil voltages	PF coil power supplies
TF	Set TF current reference	TF power supply
Fuelling	Control plasma fuelling/density	*Flow category*
Detachment	Control detachment	*Flow category*
Radiation	Control edge radiation	*Flow category*
Impurity	General impurity gas injection	*Flow category*
Flow	Map virtual gas actuators to physical gas	*Gas category*
Gas	Specify gas valve voltages	Gas plant
ELM	Specify ELM coil currents	ELM coil power supplies
EF	Specify Error field coil voltage	Error field coil power supplies
RP	Drive Reciprocating probe	Reciprocating probe
Z	Configure Z controller	Z controller

The acquisition category processes raw data from ADCs into useful physical values. It provides compensation for DC input offset and magnetic integrator drift by tracking the baseline of the input signals before any plant is turned on. It also removes known stray toroidal field pickup in the poloidal field measurements. In simulation mode, PCS replaces the device I/O with a network connected simulation server, of which there are two types. The “data” version replicates previous pulse data whilst the “physics” version from the TokSys control design suite [4] uses a Simulink plant and tokamak model for closed loop simulation. The acquisition algorithm needs to know if it is running from a simulated physics model so that it can skip the “real world” data corrections that aren’t needed when handling synthetic measurements. This can also allow the use of “shortcut” signals where the simulation can just tell PCS what the plasma current or geometry is, allowing validation of the control algorithms to be separated from commissioning and validation of the real-time reconstruction.

4.2. Real-time plasma shape reconstruction

The reconstruction category’s principal algorithm, named LEMUR (Local Expansion for MAST Upgrade Reconstruction) [5], determines the plasma boundary’s shape, which is represented by the separatrix between the closed and open poloidal flux surfaces. In each real-time cycle, the algorithm calculates a poloidal flux map on a regular (R, Z) grid in the lower X-point region using a local expansion method based on [6] and [7]. The co-ordinates of the X-point, (R_X, Z_X), are found using a saddle-point search routine and the poloidal flux at the X-point is chosen to represent the poloidal flux of the separatrix if it is greater than that calculated on the inner limiter, otherwise the flux at the limiter touchpoint is used. Next, poloidal flux profiles are calculated on linear segments, each of which represents a plasma shape parameter, and the intersection point with the poloidal flux of the separatrix is found for each segment. Fig. 3 shows the reconstructed parameters, which include the outer and inner radius of the separatrix at mid-plane (R_{out} and R_{in}, respectively), the gap between the separatrix and the divertor nose (R_{gap}) and the location of the outer strike-point in the lower divertor chamber (R_{stk}, Z_{stk}). Fig. 4 shows the comparison of the parameters reconstructed by LEMUR in real-time with those from an offline reconstruction based on the code EFIT++, which is used at MAST-U as the reference plasma shape reconstruction method [8]. There is some discrepancy in X-point location due to the large low field region causing error magnification, but this has minimal impact in the resulting determination of the other geometric properties.

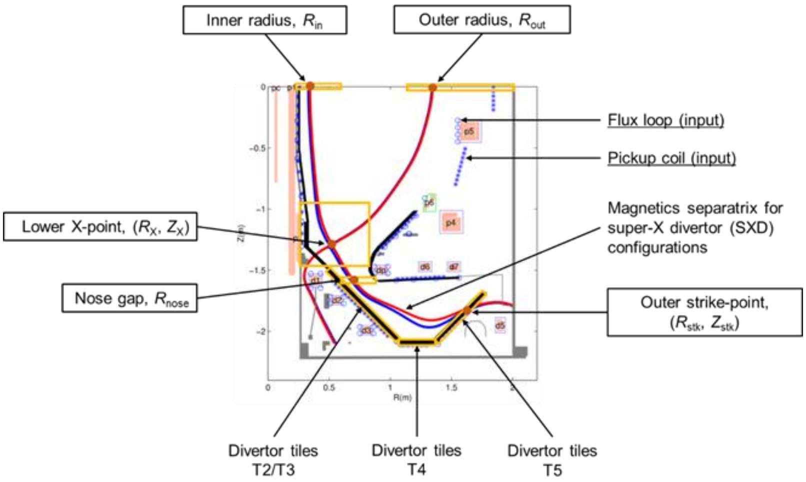

FIG. 3. MAST-U plasma shape parameters (red circles) reconstructed in real time based on the magnetic separatrix. The magnetics sensors (flux loops and pickup coils) act as inputs to the reconstruction.

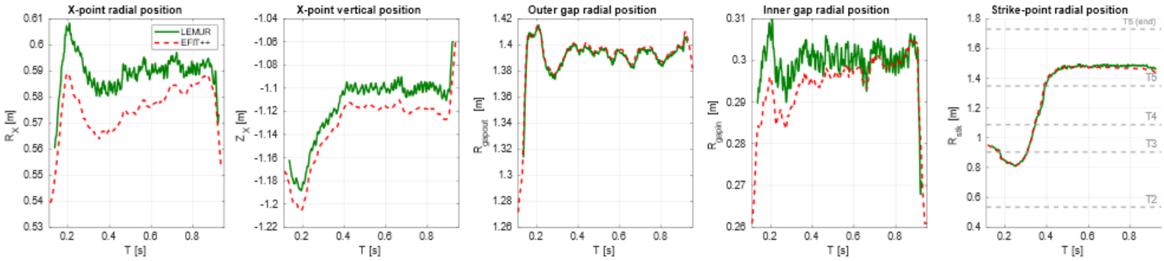

FIG. 4. A comparison of a real-time reconstruction (LEMUR) and an offline reconstruction (EFIT++) of plasma shape parameters that are relevant to downstream control algorithms (shot 47985).

4.3. Coil control with virtual circuits

Note the multiple categories in Table 1 that provide output to the circuit and flow categories. These two categories provide “virtual actuator” management for PF coils and gas respectively, as also detailed in [1]. In essence the upstream control categories are assigned a set of virtual actuator “channels” that they can write to, and the actuator managers define the mapping from virtual to physical plant. In the case of coil control, the architecture allows the independent selection and scheduling of separate controllers for plasma current, shape and divertor properties, all of which are driving virtual circuits for controlling these properties. The circuit category then defines these circuits as linear combinations of physical coil currents. The “IcoilPert” category allows arbitrary feedforward bias waveforms to be added to any of the resulting PF coil current demands.

The PF category is responsible for driving all the PF coil power supplies. For testing and commissioning purposes it can run a self-contained algorithm that defines the commissioning waveforms to be sent to the power supplies, but in normal operations it runs a multi-coil control algorithm that receives control requests from an upstream category. These requests are first ‘vetted’ by an immutable function in the system category, ensuring that all operating limits (max current and ramp rate, max temperature rise, etc.) are enforced irrespective of the version or choice of control function that is producing the control requests either now or in the future.

To be able to maintain adequate predictive control of inductive coil currents, the controller needs to be given both the target currents and their required rate of change. Also, since the upstream categories producing the coil current requests may be running different algorithms at different times during the pulse, we arrange that all upstream controllers only produce requests in terms of the rate of change of current needed to converge on the target objective. The absolute target current is therefore derived from the integral of the previous control requests over the duration of the pulse. Any change of controller may therefore result in a change in the trajectory of coil current ramp rates but will not cause a discontinuous step change in their absolute target values.

4.4. Density and detachment control with virtual gas flow actuators

The fuelling category can provide either feedforward fuelling requests or density feedback control. A laser interferometer system [10] determines the line-integrated density in real time and provides the measurement as an analogue voltage to PCS. A proportional-integral (PI) controller is used to calculate the fuelling gas flow rate required to approach the given reference. In a similar manner a detachment category was provisioned for allowing a control algorithm to be implemented concurrently to produce a separate gas flow request to control divertor detachment.

Note that the fuelling, detachment, radiation and impurity categories all run independent gas control functions and drive their own flow requests to sets of virtual gas role actuators. These are managed by the flow category to assign the role flow requests to specific gas valve groups. The flow and gas categories then take care of mapping the above requests to the selected gas valve groups and driving the appropriate voltage to each valve respectively.

5. RESULTS

The MAST-U PCS has been used to successfully commission both the plant and first plasma. Introduction of various elements have been staged since first plasma such that, as of the third MAST-U experimental campaign, PCS is now capable of plasma current, shape, strike-point, density, and detachment feedback control.

5.1. Commissioning

For initial operations some special-purpose commissioning algorithms were implemented in the PF category to directly drive the PF coils without input from upstream categories. When the power supplies were commissioned and the coils were calibrated, we then implemented a multi-coil control algorithm that would receive coil control requests from the circuits category (after passing through an ever-present limit-checking algorithm). Initially the algorithm deployed in the circuits category would generate waveforms as input by the operator. Whilst this function is still used for pre-magnetising the solenoid and setting other coil currents in the desired state for plasma breakdown, the virtual circuit manager then takes over to provide a mapping transformation from virtual circuits driven by upstream categories to physical circuits. The first virtual circuit to be implemented was the ohmic circuit, which can be as simple as just 100% solenoid current, but more typically it would include an appropriate proportion of the divertor coil currents to help exclude the solenoid stray field from the vessel. Note that it can be useful to implement multiple definitions of the ohmic circuit as the scenario progresses from midplane breakdown, where divertor stray field is immaterial to the plasma and it’s more important to minimise excursion in divertor coil current, to a fully diverted plasma, where the solenoid field needs to be compensated over a large region at the expense of greater use of divertor coils and less complete field cancellation. There are other early constraints on virtual circuits, e.g. the Px coil cannot be brought into use until the P1 solenoid current has fallen below 20kA for machine protection purposes. Sequencing of virtual circuits allows these constraints to also be met.

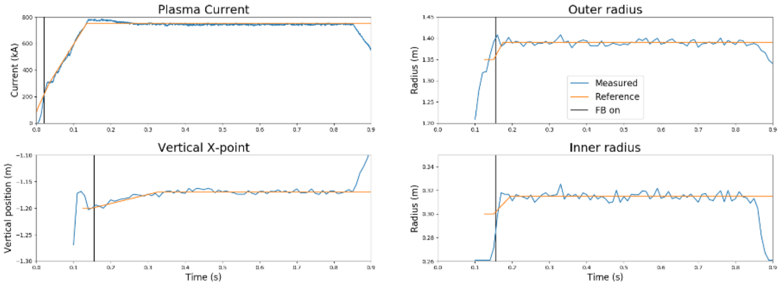

FIG. 5. Controlled plasma current and shape values with references for shot 46977.

5.2. Position, Shape and divertor control

Full main chamber shape control and strike point position control has been achieved on MAST-U in collaboration with General Atomics [11]. Rapid progress was possible due to the ability to load virtual circuit actuators into PCS at runtime, as well as arbitrary combinations of actuators with different start times. Fig. 5 shows the plasma current and shape control parameters under feedback control for shot 46977 and illustrates the excellent control obtained. Fig. 6 shows the measured strike point position under feedback control using the same virtual circuits control scheme as the plasma shape control.

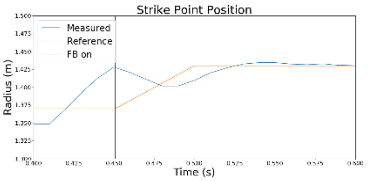

FIG. 6. Strikepoint position in feedback control for shot 47577.

In collaboration with DIFFER [12] the fuelling valves and plasma response were characterised and modelled to enable systematic design of the density control gains. This has resulted in the demonstration of density control for MAST-U. Fig. 7 shows programmed step changes in density in shot 46813 using a single gas valve actuator.

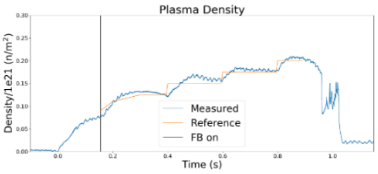

FIG. 7. Feedback control of step changes in plasma density using a single gas actuator in shot 46813.

Also, in collaboration with DIFFER, an algorithm for the real-time control of detachment was implemented in PCS. The core content of this algorithm was carefully matched to a validated Simulink model. The MWI diagnostic incorporates a real-time detachment front locator [2] and drives an analogue output to PCS. The detachment feedback algorithm calculates the response and produces the request for detachment gas flow output. The flow and gas categories then take care of mapping this request to the selected gas valve groups and driving the appropriate voltage to each valve.

6. FUTURE WORK

The capabilities of the control system continue to evolve according to programme needs.

The modular architecture supports drop-in upgrades for existing algorithms, such as multi-variable coil control taking account of different dynamics between fast and slow-response coil power supplies, or replacing the linear gas flow to piezo voltage mapping with an algorithm that fully accounts for nonlinearity and hysteresis in the valve response.

With increased interest in collaboration on algorithm developments and deploying those from other tokamaks, we intend to update the build framework for PCS to support calling functions compiled from Simulink models.

We intend to extend our real-time reconstruction capabilities to report additional parameters, such as internal inductance (l_i), plasma elongation, squareness and triangularity parameters. We also envisage the introduction of reconstruction of the B-field at select locations as a potential constraint for advanced downstream control schemes, such as would be needed to enable the control of a snowflake configuration and/or of a secondary X-point target.

A new prototype PCS hardware platform is under development, still based on standard x86_64 computer hardware and still using an I/O subsystem that will be able to directly read/write the host memory. A Real-Time Data Network (RTDN) is under development for connecting additional diagnostics to the PCS. The first candidate diagnostic for this network is the magnetics integrator units. This will remove a large portion of the analogue input channel capacity required for PCS and greatly simplify cabling and reduce noise.

7. CONCLUSIONS

Among the new actuators of MAST Upgrade are numerous divertor coils for exploring alternative advanced divertor geometries and multiple gas injection locations to study detachment and edge physics. The plasma control system consolidates all real-time diagnostic measurement inputs and actuator outputs into one integrated system with globally shared data supporting multiple concurrent control functions on a distributed multi-processing platform. The software architecture was built as a set of modular layers to implement a functional chain from input to output where each processing stage has pluggable functionality. This approach limits the scope and complexity of each function whilst maximising the flexibility and configurability. We have shown how this framework has supported the rapid development of new control functions including plasma current, shape, strike-point, density, and detachment feedback control. We continue to add to the capabilities to support future missions.

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