EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(04)06-37

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2002 (Proc. 19th IAEA Fusion Energy Conference, Lyon (2002)).*

Preprint of Paper to be submitted for publication in Proceedings of the
23rd SOFT Conference,
(Venice, Italy 20-24 September 2004)

ABSTRACT

This paper describes the installation of the new JET Shape Controller System especially focusing on the addition of the Extreme Shape Controller. The activity was performed by the JET Operator in co-operation with the ENEA-CREATE design team, and involved both changes in the hardware and system software of JET and tuning of the proposed XSC design to satisfy the practical requirements of tokamak operation. The application of ten years experience of controller implementation and commissioning combined with a modern and efficient modelling and design methodology has allowed an unprecedented fast and easy commissioning of the new system.

1. INTRODUCTION

JET Shape Controller hardware has been recently upgraded both to replace obsolescent hardware and to provide sufficient processing power to allow for a further development of the controller and in particular to allow the implementation of the Extreme Shape Controller (XSC) . This new control system is designed to provide a precise and rigid boundary control of highly shaped plasma configurations and needs to be implemented as component of the new Shape Controller System (SC2), since it shares all the interfaces. During the implementation phase the new controller has been redesigned and extended as a configurable control algorithm, the XSCM (eXtreme Shape Controller Module), not only capable of implementing the XSC but also able to feedback on any selection of plasma measurements provided by RTDN (Real Time Data Network). In addition much work was dedicated to the optimisation of the user interface, so that the main users, the Session Leaders (SLs) are not burdened by an increased controller complexity but are instead attracted by the new enhanced and easy to use capabilities.

2. HARDWARE AND SOFTWARE DEVELOPMENT

The first step to the development of SC2 was the substitution of the existing multi Texas- 40Mhz C40 DSP architecture with a more capable state of the art 400Mhz PowerPC based VME system. The choice provided both a 5-fold step in performance and a programmer friendly environment. While the software development on the DSP platform requires deep knowledge of the processor characteristics and of the hardware platform, the PowerPC with the VxWorks operating system offers a UNIX like general purpose platform usable by a wider range of programmers. One of the most important constraints to the project was that the old Shape Controller System (SC1) was to be kept operational until the new system was fully functional and tested. The reason was that while the SC was needed to run every JET experiment, the machine time dedicated to the new system commissioning was very little and fragmented in a few restart sessions spread over a year period. Moreover there was neither the time nor the resources to prepare a parallel system, because it would have meant building a new cubicle, wiring the connections to the plant, and commissioning the installation. The only solution compatible with these strict requirements was the hosting of the new processor card in the same VME crate containing the C40s and the switching between the old and new systems via software. The first step to install the SC2/XSC controller at JET was to port the existing controller code to the single processor PowerPC architecture, which meant rewriting the original multiprocessor software, rescheduling the order of operations to obtain a single thread, and removing any C40 specific routine. A result of the RTDN development effort, a highly configurable and portable real-time software framework, JET-RT, has been designed for the PC platform, which allows both a fast prototyping of a real-time system and a comprehensive laboratory test of the algorithms. The need for a fast development cycle, for software standardisation and especially for a good off-line testing facility, was the reason for adopting this platform also for the XSC development.

3. THE ARCHITECTURE OF SC2

SC2 is implemented as the “user application” module for the JET-RT framework. The code is organised in such a way as to become part of a standard main program, the JET-RT that provides the interfaces to the hardware, to the real-time I/O and to the JET computers according to the information coded in a configuration file. This architecture means that SC2 code has no reference to the hardware and is therefore fully portable. The real-time control algorithm is implemented as a single thread, periodically reading the measurements, calculating the outputs and finally sending the references to the amplifiers. The calculation is divided into modules whose call sequence is:

1) **measurement elaboration**, where the raw data is converted into useful measurements, and where the XLOC plasma boundary reconstruction code is located;
2) **control mode selection**, where the status of the controller is updated in response to the exceptions that might have been detected in the previous cycle or to follow the programmed sequence of control law variations;
3) **waveform generator**, producing the references in accordance to the controller status;
4) **eXtreme Shape Controller Module (XSCM)**, the new configurable control module that if activated provides its own outputs as references to the shape controller module;
5) **Shape Controller Module (SCM)**, implementing the SC control scheme selected by the controller status;
6) **diagnostic**, the module that checks if any variable has reached a limit.

The main addition to the SC1 is the introduction of the XSCM a controller that operates on the shape measurement produced by XLOC and, depending on the main controller status, sends its outputs as references to the SCM, replacing those produced by the waveform generator. The remaining processing modules perform their measurement, control and limit avoidance action independently of the XSCM activation status. Since these algorithms havebeen designed to provide an acceptable level of machine protection against errors in theprogramming of the references, this same safety net now protects against potential errors in the XSCM coding or in the parameters. Consequently the re-commissioning of the limits and exceptions logic under the Shape Controller can be considered enough to guarantee that the same protections work correctly when the XSCM is active.

4. XSCM

XSCM implements a multivariable controller that acts on a selection of 10 current measurements 16 configurable external RTDN inputs and 38 geometrical descriptors, and provides the reference to the 9 JET poloidal field (PF) circuits and an optional selection of 8 external actuators controllable via RTDN.

$$Y_j (s) = f_j (s) \cdot (FF_j (s) + (k_p = \frac{k_I}{s}) \cdot \mathbf{M}_j \cdot (\mathbf{X_{ref}} (s) - \mathbf{X}_{meas} (s))) \text{ (Block diagram in figure 1)}$$

The implemented control algorithm can be summarised in the following equation $\mathbf{X}_{meas}$ is the input vector, $\mathbf{X}_{ref}$ are the reference waveforms and Y_j is a component of the output. $\mathbf{M}_j$ is a row of the control matrix and FF_j is a feed forward waveform. f_j is a filter, k_I and k_p are the parameters of the PI and j is an index spanning all the actuators.

SC divides the experiment in time windows, intervals where a specific selection of control laws can be selected. The $\mathbf{X}_{ref}$ (t) and **FF**(t) arrays of waveforms are prepared during the first cycle of any time window where the XSCM is active and are constructed so that to linearly bridge, in the specified transition time ttrans, the difference between the current values of the actuators, **Y***start*, and of the measurements, $\mathbf{X}_{star}t$, and those specified by the XSCM parameters, $\mathbf{X}_0$, $\mathbf{Y}_0$. Since at the transition all the integrators are loaded with 0 the controller output does not manifest any jump. The filters array **f**(s) is added to equalise the dynamic behaviour of the actuators. In the case of the PF currents, this is necessary because SC implements a different current control bandwidth for each circuit. The integrators anti-windup scheme is designed to progressively reduce to 0 the status of the integrators where the reference to the actuator has reached the saturation level. The integrators are implemented using the following equation:

$$\mathbf{output}(t) = \mathbf{status}(t+1) = \tau \cdot \mathbf{input}(t) + \mathbf{status}(t) \cdot \mathbf{I}_{MAP}.$$

I_{MAP} is a square matrix that implements the following mapping

$$\begin{cases} \mathbf{I}_{MAP} \,.\, \mathbf{v} = \mathbf{v} \quad \forall \mathbf{v} \in Span(\mathbf{M}) \\ \mathbf{I}_{MAP} \,.\, \mathbf{v} = 0 \quad \forall \mathbf{w} \in Ker(\mathbf{M}) \end{cases}$$

Any component of the Ker(M) that can be introduced by numerical errors or by the action of the anti-windup, which cannot be suppressed by the controller, is then cancelled by the $\mathbf{I}_{MAP}$ matrix. The XSC module also implements a check on the quality of its control by performing the following algorithm:

$$errMax_j > \mathbf{E}_j \cdot ((\mathbf{X}_{ref} - \mathbf{X}_{meas}) \cdot *(\mathbf{X}_{ref} - \mathbf{X}_{meas}))$$

where **E** is a matrix of weights with a number of rows equal to the number of actuators, and **errMax** is a vector of thresholds. If any threshold is reached the controller immediately disables the XSCM module and initiates a soft termination of the discharge.

5. THE XSC IMPLEMENTATION

The originally proposed XSC design has been somewhat changed to adapt it to the SC2 implementation. The main departure from the original concept is the decision to move the control matrix calculation outside the real time controller and into an offline XSC Tool (XSCT). The reason is that the algorithm is too computationally expensive and not adequate for real time since it employs the Singular Value Decomposition (SVD), a code that requires a variable number of iterations to converge. The consequence is that the controller cannot vary its control strategy and produce a new matrix as a response to variation in the actuator saturation status. On the other hand, the real time calculation of the controller matrix poses some validation issues, since it means trusting a set of parameters that has never been validated on a plasma simulation. XSCT produces two matrices **U** and **V**, respectively mapping the 9 actuators and the 64 geometrical measurements into the controller space, where the PI algorithms can operate on independent control variables and where the less useful actuator combinations and the uncontrollable reference combinations are cancelled. In the actual implementation, the PI controllers are moved on the actuators space, and the **M** matrix is loaded with the product between **U** and **V**, an algebraically equivalent solution if all the PI parameters are the same. This solution was adopted to help the implementation of the anti-windup that in the original scheme would have been complicated by the complex formulation of the actuator limits in the controller space. XSC, acting only on a subspace of the actuator currents, needs a feed forward term to locate the currents references within the actuators limits. This component is calculated by the non linear plasma simulation as the currents needed to achieve the reference shape. The implementation allows the user to specify for each time window the shape, $\mathbf{X}0$, and the feed forward currents, $\mathbf{Y}0$, as the target for the controller after the transition time.

6. USER INTERFACE

One of the main targets of the XSCM implementation effort was to provide the SL with a new set of control facilities without unnecessarily increasing the complexity of the user interface. There are already too many waveforms and parameters that the SL has to check when preparing an experiment, adding a new waveform for each of the new geometrical parameters would have made his job impossible. This is why there are no selectable waveforms or parameters for the XSCM, only the ability to select among extreme shape controller scenarios, files containing all the XSCM parameters $\mathbf{X}_0$, $\mathbf{Y}_0$, **M**, $\mathbf{I}_{MAP}$, **E** and, **f**. The SL can activate the new controller by selecting an extreme scenario and choosing the appropriate transition time. The proliferation of scenarios is avoided by providing the SL to apply small variations to the target shape. The extreme shape controller scenarios are produced by the XSC tool chain, a set of algorithms that allows the development of optimised controllers.

6. FUTURE

Presently XSCM cannot perform strike point sweeping, a functionality that will be very important in the next campaigns. The main problem is that the controller bandwidth is limited to the speed of the slowest actuator, 10Hz, by the equalisation filters **f**, while the triangular sweeping requires a controller bandwidth of at least 20Hz. In addition the broader sweeping patterns are shape variations so wide that a single linear model cannot be used to describe it correctly. A simple but not precise solution under investigation implements the sweeping for both XSC and SC by inserting a sweep controller module between the XSCM and SCM. The module applies periodic feed forward current components to the SCM references according to user-selected pattern, while at the same time varying the references to the XSC accordingly. XSCM operates on a subspace of the actuators, leaving typically between 2 to 3 degrees of freedom unused, which could be instead used to help avoiding current limits. A different solution is to provide a set of alternative control matrices each to be used when a different actuator saturates.

CONCLUSIONS

The SC2 development has been a very successful application of good system development and testing practices, being able to replace completely SC1 after a very short commissioning period. The new XSC controller has been installed satisfactorily as a SC2 component and has been used to perform scientific experiments during the 2003-2004 experimental campaign. The ITER modelling and control design techniques have been validated on a relevant experimental environment, confirming that they can produce optimised plasma controllers without the need of much machine testing time. On the other hand, the combined experience of developing and operating SC and XSC at JET has shown that a real plasma controller needs to be a composite system. In order to cater for all the experimental and technical needs, the system must be able to perform a variety of feedback strategies, ranging from the simple driving of the PF current to the complex full boundary control. The implementation of the more general XSCM controller has also proven very useful during the initial XSC commissioning, where it was necessary to validate the software by closing the loop on the actuator currents. The added flexibility proved essential to help preparing a set of experiments where it was necessary to close the loop between the TAE dumping rate and the plasma elongation. Finally it has become the key element necessary for the implementation of any XSC phase-2 integrated controllers that might require the use of both PF and additional heating actuators.

ACKNOWLEDGEMENTS

This work is funded in part by the UK Department of Trade and Industry, and Euratom and has been performed under the European Fusion Agreement.

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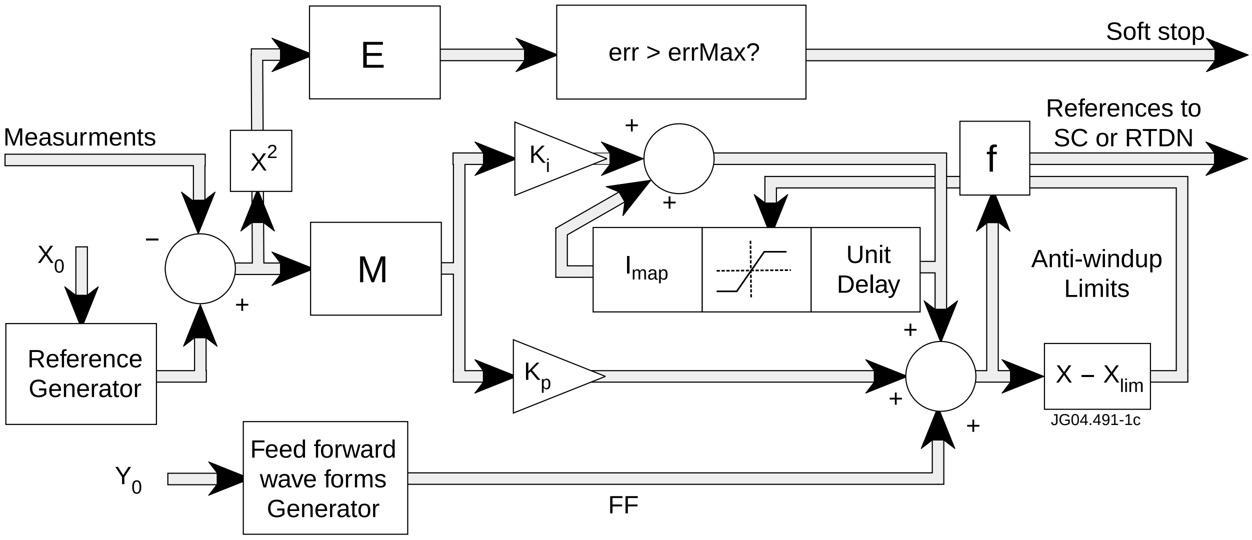

Figure 1: The XSCM block structure. Note that the reference generator blocks generate ramps from the plant values at the transition to the specified $\mathbf{X}_0$, $\mathbf{Y}_0$ *values. The SOFT STOP output is sent to the control mode selection logic.*