G Model
FUSION-9163; No. of Pages 4
ARTICLE IN PRESS
Fusion Engineering and Design xxx (2017) xxx–xxx

ELSEVIER
Fusion Engineering and Design
journal homepage: www.elsevier.com/locate/fusengdes

Integration of the state observer RAPTOR in the real-time MARTe framework at RFX-mod

Chiara Piron[a,*], Gabriele Manduchi[a], Paolo Bettini[a], Federico Felici[b], Claudio Finotti[a], Paolo Franz[a], Ondrej Kudlacek[c], Giuseppe Marchiori[a], Lionello Marrelli[a], J.-M. Moret[d], Paolo Piovesan[a], Olivier Sauter[d], Cesare Taliercio[a], the EUROfusion MST1 Team[1]

[a] Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), Corso Stati Uniti 4, 35127 Padova, Italy
[b] Eindhoven University of Technology, Mechanical Engineering, Control Systems Technology, PO Box 513, 5600MB Eindhoven, The Netherlands
[c] Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstr. 2, 85748 Garching, Germany
[d] École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

HIGHLIGHTS

- The state observer RAPTOR predicts tokamak plasma profile evolution in real-time.
- The integration of the state observer RAPTOR in MARTe on RFX-mod is presented.
- The validation of the state observer RAPTOR on RFX-mod q(a) <2 plasmas is discussed.

ARTICLE INFO

Article history:
Received 3 October 2016
Received in revised form 24 January 2017
Accepted 24 February 2017
Available online xxx

Keywords:
Tokamak control
Real-time framework
Integrated control
RFX-mod

ABSTRACT

The RAPTOR – RApid Plasma Transport simulatOR code is a model-based control-oriented code that predicts Tokamak plasma profile evolution in real-time. One of its key applications is in a state observer, where the real-time predictions are combined with the measurements of the available diagnostics, yielding a complete estimate of the plasma profiles. The state observer RAPTOR is currently installed in the real-time control system of TCV, where it has been originally developed, ASDEX-Upgrade and recently RFX-mod. The latter has pioneered its integration in the real-time MARTe – Multi-threaded Application Real-Time executor framework, which will be the topic of this work. Thanks to this, RFX-mod can now contribute to develop integrated control techniques based on the state observer RAPTOR to avoid disruptions, which are highly reproducible in q(a) <2 RFX-mod Tokamak plasmas if they are left uncontrolled.

1. Introduction

In order to satisfy the high reliability and performance requirements of the future fusion reactors, a well-coordinated control of many plasma parameters and profiles has to be ensured in real-time. Some of them, like the radial distribution of the current density, are not accurately measured even in present fusion experiments. Furthermore, the diagnostics that will be available in the future fusion reactors will be likely limited both in variety and resolution, due to the harsh nuclear environment. This partial knowledge of the plasma state can be completed if the diagnostic data are combined with the predictions of a transport code, which has to be complex enough to reproduce the plasma dynamics but also compatible with real-time implementation. The RApid Plasma Transport simulatOR code (RAPTOR) [1] satisfies both these features. When combined with a state observer algorithm, the predictions of the code are corrected by the real-time diagnostic data. These predictions can be used to develop integrated control applications to ensure a simultaneous control of plasma profiles, Magneto Hydro Dynamics (MHD) instabilities and off-normal events, like diagnostic faults and plasma disruptions.

In this work we present the first integration and application of the state observer RAPTOR in the real-time MARTe framework [2] at RFX-mod. A brief overview of the RAPTOR code will be provided in Section 2. The integration of the code in the RFX-mod control system, which is based on the real-time MARTe framework, will be described in Section 3. Section 4 will present and discuss the first

* Corresponding author.
E-mail address: chiara.piron@igi.cnr.it (C. Piron).
[1] See http://www.euro-fusionscipub.org/mst1.

http://dx.doi.org/10.1016/j.fusengdes.2017.02.093

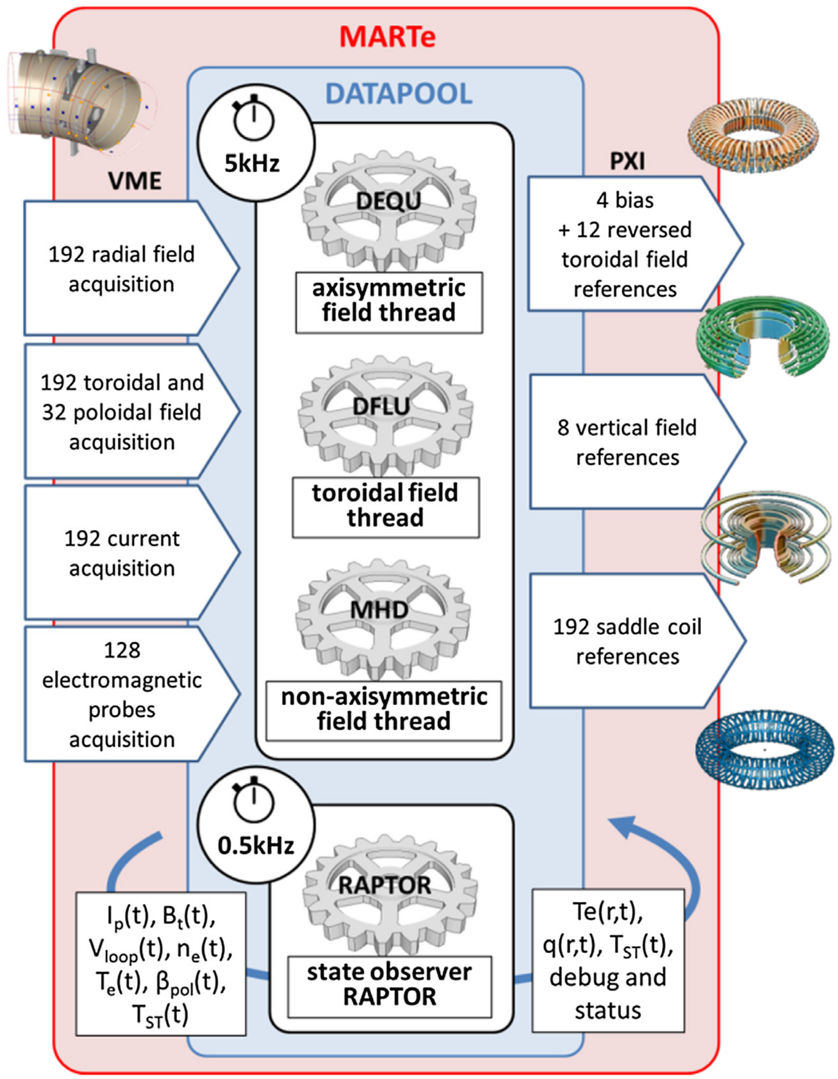

Fig. 1. Skectch of the integration of the state observer RAPTOR in the RFX-mod real-time control system based on the MARTe framework.

experimental outcomes of this integration. Eventually, a demonstrative control strategy which is based on RAPTOR predictions for plasmas close to the current limit, will be presented in Section 5.

2. The state observer RAPTOR code

The RApid Transport simulatOR code (RAPTOR) [1] is a 1D control-oriented transport code capable of predicting in real-time the evolution of several plasma profiles and parameters, thanks to its accurate yet simplified physics model. The code solves two coupled partial differential equations for the poloidal flux $\Psi(\rho, t)$ and the electron temperature $T_e(\rho, t)$, where $\rho = \sqrt{\Phi/B_0\pi}$ is the normalized square-root toroidal flux coordinate, Φ the toroidal magnetic flux and B_0 the equilibrium magnetic field. When RAPTOR is combined with a state observer, the solutions of the equation for the electron temperature profile diffusion are corrected by the real-time experimental measurements.

In this work, all the terms that depend on the flux surface geometry are evaluated once for a one particular equilibrium and then fixed afterwards. Nonetheless RAPTOR can handle time-varying magnetic equilibria. In this regard it is noteworthy its coupling with the equilibrium reconstruction code LIUQE [3], which is under development on TCV and RFX-mod [4]. As a result of this work, RAPTOR will receive the 2D equilibrium geometry from LIUQE and it will give it back the model-based pressure and current density profiles, which will be used by LIUQE to improve the accuracy of the equilibrium reconstruction in the next iteration.

Heating and current drive sources, like Electron and Ion Cyclotron (EC, IC) waves or Neutral Beam Injection (NBI) are modeled as a sum of Gaussian deposition profiles in RAPTOR. A simple transport model, that is based on a closed-form expression for the heat diffusivity [5], has been applied in this work. It is noteworthy that here we also validate a model for the sawtooth instability [6], that has been recently implemented in RAPTOR [7]. This model predicts in real-time the sawtooth crashes and it evolves instantaneously both magnetic and kinetic profiles according to either a complete [8] or incomplete [9] magnetic reconnection model. The former has been validated in the real-time RAPTOR simulations of RFX-mod sawtoothing plasmas that will be presented in Section 4.

The integration of RAPTOR in a state observer algorithm based on an extended Kalman Filter [10] has been originally developed at TCV [11]. At present, the state observer RAPTOR is installed in the Système de Contrôle Distribué (SCD) at TCV [12], in the Discharge Control System (DCS) at ASDEX Upgrade [13,14] and in the Multi-threaded Application Real-Time executor (MARTe) at RFX-mod [15]. The integration in the latter will be the topic of the next section.

Please cite this article in press as: C. Piron, et al., Integration of the state observer RAPTOR in the real-time MARTe framework at RFX-mod, Fusion Eng. Des. (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.02.093

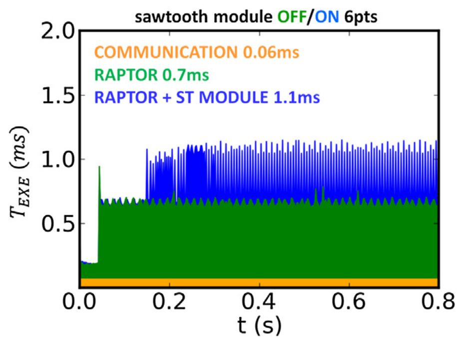

Fig. 2. Execution time of the state observer RAPTOR with a mesh of 6 points in the real-time MARTe framework on RFX-mod. The activation of the sawtooth model increases the execution time of around 36%. The UDP communication time is around 0.06 ms.

3. The integration of the state observer RAPTOR in the real-time MARTe framework

Thanks to the flexibility of its control system and power supplies, RFX-mod [16] can be operated both as a Reversed Field Pinch and as an Ohmic Tokamak. In the latter configuration both circular and D-shaped magnetic equilibria are routinely explored. The former at q(a) <2 is the reference plasma scenario of the real-time RAPTOR simulations that are presented in this work. A unique feature of RFX-mod is its sophisticated control system. As it is sketched in Fig. 1, three real-time threads are executed in parallel in the real-time MARTe framework of this device. Two of them, which are implemented in Matlab Simulink, supervise the magnetic equilibrium and one the MHD stability. These threads acquires more than 700 signals and generates more than 200 signals every 0.2 ms. As for the equilibrium threads, the state observer RAPTOR is automatically converted into a C++ code using the Simulink Coder^{TM}, which is then compiled in MARTe. Dedicated C++ classes have been developed to manage the I/O data and the code execution. On RFX-mod, RAPTOR is integrated as a subsystem of MARTe, that communicates with the other threads via the connectionless User Datagram Protocol (UDP). This choice prevents the occurrence of code exceptions and delays while the other RFX-mod real-time threads, which have the highest priority, are executed.

The cycle time of the state observer RAPTOR in MARTe on RFX-mod is fixed at 2 ms in this work. This value is a conservative compromise between the highest time and spatial resolution of the model predictions. In Fig. 2 we report the execution time of the RAPTOR process, as it is measured by MARTe. The plot shows that the state observer RAPTOR takes around 1.1 ms to simulate a RFX-mod sawtoothing plasma (in blue) with a radial mesh of 6 points. If the sawtooth model is not activated in the model (in green) the execution time diminishes by around 36%. Eventually, a baseline of nearly 0.06 ms is due to the UDP streaming of the I/O data between the process and the MARTe datapool (in orange).

Among the RAPTOR input data, the electron temperature T_e, density n_e and the experimental sawtooth period T_{ST} are the new signals that have been implemented in real-time for the first time on RFX-mod. All of them are evaluated on the basis of 4 channels of a multichord Soft X-Ray (SXR) diagnostic. T_e is measured by applying the Double Filter technique to a couple of them [17], n_e is estimated combining the latter with the diamagnetic beta which is estimated from magnetic measurements [18] and a dedicated algorithm evaluates T_{ST} directly from the diagnostic data. In the version of the RAPTOR code that has been used in this work, the output data are the predicted sawtooth period and both T_e and q profiles. It is noteworthy that, thanks to this work, the latter are available in real-time for the first time on RFX-mod. Similarly to the experimental data, the storage and the visualization of the RAPTOR I/O data are handled with the MDSplus software.

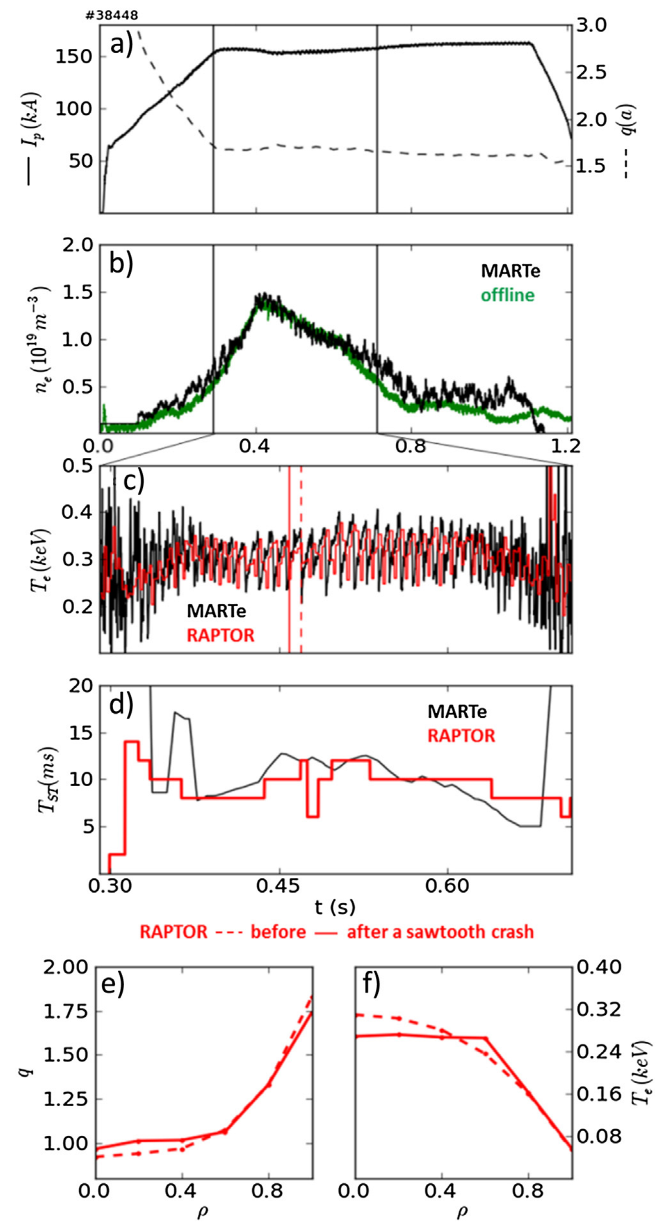

Fig. 3. Real-time validation of a sawtoothing plasma in RFX-mod operated as a circular ohmic tokamak. Time evolution of a) the plasma current (continuous line) and edge safety factor (dashed line), b) the real-time electron density (black) and the corresponding offline measure from inteferometric data, c) real-time electron temperature (black) and the RAPTOR predicted one (red), d) the real-time measured (black) and predicted (red) sawtooth period. The predicted profiles of e) the safety factor and f) the electron temperature before (dashed line) and after (continuous line) a sawtooth crash. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. A real-time validation of the state observer RAPTOR in a q(a) <2 RFX-mod tokamak plasma

In Fig. 3 we report the results of the real-time validation of the state observer RAPTOR in a RFX-mod circular tokamak plasma. As it is shown in panel a), in this experiment the plasma is maintained well above the current limit q(a) <2 by the MHD control thread, which suppresses the m = 2, n = 1 Resistive Wall Mode. During the flat-top, we increase and then switch off the gas puffing to modulate n_e, whose real-time estimate (in black) is shown to be in good agreement with a more accurate offline interferometric measure (in green) in panel b). The effect on sawteeth is documented in panels c) and d), which compare the real-time measurements (in black) and the RAPTOR predictions (in red) of the on-axis T_e and T_{ST}, respectively. These panels show that the modeled data follow the experimental ones, though with a limited resolution. The latter can be improved by reducing RAPTOR cycle time and increasing the resolution of the spatial grid. According to Fig. 2, the margin for the reduction of the cycle time is around 25% with a mesh of 6 points. Offline tests, which have been performed on a double core INTEL® processor running at 2.26 GHz, suggest an almost linear increase of the execution time with the resolution of the mesh, therefore we expect a grid with 10 points to be the upper limit for a cycle time of 2 ms. It is worth noting here that the energy confinement time in q(a) <2 RFX-mod tokamak plasmas is ~30 ms, the shell time constant for vertical magnetic field penetration is ~50 ms and that a typical discharge lasts ~1 s.

At each time step the execution of the state observer RAPTOR stores in the MARTe datapool the safety factor and temperature profiles. We report them before (dashed line) and after (continuous line) a sawtooth crash in panels e) and f), respectively. The corresponding time instants are identified with vertical lines in panel c). These panels show that the sawtooth model implemented in RAPTOR correctly reproduces the typical effects of this instability on the plasma profiles, which significantly affect the plasma core.

5. A demonstrative model-based disruption prediction with RAPTOR for plasmas approaching the current limit

RFX-mod tokamak plasmas are very reproducibly disrupted by m = 2, n = 1 Resistive Wall Modes and locked Tearing Modes in the proximity of the q(a) = 2 current limit, if they are left uncontrolled. Due to toroidal coupling to the internal kink, the growth of both instabilities is associated with the reduction of the sawtooth oscillations [19]. At present RAPTOR does not reproduce this MHD dynamics since neither model for RWMs and TMs has been developed yet, nor magnetic measurements have been included. Therefore it is expected to predict stationary sawteeth in these plasmas. This discrepancy is exploited to develop a prototype demonstration of a model-based disruption prediction technique, where the real-time comparison of the measured sawtooth period to the modeled one possibly predicts plasma disruptions a few tens of milliseconds earlier, allowing a dedicated MARTe controller to take preventive actions, i.e. ramping down the plasma current. This disruption prediction technique has not been tested in real-time yet on RFX-mod, nonetheless efforts to extend it to TCV and ASDEX-Upgrade are on-going. It is noteworthy that the idea upon which it is developed can be extended to develop disruption prediction and avoidance schemes on those tokamaks that operate in more reactor relevant scenarios, like ASDEX Upgrade or JET, where other off-normal events, like impurity accumulation, can likely trigger plasma disruptions.

6. Conclusions

A real-time integrated control of both magnetic and kinetic plasma parameters and profiles is likely a promising strategy to satisfy the stringent requirements on safety and performance of the effective fusion scenarios. The global knowledge of the plasma state that is provided in real-time by the state observer RAPTOR is being exploited in several fusion experiments, like TCV, ASDEX Upgrade and RFX-mod, to concretize this perspective. Here we present the first integration and application of the state-observer RAPTOR in the real-time MARTe framework, which has been pioneered by RFX-mod. In this device, the code has been successfully validated in real-time in circular sawtoothing plasmas at q(a) <2. For the future, an optimization of both time and spatial resolution is planned to improve the accuracy of the model predictions in compliance with real-time requirements.

An original outcome of the integration of the state observer RAPTOR in MARTe on RFX-mod is the real-time availability of both electron temperature and safety factor profiles. Furthermore, this work has enabled RFX-mod to actively contribute to the coupling of RAPTOR to LIUQE and to the development and validation of integrated control applications. In this regard, a demonstrative disruption prediction strategy, that is based on the real-time comparison of experimental and modeled data, has been developed for sawtoothing plasmas close to the current limit. This strategy can be applied also to larger tokamaks, where other off-normal events can likely trigger plasma disruptions.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] F. Felici, et al., Real-time physics-model-based simulation of the current density profile in tokamak plasmas, Nucl. Fusion 51 (2011) 083052.
[2] A.C. Neto, et al., MARTe: a multi-platform real-time framework, Trans. Nucl. Sci. 57 (2010) 479–486.
[3] J.-M. Moret, et al., Tokamak equilibrium reconstruction code LIUQE and its real time implementation, Fusion Eng. Des. 91 (2015) 1.
[4] J.-M. Moret, et al., Tokamak equilibrium reconstruction code LIUQE: implementation, applications, developments, in: Proceeding of the 42nd EPS Plasma Physics Controlled Fusion Conference, Lisbon, Portugal, June, 2015 (P2.147).
[5] F. Felici, Real-Time Control of Tokamak Plasmas: from Control of Physics to Physics-Based Control, Thèse École Polytechnique Fédérale de Lausanne EPFL 5203 (2011).
[6] S. von Goeler, et al., Phys. Rev. Lett. 33 (1987) 1021.
[7] C. Piron et al. in Proceeding of the 42st EPS Plasma Physics Controlled Fusion Conference, Lisbon, Portugal, June 2015, P1.145.
[8] B.B. Kadomtsev, et al., Rep. Prog. Phys. 50 (1987) 115.
[9] F. Porcelli, et al., Plasma Phys. Control. Fusion 38 (1996) 2163.
[10] Felici, et al., A dynamic state observer for real-time reconstruction of the tokamak plasma profile state and disturbances, Proceedings of the 2014 American Control Conference (2014) 4816–4823.
[11] F. Felici, et al., Non-linear model-based optimization of actuator trajectories for tokamak plasma profile control, Plasma Phys. Control. Fusion 54 (2) (2012) 025002.
[12] J.I. Paley, et al., Architecture and commissioning of the TCV distributed feedback control system, in: Real Time Conference (RT), 2010 17th IEEE-NPSS, Lisbon, 2010, pp. 1–6.
[13] W. Treutterer, et al., ASDEX upgrade discharge control system – a real-time plasma control framework, Fusion Eng. Des. 89 (2014) 146.
[14] F. Felici, et al., First results of real-time plasma state reconstruction using a model-based dynamic observer on ASDEX-Upgrade, in: Proceeding of the 41st EPS Plasma Physics Controlled Fusion Conference, Berlin, Germany, June, 2014 (P2.002).
[15] G. Manduchi, et al., The new feedback control system of RFX-mod based on the MARTe real-time framework, Trans. Nucl. Sci. 61 (2014) 1216.
[16] P. Sonato, et al., Machine modification for active MHD control in RFX, Fusion Eng. Des. 66 (2003) 161–168.
[17] P. Franz, et al., Experimental investigation of electron temperature dynamics of helical states in the RFX-mod reversed field pinch, Nucl. Fusion 53 (2013) 053011.
[18] A.S. Elahi, et al., Simultaneous simple measurements of tokamak plasma parameters especially based on plasma diamagnetic effect, J. Nucl. Part. Phys. 1 (2011) 10–15.
[19] C. Piron, et al., Interaction of external n = 1 magnetic fields with the sawtooth instability in low-q RFX-mod and DIII-D tokamaks, Nucl. Fusion 56 (2016) 106012.

Please cite this article in press as: C. Piron, et al., Integration of the state observer RAPTOR in the real-time MARTe framework at RFX-mod, Fusion Eng. Des. (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.02.093