

FR-FCM 2011 Final report:

Safety factor profile control and IR hot spots detection

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Abstract

This project report summarizes the collaboration results between GIPSA-lab and CEA/IRFM on:

- 1) *Control methodologies for the tracking of a desired safety factor or current profile* in Tore Supra tokamak. Such topic is of immediate interest for ITER and the EFDA Feedback Control group. The approaches considered necessitate advanced technical skills in automatic control and systems theory. They are based on control theory tools applied to a simplified distributed (PDE) model of the plasma magnetic flux dynamics. Several issues, such as the nonhomogenous properties of the transport phenomena, actuation limitations, and control robustness are addressed.
- 2) *Hot spots tracking in infrared videos of a tokamak using the Level Set framework*. Infrared imaging is increasingly used in Magnetic Confinement Fusion for real-time machine protection. Indeed since a large amount of power is required to induce the fusion reactions, plasma facing components (PFCs) are subjected to high heat fluxes that can damage them. For the operation of JET with its ITER like wall made of Beryllium and Tungsten components, detection and tracking of hot spots on the PFCs are two very important issues to guarantee the safe operation of the machine. The approach proposed in this paper is based on a constrained level set method driven by an initial detection stage. The main advantage of this method is to allow tracking efficiently the hot spots thanks to a constrained shape evolution criterion.

I. SAFETY FACTOR PROFILE CONTROL

A. Project objectives

1) *Scientific framework*: In the coming years the main challenge in the fusion community will be the development of experimental scenarios for the International Tokamak Experimental Reactor (ITER). Amongst them, the so-called advanced tokamak steady-state ones will play a significant role, since they will allow reproduction and study (on a smaller scale) of the conditions that are expected to be obtained in a fusion plant of reduced size and costs [1]. In these scenarios particular emphasis is given to the current density profile and to the way of producing the plasma

current IP: due to the intrinsic limited availability of magnetic flux in the fusion devices, needed to sustain a purely inductive current, IP will have to be generated mainly by non-inductive sources. In particular, the importance of the real-time safety factor profile (q-profile) control has been emphasized in several works.

Previous control approaches have shown the interest of appropriate control methods to improve the plasma performances. Nevertheless, they are based on identified linear models of the plasma and/or semi-empirical tuning of the gains of a proportional-integrator controller, rendering the real-time control particularly sensitive to the operating conditions. The aim of our work is then to propose a new, model-based control approach focused on the dynamics of the magnetic flux profiles. More specifically, we will use the control-oriented model described in [2], where the current profile dynamics is derived based on a consistent set of simplified relationships, in particular for the microwave current drive sources, rather than exact physical modeling. This model has been compared with experimental results and has shown its efficiency to represent key issues for profile control on Tore Supra, while fulfilling tight real-time computation constraints. The core of this distributed model (described by a 1-D Partial Differential Equation) is composed of a non-homogeneous transport coefficient (resistivity), a nonlinear term (bootstrap current), distributed non-inductive sources (LH and ECCD inputs) and time-varying boundary conditions (magnetic coils).

2) *Specific objectives*: Considering that the magnetic coils are dedicated to the plasma shape stabilization and inductive current generation, they are considered as exogenous inputs and not explicitly considered in the regulation scheme. Supposing a consistent desired safety factor profile q_{ref} , the control objective is then to regulate the non-inductive sources such that q_{ref} is tracked efficiently according to dynamical and actuation constraints.

Particular objectives for 2011 included:

- Obtention of real-time control laws (i.e. based on algorithms that can run fast enough for a real-time implementation) based directly on the PDE model.
- Study of the robustness properties of the proposed control laws.
- Extension of the proposed control laws to the engineering parameters of the LHCD antennas including saturation constraints and other implementation issues and test under simulation using the METIS code.
- Prepare a benchmark tool for the validation and comparison of the different control approaches and implement it using METIS to use as test platform.

All of these objectives were adequately met. The remaining objective is to implement and experimentally test the proposed (and simulation-validated) control laws. Due to time constraints, no experiments could be carried out this year in Tore Supra.

B. Work description

1) *Context, background, positioning*: This work is in the direct continuation of the post-doc done by E. Witrant at CEA-Cadarache in 2006, when the control-oriented model [2] was derived. The aim of the present project is to use this model in an optimal model-based profile control approach for long pulses scenarios, a topic that has been classified as “very high priority” during the EFDA Feedback Control group meeting in July 2009. Integrated plasma control, and more particularly the control of profiles peaking during the current ramp-up phase, is recognized as a key issue for ITER and can be considered as a direct outcome of the proposed control approach. A collaboration with the Universities of Nice, Anger and Grenoble, managed by CEA-IRFM, has been set to address several aspects of model-based profile control.

2) *Scientific methods and main results*: We considered the simplified diffusion equation describing the dynamics of the poloidal flux, as stated in [2]:

$$\frac{\partial \psi}{\partial t}(\rho, t) = \frac{\eta_{\parallel}}{\mu_0} \frac{\partial^2 \psi}{\partial \rho^2} + \frac{\eta_{\parallel}}{\mu_0 \rho} \frac{\partial \psi}{\partial \rho} + \eta_{\parallel} R_0 j_{ni} \quad (1)$$

where $\eta_{\parallel}(\rho, t)$ is the plasma resistivity, $\mu_0 = 4\pi \times 10^{-7} \text{ H m}^{-1}$ is the permeability of free space, R_0 is the geometric center of the plasma torus and j_{ni} is the source term due to non inductive current sources (bootstrap effect and microwave current drives). The spatial index ρ is replaced with the normalized variable $x = \rho/a$, where a is the minor radius corresponding to the last closed magnetic surface (is considered constant). The inclusion of peripheral dynamics (temperature, density, bootstrap computation, antennas coupling with the plasma, etc.) is done according to Tore Supra configuration and scaling laws, as detailed in [2]. The control objective was formulated as a tracking

problem, namely to regulate the profile $\psi(t)$ around a reference operating point profile $\bar{\psi}$. The controlled input was the non-inductive current deposit and the loop voltage was considered as an exogenous time-varying input (not controlled).

a) *Lyapunov-Based Infinite-Dimensional Control of the Magnetic Flux Profile in a Tokamak Plasma [3]*: In this work, the magnetic flux dynamics was expressed in terms of the spatial derivative of ψ (denoted as ψ_x) as:

$$\frac{\partial \psi_x(x, t)}{\partial t} = \frac{1}{\mu_0 a^2} \frac{\partial}{\partial x} \left(\eta_{\parallel}(x, t) \frac{\partial}{\partial x} (x \psi_x(x, t)) \right) + R_0 \frac{\partial}{\partial x} (\eta_{\parallel}(x, t) j_{ni}(x, t)).$$

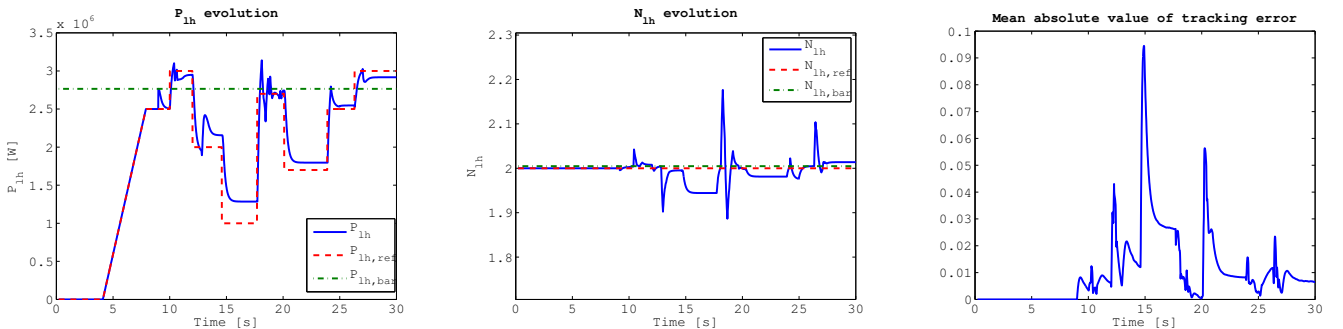
The advantage of this formulation is to allow a direct computation for the safety factor profile q with:

$$q(x, t) \doteq \frac{\partial \phi / \partial x}{\partial \psi / \partial x} = \frac{-B_{\phi_0} a^2 x}{\partial \psi / \partial x},$$

where B_{ϕ_0} is the toroidal magnetic field at the plasma center and ϕ is the magnetic flux of the toroidal field.

Our goal was to design a controller for the dynamics of $\psi_x(x, t)$ without discretization of the PDE. One of the main features of this work is that the diffusivity coefficients are allowed to be rapidly time-varying (which is based on the fact that the temperature profile changes much faster than the current redistribution time). The shape of the resistivity profiles was approximated by a family of exponentials $\eta(r, t) = a(t)e^{\lambda(t)r}$. A Lyapunov function equivalent to a weighted L^2 norm of the state was used and a suitable weighting function to guarantee the stability of the system with time-varying coefficients was numerically found.

Both a constrained and an unconstrained version of a control algorithm are found such that the system can be accelerated or disturbances can be attenuated. The usefulness of the proposed algorithms for tracking purposes was also tested under simulation with positive results, as can be seen in Figure 1.



(a) Reference P_{1h} profile, obtained P_{1h} profile and equilibrium value used (b) Reference N_{1h} profile, obtained P_{1h} profile and equilibrium value used (c) Mean tracking error obtained in METIS

Figure 1: METIS simulation of the Lyapunov-based real-time controller incorporating actuation constraints

b) *Lyapunov-Based Infinite-Dimensional Control with Boundary Disturbances [4]*: In this work, a systematic way of finding suitable weighting functions to guarantee the stability of the system presented in the previous subsection was developed. It is based on the solution by parts of a differential inequality involving the diffusivity coefficients and the weighting function. The influence of boundary disturbances (such as uncertainties in the total plasma current regulation using magnetic coils) was also considered.

C. Conclusions

Most of the main objectives of this project, concerning the *Control of safety factor profile in tokamaks*, were met satisfyingly. More precisely:

- Obtention of real-time control laws (i.e. based on algorithms that can run fast enough for a real-time implementation) based directly on the PDE model.
- Study of the robustness properties of the proposed control laws.
- Extension of the proposed control laws to the engineering parameters of the LHCD antennas including saturation constraints and other implementation issues and test under simulation using the METIS code.

- Prepare a benchmark tool for the validation and comparison of the different control approaches and implement it using METIS to use as test platform.

Each of these steps motivated theoretical advances in control systems theory and involved important implementation efforts.

II. IR HOT SPOTS TRACKING

A. Project objectives

1) *Scientific framework:* As discussed in [5], [6] several challenges, such as the sources of signals (reflection), the signal transmission or the acquisition and signal processing, are associated with the use of IR cameras in ITER. Considering the signal processing problem, a vision-based approach (including thermal object detection, classification and thermal event recognition) for the automatic detection of thermal events is proposed in [7] and an integrated open-source software is now available [8]. These approaches have been successfully applied to Tore Supra. For the operation of JET with an ITER like wall, the detection of hot spots on the plasma facing components will be a crucial issue to guarantee the safe operation of the machine and to gather experience for ITER. Therefore developing reliable infrared thermography diagnostics to determine the surface temperature of the plasma facing components in the main chamber and in the divertor is a very significant issue for JET [9].

The image analysis is rendered difficult by the complexity of deriving in-vessel components surface temperature from an infrared imaging system. Indeed the temperature measurement not only depends on the emissivity of the surface, which is not a priori known, but also on the viewing direction, wavelength and physical state of the surface, the latter being subject to variations during plasma operation. Moreover, reflections from hot spots can also induce errors due to their parasitic contribution on the thermography signal. In addition, due to the huge amount of data generated by these imaging systems, the use of traditional techniques for hot spot detection based on absolute temperature measurements are not efficient. In that context, recent advanced image processing techniques have been investigated to achieve a visual analysis of PFCs heating, by hot spot detection and tracking in infrared videos.

2) *Specific objectives:* We propose in this work a new hot spots tracking method based on the localization of active contours. The computation of this localization is driven by a 1D initial detection stage combined with a classification method. More precisely, our aim was to investigate the use of the level sets framework and its implementation on tokamaks. Specific investigations have to be carried on the processing time optimization method by integrating dynamic information and the sub-image computations. Preliminary results are obtained on a JET IR video sample.

B. Work description

1) *Context, background, positioning:* Infrared (IR) diagnostics is a topic of prime interest among the EFDA goals and CEA-IRFM has a leadership position in this area. More specifically, IR cameras have been instrumented at JET to detect hot spots and excessive heating of plasma-facing components. Dedicated skills on image processing, automated diagnostics and real-time operation are necessary to get the full benefit of this instrumentation. Research corresponding to these specific skills is also developed at GIPSA-lab, who is thus well suited to contribute to this task.

Palazzo et al. described in [9] an approach based on the combination of Cellular Nonlinear Network (CNN) with Field Programmable Gate Arrays (FPGA) with the aim of performing hot spots recognition on images captured by JET wide angle infrared camera. This system achieved good performance compared to software approaches with a computational time reduction to a millisecond per frame. Martin et al. described in [7] a new vision-based approach for the automatic recognition of thermal events. This approach, focused on hot spot detection and thermal event recognition, is based on a priori knowledge of the tokamak geometry as well as the temperature and temporal attributes of each region of interest. This method improved the PFC monitoring system used in Tore Supra.

2) *Scientific methods and main results:* To reduce the computation time of level sets and allow a tracking of the hot spots shape, we introduced a step consisting in an automatic selection of the regions of interest (ROI), which correspond to areas where hot spots may appear. The level set function thus evolves in a reduced size region and for each ROI a new level set function is attributed. This step consists in a combination between a 1D supervision tool and a region growing method. A memory constraint was then added to the variational framework, in order to introduce tracking capabilities in the algorithm.

a) 1D supervision tool: This tool consists in an Archimedean spiral scanning of each image in the infrared video (Figure 2). The advantage of this scanning is to avoid exploring each pixel in the image. The aim of this spiral scanning is to detect hot spot pixels that serve as initial seeds for the region growing algorithm (described in next section). An appropriate tuning of this supervision tool involves the choice of the separation distance between successive turns (set constant in our case) and the sampling along the spiral, which can influence the detection of hot spot pixel. Furthermore, the detection of hot spot pixel necessarily needs to choose a gray level threshold on the image.

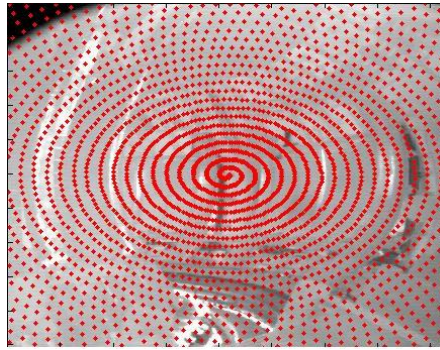


Figure 2: Example of spiral scanning of an infrared image.

b) Memory constraint and tracking: The detection algorithms typically allow hot-spot-like regions to be detected in a single image but do not take into account the system dynamics. Indeed a hot spot may be present at the same location for many consecutive frame. It is thus interesting to propagate the information obtained from one image to the one taken at the next sampling time to reduce the computation time and to track the hot spots duration on specific plasma-facing components (which determines the energy flow that they have to endure). The previously described Level set framework is only able to process an image at a time and consequently needs to be improved in order to include memory characteristics. This is achieved by adding extra constraint terms to the energy functional that has to be minimized. More precisely, we introduced the memory characteristic by constraining the level set function, for each frame, to be close to the segmentation result obtained at the previous frame.

c) Global Algorithm: The proposed image processing method is summarized by the following algorithm.

Repeat: until the end of the video,

Step 1: Spiral scanning of the image and detection of hot spot pixel (seeds)

If new areas are detected

Step 2: Application of the region growing (RG) algorithm from the detected seeds and selection of the regions of interest (ROIs).

Step 3: Application of Level sets in the ROIs to get the final segmentation.

Else

Step 2: Use Segmentation Level set combined with the memory constraint from the previous frame.

End if

d) Experimental results: Our image processing method has been applied to hot spot detection in JET. The video analyzed was recorded with the JET wide angle KL7 infrared camera. The diagnostic is designed to measure temperature in the range of 200-2000 °C. As the temperature information is not available, we work only on data converted into grayscale images. The final results of our segmentation method for hot spots detection with an infrared video by the automatic localization of level set using a memory constraint (ALSM) are presented in Figure 3. Most of hot spot regions are successfully detected despite the fact that no a priori knowledge is supposed concerning the tokamak topology or hot spots location.

3) Conclusions: The first advantage of our approach is that the convergence of the process is reached more quickly than traditional level sets methods. The second advantage is to provide a diagnostic on the time constant and evolution of each hot spot.

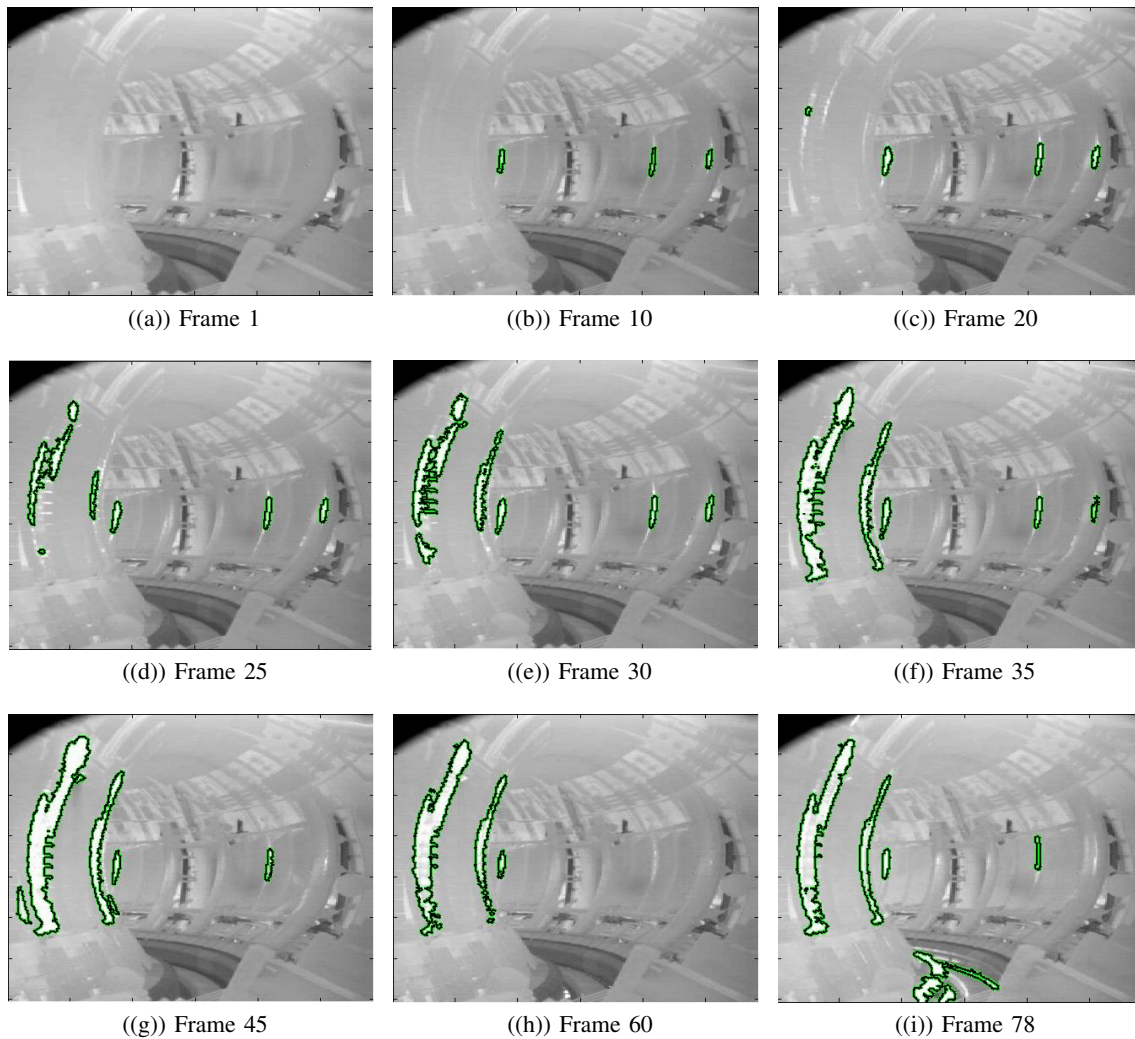


Figure 3: Hot spots segmentation through infrared video of tokamak with ALSM.

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The Papers and Conference contributions

Journal paper:

- 1) Bribiesca Argomedo, F., C. Prieur, E. Witrant and S. Brémond "Lyapunov-based infinite-dimensional magnetic flux profile control of a tokamak plasma." Conditionally accepted for publication, IEEE Transactions in Automatic Control 2012.*

Peer-reviewed conferences with papers published in the proceedings:

- 1) Bribiesca Argomedo, F., E. Witrant, C. Prieur "Input-to-State Stability of a Time-Varying Nonhomogeneous Diffusive Equation Subject to Boundary Disturbances." Submitted for publication, American Control Conference 2012.*
- 2) Bribiesca Argomedo, F., C. Prieur, E. Witrant and S. Brémond "Polytopic control of the magnetic flux profile in a tokamak plasma." 18th IFAC World Congress, Milano, Italy. August 2011.
- 3) A. Gahlawat, M.M. Peet and E. Witrant, "Control and verification of the safety-factor profile in tokamaks using Sum-of-Squares polynomials", 18th IFAC World Congress, Milano, Italy. August 2011. Invited paper.
- 4) E. Witrant and S. Brémond, "Shape Identification for Distributed Parameter Systems and Temperature Profiles in Tokamaks", Proc. of 50th IEEE Conference on Decision and Control, Orlando, USA, December 12-15, 2011. Invited paper.
- 5) E. Santiago, E. Witrant, M. Goniche and F. Clairet, "An Optimal Feedback Approach to Particle Source Identification in Tokamaks", Proc. of the 15th IEEE International Conference on System Theory, Control and Computing, Sinaia, Romania, October 14-16, 2011. Best Paper Award.

Conference based on abstract submissions:

- 1) E. Witrant and S. Brémond, "Parameter Dependant Shape Identification of Temperature Profiles in Tokamak Plasmas", *submitted to 7th International Congress on Industrial and Applied Mathematics (ICIAM)*, Vancouver, BC, Canada, July 18-22, 2011. Invited talk.

Internal report:

- 1) B. Touil, E. Witrant, M. Alamir, V. Martin, "Hot Spots Tracking in Infrared Videos of a Tokamak Using the Level Set Framework", GIPSA-lab report, 2011.*

*: the publication decision for these papers is still pending, please do not diffuse over the internet.

Appendix

Related publications/drafts:

- 1) F. Bribiesca Argomedo, C. Prieur, E. Witrant and S. Brémond "Polytopic control of the magnetic flux profile in a tokamak plasma." 18th IFAC World Congress, Milano, Italy. August 2011.
- 2) A. Gahlawat, M.M. Peet and E. Witrant, "Control and verification of the safety-factor profile in tokamaks using Sum-of-Squares polynomials", 18th IFAC World Congress, Milano, Italy. August 2011. Invited paper.
- 3) E. Witrant and S. Brémond, "Shape Identification for Distributed Parameter Systems and Temperature Profiles in Tokamaks", Proc. of 50th IEEE Conference on Decision and Control, Orlando, USA, December 12-15, 2011. Invited paper.
- 4) E. Santiago, E. Witrant, M. Goniche and F. Clairet, "An Optimal Feedback Approach to Particle Source Identification in Tokamaks", Proc. of the 15th IEEE International Conference on System Theory, Control and Computing, Sinaia, Romania, October 14-16, 2011. Best Paper Award.
- 5) F. Bribiesca Argomedo, C. Prieur, E. Witrant and S. Brémond "Lyapunov-based infinite-dimensional magnetic flux profile control of a tokamak plasma." Conditionally accepted for publication, IEEE Transactions in Automatic Control 2012.*
- 6) F. Bribiesca Argomedo, E. Witrant, C. Prieur "Input-to-State Stability of a Time-Varying Nonhomogeneous Diffusive Equation Subject to Boundary Disturbances." Submitted for publication, American Control Conference 2012.*
- 7) B. Touil, E. Witrant, M. Alamir, V. Martin, "Hot Spots Tracking in Infrared Videos of a Tokamak Using the Level Set Framework", GIPSA-lab report, 2011.*

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