UNIVERSITA' DEGLI STUDI DI NAPOLI FEDERICO II
DIPARTIMENTO DI INGEGNERIA ELETTRICA E TECNOLOGIE DELL'INFORMAZIONE
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STATEMENT ON THE RELEVANCE OF THE PHD THESIS:

"TOKAMAK MAGNETIC CONTROL SIMULATION: APPLICATIONS FOR JT-60SA AND ISTTOK OPERATION"
BY
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<u>Reported by</u>:

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STATEMENT CONCERNING THE RELEVANCE AND IMPORTANCE OF THE RESEARCH PRESENTED IN THE PHD THESIS SUBMITTED BY:

LILIA DOMÉNICA CORONA RIVERA

"TOKAMAK MAGNETIC CONTROL SIMULATION: APPLICATIONS FOR JT-60SA AND ISTTOK OPERATION"

GENERAL COMMENT

The doctoral thesis presented by Lilia Doménica Corona Rivera deals with plasma magnetic diagnostic and control for two different tokamak devices: ISTTOK, currently operated by Instituto de Plasmas e Fusão Nuclear (IPFN), in Lisbon, and JT-60SA the joint EU-Japan superconductive machine that will start the operation in early 2021.

The thesis proposes model-based design techniques that can be used to develop the magnetic control systems in the two considered devices. Indeed, these two tokamaks are different, not only in size, but also because of their operation regimes. ISTTOK is a small size tokamak, which operates with limiter plasmas in AC mode, and whose pulse last about 100 ms. On the other side, JT-60SA is going to be the world's biggest superconductive tokamak in operation before ITER first plasma, and it is envisaged to run a 100 s long pulse in advanced tokamak regimes, with elongated unstable plasmas and high injected power.

When designing magnetic control algorithms for devices like JT-60SA, it is possible to rely on sophisticated model-based design approaches, such as the one proposed in this thesis. Thanks to this model-based techniques, it is possible to very good performance – as proved also in similar devices like EAST - by achieving a very tight control of the plasma boundary also in presence of major disturbances.

As far as model-based control design is concerned, ISTTOK represents a more challenging problem when compared to JT-60SA. Indeed, although the magnetic control problem is limited to the tracking of plasma current and the position of its centroid - being the ISTTOK plasma a limiter one - the AC operating mode is strongly nonlinear. In this context, it is not possible to derive reliable control-oriented models to be used for the design. However, in this thesis the candidate succeeded to develop a multi-input-multi-output (MIMO) plasma centroid controller, whose design is based on a black-box linear model that has been identified with data collected from dedicated experiments. The effectiveness of the proposed approach is proved in the thesis by a sufficient number of experiments.

DETAILED COMMENTS

The present version of the Corona's doctoral thesis is structured in six chapters.

After a concise but effective introduction to nuclear fusion and magnetic confinement in tokamak devices, the *first chapter* briefly elaborates on relevance of plasma control in a tokamak device and then and gives an overview of the thesis structure (in Section 1.3).

Chapter 2 gives an overview of some of the architectures that have been adopted in the world to deploy the so called Plasma Control System (PCS). This same chapter then focuses on the MARTe framework, being the real-time software infrastructure currently used at ISTTOK to implement the plasma control system. The chapter ends by recalling some basic concepts on the state-space representation of linear dynamical systems and feedback control, since these analysis and design tools will be exploited in the next chapters.

***Chapter 3* represents the main contribution of this thesis, as far as the magnetic control of JT-60SA is concerned.** In this chapter a model-based plasma shape controller whose design is based on the CREATE modelling tools is presented. The so-called eXtreme Shape Controller (XSC) approach has been followed to design a multi-input-multi-output (MIMO) plasma shape controller that feedbacks either the poloidal flux at the control points or the gaps. The performance of the proposed controller are assessed against a set of *canonical* disturbances, defined in terms of variation of internal inductance and poloidal beta. Moreover, the CREATE modelling tools have been used also to benchmark the performance of the control approach proposed by the JT-60SA home team. The main conclusion is that the XSC approach assures a better control in terms of least-mean-square error on the plasma boundary control, when compared with standard approaches based on a set of single-input-single-output (SISO) loops.

***Chapters 4* and *5* deal with the control of the plasma centroid position in the ISTTOK tokamak. They can be considered as the major contribution of this thesis.** Indeed, the overall control design cycle, from the definition of the reconstruction algorithms, to the real-time implementation of the controllers, passing through the identification of a plant model, have been presented, as well as relevant experimental results (some of which have been also included in Appendix A).

Conclusive remarks are given in *Chapter 6*.

SUGGESTIONS

The following comments are aimed at suggesting some minor changes that may further improve the already good quality of Mrs. Corona's doctoral thesis.

1. As a general suggestion, I strongly invite the candidate to add a small paragraph at the beginning of each chapter to briefly summarize the content of the chapter itself. This would improve the overall readability of the thesis.
2. At pg. xxvii, I would use "Input vector" and "Output vector" rather than "Inputs vector" and "Outputs vector".
3. In Chapter 1, before discussing in detail the outline of the thesis, a small section that summarizes the main contributions of this doctoral work should be added.
4. At the beginning of pg. 3 "…DC magnetic field \bar{B} can penetrate and it is this…" rather than "…DC magnetic fields \bar{B} can penetrate and it is these…".
5. At beginning of pg. 6 "Shafranov equation ([2, Chapter 6],…", please remove the space between "(" and "[2, chapter 6]"
6. The contents included in Chapter 2 is for sure useful but includes rather different things which are all somehow related to plasma control. There is some technological content mainly related to the deployment of plasma control in real-time systems (i.e., the overview of PCS architectures currently adopted in the fusion community, and the detailed discussion of the MARTe framework), as well as some methodological contents, which are more related to the design of control algorithms. I do not see a big problem in putting all the above mentioned content in the same chapter; however I would strongly suggest the candidate to make clear what are the different aspects that are tackled in this chapter, by adding an introductory paragraph at the beginning of the chapter itself (see also my comment #1). Moreover, although the chapter is titled "Plasma magnetic control", the contents of the chapter (architecture, real-time frameworks, control design techniques, etc.) apply in general to any plasma control problem. Hence, I would consider to rename the paper simply as "Plasma control"
7. Again in Chapter 2, in the brief overview of the PCS systems, other than the General Atomics PCS and the TCV system, I would also mention the IPP DCS , since it is used both at ASDEX and at WEST. See also

   Treutterer, W., et al. "ASDEX Upgrade Discharge Control System—A real-time plasma control framework." Fusion Engineering and Design 89.3 (2014): 146-154.

8. At pg. 14 in Chapter 2, when mentioning the Multiplatform C++ library, also the following reference can be given, since it deals with

   De Tommasi, G., et al. "A flexible software for real-time control in nuclear fusion experiments." Control Engineering Practice 14.11 (2006): 1387-1393.

9. At the bottom of pg. 36, "Start of Heating(SOH)" and "End of Cooling(EOC)" there is a missing blank space between "Heating" and "SOH" and between "Cooling" and "(EOC)".

10. At pg. 38, "At JET, the XSC recently enabled the control of high triangularity…", I would remove "recently", since the XSC was deployed at JET in 2003, and I would cite [62] in this context (since it contains the latest results achieved with XSC at JET. Moreover, I would also mention that the XSC approach has been deployed on the EAST superconductive machine; a recent publication that shows the results achieved at EAST is

    Ambrosino, R., et al. "Model-based MIMO isoflux plasma shape control at the EAST tokamak: experimental results." 2020 IEEE Conference on Control Technology and Applications (CCTA). IEEE, 2020.

11. In Chapter 3, the candidate is strongly invited to conclude the chapter itself with some conclusive remarks (also by anticipating some of those given in Chapter 6), since this chapter is the only one that deals with JT-60SA.
12. In Chapter 4, at pg. 72, I would rename section 4.6 as "Reconstruction algorithm for the plasma centroid position".
13. Similarly to what suggested for Chapter 3, also at the end of Chapter 5, I would anticipate some of the conclusions related to the proposed controllers.
14. At pg. 99, the details of most of the publications have some typographical typos, like missing spaces after ','. Moreover, "Fusion4Energy" should be "Fusion for Energy".

OPINION

The work presented by the candidate in her doctoral thesis focuses on magnetic control in tokamak devices. **It is a strong opinion of this reporter that this work can be considered as a relevant research work in the field of real-time implementation of model-based control systems**. This opinion of this reporter is mainly based on the work related to the control of ISTTOK. Indeed, this tokamak operates in AC mode, which is a strongly nonlinear operating regime. In this context, the control approaches typically adopted are mainly based on a mix of feedforward recipes and empirical tuning of simple proportional-integral-derivative controllers (PIDs), put in place by experienced operators. In her work, the candidate proved that it is possible to follow a model-based control design approach also in such a challenging environment. Obviously the tools adopted in this case are less sophisticated if compared to those one that can be applied in big tokamaks, like JT-60SA, where the operating regimes allow to base the control design on reliable dynamic models that descend from first physics principles.

Concerning the structure and the presentation, the current version of the Corona's doctoral thesis is well structured and well written, although the overall quality may benefit from some minor changes (see the given suggestions).

Based on the opinion summarized above, **the overall assessment of the doctoral thesis "Tokamak Magnetic Control Simulation: Applications for JT-60SA and ISTTOK Operation" by Lilia Doménica Corona Rivera is positive.**

CONCLUSION

The present version of the doctoral thesis "Tokamak Magnetic Control Simulation: Applications for JT-60SA and ISTTOK Operation" by Lilia Doménica Corona Rivera **would benefit from some minor changes. Once these changes are provided, the thesis should be accepted for public argument and discussion.**

Napoli, Italy, November 29th 2020

Prof. Gianmaria De Tommasi

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