Density Control in ITER: an Iterative Learning Control and Robust Control Approach

Timo Ravensbergen
Dutch Institute for Fundamental Energy Research

Peter C De Vries
ITER

Rémy Nouailletas
Atomic Energy and Alternative Energies Commission

Density Control in ITER: an Iterative Learning Control and Robust Control approach

T. Ravensbergen[1], P.C. de Vries[2], F. Felici[1] R. Nouailletas[3] T.C. Blanken[1] L. Zabeo[2]

[1] *Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*

[2] *ITER Organization, CS 90 046, 13067 St. Paul-lez-Durance, France*

[3] *CEA Cadarache, 13108 St. Paul-lez-Durance, France*

Introduction

ITERs larger size gives rise to multiple challenges, one of which is plasma density control. Density control is usually, in present day devices, achieved by well-tuned feedback control of gas valves [1]. However, in ITER, the response of gas valves might be too slow for feedback control. Firstly, because of the long time the gas has to travel from the valve to the plasma, and secondly, because of the limitations on the depth the gas can penetrate in the plasma before ionizing. Pellet injection is available as a second actuator, which directly fires pellets of frozen fuel into the plasma, which penetrate further. However, since these pellets are fast, they lead to localized density increases, and they may not yet be able to ablate in the early phase of the tokamak discharge. Also, the maximum achievable pellet frequency is limited by technology and reliability of the pellet launcher. Beside these two key actuators, other factors influence the density evolution, including the vacuum vessel pumps and the presence of the plasma facing components.

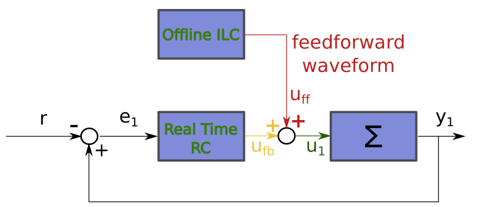

Figure 1: Controller architecture in the standard tracking loop format. A feedback controller and a feedforward controller, constructed using Robust control and ILC respectively, work together to achieve control performance.

The topic of this work[1] is to control the particle density in ITER despite the issues mentioned above. This controller must be able to deal with the large time scale separation in actuators (pellets and gas), fast transitions, changes in dynamics of the plasma during the plasma ramp-up, and complications in the modelling of plasma fuelling. Furthermore, two tight density limits need to be avoided during ramp-up, namely an indirect upper limit set by divertor detachment, and a lower limit to prevent NBI shine-through. These complications make simple linear feedback control not suitable for ITER: feedforward control is needed in addition to more advanced feedback control. A well-tuned feedforward controller is able to act effectively and is inherently non-causal, enabling corrections before they are needed, e.g. to inject gas in anticipation of a density change request. In present tokamaks, to achieve the needed performance, this feedforward control signal is the result of meticulous tuning. For ITER, this is not advisable because of the much higher cost of a single shot. We therefore propose to use Iterative Learning

[1]The views and opinions expressed in this work do not necessarily reflect those of the ITER Organization. FuseNet funding was obtained to make the work/internship possible.

Control (ILC), a control method whereby the time trajectory of the actuator input signals is modified from preceding experiments in such a way that the norm of the tracking error over the period of interest is reduced.

This can be achieved by using the result of one trial to design a feedforward signal for the next. The use of ILC in tokamaks was proposed in [2], including a first application. In ILC, actuator and operational constraints can be easily implemented, which is not the case for feedback control design. It is important to recognize, however, that even for two identically prepared tokamak discharges, each shot will be slightly different due to for example different wall conditioning. Pure feedforward based control cannot deal with these non-repetitive disturbances. Feedback control is therefore necessary to deal with the possible loss in reference tracking performance and can work together with any type of feedforward, including ILC. To guarantee stability and feedback control performance during the whole ramp-up, the advanced robust H_∞ synthesis technique is used to synthesize the feedback controller [3].

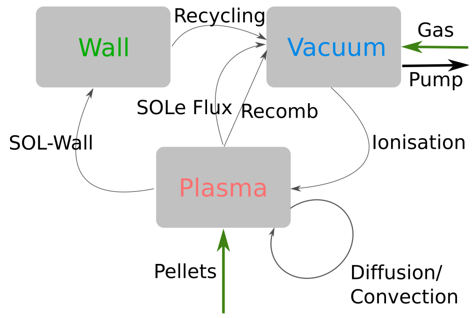

Figure 2: Considered particle fluxes in the three inventory model. The plasma is modelled in 1D, whereas vacuum and wall inventories are 0D. Pellet and Gas act as inputs to the system, the pumping as a sink.

With this technique, feedback controllers can be designed for systems with uncertainties. In Figure 1 the proposed controller architecture is visualized. The block indicated by Σ denotes the tokamak, r the reference signal of the average density, and y_1 the average density that is achieved. Here, we will apply this controller structure to simulations of the particle density evolution expected in ITER, and show that this control methodology is able to resolve the aforementioned problems. To test our controller, we use a control-oriented model of the plasma particle density evolution [4], which has been specially updated to include issues that govern the particle density evolution in ITER. This model is summarized in Figure 2. It contains three particle inventories, with simple, heuristic, descriptions for particle flows. Parameters can be tuned to obtain the density evolution expected for ITER. It is important to realize that the objective of this work is not to make quantitative statements about how the physics of the density evolution in ITER work and the possibility for control. The detachment limit is determined via a simple model for the SOL. All power that passes through the SOL is transported along the field lines in the direction of the divertor. An analytical two-point model can be used to relate the upstream edge density to the temperature on the divertor target as a function of the heat flux. Experiments have shown that when the plasma temperature at the

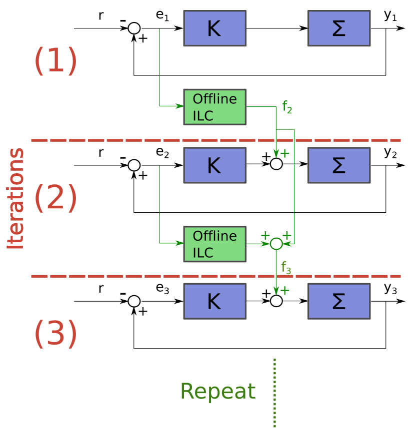

Figure 3: Schematic view of the principle of Iterative Learning Control. A new feedforward is calculated based on the tracking error of the previous trial [2].

target becomes smaller than 5 eV, the plasma will detach [5].

ILC approach

In Figure 3, the basic structure of an Iterative Learning Control scheme is visualized. In this Figure, a standard feedback interconnection of a plant Σ and controller K can be seen. The system Σ denotes the *true system*, i.e. the real tokamak, cf. Figure 1. Upon carrying out the first experimental trial, this results in an error signal $e_1(t)$ in the time domain. This error is smoothed off-line to discard oscillations in the error signal due to pellet injection. Then, a new feedforward signal for the next trial (2) is designed off-line based on this error. In this work, we will use so-called optimal ILC, where the change in each new feedforward signal is the optimizer of a (constrained) optimization problem. This approach enables natural incorporation of both actuator and density constraints in the determination of a new actuator input trajectory. The cost function in the optimization problem penalizes the use of pellets and gas, changes from their original trajectories, and of course the tracking error itself. Constraints incorporate the maximum pellet frequency and gas flow, the detachment limit, and 20 % of the Greenwald density to prevent NBI shine-through.

Results

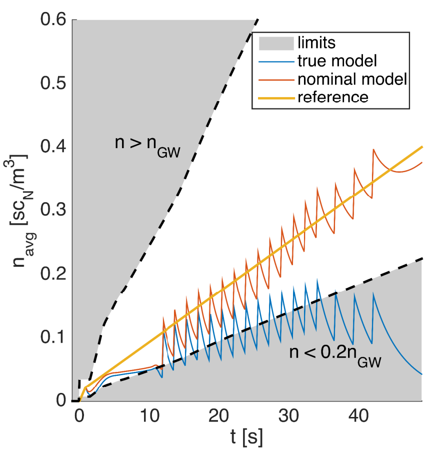

Figure 4: Starting point of the ILC simulations. Here, the model mismatch is such that the real system fuels less efficiently, resulting in a lower density for a given input compared to the model.

For simulations, two types of model mismatches are introduced: the model of the true system has both a fixed model mismatch, having different transport coefficients, and simulated shot to shot differences. The simulated shot-to-shot differences are significantly smaller than the constant nominal model mismatches, which is expected to be the case during real operation. For the first shot, a simple feedforward trace is chosen, resulting in reasonable tracking for the model. However, due to the model mismatches, the same trace results in poor tracking for the true system. This is indicated in Figure 4. Then, within 6 discharges, the norm of the tracking error is reduced by a factor ten, and no cases of convergence loss were observed due to the adaptive nature and overall robustness of the algorithm. According to these simulations, the density reference can be tracked even in the presence of the detachment fuelling limit and actuator constraints. The first five ramp-ups are solely ILC based, in order to relax the effort of the feedback controller. Then, 5 iterations using both controllers are performed. The resulting density evolution is plotted in Figure 5. Despite the shot-to-shot differences, tracking performance is greatly improved. For this simulation, convergence is not monotonic due to shot-to-shot differences. This is indicated in Figure 7. The changes in inputs that had to be made to achieve the increase in performance are indicated in Figure 6.

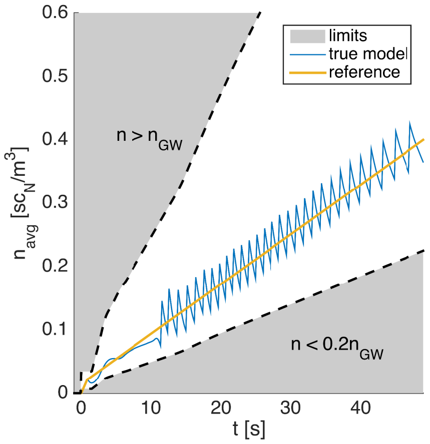

Figure 5: Performance of ILC and RC combined after 10 simulated shots including simulated shot-to-shot differences.

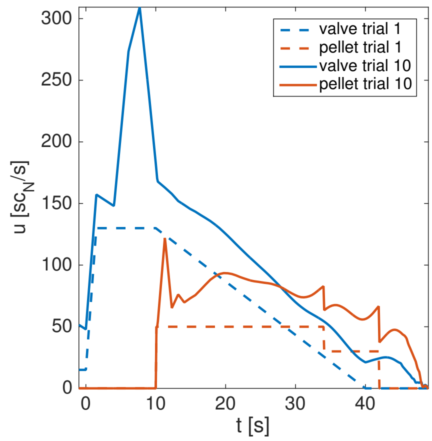

Figure 6: Optimal inputs as determined by the ILC algorithm.

Conclusions

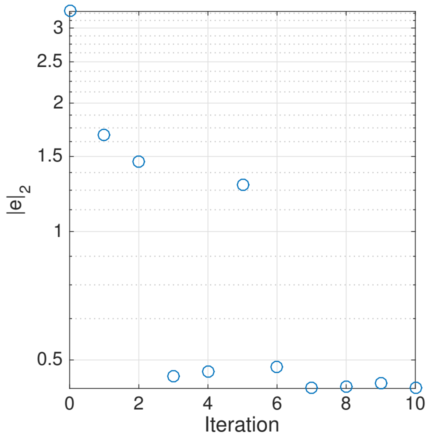

Figure 7: Error 2-norm convergence is not monotonic, because of the randomized shot-to-shot differences.

A control-oriented transport model for the plasma density evolution in ITER was used to design a combined feedback and feedforward control solution for density control during the ITER ramp-up. It has been shown that simple proportional feedback control lacks performance for the ITER ramp-up scenarios. ITER density control needs advanced controllers mainly because of two reasons. First, the delay of the gas valve is so large that feedback alone inherently fails to achieve enough performance after breakdown. Second, feedforward is, in theory, able to achieve this performance, but is difficult to tune for a new device like ITER. Therefore, a self-learning algorithm based on Iterative Learning Control (ILC) has been implemented. This technique has shown to resolve delay problems and achieve sufficient reference tracking for deterministic ramp-up scenarios. Unfortunately, on a real tokamak, not every ramp-up is the same. Therefore, a robustly stabilizing feedback controller has been developed that can deal with the disturbances due to small shot-to-shot differences. It has been shown that together with ILC, this robust controller can achieve convergence in the tracking error.

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