Actuator Management via Real-time Optimization for Integrated Control in Tokamaks

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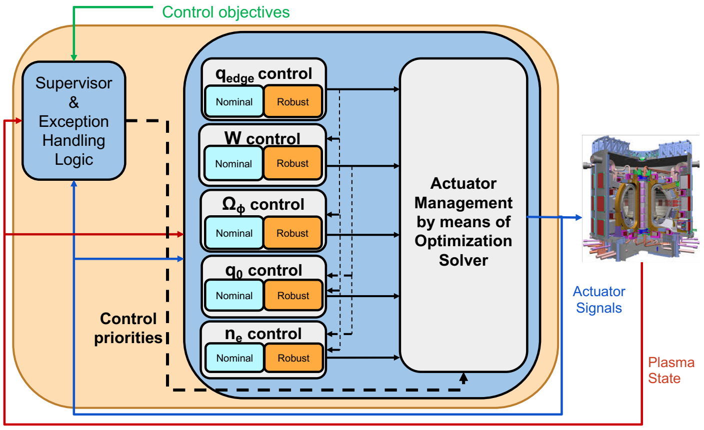

Figure 1: *Integrated control architecture combining controller, supervisor, and actuator manager within the PCS*

In ITER, only a limited number of actuators is available to carry out a great variety of control tasks, some of which may be closely coupled. Safe operation while attaining high plasma performance will require an integrated Plasma Control System (PCS) that has the capability of simultaneously regulating as many aspects of the plasma dynamics as possible. Moreover, such integrated PCS must include supervisory and actuator management systems. The goal of such systems is to determine and assign in real time the authority of each control task over the available actuation mechanisms depending on the plasma state. In this work, an integrated controller with actuator management capabilities is proposed for simultaneous control of the central safety factor, q_0, the edge safety factor, q_{edge}, the total stored energy, W, the bulk toroidal rotation, Ω_ϕ, and/or line-average electron density, $\bar{n}_e$. Figure 1 shows a simplified schematic of a possible PCS architecture in which the integrated controller proposed in this work could be embedded. The integrated controller is based on zero-dimensional, control-level models of the plasma dynamics, and is synthesized using nonlinear, robust Lyapunov techniques to ensure high performance despite nonlinear, unknown plasma dynamics. The actuator management algorithm employs the time-varying, plasma-state-dependent control priorities to decide which actuators are utilized for each control task. The actuator management problem is solved as a real-time optimization problem, providing substantial flexibility to include changing control objectives in the form of time-varying constraints. Also, this scheme allows for performing the two main kinds of actuator sharing envisioned for ITER: Simultaneous Multiple Mission (SMM) sharing and Repurposing (RP) sharing [1]. The proposed control algorithm is tested in one-dimensional simulations using the Control Oriented Transport SIMulator (COTSIM) code.

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Introduction

In ITER, only a limited number of actuators will be available to carry out a great variety of control tasks, some of which may be closely coupled. Safe operation while attaining high plasma performance will require an integrated Plasma Control System (PCS) with the capability of simultaneously regulating as many aspects of the plasma dynamics as possible. Moreover, such integrated PCS must include supervisory and actuator management systems. The goal of such systems is to determine and assign in real time (i.e., depending on the plasma state) the authority of each controller (or control task) over the available actuators.

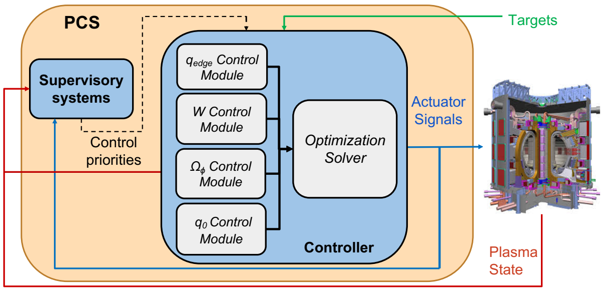

Figure 1: *Integrated PCS architecture combining controller, supervisor, and actuator manager.*

Recently, there has been a significant increase in the amount of research carried out on multivariable control and integrated PCS designs [1]-[8]. In this work, an integrated controller with actuator management capabilities is proposed for simultaneous control of the central safety factor, q_0, edge safety factor, q_{edge} (or, alternatively, q_{95} for diverted plasmas), total plasma stored energy, W, and average ion toroidal-rotation frequency, Ω_ϕ. The control laws for these individual scalars are presented in our previous work [8]. The actuator management problem is solved as a real-time optimization problem, providing substantial flexibility to include changing control objectives in the form of time-varying constraints. Fig. 1 shows a possible controller's integration with the actuator manager in a PCS.

Controller and Actuator Management Design

Four individual controllers for q_0, q_{edge}, W, and Ω_ϕ are designed using zero-dimensional, physics-based, control-oriented models derived from the magnetic diffusion equation, ion and electron heat transport equations, and ion toroidal momentum transport equation [8],

$$\dot{q}_0 = q_0\lambda_\eta u_\eta + q_0^2\Big(\sum_i \lambda_{NBI,i}u_{NBI,i} + \lambda_{EC}u_{EC}\Big) + q_0^3\lambda_{BS}u_{BS} + \delta_{q_0},\ \dot{q}_{edge} = k_{I_p}\frac{dI_p}{dt} + \delta_{q_{edge}}, \quad (1)$$

$$\dot{\Omega}_\phi = -\frac{\Omega_\phi}{k_{\Omega_\phi}\tau_E} + \frac{1}{m_p R_0^2}\Big(\sum_i k_{NBI,i}P_{NBI,i} + k_{int}\frac{W}{I_p} + \delta_{\Omega_\phi}\Big),\ \dot{W} = -\frac{W}{\tau_E} + P_{NBI,i} + P_{EC} + \delta_W, \quad (2)$$

where I_p, $P_{NBI,i}$, and P_{EC}, which are the plasma current, the i-th NBI power, and the EC power, respectively, are the controllable inputs. The terms $u_{(\cdot)}$ are normally referred to as virtual inputs because they are nonlinear functions of the controllable inputs. The constants $\lambda_{(\cdot)}$ and $k_{(\cdot)}$ are model parameters, τ_E is the energy confinement time, m_p is the total plasma mass, R_0 is the tokamak major radius, and $\delta_{(\cdot)}$ model the unknown/uncertain dynamics neglected in the control-oriented models. In order to handle the model uncertainties $\delta_{(\cdot)}$, Lyapunov redesign control techniques are employed [8]. Each controller produces one constraint: the q_{edge} controller creates a plasma current request, I_p^{req}, the W controller creates a total power request, P_{tot}^{req}, the Ω_ϕ controller creates a total NBI torque request, T_{NBI}^{req}, and the q_0 controller creates a request for the auxiliary-driven current, j_{aux}^{req}.

The actuator management strategy proposed in this work is based on solving an optimization problem in real time. At every time step, a cost function of the controllable inputs, J, is minimized while satisfying the four time-varying constraints imposed by the individual controllers. Physical saturation limits are also imposed by forcing the controllable inputs to be within the set of feasible inputs, denoted by $\mathscr{U}$. The optimization problem can be modified by a supervisory system by overriding and/or removing some of the control laws and/or adding additional constraints. Mathematically, the problem is written as,

$$\min_{I_p, P_{NBI,i}, P_{EC}} \ J \tag{3}$$

$$I_p^{req} = I_p, \qquad \text{(if the } q_{edge} \text{ controller is activated)} \tag{4}$$

$$P_{tot}^{req} = \sum_i P_{NBI,i} + P_{EC}, \qquad \text{(if the } W \text{ controller is activated)} \tag{5}$$

$$T_{NBI}^{req} = \sum_i k_{NBI,i} P_{NBI,i}, \qquad \text{(if the } \Omega_\phi \text{ controller is activated)} \tag{6}$$

$$j_{aux}^{req} = q_0^2 \big(\sum_i \lambda_{NBI,i} u_{NBI,i} + \lambda_{EC} u_{EC} \big), \qquad \text{(if the } q_0 \text{ controller is activated)} \tag{7}$$

$$I_p, P_{NBI,i}, P_{EC} \in \mathscr{U} \ + \ \text{Additional constraints from supervisory system} \tag{8}$$

An example of possible additional constraints and problem modification is as follows. Assume that the supervisory system detects a plasma state such that neoclassical tearing modes (NTMs) are close to be triggered, and it is determined that the total power $\sum_i P_{NBI,i} + P_{EC}$ must be reduced to avoid the onset of the mode. Then, the supervisory system must override the W controller request by setting a different P_{tot}^{req}. In addition, if the NTM actually develops, the available P_{EC} for W control must be modified to allocate some P_{EC} for mode suppression. Other options would be decreasing I_p^{req} in (4) to increase the whole q profile, or setting $P_{NBI,i} \equiv 0$ for the i-th NBI to reduce the total available power.

The nature of the optimization problem is determined by the choice of both the function J and the imposed constraints. If constraints on I_p and $\sum_i P_{NBI,i} + P_{EC}$ are imposed like in (4) and (5), $u_{NBI,i}$ and u_{EC} are linear functions of $P_{NBI,i}$ and P_{EC} (see [8]). In this case, all the constraints (4)-(7) are linear with respect to the controllable inputs and the optimization problem (3)-(8) becomes a linear or quadratic program if the cost function J is chosen linear or quadratic, respectively, assuming that the additional constraints in (8) are also linear in I_p, $P_{NBI,i}$, and P_{EC} (as found, for instance, in the example given in the previous paragraph). The theoretical and computational complexity of such problems is significantly lower than if nonlinear constraints or cost functions were considered. However, it is not guaranteed that a feasible solution within $\mathscr{U}$ can be found for any arbitrary control (I_p^{req}, P_{tot}^{req}, T_{NBI}^{req}, j_{aux}^{req}) and additional supervisory-system constraints. In this case, the constraints may need to be relaxed to make the problem feasible.

Simulation Study

The proposed control algorithm is tested in one-dimensional simulations using the Control Oriented Transport SIMulator (COTSIM). The simulation scenario corresponds to DIII-D shot 147634, in which 8 NBIs are available. In order demonstrate the controller's capability to perform actuator management, the following constraints are imposed: the 2nd NBI is constrained for MSE measurements during the whole shot ($P_{NBI,2} = 1$ MW), the 4th NBI is turned off ($P_{NBI,4} = 0$) between $t = 1$s and $t = 2$s, and a gyrotron is assumed lost ($P_{EC,1} = 0$) after $t = 5$s. The target for q_{edge} is taken as $\bar{q}_{edge} = q_{edge}^{exp} - 0.2$, where q_{edge}^{exp} is the evolution during shot 147634. The targets for q_0, W, and Ω_ϕ correspond to the experimental values from shot 147634.

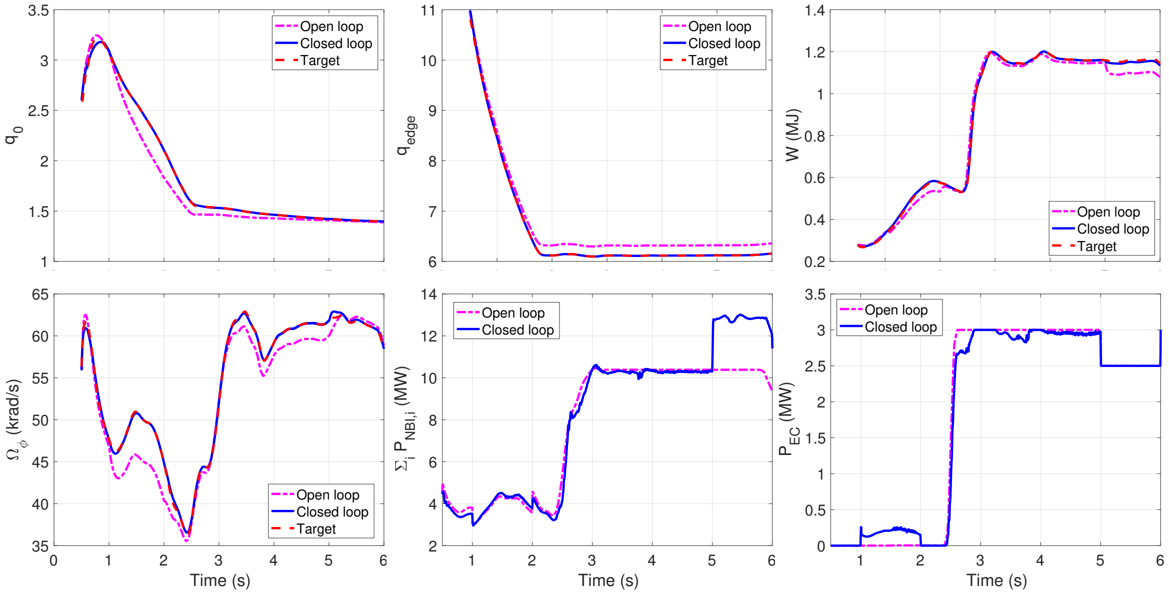

Figure 2: *Time evolution of the individual scalars, q_0, q_{edge}, W, and Ω_ϕ, together with the controllable inputs $\sum_i P_{NBI,i}$ and P_{EC}, in open loop and closed loop simulations, and their corresponding targets.*

Fig. 2 shows the time evolution of the individual scalars and controllable inputs in open loop (i.e., experimental inputs from shot 147634 constrained as explained in the previous paragraph) and closed loop (i.e., feedback control activated), together with the targets. In open loop, the system evolves to values that are substantially different from the target, as expected from using the constrained inputs. In closed loop, the individual scalars are driven to their targets despite the aforementioned constraints. The controller increases P_{EC} between $t = 1$s and $t = 2$s (to compensate for $P_{NBI,4} = 0$), and also increases $\sum_i P_{NBI}$ after $t = 5$s (to compensate for $P_{EC} = 0$).

Summary and Future Work

The individual-scalar controllers plus the actuator manager scheme proposed in this work has the capability of reproducing the experimental evolution of the individual scalars while handling input constraints in simulations. This control capability can be implemented in integrated PCS designs like the one envisioned for ITER and can play a critical role in tokamak-scenario planning and development. Future work includes experimental testing in the DIII-D tokamak.

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