Nonlinear Burn Control of ITER's Two-temperature Plasmas Using Optimal and Adaptive Allocation of Actuators with Uncertain Dynamics

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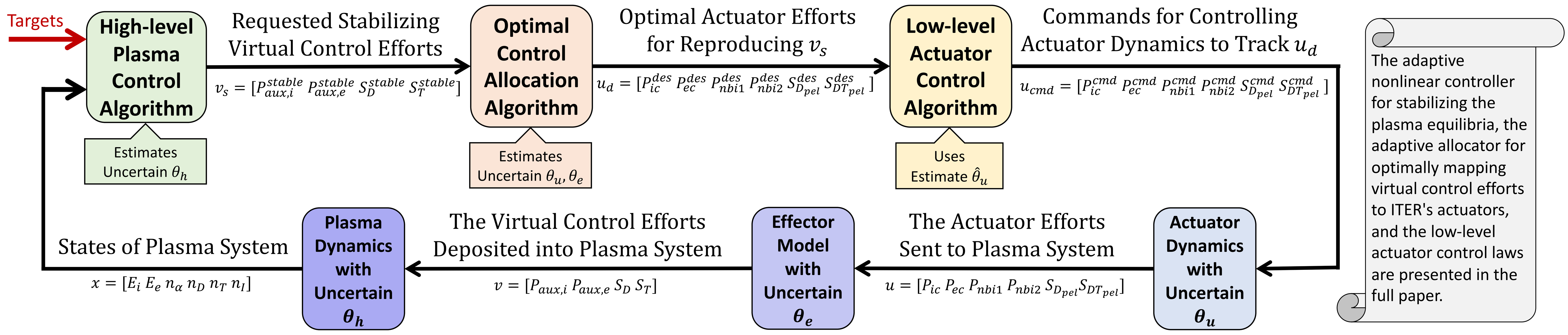
Background on Nonlinear Burn Control in ITER with Actuator Allocation

The operation of ITER will require robust regulation of the plasma temperature and density. Using Lyapunov techniques, a nonlinear controller was synthesized from a two-temperature model that contains uncertainty in the fraction of alpha-particle power deposited into the plasma ions and other complex phenomena. The controller determines virtual control efforts (plasma heating and fueling) that will drive the plasma to desired targets. An adaptive control allocator optimally maps these virtual control efforts to ITER's actuators (e.g., neutral beam injectors and pellet injectors) despite uncertainty in the actuator efficiencies, the fraction of neutral beam heating deposited into the plasma ions, and the tritium concentrations of the fueling pellets. Furthermore, the allocator considers uncertain actuator dynamics (specifically actuation lags).

Block Diagram of Closed-Loop System with Control and Allocation Algorithms



- The burning plasma dynamics consists of six (measured) states: the ion energy E_i, the electron energy E_e, the alpha-particle density n_α, the deuterium density n_D, the tritium density n_T, and the impurity density n_I. Uncertain parameters for the alpha-particle ion-heating fraction, the wall deuterium-tritium recycling, the impurity sputtering and the plasma confinement quality are lumped into θ_h.
- The high-level burn controller determines the virtual control efforts that will stabilize the target equilibrium of the nonlinear plasma system. The four virtual control efforts are the auxiliary ion heating $P_{aux,i}$, the auxiliary electron heating $P_{aux,e}$, the deuterium fueling S_D, and the tritium fueling S_T. Adaptive laws provide estimate $\hat{\theta}_h$ to handle uncertainty in the plasma conditions.
- The optimal control allocator receives the requested stabilizing virtual control efforts v_s from the high-level burn controller. Using dynamic update laws, it determines the optimal actuator efforts u_d for reproducing v_s. The six actuator efforts u are the heating from the ion cyclotron actuator P_{ic}, the heating from the electron cyclotron actuator P_{ec}, the heating from the two neutral beam injection actuators P_{nbi1} and P_{nbi2}, the fueling from the deuterium pellet injection actuator $S_{D_{pel}}$, and the fueling from the deuterium-tritium pellet injection actuator $S_{DT_{pel}}$.
- The low-level actuator controller receives the optimal actuator efforts u_d from the allocator. It determines what commands u_{cmd} should be sent to the actuators in order to track u_d despite the actuator dynamics. The actuator dynamics include lags in the actuation and uncertain parameters θ_u. These dynamic equations output the actual actuator efforts u that are translated back into virtual control efforts v through an effector model. These heating and fueling efforts v are deposited into the plasma system. The effector model contains uncertainty θ_e in the actuator efficiencies, the neutral beam ion-heating fraction, and the tritium concentration of the fueling pellets. The adaptive allocator generates estimates $\hat{\theta}_e$ and $\hat{\theta}_u$ to handle the aforementioned uncertainty. The goal of the allocator is to minimize $|v - v_s|$.

Plasma Dynamics

Energy E and density n response equations:

$$\dot{E}_j = -\frac{E_j}{\tau_j} + \sum P_j + P_{aux,j}$$
$$\dot{n}_j = -\frac{n_j}{\tau_j} + \sum S_j + S_{ext,j}$$

- Energy and particle confinement times τ_j
- $\sum P_j$ & $\sum S_j$ are sources/sinks such as radiation P_{rad} and deuterium recycling S_D^R
- $P_{aux,j}$ & $S_{ext,j}$ are virtual control efforts v
- Adaptive control laws for v_s and $\hat{\theta}_h$ stabilize the nonlinear plasma dynamics

Effector Model

Static mapping between virtual control efforts v & the efforts produced by actuators u:

$$P_{aux,j} = \Phi_j(P_{ic}, P_{ec}, P_{nbi1}, P_{nbi2}, \theta_{e,j})$$
$$S_{ext,j} = \Phi_j(S_{D_{pel}}, S_{DT_{pel}}, \theta_{e,j})$$

- Auxiliary ion $P_{aux,i}$ & electron $P_{aux,e}$ heating maps to P_{ic}, P_{ec}, P_{nbi1}, P_{nbi2} actuators
- External deuterium S_D & tritium S_T fueling maps to $S_{D_{pel}}$ & $S_{DT_{pel}}$ actuators
- Adaptive control allocator determines the optimal u (denoted u_d) for generating v_s

Actuator Dynamics

First-order actuation lag equations:

$$T_{lag}\dot{u} + u = u_{cmd}$$
$$T_{lag} = \text{diag}(\tau_{ic}^{lag}, \tau_{ec}^{lag}, \tau_{nbi}^{lag}, \tau_{nbi}^{lag}, \tau_{pel}^{lag}, \tau_{pel}^{lag})$$

- An example: lag can result from the thermalization delay of neutral beam particles
- The uncertain time constants T_{lag} are put into θ_u vector which the allocator estimates
- Low-level control laws u_{cmd} track the desired u_d received from the allocator

Simulation Study to Illustrate Performance of Controller and Allocator

Despite the model uncertainty and actuation lag, the burn control and control allocation algorithms successfully drive the plasma conditions to the desired reference values using ITER's various heating and fueling actuators. Note that the plots for the stabilization of the plasma density and the pellet injection can be found in the full paper.