Control of Advanced Divertors in NSTX-U and ITER

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Motivation
- Reduce heat flux to the diverters in NSTX-U and ITER
  - Snowflake — secondary x-point placed next to primary x-point.
  - X-divertor — secondary x-point placed near outer strike point.
- Snowflake is possible on NSTX-U [1], but core currents are too high for ITER [2].
- X-divertor is possible on ITER [3], but no studies on how to achieve transition.

Method
- Maintain shape via biicflow method (minimizes flux error between plasma boundary and control points).
- Use reference tracking on the x-point positions.
- NSTX-U — Linear Quadratic Integral (LQI) with set point tracking on the x-point positions. Use proportional control to maintain plasma shape.
- ITER — Model Predictive Control (MPC)

Dynamics Model
The vacuum vessel elements, poloidal field (PF) coils, and plasma are treated as toroidally looped circuits:

\[ v_i = R_i I_i + \Psi_i, \quad \text{poloidal} \]

\[ \frac{d}{dt} I_i = \frac{\Delta I_i}{\Delta t} \]

Flux change due to induced currents. Flux change due to plasma motion. Computed via linearization to Grad-Shafranov equation [3].

Output Model
Control plasma current, x-point positions, strike point positions, and shape.

\[ Z = \begin{bmatrix} I_p & r_s & X & Y & \phi_r & \phi_p \end{bmatrix}^T \]

Write the output equation in the linearized frame (to match dynamics).

\[ \dot{Z} = (A + B_i\theta_i)v_i \]

Final feedback law:

\[ u = -K_p(x - f_c) + f_r + \int (u - r) dt \]

ITER MPC Constraints
- Constrained variables include the coil currents, applied coil voltages, power characteristics, and shape.
- Constraints written in the linearized reference frame, in terms of the optimization variable \( \theta \).

ITER Control
Control strategy: coil current limits and output constraints are a concern. Use Model Predictive Control (MPC) with target tracking.

Cost function minimization simplifies to:

\[ \min \left[ \frac{1}{2} \sum_{i=1}^{n} (r_{i+1} - x_{i+1}^c)^T \right] \]

ITER Results
- A time-variant plasma model coupled with LQI control can create the snowflake divertor and gives good tracking error (≤1cm).

Future Work
- Identify the time-variant plasma models present in the NSTX-U ramp-up phase, so that shape control can be implemented during ramp-up (allows for more consistent entry into H-mode).
- Implement series connection on ITER CS1U/L, and identify when conditions the x-divertor can still be created.

References