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Control and machine learning algorithms for disruption avoidance and proximity control

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Achieving acceptably low disruptivity on ITER and future reactors will require active monitoring and control of the proximity of operating points to unsafe regions. Although mitigation strategies can protect the infrastructure from disruptions and engineering limits, maximizing scientific or economic output of a device demands avoiding triggering mitigation systems while optimizing performance. Model-based control combined with system identification, AI/ML, and other data science techniques offers a potential solution to this problem. Model Predictive Control (MPC) strategies use dynamic models to repeatedly plan actuator trajectories over a finite horizon in real time, enabling optimization of operating points within actuator and state constraints. Two main challenges to applying these techniques to tokamak control and disruption avoidance are the need for suitably fast and accurate models, and selection of appropriate constraints. Novel algorithms have recently been developed to address these issues, enabling (1) accelerated, real-time forecasting of plasma behavior and (2) identification of the local safe operating region. These new tools, coupled with model predictive control techniques, will enable real-time optimization of tokamak operating points within a set of constraints approximating the safe operating region.
Accelerated modeling: Surrogate modeling approaches are used to identify fast, local (to the distribution of training data) approximations of physics models. This technique has been used to develop accelerated approximations of actuator models (e.g., NUBEAM), free boundary equilibrium solutions, and predictive integrated modeling simulations (e.g., TRANSP). Where physics models are lacking, the same modeling techniques can be applied to empirical data. Combining these approaches enables physics-informed modeling that can learn from empirical data to improve predictions, while maintaining real-time-relevant execution times.
Identification of constraints: The proposed safe operating region identification algorithm enables use of state-of-the-art disruption prediction models as tools for active disruption avoidance. A GPU implementation enables rapid (~10ms) evaluation of the disruption prediction model at many points in a region around the local operating point, followed by identification of a set of convex linear constraints bounding the local safe operating region. The identified constraints are in a form that enables calculation of the proximity to disruption boundaries (in terms of controllable physical quantities) and can be used within fast model predictive control algorithms.
Simulations and experiments: Closed loop TRANSP simulations have been used to test constrained model predictive control strategies. For example, simultaneous control of stored energy, internal inductance, and loop voltage while actively avoiding vertical stability limits has been simulated for KSTAR. Initial progress toward experimental implementation of the proposed methods on DIII-D will be discussed. Demonstration of these approaches is expected to inform development of control strategies for ITER and future burning plasma experiments.

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