TOWARDS DUAL PLASMA EQUILIBRIUM AND TRANSPORT SCENARIO PLANNING FOR TOKAMAKS USING COTSIM

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Effective scenario planning is essential for optimizing plasma transport and equilibrium, ensuring stable operation of next-generation fusion devices such as ITER and future FPPs in high-energy regimes. This work advances scenario planning by introducing a fully integrated dual transport and equilibrium optimization framework, unlike previous approaches that have decoupled transport and equilibrium or relied on iterative pseudo-coupling. The optimizer leverages the predictive capability of the Control-Oriented Transport SIMulator (COTSIM), a modular 1.5D transport and equilibrium code that combines physics-based models with neural-network surrogates. A systematic evaluation of different equilibrium models as well as various coupling strategies between the optimizer and simulator is conducted to improve computational efficiency and accuracy. Additionally, several optimization techniques including reinforcement learning, evolutionary algorithms, and global sequential quadratic programming are benchmarked to identify the most effective method for navigating the non-convex solution space. The framework is validated on an NSTX-U scenario, demonstrating its capability to achieve target plasma states with enhanced precision and computational efficiency.

As next-generation tokamaks advance into higher-energy plasma regimes, there is a greater likelihood that disruptions will cause significant damage to the machine. Therefore, these devices must operate with minimal disruption risk. This increases the need for tools that can explore possible plasma configurations without risking the machine. One such tool is scenario planners, which couple an algorithmic optimization scheme to a plasma simulation code. Since deviations between the simulation model and the experiment reduce the usefulness of the arrived upon solution, there is a desire to use the most advanced plasma simulation codes as possible. However, since optimization methods require many plasma simulations, often the calculation times of these simulation codes make their incorporation into scenario planning impractical. Consequently, scenario planners choose codes that have suitable tradeoffs in terms of accuracy and speed. COTSIM's modular design and its integration of neural-network surrogate models [1], [2] help computation times remain low, keeping optimizations tractable even with large numbers of parameters. Previous work such as [3] and [4] established that COTSIM could be used to determine the optimal actuator power trajectories for reaching specific target regimes. Notably, the plasma equilibrium was held fixed during most of these transport optimizations. Since equilibrium and transport are strongly coupled, fixing the equilibrium inherently limits the parameter space explored when attempting to reach advanced tokamak scenarios, potentially reducing the optimizer's effectiveness.

This work builds off previous efforts by simultaneously optimizing the plasma shape, allowing the scenario planner more flexibility when attempting to reach target plasma regimes. The work detailed in [5] used a pseudo-coupled approach, which optimized transport and equilibrium separately and iteratively passed variables between them until the process converged on a self-consistent solution. The method presented here streamlines the process by performing a singular dual transport and equilibrium optimization that simulates the plasma behavior using COTSIM with a time-varying equilibrium. Figure 1 shows the general workflow for the scenario planner. An initial guess of input parameters, representing reduced-dimensional versions of the time-varying actuator trajectories, is provided to COTSIM to predict the resulting plasma scenario. The actual (simulated) plasma state is then mathematically compared to the target plasma state via a user-defined cost function. An optimization code updates the input parameters while trying to minimize this cost function, and the process repeats until an end condition is met. Partially enabled by COTSIM's modular design, different equilibrium models and coupling methods are explored to determine tradeoffs in eventual solution and computation speed. COTSIM has several analytical fixed-boundary equilibrium solvers, including those based on the methods in [6] and [7], as well as a numerical, free-boundary solver, [8]. The free-boundary solver can run both in direct mode (calculating the plasma boundary from a given combination of poloidal field (PF) coil currents), or in indirect mode (calculating the PF coil currents that produce a given plasma boundary). First, optimizations are conducted using fixed boundary solvers, which consider the plasma boundary parameters as inputs. However, these optimizations do not determine how to achieve the desired plasma boundary using the PF coils. Therefore, optimizations are next performed using a free-boundary solver, with the goal of determining suitable PF coil currents. Since only certain combinations of PF coil currents yield viable plasma configurations, the optimizer could potentially choose a non-viable configuration while exploring the parameter space. In anticipation of this, the optimizer explores different couplings with the free-boundary solver, running optimizations with the solver operating in direct and indirect mode. Each method is assessed on their efficiency and arrived upon objective.

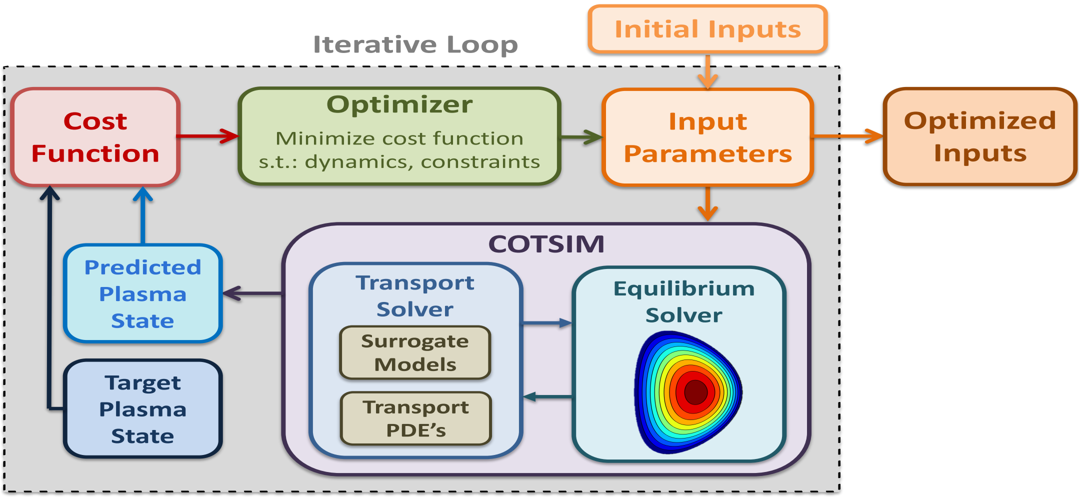

Figure 1: Workflow schematic demonstrating how the scenario planner is coupled with COTSIM.

Figure 2 shows initial optimization results for an NSTX-U scenario. For this optimization, COTSIM predicts the anomalous diffusivities and neutral beam injection depositions using the embedded neural-network surrogate models and evolves the equilibrium via an analytical solver. The to-be-optimized input parameters are the plasma boundary shape, the power of several neutral beam injectors, and the plasma current. The target state is characterized by normalized beta, noninductive current fraction, and plasma volume. To demonstrate that the optimizer could find the global minimum in the parameter space, the target was designed to be achievable. Global sequential quadratic programming was chosen as the optimization method. The scenario planner successfully recreates the target scenario, with only minimal mismatch between the optimizer and the target.

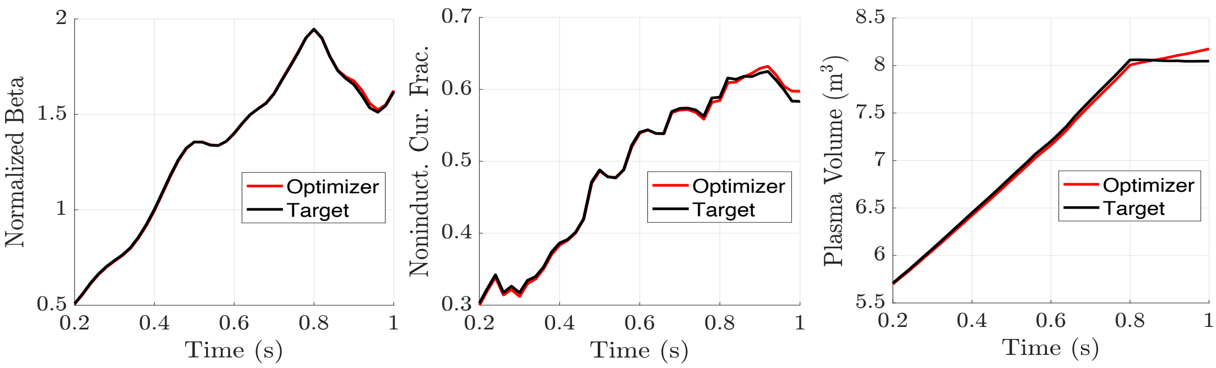

Fig. 2: Comparisons between the target values and the optimized values for the dual equilibrium-transport scenario planner.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Science, under Award DE-SC0021385 and the Office of Science Graduate Student Research (SCGSR) Program.

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