Development of a Deep Learning-Based Grad-Shafranov Equation Solver and Verification Using Explainable Artificial Intelligence

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Nuclear fusion energy is emerging as a next-generation energy source. As a clean form of energy, it holds the potential to solve energy-related problems. However, maintaining plasma equilibrium in a tokamak remains a key challenge for securing the performance and stability of nuclear fusion. Theoretically, this equilibrium is described by the Grad-Shafranov (GS) equation, which usually takes a long time to solve. However, for real-time plasma control, it is essential to determine the plasma state within the tokamak rapidly. Therefore, recent studies have utilized deep learning to solve this equation quickly and apply it to real-time control. However, only the mean squared error on the magnetic flux is often used in the loss function, leading to inappropriate angular deviations in the results. To address this, this study proposes a method that adds a weighted mean squared error term on the GS equation to the loss function, reducing angular deviations and yielding more accurate results. As a result, this method showed results that were approximately 4.07 times more accurate compared to previous approaches, and the computation time remained similar to that of existing AI-based solvers. Additionally, this study proposes a method to verify the prediction validity of the AI-based GS equation solver using the SHAP analysis among XAI techniques. This approach confirmed that the prediction process of the developed model aligns with physical theory and trends of actual tokamak operation. The method is also expected to be applicable to other AI-based GS equation solvers in the future.

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