DEVELOPMENT OF DATA ASSIMILATION SYSTEM ASTI TOWARD DIGITAL TWIN CONTROL OF FUSION PLASMA

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We develop a model predictive control system for fusion plasmas based on data assimilation (DA), which integrates predictive model (digital twin) adaptation using real-time measurements and control estimation robust to model and observation uncertainties. The core part of the control system, ASTI (Assimilation System for Toroidal plasma Integrated simulation), predicts the probability distribution of future plasma states and estimates both the optimal control input and the actual plasma state based on Bayes' theorem. In this study, the ASTI-centered control system was implemented in the Large Helical Device (LHD) and successfully applied to control the plasma temperature and density. The control experiments demonstrate the effectiveness of the DA-based approach, which enables the synergistic interaction of measurement, heating, fueling, and simulation. This approach provides a flexible platform for digital twin control of future fusion reactors.

INTRODUCTION The operation of future fusion reactors requires nonlinear and multivariate control of fusion plasma behavior under conditions of limited measurement. However, a predictive model (digital twin) essential for such complex control generally involves large uncertainties because it is inherently difficult to model all the components affecting the plasma behavior and their interactions with sufficient accuracy. To address this challenge, we are developing an analysis and control system, ASTI, based on a DA framework that integrates model adaptation and control estimation [1]. Typical DA is a statistical method to estimate the state vector, which consists of the variables in a numerical model, based on observation data and can make the behavior of the model similar to that of the real system. In addition to the state estimation, our DA framework includes the estimation of control input that leads the system state to the target state, which allows ASTI to achieve adaptive predictive control. The effectiveness of this control approach was demonstrated through a simple control experiment in LHD [2]. ASTI approximates the probability distribution of the state vector with a number of ensemble members (simulations with slightly different conditions) to realize its time evolution and the DA computation. ASTI can control both observable and unobservable variables and can be applied to complex control with multiple variables. In recent years, while research on machine learning-based control for individual control problems has advanced (e.g., [3]), studies on comprehensive control systems that harmoniously integrate numerous observations and actuators remain limited. The DA-based control provides a foundational framework for the harmonious overall control. In this approach, physical knowledge and control constraints can be easily incorporated into the control system through the state vector and the digital twin.

CONTROL SYSTEM IN LHD To investigate the control performance of ASTI for complicated control problems, we have built a control system based on ASTI at LHD, as shown in Fig.1. We employ the integrated simulation code, TASK3D, as the digital twin of the LHD plasma in ASTI. The neutral beam injection (NBI) heating, electron cyclotron heating (ECH), and gas-puff systems are connected to ASTI as the actuators to control the plasma density and temperature. ASTI adjusts on/off of the four neutral beams, on/off of the five gyrotrons, and the valve voltage of the gas-puff every 0.3 seconds. The response of the LHD plasma is observed as the radial profiles of electron temperature and density by the real-time Thomson scattering measurement system, and the profiles are assimilated into the state distribution every 0.3 seconds. ASTI runs on a vector machine (128

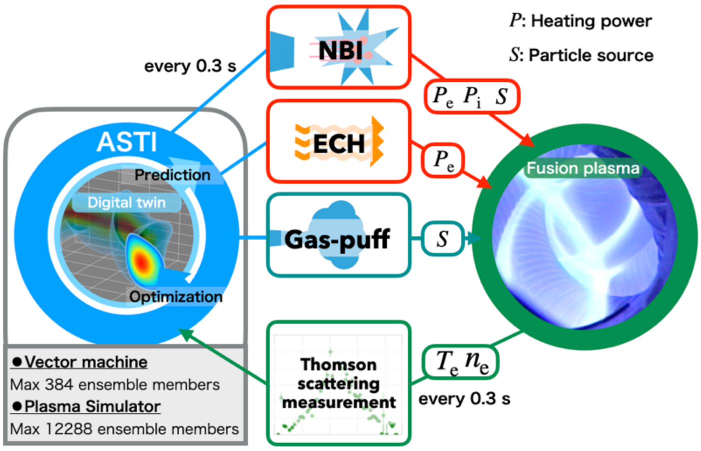

Fig. 1: Digital twin control system based on ASTI in LHD.

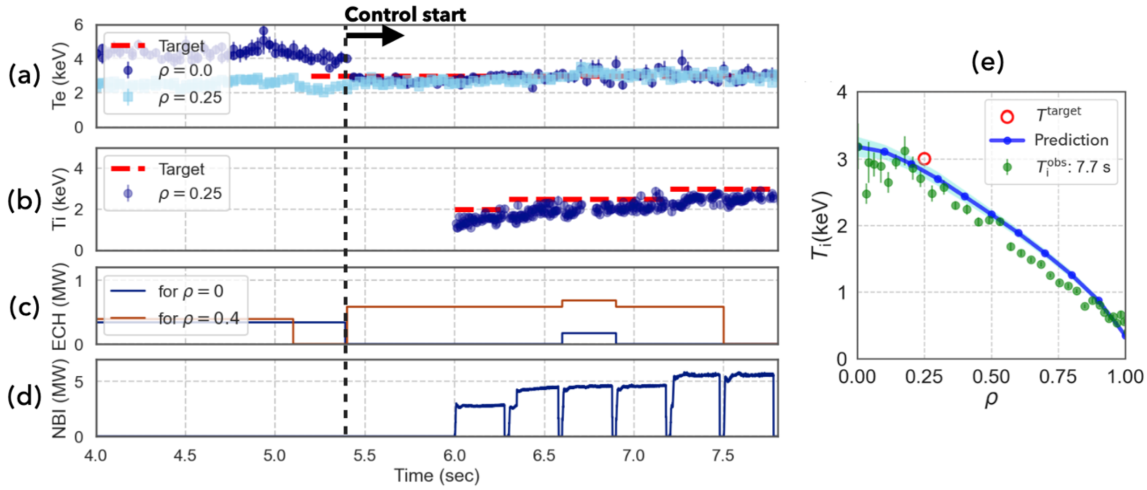

Fig. 2: Results of an experiment to control the electron and ion temperatures using NBI heating and ECH. (a and b) Control results of electron temperature and ion temperature. (c and d) ECH and NBI heating power adjusted by ASTI. (e) Radial profiles of predicted electron temperature and the observation at t=7.7 s. The hatching area around the prediction profile represents the standard deviation of the predicted distribution.

parallel processes, maximum 384 ensemble members) or a part of Plasma Simulator RAIJIN (6144 parallel processes, maximum 12288 ensemble members). We have applied this control system to control problems such as radial profile control of electron temperature, simultaneous control of electron density and temperature, and simultaneous control of electron temperature and ion temperature.

CONTROL EXPERIMENTS Here, we show the results of the simultaneous control of electron temperature and ion temperature. The target variables of this experiment are the electron temperature T_e (at normalized minor radius ρ=0 and 0.25) and the ion temperature T_i (ρ=0.25). The actuators are the perpendicular NBI and the ECH, which has two separate heating positions to control the radial profile of T_e: two gyrotrons (total ~700 kW) for ρ=0 and the other three (total ~1500 kW) for ρ=0.4. Factors for the electron and ion thermal diffusivities and parameters in the NBI heating model are included in the state vector and optimized by assimilating the observed T_e and T_i. The constant model and the gyro-Bohm model are employed for the electron and ion thermal diffusivities, respectively, based on the previous LHD experimental data. Figure 2 shows the results of a control experiment (#193553). The target T_e is 3 keV (both ρ=0 and 0.25), and the target T_i varies stepwise, as shown by the red dashed line in Fig. 2(b). It can be seen from Fig. 2(a) and (b) that the T_e reaches the target temperature quickly from the start of the control, and the T_i also increases following the target temperature. The assimilation of observations optimizes the model parameters and improves both the prediction performance of the digital twin and the control performance. Figure 2(e) shows the predicted and observed radial profile of T_i. We can see good agreement between the prediction and the observations. Note that the plotted observations of T_i in Figs. 2(b) and (e) were obtained after the experiment and not in real time. Multivariate predictive control involving unobserved variables has been achieved by combining the digital twin prediction, which captures the characteristics of the LHD plasma, with the actual partial observations. We have also confirmed the effectiveness of this DA-based control approach for other control problems, such as radial profile control of electron temperature and simultaneous control of electron density and temperature.

This study has demonstrated the effectiveness of the DA-based control using ASTI, which compensates for the digital twin imperfections using real-time observations and addresses complex multivariate control problems involving unobserved variables. This approach enables the construction of a comprehensive control system for fusion plasmas by synergistically integrating physical knowledge (including data-driven models), real-time observations, and actuators. ASTI can also contribute to control tasks that require the avoidance of terminating events by implementing relevant alarm rates and to physics experiments that require a high degree of control. Currently, ASTI is being extended for tokamak plasma control, and actual digital twin control experiments are planned. ASTI enables nonlinear and multivariate control of fusion plasma behavior under conditions of limited measurement and provides a foundation for flexible control of fusion reactors.

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