Real-time plasma state reconstruction and fault detection using a model-based dynamic observer

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Precise and reliable real-time knowledge of the state of a tokamak plasma, including 1D kinetic profiles, the safety factor profile and 2D equilibrium, is of paramount importance for feedback control, performance supervision, safety monitoring and disruption prevention. In many tokamaks, this plasma state is provided by a combination of real-time equilibrium reconstruction algorithms and inversion of diagnostic measurements. These methods suffer from the fact that they are numerically ill-conditioned and that precise diagnostic data is necessary to accurately obtain crucial information such as the central q profile.

This work presents a new method to reconstruct the radial profiles of a tokamak plasma by combining real-time diagnostic measurements with a physics model prediction. A so-called *dynamic state observer* is used, in which a physics-based dynamic model directly provides a prediction of the state, and diagnostic measurements are then used to apply a correction to this state estimate. This method uses the expected time evolution of the system to make predictions, and does not require numerical inversion of diagnostic data. The resulting state estimate is independent of the temporal and spatial sampling characteristics of individual diagnostics, and provides information that can not directly be measured such as non-inductive current fraction, loop voltage profile, and magnetic shear.

To account for modeling errors, a time-varying disturbance, which compensates for these errors, is estimated in real-time together with the state. This disturbance then provides a basis for identifying faults and other unexpected events in the plasma. Similarly, by monitoring the difference between expected and actual diagnostic measurements, diagnostic faults can also be systematically detected.

As its internal model of system, the state observer uses the RAPTOR real-time profile evolution code [1],[2] as a real-time-capable simulator for the evolution of the poloidal flux and temperature profile. Since the model is nonlinear, we employ the Extended Kalman Filter (EKF) algorithm [3], a nonlinear variant of the more widely known linear Kalman Filter.

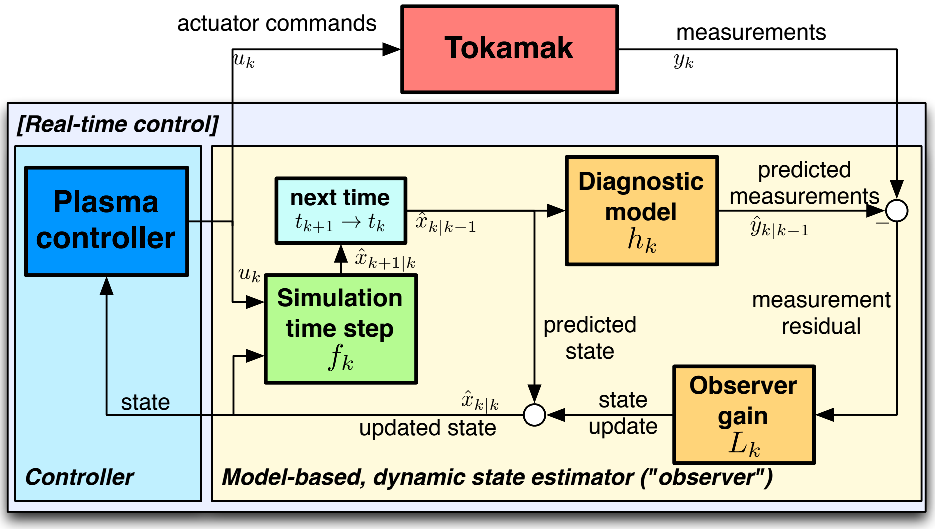

Figure 1: State observer for tokamak plasma profiles. A real-time simulation (green) running in parallel with the tokamak, is at the core of the algorithm. The predicted state estimate based on the previous time step $\hat{x}_{k|k-1}$ is corrected by the state update $L_k(\hat{y}_{k|k-1} - y_k)$ which weighs the difference between simulated and true measurements.

RAPTOR real-time profile evolution code

The RAPTOR code simulates the time evolution of poloidal flux and electron temperature, and serves as the real-time code used in the simulation time step of the observer (figure 1). In the present implementation, the 2D geometry of the flux surfaces is fixed and the density profile is assumed to known, or measured directly from diagnostics. However, the nonlinear interaction between the profiles via bootstrap current, neoclassical conductivity and shear-dependent confinement are modeled. For the thermal transport, an ad-hoc model is used that can be tuned to existing experimental data. This way, the transport model used in the observer can first be adapted (off-line) to existing tokamak discharges. Crucially, the RAPTOR code also returns the local linearization of the model around its nonlinear trajectory in real-time, which is important for the EKF algorithm.

Design of the state observer

The observer algorithm is schematically illustrated in figure 1. The to-be-estimated state vector at discrete time instant t_k is referred to as x_k. It contains the coefficients that completely determine the ψ (poloidal flux) and T_e (electron temperature) profiles via a basis function expansion. This state vector evolves in time following the physical evolution of the system. This is modeled by the state update law $x_{k+1} = f(x_k, u_k)$. Here, u_k is the input vector representing external actuators (for the case of profile estimation, these are the auxiliary powers, but also plasma current is regarded as an actuator here). To anticipate for modeling errors, a constant additive disturbance vector is explicitly introduced into the state update equation $x_{k+1} = f(x_k, u_k) + d_k$. This disturbance is to be estimated together with the state, based on the measurements, hence its estimate will vary in time. The diagnostic measurements are modeled by a (possibly time-varying and nonlinear) function of the state $y_k = h_k(x_k) + v_k$ where v_k is a white noise sequence which can be characterized for each diagnostic.

We design the observer to simultaneously estimate x_k and d_k by defining an *augmented state* $z_k^T = [x_k^T, d_k^T]^T$ and selection matrix $\mathbb{S}_x$ such that $x_k = \mathbb{S}_x z_k$. The augmented state-space model is then written as:

$$\begin{bmatrix} x_{k+1} \\ d_{k+1} \end{bmatrix} = \begin{bmatrix} f(x_k, u_k) \\ 0 \end{bmatrix} + \begin{bmatrix} I \\ I \end{bmatrix} d_k + \begin{bmatrix} w_k^x \\ w_k^d \end{bmatrix} \tag{1}$$

Then we can write the Extended Kalman Filter state update and prediction equations [3] as

$$\hat{z}_{k|k} = \hat{z}_{k|k-1} + L_k[y_k - h(\mathbb{S}_x \hat{z}_{k|k-1})] \quad \text{State update} \tag{2}$$

$$\hat{z}_{k+1|k} = \begin{bmatrix} f(\mathbb{S}_x \hat{z}_{k|k}, u_k) + d_k \\ d_k \end{bmatrix} \quad \text{State prediction} \tag{3}$$

At the same time, the Kalman gain L_k is computed at each time step based on the estimated state covariance matrix, which is also evolved together with the state. The statistical properties of w_k^x and w_k^d determine how rapidly the state estimate may diverge from the pure model-baed estimate. They can hence be tuned in order to attatch a greater confidence to the model or to the measurements.

Unexpected plasma behavior or faults can also be detected by monitoring in the disturbance estimate d_k, and the measurement residual $(\hat{y}_{k|k-1} - y_k)$ in real-time. Systematic deviations of the model with respect to measurements are contained in d_k and can be classified as normal (due to modeling errors) or abnormal (actuator faults, unexpected plasma behaviour). Similarly, sudden deviations in one element of $(\hat{y}_{k|k-1} - y_k)$ may indicate a sensor fault, while a sudden deviation of several diagnostics simultaneously may indicate an impending plasma disruption.

Implementation on ASDEX-Upgrade

The state observer algorithm is being implemented in the ASDEX-Upgrade (AUG) real-time Discharge Control System (DCS) [4]. It builds upon the pilot implementation previously developed in TCV [1]. The algorithm is implemented in SIMULINK with the core RAPTOR simulator embedded in a MATLAB block. The SIMULINK model is converted into C code and compiled to a DCS application. The algorithm is configured to run every 10ms, which is compatible with typical thermal confinement time scales of $\sim$ 50ms for ASDEX-Upgrade plasmas. The observer presently uses measurements of the total plasma current, 60 ECE channels with real-time computed radial measurement coordinates, estimates of the edge poloidal flux and plasma geometry

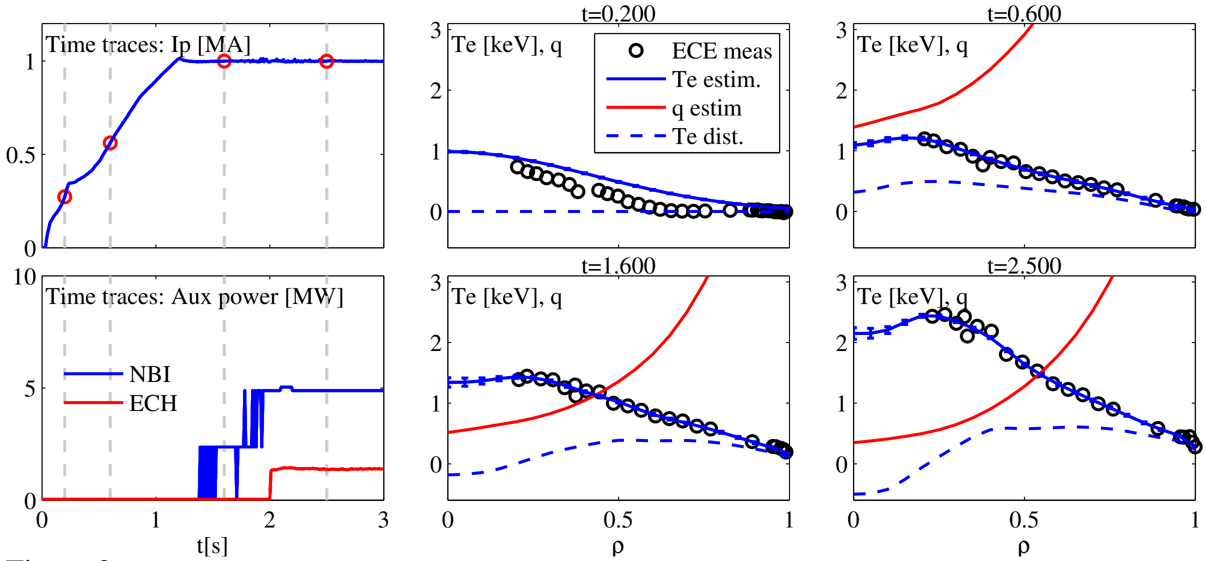

Figure 2: Demonstration of the dynamic observer using ASDEX-Upgrade RT diagnostic data (#30053). The estimated T_e disturbance shows that the model underestimates the temperature profile except for in the center, where no measurements are available to provide a good estimate.

from real-time equilibrium reconstruction, as well as the command inputs for NBI and ECH auxiliary power sources. First results are shown in figure 2. When the algorithm is started, the observer's initial state significantly differs from the measurements. The observer heavily weighs the measurement data for T_e, so the observer estimate rapidly converges to the measurements. First tests indicate that the compiled algorithm computes in 3ms per time step, opening up the possibility of performing faster-than-real-time predictive calculations with existing hardware in the very near future.

Conclusions and outlook

A new algorithm for real-time reconstruction of the plasma profiles has been developed and has recently been implemented on ASDEX-Upgrade. It uses real-time ECE, I_p and ψ_{edge} data and estimates the current density and temperature profile by merging model predictions with diagnostics. Detailed comparisons to off-line profile reconstructions are underway with the aim of validating the results and routinely providing reliable estimates. More real-time diagnostics will be integrated in the future.

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