Use of virtual actuators in ASDEX Upgrade control

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Abstract

Actuator management is an essential part of a modern tokamak plasma control system. It has to deal with a large number of control task simultaneously, needs to be able to operate close to stability limits and to avoid disruptions. In the ASDEX Upgrade tokamak experiment, the process of actuator management development is ongoing. As a first step, we have removed direct assignment of physical actuators to controllers responsible for the control task execution. Instead, the controller is communicating to the so-called virtual actuator, which groups an arbitrary number of actuators of the same type (so far ECRH only) and distributes the controller command between them. The virtual actuator has been implemented and used on ASDEX Upgrade in the 2019 experimental campaign. It gave valuable contributions to several physics experiments. First, the implementation of the virtual actuator enabled β_p control by ECRH power, which is of interest especially for I-mode and ELM-free H-mode discharges. Second, it was used in the electron temperature control experiments, which is a useful control tool for transport studies. Third, the concept was used for the density limit disruption avoidance experiments where central ECRH power is applied to recover the plasma from a disruptive zone. The current paper describes the use of the virtual actuator in these cases and based on the gained experience, it suggests future developments and improvements of the virtual actuator on ASDEX Upgrade discharge control system.

Keywords: tokamak, plasma control, actuator management

1. Introduction

In advanced tokamak operation, the plasma control system (PCS) needs to deal simultaneously with a large number of control tasks such as kinetic and current profile control, MHD control, or disruption avoidance. There is only a small number of actuators that can carry out these tasks. To handle these issues, an effective and reliable actuator management system is needed to allocate the most convenient actuators to the control tasks which are of the highest importance. Actuator management is being developed for example for TCV [1] and DIII-D [2]. The initial work on this topic on ASDEX Upgrade (AUG) is presented in [3]. As continuation of this activity, we have introduced a virtual actuator to the AUG Discharge Control System (DCS) [4]. The details about virtual actuator principles can be found in [5].

The virtual actuator represents a group of actuators serving the same purpose sorted by priority. It can be connected to a controller: the virtual actuator provides the limits to the controller and distributes the controller command between its member actuators. The actuators with the highest priority are used first. So far the virtual

actuators have been introduced for the 8 ECRH gyrotrons on AUG. Where only a fraction of the maximum power is requested, gyrotrons will be pulse-width modulated. Using this concept has several advantages compared to the original DCS strategy, where each controller using ECRH power was connected to a single gyrotron: first, it provides more power for the control task. This used to be restricted by the maximal power of a gyrotron, which is approximately equal to 700 kW at AUG. Second, it enables replacement of the tripped actuators. So far we have introduced two virtual actuators for the 8 ECRH gyrotrons on AUG. The gyrotrons can be assigned to the virtual actuators in the pulse schedule. Strictly, each gyrotron can be only in one of the two virtual actuators. A virtual actuator still can be used for several control tasks, which, however, are not concurrent but are executed sequentially by selecting different control modes. Dynamic allocation of the gyrotrons to the virtual actuators depending on the plasma state is foreseen in future (see Section 4.1).

During the AUG 2019 campaign, the virtual actuator proved to be a useful and powerful concept for several applications, namely density limit disruption avoidance [6], [7] (not discussed in detail, some information is provided in Section 4.1), β_p control by ECRH in the I-mode [8] and ELM-free H-mode discharges [10] (section 2), and the electron temperature control, both central and profile [11]

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(section 3). In this paper, we will discuss each of these applications, the role of the virtual actuator, and possible extensions of the virtual actuator properties that would further help to accomplish the control task.

2. β_p control by ECRH

Some tokamak confinement regimes exist only in a quite narrow β_p window on AUG. For instance, the ELM-free H-mode has to be kept away from the peeling-ballooning instability, which - at the moment - only seems possible at a certain heat flux through the separatrix. Furthermore, on AUG the I-mode exists in a narrow β_p window between L-mode and H-mode, and often the heating power has to be reduced when I-mode is entered in order to keep the regime stationary. It is therefore interesting for physics studies to use feedback on β_p and try to keep its value in the β_p range where the regime of interest exists. Traditionally, this control has been done using Neutral Beam Injection (NBI) [9], which has the following limitations:

- The β_p control by NBI heating is not useful for all discharges. Namely, it is not efficient in AUG reversed plasma current and reversed toroidal magnetic field regime due to high fast particle losses, which makes NBI heating inefficient and can pose a threat to the first wall.
- NBI heating influences plasma rotation by applying torque. For physics studies, it is interesting to control β_p while not influencing plasma rotation. ECRH heating is an actuator which can control β_p while not applying any torque.

To achieve good β_p control with ECRH, more power than available in one ECRH gyrotron is needed. This makes the virtual actuator a suitable tool for such control task. One can use up to 8 central gyrotrons to control β_p including possible replacement of tripped gyrotrons. A good example where all these features of the virtual actuator were used is shot 36288, which was partly used to develop β_p control by ECRH. In this discharge, the virtual actuator connected to the β_p controller comprises 6 ECRH gyrotrons with the following priority order: 7,8,2,3,4,1, where the numbers are gyrotron identifiers. In Figure 1, one can see the power requested by the β_p controller and the power distribution between individual gyrotrons.

First of all, the controller requested more power than available in one gyrotron two times during the discharge. This would lead to controller saturation if the original strategy was used. The virtual actuator expands the window where the controller can operate without saturation. The second useful feature of the virtual actuator is the automatic replacement of a tripped actuator. In Figure 1, it is depicted that fractional power is requested, thus the gyrotrons are modulated, which increases the risk of the actuator trip. During this discharge, gyrotron 7 was lost at 3.46 s and immediately replaced by gyrotron 8, which

Figure 1: The time evolution of the reference β_p and the real value (upper plot) and the power requested by the β_p controller (lower plot). The lower plot shows how is the power command distributed between individual gyrotrons. The change of the active gyrotron seen in the lower plot is caused by that fact that a gyrotron with higher priority tripped.

was lost at 3.7 s and replaced by gyrotron 2. Gyrotron 2 tripped at $t = 4.56$ s and was replaced by gyrotron 3, which stayed on until the end of the shot. Closer to the end of the discharge, the next gyrotron in the list (gyrotron 4), was used to accomplish controller request higher than the full power of one gyrotron.

If the original strategy without virtual actuator was used, it would compromise the control quality in the intervals when more than 1 gyrotron is requested and the control would be fully lost after the first gyrotron trip. In future, the possibility of reducing the gyrotron modulation for some of the control tasks is foreseen.

3. Electron temperature control

The second application where the virtual actuator was used is the electron temperature (T_e) control. The goal of the controller is to keep the T_e or its profile constant. This paper does not describe the details of the controller design and performance, as this information can be found in [11]. It is only focused on the use of the virtual actuators to this purpose.

At AUG, one can control either central T_e using single output controller acting on virtual actuator containing centrally located ECRH, or the T_e profile using MIMO controller with two outputs connected to two virtual actuators: one for central ECRH and the other virtual actuator for off-axis ECRH. The central T_e control is, from the virtual actuator point of view, very similar to the β_p control described in section 2 since only one virtual actuator is

Figure 2: Uppermost plot: The time evolution of the T_e reconstructed by RAPTOR and the T_e reference at the following toroidal ρ locations: $\rho = 0.15, 0.3, 0.4, 0.5, 0.6$, and 0.7 . The reference is taken at the time when the controller starts. At the moment the control starts ($t = 4.8$ s), the NBI beams are swapped from two radial to two tangential. Middle plot: the power request on the virtual actuator containing central gyrotrons and its distribution between individual sources. Lower plot: the power request on the virtual actuator containing off-axis gyrotrons and its distribution between individual sources

used. The more interesting case, where we used two virtual actuators for one control task, is the T_e profile control. An example is shown in Figure 2, where the NBI heating was swapped from tangential beams to radial beams (the control starts at the time of the swap), which can result in the T_e profile change. The T_e profile controller eliminates this change by adapting the power in the central and off-axis gyrotrons.

As mentioned above, the controller is connected to two virtual actuators, one central and one off-axis. Each of the virtual actuators contains 4 gyrotrons. For the central virtual actuator, 3 gyrotrons are requested in feedforward before the beam swap from tangential to radial, since it is expected that the central ECRH power will need to be decreased. After the controller was turned on, the virtual actuators switched on the off-axis gyrotrons and reduced the power delivered by the central gyrotrons. If a gyrotron trips (such as gyrotron 2 from the central virtual actuator which trips at 5.6 s), additional gyrotrons can be used for replacement if available in the same virtual actuator.

Overall, using two virtual actuators enabled execution of the T_e profile control discharges without major controller saturation problems. The details of the results and detailed analysis are discussed in [11].

4. Outlook and near future plans

On the examples of the β_p control by ECRH (Section 2), T_e control (Section 3), we have shown that the virtual actuator is a useful concept for broad range of applications,

there are several obvious ways to improve and extend it. In this section, our near-future plans will be presented.

4.1. Changing task of an actuator

The first possibility to improve the virtual actuator is to enable reallocation of an ECRH power source from one virtual actuator to another, either in a pre-set time or in real time using a decision algorithm. After changing the virtual actuator the gyrotron belongs to, the corresponding mirror would be steered to match the power deposition location requested by the new virtual actuator. This corresponds to the change of the gyrotron task, which is rigidly connected to the virtual actuator. The location is calculated in real time using the code TORBEAM [12] and can be changed by moving the ECRH mirror. For example, in the T_e profile control described in Section 3, more gyrotrons are needed in the off-axis virtual actuator than in the central virtual actuator during the control phase where radial beams are used. Conversely, before the beam swap, one needs more feedforward gyrotrons in the central virtual actuator. For such situations, it would be beneficial to have a possibility to move the mirror corresponding to the gyrotron of interest from the off-axis to central location and back. Also, one could correct the mirror angles if the gyrotrons point to a wrong location due to initial mirror settings or due to density profile different from initial expectations.

Another interesting use case is the density limit disruption avoidance [6]. In this application, the distance of the plasma state from disruptive zone in the space of greenwald fraction and H98 factor is monitored in real time. If the distance is small, central ECRH power is applied to recover the plasma to the safe state. For this purpose, one needs typically several gyrotrons, which are provided using the virtual actuator. The first experimental results are presented in [7]. In future, this type of disruption avoidance should become a routinely available tool.

The density limit disruption avoidance might not be needed in all phases of the discharge: it seems to be most common in the plasma current ramp-up and ramp-down. The possibility of changing the control task the gyrotron is assigned to opens the possibility of having a sufficient number of gyrotrons for the density limit disruption avoidance in the beginning and at the end of the shot, while using them for other applications of interest during the flat-top.

The virtual actuator of the control task the gyrotron is assigned to should be responsible for this movement. The virtual actuator should receive the list of the gyrotrons, either as a trajectory, or automatically from an actuator manager (which is to be developed later, see [5]) and move the mirrors to the right power deposition location. The power command would not be given to a gyrotron until the right deposition location interval is reached.

4.2. Extension of the virtual actuator to all heating sources

Currently, each of the actuator types is treated separately and such a unification of the features communi-

cated to the virtual actuator will have to be introduced. The next extension of the virtual actuator should focus on the possibility of combining more types of heating sources to one control task. In AUG, it is the ECRH, NBI, and ICRH. To achieve this, virtual actuators must be capable of combining a mix of heating sources type. This possibility would be beneficial for tasks like density limit disruption avoidance, where all heating sources could be combined, or β_p control (Section 2) where the combination of ECRH and ICRH heating would be of interest. In both cases, different heating sources could be used to provide more power to the controller.

Introducing this feature requires that all heating actuators at AUG are represented by a set of common properties which are sufficient to describe any of the heating actuators. The foreseen properties are the actuator availability, maximum and minimum power command, movability of the power deposition location, and power deposition boundaries. To achieve this, we will introduce a general actuator class with derived classes for each type of the heating actuators. The actuator-type specific part of the class will handle the actuator-specific features such as mobility of the power deposition, deposition profile or check the interlock limits (for example, NBI heating can not be used if the density is too low), while the generic part will be used to communicate with the virtual actuator.

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