Actuator allocation for integrated control in tokamaks: architectural design and a mixed-integer programming algorithm

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ARTICLE INFO

ABSTRACT

Plasma control systems (PCS) in tokamaks need to fulfill a number of control tasks to achieve the desired physics goals. In present-day devices, actuators are usually assigned to a single control task. However, in future tokamaks, only a limited set of actuators is available for multiple control tasks at the same time. The priority to perform specific control tasks may change in real-time due to unforeseen plasma events and actuator availability may change due to failure. This requires the real-time allocation of available actuators to realize the requests by the control tasks, also known as actuator management.

In this paper, we analyze possible architectures to interface the control tasks with the allocation of actuators inside the PCS. Additionally, we present an efficient actuator allocation algorithm for Heating and Current Drive (H & CD) actuators. The actuator allocation problem is formulated as a Mixed-Integer Quadratic Programming optimization problem, allowing to quickly search for the best allocation option without the need to compute all allocation options. The algorithms performance is demonstrated in examples involving the full proposed ITER H & CD system, where the desired allocation behavior is successfully achieved. This work contributes to establishing integrated control routines with shared actuators on existing and future tokamaks.

1. Introduction

Tokamaks require a plasma control system (PCS) to control plasma quantities of interest, in order to ensure that physics goals are met while remaining within operational and machine limits. For this purpose, the PCS can use multiple actuators to affect the plasma state in real-time.

A control task typically compares present plasma quantities with their references and calculates commands to actuators such that references values are achieved. In present-day devices, actuators are usually assigned to a single control task for an entire experiment, e.g. to density control, plasma beta control or the control of Neoclassical Tearing Modes (NTMs). Performing multiple control tasks at the same time is sometimes done in tokamaks and is known as integrated control [1,2]. This is still an area of research and integrated control of all relevant phenomena is not performed routinely today.

However, in future tokamaks it will become increasingly important to use a limited set of actuators for multiple purposes during a plasma discharge [3–8]. Also, the priority to perform a specific control task may vary in real-time due to unforeseen plasma events and the availability of the actuators may change due to failure. Hence, real-time management of actuators is required to achieve integrated control using these shared actuators.

The importance and complexity of this integrated control problem is best illustrated for the ITER Electron Cyclotron (EC) Heating and Current Drive (H & CD) system. This system with its 24 gyrotrons and 11 steerable mirrors needs to be used by at least 4 control tasks with time-varying priorities in the flat-top alone: impurity control, sawtooth control, NTM control and profile control [9].

The PCS architecture defines the role of its components (such as a number of control tasks) and the interfaces between these components. PCS architectural designs are recently presented in literature for the tokamaks ASDEX Upgrade [10,11], WEST [12,13] and ITER [6,7]. Although different in details, these papers represent a coherent approach to the PCS architecture.

Recently an actuator allocation algorithm was developed and successfully implemented for the ECRH system at ASDEX Upgrade [14,15]. This algorithm computes in real-time for all possible allocation options the benefits (are control task requests achieved) minus the costs (required movements of launchers, etc.), while taking actuator availability into account. This is an excellent first demonstration of real-time actuator management. However, as noted in [14,15], computing all allocation options for a large and complex actuator system like the one foreseen in ITER may not be feasible in real-time. This work therefore provides an algorithm that is inspired by [14,15], but which can be

executed sufficiently rapidly for real-time implementation on e.g. ITER.

In this work we first evaluate possible architectures to interface the control tasks with the allocation of actuators inside the PCS. We confirm that hierarchical schemes are favorable and recommendations are given to choose a specific hierarchical architecture dependent on the scale and complexity of the actuator systems involved.

Secondly we provide a generic actuator allocation algorithm for the H & CD systems using a Mixed-Integer Quadratic Programming (MIQP) optimization problem formulation, allowing to quickly search for the best allocation option without the need to compute all allocation options. The desired allocation behavior can be clearly defined in a cost function, whereas actuator availability and infeasible allocation options can be described in constraints. Simple examples are used to illustrate that the chosen desired allocation behavior is effectively achieved. Examples involving the full planned ITER H & CD system size, including Neutral Beam Injection (NBI), Ion Cyclotron (IC) and EC H & CD systems, demonstrate the algorithm's capability to perform the actuator allocation in real-time in correspondence to the desired allocation behavior. Simulations of a 100s ITER shot show effective handling of actuator failures by selecting redundant actuators according to a defined actuator preference.

The remainder of this work is organized as follows. In Section 2 possible PCS architectures for integrated control are evaluated. The MIQP-formulation of the actuator allocation problem is introduced in Section 3. Section 4 presents the performance of the actuator allocation algorithm in examples. Finally, conclusions and outlook are given in Section 5.

2. Overview and brief evaluation of architectures for integrated control

2.1. Introduction to PCS schemes

Tokamak plasmas need to be actively monitored and controlled by a plasma control system (PCS) to ensure that the desired plasma performance is achieved while operational and machine limits are satisfied. The architectural design of a PCS defines its components and the interfaces between these components. Recently, a number of PCS

architectural designs were presented in literature [6,7,10–13]. These PCS architectural designs can be summarized as given in Fig. 1. Herein we can identify, next to the tokamak itself with its actuators and diagnostics, the following components:

Diagnostic signal processing and plasma state reconstruction. Here the signals of multiple diagnostics are processed and integrated (possibly by including model-based predictions) into an estimate of the present plasma state. In future tokamaks the PCS is expected to have a clear separation between plasma state reconstruction and control and supervision tasks [3].

Supervisory layer. In this supervisory layer (green) the important central decisions are taken to meet pre-defined plasma scenario objectives and handle events based on provided information about the plant and plasma state [6,10–13]. The supervisor activates control tasks and sets their parameters and references, possibly by switching between pre-defined segments, where each segment is applicable for a range of plasma and hardware states and contains a set of active control tasks with corresponding parameters and references. Also priorities of control tasks can be set by the supervisor in response to detected events [3]. More information on event handling strategies in the PCS can be found in [16].

Actuator control systems. These low-level actuator control systems deal with the control of the actuator hardware to ensure that the PCS actuator commands are realized, e.g. to regulate the operating settings of a gyrotron such that it will deliver the requested power. At the same time, the actuator control systems will provide information to the PCS with information on the actuator status, parameters and constraints.

Control tasks. A control task computes what actions are necessary such that the control task objective will be achieved. The control task objective maybe specified as minimizing the difference between a reference and present estimated value of a controlled variable. Depending on the interface between controllers and actuators (discussed in more detail in Section 2.4), the action may be specified directly as a command to an actuator, or as a more generic request for actuation.

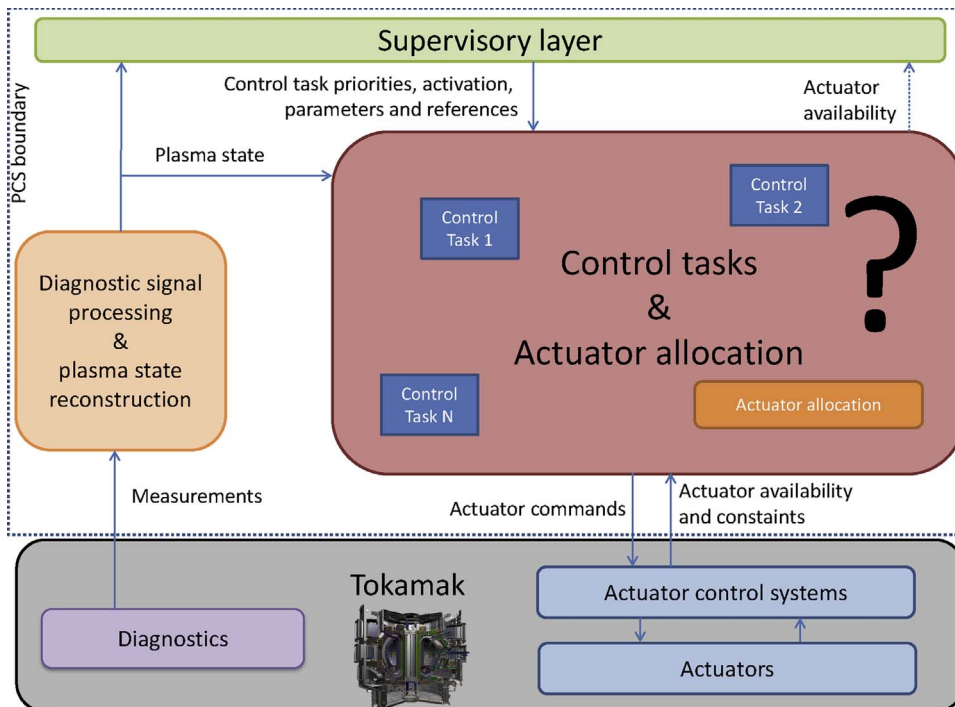**Actuator allocation.** The purpose of actuator allocation is to assign

Fig. 1. General scheme of a plasma control system (PCS) with multiple control tasks.