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Survey paper

Reference and command governors for systems with constraints: A survey on theory and applications[☆]

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ABSTRACT

Reference and command governors are add-on control schemes which enforce state and control constraints on pre-stabilized systems by modifying, whenever necessary, the reference. This paper surveys the extensive literature concerning the development of such schemes for linear and nonlinear systems. The treatment of unmeasured disturbances and parametric uncertainties is also detailed. Generalizations, including extended command governors, feedforward reference governors, reduced order reference governors, parameter governors, networked reference governors, and decentralized/distributed reference governors, are discussed. Practical applications of these techniques are presented and surveyed as well. A comprehensive list of references is included. Connections with related approaches, including model predictive control and input shaping, are discussed. Opportunities and directions for future research are highlighted.

1. Introduction

With the advances in control theory, many effective techniques have become available for the design of feedback control laws with the desired stability, performance and disturbance rejection properties. The interest in treating requirements that have the form of *pointwise-in-time state and control* constraints has also been growing, given their importance for industrial applications. Examples of constraints in real-world applications include actuator magnitude and rate limits, bounds imposed on process variables to ensure safe and efficient system operation, and collision/obstacle avoidance requirements.

A control engineer faced with the task of satisfying constraints has several choices. One route is to re-design the controller within the Model Predictive Control (MPC) framework (Camacho & Bordons, 2007; Goodwin & de Doná, 2005; Kwon & Han, 2006; Maciejowski, 2002; Morari & Lee, 1999). Another route is to augment a well-designed nominal controller, that already achieves high performance for small signals, with constraint handling capability for larger signals and transients that have the potential to induce constraint violation. This second route is attractive to practitioners who may be interested in preserving an existing/legacy controller or are concerned with the computational effort, tuning complexity, stability, robustness, certification issues, and/or other requirements satisfactorily addressed by the existing controller. Anti-windup compensation (Aström & Wittenmark, 1997) and the augmentation of Lyapunov controllers with barrier functions (Tee, Ge, & Tay, 2009) are examples of this second approach, and so are the reference governors (RGs) and command governors (CGs).

As its name suggests, the reference governor (see Fig. 1) is an *add-on* scheme for enforcing pointwise-in-time state and control constraints by modifying the reference command to a well-designed (for small signals) closed-loop system. The reference governor plays the role of a pre-filter that, based on the current value of the *desired reference command* $r(t)$ and of the state (measurement or estimate) $x(t)$, generates a *modified reference command* $v(t)$ whenever propagating the reference command without modifications may lead to constraints violations.

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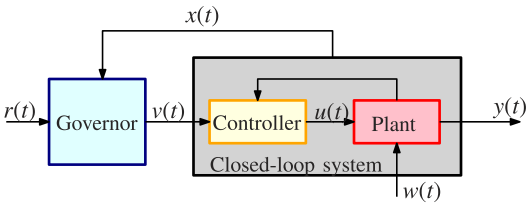

Fig. 1. Reference/command governor applied to closed-loop (Plant + Controller) system subject to constraints.

The use of low pass pre-filters to enforce constraints is a classical control technique, see e.g., the discussion in (Vahidi, Kolmanovsky, & Stefanopoulou, 2007), which usually results in a modified reference which is always different from the actual reference (other than asymptotically). Instead, the reference governor exploits state feedback, prediction, optimization, and set-invariance arguments (Blanchini, 1999; Blanchini & Miani, 2007) to ensure that modifications of the command are performed only when necessary to avoid compromising the system performance.

As an example, consider the application of a reference governor to the double integrator $x_1(t+1) = x_1(t) + 0.1x_2(t), x_2(t+1) = x_2(t) + 0.1u(t)$, controlled through an LQ control law, $u(t) = 0.9170(v(t) - x_1(t)) - 1.6821x_2(t)$, and subject to constraints $|u(t)| \leq 0.1$, $|x_1(t)| \leq 1$, $|x_2(t)| \leq 0.1$, and $|v(t)| \leq 0.6$. The operation of this system is illustrated in Fig. 2, for $v(t) = r(t)$ and for $v(t)$ assigned by a reference governor. Note that, using a reference governor, the command and response are slowed down in order to keep constraints satisfied. However, the modification to the reference is much smaller than what would be with a low pass filter. In fact, with the reference governor, the constrained variables ride the constraint boundary, which is a behavior that is usually impossible to achieve through a simple low pass filter.

A number of governor schemes have been proposed in the literature. The range of potential options includes, among others, scalar and vector reference governors, command governors, extended command governors, incremental reference governors, feedforward reference governors, network reference governors, reduced order reference governors, distributed reference governors, parameter governors, and virtual state governors. While different in obtained properties and implementation aspects, the common intent of these governors is to preserve, whenever possible, the response of the closed loop system designed by conventional control techniques. Frequently (but not always), they achieve this by ensuring that the modified reference command is as close as possible to the original reference command subject to satisfying the constraints.

Reference governors were first proposed as continuous-time algorithms in Kapasouris, Athans, and Stein (1990). Techniques and analysis sharing a similar philosophy with the continuous-time reference governor of Kapasouris et al. (1990) have appeared in Blanchini and Miani (1997, 2000, 2001). The discrete-time framework (Gilbert, Kolmanovsky, & Tan, 1995, 1994) has also emerged later due to some advantages from an implementation standpoint. The static reference governor (Gilbert et al., 1994) used $v(t) = \kappa(t)r(t)$, where the parameter $\kappa(t), 0 \leq \kappa(t) \leq 1$, was maximized subject the condition $x(t+1) \in O_\infty$, where O_∞ is the maximal output admissible set (Gilbert & Tan, 1991) of all states that, with reference command equal to zero, do not lead to subsequent constraint violation. Because of the possibility of oscillations (Gilbert et al., 1994), the static reference governor was abandoned and replaced by a dynamic reference governor for which finite-time convergence for constant or nearly constant reference commands is ensured. Other formulations of reference and command governors have appeared in Bemporad, Casavola, and Mosca (1997), Bemporad and Mosca (1994, 1995, 1998), Casavola, Mosca, and Angeli (2000) and Gilbert and Kolmanovsky (1999a), see also references therein. The developments included the treatment of linear systems with uncertainties and set-bounded disturbance inputs, the case of output feedback, and the implementation based on non-positively invariant sets. Extended command governors (Gilbert & Ong, 2011) provided a further generalization with the potential to achieve a larger constrained domain of attraction and faster response, at the price of increased computational complexity.

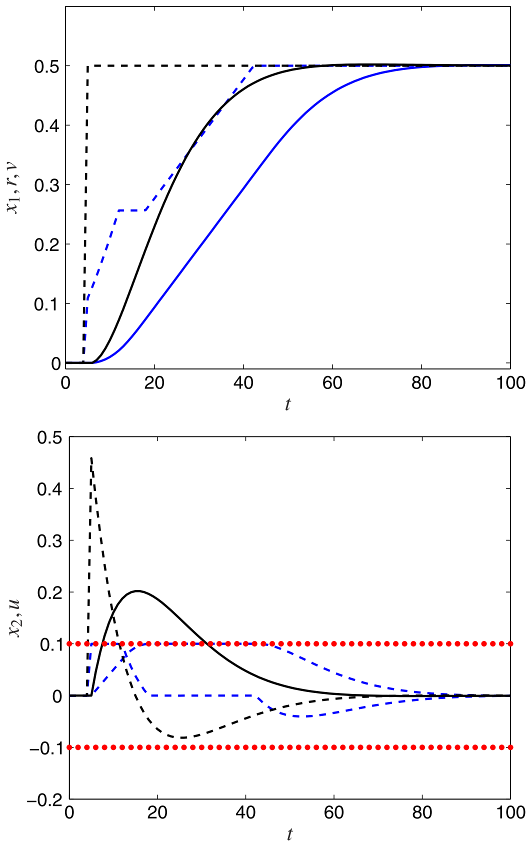

Fig. 2. Double integrator simulations. Above: Time histories of command (dash) and position responses (solid), without (black) and with (blue) reference governor. Below: Time histories of velocity (solid) and control input (dash) responses, without (black) and with (blue) reference governor; constraints in red (dot). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Several reference governors for nonlinear systems have also been developed, see e.g., Bemporad (1998b), Bemporad, Tarn, and Xi (1999), Borrelli, Falcone, Pekar, and Stewart (2009), Gilbert and Kolmanovsky (1999b, 2002), Miller, Kolmanovsky, Gilbert, and Washabaugh (2000), and references therein. Some of these approaches exploit on-line prediction through simulations or level sets of Lyapunov functions to guard against constraint violation. The parameter governor has been proposed in Kolmanovsky and Sun (2006) to adjust constant controller parameters or controller states based on prediction and optimization.

More recently, classical reference and command governor ideas have been extended in several directions related to the general area of cyber–physical systems (CPS), including the distributed control of large scale systems, modular control architectures, and network control systems.

The aim of this survey paper is to collect and systematize in a common framework the numerous contributions that at the current stage are dispersed in a number of different papers, to discuss the most recent results, to illustrate the potential for the impact on real world applications, and to provide a perspective on some open research directions. Accordingly, we will first