

Application of Reference Governor Using Soft Constraints and Steepest Descent Method to Diesel Engine Aftertreatment Temperature Control

Hayato Nakada
Toyota Motor Corporation

Gareth Milton and Peter Martin
Ricardo UK Ltd

Akiyuki Iemura and Akira Ohata
Toyota Motor Corporation

ABSTRACT

This paper considers an application of reference governor (RG) to automotive diesel aftertreatment temperature control. Recently, regulations on vehicle emissions have become more stringent, and engine hardware and software are expected to be more complicated. It is getting more difficult to guarantee constraints in control systems as well as good control performance. Among model-based control methods that can directly treat constraints, this paper focuses on the RG, which has recently attracted a lot of attention as one method of model prediction-based control. In the RG, references in tracking control are modified based on future prediction so that the predicted outputs in a closed-loop system satisfy the constraints. This paper proposes an online RG algorithm, taking account of the real-time implementation on engine embedded controllers. In order to realize the online RG algorithm, the following three elements are needed: (i) a plant model to predict future behavior of the control system, (ii) an objective function that quantifies how suitable a modified reference candidate is, and (iii) an online optimization algorithm that computes the most suitable modified reference from a set of candidates. For (i), a catalyst temperature model is derived based on thermal exchanges. In regards to (ii), three objective function candidates are considered and, through simulations, one in which a constraint is characterized as a soft constraint by a barrier function that penalizes the constraint violation is chosen. Owing to the parameters in the objective function selected, the resulting transient responses of the catalyst temperature can be tuned. (iii) The optimization algorithm is realized in the RG based on the steepest descent method, which minimizes a nonlinear objective function iteratively online. Finally, an experimental result is shown in which the present RG algorithm is applied to a production vehicle controller. The result shows the applicability and effectiveness of the present method.

CITATION: Nakada, H., Milton, G., Martin, P., Iemura, A. et al., "Application of Reference Governor Using Soft Constraints and Steepest Descent Method to Diesel Engine Aftertreatment Temperature Control," *SAE Int. J. Engines* 6(1): 2013, doi:10.4271/2013-01-0350.

INTRODUCTION

Real-world control systems have constraints to be considered in the control design. For example, in aftertreatment temperature control in automotive diesel engines, there is an allowable maximal catalyst temperature. Neglecting such constraints in control systems and in designing a control algorithm is well-known to degrade control performance, or worse, lead to instability [2].

In industry, constraints in control systems are satisfied through a lot of experiments and efforts to calibrate many constants, tables and maps. In particular, automotive engine control consists of complicated programs with if-then switches and sub-routines. Recently, the emissions regulations for vehicles are becoming more stringent and it is anticipated that vehicle hardware will become more complex, which will make software more complicated. For this reason, model-based control methods that can treat constraints have

received much attention from researchers, from both academia and industry [6].

As one of the control methods in which constraints can be considered, this paper focuses on a reference governor (RG) [1, 3] that modifies references of control systems so that constraints are satisfied. Recently, several researchers have tried to apply the RG to actual control systems [5, 10, 12, 13]. Albertoni et al. [5] applied the hybrid command governors for idle speed control in gasoline engines. Kogiso and Hirata [10], Oh-hara and Hirata [13] applied the RG to a position servomechanism. Oh and Agrawal [12] considered the cable robot application. The authors [11] reported a preceding research result of an RG application based on bisectional search to aftertreatment temperature control. There are not so many application results of the RG reported for embedded controllers. In order to apply the RG to real-world embedded controllers such as those in vehicle control, an efficient algorithm is required for online computation.

When applying control theory to real-world control systems, one difficulty is the selection of a performance index and its parameters. For example, in the so-called linear quadratic (LQ) control theory, a control designer needs to choose weighting matrices in a linear quadratic performance index. It is well-known that the control performance depends on the weighting matrices. At this moment, there are few guidelines on how to select them in the chosen control theory or in a performance index. Hence, in the application to real-world plants, it is important to consider whether a desirable control performance is achieved by the theory and whether the parameter adjustment is easy and can be done systematically. In the RG case, there are a variety of objective functions and optimization algorithms candidates. Depending on the choice, the modified reference computed by the RG could vary, leading to different control performance. Umeda et al. [14] have pointed out that the selection of objective functions and their parameters are important to obtain good control performance.

This paper considers an application of the RG to aftertreatment control of automotive diesel engines. An objective function in optimization of modified references is selected based on simulations. The objective function to be chosen is a nonlinear function, since it is based on a barrier function that penalizes the violation of constraints and is based on the model prediction over a finite future horizon. To optimize the nonlinear function, an iterative optimization algorithm based on the steepest descent method [16] is employed. The method is one of the fundamental optimization algorithms used to minimize the nonlinear objective function.

REFERENCE GOVERNOR

Recently, control design methods for constrained systems based on model prediction have attracted much attention from researchers in academia and industry. Among the control design methods for constrained systems, RGs [1, 3, 7, 10, 12,

13, 15] that modify original references are considered, to ensure that the closed-loop system meets constraints. As shown in Figure 1, placing the RG in front of a closed-loop system with the plant and the feedback controller changes the original reference r optimally to a modified reference w through the prediction of future closed-loop response over a finite prediction horizon.

Recently, there have been several theoretical approaches on the RGs such as an iterative online approach named 'fast RG' [15], a positive invariant-based approach [7] and a piecewise affine function-based modification approach [10]. Recent research work requires a lot of online or offline computations. Indeed, in the applications to real-world control systems, the limitation on computation resources and memory must be considered. For automotive controllers with computational limitations, this paper considers the online RG algorithm to be solvable in automotive control units.

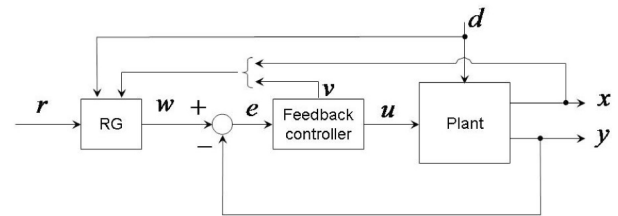


Figure 1. A feedback control system with reference governor.

The feedback system with RG shown in Figure 1 is considered. Here, the plant is given by

$$\begin{aligned} x_{k+1} &= f(x_k, u_k, d_k) \\ y_k &= g(x_k, u_k, d_k), \end{aligned} \quad (1)$$

where $x_k \in \mathbf{R}^n$, $u_k \in \mathbf{R}$, $d_k \in \mathbf{R}^l$, $y_k \in \mathbf{R}$ are the state of the plant, control input, exogenous input and control output respectively. For simplicity, the case of a single-input-single-output system is considered. The subscript $k = 0, 1, \dots$ denotes the discrete time steps. The feedback controller is a proportional plus integral (PI) feedback controller given by

$$\begin{aligned} u_k &= K_p e_k + K_i v_k \\ v_k &= v_{k-1} + e_k \\ e_k &= w_k - y_k, \end{aligned} \quad (2)$$

where $v_k \in \mathbf{R}$ is the state of integrator of the tracking error $e_k \in \mathbf{R}$. The controller parameters $K_p, K_i \in \mathbf{R}$ denote proportional and integral gains, respectively. The signal $w_k \in \mathbf{R}$ shows the reference. The RG is placed to modify the original reference $r_k \in \mathbf{R}$ so that the constraints in the closed-loop system are satisfied.

There are several approaches to the RG, but this paper pursues an online RG algorithm for implementation on real-world vehicle controllers. It is preferable to minimize the

calculation burden of a modified reference and save memory. In the calculation of a modified reference, an optimization problem is solved to obtain the optimal solution in some sense. The solution and the resulting control performance greatly depend on the choice of the objective function to be optimized. Regarding the selection, there are few suggestions and unified guidelines in research work on control theory, as it is dependent on the respective system, and its control specifications. Applying the RG to real-world control applications requires starting with the selection of the objective function to obtain a desirable control performance.

SIMULATION STUDY OF OBJECTIVE FUNCTIONS FOR REFERENCE MODIFICATION

In [11], the authors had considered the application of an RG algorithm based on bisectional search to an aftertreatment system for automotive diesel engines. In the literature, the modified reference is allowed to change in the opposite direction to reference change in order to ensure constraints under model uncertainties and measurement noises. Still, it is not easy to know the relation between the range of the search region for modified reference and such uncertainties. If excessive noise is added to a measured signal, the possibility of degrading transient control performance, or worse, constraint violation still remains.

This section first presents a numerical example to show the effects of the model uncertainties on the constraint satisfaction and the transient response in the RG application. In order to improve the robustness in the RG, it is necessary to go back to the optimal modified reference calculation. Specifically, the kind of objective functions suitable in the optimization to obtain a modified reference giving a good transient response with constraint satisfaction are considered. The introduction of three objective function candidates allows the selection of a suitable objective function by simulating the numerical example.

Motivating Numerical Example

The control system in Figure 1 considers two types of plant models. One is the nominal plant model described by

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k \\ y_k &= Cx_k \end{aligned} \quad (3)$$

with

$$x_k = \begin{bmatrix} x_{1,k} \\ x_{2,k} \end{bmatrix} \in \mathbf{R}^2, A = \begin{bmatrix} 0.7 & 0 \\ 0.3 & 0.7 \end{bmatrix}, B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, C = [0 \quad 1],$$

where the vector x_k denotes the state. The equivalent transfer function is expressed as

$$y_k = \frac{0.3}{(z-0.7)^2} u_k$$

where z denotes the shift operator. The second type is a perturbed model with three-step input delay and parameter perturbation as

$$\begin{aligned} \xi_{k+1} &= A_\Delta \xi_k + B_\Delta u_k \\ y_k &= C_\Delta \xi_k \end{aligned} \quad (4)$$

with

$$\xi_k = \begin{bmatrix} \xi_{1,k} \\ \xi_{2,k} \\ \xi_{3,k} \\ \xi_{4,k} \\ \xi_{5,k} \end{bmatrix} \in \mathbf{R}^5, A_\Delta = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0.72 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0.29 & 0.71 \end{bmatrix},$$

$$B_\Delta = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, C_\Delta = [0 \quad 0 \quad 0 \quad 0 \quad 1],$$

where the vector ξ_k denotes the state of the perturbed system. The equivalent transfer function is expressed as

$$y_k = \frac{0.29}{(z-0.71)(z-0.72)z^3} u_k.$$

Below, the perturbed system (4) is treated as the real plant and the nominal system (3) is regarded as the plant model with which the control design is done. Further, the gains of the PI feedback controller are set to $(K_p, K_i) = (0.12, 0.03)$ to stabilize the nominal plant. These values are fixed by trial and error. The output y_k is supposed to be constrained, i.e., $y_k \leq \bar{y}$, $\forall k \geq 0$ where $\bar{y}$ is the upper limit of the output and is set here to 1.05.

The following optimization problem is considered. In the optimization, the distance between the original reference r_k and the modified reference w is minimized so that the output constraint is satisfied over a finite prediction horizon.

$$\begin{aligned} \min_w J(w) &= \|r_k - w\|^2 \\ \text{subject to } \hat{y}(k+i|k) &\leq \bar{y} \quad \forall i=1,2,\dots,N_h. \end{aligned} \quad (5)$$

The optimal solution w is applied to the closed-loop system as the modified reference w_k at time k . Here, $\hat{y}(k+i|k)$ represents the predicted output of time $k+i$ at time k . The number $N_h \in \mathbf{N}$ denotes the prediction horizon. Here $N_h = 30$ is set.