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Robustness analysis and tuning of generalized predictive control using frequency domain approaches

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ABSTRACT

The paper presents a new frequency-domain methodology to explicitly address the robustness margins for analysis and tuning of generalized predictive control (GPC). The GPC is formulated in two-degree-of-freedom configuration to allow for simultaneous execution of robustness analysis and frequency characteristic shaping. The underlying idea is to present a robust tuning scheme for GPC scheme by synthesizing some sensitivity functions in discrete-time domain, quantifying the relevant cause-and-effect perturbations, in order to shape them so that the effects of influences can be reduced in a specific frequency range. Several frequency-domain templates have been introduced to practically demonstrate usefulness of output, noise, and input sensitivity functions as complementing analysis tools for robust tuning of GPC. The proposed method ensures robust adjustments of the non-trivial tuning of GPC free parameter knobs through simultaneous realization of robustness analysis and frequency characteristic shaping. The method can hence be utilized as a powerful method for tuning of GPC for a wide range of single-input single-output (SISO) linear systems. Illustrative simulation examples have been conducted to explore the effectiveness of the proposed method.

1. Introduction

Model predictive control (MPC) strategies have found an ever increasing popularity in industrial applications [1–5]. This is mainly due to their appealing features, enabling the designer to systemically accommodate for practical constraints imposed both on plant inputs and outputs. Generalized predictive control (GPC) presents [6,7] a strategy which aims to incorporate all major features of the predictive control in a unified framework. The strategy could deal with non-minimum phase and open-loop unstable systems and systems having unknown or varying time-delay characteristic. Derivation of the GPC control law, however, inherits mathematical complexities, leading to diverse set of tuning parameters with nonlinear influences on the resulting GPC performance. This critical issue has motivated further research studies to explore for proper parameter tuning procedures to fine-tune the closed-loop response for good performance and stability assurance. The recorded literature signifies domination of time-domain approaches to address the problem [7–11]. Clarke et al. [7] emphasize the equivalent relationships between some well-known digital controllers, such as deadbeat, pole-placement and GPC formulation structure to facilitate the tuning task. In [8], poles and zeros variations of closed-loop system have been investigated for the choice of different tuning parameters. A complete survey of GPC tuning methods has been introduced in [9].

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The rationale underlying each individual method, however, is heuristic and hence their implicated merits have been cast on the basis of the conducted simulation results. Normey-Rico and Camacho [12] and Neshasteriz et al. [10] have established GPC tuning formulas for First-Order Plus Dead-Time (FOPDT) and Second-Order Plus Dead-Time (SOPDT) processes. Obviously, these approaches are limited to low-order models which may not represent dynamics of higher-order and/or unstable processes. Some articles have used artificial intelligence methods such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and fuzzy decision making to properly tune MPC [13,14]. Furthermore, introduction of a higher number of tuning knobs with their potential over-applying effects on the nonlinearity of the process dynamics could make these tuning procedures ambiguous and case sensitive. Garriga et al. [15] have studied the effects of tuning parameters on the locations of closed-loop eigenvalues. Some texts are considered Continuous-time GPC (CGPC), e.g., Demircioglu and Gawthrop [16], as a more robust scheme compared to the alternative Discrete-time GPC (DGPC), but the heuristic tuning problem still remained [17]. Demircioglu and Karasu [18] have performed a practical comparative study between CGPC and DGPC and sustained the positive effect of suitable choice *T* filter in closed loop robustness.

Many heuristic rules have been introduced in the literature to fine-tune the GPC free parameters to achieve good performances. Nevertheless, they all have a trial-and-error nature-based which is not able to explicitly address the robustness margins. Furthermore, weakness of the available time-domain GPC tuning approaches to explicitly address the robustness margins has motivated the interest to propose frequency-domain approaches. Benyo et al. [19] have utilized frequency-domain measures to investigate robustness of cascade GPC against the effects of noise filter. Yoon and Clarke [20] and Normey-Rico and Camacho [12] focused on adequate choosing of a pre-filtering polynomial *T* to enhance the GPC robustness against unmodeled dynamics and time-delay variation, respectively. Rodriquez et al. [33] have introduced a similar approach to appropriately formulate a robust GPC design and implementation framework. But, these contributions and similar ones complicate the GPC realization and hence may hinder their applications [34]. Most of the MPC tuning guidelines have been recently reviewed [11]. The authors have discussed about some of the tuning guidelines on a system performance, formulated in state-space [11].

This paper presents a conceptually simple and yet powerful frequency-domain methodology, inspired from Landau's early works on robust Self-Tuning Regulator (STR) controller design [21,22], to present a new methodology for robust analysis and tuning of GPC schemes. For this purpose, the GPC is formulated in two-degree-of-freedom or STR controller configuration to allow simultaneous execution of robustness analysis and frequency characteristic shaping of the feedback loop. This method makes advantage of Landau's early works in the robust STR controller design to provide a general approach for tuning a robust GPC. This method has a general appliance for unconstrained linear systems and could be regarded as a design scheme with no large additional complexity and computational burden. Frequency-domain analysis and shaping the sensitivity function play a key role in robust controller design for a linear feedback loop [23,17,24]. These functions provide meaningful data about the disturbance rejection, noise attenuation and robustness against various uncertainties. Several methods have been presented in the literature to address this issue and design a controller on the basis of sensitivity functions [23,24,22]. The underlying idea is to construct and evaluate several sensitivity functions in order to shape them so that the effect of perturbations can be reduced in a specific frequency range. However, less attention has been paid to manipulation of sensitivity functions in digital control [25,26,22]. Having the GPC formulation in digital form, it is hence crucially important to synthesize the sensitivity functions in discrete-time domain so as to present a tuning scheme for GPC design and implementation. In a simple term, a sensitivity function can be defined in terms of a linear transfer function, describing the relationship between an arbitrarily output and a specific input, in a feedback control loop to quantify their cause-and-effect influence. In this paper, a formulation is first derived for feedback control loop configuration to demonstrate the way each induced input, including the desired set-point, the output disturbance and the sensor noise may affect the output. On this basis, proper sensitivity functions are then defined to show the effects of disturbance, noise, and input on the system output. For instance, output sensitivity function represents the transfer function between output disturbance and system output. Inverse of infinity norm of the output sensitivity function will then be set equal to modulus margin. The modulus margin is treated as an important measure for robust linear controller design, representing disturbance rejection ability of controller in a specific frequency band and its tolerance against time-varying or nonlinear elements [22]. Similarly, noise-output sensitivity function is defined to represent how noise affects the system output. Finally, input sensitivity function is defined as the transfer function between input and output disturbance of the system. Several templates will then be introduced to practically demonstrate the usefulness of output and noise output sensitivity functions as two complementing analysis tools for robust tuning of GPC. The paper utilizes the general idea of Landau's templates [22], defined on the basis of sensitivity functions, to present a methodology for both robustness analysis and parameter tuning of GPC. The definitions of modulus and delay margins are used for this purpose. A GPC has several free tuning parameters to be adjusted by the designer. Obviously, tuning these parameter settings may affect the robustness property of the resulting GPC which is often neglected in the available design procedures. In this paper, the proposed frequency-domain methodology is evaluated in the context of some individual illustrative examples to address the crucial issue of free parameter tuning for robust GPC design goal.

Section 2 introduces the GPC formulation in terms of two-degree-of-freedom configuration and the relevant tuning parameters that will be addressed in the proposed design procedure. Section 3 includes some useful information about sensitivity functions from digital control system perspective. The GPC tuning methodology is proposed in Section 4. Finally, the concluding remarks will be summarized in Section 5.