Journal of Process Control 24 (2014) 1720–1732

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Improved methodology and set-point design for diagnosis of model-plant mismatch in control loops using plant-model ratio

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ARTICLE INFO

Article history:
Received 28 February 2013
Received in revised form 3 September 2014
Accepted 12 September 2014
Available online 13 October 2014

Keywords:
Model-based control
Uncertainty
Model-plant mismatch
Process control
SISO
Frequency domain
Plant model ratio

ABSTRACT

Performance of any model-based control scheme depends on the quality of model. When these schemes deliver poor loop performance due to model-plant mismatch (MPM), a detection of the same needs to be in place. A recently introduced plant model ratio (PMR) not only detects MPM but also facilitates a unique identification of the source of mismatch, namely, *gain*, *dynamics* (time constant) and *delay* mismatches. The prime objective of this work is to improve the PMR approach in a few key aspects, namely, estimation and experimental effort, and assessment procedure by taking a fresh perspective of PMR and conducting a detailed theoretical study of its signatures. A rigorous assessment procedure based on the theoretical properties of PMR is devised. Three threshold-based hypotheses tests are proposed for significance testing of PMR. A key contribution of this work is the design of set-point with minimal excitation for diagnosis of MPM, based on the features of PMR. The revised methodology is demonstrated and compared with the existing method through simulation examples. The study also demonstrates the potential of the proposed method in serving as a prelude to full/partial model re-identification.

1. Introduction

The safety and economy of an industrial process is crucially tied to the performance of the hundreds of control loops that drive or maintain the respective variables to/at their targets. Naturally controllers are designed and fine tuned to deliver good performance, but the fact remains that their performance usually deteriorates over time. The reasons for the performance drops could be one or more of sensor/actuator failure, shifts in operating conditions, fouling, seasonal effects, *etc.* [2].

A model is one of the critical elements of any control systems design. Classical controller tuning approaches use models off-line in combination with well-established tuning guidelines. On the other hand, "model-based", specifically model predictive control schemes [4] deploy models on-line to predict the (future) course of the process and take corrective measures in the present. An important feature of these schemes is that predictions of the model are also available in tandem with measurements, thereby providing opportunities for detecting significant deviations of the model from the plant, if any. Further, these schemes facilitate incorporation of model uncertainties in controller design in addition to the constraint handling ability. The performance of model-based schemes (and in general classical control as well) is significantly influenced by the model quality, *i.e.*, how accurately the model is able to describe the plant dynamics. It is a widely accepted fact that no model of a realistic process is accurate; uncertainties always exist due to modelling errors, unmeasured disturbances, noise and/or any time-varying system characteristics [5].

The objective of this work is to develop a concrete method for detection and diagnosis of model-plant mismatch in the frequency domain for single-input single-output (SISO) systems with suggestions for extensions to multi-input, multi-output (MIMO) systems. Specifically, it is a refinement and extension of a recently proposed measure known as the plant-model ratio (PMR) [1] for loops designed using the Internal Model Control (IMC) schemes [3]. The reason for adopting the IMC framework because it not only characteristically represents the MPC and contains the classical control schemes but also more importantly lends itself to tractable mathematical analysis of the closed-loop performance in presence of MPM. A formal analysis of MPM effects in the IMC framework is possible because the model-plant uncertainty explicitly appears in the closed-loop expressions. In comparison, the MPC setup is not easily amenable to analysis due to lack of any closed-form expression for the non-linear controller. The results drawn on IMC scheme can be used to obtain valuable insights into the workings of generic model-based control loops.

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http://dx.doi.org/10.1016/j.jprocont.2014.09.005

These uncertainties are usually classified into two categories: (a) *structured*, wherein there is a mismatch in the parameters of plant and model descriptions, also known as parametric uncertainty; or, (b) *unstructured*, wherein a mismatch lies in the structures of the two descriptions, which may be due to un-modelled dynamics. The present work is built on an intermediate scenario to be explained shortly, but primarily in the context of parametric uncertainty. Note that the proposed method is potentially extensible to the case of unstructured uncertainties.

A considerable, but far from being exhaustive, portion of the performance assessment literature is devoted to the diagnosis of poor performance of control loops that occurs due to model-plant mismatch. In a work by Patwardhan and Shah [6], the effects of several factors on the achieved performance of a controller have been quantified. Badwe et al. [7] studied the impact of model-plant mismatch on the controller performance of a MIMO closed-loop system. The root cause of controller performance degradation is isolated by analysing certain key closed-loop sensitivities. Since the performance of a model-based control system is intimately linked to the extent of MPM, it is useful to detect the presence and possibly locate the source of a mismatch without having to re-identify the plant which may be quite tedious. Stanfelj et al. [8] examined the correlation between the input and the model residuals for detecting model plant mismatch for a single-input-single-output (SISO) system where white noise corrupts the output. For coloured disturbances, they have used cross-correlation between the set-point (or dither) and prediction error. Webber and Gupta [9] extended this method to a multiple-input-multiple-output (MIMO) system in order to detect which element of the transfer function matrix has a significant mismatch. In a similar work, Badwe et al. [10] suggested a method to detect model-plant mismatches in MIMO model predictive control based schemes using routine-operating data, which involves analysis of partial correlations between the manipulated variables and the model residuals. Kano et al. [11] made use of the stepwise method and a mismatch score to select those sub-models of a MIMO MPC system which contain significant MPM.

The scenario relevant to the work is that of parametric uncertainty in SISO systems. However, the objective is not to diagnose the specific parameter(s) as root causes for MPM. Rather it is to detect the subset of parameters that need attention in a re-identification exercise. Specifically, the parameters are categorized into sets that directly correspond to process characteristics, namely, *gain*, *dynamics* and *delay*. The objective is then to essentially determine which among these are the source(s) of poor performance. The basic premise is that a full parametric re-identification is usually expensive and the proposed method serves as an intermediate step in pin-pointing the subset of parameters that need to be re-identified. The value of this intermediate step assumes much prominence in MIMO systems where the number of parameters that require re-identification is usually high. In this sense, the proposed work, based on SISO systems, provides founding ideas and offers directions to the development of a method for MIMO systems.

With the above objectives in mind, Selvanathan and Tangirala [1] defined a quantity known as the plant-model ratio (PMR) in order to represent uncertainty. They show that theoretically this representation of uncertainty is advantageous in that there exists a unique mapping between properties (signatures) of the PMR and the source of mismatch, namely, gain, time constant and delay mismatches. As a consequence of this unique mapping, PMR can not only be used to detect, but also identify the cause of mismatch. They also proposed an assessment procedure for diagnosing model-plant mismatch using PMR. The method detects the corrupt parameters by estimating PMR at a large number of frequency points followed by an examination of its signatures. This signature-based method also reveals the direction of mismatch. The motive behind this exercise is to re-estimate only those parameters which show significant MPM, rather than estimating all parameters of the plant again. However, the implementation and execution of those ideas significantly falls short of addressing two important motivating factors for methods that diagnose the source of MPM in general. The two factors being (i) minimal estimation effort in terms of the number of unknowns to be estimated and (ii) optimal set-point design for use with the PMR method. Furthermore, we show that a more appropriate utility of PMR is in detecting mismatch in *dynamics* (apart from *gain* and *delay*) rather than *time-constants*. This work addresses these specific issues, particularly that of estimation effort and set-point design, in a systematic manner and in a statistical framework.

The net outcome of this work is the development of an *improved* assessment procedure for detection and diagnosis of the source of MPM, consisting of a statistical procedure and a method for optimal set-point design for this purpose. Specifically, this paper addresses the following questions: (a) Can the number of estimations be minimized by searching for optimal features in PMR? (b) To what extent can the set-point be exploited? By lowering the number of estimations and hence the requisite external excitation, the proposed assessment procedure minimizes the *effort* involved in detecting MPM and identifying if which among the steady-state, transient or the delay characteristics require to be re-estimated. Recommendations for input design and threshold calculation (needed for significance testing of MPM) are also made. Furthermore, a fresh perspective of the plant-model ratio and a study of its signatures for processes with complex dynamics are presented.

The article is structured as follows. In Section 2, a brief review of the Internal Model Control (IMC) scheme and a description of the problem under investigation are presented. Section 3 deals with a review of PMR and presents extensions to some complex scenarios of practical importance. The sensitivity of PMR to changes in the plant parameters, which forms the theoretical basis of the work, is also discussed. The main results of this work appear in Section 4, where the improved assessment procedure is presented. Simulation studies are reported in Section 5, which also constitutes a comparison of the revised methodology with the existing PMR method and parametric re-identification of the plant model. The paper concludes in Section 6.

2. Preliminaries

2.1. Internal Model Control (IMC) scheme

The problem setting of PMR is originally based on an Internal Model Control scheme. IMC was introduced by Garcia and Morari [3] and developed further by Rivera et al. [12] and Economou and Morari [13]. Fig. 1 shows a schematic of an IMC configuration.

The developments in this work rely on certain key closed-loop relationships, as reviewed below. In Fig. 1, the set-point, $R(s)$, and noise, $V(s)$, are independent external signals and hence all other

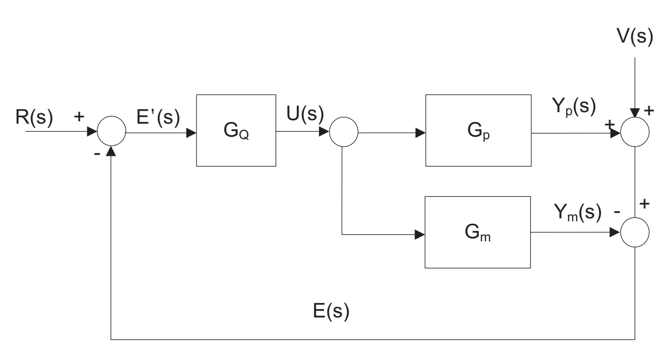

Fig. 1. Schematic of a SISO IMC configuration.