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An example of robust internal model control under variable and uncertain delay☆

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ABSTRACT

This paper proposes a particular study of the classic internal model control algorithm for a sampled-data system in a generalized context of uncertainty. Besides the usually considered model mismatch, the particularity of the case under consideration is that the measurements available to the control algorithm suffer from large, varying and uncertain delays. The presented study considers a simple SISO nonlinear system. The control algorithm is a sampled nonlinear model-based controller with successive model inversion and bias correction. The main contribution of this article is its proof of global convergence and robustness despite time-varying delays and uncertain measurement dating. In particular, the model error, the varying delays and measurements dating error are treated using monotonicity of the system and a detailed analysis of the closed-loop behaviour of the sampled dynamics, in an appropriate norm.

1. Introduction

In this article, we investigate the effects of delay variability and uncertainty on the internal model controller (IMC, see e.g. [1]) of a single-input single-output (SISO), static, nonlinear, sampled-data process with delayed measurements whose dating is uncertain. As is well-known, the uncertainty and the variability of delays lead to challenging control problems that may jeopardize closed-loop stability, see [2,3] and references therein. It is also known, see [4], that metrology delays coupled with inaccurate process models could lead to closed-loop instability. Interestingly, the general treatment of these issues is still an open problem.

The process and its controller constitute a sampled-data system (following the terminology employed in e.g. [5,23]) which can be reformulated using a classic discrete time representation. The specific case under consideration is actually also formally very similar to a scalar run-to-run controller, the robustness of which is not trivial. Run-to-run control is a popular and efficient class of techniques, originally proposed in [6], specifically tailored for processes lacking in situ measurement for the quality of the production (see [7]). Numerous examples of implementations have been reported in the semiconductor, and materials industry, in particular, see e.g. [7,8] and references therein. Indeed, the field of run-to-run control encounters two of the practical problems addressed in this article: nonlinear model uncertainty and variable metrology delays. While these issues have often been reported (see, e.g. [4,9–11]), they have not received any definitive treatment from a theoretical viewpoint.

In the problem considered here, model uncertainty stems from the interactions between the input and the system states which can be rather complex, and, in turn, cause some non-negligible uncertainty on the quantitative effects of the input. On the other hand, the measurements are available after a long time lag covering the various tasks of sample collection, receipt, preparation, analysis and transfer of data through an information technology (IT) system to the control system. Measurements are thus impacted by large delays, which can be varying to a large extent, and in some applications be state- or input-dependant. This variability of the delay builds up with the intrinsic IT dating uncertainty, because, in numerous implementations, no reliable timestamp can be associated to the measurements, see [12] and references therein. The delay variability cannot be easily represented by Gaussian models (e.g. additive noise on the measurement), nor can it be fully described as deterministic input or state dependant delay, nor known varying delays that could be exactly compensated for by predictor techniques (as done in e.g. [13–17]).

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In the absence of measurement dating uncertainty, robust stability in the presence of model mismatch can be readily established, using the monotonicity of the system and model which is formulated here as an assumption. The study of measurement dating uncertainty effects is more involved. Once expressed in the sampled time-scale, the control scheme exhibits a variable delay discrete-time dynamics. No straightforward eigenvalues or Nyquist criterion analysis (see [9]) can be used to infer stability. A complete stability analysis in a space of sufficiently large dimension, with a well chosen norm, yields a proof of robust stability under a small gain condition. Interestingly, the small-gain bound is reasonably sharp, so that it can serve as guideline for practical implementation. The novelty of the approach presented in this article lies in the proof technique. It does not treat the uncertainty of the delay using the Padé approximation approach considered in [18], but directly uses an extended dimension of the discrete time dynamics. In future works, it is believed that these arguments of proof could be extended to address more general problems, in particular to higher dimensional forms (lifted forms) usually considered to recast general iterative learning control into run-to-run as is clearly explained in [7].

The paper has two objectives. Firstly, it establishes robust stability results with respect to model mismatch when measurements are delayed but exactly dated. Secondly, it extends robust stability to small model errors when measurement are delayed and their dating is uncertain. Those results are illustrated through simulations.

2. Notations

Given $\mathcal{I}$ an interval of $\mathbb{R}$, and $f : \mathcal{I} \rightarrow \mathbb{R}$ a smooth function, let us define

$$\|f\|_\infty = \sup_{x\in\mathcal{I}} |f(x)|$$

For any vector X, note $\|X\|_1$, $\|X\|_2$ and $\|X\|_\infty$ its 1-norm, its Euclidean norm and its infinity norm, respectively. Note $\|\cdot\|_*$ any of the vector norms above. For any square matrix A, note $\|A\|_*$ the norm of A, subordinate to $\|\cdot\|_*$. Classically (e.g. [19]), for all A, B

$$\|AB\|_* \le \|A\|_* \|B\|_*$$

We note $\lfloor x \rfloor$ the floor value of x, mapping x to the largest previous integer.

For any matrix of dimension s, define E_i the matrix of general term $e_{k,l}$

$$\forall (k, l),\ \ e_{k,l} = \delta_{k,s}\delta_{l,i} \tag{1}$$

where δ is the Kronecker delta $\delta_{i,j} = 1$ if $i = j$ and 0 otherwise.

3. Problem statement

3.1. Plant (delay-free)

We note y the controlled variable (output) of the considered plant and u the control variable (input). It is assumed that there exists f_p a strictly monotonous smooth function such that

$$y = f_p(u) \tag{2}$$

Although f_p is unknown, we can use a model of it, f, which is also smooth and monotonous,[1] such that $f_p(0) = f(0)$. Usually, f is a rough estimate of f_p. Typical models are represented in Fig. 1. For the simulations considered in this article, the model error can be as large as 20–40%, which is representative of industrial applications requirements.

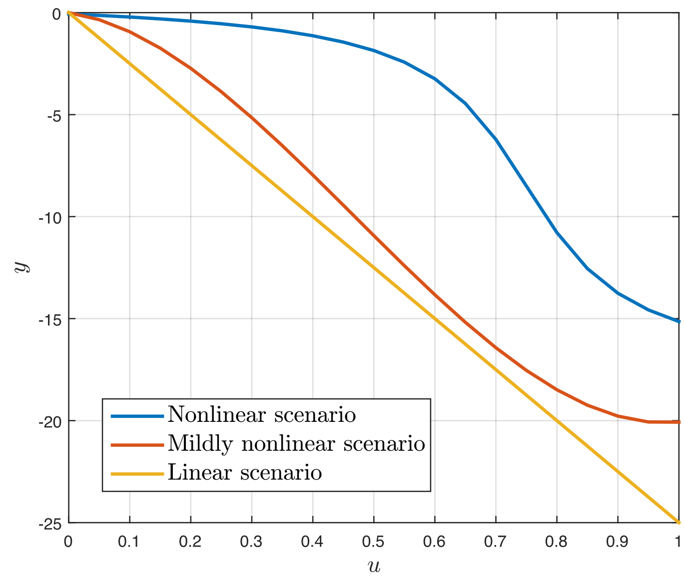

Fig. 1. Examples of possible monotonic and smooth input-output mappings f, courtesy of TOTAL.

The target value c for the controlled variable is assumed to be reachable by both the system and the model, i.e. there exists u_c and $\tilde{u}_c$ verifying

$$f_p(u_c) = c,\ \ f(\tilde{u}_c) = c \tag{3}$$

3.2. Measurement delay

A measurement system provides estimates of y with some time delay in a sampled manner. In many cases, this delay is time varying. Depending on the IT structure, measurements dating is usually done either using timestamping or an *a priori* estimation of the measurement delay. Either way, exact measurement dating is usually impractical, and some uncertainty on the measurement delay must be considered.

In the system considered in this article, the measurements available for feedback in a control loop thus have two specificities. They are delayed and the measurement delay $0 \le D$ itself is varying and uncertain. With $0 \le \hat{D}$ the available estimation of D, we note $\Delta \triangleq \hat{D} - D$ the mismatch.

Assumption 1. There exits D_{max} such that $D \le D_{max}$.

Assumption 2. There exits Δ_{max} such that $\Delta \le \Delta_{max}$. If Assumption 1 holds, it is clear from definition that $-D_{\max} \le \Delta$.

3.3. Control problem

A closed-loop controller can be designed for the system. Each time a measurement is received, the control is updated and the value of the control is kept constant until the next measurement is received, creating piece-wise constant control signals (with varying step-lengths). Repetitive application of this process generates a sequence of inputs and outputs. The delay results in shift of index in the measurement sequence.

Formally, the control design should aim at solving the following problem.

Control problem. *Create a sequence* (u_n) *using the approximate model* f *and the delayed measurements* $(f_p(u_{n-D_n}))_{n\in\mathbb{N}}$ *of* y_n *such that* $\lim_{n\to+\infty} f_p(u_n) = c$

[1] In practice, it can result from the analysis of sensitivity look-up tables obtained from experiments and derivation of interpolating models.