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Systems with uncertain and variable delays in the oil industry: some examples and first solutions

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Abstract: In this article we expose typical examples of systems from the oil industry having variable delays. The root causes of the variability can be the transport phenomena, the clocks mis-synchronisation in the employed information technology, or the transmission of waves in surrounding medium. We discuss these problems and sketch solutions.

Keywords: process control, uncertain delays, variable delays, monitoring algorithms, synchronisation of data, information technology, feedback control

1. INTRODUCTION

As many industries, the oil sector has to cope with dynamical systems with delays. One main reason why delays are ubiquitous in this field is that transport of fluid material is a dominant problem in almost all applications related to oil. Another factor is the long distances over which fluid transport (horizontal or vertical) has to be considered. In this article, we present several representative practical examples. With simplifying assumptions, we expose some problems where mitigation of the effects of delays are the central question.

Control engineers know that delays have negative impacts on closed-loop control. However, the malicious effects of the variability of the delay are often underestimated. The examples chosen in this article all feature varying delays. We explain why, and we stress why this is a problem. After some recall on recent methodological tools developed to control delay systems, the paper covers three distinct types of variation.

First, we explain the *control-induced delay variations*. In the blending problem we consider, the delay is defined by an implicit integral equation where the controls, which are flow-rates, have an effect. In this case of deterministic variations, we stress the surprising non-symmetric behavior observed during step-ups and step-downs responses. The predictability of the delay allows one to compensate for it with good accuracy, using a motion planning technique for open-loop and a generalized predictor for closed-loop. Interestingly, this poses challenging stability analysis problems, and we sketch solution for them.

Second, we explain the problems associated with delays caused by *mis-synchronization of data* produced by geographically distributed instrumentations. Here, the delay is uncertain and can not be compensated for. We stress its harmful effects on a simple, but state-of-the-art, monitoring algorithm employed to check the mass balance of an oil and gas production network. As will appear, delay induced by dating uncertainty can be more detrimental than measurement noises.

Third, we consider the problem associated with *non-causality of communication over networks.* Inside a vertical well, we expose how the system of communication with repeaters can cause misinterpretation of measurements when received at the surface. This problem lies at the frontiers of our investigations. We briefly discuss how to address it.

2. NEW CONTROL METHOD FOR DELAY SYSTEMS

The techniques of delay compensation are not new. The most widely used methods are predictor approaches (see e.g. in Artstein (1982); Kwon and Pearson (1980); Manitius and Olbrot (1979); Smith (1958)). As established in numerous surveys and research works (Niculescu (2001); Richard (2003)), the lack of robustness of this technique with respect to the uncertainty on the delay is still a major concern in automatic control theory. This lack of robustness often appears as a performance bottleneck in applications (see e.g. Mondie and Michiels (2003)).

Lately (see Krstic (2008, 2009b); Krstic and Bresch-Pietri (2009); Krstic and Smyshlyaev (2008)), a new class of predictor-based techniques has been proposed to address this uncertainty. In particular, this methodology is based on the seminal idea (see e.g. Krstic (2008)) of modeling the actuator delay as a (fictitious) transport partial differential equation (PDE). Essentially, this is an analysis tool, useful to establish convergence. In details, one uses a backstepping boundary control method on the transport PDE introduced to model the delay. This transformation allows to use systematic Lyapunov design tools for robust stabilization and adaptation. A list of references on this topic includes Bekiaris-Liberis (2014); Bekiaris-Liberis and Krstic (2013a,c); Krstic (2009a); Bresch-Pietri et al. (2014, 2012a,b,c). We now sketch a (brief and partial) state-of-the-art in relation to the examples presented in this article.

2.1 Exact compensation of a single delay

Consider the following system

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$$\dot{X}(t) = AX(t) + BU(t - D)$$

where D is a constant delay. Due to the delay, the system is infinite-dimensional. When the delay is compensated, the system becomes finite dimensional, because it becomes delay-less. For a constant delay, exact compensation can be achieved by using a finite time prediction over the exact value of the delay Artstein (1982); Kwon and Pearson (1980); Manitius and Olbrot (1979), i.e.

$$\begin{aligned} U(t) &= KX(t + D) \\ &= K\left[e^{AD}X(t) + \int_{t-D}^{t} e^{A(t-s)}BU(s)ds\right] \end{aligned} \quad (1)$$

where the feedback gain K stabilizes the delay-free dynamics. This is, as is well-known, a non robust control strategy. In particular, uncertainties in the system dynamics and delay reveal troublesome. Fortunately, some degree of robustness can be added by employing adaptive control techniques developed on the basis of this prediction technique. For example, one can refer to Bresch-Pietri et al. (2012a) where several classic cases of equilibrium regulation are treated: parametric uncertainties, disturbance rejection, partial state measurement, or delay adaptation.

2.2 Robust compensation of a single varying delay.

Following Krstic (2009a), consider the more general system

$$\dot{X}(t) = AX(t) + BU(t - D(t))$$

In the case of a varying delay, the prediction has to be done over a varying horizon. This gives (see Nihtila (1991))

$$U(t) = KX(\eta^{-1}(t)) \quad \text{where} \quad \eta(t) = t - D(t) \quad (2)$$

Importantly, for this controller to be well-defined, the η function has to be invertible (as one has to use its inverse η^{-1}). This means that every information sent has to be received once and only one by the system. A sufficient condition for this is

$$\dot{D}(t) < 1, \quad \forall t \quad (3)$$

which we will refer from now-on as "causality condition".

In general, the prediction formula (2) does not provide exact delay compensation, since future variations of the delay are not known in advance. We have

$$\dot{X}(t) = AX(t) + BX(t \underbrace{-D(t) + D(t - D(t))}_{\neq 0})$$

At least, one shall investigate the possible impact of this mismatch on asymptotic stability. This can be done by studying a partial differential equation reformulation using a special backstepping transform. This rewriting allows a Lyapunov-Krasovskii analysis. A result is that if the control gain K in (2) can be chosen sufficiently small, then the closed-loop system is asymptotically stable (Bresch-Pietri et al., 2014, Theorem 1) [1].

2.3 Non causal delay

The generalized predictors (2) and their extensions have the capability of treating variable delays and uncertain delays (Bekiaris-Liberis and Krstic (2013a,b); Krstic (2009a)). However, all these works share the common assumption (3).

If this assumption fails, then the principle of causality is violated. The delay increases faster than the time grows. Under such circumstances, information transmitted through a channel delayed in this way does not constitute a continuous flow of data, but produces an intermittent flow. Also, the rule of first-in first-out (FIFO) does not hold anymore.

Assumption (3) has been instrumental in all the works conducted so far. It has appeared both explicitly or implicitly, as a consequence on bounds formulated in the statements of convergence results.

Interestingly, temporary violation of this assumption is not necessarily causing major trouble in the stability analysis. It is more a condition that shall be satisfied "on average", as has been formulated in Bresch-Pietri and Petit (2014), under the relaxed form

$$\frac{1}{t - h_i} \int_{h_i}^{t} \dot{D}(\tau)^2 d\tau < \delta, \quad \forall t \in [h_i, h_{i+1}] \quad (4)$$

for some ordered sequence (h_i) of discontinuity points $\lim h_i = +\infty$, $\underline{\Delta} \leq h_{i+1} - h_i \leq \overline{\Delta}$. Of course, (3) implies (4).

3. CONTROL-INDUCED DELAY VARIATIONS: TRANSPORT PHENOMENA

We now present a first example where the delay depends on past values of the control. Consider a transport phenomena where the control variable is, directly, or indirectly, the flow-rate [2]. Consider that the flow is incompressible, single dimensional, so that the flow-rate is (spatially) uniform but time-varying. At any instant, the flow-rate can be freely changed (within some physical upper and lower limits). However, propagation of material takes time. If the nature (e.g. concentration) of the fluid matters, then a delay appears, as a simple effect of finite-speed propagation of medium. This is the case in flow networks employed for blending semi-finished products in refineries. This example is pictured in Figure 1.

The flow discussed above satisfies a simple conservation principle (leaving out the effects of viscosity), which is equivalently written under the form of a simple partial differential equation defined over a spatial domain $x \in [0, 1]$

$$\partial_t \xi(x, t) = u(t) \partial_x \xi(x, t)$$

where ξ is the propagated state and u in the input (flow-rate). The (smooth [3]) solutions of this PDE are such that

$$\xi(1, t) = \xi(0, t - D(t)) \quad (5)$$

where $D(t)$ is defined by

$$\int_{t-D(t)}^{t} u(\tau) d\tau = 1 \quad (6)$$

Using (5), one defines a delayed input-output relation. This delay is defined by the implicit integral equation (6).

[1] This result has (indirect) connections with the usual robustness margin determined from the Nyquist criterion for LTI systems

[2] It may be necessary to clarify that the flow-rate can be itself a distributed variable, as is the case of compressible flow Di Meglio et al. (2012a,b); Sinègre et al. (2005)

[3] Implicitly, we ignore shocks.