Stabilization and Tracking for P/PI Combustion Control over a Communication Channel

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Abstract: In the present work, motivated by the recent inclusion of optical variables in combustion processes, we consider the control of a reduced Hammerstein plant model over an additive white noise (AWN) channel located at the feedback path. For comparison, assuming uncertainty in the knowledge of the static nonlinearity of the Hammerstein plant model, we first propose in a one degree-of-freedom (DOF) scheme, the design of a proportional controller for robust stability. We then introduce a PI controller, in a 3 DOF scheme, to achieve not only robust stability, but also AWN channel Signal-to-Noise Ratio (SNR) minimization and setpoint first moment tracking.

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Keywords: Communication control applications. Control system design. Discrete digital dynamic control. Feedback control. P and PI controllers. Networked Control Systems.

1. INTRODUCTION

For the last two decades the research area of Networked Control Systems (NCS) has concentrated the research interest of the control community. (J.Chen et al., 2011). Theoretical developments have proceeded apace based on information theory (Nair and Evans, 2004; Martins and Dahleh, 2008), optimization and linear control (Elia, 2004; Braslavsky et al., 2007; Rojas, 2012), multivariable and multiagent approaches (Jadbabaie et al., 2003; Middleton and Braslavsky, 2010; Knorn et al., 2016) and more recently event-triggered control (Heemels et al., 2012; da Silva Jr. et al., 2014; Campos-Delgado et al., 2015).

All of the previous theoretical results and more, are now the basis for an informed control practice, revisiting established control processes, as well as facing new and demanding ones, toward achieving increased performance.

Such a revisited process is the combustion process, ubiquitous in most industrial setups Ballester and Garcia-Armingol (2010), which has recently benefited with the addition of optic based sensors Huang et al. (2010); Garces et al. (2016a). Commonly, combustion processes have their flue gasses monitored through analyzers or chromatographs, which inevitably introduce transport time-delays in the plant models and a biased measurement (Kamimoto et al., 2016; Baukal, 2010). On the other hand, optical measurements of the flame can be performed in-situ, avoiding the transport time-delay and providing a more accurate description of the combustion real time status (Ballester and Garcia-Armingol, 2010). Albeit, the obtained measurement is ideally transmitted through a communication channel, see Figure 1, avoiding unnecessary and prone to malfunction cabling due to the harsh environment and demanding conditions close to the furnace.

In Garces et al. (2016b, 2015) it is argued that for such combustion processes, monitored through optic based sensors, an Hammerstein first order model is representative of the real process, under the hypothesis of a mild nonlinearity in the stationary response of the optical measurements. Since the linear part of the plant model is a first order system, this motivate the use of P/PI controller. On the other hand, the input static nonlinearity (characteristic of an Hammerstein model) is treated in Alonge et al. (2015); Gao et al. (2015); Guo et al. (2015); Sun et al. (2009) with a 2 degree-of-freedom (DOF) controller scheme.

In our first contribution, we offer explicitly the design requirement for robust stability and its trade-off with the AWN channel SNR requirement when using a P controller.

* Hugo Garcés acknowledge the support of Dirección de Investigación e Innovación at Universidad Católica de la Santísima Concepción. Alejandro Rojas is grateful for the support from the Chilean Research Agency CONICYT, through Project Grant FONDECYT Regular No. 1150116 and Basal Project FB0008.
Our second contribution extends the previous to a PI controller in a 2 DOF scheme that solves the trade-off between robust stability and AWN channel SNR reduction.

In our third and last contribution we consider a 3 DOF scheme to the setpoint tracking objective, and thus highlight the trade-off between robust performance and tracking.

The significance of this work is to present a controller design strategy for optical measurements in a combustion process, to fill the gap between instrumentation systems and a feedback operation to increase energy efficiency or reduce the pollutants emissions in a complex operation, subjected to more restricted profit margins and fuels with non-constant composition.

This paper is organized as follows. Section 2 presents the standing assumptions for this work, briefly reviewing the proposed plant model and the channel SNR definition. Section 3 derives the design requirements for a PI controller in a 2DOF scheme achieving robust stability and channel SNR reduction. Section 4 extends the results to a PI controller in a 2 DOF scheme that solves the trade-off between robust stability, AWN channel SNR reduction and setpoint tracking. Conclusions are given in Section 6. All control results in this preliminary work are simulation based, we expect to achieve experimental confirmation at a later stage.

2. PRELIMINARIES

In this section we present the standing assumptions for this work.

2.1 Assumptions

**Plant model**: In Garces et al. (2016b, 2015) it has been established that a Hammerstein first order model can be a reasonable representation of an optically sensed combustion process

\[ y(z) = \frac{K_G}{\alpha z - 1} f(u), \]  \hspace{1cm} (1)

where \( K_G > 0 \) and \( \alpha > 1 \) are the plant model gain and time constant, whilst \( f(u) \) is the input static nonlinearity. The signal \( y(k) \) corresponds to the measured total radiation \( R_\text{tot}(k) \) and the input signal \( u(k) \) to the percentage of fan speed \( \lambda(k) \) injecting air into the combustion chamber. In Figure 2 we show the scatter plot and average value of stationary total radiation \( R_\text{tot}(\infty) \) measured in a ladle furnace preheating process (described in Samuelsson and Sohlberg (2010); Zabadal et al. (2004)), where the nonlinear static response is verified as function of the stationary value of fan speed \( \lambda(\infty) \). A schematic of optically sensed ladle furnace preheating process is presented in Figure 3 where the main stages of measurements are summarized as the field flame spectra from the flame measured with the spectrometer and the spectral processing stage where the optical variables are finally calculated.

From Figure 1 we assume that the controller \( C_1 \) is such that the output feedback system is stable in the sense that for any distribution of initial conditions, the distribution of all signals in the loop will converge to a stationary distribution. The power of the channel input, defined by \( \|s\|^2_{P_{\text{row}}} \triangleq \lim_{k\to\infty} E\{s^2(k)\} \), is then required to satisfy a user defined power constraint \( P \). Under the stationarity assumption presented in (Åström, 1970, §4.4), the power of the channel input can then be computed as \( \|s\|^2_{P_{\text{row}}} = ||T_{sr}(z)||^2 \left(\sigma_r^2 + \mu_r^2\right) + ||T_{sn}(z)||^2 \sigma_n^2 \), where the \( H_2 \) norm is defined as

\[ ||T_{\ell}(z)||^2 = \frac{1}{2\pi} \int_{-\pi}^{\pi} \left| T_{\ell}(j\omega) \right|^2 d\omega. \]  \hspace{1cm} (2)

The power constraint at the channel input can be then redefined as an SNR constraint \( \frac{P}{\sigma^2} \) which must be satisfied by the squared \( H_2 \) norm of \( T_{sr}(z) \) and \( T_{sn}(z) \)

\[ \frac{P}{\sigma^2} > ||T_{sr}(z)||^2 \left(\sigma_r^2 + \mu_r^2\right) + ||T_{sn}(z)||^2. \]  \hspace{1cm} (3)

From (2) we then have bound on the AWN channel SNR. We treat the partial knowledge of \( f(u) \), represented by \( f(\cdot) \), in a worst case scenario for which we define

\[ \gamma = \max \left[ f \left( f^{-1}(v) \right) \right]. \]  \hspace{1cm} (3)