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Adaptive-Smith Predictor for Controlling an Automotive Electronic Throttle over Network

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Abstract: The paper presents a control strategy for an automotive electronic throttle, a device used to regulate the power produced by spark-ignition engines. Controlling the electronic throttle body is a difficult task because the throttle accounts strong nonlinearities. The difficulty increases when the control works through communication networks subject to random delay. In this paper, we revisit the Smith-predictor control, and show how to adapt it for controlling the electronic throttle body over a delay-driven network. Experiments were carried out in a laboratory, and the corresponding data indicate the benefits of our approach for applications.
Keywords: Adaptive-Smith predictor, electronic throttle control, networked control systems, switching control.

1 Introduction

Electronic throttle control represents a novel technology that has been used over the last years by the automotive industry to improve the efficiency of spark-ignition engines [6–8, 12, 14, 20, 24, 26]. The electronic throttle control system comprises four parts: (i) accelerator pedal module, (ii) engine/transmission control module, (iii) electronic throttle body (ETB), and (iv) network.

This paper focus on controlling the electronic throttle body (ETB) through a network.

Designing a controller for the ETB is a difficult task because the ETB has a nonlinear behavior—nonlinearities arise from gear backlash, friction on the mechanical components, limp-home effects, and nonlinear forces provoked by the security return spring [8, 21–23, 26, 28–30].

To control the ETB, the current literature proposes different approaches, such as PID controller with system nonlinearities compensated by a heuristically tuned compensator [6], dynamic programming techniques [9], variable-structure control [20], robust discrete-time model reference adaptive control [7], [14], PID controller with adaptive compensator for friction, limp-home, and backlash [8], mixed constrained H_2/H_∞ controller [26], sliding-mode controller [12], asymmetric nonlinear PI controller [24], just to name a few.

The aforementioned control strategies require that sensors, controllers, and actuators are directly connected by wires, an unfeasible requirement in many cases—in modern vehicles, for instance, control signals from controllers and measurements from sensors are exchanged using a communication network, e.g., Controller Area Network (CAN), see [11, 17].

Communication through network brings up a challenge on how to handle the effects of the network-induced delays in the control loop. Delays are time-varying by its own nature—random driven—and they degrade the performance of control systems—recall that delays can destabilize closed-loop systems, see [3, 4, 13].

Smith-predictor control appeared as a seminal approach for controlling systems subject to fixed (deterministic) delay [18, Ch. 5]. Afterwards in the literature, the classical Smith predictor was improved to deal with time-varying delays, a strategy referred to as *adaptive* Smith predictor (ASP), showing promising results [5, 10, 25]. This paper shows an extension, a contribution towards the application of ASP in the control of automotive electronic throttle body.

Not only does the contribution of the paper rely on applying the ASP in the control of the throttle, but also it does present an improved ASP, a novel strategy that accounts the asymmetry of the throttle's valve. This asymmetry was firstly observed in [24]. Here, we modify the ASP strategy to account this asymmetry—checking this asymmetric-ASP strategy in practice sets the main contribution of this paper.

Our approach has implications for the automotive industry. Indeed, experiments were carried out in a laboratory testbed in which an electronic throttle body was controlled; the corresponding outcome illustrates the benefits of our approach.

2 Adaptive Smith predictor

In [10], the authors suggest using the classical Smith predictor to control systems subject to constant delay. However, the results of [10] do not apply when the underlying communication network is either random or time-varying.

Our main contribution relies upon adapting the Smith-predictor strategy to control an electronic throttle when the communication network has random delays. Our adapted strategy first recalls the so-called *adaptive Smith predictor* (ASP) from [10]. Recall that ASP stands for a scheme that modifies the classical Smith predictor so as to embed it with information of the network-induced time-varying delay. Second, we modify the ASP to include the asymmetry observed in [24], as detailed next.

Fig. 1 shows the ASP scheme. It also shows the process to be controlled, i.e., $G_p(s)$, as well as a communication network with delays in the forward path—τ^{ca}—and in the feedback path—τ^{sc}. The ASP scheme is composed by a controller $C(s)$, a process model $G_m(s)$, and a delay term that accounts the delays measured in the network τ^{est}.

As usual, $y(t)$ represents the output, $u(t)$ denotes the control input, and $r(t)$ represents the reference signal. The error signal, $e(t) = y(t) - r(t)$, should be made as small as possible.

The subscripts s and r in the variables denote 'sent' and 'received' signals, respectively, which allow us to write

$$u_r(t) = u_s(t - \tau^{ca}(t)) \quad \text{and} \quad y_r(t) = y_s(t - \tau^{sc}(t)). \tag{1}$$

2.1 Closed-loop analysis

For sake of notational simplicity, let us assume that the delays from the network links, i.e., τ^{ca} and τ^{sc}, are time invariant. In this case, the closed-loop transfer function of the block-oriented structure of Fig. 1 reads as

$$\frac{Y_s(s)}{R(s)} = \frac{C(s)G_p(s)e^{-\tau^{ca}s}}{1 + C(s)G_m(s) + N(s)}, \tag{2}$$

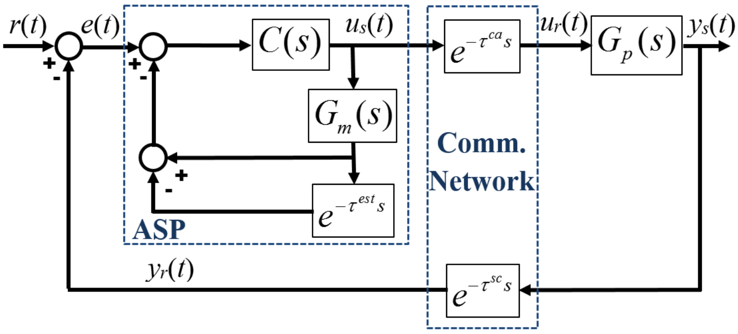

Figure 1: Adaptive Smith-predictor (ASP) controller in a closed-loop diagram. Controller communicates with the plant through a network.

where

$$N(s) = C(s)\left[G_p(s)e^{-(\tau^{ca}+\tau^{sc})s} - G_m(s)e^{-\tau^{est}s}\right]. \tag{3}$$

Remark 1. When $\tau^{ca}(t)$ and $\tau^{sc}(t)$ are time varying, one can employ the linear state-space approach to represent the block-oriented structure of Fig. 1, an approach equivalent to (2) (see [19, Sec. 2]).

The delays τ^{ca} and τ^{sc} can dramatically degrade the stability of the system—we want to minimize the negative effects of such delays in the stability. To do so, we need

$$N(s) \approx 0. \tag{4}$$

The expression in (4) does hold provided that not only the prediction model approximates the plant process, i.e., $G_m(s) \approx G_p(s)$, but also the estimated delay approximates the actual network-induced time-varying delay, i.e., $\tau^{est} \approx \tau^{sc} + \tau^{ca}$. In this case, the condition in (4) holds true so that (2) equals

$$\frac{Y_s(s)}{R(s)} = \frac{C(s)G_m(s)e^{-\tau^{ca}s}}{1+C(s)G_m(s)}. \tag{5}$$

A benefit drawn from the expression in (5) when compared to (2) is that delays cannot destabilize the system in (5).

Hereafter, we consider two assumptions: (i) the model $G_m(s)$ matches the process $G_p(s)$; and (ii) the estimated delay τ^{est} approximates the total communication delay $\tau^{sc} + \tau^{ca}$ (see [15, 16]).

2.2 Switching PID controller

In [24], the authors have observed that the behavior of the throttle valve depends on whether it is opening or closing, a feature called *asymmetric performance*. This feature is considered into the design of the adaptive Smith predictor based on a switching PID control, as follows.

The opening and closing behavior of the throttle followed the next switching rule:

$$\begin{aligned} &\dot{y}_r(t) \geq 0\text{: opening phase } (j=1),\\ &\dot{y}_r(t) < 0\text{: closing phase } (j=2). \end{aligned} \tag{6}$$

Then the switching-PID controller (SPID) reads as

$$C_j(s) = K_{p,j}\left(1 + \frac{1}{T_{i,j}s} + \frac{T_{d,j}s}{1+\alpha_j s}\right), \quad j = 1, 2, \tag{7}$$

where the constants K_p, T_i, and T_d represent the proportional, integrative, and derivative elements, respectively.

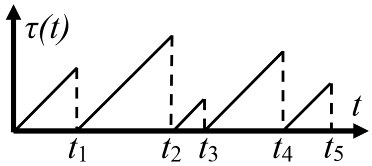

Figure 2: Example of the delays describing the zero-order hold function on aperiodic realization.

Modeling the electronic throttle valve

The literature acknowledges that nonlinear systems are the most appropriate ones to represent the electronic throttle valve [8, 21–23, 26, 28–30]; however, for sake of simplicity, we decided to let it be represented by a first order process with dead-time in the form

$$G_m(s) = \frac{K}{Ts+1}e^{-Ls}. \tag{8}$$

This simplification was purposeful to alleviate the underlying numerical burden of real-time implementation (see Section 3).

Remark. The *asymmetric* switching-PID control represents the scheme of Fig. 1, together with (7), and also with (8) modified to consider asymmetry, i.e., $G_{m,j}(s)$, $j = 1, 2$.

2.3 Delay in the communication channel modeled as a Poisson process

Recall the scheme of Fig. 1. By assumption, both delays on the forward channel $\tau^{ca}(t)$ and the feedback channel $\tau^{sc}(t)$ assume a sawtooth format, as illustrated in Fig. 2.

In addition, both delays satisfy $\dot{\tau}(t) = 1$, for all $t > 0$, almost everywhere, with discontinuous reset-to-zero points occurring at instants $t_0 = 0 < t_1 < t_2 < \cdots$, which correspond to the arrival times of a homogeneous Poisson process with rate λ. The inter-arrival times $\tau_k := t_{k+1} - t_k, k \geq 0$, form independent and identically distributed times, and the corresponding probability density function of the inter-arrival time τ_k reads as

$$\Pr[\tau_k = t] \; = \; \lambda e^{-\lambda t}, \quad \forall t \geq 0. \tag{9}$$

2.4 Delay in the ASP strategy

The adaptive Smith-predictor (ASP) strategy in Fig. 1 requires the value τ^{est}—recall that it should approximate the total communication delay $\tau^{sc} + \tau^{ca}$, as mentioned in Section 2.1.

At each sampling step, say $k > 0$, we measure the delay from the $(k-1)$-th step using a time-stamping technique. Next, following the suggestion of [2], we replace the term τ^{est} in the ASP scheme (see Fig. 1) by the time-varying process

$$\tau_k^{est} = \frac{2}{N} \sum_{\ell=k-N}^{k-1} \tau_\ell^{sc}, \tag{10}$$

where τ_ℓ^{sc} represents the communication delay from sensor-to-controller. The constant "2" in (10) arises from the simplifying assumption that τ_ℓ^{sc} and τ_ℓ^{ca} are identical.

3 Experimental results

This section presents experimental data obtained from a laboratory testbed, designed to control an electronic throttle body through a communication-emulated network.

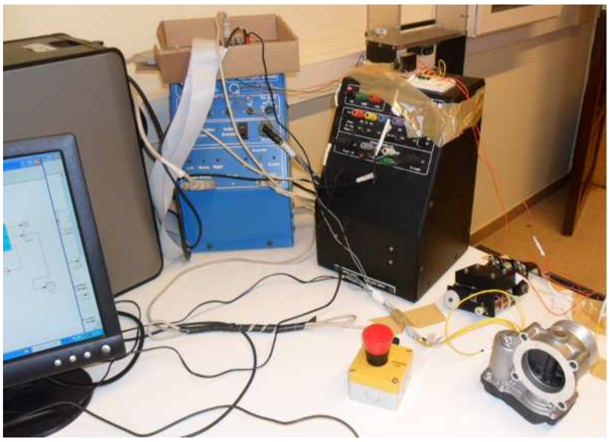

Figure 3: Laboratory testbed. Experimental setup for controlling the electronic throttle: Quanser power amplifier, Quanser real-time control board, and ETB.

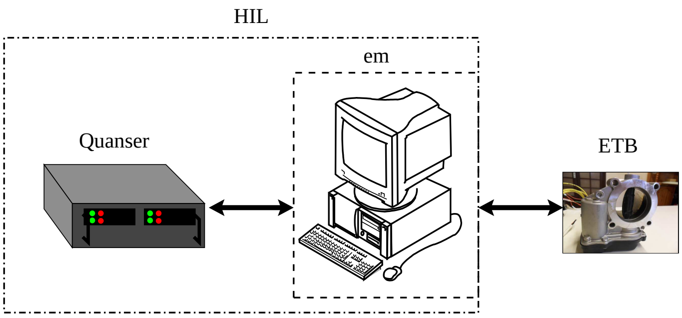

Figure 4: Diagram representing the setup assembled in the laboratory testbed. The Hardware-in-the-loop (HIL) device sends and receives signals from the electronic throttle body (ETB), and the signals reaches the Quanser board through a computer that emulated a network

3.1 Hardware-in-the-loop platform

The control strategy of Fig. 1 was implemented in a laboratory testbed that included both an automotive electronic throttle and a Hardware-in-the-Loop (HIL) device (Fig. 3). The laboratory was composed by the following elements [24]:

- Quanser Q4 real-time control board that sets the operation clock of the closed-loop (effective control, discrete time) at a fixed sampling rate of $T_s = 1$ ms;
- Quanser UPM180-25-B-PWM power amplifier (to supply the voltage and electrical current consumed by the equipment);
- Continental VDO electronic throttle body (c.f, [24]). The throttle device is equipped with a position sensor, an important device in feedback control systems [27]. The position sensor generates a proportional voltage ranging from 0 V (completely closed) to +5 V (completely opened);
- Computer that emulated a communication network with random delays, following the scheme of Fig. 4—delays were driven by a Poisson process (see Section 2.3).

3.2 Control methods: experimental comparison

For comparison purposes, six controllers were designed and checked in the laboratory testbed, all under the scheme of Fig. 1, as follows:

1. PID controller in $C(s)$. Set $G_m(s) \equiv 0$ and $\tau^{est} \equiv 0$;
2. Switching PID controller (SPID) as in (7). Set $G_m(s) \equiv 0$ and $\tau^{est} \equiv 0$;
3. Classical Smith Predictor based on the PID controller (SP-PID);
4. Classical Smith Predictor based on the switching PID controller (SP-SPID);
5. Adaptive Smith Predictor based on the PID controller (ASP-PID);
6. Adaptive Smith Predictor based on the switching PID controller (ASP-SPID).

The experiments that were carried out in the laboratory considered the aforementioned six control strategies with parameters designed by the Approximate M-constrained Integral Gain Optimization (AMIGO) tuning rules [1], which were calculated for PID tuning in process control:

$$\begin{aligned} K_p &= \frac{1}{K}\left(0.2 + 0.45\frac{T}{L}\right) - \text{proportional term}, \\ T_i &= \frac{0.4L + 0.8T}{L + 0.1T}L - \text{integral term}, \\ T_d &= \frac{0.5LT}{0.3L + T} - \text{derivative term}. \end{aligned} \tag{11}$$

The switching strategies, in particular, were designed by setting a simple average model $(G_{m,1} + G_{m,2})/2$ into AMIGO with $T = 0.4$.

First-order representation

Aiming for simplicity in the computational implementation, we decided to represent $G_m(s)$ as a first-order linear model (e.g., Section 2.2). Step responses allowed us to obtain

$$G_{m,j}(s) = \frac{19.72}{a_j s + 1} e^{-0.025s}, \quad j = 1, 2, \tag{12}$$

where $j = 1, 2$ corresponds to the opening and closing valve, namely, $a_1 = 0.65$ (opening) and $a_2 = 0.15$ (closing).

3.3 Experimental results

Experiments were carefully performed to control the electronic throttle under the six proposed control strategies.

The communication-emulated network were checked under two Poisson processes: high load ($\lambda = 100$) and low load ($\lambda = 250$). A sample of Poisson delays used in the experiments is illustrated in Fig. 5 and 6. This sample was kept fixed for all control methods, just for sake of a fair comparison.

The reference input signal was constructed as follows. Two sinusoidal signals were summed up, one signal with amplitude of 25 degrees centered around 45 degrees and frequency of 1 rad/s, and the other with amplitude of 3 degrees and frequency of 5 rad/s. This reference signal was

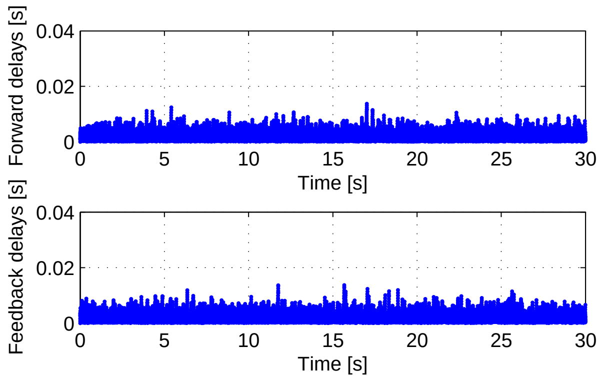

Figure 5: Part A ($\lambda = 250$): Forward channel and feedback channel delays.

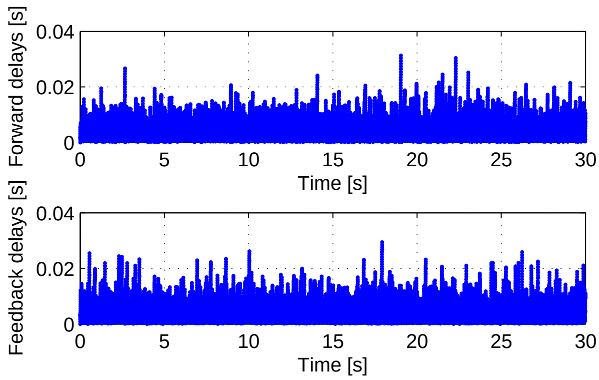

Figure 6: Part B ($\lambda = 100$): Forward channel and feedback channel delays.

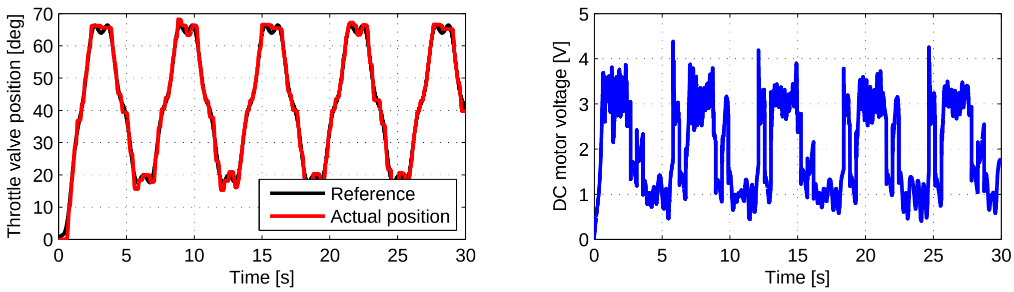

Figure 7: Part A ($\lambda = 250$): Curves for the ASP-SPID control. Throttle valve position.

useful to analyze how the controllers actuated not only to large and small variations, but also to slow and fast variations of the throttle valve position.

Experimental outcome obtained with the ASP-SPID control architecture for the two different network loads is summarized in Figs. 7 and 8. As can be seen, the effect of time-varying delays introduced by the communication network on the closed-loop seems negligible.

Figs. 9 and 10 show the corresponding experimental error signal. Data suggest that, even though the error increased with the augmented load of the network, the error kept bounded by 7 degrees, an acceptable value according to [14].

Evaluation of the classical PID was also considered in the laboratory—not surprisingly, the classical PID showed an unstable behavior. This finding emphasizes the usefulness of our approach for controlling the electronic throttle through networks subject to random delays.

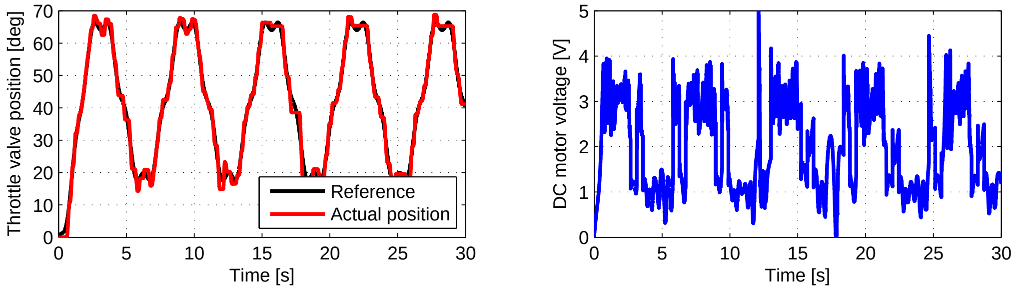

Figure 8: Part B ($\lambda = 100$): Curves for the ASP-SPID control. Throttle valve position.

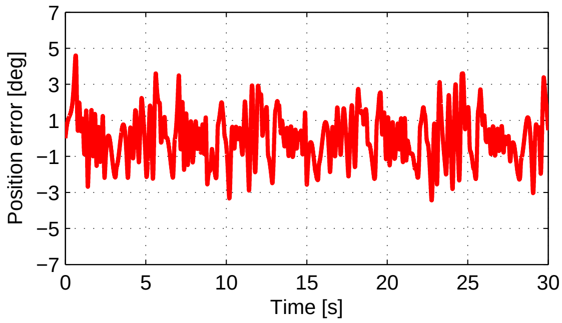

Figure 9: Part A ($\lambda = 250$): Curves for the ASP-SPID control. Error signal.

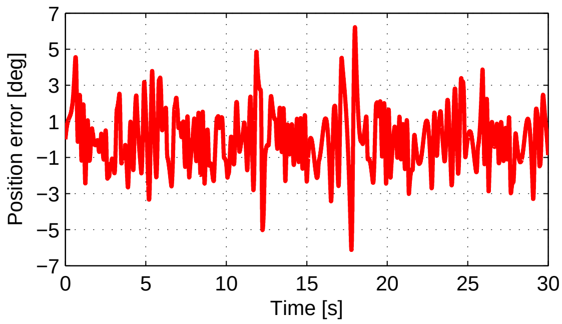

Figure 10: Part B ($\lambda = 100$): Curves for the ASP-SPID control. Error signal.

Finally, to complete the experimental analysis, we computed the cumulative error $I = \sum_{k=0}^{\infty} e_k^2$ for all methods—e_k represents the experimental, measured error at the k-th sampling time, see Table 1. As can be seen, our switching strategy—ASP-SPID—produced the lowest error for both low and high loads. This experimental evidence suggests that the switching control be a useful tool for real-time applications.

Table 1: Experimental error index for an automotive throttle body.

Controller	**Low load**	**High load**
PID	∞	∞
SPID	∞	∞
SP-PID	79.61	111.02
SP-SPID	65.81	84.20
ASP-PID	64.41	80.62
ASP-SPID	55.37	76.66

4 Concluding remarks

The paper revisits the adaptive Smith-predictor control, and shows how modify it to incorporate the asymmetry of the throttle—a feature observed in [24]. The asymmetry generated a switching PID-based control, referred to as *Adaptive Smith Predictor based on the switching PID controller*. This controller was checked in a real-time experiment, that for controlling an automotive electronic throttle device over a random-delay-driven network—the proposed controller showed promising experimental results.

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