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Two degree-of-freedom design for a send-on-delta sampling PI control strategy

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ABSTRACT

A complete event-based two-degree-of-freedom PI controller is presented. The architecture of the control system is based on two decoupled PI controllers, one for the set-point following and one for the load disturbance rejection task. The distinctive feature of the proposed approach is that the two controllers have the same parameters and the reference tracking performance is improved by suitably modifying the reference signal applied to the set-point following controller. Examples of the technique are given. In particular, the control strategy has been applied to a distributed solar collector field.

1. Introduction

Since their introduction, the Proportional-Integral-Derivative (PID) controllers are surely the most employed controllers in industry owing to the advantageous cost/benefit ratio they provide for many processes. In particular, the Proportional-Integral (PI) controllers are often preferred in many applications (Åström & Hägglund, 2006).

Their main advantages are their simplicity and the presence of many tuning techniques (O'Dwyer, 2006) and of well established additional functionalities such as anti-windup and feedforward action (Visioli, 2006). In particular, two-degree-of-freedom PI(D) controllers (obtained, for example, by weighting the set-point for the proportional action, Araki, 1988) allow the designer to decouple the set-point tracking and the disturbance rejections tasks in order to improving the controlled system performance.

In recent years, thanks to the diffusion of networked control systems, the research effort in reducing the traffic load (and therefore the latencies and the delay jitter) has strongly increased. In this context, the event-based control approach appears as one of the most interesting solutions (Åström, 2008; Heemels, Sandee, & Van den Bosch, 2008; Vasyutynskyy & Kabitzsh, 2010). Another interesting reason for the application of event-based control is the energy-saving of battery-supplied component present in the control loop by reducing the required communication efforts and the CPU utilization (Anastasi, Conti, Francesco, & Passarella, 2008; Yarvis & Zorzi, 2008).

For these reasons, many event-based PID controller architectures have been devised recently (Årzèn, 1999; Beschi, Dormido, Sánchez, & Visioli, 2012b; Durand & Marchand, 2009; Rabi & Johansson, 2008; Sánchez, Visioli, & Dormido, 2011). Among them, those based on the so-called *send-on-delta* (SOD) sampling (or absolute sampling) have received a significant attention (Sánchez, Guarnes, Dormido, & Visioli, 2009; Vasyutynskyy & Kabitzsh, 2005, 2007). In particular, in Sánchez et al. (2011) a pure state event-based two-degree-of-freedom PI control scheme has been proposed, with the aim to improve set-point tracking performance and reduce the number of events during the transient. It consists in applying a suitable feedforward controller capable to provide a minimum-time set-point transition when required and a feedback controller that handles the load disturbance rejection task. The coupling among the two controllers can be obtained in two different ways, each one with its own advantages and disadvantages.

In general, one of the main drawbacks of event-based control strategies is the presence of several parameters (for example, the sampling thresholds) which entails difficult tuning of the controller. Moreover, as the event-based controllers are nonlinear, limit cycles and stick–slip phenomenons can seriously decrease the performance (Vasyutynskyy, 2008). For this reason, in this paper (which is an expanded version of Beschi, Dormido, Sánchez, & Visioli, 2012a) we propose a new two degree-of-freedom PI control scheme whose salient feature is that the feedforward and feedback controllers can have the same PI parameters. In fact,

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a suitable reference (command) signal is introduced to obtain the minimum-time set-point transition. In this way the coupling between the two controllers is more natural and it is provided in a unique and effective manner. Further, the use of tuning rules originally devised for standard (time-based) PI controllers can be compared in the framework of event-based PI controllers. Note that the proposed controller represents a (although different from the standard one, because of the event-based sampling) two-degree-of-freedom architecture (as well as in Sánchez et al., 2011) because it is based on the activation of the set-point tracking oriented controller only during the reference changes.

The paper is organized as follows. In Section 2 the overall control scheme and the control design specifications are described. The disturbance rejection controller is explained in detail in Section 3, while the set-point following controller is addressed in Section 4. The overall control algorithm is then outlined in Section 5. Simulation results are presented in Section 6 while experimental results in laboratory-scale and full-scale plants are analyzed in Section 7. Finally, conclusions are drawn in Section 8.

2. Control architecture

The proposed control strategy is developed for overdamped self-regulating processes, which can be modelled, as it is industrial practice, by a first-order-plus-dead-time (FODPT) transfer function, namely

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

where K is the gain, T is the time constant and L is the dead time. The basic idea of this work is to realize a two-degree-of-freedom controller by using two event-based PI control loops with different sampling algorithms.

The first one has the aim of handling the load disturbance rejection task and it is named as DR-PI. The derivative action is not considered because its implementation is very critical with a varying, and possibly long, sampling period.

The second one (named SP-PI) has the aim of improving the set-point following task, for this reason it operates only during the set-point transients. The two controllers can have the same values of the parameters (namely, of the proportional and integral gains), which should be chosen to improve the disturbance rejection task, as the set-point following performance is recovered by applying a suitable piecewise constant reference to the SP-PI controller. In this way, it is possible to simplify the overall controller design.

As mentioned above, the event-based SP-PI controller works only during the transitions with the aim of generating, by supposing that there are no disturbances and model mismatches, a predefined process variable transition $y_p(t;\tau)$ from an initial value y_0 to a final value y_f in a predefined time interval τ by using just three events. These events are generated when the set-point r changes (namely, at the beginning of the transition), when the process output reaches a threshold value y_τ (see (11)) and, eventually, when the output attains the new set-point value.

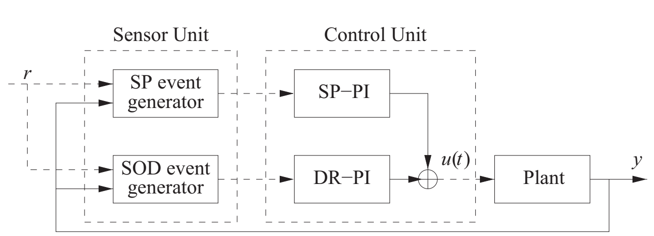

Fig. 1. Scheme of the two DOF control strategy. Dashed lines indicate event-base sampled signals.

As the model mismatches and disturbances are typically present in the controller plants, the DR-PI controller has to compensate their effects in order to keep the output $y(t)$ as close as possible to the predefined process output $y_p(t;\tau)$, which is the reference input of this controller. The event generation is done with a send-on-delta sampling.

The overall control scheme is shown in Fig. 1 and the following sections illustrate the controllers details.

3. Disturbance rejection PI controller

As already mentioned in the previous section, the task of the DR-PI controller is to handle the disturbance rejection task, that is, the controller does not work if the plant is perfectly modelled and there are no disturbances. In fact, the proportional or integral parts are updated only if there is a send-on-delta sampling event in the error or in the integrated errors signal, respectively. In particular, the proportional action is updated when the sensor unit sends a new value of the control error. The transmission occurs when the difference between the current error and the last one is greater than a predefined value. In the same way, when the sensor unit sends a new value of the integrated error the integral action is updated. This event is triggered when the integrated error changes of a predefined value with respect to the last integrated error value that has been sent.

The standard anti-windup functionality could be implemented in the control unit. In this paper, the backcalculation approach has been used. Note that the integral of the back-calculation signal can be computed without significant effort when a new event arises, because both the saturated and non-saturated control signals are constant between two events. The backcalculation time constant has been set equal to the integral time constant $T_i=K_pK_i^{-1}$.

Formally, the error and the integrated error are defined, respectively, as

$$e_{DR}(t)=(r_{DR}(t;\tau)-y(t))f(r_{DR}(t)-y(t)) \tag{2}$$

and

$$IE_{DR}(t)=\int_0^t f(r(x)-y(x))(r_{DR}(x)-y(x))\,dx \tag{3}$$

where $r_{DR}(t)$ is chosen to be equal to the predefined process output (see (9)) and $f(x)$ is the following function:

$$f(x)=\begin{cases}1 & \text{if } |x|>\varepsilon\\ 0 & \text{if } |x|\le\varepsilon,\end{cases} \tag{4}$$

which is introduced in order to “freeze” the controller when the system output reaches the desired precision band ε.

A proportional event is triggered (namely, the signal $e_{DR}(t)$ is sent to the controller) when the following condition is verified:

$$|e_{DR}(t)-e_{DR}(\bar{t}_P)|\ge\Delta_p \tag{5}$$

where Δ_p is a suitable threshold value and $\bar{t}_P$ is the last time stamp of proportional action. Similarly, the signal IE_{DR} is sent to the controller only if

$$|IE_{DR}(t)-IE_{DR}(\bar{t}_I)|\ge\Delta_i \tag{6}$$

where Δ_i is a suitable threshold value and $\bar{t}_I$ is the last time stamp of integral action. The control law can be therefore written as

$$u_{DR}(t)=K_pe_{DR}(\bar{t}_P)+K_iIE_{DR}(\bar{t}_I) \tag{7}$$

where K_p is the proportional gain and K_i is the integral gain. The control action $u_{DR}(t)$ is updated only when new values of $e_{DR}(t)$ or $IE_{DR}(t)$ are received.

Notwithstanding the tuning of these kinds of event-based controllers has been only partially addressed in the literature,