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Generalized sampled-data holds to reduce energy consumption in resonant systems

Unai Ugalde*, Rafael Bárcena, Koldo Basterretxea

Department of Electronic Technology, University of the Basque Country, UPV/EHU, School of Industrial Technical Engineering, 3 R. M. Pitxitxi Ave., Bilbao 48013, Spain

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ABSTRACT

This paper presents an exhaustive experimental study on the performance of a new design of generalized sampled-data hold function (GSHF) introduced in Ugalde, Bárcena, and Basterretxea (2012). First a simple tuning procedure is developed for the GSHF to improve the intersample response while not damaging the plant output response. Next the reconstruction algorithm is enhanced so that the GSHF can remove the steady-state errors that dry friction causes in positioning systems. The experiments conducted on a small-scale lightly damped resonant system show that significant energy savings can be achieved in regulation with no extra hardware, and that no additional computational load results, except having to call the D/A converter more than once per sampling period.

1. Introduction

In most digital control systems a zero-order hold (ZOH) performs the required discrete-to-continuous control signal reconstruction, despite the existence of other devices that implement more elaborated actions. Traditionally these alternative devices have fallen into two distinct families: on the one hand, the generalized sampled-data hold functions (GSHFs: see Chammas & Leondes, 1978; Kabamba, 1987); on the other hand, the first-order hold and the fractional-order hold (FOH and FROH: see Hagiwara, Yuasa, & Araki, 1993; Ishitobi, 1996; Passino & Antsaklis, 1988).

Although GSHFs have produced promising results in e.g. decentralized control (Aghdam, Davison, & Becerril-Arreola, 2006; Lavaei & Aghdam, 2007), the fact is that they have not yet made their way into the industrial world. This incomplete success may be due to their unsatisfactory intersample behavior (Feuer & Goodwin, 1994, 1996) as well as because of a certain degree of bad reputation they still bear in the control community since they were proposed to disguise nonminimum-phase continuous models as minimum phase discretized models (Rossi & Miller, 1999; Yan, Anderson, & Bitmead, 1994), which collides with essential limitations of control systems, as Freudenberg, Middleton, and Braslavsky (1995, 1997) so rightly pointed out.

On the other hand, FROHs do not have these weaknesses, but they have just one single tuning parameter, the gain β, whose setting has been approached only in the z-domain until now (Bárcena & De la Sen, 2003; Bárcena, De la Sen, & Sagastabeitia, 2000; Bárcena, De la Sen, Sagastabeitia, & Collantes, 2001). Therefore it remains to be seen what the full potential of the FROH would be, should its parameterization be enriched and/or its tuning be developed in other frameworks.

Precisely motivated by these facts, the recent work (Ugalde, Bárcena, & Basterretxea, 2012) introduces a new hold design that is basically a generalization of the FROH merging the advantages of the two families mentioned above: as many tuning parameters as desired like 'conventional' GSHFs, and adequate intersample behavior like FROHs. Denoting the discrete-time input u_k and the continuous-time output $\overline{u}(t)=\sum_{k=0}^{\infty}\overline{u}_k(t)$, with $\overline{u}_k$ being the portion of $\overline{u}$ for $t\in[kh,kh+h)$ and h the sampling period, this GSHF produces the reconstruction

$$\overline{u}_k(t)=u_k+f(t/h-k)\times(u_k-u_{k-1}), \tag{1}$$

$$\text{with } f(x)=\beta_0+\beta_1x+\beta_2x^2+\cdots \quad \text{and} \quad x\in[0,1), \tag{2}$$

which becomes the action of a FROH when $f(x)=\beta x$.

The advantages just mentioned are apparent in the expressions above. Indeed, on the one hand, like in FROHs, from (1) it is inferred that $u_k\to u_{k-1}\Longrightarrow\overline{u}_k(t)\to u_k$, which guarantees a ripple-free steady-state intersample; on the other hand, unlike in FROHs, now an unlimited number of gains $\beta_0,\beta_1,\beta_2,\ldots$ are available in (2) to profit from. However, there is yet no experimental evidence to determine whether this new GSHF is truly free from the

* Corresponding author. Tel.: +34 946014473; fax: +34 946014300.
E-mail address: unai.ugalde@ehu.es (U. Ugalde).

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deficiencies of conventional holds. Experimentation would also help us to identify possible implementation difficulties and practical issues that might arise should these alternative reconstruction policies be introduced in industrial environments.

Therefore this paper presents an exhaustive study on the tuning, implementation and performance of this new kind of GSHF. For the experimentation a commercially available small-scale two-mass positioning system has been chosen that consists of two rotating cylinders interconnected through a thin flexible rod (Biagiotti & Melchiorri, 2012; Lambrechts, Boerlage, & Steinbuch, 2005; Saey, Cauwe, & Deconinck, 2011). Together, these elements form a fourth-order noncollocated lightly damped system (Franklin, Powell, & Workman, 1998, Appendix A4) that contains many of the features encountered in industrial motion control systems. In particular, it exhibits a low frequency mechanical resonance like many rolling mills (Dhaouadi, Kubo, & Tobise, 1993; Vukosavić & Stojić, 1998) as well as paper machines (Valenzuela, Bentley, & Lorenz, 2005a, 2005b), and it is well known that ignoring these resonances can lead to damaging oscillations (Szabat & Orlowska-Kowalska, 2007); see also Jinbang, Wenyu, Anwen, and Zhou (2013). On the other hand, although the setup does not include backlash-producing elements, it does exhibit considerable dry friction effects (Armstrong-Hélouvry, Dupont, & Canudas de Wit, 1994).

In setting the number of gains of the GSHF and their values, the purpose will *not* be to alter the at-sample performance of the system. Indeed, as discussed above, this approach has apparently hit a dead-end for FROHs and certainly produced very questioned results for conventional GSHFs. So instead, the additional degrees-of-freedom available will be used to try to reduce the control effort by shaping the intersample response of the control signal. This approach will soon be seen to achieve considerable energy savings in the regulation of the example system against output step disturbances while keeping the at-sample performance essentially unaltered. Furthermore, if the digital feedback controller finishes its control tasks within a short fraction of the sampling time, which is often the case, then the alternative reconstruction algorithm, which basically consists in evaluating the polynomial (2) and calling the D/A converter every $t=h/N$, $N>1$, can be easily accommodated in the remaining idle time, thus making it unnecessary to add extra hardware resources.

Due to the structural similarities with the experimental setup used in this work, the first natural candidates for the industrial application of the alternative reconstructions and associated tuning procedure proposed here are precision positioning systems such as, but not only, robotic manipulators (Aghili, Buehler, & Hollerbach, 2001; Lin, McInroy, & Hamann, 2005; Sweet & Good, 1985; Zhang & Furusho, 1998) and *X*–*Y* table positioning systems (Lim, Seo, & Choi, 2001; Liu, Luo, & Rahman, 2005; Sollmann, Jouaneh, & Lavender, 2010). Furthermore, speed control systems could also benefit such as those encountered in the rolling mills and paper machine sections mentioned previously, as well as e.g. the oil drilling station recently studied by Pavković, Deur, and Lisac (2011); indeed, the disturbances endured by these systems may not necessarily coincide with the neat unit output step considered in the present work, and so the relative *power* savings attained in them may not be the same as in the present work; however, because these industrial systems are continuously facing regulation and have high energy demand, the accumulated *energy* savings might be significant.

2. Preliminaries

Let us first provide a brief background on an interesting novel FROH tuning procedure, as well as on the topic of dry friction and its potentially fatal consequences. Indeed, from an industrial perspective, the performance of a precision positioning mechanism cannot be completely studied unless this nonlinear phenomenon is also considered. In fact, although in principle the dry friction-related issues might seem to be unrelated to the main subject of this paper, they will turn out not to be so completely independent.

2.1. FROH-based signal smoothing

The study will be based on the scalar control scheme of Fig. 1, supposing that a step output disturbance occurs at $t=0$, and that different hold choices are available for the block '$H(s)$'. However, to begin with a new procedure will have to be derived in order to adjust the value of β, the gain of the FROH. Indeed, because the FROH is a particularization of the GSHF being evaluated here, it is natural to first compare the performances of these two devices. However, all FROH tuning procedures published to date are aimed at placing the *z*-zeros of the discretized plant model at some given positions, typically as close to the origin as possible. But this approach is seldom, if ever, followed in industrial applications; particularly it is not either used by Lambrechts et al. (2005) or considered in Lambrechts (2009), both of which should be followed as close as possible because they form the basis for the experimental study presented here.

Therefore in the following a new time-domain-based FROH-tuning approach will be presented briefly; although it may look like an ad hoc approach at first sight, it can be shown to be successfully applicable not only to the case being dealt with here, but also to other plants, particularly when $G(s)$ models a lightly damped resonant system and $D(z)$ is designed and tuned accordingly.

With energy savings in mind, the purpose of the new tuning procedure will be to smooth the intersample portion of the initial jump of the control signal resulting from a step disturbance, when such a jump follows the pattern of Fig. 2, i.e. the first two initial jumps $0\to u_0$ and $u_0\to u_1$ going off in opposite directions, which happens in the control setup under study. Specifically, it is proposed to choose the value of β so as to make the reconstructions of the 0th and 1st intervals point towards the same end value, namely

$$\overline{u}_1(2h)=\overline{u}_0(h); \tag{3}$$

then, from (1) to (2) and because $f(x)=\beta x$ in a FROH, Eq. (3) becomes simply

$$u_1+\beta(u_1-u_0)=u_0+\beta u_0,$$

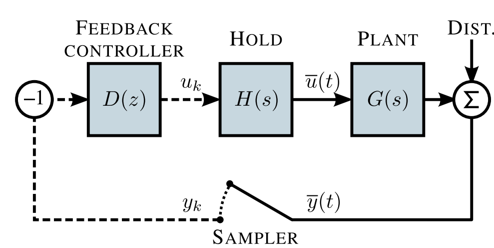

Fig. 1. Control system under study; tracking elements (trajectory planner, feedforward controller, etc.) not shown.

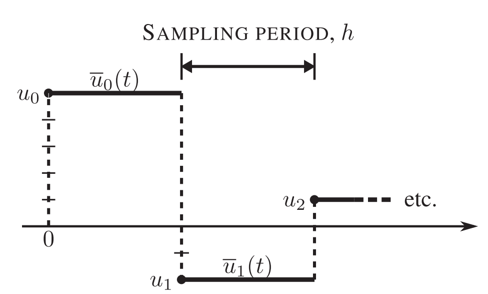

Fig. 2. Digital control signal with first two initial jumps going off in opposite directions ($0\to u_0$ upwards, $u_0\to u_1$ downwards) resulting in $\alpha=1.4$.