



**HAL**  
open science

## Stability of time-delay reset control systems with time-dependent resetting law

Miguel A. Davó, Frédéric Gouaisbaut, Alfonso A Baños, Sophie Tarbouriech,  
Alexandre Seuret

► **To cite this version:**

Miguel A. Davó, Frédéric Gouaisbaut, Alfonso A Baños, Sophie Tarbouriech, Alexandre Seuret. Stability of time-delay reset control systems with time-dependent resetting law . 5th IFAC Conference on Analysis and Design of Hybrid Systems (ADHS 2015), Oct 2015, Atlanta, United States. 6p. hal-01587482

**HAL Id: hal-01587482**

**<https://hal.science/hal-01587482>**

Submitted on 14 Sep 2017

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Stability of time-delay reset control systems with time-dependent resetting law <sup>1</sup>

M. A. Davó\* F. Gouaisbaut\*\*\*\* A. Baños\*  
S. Tarbouriech\*\*\*\* A. Seuret\*\*\*\*

\* *Dpto. Informática y Sistemas, University of Murcia, 30071 Murcia, Spain.*

\*\* *CNRS, LAAS, 7 avenue du Colonel Roche, F-31400 Toulouse, France.*

\*\*\* *Univ de Toulouse, UPS, LAAS, F-31400, Toulouse, France.*

\*\*\*\* *Univ de Toulouse, LAAS, F-31400, Toulouse, France.*

---

**Abstract:** This work presents results on the stability of time-delay reset control systems under time-dependent resetting conditions. The stability of a reset control system composed by a time-delay process and a proportional and integrative plus Clegg integrator (PI+CI) compensator is tackled by using the framework of sampled-data systems. It leads to sufficient stability conditions expressed in terms of LMIs (Linear Matrix Inequality), that depend explicitly on the reset times. In contrast to previous results, the proposed conditions allow to guarantee the stability of reset systems with unstable base system.

*Keywords:* Reset control, Time-Delay, Impulsive systems, Sampled-data control

---

## 1. INTRODUCTION

Reset control systems are a special type of hybrid systems, in which the system state (or part of it) is reset at the instants it intersects some reset surface. When the reset is defined as a function of time one can consider the reset control system as an impulsive system. In the past decades, the importance of impulsive systems has been highlighted by many researchers due to the number of potential broad applications in various fields, such as control systems with communication constraints, sampled-data systems, mechanical systems (Haddad et al. (2006); Chen and Zheng (2009b); Hespanha et al. (2008); Naghshabrizi et al. (2008) and the monographs Bainov and Simeonov (1989) and Lakshmikantham et al. (1989)). In general, impulsive systems may be classified in (i) systems with impulses at fixed instants, (ii) systems with impulses at variable instants, and (iii) autonomous systems with impulse effects. Reset control systems are included in (iii) since they have a reset surface which does not depend on the time. Significant progress on the stability of impulsive dynamical systems has been made during the past 20 years, see Chen and Zheng (2009c,a, 2011); Guan (1999); Khadra et al. (2009); Liu et al. (2007); Wang and Liu (2005); Yang and Xu (2007); Hetel et al. (2013) and references therein. However, most of the research effort has been dedicated to cases (i) and (ii), and then many results are not directly applicable in the case of reset systems.

Recently different results on the stability of time-delay reset control systems have been developed for the zero crossing reset condition. A delay-independent condition was

presented in Baños and Barreiro (2009), and extended to delay-dependent condition in Barreiro and Baños (2010); Prieto et al. (2012). Quadratic stability of time-delay reset control systems with reset surface uncertainty was considered in Guo and Xie (2012). More recently the previous results have been extended to input-to-output stability in Mercader et al. (2013b), Mercader et al. (2013a). All these results are based on a generalization of the so-called  $H_\beta$  condition (see Beker et al. (2004)) for non delay reset control systems. The main idea is the existence of a Lyapunov-Krasovskii (LK) functional which must always decrease during the flow and must decrease or remain equal during the jumps. In general, this basic result may be conservative. In Davó and Baños (2013a) a less conservative result is obtained by allowing some bounded increments of the functional after the reset instants. Nevertheless, these sufficient conditions are still conservative. The conditions obtained are not able to guarantee asymptotic stability if the base system is not stable. This limitation of the approach comes from the fact that in general the reset action with state-dependent resetting law cannot be guaranteed, which means that the reset control system may evolve without reset action for some initial conditions, implying the stability of the base system.

In this work, we focus on the stability of a reset control system submitted to a single time-delay, and with a time-dependent resetting law. In this case, the time between two consecutive reset instants is considered to be in a given interval. Therefore, the existence of an infinity number of reset actions for any initial condition is guaranteed. In contrast to the previous work, here the stability of the base system is not needed, and then less conservative results are expected. In spite of the fact that most of the results of impulsive systems may be applied, they are limited to a

---

<sup>1</sup> This work was supported by FEDER (European Union), 'Ministerio de Ciencia e Innovación' of Spain under project DPI2010-20466-C02-02 and the ANR Project LIMICOS 12-BS03-005-01.

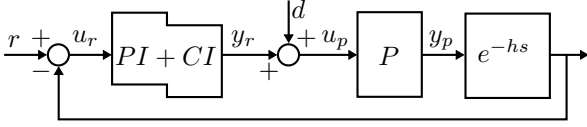


Fig. 1. Reset control system setup.

strict decrement of the LK functional during the impulse actions. Therefore, they cannot be applied to the setup of this paper, since the reset actions cannot affect the states of the process in a reset control system.

The main idea of this paper is the transformation of the reset control system into a sampled-data system, so that the latest stability results in the framework of sampled-data systems can be applied. This transformation can be directly made for a particular reset compensator which is called PI+CI (Baños and Vidal (2012)). This compensator is a simple modification of a PI compensator, which includes a Clegg integrator (CI) in parallel. PI+CI has been shown to be effective in several control experiments of processes with time-delay (Vidal and Baños (2012); Davó and Baños (2013b)). In addition, the stability of the PI+CI has been analyzed in Vidal (2009) for non delay processes. The reset control system composed by the PI+CI compensator can be modeled as a sampled-data system where the controlled process consists of a closed-loop system with internal time-delay. In this way, the results of Seuret (2011, 2012) are extended with a new LK functional (Seuret and Gouaisbaut (2014)), and delay-dependent criterion is developed for the asymptotic stability.

*Notation:* Throughout the article, the sets  $\mathbb{R}$ ,  $\mathbb{R}^+$ ,  $\mathbb{R}^n$ ,  $\mathbb{R}^{n \times n}$  and  $\mathcal{S}_n$  denote the sets of real numbers, nonnegative real numbers, the  $n$ -dimensional Euclidean space,  $n \times n$  matrices and symmetric matrices, respectively. A column vector is denoted by  $\mathbf{x} \in \mathbb{R}^n$ . Given two vectors  $\mathbf{x}_1$  and  $\mathbf{x}_2$ , we write  $(\mathbf{x}_1, \mathbf{x}_2)$  to denote  $[\mathbf{x}_1^\top, \mathbf{x}_2^\top]^\top$ . The notation  $\|\mathbf{x}\|$  is the euclidean norm for  $\mathbf{x} \in \mathbb{R}^n$ .  $\mathcal{C}([a, b], \mathbb{R}^n)$  stands for the set of continuous functions mapping  $[a, b]$  to  $\mathbb{R}^n$ , with the norm  $\|\phi\| = \max_{\theta \in [a, b]} |\phi(\theta)|$ . The identity matrix and the zero matrix of adequate dimensions are denoted by  $I$  and  $0$ , respectively. The notation  $P \succ 0$  for  $P \in \mathcal{S}_n$  means that  $P$  is positive definite. The set of positive definite matrices is denoted by  $\mathcal{S}_n^+$ . For a matrix  $A \in \mathbb{R}^{n \times n}$ , the notation  $He(A)$  refers to  $A + A^\top$ .

## 2. PRELIMINARIES AND PROBLEM MOTIVATION

Consider a time-delay reset control system as shown in Fig. 1, given by the feedback interconnection of a linear and time invariant (LTI) system  $P$  and a PI+CI (both single-input-single-output).  $P$  is given by the state-space system

$$P : \begin{cases} \dot{\mathbf{x}}_p(t) = A_p \mathbf{x}_p(t) + B_p u_p(t), \\ y_p(t) = C_p \mathbf{x}_p(t), \end{cases} \quad (1)$$

where  $\mathbf{x}_p \in \mathbb{R}^{n_p}$  and  $A_p \in \mathbb{R}^{n_p \times n_p}$ ,  $B_p \in \mathbb{R}^{n_p \times 1}$ ,  $C_p \in \mathbb{R}^{1 \times n_p}$ . The PI+CI compensator is simply a parallel connection of a PI compensator and a Clegg integrator. In the state-space, the PI+CI can be expressed by using a state  $\mathbf{x}_r = (x_i, x_{ci}) \in \mathbb{R}^2$ , where  $x_i$  is the integral term

state, and  $x_{ci}$  corresponds to the Clegg integrator state. Its state-space realization is given by

$$PI + CI : \begin{cases} \dot{\mathbf{x}}_r(t) = B_r u_r(t), & t \notin \mathcal{T}, \\ \mathbf{x}_r(t^+) = A_\rho \mathbf{x}_r(t), & t \in \mathcal{T}, \\ y_r(t) = C_r \mathbf{x}_r(t) + k_p u_r(t), \end{cases} \quad (2)$$

where  $t^+ = t + \epsilon$  with  $\epsilon \rightarrow 0^+$ , and the matrices  $B_r$ ,  $C_r$ , and  $A_\rho$  are given by

$$B_r = \begin{bmatrix} k_i \\ 0 \end{bmatrix}, \quad C_r = [1 \quad 1], \quad A_\rho = \begin{bmatrix} 1 & 0 \\ -p_r & 0 \end{bmatrix}. \quad (3)$$

In this work, we consider for simplicity that the connection between  $P$  and PI+CI is only affected by a time-delay  $h$  at the output of system  $P$ . The proposed approach can also be applied to obtain similar results when the time-delay is at the input of  $P$ . The autonomous closed-loop system (with zero exogenous signals, that is  $r = d = 0$ ) is obtained by making the connections  $u_p(t) = y_r(t)$  and  $u_r(t) = -y_p(t - h)$ :

$$\begin{cases} \dot{\mathbf{x}}(t) = A \mathbf{x}(t) + A_d \mathbf{x}(t - h), & t \notin \mathcal{T}, \\ \mathbf{x}(t^+) = A_R \mathbf{x}(t), & t \in \mathcal{T}, \\ y(t) = C \mathbf{x}(t - h), \\ \mathbf{x}(t) = \phi(t), & t \in [-h, 0], \end{cases} \quad (4)$$

where  $\mathbf{x}(t) = (\mathbf{x}_p(t), \mathbf{x}_r(t)) \in \mathbb{R}^n$  with  $n = n_p + 2$ ,  $\phi \in \mathcal{C}([-h, 0], \mathbb{R}^n)$  is the initial condition function, and matrices  $A$ ,  $A_d$ ,  $C$ , and  $A_R$  are given by

$$A = \begin{bmatrix} A_p & B_p C_r \\ 0 & 0 \end{bmatrix}, \quad A_d = \begin{bmatrix} -k_p B_p C_p & 0 \\ -B_r C_p & 0 \end{bmatrix}, \quad (5)$$

$$C = [C_p \quad 0], \quad A_R = \begin{bmatrix} I & 0 \\ 0 & A_\rho \end{bmatrix}.$$

In some previous works (Vidal (2009); Baños and Vidal (2012)), a PI+CI is proposed with a state-dependent resetting law, that is the reset is applied at time  $t$  in which  $(\mathbf{x}(t), \mathbf{x}(t - h)) \in \mathcal{M}$ , for a given reset set  $\mathcal{M}$ . In this work, the reset is applied at time  $t$ , which belongs to an infinite and strictly increasing sequence of reset times defined by  $\mathcal{T}(\phi) = (t_1, t_2, \dots)$ , which may depend on the initial condition. In addition, we assume that there exist two positive scalars  $0 < \mathcal{T}_1 \leq \mathcal{T}_2$  such that  $T_k = t_{k+1} - t_k \in [\mathcal{T}_1, \mathcal{T}_2]$  for any  $k > 0$ .

From the definition of the reset instants, it is clear that there exists a unique solution  $\mathbf{x}(t, \phi)$ , or simply  $\mathbf{x}(t)$ , for  $t \in [-h, \infty)$  (see Section II of Baños and Barreiro (2012) for a more detailed discussion about existence and uniqueness of solutions).

*Remark 1.* Note that there are not stability results in the literature that can deal with time-delay reset control systems composed by a PI+CI (there are several results for reset control systems without time-delay, see e.g., Loquen et al. (2010); Baños et al. (2011)). The main reason is that the base system of (4)-(5) is not asymptotically stable.

## 3. STABILITY ANALYSIS

In this section, the stability of the time-delay reset control system (4) is analyzed by using the framework of sampled-data systems (see, e.g., Fridman (2014) and the references therein). The proposed approach consists in transforming the reset control system (4) into a linear system interconnected with a sample and hold device as shown in

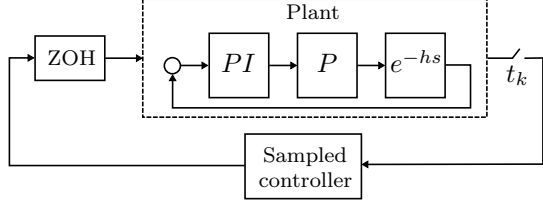


Fig. 2. Sampled-data system setup.

Fig. 2. Then the stability of the sampled-data system is analyzed by using the framework developed by Seuret (2012). However, in contrast to the literature, the plant considered in Fig. 2 consists of a closed-loop system with a time-delay, and hence previous results (Seuret (2011, 2012)) cannot be applied directly.

Firstly, let us rewrite the original reset control system as a sampled-data system. Consider a continuous function  $\chi(t)$  given by

$$\chi(t) = \mathbf{x}(t) - (A_R - I) \sum_{t_k \in [0, t]} \mathbf{x}(t_k), \quad (6)$$

where  $\mathbf{x}(t)$  is the solution of the system (4), and  $t_k$  are the reset instants. Noting that  $A_R(A_R - I) = 0$ , it is also satisfied the following equation

$$\mathbf{x}(t) = \chi(t) + (A_R - I)\chi(t_k) \quad (7)$$

with  $t \in (t_k, t_{k+1}]$ . Since  $A_d(A_R - I) = 0$ , using the differential equation of the base system, it is obtained

$$\dot{\chi}(t) = \dot{\mathbf{x}}(t) = A\chi(t) + A_d\chi(t-h) + A(A_R - I)\chi(t_k) \quad (8)$$

for  $t \in (t_k, t_{k+1}]$ . Therefore, the reset control system can be transformed into the following sampled-data system with augmented state  $\chi(t) = (\mathbf{x}_p(t), x_i(t))$ :

$$\begin{cases} \dot{\chi}(t) = A\chi(t) + A_d\chi(t-h) + Au(t), \\ u(t) = (A_R - I)\chi(t_k), \\ u(0) = x_i(0) - x_{ci}(0), \end{cases} \quad t \in (t_k, t_{k+1}], \quad (9)$$

where matrices  $A$ ,  $A_d$ ,  $A_R$  are

$$A = \begin{bmatrix} A_p & B_p \\ 0 & 0 \end{bmatrix}, \quad A_d = \begin{bmatrix} -B_p k_p C_p & 0 \\ -k_i C_p & 0 \end{bmatrix}, \quad (10)$$

$$A_R = \begin{bmatrix} I & 0 \\ 0 & 1 - p_r \end{bmatrix}.$$

Straightforwardly it is clear that the reset control system (4) is asymptotically stable if the above system is asymptotically stable, since states  $\mathbf{x}_p$  and  $x_i$  are directly obtained from  $\chi(t)$  and  $x_{ci}(t) = [0 \cdots 0 \ 1]\chi(t) + u(t)$ .

Let define, for all integer  $k$ , the function  $\chi_k : [0, T_k] \times [-h, 0] \rightarrow \mathbb{R}^n$  such that for all  $\tau \in [0, T_k]$  and all  $\theta \in [-h, 0]$ ,  $\chi_k(\tau, \theta) = \chi(s_k + \tau + \theta)$ . The set  $\mathbb{K}$  represents the set of functions defined by  $\chi_k$  as the set of continuous functions from  $[0, T_k] \times [-h, 0]$  to  $\mathbb{R}^n$ .

### 3.1 Asymptotic stability analysis

Let us now present results on asymptotic stability of system (9)-(10) allowing to conclude on the stability of the system (4)-(5).

*Proposition 1.* Let  $V : \mathcal{C}([-h, 0], \mathbb{R}^n) \rightarrow \mathbb{R}^+$  be a functional for which there exist real numbers  $0 < \mu_1 < \mu_2$  such that for all  $\Psi \in \mathcal{C}([-h, 0], \mathbb{R}^n)$

$$\mu_1 |\Psi(0)|^2 \leq V(\Psi) \leq \mu_2 \|\Psi\|^2. \quad (11)$$

The two following statements are equivalent:

- (1) The increment of the functional  $V$  is strictly negative for all  $k \in \mathbb{N}^+$  and all  $T_k \in [\mathcal{T}_1, \mathcal{T}_2]$

$$V(\chi_k(T_k, \cdot)) - V(\chi_k(0, \cdot)) < 0. \quad (12)$$

- (2) There exists a continuous functional  $\mathcal{V} : \mathbb{R} \times \mathbb{K} \rightarrow \mathbb{R}$ , which satisfies for all  $k \in \mathbb{N}^+$  and all  $T_k \in [\mathcal{T}_1, \mathcal{T}_2]$

$$\mathcal{V}(T_k, \chi_k) = \mathcal{V}(0, \chi_k) \quad (13)$$

and such that, for all  $k > 0$  and all  $\sigma \in [0, T_k]$ , the following inequality holds

$$\dot{W}(\sigma, \chi_k) = \frac{d}{d\sigma} \{V(\chi_k(\sigma, \cdot)) + \mathcal{V}(\sigma, \chi_k)\} < 0. \quad (14)$$

Moreover, if one of these statements is satisfied and there exist real numbers  $\eta_1, \eta_2 \geq 0$  such that

$$\mathcal{V}(0, \chi_k) \leq \eta_1 V(\chi_k(0, \cdot)), \quad (15)$$

$$-\eta_2 V(\chi_k(0, \cdot)) \leq \mathcal{V}(\tau, \chi_k) \quad (16)$$

for all  $\tau \in [0, T_k]$ , then system (9) is asymptotically stable.

**Proof.** The equivalence between the two statements is proved in Seuret (2011). On the other hand, integrating  $\dot{W}$  with respect to  $\sigma$  over  $[0, \tau]$ , we get

$$V(\chi_k(\tau, \cdot)) - V(\chi_k(0, \cdot)) + \mathcal{V}(\tau, \chi_k) - \mathcal{V}(0, \chi_k) < 0 \quad (17)$$

with  $\tau \leq T_k$ . By inequalities (15) and (16) it satisfies

$$V(\chi_k(\tau, \cdot)) < (1 + \eta_1 + \eta_2)V(\chi_k(0, \cdot)). \quad (18)$$

The above condition and (12) guarantee that  $V(\chi_k(\tau, \cdot))$  converges to zero as  $k$  goes infinity for  $\tau \in [0, T_k]$ . Finally, condition (11) proves that the solution  $\chi_k$  tends asymptotically to the origin.

*Remark 2.* In comparison to Seuret (2011) and Seuret (2012), the sampled-data system considered here is composed by a sampled plant with an internal time-delay (see Fig. 2). Therefore, stability conditions from Seuret (2011) and Seuret (2012) cannot be used directly to prove the stability of the system. That is the reason why conditions (15) and (16) have been added. The objective of these conditions is to bound the increments of the functional  $V$  between the reset instants, and to guarantee the convergence of the bound to zero.

A delay-dependent asymptotic stability conditions for the time-delay reset control system (4) is now provided in the sequel. The following proposition is provided by the use of a Bessel-Legendre inequality developed in Seuret and Gouaisbaut (2014).

*Proposition 2.* The sampled-data system (9) is asymptotically stable for the given constant time-delay  $h$ , if for a given integer  $N \geq 0$  and scalars  $0 < \mathcal{T}_1 \leq \mathcal{T}_2$ , there exist a matrix  $P \in \mathcal{S}_{(N+1)n}$ , matrices  $S, R, U, X_2 \in \mathcal{S}_n^+$ , matrices

$S_1, X_1 \in \mathcal{S}_n$ , matrix  $S_2 \in \mathbb{R}^n$  and  $Y \in \mathbb{R}^{(N+3)n \times n}$  such that the LMIs

$$\begin{cases} P \succ 0, & N = 0, \\ P + \frac{1}{h} \text{diag}\{0, S_{N-1}\} \succ 0, & N > 0, \end{cases} \quad (19)$$

$$\Pi_1 + \mathcal{T}_i (N_2^\top X_1 N_2 + \Pi_2) \prec 0, \quad (20)$$

$$\begin{bmatrix} \Pi_1 - \mathcal{T}_i N_2^\top X_1 N_2 & \mathcal{T}_i Y \\ \star & -\mathcal{T}_i U \end{bmatrix} \prec 0, \quad (21)$$

$$\begin{bmatrix} S_1 & S_2 \\ S_2^\top & \frac{1}{\mathcal{T}_2} X_2 \end{bmatrix} \succ 0 \quad (22)$$

hold for all  $i \in \{1, 2\}$ , where the matrices are given in (24).

**Proof.** Consider the following LK functional

$$\begin{aligned} V(\chi_k(\tau, \cdot)) &= \tilde{\chi}_k^\top(\tau) P \tilde{\chi}_k(\tau) + \int_{-h}^0 \chi_k^\top(\tau, s) S \chi_k(\tau, s) ds \\ &+ h \int_{-h}^0 \int_{\beta}^0 \dot{\chi}_k^\top(\tau, s) R \dot{\chi}_k(\tau, s) ds d\beta. \end{aligned} \quad (24)$$

This functional has been designed in Seuret and Gouaisbaut (2014) based on the sequence of Legendre polynomials, that we will denote in the sequel by  $L_k$ . Indeed the functional requires the augmented state  $\tilde{\chi}_k$  given by

$$\tilde{\chi}_k(\tau) = \begin{bmatrix} \chi_k(\tau, 0) \\ \int_{-h}^0 L_0(s) \chi_k(\tau, s) ds \\ \vdots \\ \int_{-h}^0 L_{N-1}(s) \chi_k(\tau, s) ds \end{bmatrix} \quad (25)$$

if  $N > 0$  and  $\tilde{\chi}_k(\tau) = \chi_k(\tau, 0)$  if  $N = 0$ . The time-derivative of the augmented state  $\tilde{\chi}_k$  is given by

$$\dot{\tilde{\chi}}_k = H \xi_k(\tau), \quad (26)$$

where

$$\xi_k(\tau) = \begin{bmatrix} \chi_k(\tau, 0) \\ \chi_k(\tau, -h) \\ \frac{1}{h} \int_{-h}^0 L_0(s) \chi_k(\tau, s) ds \\ \vdots \\ \frac{1}{h} \int_{-h}^0 L_{N-1}(s) \chi_k(\tau, s) ds \\ \chi_k(0, 0) \end{bmatrix} \quad (27)$$

if  $N > 0$  and  $\xi_k(\tau) = (\chi_k(\tau, 0), \chi_k(\tau, -h))$  if  $N = 0$ .

The positivity of  $V$  is guaranteed by condition (19) along the trajectories of (9). The time-derivative of  $V$  and (26) lead to

$$\begin{aligned} \dot{V}(\chi_k(\tau, \cdot)) &= 2\tilde{\chi}_k^\top(\tau) P \dot{\tilde{\chi}}_k(\tau) + \chi_k^\top(\tau, 0) S \chi_k(\tau, 0) \\ &- \chi_k^\top(\tau, -h) S \chi_k(\tau, -h) + h^2 \dot{\chi}_k^\top(\tau, 0) R \dot{\chi}_k(\tau, 0) \\ &- h \int_{-h}^0 \dot{\chi}_k^\top(\tau, s) R \dot{\chi}_k(\tau, s) ds. \end{aligned} \quad (28)$$

Note that  $\tilde{\chi}_k(\tau) = G \xi_k(\tau)$ , then by equation (26), it yields

$$\dot{V}(\chi_k(\tau, \cdot)) = \xi_k^\top(\tau) \Phi \xi_k(\tau) - h \mathcal{I}(\dot{\chi}_k(\tau, \cdot)) \quad (29)$$

with

$$\mathcal{I}(\dot{\chi}_k(\tau, \cdot)) = \int_{-h}^0 \dot{\chi}_k^\top(\tau, s) R \dot{\chi}_k(\tau, s) ds. \quad (30)$$

Consider now an additional functional given by

$$\begin{aligned} \mathcal{V}(\tau, \chi_k) &= (T_k - \tau) [\zeta_k^\top(\tau) S_1 \zeta_k(\tau) \\ &+ He(\zeta_k^\top(\tau) S_2 \chi_k(0, 0))] \\ &+ (T_k - \tau) \int_0^\tau \dot{\chi}_k^\top(s, 0) U \dot{\chi}_k(s, 0) ds \\ &+ \tau (T_k - \tau) \chi_k^\top(0, 0) X_1 \chi_k(0, 0) \\ &+ \chi_k^\top(0, 0) X_2 \chi_k(0, 0), \end{aligned} \quad (31)$$

where  $\zeta_k(\tau) = \chi_k(\tau, 0) - \chi_k(0, 0)$ . This functional satisfies condition (13) since

$$\mathcal{V}(T_k, \chi_k) = \mathcal{V}(0, \chi_k) = \chi_k^\top(0, 0) X_2 \chi_k(0, 0) \quad (32)$$

From the above equation it is clear that condition (15) is also satisfied for some  $\eta_1 \geq 0$ . Condition (22) and  $U > 0$  guarantee that

$$\tau (T_k - \tau) \chi_k^\top(0, 0) X_1 \chi_k(0, 0) \leq \mathcal{V}(\tau, \chi_k) \quad (33)$$

$$\begin{array}{l} N_1 = [I_n \ 0_{n, n(N+1)}] \\ \tilde{S}_N = \text{diag}\{S, -S, 0_{(N+1)n}\} \\ F = [A \ A_d \ 0_{n, nN} \ A(A_R - I)] \\ \Gamma_N = [\Gamma^\top(0) \ \dots \ \Gamma^\top(N)]^\top \end{array} \left| \begin{array}{l} N_2 = [0_{n, n(N+1)} \ I_n] \\ R_N = \text{diag}\{R, 3R, \dots, (2N+1)R\} \\ G = \begin{bmatrix} I & 0_n & 0_{n, nN} & 0_n \\ 0_{nN, n} & 0_{nN, n} & hI_{nN} & 0_n \end{bmatrix} \\ \Phi = He(G^\top P H) + \tilde{S}_N + h^2 F^\top R F \end{array} \right| \begin{array}{l} N_{12} = N_1 - N_2 \\ S_N = \text{diag}\{S, 3S, \dots, (2N+1)S\} \\ H = [F^\top \ \Gamma^\top(0) \ \dots \ \Gamma^\top(N-1)] \\ \Pi_2 = F^\top U F + He(F^\top S_1 N_{12}) + He(F^\top S_2 N_2) \end{array}$$

$$\Pi_1 = \Phi - \Gamma_N^\top R_N \Gamma_N - N_{12}^\top S_1 N_{12} - He(N_2^\top S_2 N_2) + He(Y N_{12})$$

$$\Gamma(k) = \begin{cases} [I \ I \ 0_n], & N = 0 \\ [I \ (-I)^{k+1} \ \gamma_k^0 I \ \dots \ \gamma_k^{N-1} I \ 0_n], & N > 0 \end{cases} \quad \gamma_k^i = \begin{cases} -(2i+1)(1 - (-1)^{k+i}), & i \leq k \\ 0, & i > k \end{cases}$$

(24)

Therefore, there exists  $\eta_2$  such that condition (16) is satisfied, since  $\tau(T_k - \tau)$  is bounded for  $\tau \in [0, T_k]$ ,  $T_k \in [\mathcal{T}_1, \mathcal{T}_2]$ , and the functional  $V$  satisfies condition (11).

Defining  $\mathcal{W} = V + \mathcal{V}$ , its time-derivative is given by

$$\begin{aligned} \dot{\mathcal{W}}(\tau, \chi_k) &= \xi_k^\top(\tau) \Phi \xi_k(\tau) - h \mathcal{I}(\dot{\chi}_k(\tau, \cdot)) \\ &+ (T_k - \tau) [\dot{\chi}_k^\top(\tau, 0) U \dot{\chi}_k(\tau, 0) + H e(\dot{\chi}_k^\top(\tau, 0) S_1 \zeta_k(\tau)) \\ &+ H e(\dot{\chi}_k^\top(\tau, 0) S_2 \chi_k(0, 0))] - \zeta_k^\top(\tau) S_1 \zeta_k(\tau) \\ &+ H e(\zeta_k^\top(\tau) S_2 \chi_k(0, 0)) - \int_0^\tau \dot{\chi}_k^\top(s, 0) U \dot{\chi}_k(s, 0) ds \\ &+ (T_k - 2\tau) \chi_k^\top(0, 0) X_1 \chi_k(0, 0). \end{aligned} \quad (34)$$

The integral term  $\mathcal{I}(\dot{\chi}_k(\tau, \cdot))$  of the above equation is bounded by the following Bessel-Legendre inequality (see Corollary 4 in Seuret and Gouaisbaut (2014))

$$\mathcal{I}(\dot{\chi}_k(\tau, \cdot)) \geq \frac{1}{h} \xi_k(\tau)^\top \left[ \sum_{j=0}^N (2j+1) \Gamma_N^\top(j) R \Gamma_N(j) \right] \xi_k(\tau). \quad (35)$$

On the other hand, the other integral term is bounded as follows (see Seuret (2011)):

$$\begin{aligned} - \int_0^\tau \dot{\chi}_k^\top(s, 0) U \dot{\chi}_k(s, 0) ds &\leq 2 \xi_k^\top(\tau) Y \zeta_k(\tau) \\ &+ \tau \xi_k^\top(\tau) Y U^{-1} Y^\top \xi_k(\tau). \end{aligned} \quad (36)$$

Hence, the following inequality is obtained

$$\begin{aligned} \dot{\mathcal{W}}(\tau, \chi_k) &\leq \xi_k^\top(\tau) [\Pi_1 + (T_k - \tau) \Pi_2 \\ &+ (T_k - 2\tau) N_2^\top X_1 N_2 + \tau Y U^{-1} Y^\top] \xi_k(\tau). \end{aligned} \quad (37)$$

Hence, if LMIs of Proposition 2 are satisfied, condition (37) is fulfilled, proving therefore inequality (14) and the stability of (9).

*Remark 3.* The interpretation of the bunch of LMIs in Proposition 2 is rather simple. First, the LMI (19) guarantees the positivity of the LK functional. The LMIs (20) and (21) concern with the negativity of  $\dot{W}$ . In particular, (20) and (21) ensure  $\dot{W}(0, \chi_k) < 0$  and  $\dot{W}(T_k, \chi_k) < 0$  for all  $k > 0$ , respectively. Then by convexity arguments, it is guaranteed  $\dot{W}(\sigma, \chi_k) < 0$ ,  $\sigma \in [0, T_k]$ . Finally, the LMI (22) is necessary to fulfill condition (16) in Proposition 1, which guarantees the boundedness of the LK functional between the reset instants.

#### 4. EXAMPLE

Consider the closed-loop system composed by the following system P

$$P : \begin{cases} \dot{\mathbf{x}}_p(t) = \begin{bmatrix} 0.5 & 1 \\ 0 & 0 \end{bmatrix} \mathbf{x}_p(t) + \begin{bmatrix} 1 \\ 1 \end{bmatrix} u_p(t), \\ y_p(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} \mathbf{x}_p(t) \end{cases} \quad (38)$$

and the PI+CI compensator defined in (2)-(3) with  $k_p = 1$ ,  $k_i = 1$ , and  $p_r = 0.99$ . The base closed-loop system is not asymptotically stable independently of the time-delay. However, the system can be stabilized by reset actions with a proper reset period. Table. 1 shows the maximum time-delay, the maximum and minimum reset period for several

$N$	0	1	2	3	5
Max. $h$	0.3613	0.406	0.4079	0.4079	0.4079
Max. $T$	0.3039	0.2802	0.2393	0.2405	0.2405
Min. $T$	0.2670	0.1669	0.2052	0.2050	0.2041

Table 1. Example 1: Maximum time-delay, maximum and minimum reset period.

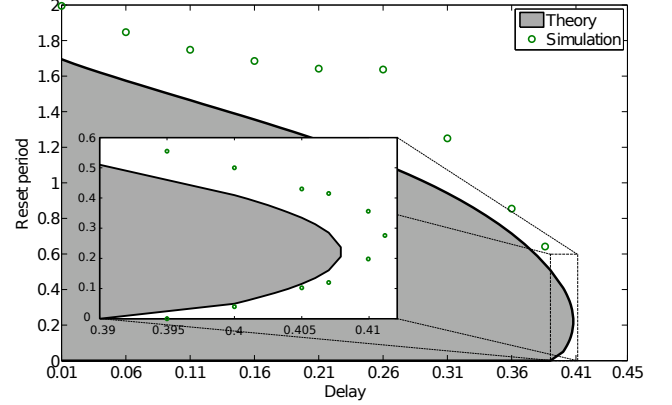


Fig. 3. Example: Maximum and minimum reset period (Prop. 2,  $N=3$ ). Stability proved for a reset period in the shaded area.

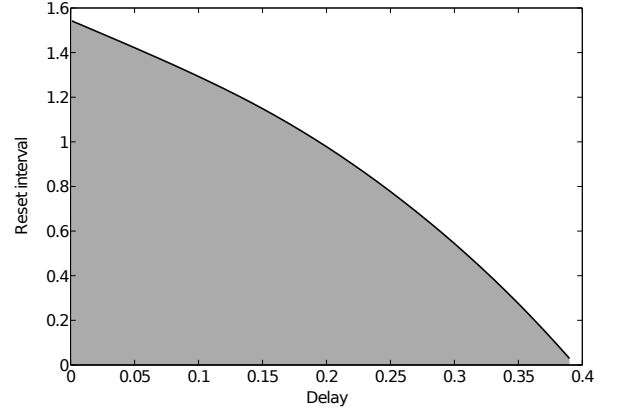


Fig. 4. Example: Asynchronous reset (Prop. 2,  $N=3$ ).

values of the parameter  $N$ . By simulation the system is unstable for  $h = 0.412$ , and the maximum obtained by Proposition 2 is 0.4079, showing the weak conservatism of the results. In addition, Fig. 3 shows all the possible reset periods for which Proposition 2 guarantees the stability of the system. It is also shown the maximum and minimum time-delay obtained by simulation for which the system is known to be unstable. In this case, there is not previous method which guarantees the stability of the system, since the base closed-loop system is unstable. On the other hand, let consider  $\mathcal{T}_1 = 10^{-6}$  for the case of asynchronous reset, then Fig. 4 shows the maximum  $\mathcal{T}_2$  for several values of the time-delay.

#### 5. CONCLUSIONS

The paper provides a novel analysis of time-delay reset control systems under time-dependent resetting law. The

reset control system considered is composed by a PI+CI compensator and a time-delay process. The proposed approach is based on new results for sampled-data systems. LMI conditions are derived to ensure the asymptotic stability by using a new LK functional based on Bessel-Legendre inequalities. An illustrative example shows the reduction of the conservatism compared with previous results, guaranteeing the stability of a time-delay reset control system with unstable base system.

## REFERENCES

- Bainov, D. and Simeonov, P. (1989). *Systems with impulse effect: Stability, theory and applications*. Ellis Horwood.
- Baños, A. and Barreiro, A. (2009). Delay-independent stability of reset control systems. *IEEE Trans. on Automatic Control*, 54, 341–346.
- Baños, A. and Barreiro, A. (2012). *Reset Control Systems*. Advances in Industrial Control. Springer.
- Baños, A., Carrasco, J., and Barreiro, A. (2011). Reset times-dependent stability of reset control systems. *IEEE Transactions on Automatic Control*, 56(1), 217–223.
- Baños, A. and Vidal, A. (2012). Design of reset control systems: The PI-CI compensator. *Journal of Dynamic Systems, Measurement, and Control*, 134(5).
- Barreiro, A. and Baños, A. (2010). Delay-dependent stability of reset control systems. *Automatica*, 46, 216–221.
- Beker, O., Hollot, C., Chait, Y., and Han, H. (2004). Fundamental properties of reset control systems. *Automatica*, 40(6), 905–915.
- Chen, W. and Zheng, W. (2009a). Global exponential stability of impulsive neural networks with variable delay: an LMI approach. *IEEE Trans. on Circuits and Systems*, 56(6), 1248–1259.
- Chen, W. and Zheng, W. (2009b). Input-to-state stability and integral input-to-state stability of nonlinear impulsive systems with delays. *Automatica*, 45(6), 1481–1488.
- Chen, W. and Zheng, W. (2009c). Robust stability and  $H_\infty$ -control of uncertain impulsive systems with time-delay. *Automatica*, 45(1), 109–117.
- Chen, W. and Zheng, W. (2011). Exponential stability of nonlinear time-delay systems with delayed impulse effects. *Automatica*, 47(5), 1075–1083.
- Davó, M. and Baños, A. (2013a). Delay-dependent stability of reset control systems with input/output delays. In *IEEE Conference on Decision and Control*, 2018–2023.
- Davó, M. and Baños, A. (2013b). Reset control of a liquid level process. In *IEEE Conference on Emerging Technologies & Factory Automation*, 1–4.
- Fridman, E. (2014). *Introduction to Time-Delay Systems: Analysis and Control*. Birkhäuser.
- Guan, Z. (1999). Decentralized stabilization for impulsive large scale systems with delays. *Dynamics of Continuous, Discrete and Impulsive Systems*, 6(3), 367–379.
- Guo, Y. and Xie, L. (2012). Quadratic stability of reset control systems with delays. In *10th World Congress on Intelligent Control and Automation*, 2268–2273.
- Haddad, W., Chellaboina, V., and Nersesov, S. (2006). *Impulsive and hybrid dynamical systems: stability, dissipativity, and control*. Princeton University Press.
- Hespanha, J., Liberzon, D., and Teel, A. (2008). Lyapunov conditions for input-to-state stability of impulsive systems. *Automatica*, 44(11), 2735–2744.
- Hetel, L., Daafouz, J., Tarbouriech, S., and Prieur, C. (2013). Stabilization of linear impulsive systems through a nearly-periodic reset. *Nonlinear Analysis: Hybrid Systems*, 7(1), 4–15.
- Khadra, A., Liu, X., and Shen, X. (2009). Analyzing the robustness of impulsive synchronization coupled by linear delayed impulses. *IEEE Trans. on Automatic Control*, 4(4), 923–928.
- Lakshmikantham, V., Bainov, D., and Simeonov, P. (1989). *Theory of impulsive differential equations*. Word Scientific.
- Liu, X., Shen, X., Zhang, Y., and Wang, Q. (2007). Stability criteria for impulsive systems with time delay and unstable system matrices. *IEEE Trans. on Circuits and Systems*, 54(10), 2288–2298.
- Loquen, T., Nešić, D., Prieur, C., Tarbouriech, S., Teel, A.R., and Zaccarian, L. (2010). Piecewise quadratic lyapunov functions for linear control systems with first order reset elements. In *8th IFAC Symposium on Nonlinear Control Systems*, 807–812. Bologna, Italy.
- Mercader, P., Carrasco, J., and Baños, A. (2013a). IQC analysis for time-delay reset control systems with first order reset elements. In *IEEE Conference on Decision and Control*, 2251–2256.
- Mercader, P., Davó, M., and Baños, A. (2013b).  $\mathcal{H}_\infty / \mathcal{H}_2$  analysis for time-delay reset control systems. In *Int. Conference on Systems and Control*, 518–523.
- Naghshtabrizi, P., Hespanha, J., and Teel, A. (2008). Exponential stability of impulsive systems with application to uncertain sampled-data systems. *Systems & Control Letters*, 57(5), 378–385.
- Prieto, J.A., Barreiro, A., Dormido, S., and Tarbouriech, S. (2012). Delay-dependent stability of reset control systems with anticipative reset conditions. In *IFAC Symposium on Robust Control Design*, 1, 219–224.
- Seuret, A. (2011). Stability analysis of networked control systems with asynchronous sampling and input delay. In *American Control Conference*, 533–538.
- Seuret, A. (2012). A novel stability analysis of linear systems under asynchronous samplings. *Automatica*, 48(1), 177–182.
- Seuret, A. and Gouaisbaut, F. (2014). Hierarchy of LMI conditions for the stability analysis of time delay systems. Technical Report hal-01065142, Laboratoire d’analyse et d’architecture des systèmes and Université Paul Sabatier.
- Vidal, A. (2009). *Diseño de Sistemas de Control Reseteados: Aplicaciones en Control de Procesos*. Ph.D. thesis, University of Murcia.
- Vidal, A. and Baños, A. (2012). Reset compensation for temperature control: Experimental application on heat exchangers. *Chemical Engineering Journal*, 155(1-3), 170–181.
- Wang, Q. and Liu, X. (2005). Exponential stability for impulsive delay differential equations by Razumikhin method. *Journal of Mathematical Analysis and Applications*, 309(2), 462–473.
- Yang, Z. and Xu, D. (2007). Stability analysis and design of impulsive control systems with time delay. *IEEE Trans. on Automatic Control*, 52(8), 1448–1454.