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Interactive Tool for Analysis of Reset Control Systems

S. Dormido, A. Baños, and A. Barreiro

Abstract— **The paper describes an interactive tool focused on the analysis of reset control systems. Reset control systems are essentially linear control systems that reset certain controller states to zero according to a reset rule. The tool has been developed using Sysquake, a Matlab-like language with fast execution and excellent facilities for interactive graphics, and is delivered as a stand-alone executable that is readily accessible to students and users. The highly visual and strongly coupled nature of reset control system is very amenable to interactive tools, and the tool presented in this paper enables to discover a myriad of important properties of these systems.**

I. Introduction

ADVANCES in information technologies have resulted in novel teaching methods that increase student motivation and improve educational outcomes. In the control engineering field, interactive tools have resulted in particularly useful techniques with high impact on the visualization, analysis and design of control systems [1], [2], [3], [4]. Interactive tools provide a real-time connection between decisions made during the design phase and results obtained in the analysis phase of any control-related project. As a consequence of interactivity, the impact of problem variables chosen in the analysis step can be contrasted with specifications made in the design stages. Such functionality has clear benefits from the designer control systems point of view [5].

Reset control is a kind of impulsive/hybrid control in which some of the compensator states are set to zero at those instants in which its input is zero [6]. One of the main difficulties of reset compensation is that closed-loop stability may be not guaranteed if reset actions are not properly performed, and in fact it is well known [6] that reset can unstabilize a stable base control system. Thus, stability of reset control systems is a main concern from a theoretical and practical point of view, and several recent works. Nesic et al. [7] and Baños et al.[8] have approached the stability problem from different perspectives, and incorporating new definitions of the reset law. For example, in [7] a sector-based definition of the reset law is used that although is equivalent to the zero crossing law in some cases, in general lead to different solutions (for example in the case of partial reset compensation). On the other hand [8] introduces a dwell-time stability conditions that are applicable in general to any type of reset law.

In principle, this work will used the zero crossing reset law and a particular relaxation of this law given by a reset band, but the developed interactive tool can be easily extended to consider other types of reset laws. Note that an important practical issue of reset control is that compensator implementation is usually done by using reset band. In addition, it has been noted that the use of a reset band may improve stability and performance in systems with time-delays, due to the phase lead characteristic that is common to reset compensators. Phase lead can be even improved by using reset band [9]. However, a formal analysis of how the reset band can affect stability and performance of a reset control system is still an open issue. In this work, a frequency domain analysis by means of the describing function will be an important part of the tool, and will be used to approach important questions such as the existence and stability of limit cycles in reset control systems with reset band. Consequently, the ability to implement reset control techniques interactively is expected to have an impact on both reset control analysis and design. From this perspective the objective of this paper is to present an interactive tool that has been developed by the authors for the purpose of exploring field.

The interactive tool is coded in Sysquake, a Matlab-like language with fast execution and excellent facilities for interactive graphics [10], and is delivered as a stand-alone executable that makes it readily accessible to users [11].

The idea of changing properties and immediately being able to see the effects of the changes is very powerful both for analysis and design. The dynamics of the changes provides additional information that is not available in a static plot. There are many interesting issues that have to be dealt with when developing interactive tools for the automatic control field which are related to the particular graphics representations used. It is straight forward to see the effects of parameters on the graphics but not so obvious how the graphical objects should be manipulated. There are natural ways to modify pole-zero plots for example by adding poles and zeros and by dragging them. Bode plots can be manipulated by dragging the intersections of the asymptotes. However, it is less obvious how a Nyquist plot should be changed.

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The paper is organized as follows: a brief introduction to the theoretical background behind reset control systems is described in Section 2. A summary of the tool's functionality is presented in Section 3, with a series of illustrative examples described in Section 4. The paper concludes with a brief discussion of development plans for the future.

II. RESET CONTROL FUNDAMENTALS

It is well-known that Bode's gain-phase relationship places a hard limitation on performance tradeoffs in linear, time-invariant (LTI) feedback control systems. Specifically, the need to minimize the open-loop high-frequency gain often competes with required high levels of low-frequency loop gains and phase margin bounds [15].

The origin of reset controllers is the so-called Clegg integrator (CI) introduced in 1958 by Clegg [12]. Reset controllers allow more flexibility in controller design and they may remove some fundamental limitations in linear control systems imposed by Bode's gain-phase relationship [6]. A CI, has a describing function similar to the frequency response of a linear integrator but with only 38,1º phase lag First systematic procedures for controller design exploiting the CI structure were proposed in Horowitz and Rosenbaum [13] and Krishnan and Horowitz [14].

A nice account of these results and their relation to more recent developments in reset control is given in Chait and Hollot [15]. Stability analysis of general reset systems can be found in Beker, Hollot, Chait, and Han [6], where Lyapunov-based conditions for asymptotic stability of general reset systems were presented. Additional stability results may be found in Nesic et al.[7] and Baños et al.[8]. On the other hand, stability results for reset systems with time delays have been investigated by Baños and Barreiro [16] and Barreiro and Baños [17]. In these papers have been proposed computable conditions for quadratic stability based on linear matrix inequalities (LMIs).

A. Reset compensators with reset band

The main motivation for the use of reset compensation is to improve the performance of a previously designed LTI control system, the goal being to reset some states of a base LTI compensator to improve control system performance, both in terms of velocity of response and relative stability. In general, these specifications will be impossible to achieve by means of LTI compensation.

Consider a reset control system as shown in Fig.1, formed by a plant P and a reset controller C given by:

$$P:\begin{cases}\dot{x}_p = A_p x_p B_p u_p \\ y_p = C_p x_p\end{cases} \tag{1}$$

$$C:\begin{cases}\dot{x}_c = A_c x_c + B_c u_c & \text{if } c(t) \text{ false} \\ x_c^{+} = A_\rho x_c & \text{if } c(t) \text{ true} \\ y_c = C_c x_c + D_c u_c\end{cases} \tag{2}$$

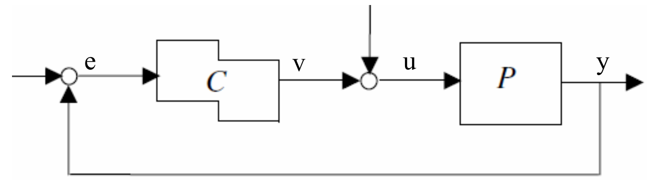

Fig. 1. Reset compensator C and LTI plant P

In this paper will consider reset controllers with *reset band* [9]. This means that resetting could be applied when the error enters the band $|e(t)| \le \delta$. More precisely, the reset condition is activated when the error hits the *reset lines* shown in Fig.2, in the plane (e, $\dot{e}$), where:

$$B^{+} = \{(e, \dot{e}): e = \delta, \dot{e} \le -\varepsilon\}$$

and B^{-} is symmetric to B^{+}. The number $\delta > 0$ is the width of the band, or simply the *band*, and $\varepsilon \ge 0$ is a small *threshold*. In this way, the reset condition becomes:

$$c(t):\ \{(e(t), \dot{e}(t)) \in B := B^{+} \cup B^{-} \tag{3}$$

When no threshold is specified, it is assumed by default $\varepsilon = 0$. The case $\delta = \varepsilon = 0$ recovers the *standard reset* without band. On the other hand, if δ is big enough in relation to the error amplitude, then no reset action is produced and the reset compensator reduce to its base compensator, given by the transfer function $C_{base}(s) = C_c(sI - A_c)^{-1}B_c + D_c$.

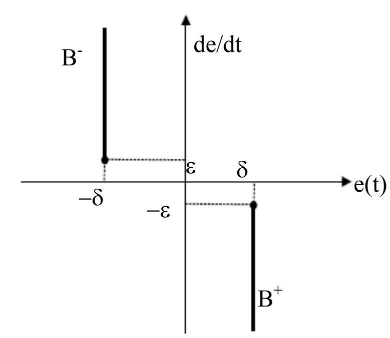

Fig. 2. Reset set $B = B^{+} \cup B^{-}$ and the two reset lines B^{+}, B^{-}

Reset control systems can be more generalized by designing the reset law and the after-reset values to improve its performance. Besides the zero crossing reset law and full/partial reset, several reset laws have been investigated: fixed reset times and variable after-reset values [18], sector based reset law and full reset [7], reset band [9]. For example, in [18] reset time instances are pre specified and the controller states are reset to certain non-zero values, which are calculated online in terms of the system states for optimal performance.

III. Interactive Tool Description

This section describes the functionality of the developed tool, which highlights the concepts described in the previous section. The tool is freely available by contacting with the authors and can be used in Windows, Mac, and Linux operating systems without the need for a Sysquake license. One consideration that must be kept in mind is that the tool's main feature -interactivity- cannot be easily illustrated with written text. Nonetheless, some of the features and advantages of the application are shown below. The reader is cordially invited to use the tool and personally experience its interactive features.

When developing a tool of this kind, one of the most important things that the developer needs to keep in mind is the organization of the main windows and menus to assist the user in understanding the reset control technique.

The main window of the tool is divided into several sections represented in Fig.3 (basic screen of the developed interactive tool) which are described as follows:

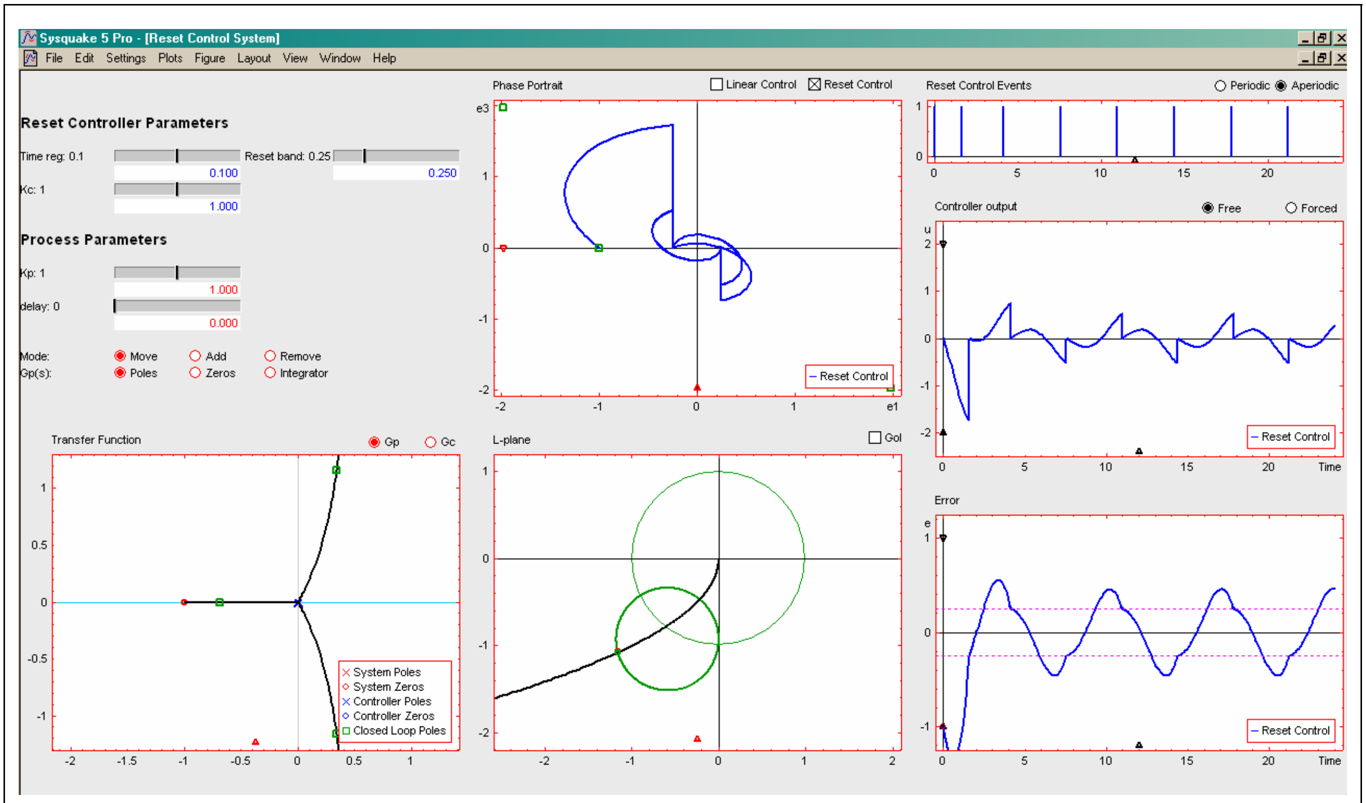

Fig. 3. Interactive tool user interface

- *Graphics*. There are different graphic elements which represent the process input (Controller Output), the error signal (Error), the root locus of the linear base system associated with the reset control system (Transfer Function), a plane phase representation of the trajectory of the system (Phase Portrait), the Nyquist plot of the linear base system associated to the reset control system and the describing function of the reset compensator (*L*-plane), and the temporal sequence of reset control events (Reset Control Events).

The first two graphics show the simulation results of the control algorithm selected for the free response or a step change in the set-point and load disturbance (in the input). This depends on the state of the radio buttons located above on the Controller output graphic. In the Error graphic the user can interactively modify the initial condition of the error and the reset band δ. The third graphic shows the root locus of the linear base system selected by the user in the setting menu. The fourth graphic represents the evolution of the system in the phase plane. It can be noted in the example shown in Fig. 3 the resetting of the controller output when the output cross inside the reset band.

On top of the Phase Portrait graphic, there is two checkboxes allowing simulating the reset control system and/or the linear base system.

In this tool it is possible to analyze the existence of limit cycles of reset control systems with reset band, by using the describing function of the reset compensator. A well-known method is to compute possible values of the amplitude (E) and the frequency (ω) such that the describing function of the reset compensator $C_\delta(E, j\omega)$ verifies that $1+C_\delta(E, j\omega)P(j\omega)=0$, which is usually referred to as the harmonic balance principle. This is usually made by analyzing the crossings of the Nyquist plot of the plant P with plots of $-1/\ C_\delta(E,\ j\omega)$ vs ω, for different values of E. It is well known [16] that this method only gives approximate results, and that it works well only if the plant $P(s)$ filters higher order harmonics of the periodic signal y_c in Fig.1 (low pass condition).

The L-plane graphic shows the use of the describing function to evaluate the existence of limit cycle in a reset control system with reset band. Finally the Reset Control Events graphic show the instants where the reset events occur. The radio button located on the top of this graphic allows choosing between the conventional reset system and an extended reset control system, where the reset time instances are pre specified with a reset sampling period.

- *Parameters*. The different parameters available in the tool are shown on the left-hand corner of the screen (see Fig.3). These elements allow to modify process parameters (for the transfer function selected in the Setting menu), the controller type (Clegg integrator, FORE compensator, etc) and the Reset Controller parameters like the amplitude of the reset band δ and the regularization time. This last parameter means the minimum time that it is necessary in order to the reset event may be produced. That it is important in order to control the existence of some problematic problems from the simulation point of view like the existence of Zeno behavior. In fact this is an indirect mechanism to study this kind of phenomenon in the reset control system with band.
- *Settings menu*. Several options can be chosen from this menu. There is one entry called Process Transfer Function where it is possible to choose between ten typical plants most used in the study of systems and found in industry. It is also possible to introduce a free transfer function given by the user in the typical Matlab format or in an interactive way adding poles/zeros in the Transfer Function graphic. The user has also the possibility to define in an interactive way the reset compensator choosing by the radio buttons that are located above of this graphic G_p (plant) or G_c (compensator). In order to do that the tool provides a graphical editor of the transfer function with the capabilities to Move/Add/Remove the elements that define the transfer function: Poles/Zeros/Integrators.

Therefore, the interactive tool contains many parameters related with the reset control strategy, the process to be controlled, and for the simulation setting.

IV. Illustrative Example

The following notation will be used to distinguish between reset compensators with and without reset band: C_δ will denote a reset compensator with reset band B. Consider the feedback system of Fig.1, in this case with a Clegg integrator CI_δ as reset compensator with $B^+ = 0.25$, and a second order plant $P(s) = (s+1)/s^2$. For this example in Fig.3 it is shown that there exist a limit cycle, with amplitude $E = 0.5$ and frequency $\omega = 0.92$ rad/s.

A. Limit cycles analysis

Let us consider now the use of the describing function method. The describing function of the CI_δ can be shown that is the following [9]

$$CI_\delta(E,\omega) = \frac{1}{j\omega}\left(1 + \frac{j4\sqrt{1-(\delta/E)^2}}{\pi}e^{j\sin^{-1}(\delta/E)}\right) \tag{4}$$

From (4) can be demonstrated that reset band introduces extra phase lead for values $0 < \delta/E < 0.8$, and at every frequency. Note that after some computation it can be shown that critical loci $-1/CI_\delta/E(1,\ \omega)$, is a circle with centers x_c + jy_c and radii r_c , dependent on the frequency, given by:

$$x_c(\omega) = -\frac{2\omega}{K\pi}$$
$$y_c(\omega) = -\frac{\omega}{K}$$
$$r_c(\omega) = -x_c(\omega)$$

Then, it is possible to evaluate numerically those crossings corresponding to a limit cycle, and in addition values of δ/E and ω. The result is that there exist limit cycles for any value of E such as $\delta/E = 0.82$, and for ω = 0.92 rad/s. In this example, the amplitude will be $E=\delta/0.82=0.3$. Note that the describing function method gives a very accurate prediction of the limit cycle.

B. Zeno solutions

Zeno solutions are present in hybrid/impulsive systems, and in particular in reset systems. For a given initial condition, a Zeno solution is a solution of the reset system that exhibits a sequence of resets instant that is convergent to a finite time instant.

The proposed tool is especially well suited for investigation of Zeno solutions. The simulation of the reset system is performed by using a time regularization constant that can be chosen by the user. Then, when several decreasing reset instant are detected in a simulation, and in addition that sequence is enlarged for decreasing values of the regularization constant, it is likely that a Zeno solution occurs.

In Fig.4, the reset control system example is investigated with a reset band given by $B^+ = 1.0$.

Note that for the initial condition given in the phase portrait, the reset control plot clearly shows that the reset control system exhibit a Zeno solution.

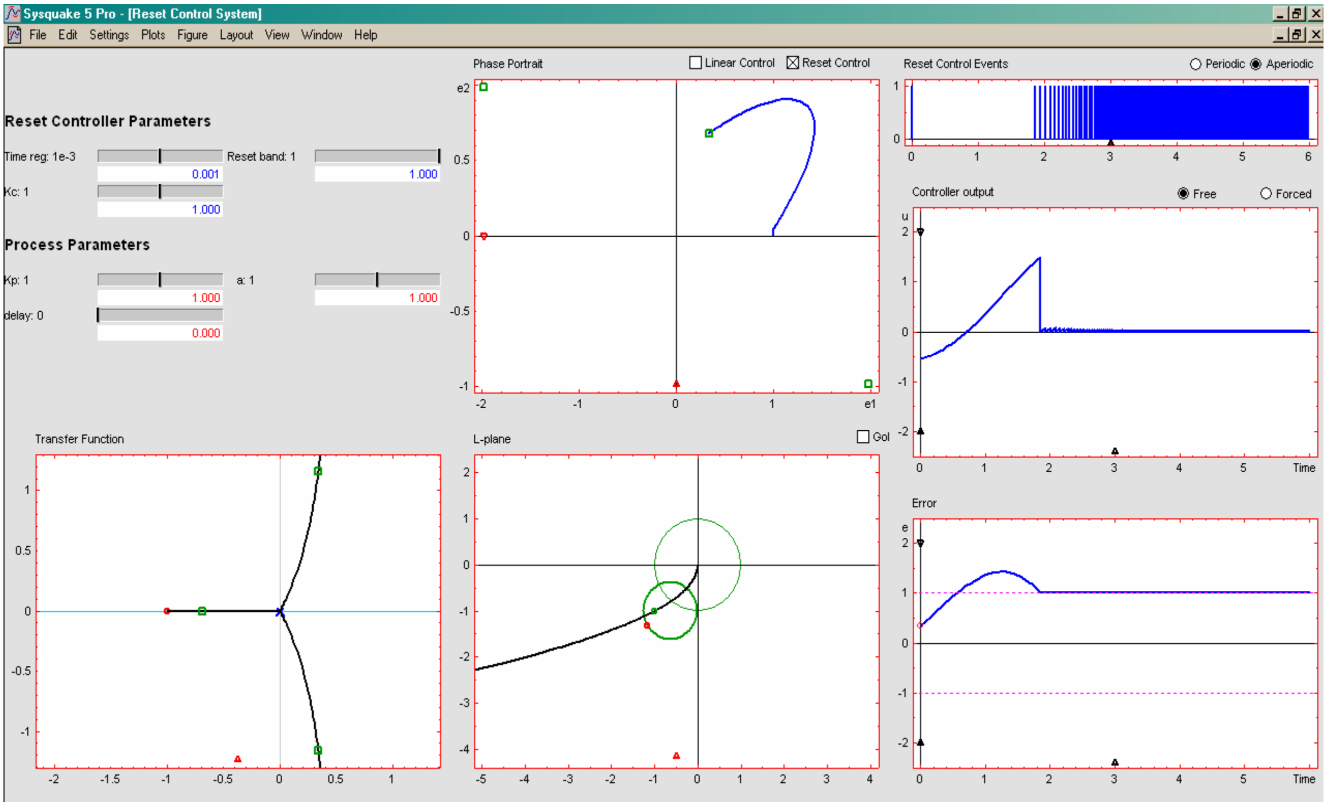

Fig. 4. Zeno solution

V. Conclusions

A new interactive tool for analysis and design of reset control systems has been described. The purpose is to enhance the knowledge of reset control systems by exploiting the advantages of immediately seeing the effects of changes that can never be shown in static pictures.

In particular, investigation of limit cycles and Zeno solutions in reset control systems with reset band has been illustrated. The module is implemented in Sysquake, a Matlab-like language with fast execution and excellent facilities for interactive graphics. The tool is available on request to the authors.

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References

[1] S. Dormido, S. Dormido-Canto, R. Dormido-Canto, J. Sánchez, N. Duro, "The role of interactivity in control learning", *The International Journal of Engineering Education*: Especial issue on Control Engineering Education, vol. 21, nº 6, pp. 1122-1133, 2005.

[2] J. L. Guzmán, M. Berenguel, S. Dormido, "Interactive teaching of constrained generalized predictive control", *IEEE Control Systems Magazine*, vol. 25, nº 2, pp. 52-66, april 2005.

[3] J. L. Guzmán, "Interactive Control System Design", Universidad de Almería, PhD Thesis, 2006.

[4] J. L. Guzmán, K. J. Åström, S. Dormido, T. Hägglund, M. Berenguel, Y. Piguet, "Interactive Learning Modules for PID Control: Using interactive graphics to learn PID control and develop intuition", *IEEE Control Systems Magazine*, vol. 28, nº 5, pp. 118-134, october 2008.

[5] S. Dormido, "Control learning: Present and future", *Annual Reviews in Control*, vol. 28, pp. 115-136, 2004.

[6] O. Beker, C.V. Hollot, Y. Chait, H. Han, "Fundamental properties of reset control systems", *Automatica*, vol. 40, pp. 905–915, 2004.

[7] D. Nesic, L. Zaccarian, and A. R. Teel, "Stability properties of reset systems", *Automatica*, vol. 44, no. 8, pp. 2019-2026, 2008.

[8] Baños, J. Carrasco, A. Barreiro, "Reset times dependent stability of reset systems", *IEEE Transactions on Automatic Control*, vol. 56, no. 1, pp. 217-223, 2011.

[9] A. Baños, S. Dormido, A. Barreiros, "Limit Cycles Analysis of Reset Control Systems with Reset Band", *Nonlinear Analysis: Hybrid Systems*, 2010, doi:10.1016/j.nahs.2010.07.004

[10] Y. Piguet, "Sysquake 3 User Manual", Calerga Sàrl, Lausanne, Switzerland, 2004.

[11] J. L. Guzmán, P. García, T. Hägglund, S. Dormido, P. Albertos, M. Berenguel, "Interactive tool for analysis of time-delay systems with dead-time compensators", *Control Engineering Practice*, vol 16, 7, pp. 824-835, 2008.

[12] J.C. Clegg, "A nonlinear integrator for servomechanisms", *Trans. A. I. E. E. m*, Part II, vol. 77, pp. 41–42, 1958.

[13] I.M. Horowitz, P. Rosenbaum, "Nonlinear design for cost of feedback reduction in systems with large parameter uncertainty", *International Journal of Control*, vol. 24, 6, pp. 977–1001, 1975.

[14] K.R. Krishman, I.M. Horowitz, “Synthesis of a nonlinear feedback system with significant plant-ignorance for prescribed system tolerances”, *International Journal of Contro*, vol.19, 4, pp. 689–706, 1976.

[15] Y. Chait, C.V. Hollot, “On Horowitz’s contributions to reset control”, *International Journal of Robust and Nonlinear Control*, vol. 12, pp. 335–355, 2002.

[16] A. Baños, A. Barreiro, “Delay-independent stability of reset systems”, *IEEE Trans. Automat. Control*, vol. 54, 2, pp. 337–341, 2009.

A. Barreiro, A. Baños, “Delay-dependent stability of reset systems”, *Automatica*, vol. 46, no. 1, pp. 216-221, 2010.

[17] J. Zheng, Y. Guo, M. Fu, Y. Wang, L. Xie, “Development of an extended reset controller and its experimental demonstration”, *IET Control Theory Appl*., vol. 2, nº. 10, pp. 866–874, 2008.

[18] Gelb A, VanderVelde W. E. *Multiple-Input Describing Functions and Nonlinear System Design*. McGraw-Hill, New York, 1968