PID Posicast Control for Uncertain Oscillatory Systems: A Practical Experiment

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Abstract: Half-cycle Posicast Control is currently used in a vast range of applications. Although the proved benefits of this technique, one of its major disadvantages concerns model uncertainties. This has motivated the development and integration of robust methods to overcome this issue. In this paper, a practical experiment for auto-tuning of a two degrees of freedom control configuration using a Half-Cycle Posicast pre-filter (or input-shaping), and a PID controller under parametric variations is presented. The proposed method requires using an oscillatory system model in an auto-tuning control structure. The error derivative among the model and system output is used to trigger both the identification and retuning procedure. The proposed method is flexible for choosing identification plus optimization methods. Practical results obtained for electronic filter plants suggest improved performance for the considered cases.

Keywords: PID control, Posicast control, Robustness, Oscillatory systems.

1. INTRODUCTION

Posicast Control (PC) was originally proposed by Smith (1957) to achieve dead-beat responses for underdamped second-order systems. Since then, many other input command shaping techniques were derived from the pioneering Posicast concept such as: Zero Vibration (ZV) and Zero Vibration and Derivative (ZVD) (Singer and Seering (1990)). This type of control technique has wide range of practical applications such as in: crane control (Sorensen et al. (2007)), vibration control (Singhose (2009)), robot control (Singhose and Seering (2005)), electronics (Ahumada et al. (2016)) etc. A major problem with the original half-cycle PC (ZV) is the high sensitivity to model uncertainties. This motivated the development of robust command shaping techniques to control flexible structures (Singhose (2009), Chatlatanagulchai et al. (2017)). Most of these techniques require obtaining several sequence impulses (or steps) input commands amplitudes and respective occurrence time instants. Often, many oscillatory systems require the use of optimization methods to obtain both amplitudes and time instants (Singh (2002)). PC shapers can be combined with feedback control using different feedforward/feedback configurations. Two of the main strategies are: i) as an input reference signal pre-filter within a two-degrees of freedom (2DOF) configuration; ii) inside the control loop often in series with the feedback controller (e.g. see Hung (2007)). The simultaneous design of both the input command shaper and the feedback controller is also known as concurrent design (Kenison and Singhose (2000), Kenison and Singhose (2002), Chang and Park (2001)). While some of these works addressed the design of PD, the concurrent design of input shapers with PID controllers is also addressed by Huey (2006). The design of PID control structures using a switching technique between feedforward control using half-cycle PC and PID control was proposed by Oliveira and Vrančić (2012). A technique to design PID controllers with half-cycle PC within the feedback loop based on the magnitude optimum method was proposed by Oliveira and Vrančić (2012). More recently, the gravitational search algorithm was proposed to design 2DOF control structures with half-cycle PC in Oliveira et al. (2015). However, 2DOF configurations using a half-cycle PC as pre-filter do not perform well when the system is subjected to model parametric uncertainties. This is mostly due to the input shaper sensitivity to model uncertainties, but also depends on the selected PID gains. Thus, in Oliveira et al. (2017) an auto-tuning technique was proposed based on a plant model, which retunes the system controllers. This technique is based on the particle swarm optimization (PSO) algorithm (Kennedy and Eberhart (1995)), which is deployed as optimizer both for the model parameter identification as well as half-cycle PC and PID controller retuning. The controlled methodology was shown to function well in Oliveira et al. (2017) achieving good simulation results. In this paper, a practical experiment is proposed to validate the simulation results. The selected practical experience is based on oscillatory systems implemented as low pass filters with operational amplifiers. The overall practical experiment goal is to implement simple electronic circuits which can be used to validate the technique proposed in Oliveira et al. (2017) using real-time synchronization for control. All the models are implemented in Simulink® and the algorithms in Matlab®. The interface with the computer was accomplished using a National Instruments AD/DC acquisition board (PCIe 6361). The remaining of the paper is organized as follows: Section II states the problem of auto-tuning requirement under uncertainties, presents system and controller structures and describes the methodology and practical experiment set-up, followed by results and discussion at Section III. In the end, Section IV presents some conclusions along with recommendations for future works.

2. PROBLEM STATEMENT

Consider the classical 2DOF control configuration presented in Figure 1, with the following variable correspondence: r represents the reference input, y the controlled variable, u the controller output, d a load perturbation, G_f, G_c and G_p represent respectively the transfer function for the pre-filter (or input shaper), PID controller and process to be controlled. In simple terms, the design

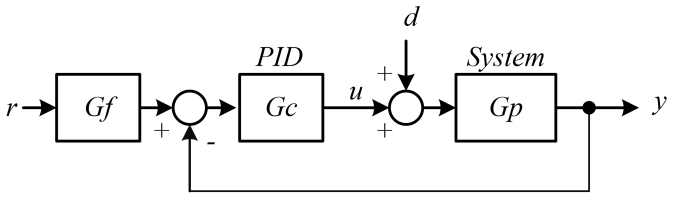

Fig. 1. Two-degrees of freedom control configuration used

problem consists in tuning both the pre-filter and PID controller parameters in order to achieve good set-point tracking and load disturbance rejection. There are multiple approaches to design this type of 2DOF control systems. Here, the same approach presented in Oliveira et al. (2015) is deployed, in which both the pre-filter and PID controller are designed simultaneously. The pre-filter considered in this study is the half-cycle Posicast (HC-PC) represented by:

$$G_f(s) = A_1 + A_2 e^{-t_1 s}, \tag{1}$$

with A_1 and $A_2 = 1 - A_1$ representing the first and second steps amplitude and t_1 the delay time applied to the second step, relatively to the first step. When parametric uncertainties and/or unmodeled dynamics affects the actual system G_p, HC-PC and PID controller may require to be retuned to continue providing the performance requirements. The HC prefilter is much more sensitive to plant parametric variations than PID. For motivation purpose, Figure 2 shows this behavior when an unmodeled significant time delay is inserted into the system for $t > 12s$.

2.1 Methodology and Materials

In order to evaluate different real scenarios, four systems are considered: two canonical second order system models,

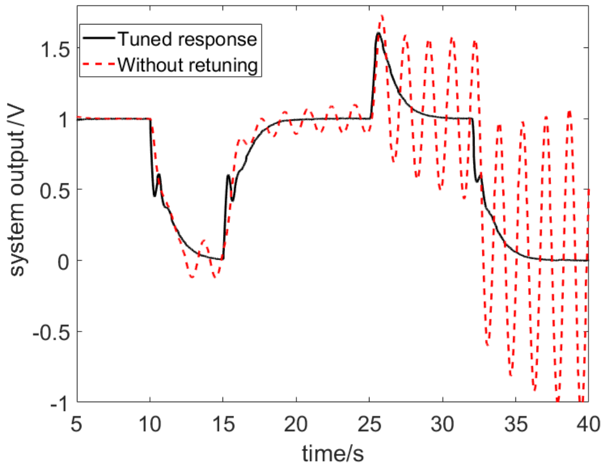

Fig. 2. Effect of uncertain time delay: tuned response (solid curve) × without retuning (dashed line)

Gp_1 and Gp_2, and two second order systems with a first order low pass filter in series, Gp_3 and Gp_4, to represent a third order system. All second order filters are implemented based on the Sallen-Key topology, as depicted in Figure 3, with *LM741* general purpose operational amplifiers. The switches for C_{11} and C_{12} allow the system variation at execution time. C_1 in (3)−(6) refers to C_{11} or C_{12} in Figure 3. With this topology the following transfer

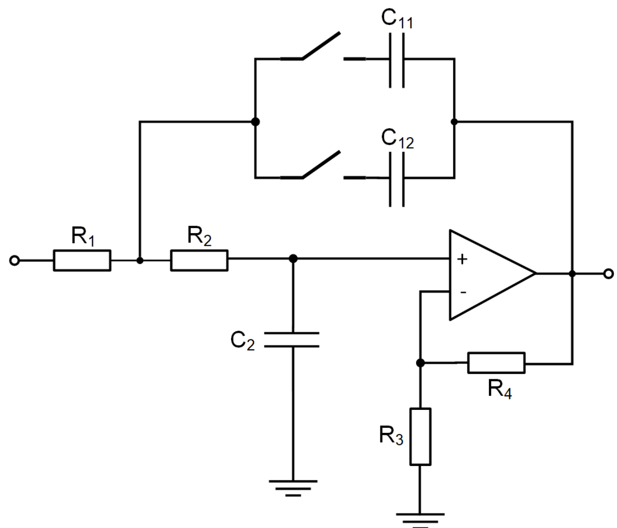

Fig. 3. Second order active low pass filter - Sallen-Key topology

function can be considered:

$$Gp(s) = K\frac{a_0}{s^2 + a_1 s + a_0} = \frac{\omega_0^2}{s^2 + \frac{\omega_0}{Q} + \omega_0^2} \tag{2}$$

where $K = 1 + \frac{R_4}{R_3}$ is the gain, but here the relation $\frac{R_4}{R_3}$ was chosen to get almost unitary gain. To get a better tuning, $R_3 = 2.2k\Omega$ and R_4 is a $22k\Omega$ potentiometer. The parameters are function of the physical components (resistors and capacitors) as follows:

$$a_0 = \frac{1}{C_1 C_2 R_1 R_2}, \tag{3}$$

$$a_1 = \frac{R_1 + R_2}{C_1 R_1 R_2}, \tag{4}$$

and, therefore, specifications can be extracted from (2), namely, the natural oscillation frequency ω_0, quality factor Q and the damping coefficient ζ,

$$\omega_0 = \sqrt{\frac{1}{C_1 C_2 R_1 R_2}}, \tag{5}$$

$$Q = \frac{1}{R_1 + R_2}\sqrt{\frac{C_1 R_1 R_2}{C_2}}, \quad \zeta = \frac{1}{2Q}. \tag{6}$$

Based on (2)-(6), Table 1 summarizes the component values and parameters for Gp_1 and Gp_2, with fixed $R_1 = R_2 = 100k\Omega$ and $C_2 = 680nF$:

Table 1. Parameters for canonical second order systems Gp_1 and Gp_2

	Gp_1 C_{11}	Gp_2 C_{12}
a_0	14.7059	3.1289
a_1	2	0.4255
Poles	$-1 \pm 3.7021j$	$-0.2128 \pm 1.7560j$
ω_0 **rad/s**	3.8348	1.7689
ζ	0.2608	0.1200
Q	1.9174	4.16

and, therefore, such systems are modeled as:

$$Gp_1(s) = \frac{14.7059}{s^2 + 2s + 14.7059}, \tag{7}$$

$$Gp_2(s) = \frac{3.1289}{s^2 + 0.4255s + 3.1289}. \tag{8}$$

Systems Gp_3 and Gp_4 are built from the scheme in Figure 4, with a fixed $R_5 = 100k\Omega$ and a switching C_3, which modifies the cutoff frequency ω_c of the low pass filter (second stage). If necessary, a similar gain loop can be added, as in Figure 3. The first stage is the same Gp_1 from Table 1. If a simple first order system transfer function is assumed to model a time delay, this configuration can be seen as a time delayed second order model. For other delay approximations (Pade, for instance), additional components and circuits would be necessary, depending on approximation order. For Gp_3, $C_3 = 4.7\mu F$ and therefore $\omega_c = R_5 C_3^{-1} = 10$ rad/s. For Gp_4, C_3 is changed to $1\mu F$, $\omega_c = 2.13$ rad/s. Therefore, nominal models can be described as:

$$Gp_3(s) = \frac{14.7059}{s^2 + 2s + 14.7059}\frac{1}{s + 10} \tag{9}$$

$$Gp_4(s) = \frac{14.7059}{s^2 + 2s + 14.7059}\frac{1}{s + 2.13} \tag{10}$$

The same approach proposed by Oliveira et al. (2017) is applied in a practical set-up (Figure 5). However, each stage is open to be implemented using any tools/algorithms. In this paper, uncertainty detection is based on nominal model output comparison with the actual output (a common fault detection strategy). When the error derivative exceeds a pre-defined threshold which depends on the uncertainty type/magnitude, a detection signal starts the system identification stage. Since the focus is on oscillatory systems, usually open loop step responses are enough to provide an accurate model, from overshoot and peak times estimation. However, due to measurement noise, a simple software filtering before identification improves the results. Once the identified model is available, the optimization routine gets new controller parameters for non-stop operation. For Gp_1 and Gp_2 PSO (Kennedy and Eberhart (1995)) is applied for 2DOF controllers, whereas a Matlab® command line *pidtool* is applied only for the PID controllers for Gp_3, Gp_4. The general block diagram

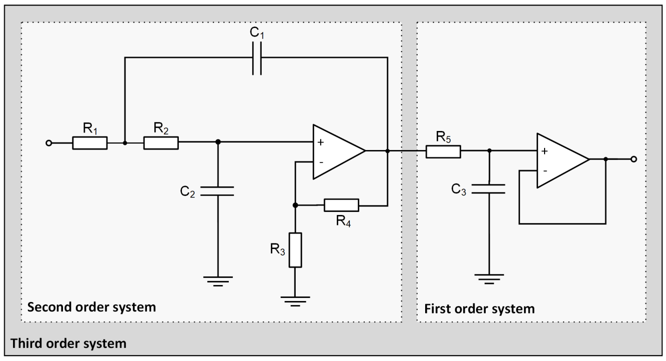

Fig. 4. Second order plus low pass first order filter

is given in Figure 6 and it is noteworthy that for accurate Matlab® continuous model simulation and uncertainty detection, the Digital Analog output (DA) was emulated with a quantizer and ZOH block (Figure 7). For the practical controller/plant, besides data acquisition blocks (analog input/analog output), a real time synchronization block guarantees the sampling time $T_s = 0.01s$, which is compatible with this feature.

Non filtered discrete PID blocks (11) for Gp_1, Gp_2 and with derivative filter (12) for Gp_3, Gp_4 were added, using trapezoidal approximation and sampling time $T_s = 0.01$ seconds:

$$K_p + K_i \frac{T_s}{2}\frac{z+1}{z-1} + K_d \frac{1}{T_s}\frac{z-1}{z} \tag{11}$$

$$K_p + K_i \frac{T_s}{2}\frac{z+1}{z-1} + K_d \frac{N}{1 + N\frac{T_s}{2}\frac{z+1}{z-1}} \tag{12}$$

where K_p, K_i and K_d represent respectively the proportional, integrative and derivative gains, and N is the filter constant. The controller output is limited in the interval $-10V \leq u(t) \leq +10V$, according to the used AD/DA card specifications (PCIe 6361, National Instruments, Austin, USA). Next section presents the practical results and give implementation details.

3. RESULTS AND DISCUSSION

To evaluate the method in Oliveira et al. (2017) (Figure 8), two experiments were carried out. **Experiment I**: starting with Gp_1 and a previously tuned 2DOF controller for it ($Ctrl_1$), the objective is to trigger identification and optimization stages for tuning both Posicast and PID control ($Ctrl_2$) when for $8s < t < 10s$ the system is switched to Gp_2. The start time for Figures 2, 9-13 was set next to $t = 5s$ to avoid the initial oscillation every time the acquisition card is initiated. For a real world scenario,

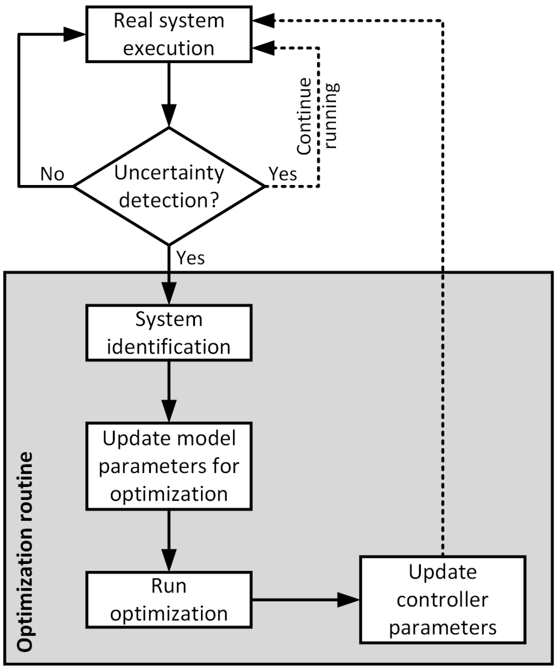

Fig. 5. Proposed methodology

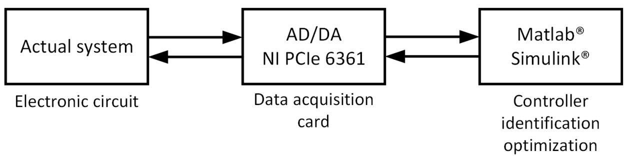

Fig. 6. General block diagram - experiment

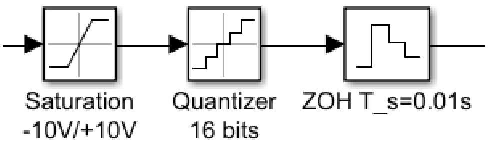

Fig. 7. DA blocks for continuous model simulation

this is not necessary, since the card is initiated just a single time. The effect of this parametric variation on tracking

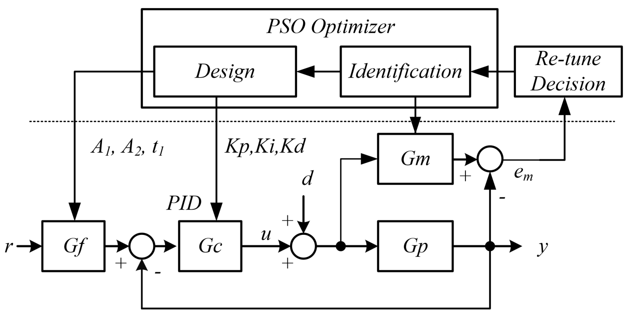

Fig. 8. General block diagram as in Oliveira et al. (2017)

of reference changes can be seen in Figure 9, suggesting that the HC parameters need to be optimized, whereas the PID suggests robustness to this particular variation. Several tests were conducted to set a threshold $Thde_m$ for the modeling error $e_m = y - y_m$ derivative, where y_m is the estimated model output. For this case $Thde_m > 5V$. Since only one variation is considered, a global counter controls the identification trigger. When a parametric variation occurs, its effect in HC-PC is felt in the next reference change. In **Experiment II** the same procedure is applied to Gp_3 with $Ctrl_3$ after changing to Gp_4 and $Ctrl_4$. The main objective is to compare and analyse this effect when the system changes while the previous controller is kept. For both experiments, an unit step load disturbance is applied at $t = 25s$.

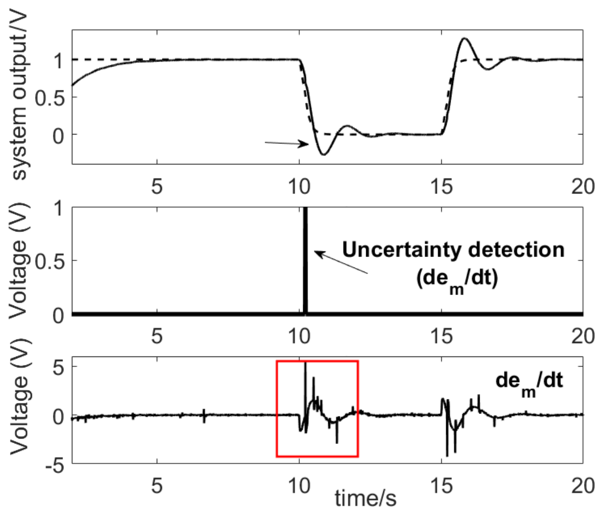

Fig. 9. Gp_1 and Gp_2 variation detection: system output (top plot), uncertainty detection trigger when the threshold exceeds (middle plot) and model mismatch error derivative (bottom plot)

3.1 Optimization

To highlight the flexibility of this approach, two different methods are used, PSO for Gp_1, Gp_2 and Matlab® *pidtune* tool for Gp_3 and Gp_4, which was configured to get an overshoot as small as possible. The PSO configuration was $c_1, c_2 = 2$ and inertia factor ω linearly decreasing from $0.9 - 0.4$, with 150 iterations and 50 particles. The optimization is subject to the following constraints: $0.1 \leq A_1 \leq 0.8$, $0.2s \leq t_1 \leq 5s$ and $0.1 \leq K_p, K_i, K_d \leq 5$, which define the search interval. However, other intervals may be considered. Alternatively, an informed initialization procedure can be used, based on classical tuning methods (Vrančić et al. (2001)), to decide on the search interval. After the identification stage, the optimization runs for $\hat{G}p_2$ estimated model:

$$\hat{G}p_2 = \frac{2.819}{s^2 + 0.4082s + 2.819}, \quad (13)$$

with a suitable approximation of $R^2 = 0.9894$ when compared to the data in Table 1. Since the practical step responses for both filters Gp_3, Gp_4 represented common second order responses/curves, the identification method got:

$$\hat{G}p_3(s) = \frac{1.836}{s^2 + 1.962s + 1.836}, \quad R^2 = 0.8463, \quad (14)$$

$$\hat{G}p_4(s) = \frac{1.55}{s^2 + 0.7598s + 1.55}, \quad R^2 = 0.9305 \quad (15)$$

However, if necessary, other identification methods can be used to get other dynamics. The statistical index R^2 is a common way to check how the model explains the actual measurements and, for the proposed technique, $R^2 > 0.8$ was found suitable. For these estimated models, Tables 2 and 3 summarize the 2DOF controllers:

Table 2. 2DOF controller parameters - PSO

Controller	Plant	A_1	A_2	t_1	K_p	K_i	K_d
$Ctrl_1$	Gp_1	0.7	0.3	$0.2s$	5	5	1.0497
$Ctrl_2$	Gp_2	0.7	0.3	$0.8s$	5	5	1.0956

Table 3. 2DOF controller parameters - *pidtune* tool

Controller	Plant	A_1	A_2	t_1	K_p	K_i	K_d	N
$Ctrl_3$	Gp_3	0.8	0.2	$0.8s$	0.0047	0.95	0.1	100
$Ctrl_4$	Gp_4	0.8	0.2	$0.8s$	0.5	1.1	0.3	100

From Table 2 and Figures 10-11, the influence of the parameter t_1 to improve tracking is highlighted and the other parameters were enough to maintain performance after optimization. A slightly increase in K_d provided a better disturbance rejection (11). A detail on the control signal can be seen in Figure 13, which corroborates a higher T_u index in Table 5.

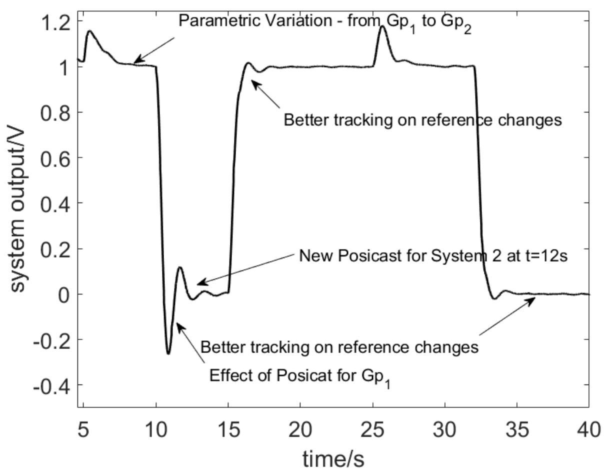

Fig. 10. Gp_2 output improvement with retuned 2DOF controller

For delayed-like systems Gp_3, Gp_4, the optimization retuned all PID gains in Table 3 and a better disturbance rejection is presented in Figure 12.

Common performance indexes used in process control are used to analyse the auto tuning methodology, namely, Integral of Absolute Error (IAE), Integral of Time Weighted Absolute Error ($ITAE$) and Integral of Squared Error (ISE). Besides, the total control effort $T_u = \sum |u|$, maximum overshoot M_p to measure load disturbance effect and output total variation $TV_y = \sum |(y(t) - y(t-1)|$ give insight for performance comparison. Tables 4 and 5 present the overall improvement when the retuned controller is used for each system.

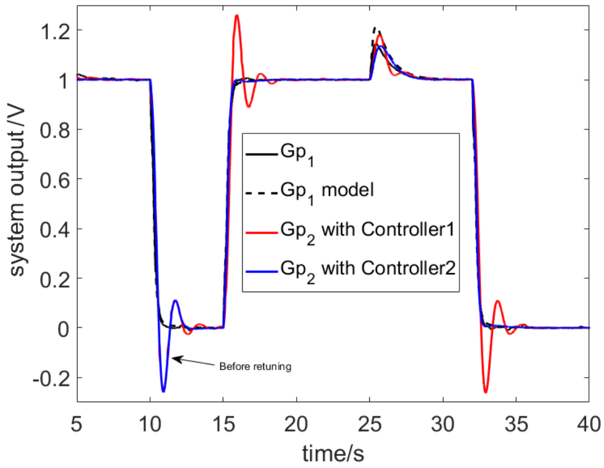

Fig. 11. Gp_1 and Gp_2 responses

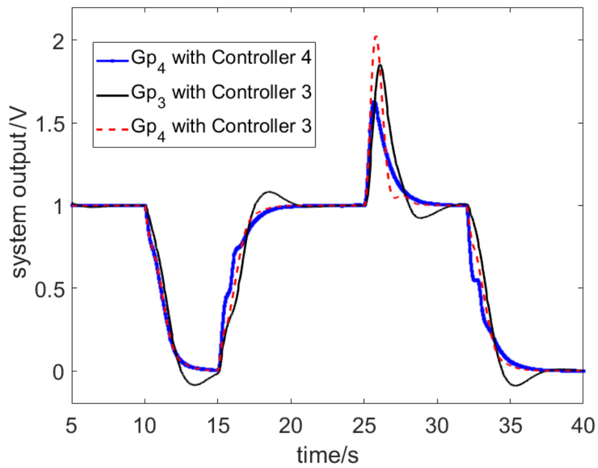

Fig. 12. Gp_3 and Gp_4 responses

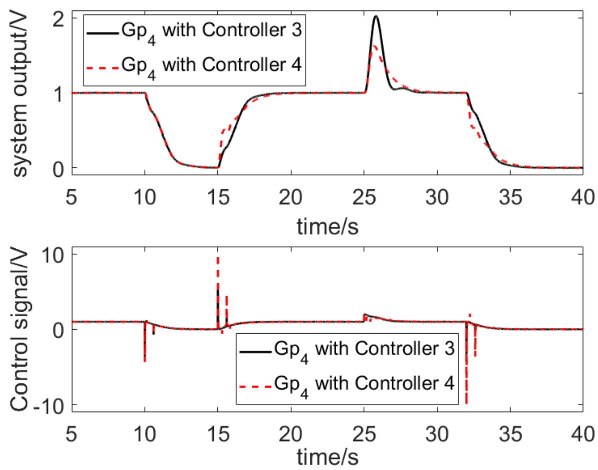

Fig. 13. Gp_3 and Gp_4 responses: (top plot) and control signal (bottom plot)

4. CONCLUSIONS

A practical experiment with electronics circuits was conducted to validate the simultaneous 2DOF optimization

Table 4. Performance canonical second order systems

	Gp_1,$Ctrl_1$	Gp_2,$Ctrl_1$	Gp_2,$Ctrl_2$
IAE	24.3	108.5	51.1
$ITAE$	547.6	2200	845.5
ISE	0.7	17.7	6.8
T_u	2500	2700	2800
M_p	14.39	26.17	13.55
TV_y	20.5	19.3	8.6

Table 5. Performance second order systems plus first order filter

	Gp_3, $Ctrl_3$	Gp_4,$Ctrl_3$	Gp_4,$Ctrl_4$
IAE	170.1	135.0	115.6
$ITAE$	3900	3200	2700
ISE	23.7	24.7	10.3
T_u	2470	2460	2480
M_p	85.16	102.7	62.8
TV_y	7.3	7.1	6.3

and identification under parametric variations. Several tests were conducted in order to evaluate the performance of the proposed robust methodology. For the considered systems, the retuning procedure was found suitable, however other systems can be investigated to cause a higher variation in controller parameters after optimization. Due to the large flexibility in choosing the identification/optimization technique, future works can address closed loop identification methods and observers for general parametric variation detection. Moreover, the parametric variation detection under lower signal-to-noise ratio should be investigated.

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