PID CONTROL OF ANALOG THREE-DIMENSIONAL PLANT

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***Abstract* - Multi-loop (decentralized) Proportional-Integral-Derivative controllers find extensive use in industrial systems. An auto-tune method is present in the paper. The independent design approach is used. The method treats the multivariable system as independent SISO systems with interactions as an additive uncertainty. Modified relay feedback is applied. A software is developed using Siemens TIA Portal V15. The approach is tested on a three-dimensional multivariable system, modelled by an analog board.**

Keywords— Auto-tune, Multi-loop PID, multivariable system, PLC

I. INTRODUCTION

Despite the existence of advanced methods and the big research around them, the PID control is still dominant in industrial systems. The main factors are simple structure, small number of tuning parameters, possibility for fine manual tuning. Most of the tuning methods are based on simple models, making auto tuning easier task. For a long time there exist software implementations and libraries of the algorithm. All of this makes the practical implementation easier.

The main problem when dealing with MIMO systems is the existence of interconnections. Reference or parameters change, presence of disturbance or noise in one of the loops impact all the others and because of the feedback the last form a reaction to the source loop. Treating this problem is of utmost importance when controlling MIMO plants. In the literature one can find different methods like – full dynamic decoupling [1], decoupling for fixed frequency range [2] or static decoupling, effective open loop [3], sequential tuning, detuning, inverted decoupling [4]. The present work use the principle of independent design [5]. A control system for PID auto tuning is developed using minimal plant information.

II. INDEPENDENT DESIGN

The essence of the independent design is finding n independent controllers in the presence of some constraints imposed by the interconnections of the MIMO plant. Two problems arise, first the bigger the interconnection strength the bigger the constraints imposed are, the poorer the performance of the closed loop system would be. Second, the lack of information for other loop's controllers additionally could degrade performance. The present work offers an approach for auto tuning with minimal information.

Let the plant is described by its transfer matrix (1), where m is the number of inputs, r is the number of outputs. For a decentralized control a square matrix is required, i.e. m=r.

$$G(s)=\begin{vmatrix} G_{11}(s) & \dots & G_{1m}(s) \\ \dots & \dots & \dots \\ G_{r1}(s) & \dots & G_{rm}(s) \end{vmatrix} \tag{1}$$

For the MIMO plant to be treated as m SISO plants let's assume that each diagonal element of the transfer matrix is a nominal plant of an uncertain family of plants. Then one assumes that the sum of each row of the off-diagonal elements represents additive uncertainty for each family (2).

$$\begin{vmatrix} G_p^i(s)=G_n^i(s)+G_a^i(s) \\ G_n^i(s)=G_{sh}^{ii}(s) \\ G_a^i(s)=\sum\limits_{i=1,\,j=1}^{r,m} G_{sh}^{ij}(s)\,,\, i\neq j \end{vmatrix} \tag{2}$$

Where $G_p^i(s)$ is the uncertain (or perturbed) plant, $G_n^i(s)$ is the nominal plant, $G_a^i(s)$ is the additive uncertainty. Superscript *i* used in the first equation of (1) changes from 1 to *m* and is used to enumerate the uncertain, nominal plant and the accompanying uncertainty for every loop. $G_{sh}^{ii}(s)$ represents the *i-th* diagonal element of the transfer matrix $G_{sh}^{ii}(s)$ of the plant. $G_{sh}^{ij}(s)$ represents all the off-diagonal elements of the transfer matrix $G_{sh}(s)$. Treating the interconnections as additive uncertainty could lead to conservative results regarding system performance, but this approach makes the task easier and possible to use approved SISO methods with small modifications.

For every model $G_n^i(s)$ one could find a PID controller, providing stability margins in the presence of the additive uncertainty $G_a^i(s)$. One easy approach is using the maximum of the sensitivity function S. The reciprocal point of the maximum is the smallest distance to the Nyquist point, Fig. 1.

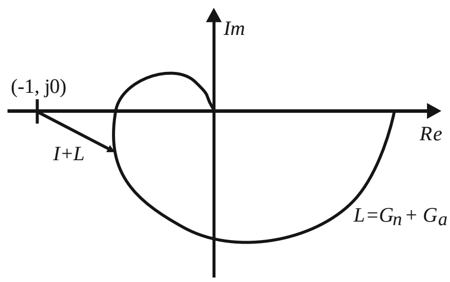

Fig. 1. Nyquist characteristic

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By using the second method of Astrom and Hagglund [6] (the kappa method) for every $G_p^i(s)$, one finds a PID controller ensuring that the nominal plant $G_n^i(s)$ does not encircle the Nyquist point in the presence of an additive uncertainty $G_a^i(s)$. To do that the experiment using relay feedback should be modified. For every diagonal element $G_n^i(s)$ the feedback should be closed only by output y_i, but the relay output should be fed to all of the plant inputs (Fig. 2.), leading to an experiment using $G_p^i(s)$=$G_n^i(s) + G_a^i(s)$.

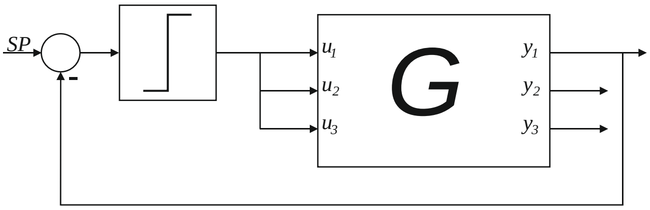

Fig. 2. Modified scheme for relay auto-tuning

One should note that this approach is feasible only for small interconnections. To address this issue one should make a pairing analysis using a tool like RGA, RNGA and the Niederlinski theorem. Some kind of compensation is also possible. Some authors suggest using the following [7]:

$$G_{sh}(s) = G(s).D \ , \tag{3}$$

$$D = G^{-1}(0) \tag{4}$$

D is a constant matrix, ensuring the corrected plant G_{sh} is an identity matrix in steady state. This removes the influence between the loops at steady state at the expense of increased high frequency interconnections. To address the issue one could use a second order filter [8] at the output of every PID, ensuring high roll-off, leading to some kind of robustness.

III. The Plant

The plant to be *controlled* consists of three inputs and three outputs. A general structure of the plant is shown on Fig. 3.

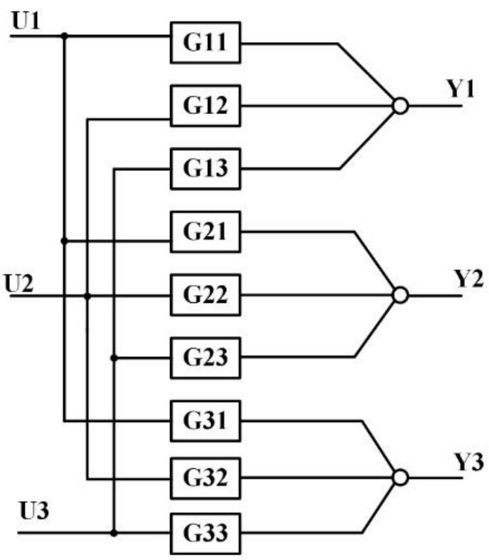

Fig. 3. Plant structure

The diagonal elements of the object are second order dynamics, the off-diagonal elements are of first order. The interconnections have strong influence, especially in steady state. There is also dynamics with opposite directions. The control object is modeled by an analog board "UNIVERSAL BOARD 2". First order dynamics, proportional gains and sum blocks are used. The plant modeled on the analog board is shown on Fig. 4. The parameters of the building blocks are set manually. Because of the poor accuracy of the potentiometers, one needs to evaluate every block's parameters by experiment. Each block's input is fed voltage by the DACs of the PLC, the outputs of the blocks are fed to the ADCs. A transient response is recorded, proportional gain and time constant of every block are estimated. The parameters are shown on TABLE I, where T_i represent time constant, K represent proportional gain. Picture of the PLC is shown on Fig. 5.

Fig. 4. Plant model on the analog board

Fig. 5. PLC – Siemens CPU S7-1500

IV. Software

The software is developed using TIA Portal V15. The program doing all the computations is written, using SCL. For ease of use HMI station is created. A structure of the closed loop system is shown on figure 11. In general the control algorithm consists of two modules. The first module contains the three discrete PIDs [9] - (5), (6). The second module contains the decoupling matrix (4).

$$u(k) = Kp\left(e(k) + I(k) + \frac{T_d}{T_0}\big(e(k) - e(k-1)\big)\right) \quad (5)$$

$$I(k) = I(k-1) + \frac{T_0}{T_i}.e(k), \quad I(0) = 0. \quad (6)$$

TABLE I. Plant parameters

Block notation	T_1, s	T_2, s	K
G_{11}	11.5	16.6	1
G_{12}	4	-	-9
G_{13}	34	-	8
G_{21}	19	-	-5
G_{22}	7	33.0	8
G_{23}	3	-	7
G_{31}	5	-	-9
G_{32}	14	-	3
G_{33}	15	24.8	1

Where u is the output of the PID, e is the control error, k is the current step, K_p is the proportional gain, T_i is the integral time constant, T_d is the differential time constant of the controller, T_0 is the sample time, chosen as 0.1s.

The HMI makes it possible to estimate the proportional gains of every element of the transfer matrix, calculate the compensation matrix D, auto tune the PIDs, choose control mode (auto/manual), observe closed loop processes like control action and process variables. Some of the functionality of the HMI is shown on Fig. 6, Fig. 7, Fig. 8 and Fig. 9.

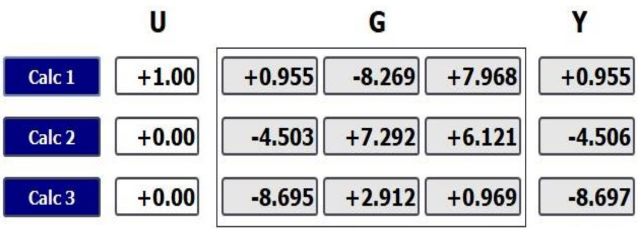

Fig. 6. Calculating gains

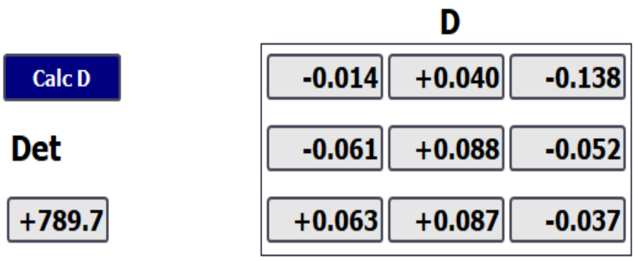

Fig. 7. Calculating compensation matrix D

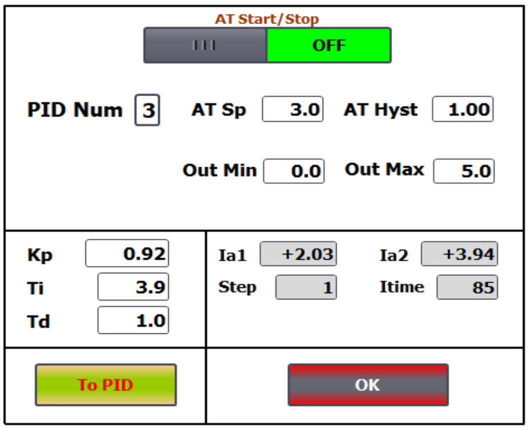

Fig. 8. Auto tuning panel

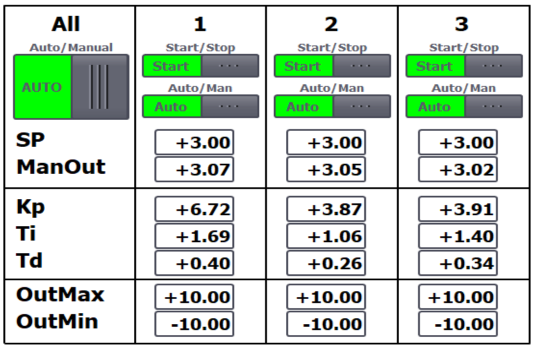

Fig. 9. PIDs control panel

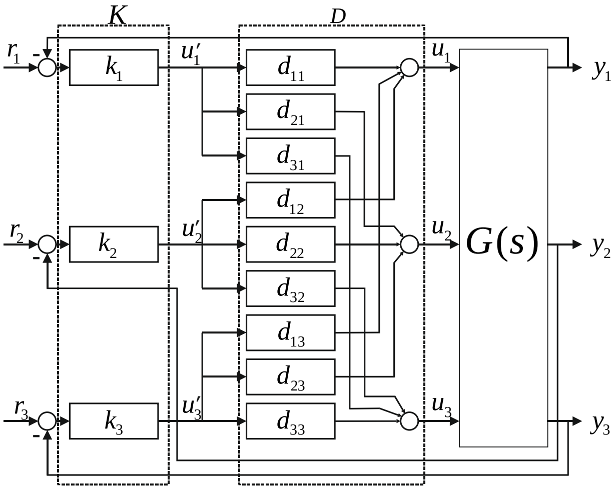

Fig. 10. Structure of the closed loop system

V. Results

For the purpose of the present work it is assumed that the model of the MIMO system is unknown. First step is estimating the proportional gains of every element of the transfer matrix.

Sequentially every input is fed constant voltage, the steady state values of the outputs are recorded. Using the newly found steady state matrix one calculates the compensation matrix D for the second step. Next using modified relay feedback as shown on figure 5, one finds the three PID controller parameters. Result of the relay feedback for the first loop is shown on Fig 11.

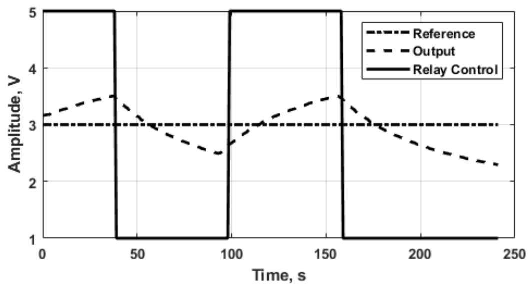

Fig. 11. Relay feedback for loop one

A symmetrical oscillation around the reference is observed, although it is not too close to a sinusoidal one. The form is dictated by the dynamics of the plant. Estimating the ultimate parameters ($K_u - ultimate\ gain,\ T_u - ultimate\ period$) after every loop's experiment, one could calculate the parameters of every PID. When the parameters of the three PIDs are found one should check the closed loop system performance. Sequentially every input is fed 3V then 0V, the results are shown on Fig. 12, Fig13 and Fig. 14.

All loops are characterized by fast transients. Loop two and three exhibit overshoot. The interconnections are either small or fast decaying. One important observation is the difference of the transient responses going up or down. Although the experiments are conducted using signal in the linear range of the board, there is still some nonlinearities. Summary of the performance of the closed loop system could be found in table two and table three. TABLE II contains transient response characteristics going up and down. TABLE III contains interconnection estimation by *ISE (Integral of the squared error)* criterion.

TABLE II. Time domain performance of the closed loop system

	Rise Time [s]	Settling time [s]	Overshoot %	Rise Time [s]	Settling time [s]	Overshoot %
Loop 1	2.7	4.8416	0	1.857	4.8482	0
Loop 2	1.5193	3.7945	12.2685	1.2653	3.689	23.05
Loop 3	2.1384	5.5951	7.0602	1.5756	5.7257	12.1528

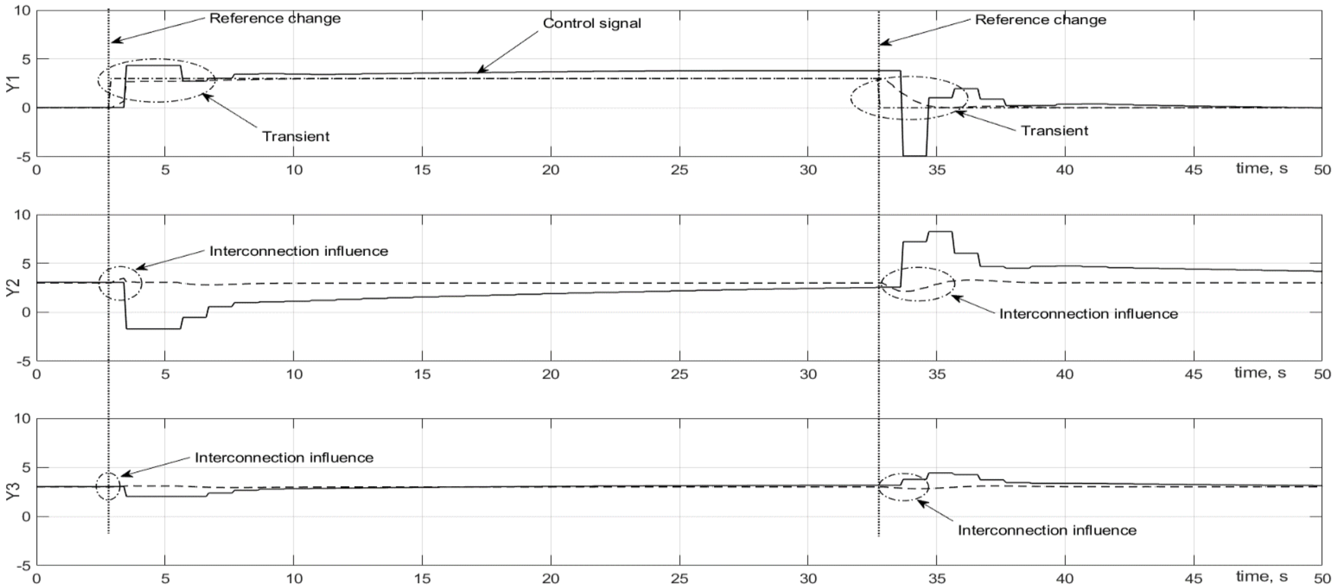

Fig. 12. Reference change at input one

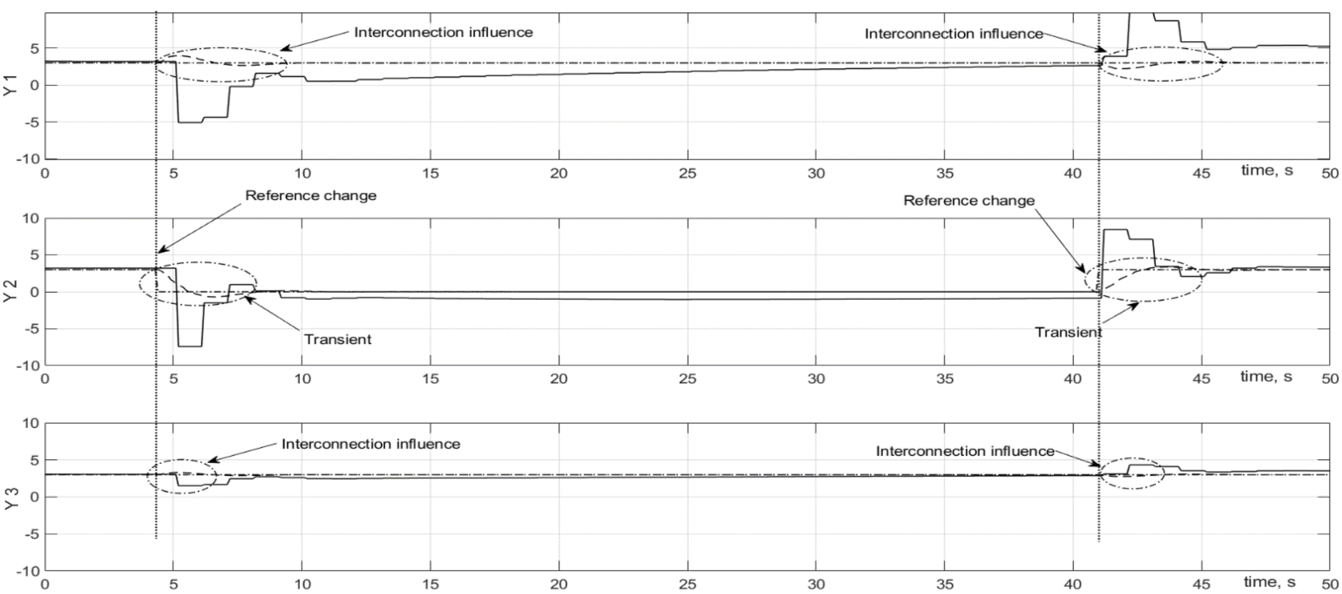

Fig. 13. Reference change at input two

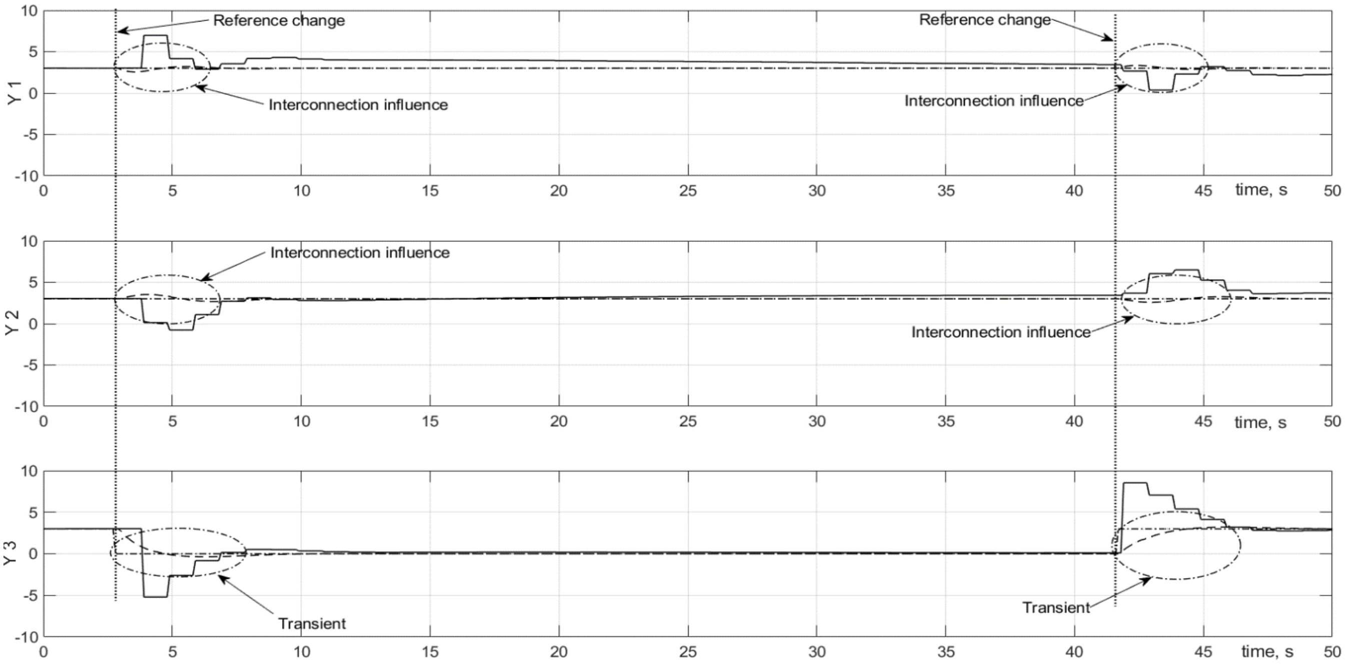

Fig. 14. Reference change at input two

TABLE III. An interaction measure by ISE criterion

	J_{u1}	J_{u2}	J_{u3}	J_{d1}	J_{d2}	J_{d3}
Loop 1	-	8.5416	1.3308	-	11.9201	2.1888
Loop 2	1.3958	-	3.3843	9.3892	-	5.0739
Loop 3	0.2634	0.7553	-	0.6211	1.0247	-

VI. Conclusion

This paper presents an auto-tune method for MIMO plant, using only information about the steady state. An optional step would be some kind of simple plant shaping or decoupling procedure in the presence of strong coupling. The present work employs a static decoupling. The remaining dynamics of the interconnections are treated as additive uncertainty. The ideology of the method is based on the independent design. The plant is to be controlled by PLC. All the necessary programs are developed using Siemens TIA Portal V15. The plant is modelled by an analog board. Three PID controllers are tuned using a modified relay experiment, making it possible to include the additive uncertainty into the procedure. Some experiments are conducted with the closed loop system, consisting of three independent PID controllers, static decoupling matrix and the plant. The step response of every loop is fast with as little as possible overshoot. The influence of the interconnections is small, thanks to the compensation matrix and the inclusion of the interconnections in the design procedure. The overall quality of the system is good, as is observed by the figures and the tables presented. One should note that the present approach is feasible when the influence of other loops is not as large or could be reduced by simple shaping or decoupling, otherwise the tuned parameters of the PID controllers would be too conservative, leading to poor quality of the closed loop response. Another weak point is the omission of a real uncertainty (not the artificial one, introduced by the interconnections) from the design procedure. Although that point is less of a concern, having in mind that one uses real experiment with the real plant and the fact that the procedure is simple, making it possible to retune the PIDs, if the plant parameters change notably.

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