A PLC BASED MIMO PID CONTROLLER FOR MULTIVARIABLE INDUSTRIAL PROCESSES

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Abstract. *Industrial processes are in general multi-input multi-output (MIMO) systems. Despite of that and because of the lack of good fine-tuning algorithms for MIMO controllers, they are usually treated as single-input single-output (SISO) ones for the purposes of control design and implementation. In that cases, the tuning procedure is frequently carried out taken one loop at a time and the results are usually not as good as would be expected. This work presents a MIMO PID structure that leads to a fine-tuning technique that can be carried out in real time. The MIMO PID new structure has been implemented in a low cost PLC. The controller was tested in a 2x2 MIMO benchmark plant with outstanding results. This paper presents details of the controller structure, the fine-tuning procedure and finally experimental results of the controller performance.*

Keywords*: PLC Based Control, MIMO PID controllers, Multivariable Systems.*

1. INTRODUCTION

The improvement of power consumption efficiency of industrial and commercial devices is one of the main issues for the incoming century. It is a fact that the next decades are going to testify a continuous and strenuous search for new devices and technologies to save energy resources. It is already acknowledge that the solution for an efficient operation of industrial plants relies on the proper choice and design of control systems. The complexity of industrial processes has continuously increased in recent years. Currently, almost every single industrial process is constituted by multiple inputs that affect and interact with all the process outputs. This has created the need for new control algorithms to cope with the current high industrial standards. The control design techniques have also evolved and produced advanced and sophisticated control algorithms. However, the required hardware capable to run these new control algorithms still is relatively expensive.

Currently, low cost simple controllers such as On/Off control and PID control are used as the standard controllers in industry. Unfortunately, they are not capable to deal with the existing I/O cross-interaction in MIMO plants. In multiple-input – multiple-output (MIMO) systems, the independent and simultaneous control of the output variables is frequently a challenging task. Besides that, model uncertainties, time delays in the control loop and strong cross-coupling interactions (that usually exists between the system inputs and outputs) are some of the problems that might deteriorate the controller ideal performance. .

Automatic control has played an important role in the development of the modern industry. The control community has proposed several new control techniques during the last decades to deal with the control problems of time varying processes, time delays and I/O cross coupling, etc. Among them, robust control, adaptive control and intelligent control are the most important. The final choice for the control of a specific application is usually determine by the plant characteristics, economical aspects and technical specifications. A drawback of these sophisticated alternatives is that they are usually expensive and required advanced computational resources. To face time-varying loads, time delays and I/O cross coupling, new low cost multi-input multi-output (MIMO) control strategies must be explored.

This paper presents a MIMO control scheme that can be implemented in a low cost Programmable Logic Controller (PLC). As an example of application, the proposed algorithm is applied to the control of an electrical oven system constituted by two heating zones, two thermocouples and two independent controlled power sources. Section 2 presents some comments on feedback control; Section 3 describes the benchmark 2x2 MIMO plant; Section 4 focuses on the designing and implementation of the proposed controller scheme; Section 5 shows a brief review on robust control concepts that are used to validate the proposed algorithm; Section 6 presents experimental results; and finally, Section 7 presents final comments and conclusions.

2. SOME COMMENTS ON FEEDBACK CONTROL

Output feedback has been the industrial standard for control purposes not only to shape the plant response, fulfilling performance specifications, but also to deal with output disturbances and model uncertainties.

Traditionally, the industrial control community has relied on the intrinsic robustness of output feedback controllers to face the control design problem for SISO plants. A diversity of controller tuning algorithms has been successfully developed and applied to SISO industrial plants. Behind this success, there has always been a property that exists for all physical system, the dominance of the low-frequency poles in the system time response. This fact has been the background of nearly every robust control design technique. Considering this concept in the controller design, there is no need for solving the modeling problem as rigorously as it could be required without the pole dominance property.

Several attempts have been made to extend the SISO design techniques to the MIMO case. In this context, the usually strong input-output cross-coupling existing in MIMO systems becomes as important as the model uncertainties due to the size (order) of large-scale systems. With some exceptions, the success of MIMO control design also depends on the pole dominance property. In recent years, the research has been focused in new uncoupling techniques. It is worth to mention the pioneer contributions from Bristol (1966), Kouvaritakis (1979), Mees (1981), McAvoy, (1983) and Grosdidier and Morari (1986). Some characteristics of the use of these techniques are: The design procedure is usually carried out in the frequency domain. Model uncertainties are easily represented in the frequency domain (particularly, non-structural uncertainties). Low frequency models are, in general, accurate enough for control design in this environment. The standard PI controller (that responds for more de 90% of the industrial controllers) is designed to perform in the low frequency range. Output disturbances are usually low frequency signals.

3. THE MIMO PLANT

Large industrial ovens usually include several heating zones with the objective of improving the internal temperature profile. However, due to the heat flow there is strong iteration among these zones. As in other cases of multiple-input multiple-output systems, this iteration may become relevant and cause serious difficulties to the control system [2].

The MIMO system, an electrical oven, has two inputs and two outputs (Figure 1). The system inputs are the voltage applied to the heating resistors. The system outputs are the temperatures at each heating zone. The control goal is to regulate the temperature profile with a minimum error. Due to the unidirectional and saturation characteristics of the power source as well as to the two different time constants for cooling and heating, the system in this case is nonlinear, however, it can be shown that for some temperature profiles the system behaves linearly allowing a linear analysis and design. In addition, a strong cross-coupling interaction among inputs and outputs characterizes this type of system. A major challenge in this case is that the thermal specifications work against the control performance, i.e., to optimize the smoothness of the temperature profile it is necessary to increase the iteration among the heating zones that causes the undesirable cross-coupling among inputs and outputs. Actually, each of the outputs is a function of both inputs as shown in Figure 2.

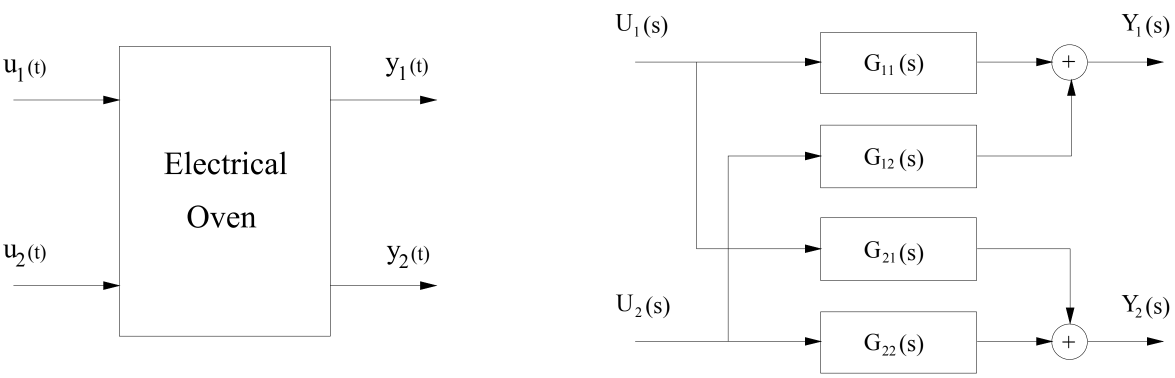


Figure 1. The Open Loop MIMO Plant.

Based on experimental results, a matrix transfer function model was built such that

$$\begin{bmatrix} Y_1(s) \\ Y_2(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} U_1(s) \\ U_2(s) \end{bmatrix} = [Y(s)] = [G(s)][U(s)] \quad (1)$$

The model identification procedure led to 2x2 matrix transfer function of the form:

$$[G(s)] = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} = \begin{bmatrix} \frac{2.8}{(521s+1)} e^{-48S} & \frac{1.5}{(340s+1)} e^{-105S} \\ \frac{1.5}{(340s+1)} e^{-105S} & \frac{2.8}{(521s+1)} e^{-48S} \end{bmatrix} \quad (2)$$

4. THE PROPOSED CONTROLLER

The proposed strategy is a frequency-domain procedure. In this case, the MIMO controller design is carried out in two steps. First a MIMO pre-compensator, $K_1(s)$, is designed to scale the system and reach diagonal dominance at low frequencies and then a MIMO controller, $K_2(s)$, is designed to meet performance specifications.

The advantage of this procedure it that for design purposes, $K_2(s)$ is diagonal and can be treated as a multiple SISO design since $G(s)K_1(s)$ is strongly diagonal dominant at low frequencies and diagonal at $\omega = 0$. Additionally, exact modeling is only required at steady state ($\omega = 0$) or at most at low frequencies.

The MIMO control law has the form:

$$[U(s)] = [K_1(s)][K_2(s)][R(s) - Y(s)] = [K(s)]\,[E(s)] \tag{3}$$

with

$$[R(s)] = \begin{bmatrix} R_1(s) \\ R_2(s) \end{bmatrix} ; \; [E(s)] = \begin{bmatrix} E_1(s) \\ E_2(s) \end{bmatrix} ; \; [U(s)] = \begin{bmatrix} U_1(s) \\ U_2(s) \end{bmatrix} \; \& \; [Y(s)] = \begin{bmatrix} Y_1(s) \\ Y_2(s) \end{bmatrix} \tag{4}$$

and

$$[K(s)] = [K_1(s)][K_2(s)] = \begin{bmatrix} K_{11}(s) & K_{12}(s) \\ K_{21}(s) & K_{22}(s) \end{bmatrix} \tag{5}$$

with $K_1(s) = K_1 = G^{-1}(0)$ (decoupling at $\omega = 0$), thus, a 2x2 MIMO PID controller can be written as

$$[K(s)] = [K_1]\,[K_2(s)] = [K_1]\begin{bmatrix} K_{P_{11}} + \dfrac{K_{I_{11}}}{s} + \dfrac{K_{D_{11}} s}{T_f s + 1} & 0 \\ 0 & K_{P_{22}} + \dfrac{K_{I_{22}}}{s} + \dfrac{K_{D_{22}} s}{T_f s + 1} \end{bmatrix} = \begin{bmatrix} \dfrac{N_{11}(s)}{D_{11}(s)} & \dfrac{N_{12}(s)}{D_{12}(s)} \\ \dfrac{N_{21}(s)}{D_{21}(s)} & \dfrac{N_{22}(s)}{D_{22}(s)} \end{bmatrix} \tag{6}$$

It should be noticed that, all entries of $K(s)$ have the general form of a SISO PI controller, however, the engineer only has to determine the diagonal elements of $K_2(s)$. The proposed designing technique leads to a closed loop transfer function that can be approximated (at low frequencies) by a diagonal matrix transfer function, Equation (20).

$$[Y(s)] \cong \begin{bmatrix} T_{11}(s) & 0 \\ 0 & T_{22}(s) \end{bmatrix} [R(s)] \Leftrightarrow \quad \begin{bmatrix} Y_1(s) \\ Y_2(s) \end{bmatrix} \cong \begin{bmatrix} T_{11}(s) & 0 \\ 0 & T_{22}(s) \end{bmatrix}\begin{bmatrix} R_1(s) \\ R_2(s) \end{bmatrix} \tag{7}$$

Because of that, the independent control of the heating zones is tangible as it is shown in the next section. Figure 4 shows the MIMO controller structure. Figure 5 shows the block diagram for the closed loop system.

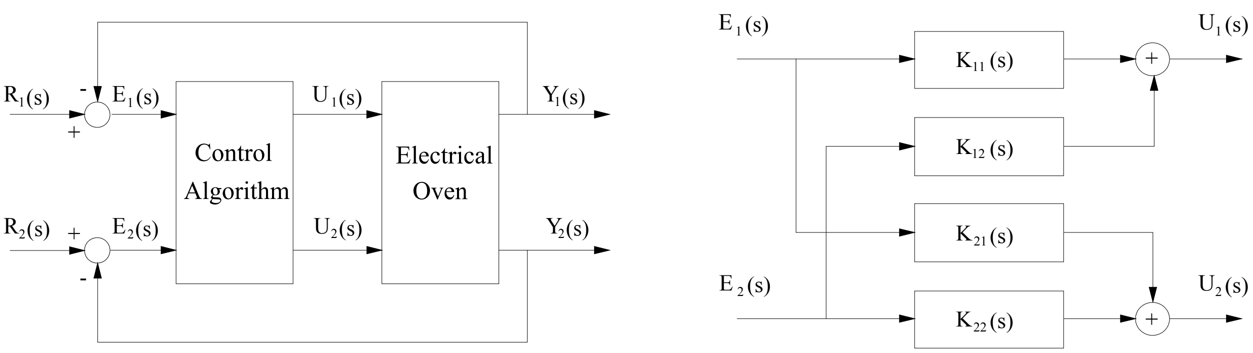


Figure 2. The MIMO Controller.

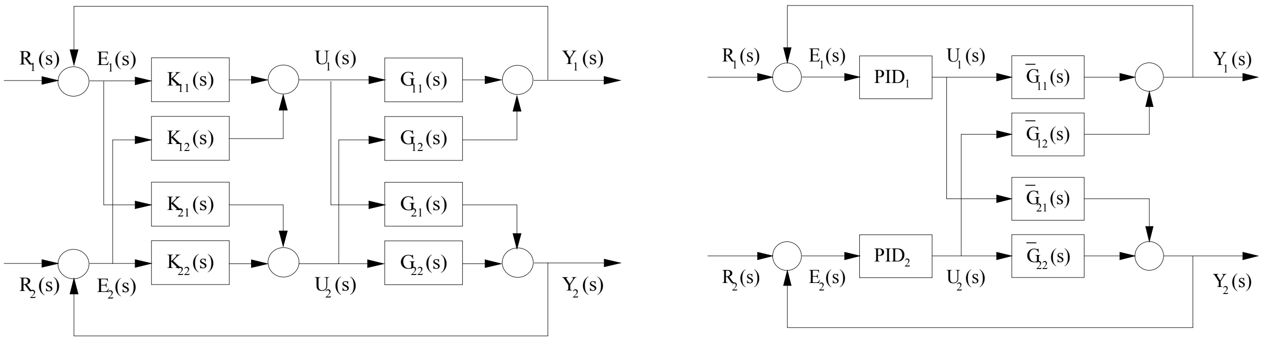
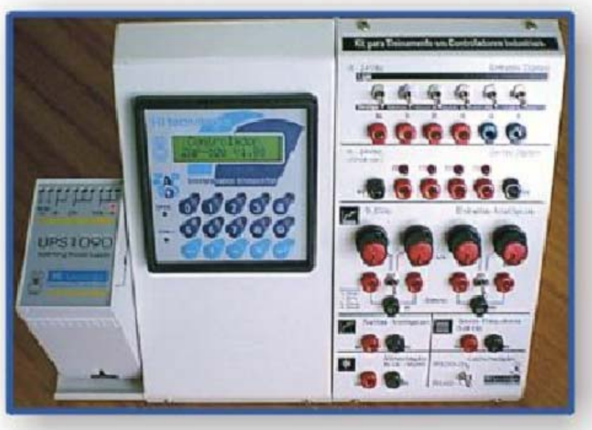


Figure 3. The MIMO Controller from the Fine Tuning View Point.

The MIMO controller was implemented in a low-cost high-performance PLC. Figure 2 shows the PLC ZAP500 from HI-Tecnologia used in this work. Figure 3 presents the internal architecture of the ZAP500 PLC.



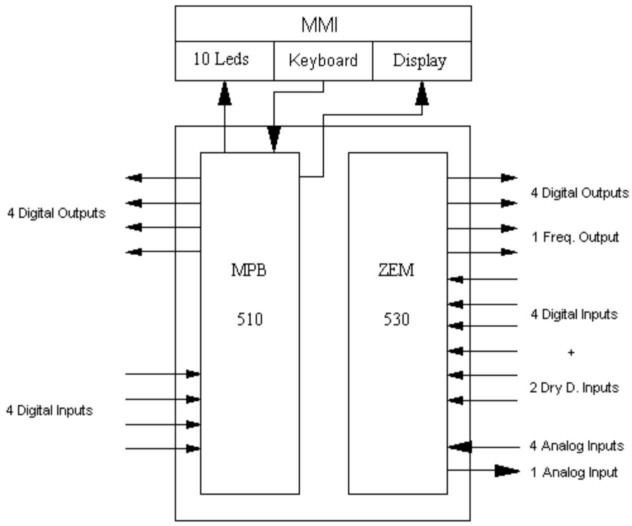


Figure 4a. The ZAP500 PLC. Figure 4b. The ZAP500 PLC Internal Architecture.

Several techniques for multivariable loop shaping can be found in the literature (Maciejowski, 1989, Skogestad, 1996, Ho & Xu, 1998). In this work, a robust performance was achieved using the following control law

$$[K(s)] = [K_1(s)]\,[K_2(s)] \tag{8}$$

with

$$[K_1(s)] = [G(0)]^{-1} = \begin{bmatrix} 2.8 & 1.5 \\ 1.5 & 2.8 \end{bmatrix}^{-1} = \begin{bmatrix} 0.5009 & -0.2683 \\ -0.2683 & 0.5009 \end{bmatrix} \tag{9}$$

and

$$[K_2(s)] = \begin{bmatrix} \dfrac{0.0075\,s^2 + 1.5\,s + 0.003}{s\,(0.005\,s + 1)} & 0 \\ 0 & \dfrac{0.0075\,s^2 + 1.5\,s + 0.003}{s\,(0.005\,s + 1)} \end{bmatrix} \tag{10}$$

Finally, the MIMO controller is given by

$$\left[K(s)\right] = \left[K_1(s)\right]\left[K_2(s)\right] = \begin{bmatrix} \dfrac{0.003757\ s^2 + 0.7513\ s + 0.001503}{s(0.005\ s+1)} & \dfrac{-0.002013\ s^2 - 0.4025\ s - 0.000805}{s(0.005\ s+1)} \\ \dfrac{-0.002013\ s^2 - 0.4025\ s - 0.000805}{s(0.005\ s+1)} & \dfrac{0.003757\ s^2 + 0.7513\ s + 0.001503}{s(0.005\ s+1)} \end{bmatrix} \quad (11)$$

Notice that the closed-loop system is given by:

$$Y(s) = T(s)\,R(s) = [I + G(s)K(s)]^{-1}G(s)K(s)\,R(s) \quad (12)$$

5. ROBUST CONTROL ASSESMENT – A BRIEF REVIEW

This section presents some basic concepts on multivariable robust control systems that are going to be used in the next section to validate the proposed design procedure and to assess the closed loop system robustness. The following is based on the books from Maciejowski (1989) and Skogestad et al (1996). The system output, y(s), can be written as

$$y(s) = T(s)P(s)r(s) + S(s)d(s) - T(s)m(s) \quad (13)$$

where *r(s)* is the reference input, *d(s)* represents the disturbances and *m(s)* is the measurement noise.

the function $S(s)$ is known as the output sensitivity function and is defined as

$$S(s) = [I + G(s)K(s)]^{-1} \quad (14)$$

and the system closed loop transfer function (or complementary sensitivity), *T(s),* is then given by

$$T(s) = S(s)G(s)K(s) \quad (15)$$

the input sensitivity function is defined as

$$S_i(s) = [I + K(s)G(s)]^{-1} \quad (16)$$

and its corresponding complementary function as

$$T_i(s) = K(s)G(s)S_i(s) \quad (17)$$

a multiplicative model for the plant uncertainty can be written as

$$G(s) = G_o(s)[I + W_i(s)] \quad (18)$$

Hence, the following criteria to assess the system performance and stability can be established:

a) The criterion for nominal performance is defined by

$$\left\|S(s)W_p(s)\right\|_\infty < 1 \qquad ; \qquad W_p(s) = w_p(s)\left[I\right] \quad (19a)$$

where $W_p(s)$ is a performance-weighting matrix, thus, the nominal performance criterion can be re-written as

$$\bar{\sigma}[S(s)] < \frac{1}{w_p(s)} \qquad ; \qquad \bar{\sigma}[\cdot] \text{ is the greatest singular value of } [\cdot] \quad (19b)$$

b) The criterion for robust performance (non-structured uncertainty) is given by

$$\gamma\,\bar{\sigma}\left(W_p(s)\,S_i(s)\right) + \bar{\sigma}\left(W_i(s)\,T_i(s)\right) \le 1 \qquad ; \qquad \gamma = \text{min (plant - controller conditioning number)} \quad (20)$$

c) The criterion for robust stability (non-structured uncertainty) is defined by

$$\left\| T(s) W_i(s) \right\|_\infty < 1 \qquad ; \qquad W_i(s) = w_i(s)\left[I \right] \tag{21a}$$

where $W_i(s)$ is an uncertainty weighting matrix, then, the criterion for robust stability can be re-written as

$$\overline{\sigma}[T(s)] < \frac{1}{w_i(s)} \tag{21b}$$

d) Structured-singular-values based robustness analysis was formerly introduced by Doyle et al (1981). In this case, a robust performance condition for structured uncertainty is given by

$$\mu\left(Q(s)\right) < 1 \qquad \forall \omega \tag{22a}$$

where, the matrix $Q(s)$ is defined as

$$Q(s) = \begin{bmatrix} Q_{11}(s) & Q_{12}(s) \\ Q_{21}(s) & Q_{22}(s) \end{bmatrix} = \begin{bmatrix} W_p(s) S_o(s) & W_p(s) S_o(s) G_o(s) \\ -W_i(s) K(s) S_o(s) & -W_i(s) K(s) S_o(s) G_o(s) \end{bmatrix} \tag{22b}$$

and

$$S_o(s) = \left(I + G_o(s) K(s)\right)^{-1} \tag{22c}$$

where $w_p(s)$ and $w_I(s)$ are defined in the frequency domain.

thus, a robust stability condition for structured uncertainty can be written as

$$\mu\left(Q_{22}(s)\right) < 1 \qquad \forall \omega \tag{23}$$

Equations from (19) to (23) are applied in Section 6 to assess the closed loop system robustness and to validate the controller design.

6. EXPERIMENTAL RESULTS

From the previous section, the nominal performance criterion was specified as

$$\overline{\sigma}[S(s)] < \frac{1}{w_p(s)} = \frac{2000\ s}{1000\ s + 1} \tag{24}$$

and the criterion for robust stability was chosen as

$$\overline{\sigma}[T(s)] < \frac{1}{w_i(s)} = \frac{2}{100\ s + 1} \tag{25}$$

Simulation results are presented next to illustrate the controller performance. Figure 5 presents the open loop frequency response of the plant. Figure 6 shows the system decoupling in the frequency domain due to the inclusion of $K_1(s)$. Figures 7 to 9 graphically display the controller designing procedure in the time domain. Figure 7 presents the open loop system steps responses; it can be observed (in quadrants I and III) the strong effect of the I/O cross coupling (in an ideal case, the time responses shown in quadrants I and III should remain at zero for all time or at least return to zero at steady state). Figure 8 presents the effects of the decoupling pre-compensator $K_1(s)$; it shows the system open loop time responses to a unit step. It can also be observed (in quadrants I and III) that the steady state effects of the I/O cross coupling were eliminated by the inclusion of $K_1(s)$. Figure 9 presents the system closed loop performance.

Finally, Figures 10 and 11 display the robustness analysis corresponding to Equations (19) to (23).

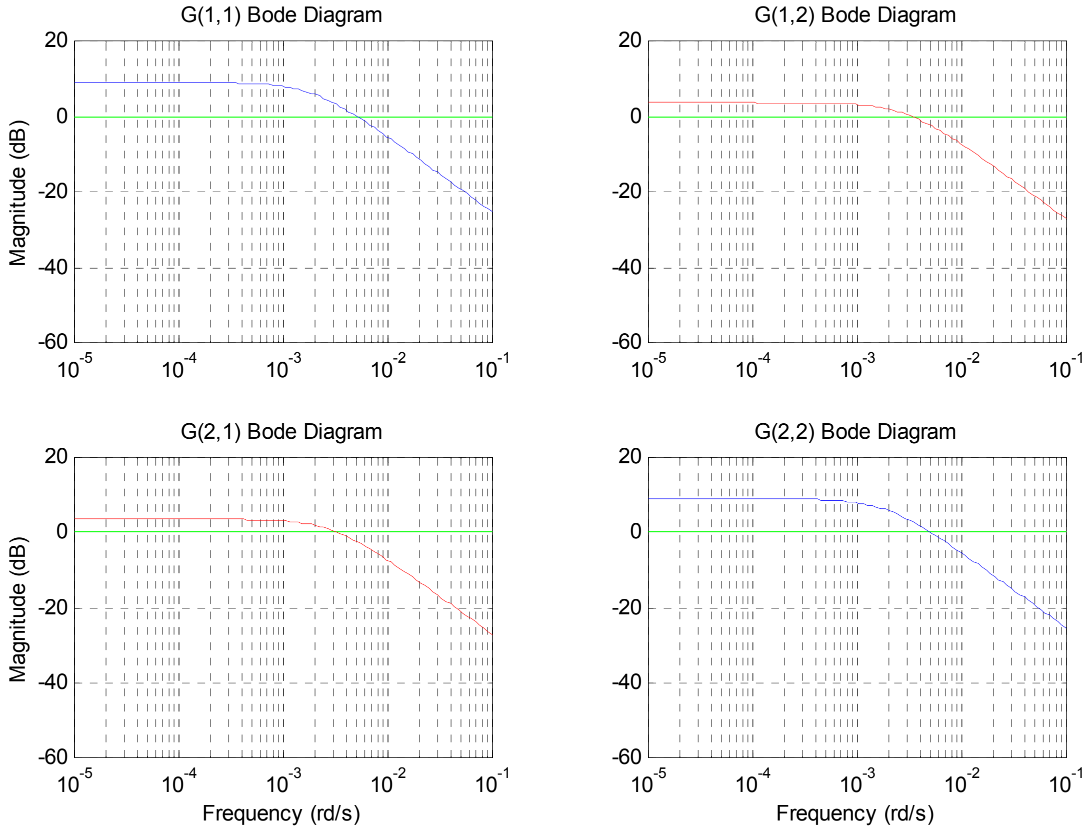


Figure 5. Open Loop Frequency Response of [G(s)].

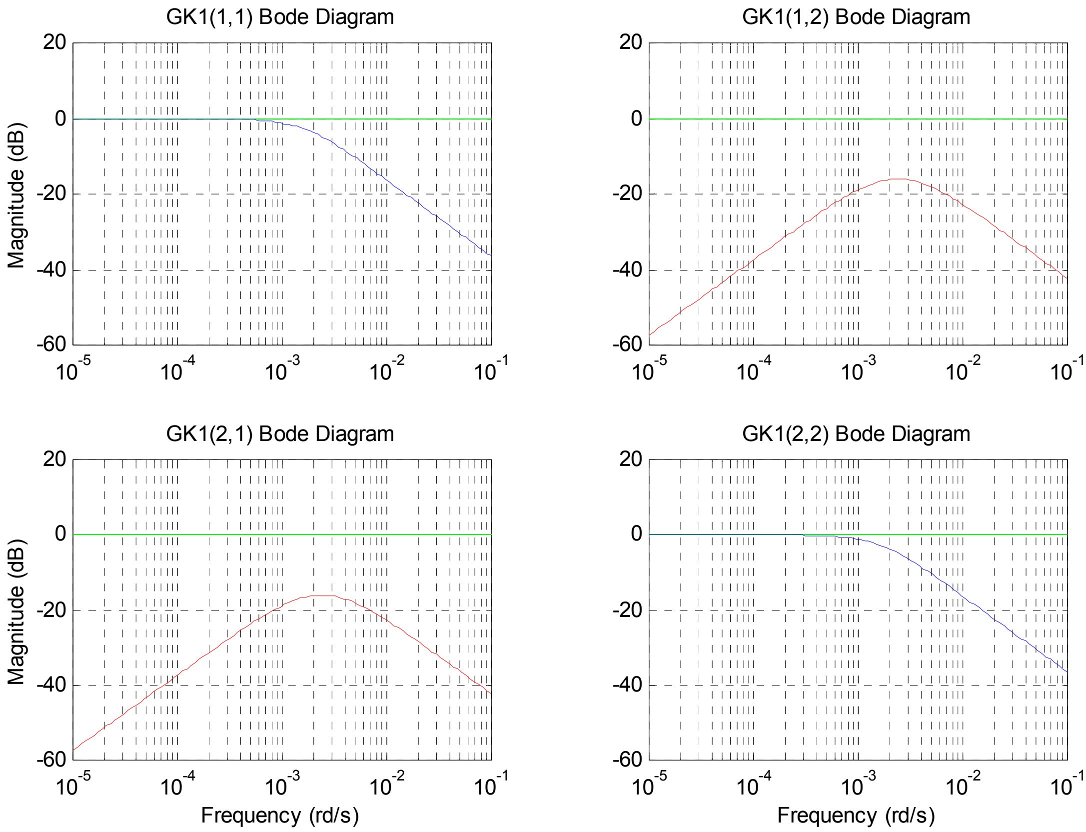


Figure 6. Frequency Response of [G(s) K_1(s)].

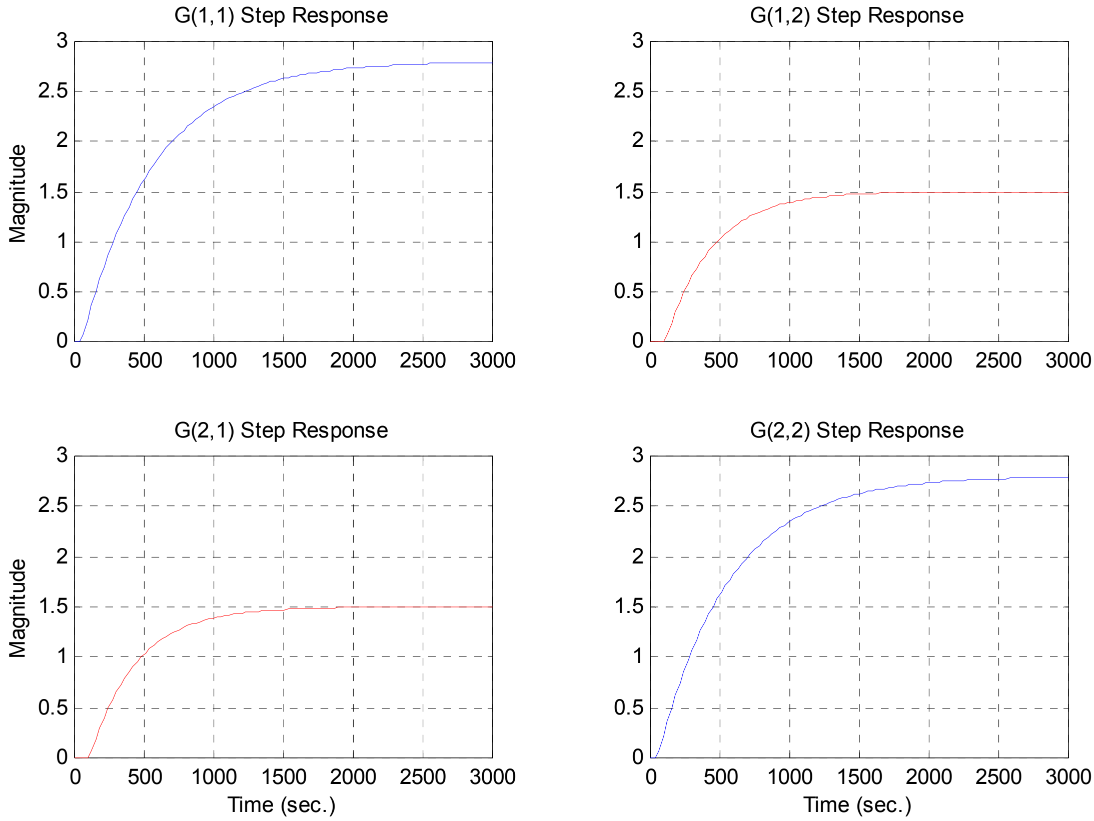


Figure 7. Open Loop Step Response of [G(s)].

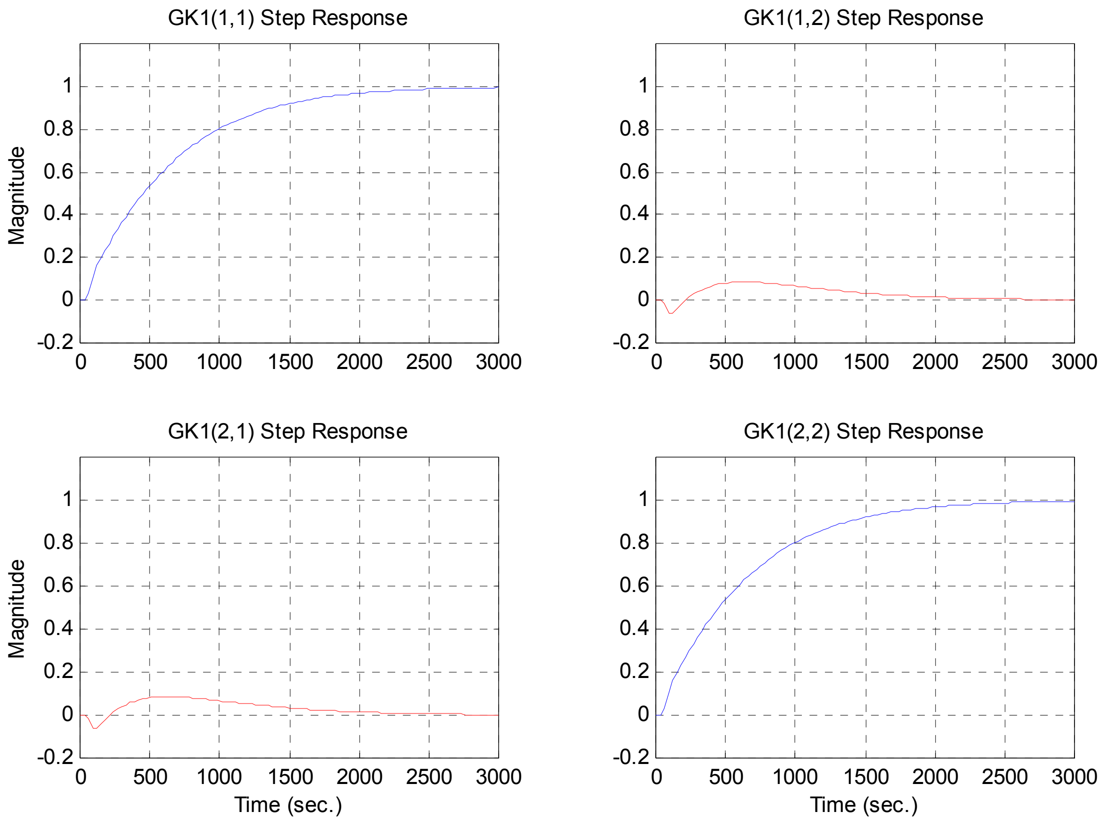


Figure 8. Open Loop Step Response of [G(s)K_1(s)].

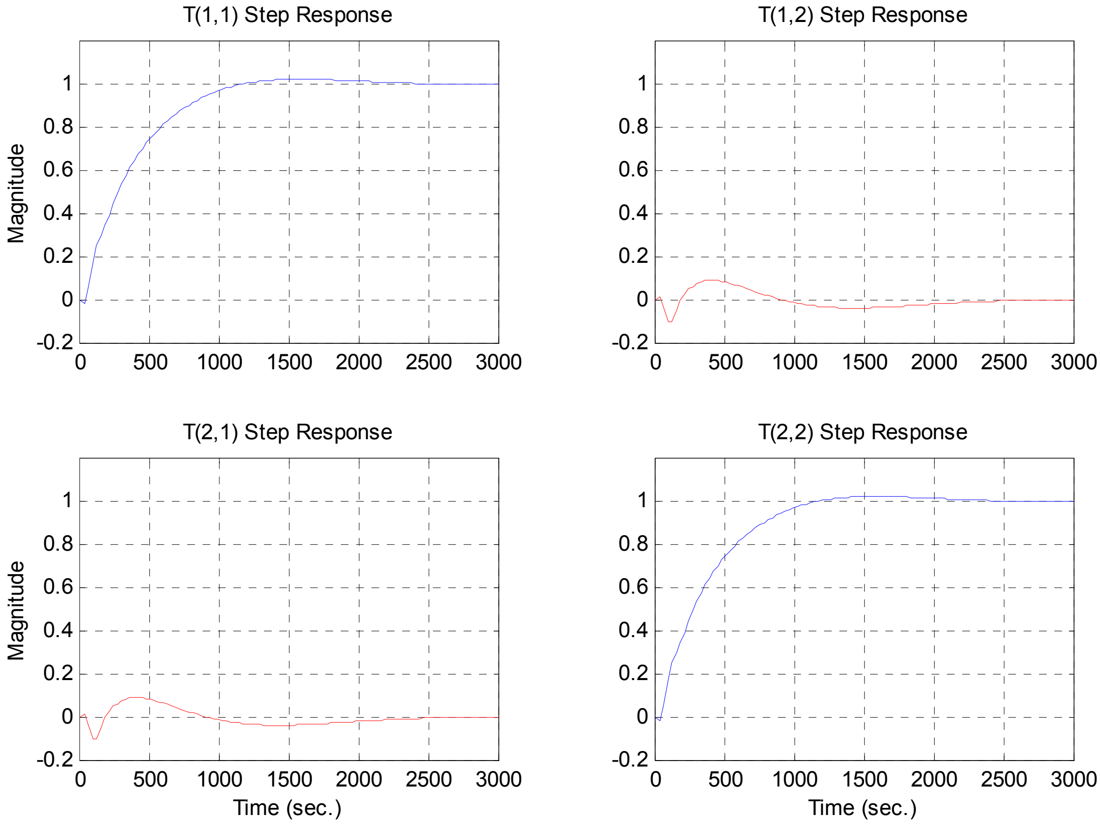


Figure 9. Closed Loop Step Response of T(s).

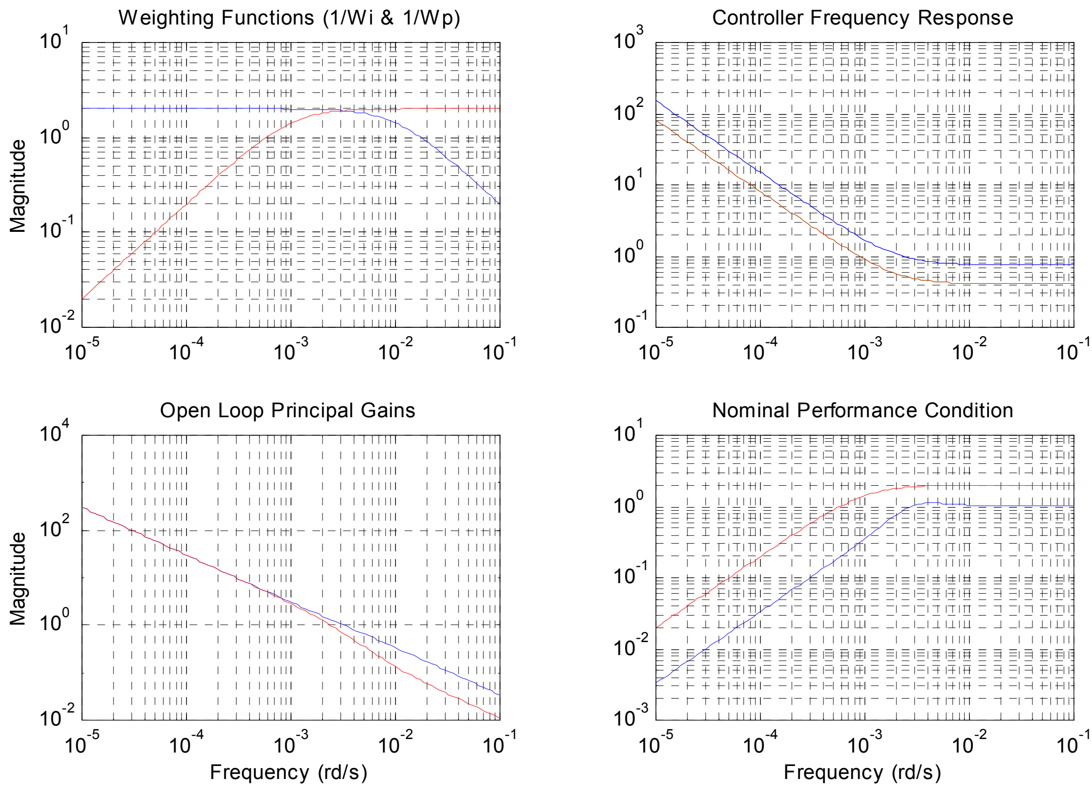


Figure 10. The Design Procedure.

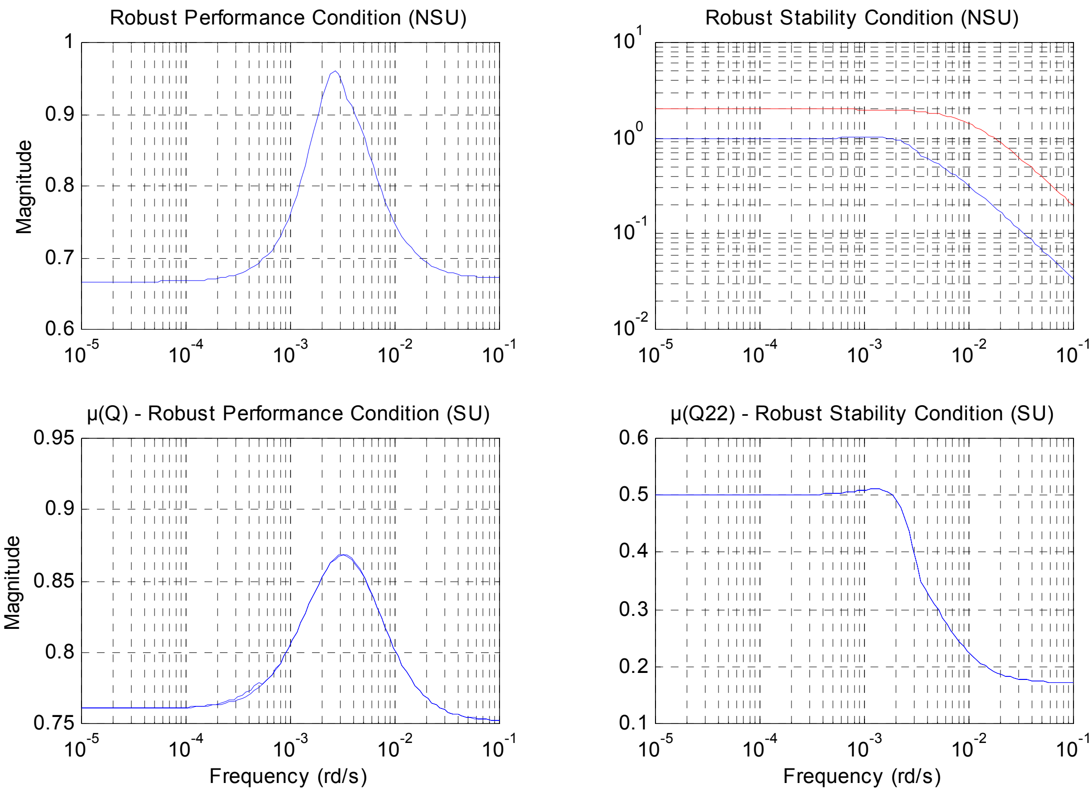


Figure 11. Controller Robustness Validation.

7. FINAL COMMENTS AND CONCLUSION

A MIMO controller design procedure has been presented. The main features of the proposed technique are:

a) It has been shown that the independent control of the heating zones in the oven system is a feasible task.

b) As long as the controller is designed to work in the frequency range in which the plant is diagonal dominant, the design can be accomplished in a SISO environment. It should be noticed that this is the general case of PI controllers in industry (that are designed to perform in low frequency).

c) The implementation and tuning of the control law can be done considering two independent single loop controls.

d) Due to the plant pre-compensator, model accuracy is in general required only at low frequencies.

e) Finally, it has been shown that due to the simplicity of the proposed control scheme, it can be easily implemented using low cost hardware.

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