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Experimental Activity for Teaching Control Structures*

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The laboratory designed and implemented at the Politecnico di Milano for the experimental activity on control structures is presented. Different structures can be experimented, at reasonably low cost, by means of a single apparatus, easy to use and maintain, and suitable for a large number of students. The pedagogical importance of experimenting with control structures is discussed, highlighting the originality of the experimental setup presented. An overview of the setup is given, and laboratory assignments are described.

INTRODUCTION

WHEN DESIGNING a control strategy of realistic complexity, the most critical step is the structuring of the strategy [1]. This is particularly true in the process control domain, where the tuning of a single regulator may depend significantly on its role in the overall control scheme. In such cases, even stipulating reasonable control specifications is extremely difficult unless the designer has a firm understanding of control structures.

To witness the importance of the problem, several works such as [2, 3] indicate that many control systems do not work satisfactorily owing to faulty structuring: decentralized controls are not properly synthesized, disturbance compensation is badly applied or not used where it should be, cascade controls are poorly tuned, loop interactions are not considered, or dealt with incorrectly, and the importance of the logic involved in all these control structures is often disregarded, though faulty choices in that logic may be very critical. Therefore, dealing with control structures effectively is of paramount importance in control education.

Undergraduate Automatic Control courses deal mostly with single-loop feedback control [4] where the structuring problem does not appear at all. Only a little time is devoted to control structures that are typically taught as mere extensions of the single-loop scheme. Most often, experiments on control structures are absent, or very sporadic. This is reasonable, especially if time and resource restrictions are considered, but it makes several people underestimate the importance of control structuring. In fact, many control engineers say they *were* taught control structures at the university, but they did not understand the importance of the matter, and had to learn the use of the major structures on the job. Indeed, such learning trajectories may contribute to the formation of a real 'knowledge gap' between theory and professional skills [3–5].

To counteract that gap, it is advisable to make the students experiment with control structures as soon as they are able, but this is not easy to do [6], as witnessed by the fact that most experimental setups deal with 'simple feedforward and feedback loops' [4, p. 155]; some setups allow to treat more articulated problems and control structures, but are correspondingly complex and expensive. In addition, to obtain an efficient laboratory with reasonable resources, several other aspects must be taken into account [7, 8]. It is desirable that the software employed be standardized and require no low-level programming skill, as explained very clearly in [9], where an effective solution is devised with the Matlab/Simulink environment, and that also the experimental plant(s) employed be reasonably priced, and flexible. The research presented below is an attempt to respond to all of these needs.

PURPOSE AND CONTRIBUTIONS OF THIS MANUSCRIPT

This manuscript is based on the previous research published in [10], where the experimental apparatus is described in detail, and some basic laboratory activities are presented, and on the preliminary results presented in [11]. The aim of this section is to point out the additional contribution of this work, and to illustrate its didactic goal.

In [10], the purpose was to introduce the apparatus, highlighting its simplicity and low cost, and to describe the activity for the course titled *Fundamentals of Automatic Control*. In that context, attention was focused on experiments aimed at making the students acquainted with the cycle of

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single-loop feedback control design: devising a process model, collecting input/output data to parameterize and validate that model, defining the control specifications, designing the regulator, simulating the control system, and finally verifying the results experimentally. The control concepts dealt with in [10] are basic and general, being addressed in most typical undergraduate courses.

In this work, the pedagogical context is radically different, more specifically oriented to the process control context, and not so typical as long as undergraduate education is concerned. More specifically, it is assumed that the students are able to synthesize a single-loop controller, and the goal is to teach them how to use that fundamental ability for the construction of control strategies of realistic complexity, evidencing and discussing the typical problems encountered when applying control structures in practice. To pursue that goal, the students are led to achieve the following objectives.

1. To understand the inherently multivariable nature of the apparatus (and of any process) and the concept of dynamic interaction. To learn how to explain interaction by means of a model and quantify it experimentally.
2. To understand the operation of feedforward control and compensation, and learn how to use them in cooperation with feedback control.
3. To be aware that, owing to the multivariable and interacting nature of any process, a control problem must be assessed by assigning a *role* in the control system to each variable and signal, and consequently to each regulator block, before defining specifications.
4. To learn that any control problem can be broken down into subproblems, where a few blocks of the overall control system are synthesized on the basis of individual specifications, which depend on (part of) the process model, and on the role of the synthesized block(s).
5. To understand that breaking down a complex control problem into subproblems must be done on a systematic basis, i.e., by identifying the presence of control structures in the overall problem.
6. To learn about the most important control structures, the methods for their synthesis, and above all their meaning connected to the previous objectives.

The first contribution of this work is the definition of a set of experiments on control structures that present the necessary variety of problems and are organized in accordance with the objectives stated above.

The second contribution is to illustrate how all the experiments are made with the same apparatus, giving the details that in [10] could not be shown. Note that, to the author's knowledge, no simple and reasonably priced system is available that deals with a variety of control problems and structures as wide as the one presented here.

Finally, it is worth noting that the laboratory has to serve a large number of students (up to about 1000 per semester). Therefore, in the manuscript, attention will be focused on the organization of the activity, and on resource allocation.

THE LABORATORY SETUP

The laboratory has 72 workstations (18 in each of four rooms) at the main site in Milano, while a secondary site in Cremona (about 100 km from Milano) has one room with 12 workstations, and another site in Como (40 km from Milano) has one room with 20 workstations. Each workstation is composed of a personal computer with analog-to-digital (A/D) and digital-to-analog (D/A) interface cards, the apparatus presented in [10], and the specific software shown here. The apparatus is a simple temperature control system, where two transistors heat a small metal plate while a fan provides cooling. The outputs of the apparatus are the measurements of the temperatures of the transistors and the plate (T_1, T_2 and T_p) while its inputs are the commands to the transistors and to the fan (Q_1, Q_2 and Q_f).

From the point of view of the problems treated herein, the apparatus can be described by the block diagram of Fig. 1, where the symbol 'Δ' denotes the variations of the variables with respect to the steady-state values.

To treat the different control problems, it is not required to change anything in the apparatus and in the connections with the computer. It is enough to take different combinations of inputs and outputs, which is accomplished by the software. As a result, the management of the laboratory is very simple.

The control software, written by the author in the LabVIEW programming language, allows open-loop experiments with various inputs and closed-loop control with different structures. Data are recorded in ASCII format for subsequent processing, e.g. in Matlab/Simulink (the adoption

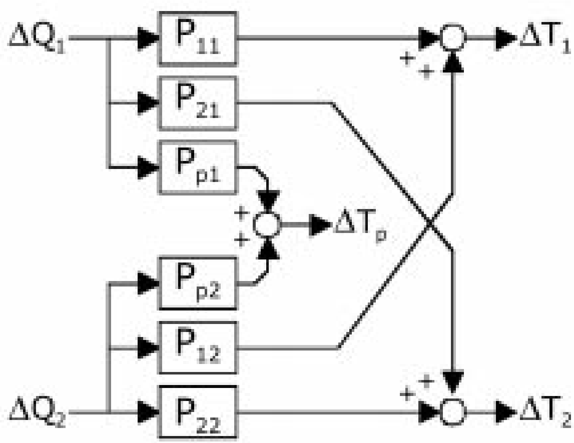

Fig. 1. Linearized model for multivariable control.

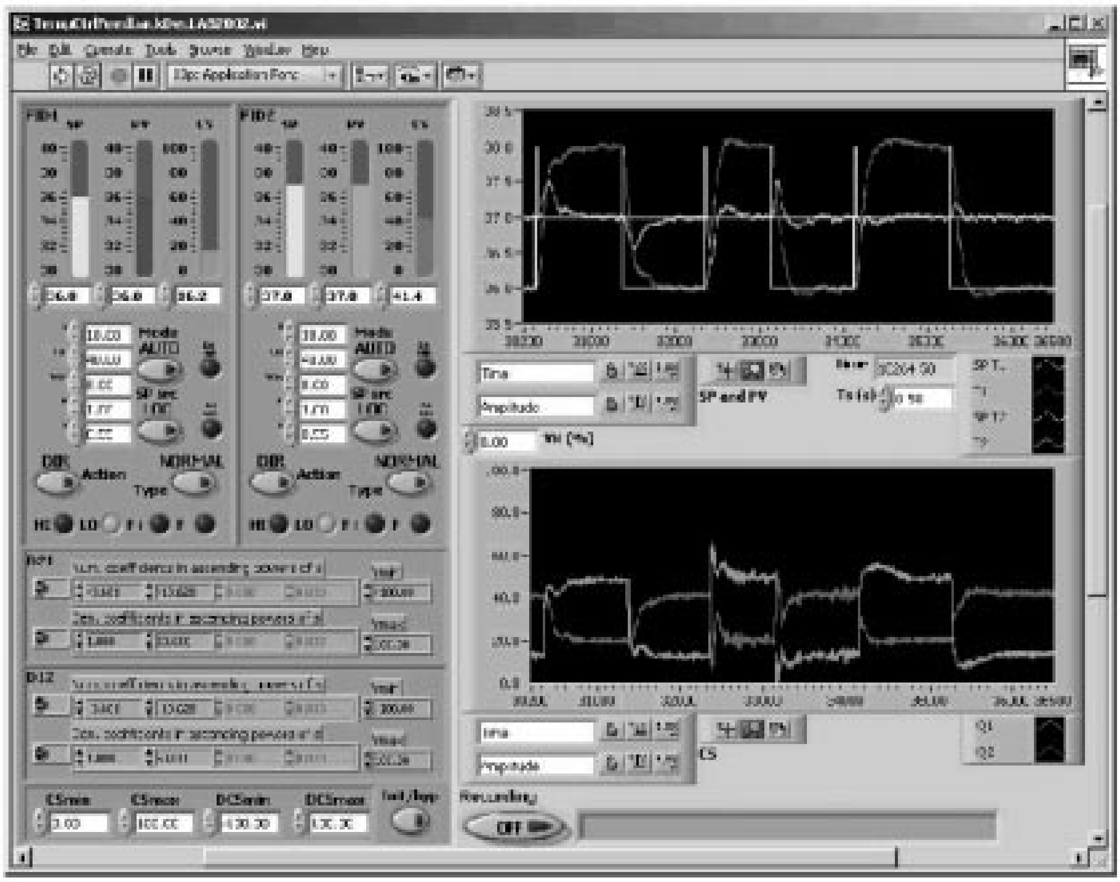

Fig. 2. The window of the program for decoupling control.

of standard environments is very important for didactic laboratories [9]). For every control structure considered, a LabVIEW program was created; students just use these programs, therefore no knowledge of the LabVIEW language is required. For example, Fig. 2 shows the window of the program for decoupling control.

The control structures treated are composed of proportional-integral-derivative (PID) regulators and transfer function blocks. The PID regulators employed are in the two-degree-of-freedom (2-d.o.f). output-derivation ISA standard form [12], i.e.,

$$CS(s) = K\left[bSP(s) - PV(s) + \frac{1}{sT_i}(SP(s) - PV(s)) + \frac{sT_d}{1 + sT_d/N}(cSP(s) - PV(s))\right] + B(s), \tag{1}$$

where SP, PV, CS, and B are, respectively, the Laplace transforms of the set point, the controlled variable, the control signal, and a bias signal, K is the PID gain, T_i and T_d are the integral and the derivative time, N is the ratio between T_d and the time constant of a second pole required for the controller properness, and b is the set point weight in the proportional action. These regulators include antiwindup, tracking, bumpless auto/manual transfer, and some other features that are typical of *industrial* PIDs, like, for example, two logical inputs that prevent the control signal from increasing or decreasing, and two logical outputs that signal the high and low saturation. These features allow the logic required in control structures to be taught—a very important and often overlooked didactic goal.

THE LABORATORY ACTIVITY

At the Politecnico di Milano, control structures are taught in the course titled Engineering and Technology of Control Systems (50 hours, 1st semester of the 3rd year), that comes after Fundamentals of Automatic Control (100 hours, 1st semester of the 2nd year). The laboratory activity on control structures involves both guided and autonomous work, and is based on the assignments presented later on. The management of this activity involves the course teacher (one per course section, note that a section may use more than one laboratory room), some instructors (one per laboratory room, typically high school teachers or Ph.D. students), and some tutors (one per room, typically graduating students). Given the modular structure of the laboratory, this section describes how a room (serving about 50 students) is managed.

First, all the assignments are illustrated by the instructor. This happens at about one third of the course. There is no explanation of the underlying theory, as this was done by the teacher in the lectures. Since the students have already seen the apparatus in Fundamentals of Automatic Control, and the control programs have a uniform aspect, the explanation of the assignments is given in 4 hours. The teaching material is handed out to the students, and includes a description of each assignment and some guidelines for writing the activity report. Then, while the lectures proceed, the students start their autonomous activity in the laboratory. They work in groups of three, and each group must complete two assignments of their own choice. From that moment to the end of the course, there are 20 hours in which the instructor and the tutor are available in the laboratory to give guidance and help. Typically, each group comes to the laboratory once to record input/output data, and one or two more times to test the synthesized control systems, for a total of about 6–8 hours. The rest of the activity (computations and report preparation) can be done at the Politecnico (Matlab and Simulink are available in all the computer rooms) or at home. A report is due at the end of the course, and is discussed with the teacher and the instructor. The students are invited to participate in the discussion of the assignments they have not chosen, to maximize the sharing of experience. The group report and its discussion provide about 10% of the course grade, the other 90% coming from two individual written tests.

In synthesis, then, each room requires one instructor and one tutor for 24 hours, plus the (variable) time spent with the teacher for the reports discussion. Each group of students is expected to complete their two assignments in a total of about 25 hours.

LABORATORY ASSIGNMENTS

This section describes the assignments for Engineering and Technology of Control Systems. All the assignments involve some regulator design, which is not shown here in detail, since the matter is treated in many books like [1, 13, 14], and in the course textbook [15]. Nonetheless, it is necessary to show how experimental facts are used to provide a counterpart for theoretical concepts. The author hopes that in this section a good equilibrium has been found, and apologizes in advance if some details appear obvious to readers with expertise in control teaching. Numeric results are omitted here for brevity, and reported in the Appendix.

In the first autonomous session, the students identify the transfer functions of Fig. 1. In Fig. 3, model step responses are compared with experimental data.

Decentralized control

With reference to the list above, the main objectives of this assignment are 1 and 3. The goal is to control T_1 and T_2 with two independent PIDs acting on Q_1 and Q_2. The students learn to

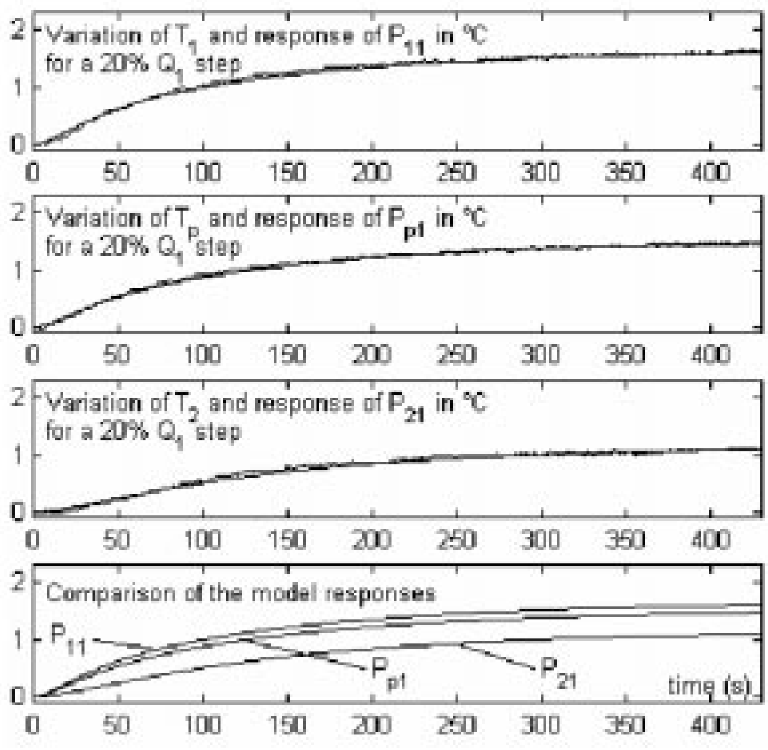

Fig. 3. Comparison between the model of Fig. 1 and data.

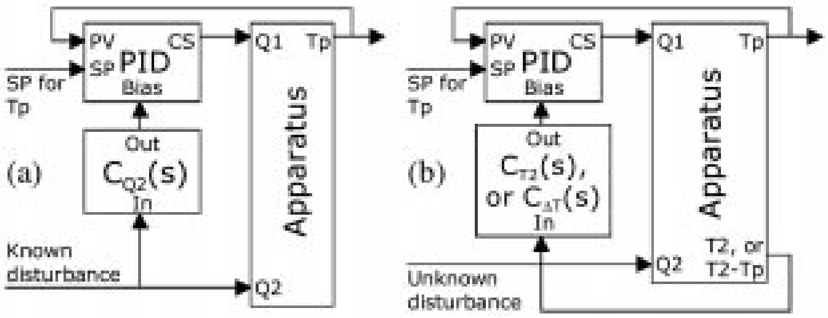

Fig. 4. Block diagram for the compensation of a known (a) or unknown (b) disturbance.

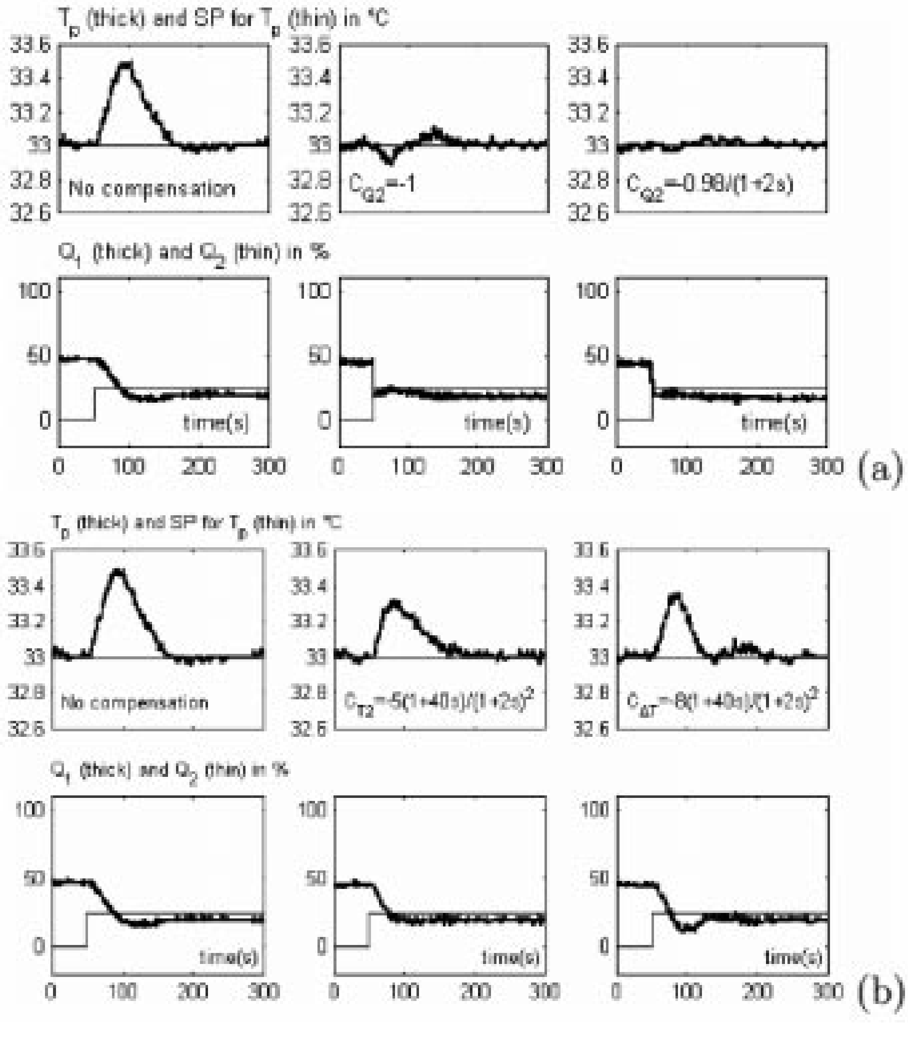

Fig. 5. Responses to 25% Q2 steps with and without compensation based on T2 (a) and T2-Tp (b).

characterize and quantify the loops' interaction, which is quite relevant. This experience shows that, in order to set up a multivariable control system, at least some model knowledge is necessary. Experimental results are shown later on, in figure 11, together with those of decoupling control.

Disturbance compensation

This assignment essentially deals with objectives 2, 4, 5, and 6. The goal is to control T_p acting on Q_1, while Q_2 is a disturbance to be compensated for. First, it is supposed that Q_2 is known, and the problem is tackled with direct feedforward compensation through a block $C_{Q2}(s)$, see Fig. 4(a). Closed-loop results are shown in Fig. 5(a). This experience is very useful to understand how feedforward and feedback control cooperate.

A more complex problem is then considered, assuming that Q_2 is unknown. In this case, indirect compensation is necessary, see Fig. 4(b), two candidate quantities for it being T_2 and T_2-T_p. It is pointed out that $C_{T2}(s)$, or $C_{\Delta T}(s)$, must 'invert' the dynamics from Q_2 to T_2, or T_2-T_p, and that is why they tend to be critical and sensitive to noise—

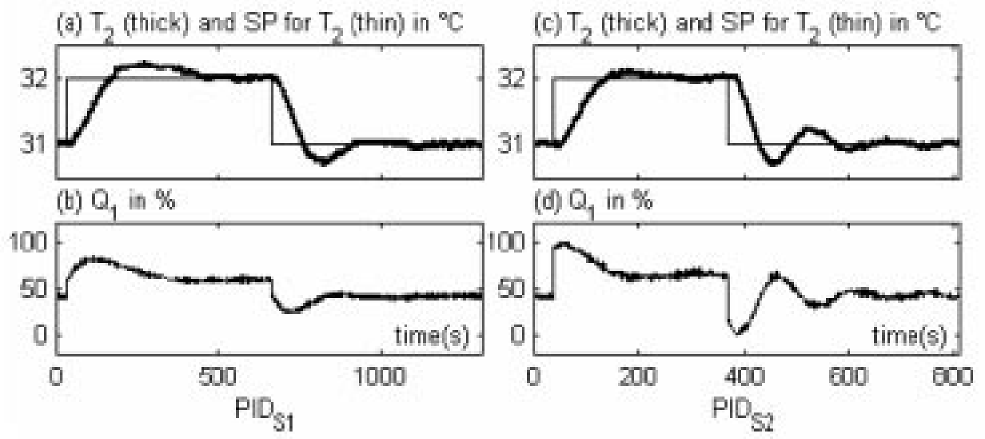

Fig. 6. Single-loop control of T_2 with Q_1.

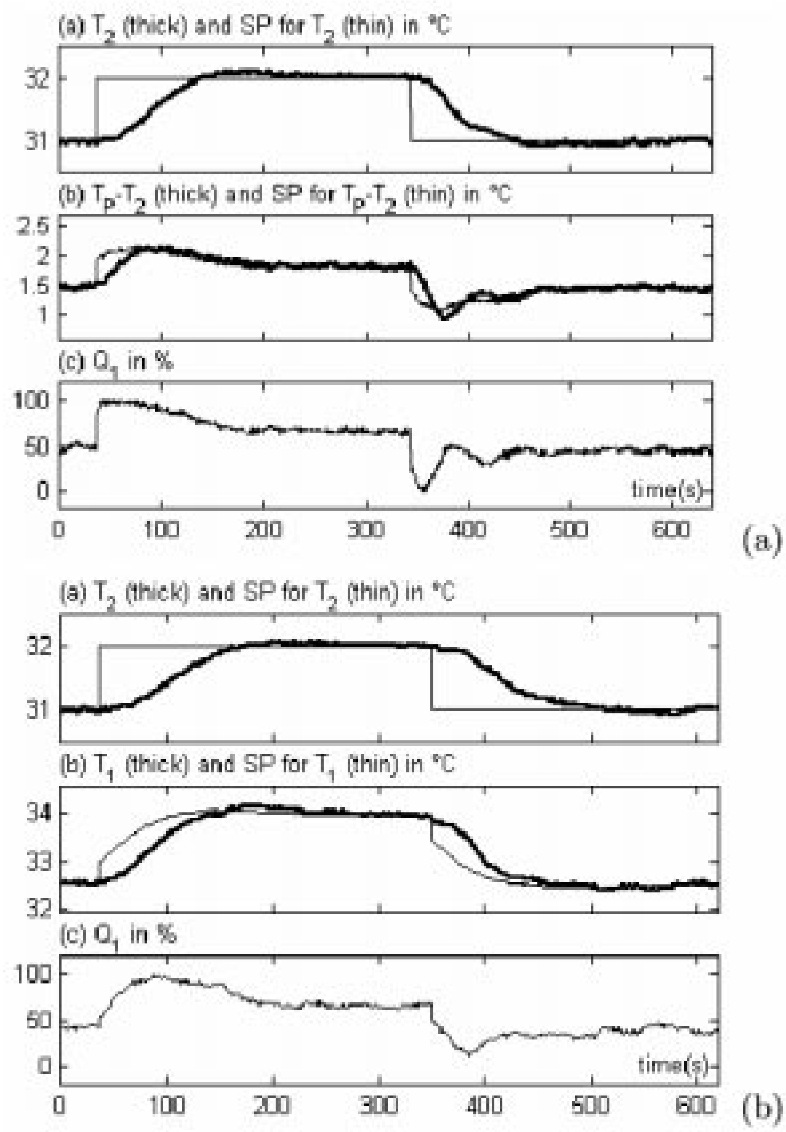

Fig. 7. Cascade control experiments having T_2-T_p (a) and T_1 (b) as the inner loop's controlled variable.

a general and useful lesson to learn. It is also demonstrated that an incorrect choice of $C_{T2}(s)$ or $C_{\Delta T}(s)$ (not shown for brevity) may jeopardize stability. This experience convinces the students that replacing a measurement with an estimate is *never* a negligible modification. Results are shown in figure 5(b), where the PID is that of figure 5(a). Indeed, the benefits of measuring Q_2 are worth the cost of the measurement—another important lesson.

Cascade control

The main objectives of this assignment are 3, 4, and 6. The goal is to control T_2 acting on Q_1. The assignment begins by verifying that a single-loop structure is not well suited for this problem, as proven by Fig. 6. The process gain increases at lower values of Q_1, and the 'up' and 'down' transients are not symmetrical, the difference being larger with the more demanding regulator (PID_{S2}, see the Appendix).

A cascade structure is then employed, taking T_p-T_2 as the inner loop's controlled variable. The students learn to evaluate the tuning by observing the experimental transients—an ability that is very useful in the field. For example, in Fig. 7(a) the inner loop 'catches' the set point in about half the time required for the outer one to reach its steady state, and this proves that the cascade control does attain its goal.

Comparing Figs 7(a) and 6, the benefit of a well-tuned cascade control is evident. It is also demonstrated that an incorrect tuning (not shown for brevity) can cause the so-called 'hunting' phenomenon in the inner loop; in that case, the outer loop might still be able to keep the set point, but the control variable Q_1 would undergo a useless upset. This proves that a poorly tuned cascade structure may work worse than a single-loop control. Moreover, the importance of observing the control variable(s) is stressed.

A second cascade structure is synthesized, taking T_1 as the inner controlled variable. The results, shown in Fig. 7(b), are similar to those of Fig. 7(a), but the control variable has a smoother behaviour. This activity illustrates that, in cascade control, a knowledgeable choice of the inner loop's controlled variable is beneficial, and a systematic tuning procedure is vital. The block diagrams of the cascade control systems are shown in Fig. 8.

The students are taught also the logic required in cascade control. It is shown that the outer regulator may raise the set point of the inner one when this regulator is in high saturation, causing an 'interloop' windup phenomenon. The solution is to connect the outputs of the outer regulator that signal the high (low) saturation to the inputs of the inner one that prevent its output from increasing (decreasing). The importance of this logic is shown in Fig. 9.

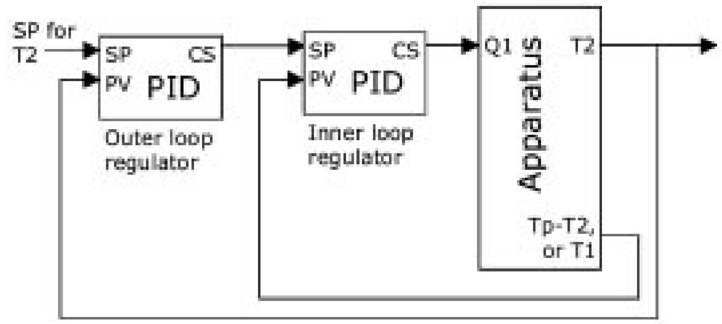

Fig. 8. Cascade control systems.

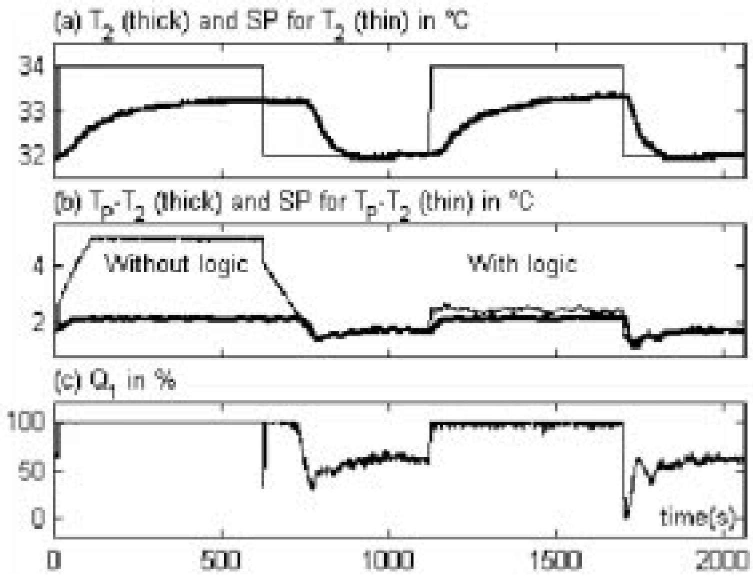

Fig. 9. Interloop windup in cascade control.

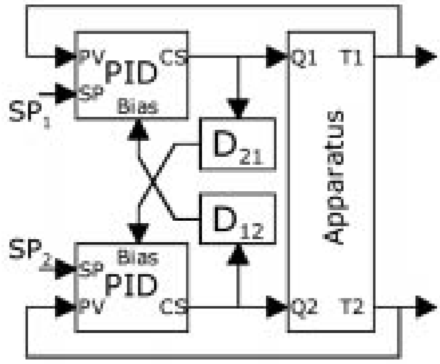

Fig. 10. Control system with decoupling.

Decoupling control

The main objectives considered here are 2, 5, and 6. The goal is to control T_1 and T_2 with two PIDs and a feedback decoupling network. The model used is that of Fig. 1, while the block diagram representing the control system with decoupling (and also that with decentralized control, which is obtained with $D_{12}(s) = D_{21}(s) = 0$) is depicted in Fig. 10.

Two examples of the experimental results are shown in Fig. 11. The regulators are those used for decentralized control, while the decoupler's blocks $D_{12}(s)$ and $D_{21}(s)$ are computed on the basis of the model of Fig. 1.

The students compare decoupling and decentralized control, and see that with decoupling the control variables 'cooperate' right from the beginning of each transient, while with decentralized control only the controller whose setpoint is modified initially reacts.

A comparison of static and dynamic decoupling is also instructive. If only the gains of $D_{12}(s)$ and $D_{21}(s)$ are employed, the results are even worse than those of decentralized control, as $D_{12}(s)$ and $D_{21}(s)$ have an overdamped step response, and therefore replacing them with their gains produces too nervous a decoupling action. If static decoupling is applied with two gains that produce the same *initial* response of the 'full' decoupler, the results (omitted for brevity) are intermediate between those of decentralized control and those of full decoupling. All these facts are revealed by

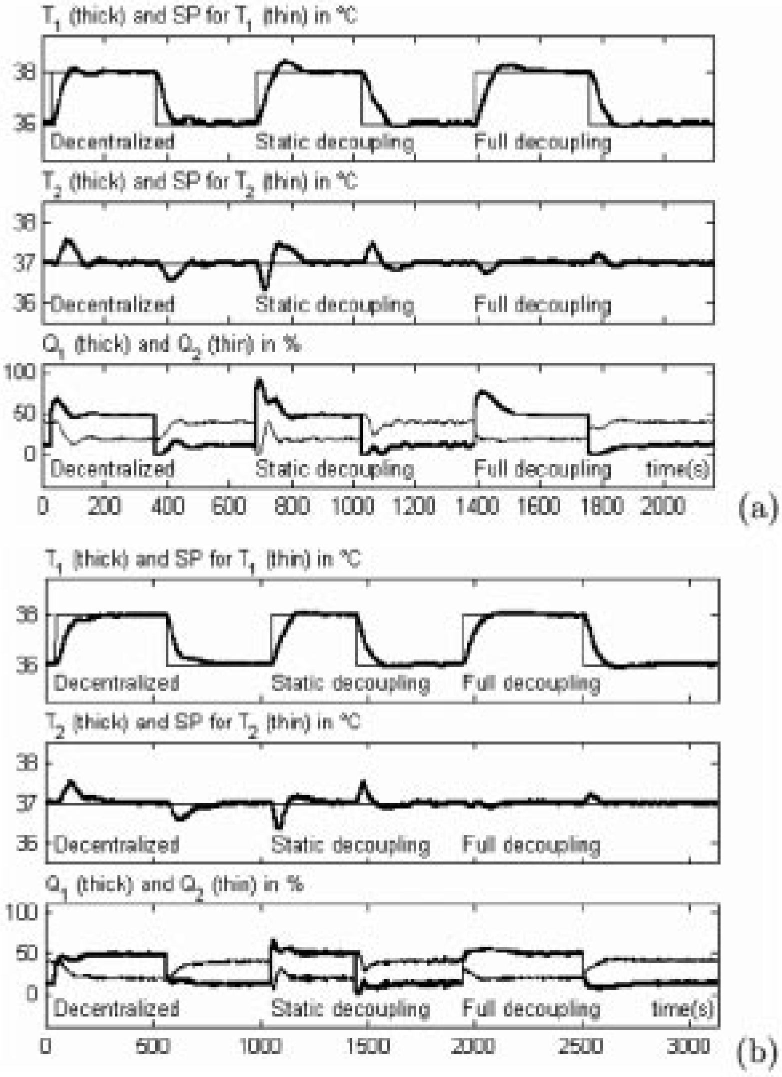

Fig. 11. Decentralized and decoupling control experiments.

simulating the control scheme. The resulting lesson is that decoupling control is powerful, but must be applied thoroughly, and with model knowledge: undue approximations may be very critical.

CONCLUDING REMARKS

The experimental laboratory for teaching control structures at the Politecnico di Milano has been presented. The activity can be made available to many students, all at the same time, with a comparatively small number of instructors. This year, the activity described above is carried out at the Cremona site of the Politecnico; then, the plans are to make it available to the other classes of Engineering and Technology of Control Systems. The laboratory and the activity have been extensively discussed with interested students, who provided invaluable help to improve the design and make it better suited for their learning needs. It is unanimous opinion that this activity is highly beneficial from several points of view. Briefly, the achievements that most satisfied the students can be summarized as follows:

- firm understanding of the concept of control structure, from both a theoretical and a practical standpoint;
- knowledge of the major control structures, their potentialities and possible pitfalls;
- ability to detect which structure, if any, is best suited for a given problem;
- ability to synthesize the components of a control structure correctly;
- clear and correct (although preliminary) ideas on how the theory and methodologies for the synthesis of single-loop controls have an impact on the construction of a more complex control system;
- comprehension of the logic involved in industrial loop controllers, its role and relevance in control structures.

A qualifying aspect of the activity presented above is that all the experiments are made with one, simple and inexpensive setup. For space limitations, the scope of this work has been limited to decentralized control, disturbance compensation, cascade control, and decoupling control, but several other experiences can be made. In particular, the setup allows to deal with additional structures (e.g., split-range control, using the fan as cooler, or override control) but also with sensor characterization, advanced methods like predictive and adaptive control, 'full' multivariable control, and identification. Finally, it is worth noting that the simplicity of the presented setup makes it suitable also for remote use. An application is being tested to allow experiments via the Web, and the matter will be treated in future works.

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APPENDIX

Models and regulator parameters

Typical outcome of the identification of the transfer functions of Fig. 1:

$$P_{11}(s) = P_{22}(s) = \frac{0.083(1+50s)}{(1+135s)(1+25s)(1+10s)},$$

$$P_{p1}(s) = P_{p2}(s) = \frac{0.076(1+45s)}{(1+135s)(1+25s)(1+10s)},$$

$$P_{12}(s) = P_{21}(s)\frac{0.057(1+15s)}{(1+135s)(1+25s)(1+10s)}.$$

Regulator parameters in the various experiments:

Experiment	**Figure**	**Regulator(s)**	**K**	**T_i**	**T_d**	**N**	**b**
Decentralized control	11(a)	2 equal Pis	25	32			0.8
and decoupling	11(b)	2 equal PIDs	18	40	8	1	0.55
Compensation	5(a, b)	PID	30	30	5	2	1
Single-loop	6	PID_{S1}	20	40	8	4	0.8
		PID_{S2}	60	60	6	2	0.8
Cascade control	7(a)	Inner (PID)	85	15	1.5	1	1
		Outer (PID)	0.7	45	4	2	0.6
	7(b)	Inner (PI)	505	30			0.3
		Outer (PI)	0.4	20			0.1

Blocks of the decoupler:

$$D_{12}(s) = D_{21}(s) = 0.687\frac{1+15s}{1+50s}.$$