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An Experimental Laboratory on Control Structures

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Abstract— **This paper presents a laboratory designed at the Politecnico di Milano, where different control structures can be experimented with by means of a single apparatus, reasonably priced, and very easy to use and maintain. The laboratory is conceived so that a large number of students (up to 150) can be managed simultaneously, both for guided and autonomous activity, with a comparatively small number of instructors. An overview of the experimental setup and the activity is given, and the main laboratory assignments for the course titled *Engineering and Technology of Control Systems* are presented.**

I. Introduction

Despite the importance and widespread use of control structures in industrial applications [10], [9], several practical problems arise from scarce knowledge of these structures: decentralized controls are not properly synthesized, disturbance compensation is not used where it should, cascade controls are poorly tuned, loop interactions are not considered or dealt with incorrectly, and so on. Moreover, the logic required for setting up a control structure is sometimes treated as an ancillary functionality, despite incorrect choices in this logic may result in poor performance even if the regulators are tuned correctly [3], [6].

Basic Automatic Control courses deal mostly with single-loop control, and devote a comparatively short time to control structures [2], [7]. This is reasonable, but may generate the idea that ‘theoretical’ knowledge is only required to synthesize the individual regulators, while the construction of the overall control strategy has more to do with programming (or computer science at large) than with systems and control theory. This attitude is somehow surprising, but not infrequent among control practitioners, and must be counteracted as early as possible. Hence, making the students capable to tackle problems involving control structures (and the associated logic) is very beneficial [4], [5], and to do this effectively, experimental activity is vital.

At the Politecnico di Milano, control structures are taught in the course titled ‘Engineering and Technology of Control Systems’ (ETCS,) that comes after ‘Fundamentals of Automatic Control’ (FAC.) The main problem in designing the laboratory for ETCS was that (at the author’s knowledge) no simple and reasonably priced setup is available that deals with a sufficiently wide variety of control structures, especially if a large number of workstations must be maintained. At the Politecnico the workstations are 72 (18 in each of four rooms) at the main site in Milano, plus 12 (in one room) at the site of Cremona, and 20 (in one room) at the site of Como, the students to manage (including all the courses served) are about 1000 per year, and there are quite strict limitations on the number of instructors and the overall budget. This paper presents the (*ad hoc*) solution devised to make guided and autonomous experience possible in such a complex situation. Different control structures can be experimented with by using the same, simple and inexpensive apparatus, already used for FAC. Because of space limitations, this paper concentrates on disturbance compensation, cascade control, and decoupling control.

The activity presented is for undergraduate education, and mainly for electrical, electronics and computing engineering majors. The important process control issues addressed are general, however, and the same laboratory could be employed for other curricula.

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II. The experimental setup

The workstation is composed of a PC with A/D and D/A cards, the apparatus, and specific software. The activity consists in solving some control problems, each of them involving one control structure. The apparatus is the temperature control of figure 1. The two transistors heat a metal plate, while the fan provides cooling. The outputs are the temperatures of the transistors and of the plate, while the inputs are the commands to the transistors and to the fan. The apparatus is described in detail in [8], while the software and the activity presented herein are new.

The software, written 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. For each control structure, a LabVIEW program was created; the students just use these programs, thus no LabVIEW knowledge is required. For example, the

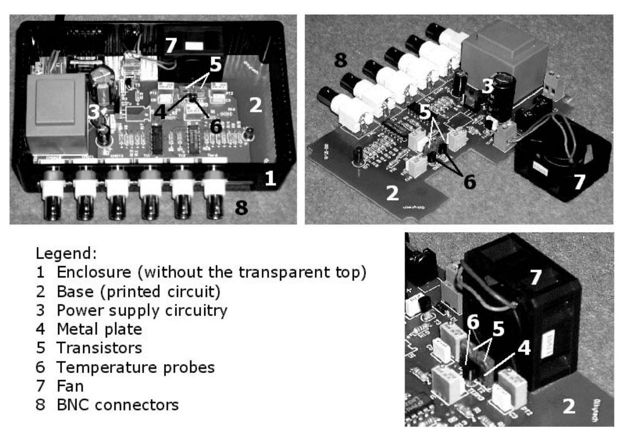

Fig. 1. Photos of the apparatus.

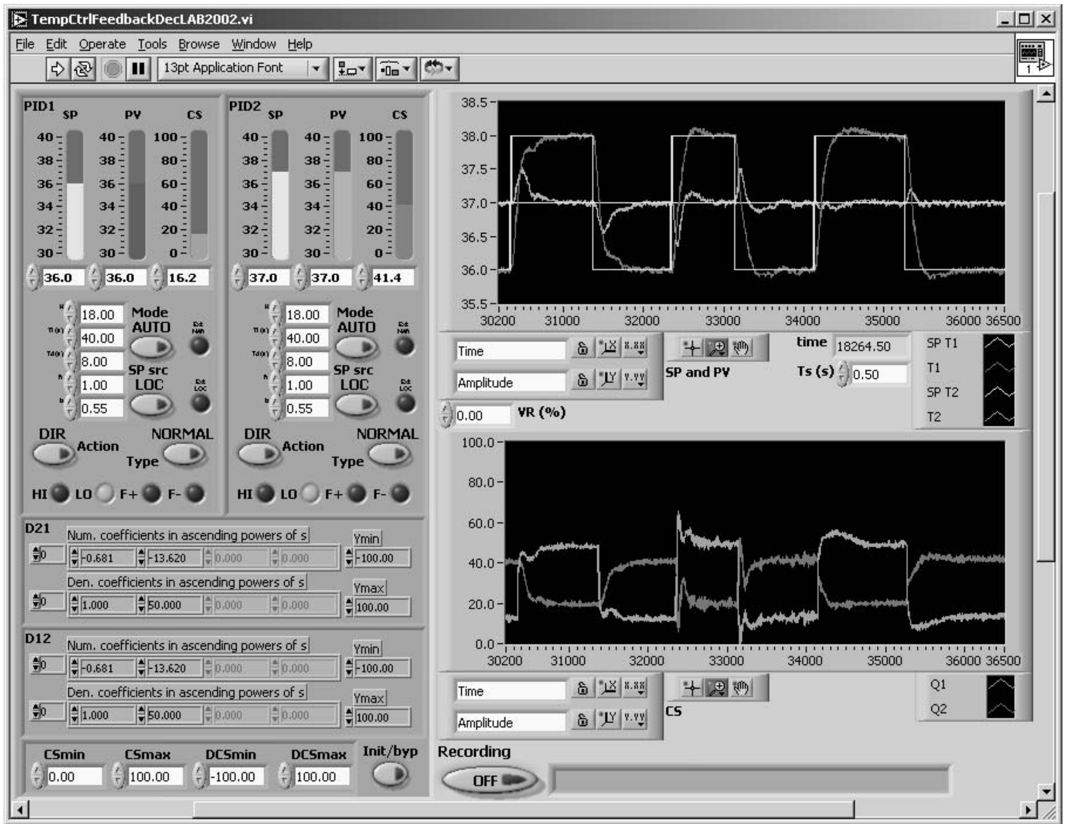

Fig. 2. The window of the program for decoupling control.

window of the program for decoupling control is shown in figure 2. The structures treated are composed of PID regulators and transfer function blocks. The PID regulators are in the 2-d.o.f., output-derivation ISA form [1], i.e.,

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

where SP, PV, CS, and B are 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 properness, and b is the set point weight in the proportional action. The PIDs include anti-windup, bumpless auto/manual switching, direct/reverse action, normal/velocity form, local/remote set point selection, two logical inputs that force the manual mode and the local set point mode (ForceMAN and Force-SPLOC,) two logical inputs that prevent the control signal from increasing or decreasing (F+ and F-,) and four logical outputs that signal the high and low saturation (HI and LO,) the local state of the set point (LOC,) and the manual state of the regulator (MAN.) The explanation of the PID operation (including the logic) is given to the students but omitted here for brevity.

A dynamic model of the apparatus is derived assuming that (a) the three temperatures of the two transistors and the plate are individually uniform; (b) heat transfer depends linearly on temperature difference; (c) the thermal powers generated by the two transistors ($P_{g1}$and P_{g2}) are nonlinear algebraic functions of the two transistor commands, denoted by Q_1 and Q_2 and being 0-100, i.e., $P_{g1,2} = P_{max} f(Q_{1,2}/100)$, where $f(0) = 0$, $f(1) = 1$, and P_{max} is a suitable constant; (d) the transistors-to-plate heat transfer coefficients (γ_{tp}) are equal and constant; (e) the transistors-to-air heat transfer coefficients (γ_{ta}) are equal; (f) γ_{ta} and the plate-to-air heat transfer coefficient (γ_{pa}) depend on the fan command Q_f, varying linearly from a minimum (Γ_{ta0},Γ_{pa0}) to a maximum (Γ_{ta100},Γ_{pa100}) as Q_f goes from 0 to 100; (g) the air temperature is constant, and does not depend on Q_1, Q_2 and Q_f, hence it can be considered an input. The model equations are

$$\left\{ \begin{array}{rcl} C_t \dot{T}_1 & = & P_{g1} - \gamma_{tp}(T_1 - T_p) - \gamma_{ta}(T_1 - T_a) \\ C_t \dot{T}_2 & = & P_{g2} - \gamma_{tp}(T_2 - T_p) - \gamma_{ta}(T_2 - T_a) \\ C_p \dot{T}_p & = & \gamma_{tp}(T_1 + T_2 - 2T_p) - \gamma_{pa}(T_p - T_a) \\ P_{g1} & = & P_{max} f(Q_1/100) \\ P_{g2} & = & P_{max} f(Q_2/100) \\ \gamma_{ta} & = & \Gamma_{ta0} + (\Gamma_{ta100} - \Gamma_{ta0}) Q_f/100 \\ \gamma_{pa} & = & \Gamma_{pa0} + (\Gamma_{pa100} - \Gamma_{pa0}) Q_f/100 \end{array} \right. \quad (2)$$

where C_t and C_p are the thermal capacities of the transistors and of the plate; T_1, T_2, T_p and T_a are the temperatures of the two transistors, the plate and air; the other symbols have

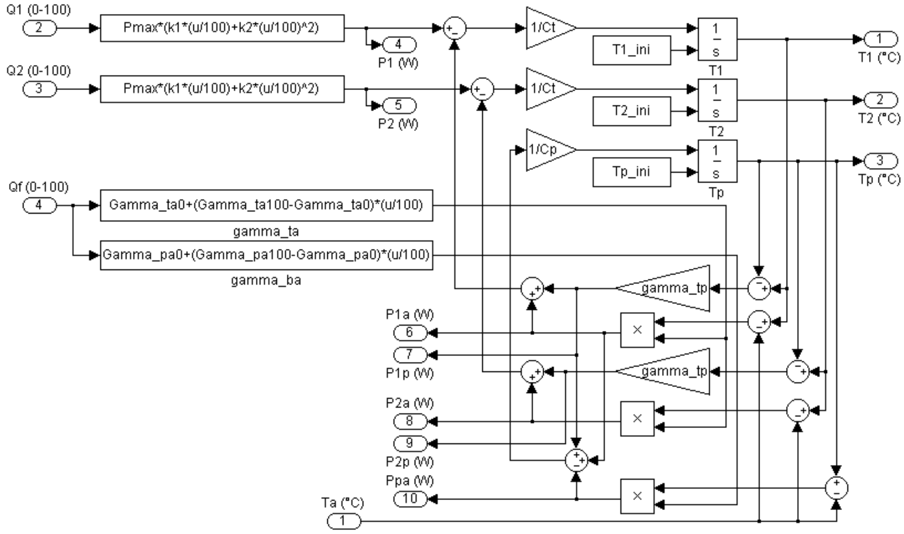

Fig. 3. Simulink model of the apparatus as described by (2).

the meaning stated above. The model (2) can be translated into a Simulink scheme like that of figure 3, that is useful to perform simple simulations and learn to set parameters based on dimensional data and experiments (an activity not described here for space limitations). In the scheme, it is advisable to select $f(Q) = k_1(Q/100) + k_2(Q/100)^2$, where k_1 and k_2 are suitable constants. The scheme of figure 3 is used to test the regulators on more accurate a model than the transfer functions used for the design. This particular activity is not described here due to space limitations.

For the problems presented herein, however, there is no need to use the complex model of figure 3, as the fan is kept off (i.e., $Q_f = 0$,) and a linear approximation of the apparatus behavior is sufficient. In view of this, the apparatus can be described by the linearized model of figure 4, i.e.,

$$\begin{bmatrix} \Delta T_1(s) \\ \Delta T_p(s) \\ \Delta T_2(s) \end{bmatrix} = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{p1}(s) & P_{p2}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix} \begin{bmatrix} \Delta Q_1(s) \\ \Delta Q_2(s) \end{bmatrix} \quad (3)$$

where the symbol 'Δ' denotes variations with respect to steady-state values (that depend also on T_a.) The students identify the six transfer functions in (3) by applying steps to Q_1 and Q_2 and recording T_1, T_p, and T_2.

Because of the apparatus symmetry, a typical outcome is

$$\begin{aligned} P_{11}(s) = P_{22}(s) &= \tfrac{0.083(1+50s)}{(1+135s)(1+25s)(1+10s)}, \\ P_{p1}(s) = P_{p2}(s) &= \tfrac{0.076(1+45s)}{(1+135s)(1+25s)(1+10s)}, \\ P_{12}(s) = P_{21}(s) &= \tfrac{0.057(1+15s)}{(1+135s)(1+25s)(1+10s)}. \end{aligned} \quad (4)$$

In figure 5, the responses of (4) are compared with experimental data. Note that the data are reproduced quite accurately by transfer functions with the same three poles, which corroborates the validity of model (2).

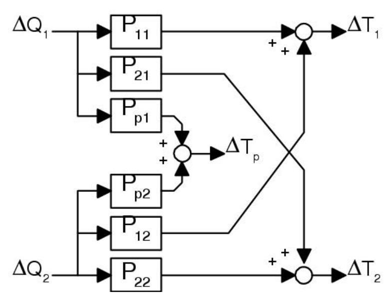

Fig. 4. Multivariable linear model.

III. Laboratory assignments

The students work in groups of three. Each group must complete two assignments of their choice. They are given an initial explanation in the laboratory, a set of guidelines, and access to the laboratory for autonomous work; there are 20 hours (distributed along the course) in which two instructors per room are available. A report is due at the end of the course, and contributes to the grading. For space limitations, details on the regulator design involved in each assignment is not described here. The matter is known to any control specialist, and is treated in any textbook.

A. Disturbance compensation

The goal is to control T_p acting on Q_1, while Q_2 is a known disturbance. Since it can be assumed that Q_1 and Q_2 act on T_p in the same way, it seems enough to connect the opposite of Q_2 to the Bias input of the PID, but since the apparatus is not perfectly symmetrical, a block $C_{Q2}(s)$ in the compensating path is useful. To set up $C_{Q2}(s)$, the students make some open-loop tests starting from a steady state, applying a step variation to Q_2 and the same step variation, filtered by $C_{Q2}(s)$, to Q_1. The objective is

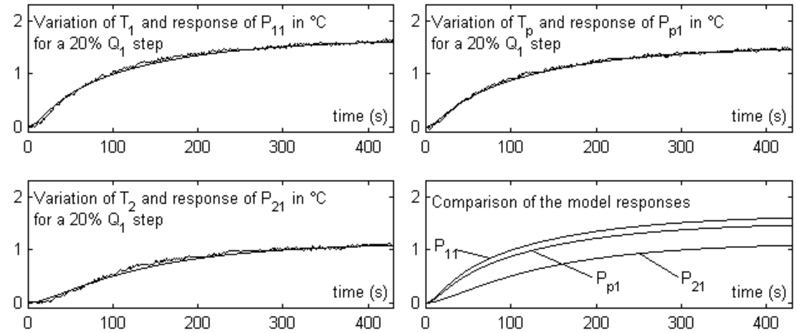

Fig. 5. Comparison between model (4) and data.

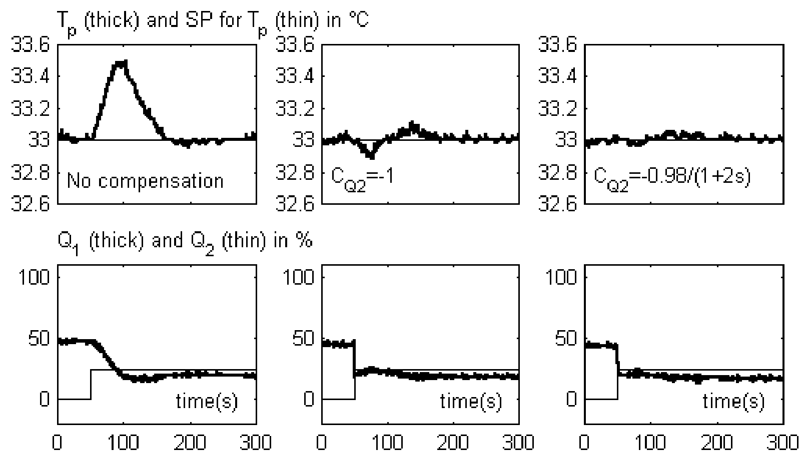

Fig. 6. Responses to 25% Q_2 steps with and without disturbance compensation.

to obtain zero effect on T_p. The first trial is made with $C_{Q2}(s) = -1$. If the steady-state value of T_p after the step is not equal to that before the step, the differential gains from Q_1 to T_p and from Q_2 to T_p are not equal, and the gain of $C_{Q2}(s)$ is adjusted. Then, if a positive Q_2 step variation causes T_p to temporarily increase, the compensating action on Q_1 is 'slower' than needed; to correct, $C_{Q2}(s)$ can include one pole and one slower zero. If a positive Q_2 step variation causes T_p to temporarily decrease, the action on Q_1 is 'faster' than needed; in this case, $C_{Q2}(s)$ can include one pole, and possibly one faster zero. Closed-loop experimental results are shown in figure 6, where the PID has $K = 30$, $T_i = 30$, $T_d = 5$, $N = 2$, $b = 1$.

This experience is very useful to understand how feed-forward and feedback control cooperate. It is also noted that, when the PID is in manual, the compensation must be disabled; when switching to automatic, it must be (re)initialized (or some other conditioning technique must be applied) to avoid a control bump.

B. Cascade control

The objective is to control T_2 acting on Q_1. The assignment begins by verifying that a single-loop structure is not particularly suited for this problem, as witnessed by

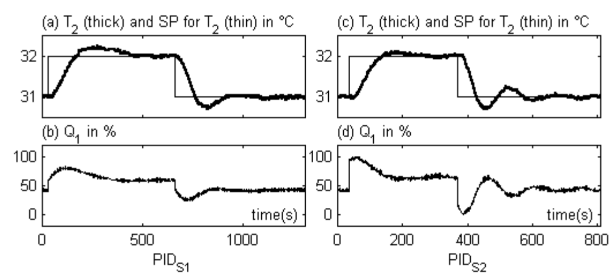

Fig. 7. Single-loop control of T_2 with Q_1.

figure 7, where the two regulators tested have $K = 20$, $T_i = 40$, $T_d = 8$, $N = 4$, $b = 0.8$ (PID_{S1},) and $K = 60$, $T_i = 60$, $T_d = 6$, $N = 2$, $b = 0.8$ (PID_{S2}.) The nonlinear dependence of P_{g1} on Q_1, see (2), causes the process gain to increase at lower values of Q_1. As a result, the 'up' and 'down' transients are not symmetrical, the difference being larger with the more demanding regulator (PID_{S2}.)

To overcome this problem, a cascade structure is employed, taking $T_p - T_2$ as the intermediate controlled variable. The choice is motivated by explaining that, in so doing, the process dynamics seen by the outer loop's regulator, when the inner loop is closed so that the ther-

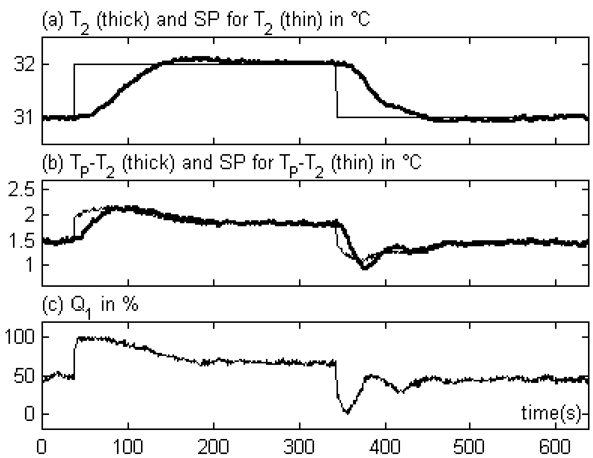

Fig. 8. Cascade control experiment.

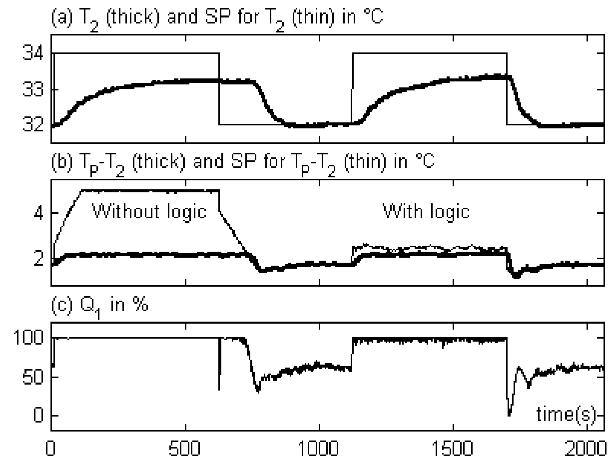

Fig. 9. Interloop windup in cascade control.

mal flow entering transistor 2 (proportional to $T_p - T_2$) is regulated, is linear and 'quite similar' to a first-order system. The students tune the two PIDs empirically, learn to synthesize them in the correct order, and to diagnose whether the cascade control system is properly tuned by observing the experimental transients—a very important ability in the field. With reference to figure 8, for example, the inner loop 'catches' the set point in about half the time required for the outer loop to reach its steady state. This means that the cascade control does attain its goal, in that (at low frequency) the outer PID can truly act as if the process input were the controlled variable of the inner loop. In figure 8, the inner PID ($\mathrm{PID_I}$) has $K = 85$, $T_i = 15$, $T_d = 1.5$, $N = 1$, $b = 1$, and the outer PID ($\mathrm{PID_E}$) has $K = 0.7$, $T_i = 45$, $T_d = 4$, $N = 1$, $b = 0.6$. An incorrect tuning (not shown for brevity) can easily cause the so-called 'hunting' phenomenon in the inner loop; in that case, the outer loop might still keep the set point, but the control variable undergoes an useless upset. This experience demonstrates that, with respect to single-loop control, a poorly tuned cascade structure may worsen the situation. Comparing Figs. 8 and 7, conversely, the benefit of well tuned cascade control is apparent, as the symmetry of the transients is improved significantly.

The students are taught also the logic required in cascade control. When $\mathrm{PID_I}$ is set to manual or its set point source is set to local, $\mathrm{PID_E}$ must be forced to manual because its loop is open. Moreover, $\mathrm{PID_E}$ outputs the set point for $T_p - T_2$, a quantity for which the saturation values are difficult to define*a priori*. Therefore, $\mathrm{PID_E}$ may raise the set point while $\mathrm{PID_I}$ is already in high saturation, causing an 'interloop' windup phenomenon. For this problem the individual PIDs' anti-windup mechanisms are useless, and the solution is to connect the HI and LO outputs of $\mathrm{PID_I}$ to the F+ and F- inputs of $\mathrm{PID_E}$ so that, when $\mathrm{PID_I}$ saturates, $\mathrm{PID_E}$ is allowed to move its output only in the direction that makes $\mathrm{PID_I}$ leave the saturation. The importance of this logic is shown in figure 9, where the set point for T_2 cannot be reached because of the saturation of Q_1, and the controllers are those of figure 8. Comparing the first couple of transients (obtained without the logic that acts on F+ and F-) with the second couple (where the logic is in place,) it can be seen that the recovery from saturation is greatly improved.

C. Decoupling control

The goal is to control T_1 and T_2 with two PIDs and a decoupling network. It is shown, by means of simulations in Simulink, that it is preferable to arrange the decoupler's blocks in a feedback configuration, see figure 10, because in a feedforward one, see figure 11, there are four main problems:

- the open-loop transfer functions of the decoupled loops are not the same as if there were no interaction;
- the PIDs cannot be easily initialized prior to switching to automatic;
- since the manipulated variables are not controller outputs, it is not easy to set up the anti-windup correctly;
- when one of the manipulated variables hits a saturation limit, its controller still attempts to regulate by modifying the other manipulated variable through the decoupler: hence, as both controllers are competing for the only unconstrained manipulated variable, both loops are lost.

Experimental results are shown in figure 12. The regulators are two PIDs with $K = 18$, $T_i = 40$, $T_d = 8$, $N = 1$, $b = 0.55$, while the decoupler's blocks, computed based on (4), are $D_{12}(s) = D_{21}(s) = -0.687(1 + 15s)/(1 + 50s)$. It is very instructive to notice how in the decoupling case the two control signals 'cooperate' right from the beginning of each transient, while with decentralized control only the PID whose set point 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

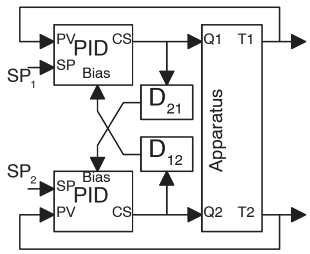

Fig. 10. Feedback decoupling scheme.

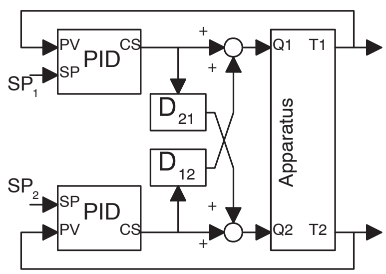

Fig. 11. Feedforward decoupling scheme.

employed, the results are even worse than those obtained with decentralized control. In fact, replacing $D_{12}(s)$ and $D_{21}(s)$ with their gains produces a too nervous decoupling action. If the static decoupling gains are computed to produce the same *initial* response of the 'full' decoupler, i.e., $D_{12}(s) = D_{21}(s) = -0.687 \cdot 15/50 = -0.206$, the results (omitted for brevity) are, as expected, intermediate between decentralized control and full decoupling. Of course, all these facts are revealed by simulating the control scheme. The lesson learned is that decoupling control is powerful but must be applied thoroughly, and with model knowledge: undue approximations may be very critical.

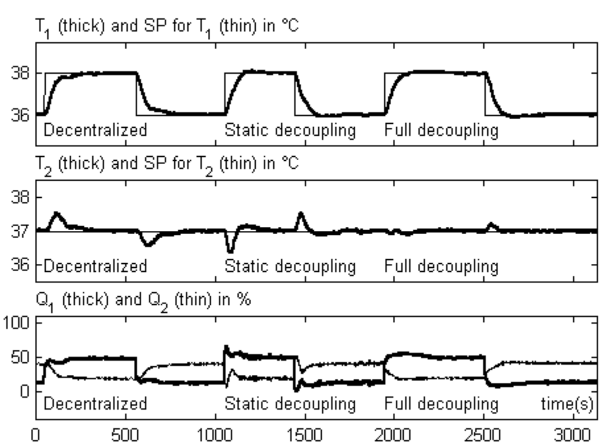

Fig. 12. Decoupling control experiment.

IV. Concluding remarks

The experimental laboratory and activity on control structures at the Politecnico di Milano have been presented. The activity, both guided and autonomous, is designed so that it can be made available to many students, with a comparatively small number of instructors. This year, it will be done at the Cremona site of the Politecnico; then, the plans are to make it available to all the classes of ETCS. During the last months, the presented design was extensively discussed with interested students. The unanimous opinion was that this activity is highly beneficial. It yields firm understanding of the concept of control structure, from both a theoretical and a practical standpoint, knowledge of the major control structures, their possibilities and potential pitfalls, ability to detect which structure (if any) is best suited for a given problem, and ability to synthesize the components of a control structure correctly. In addition, the activity helps the students to get clear and correct (though, of course, preliminary) ideas on how the theory and methodologies for the synthesis of single-loop controls impact the construction of a more complex control system, and to understand the logic involved in industrial loop controllers, its role and great relevance in control structures.

A qualifying aspect of the presented activity is that all the experiments are made with one, simple and inexpensive setup, already used for FAC. In this paper the focus has been limited to disturbance compensation, cascade control, and decoupling control, but several other experiences can be made. In particular, the setup allows to deal with additional structures like decentralized control, split-range control (using the fan as cooler,) or override control, but also with advanced methods like model-based, predictive and adaptive control, 'full' multivariable control, and identification.

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