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Physical Workbench for Technical Training in Discrete Time Control

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Abstract: The aim of this paper is to present the BANCO project and its first results. ESTIA had not experimental setups to make work labs in the discrete-time control courses. It is why some Alecop setups have been improved to use them in these work labs. They were prepared to be used in the Control courses of the second and the third year. The made improvements concern especially an electronic module and its programming. This module allows the students to implement discrete-time control algorithms and to observe the behaviour of some real thermal, hydraulic and mechatronic processes. The main hardware parts of this module designed and constructed in ESTIA are a microcontroller card and a signal shaping card. In addition, the module communicates with a PC in order to program it. Experimental results obtained with a discrete time R-S-T control algorithm programmed in the module are compared to those obtained with an analog PI controller already existing in the Alecop setups. Now, the setups are being improved even more in order to be able to change some parameters of the processes and to apply systems identification algorithm to these processes.

1. INTRODUCTION

Teaching the Discrete Time Control discipline in practice is important in engineering education for Industry, but not easy at all. Not only as a result of the intrinsic hardness of the theme, but also because of the difficulties to put the learned theory into practice. Nevertheless, Automatic Control is getting more and more digital, so engineers should have a solid background in discrete time techniques. Although full education in microcontrollers and their applications is very important, it is not enough; students need a way to test the control techniques in a physical prototype.

The experimental setup presented in this paper is a good solution to this trouble. It has been developed in the frame of BANCO (*Bancs de TP pour la Commande à Temps Discret*, i.e. Workbenches for Technical Training in Discrete Time Control) project, in collaboration between ESTIA (*Ecole Supérieure des Technologies Industrielles Avancées,* www.estia.fr) High School of Engineering and Alecop company (www.alecop.es). Making use of it, students can make plenty experiments in a short time, on a real system. Traditional education in Discrete-Time Control, on the other hand, has been based specially on simulation. It is to say, learner designs, with methods presented in theoretical classes, a discrete-time controller which is tested in simulating in a PC. This approach is not effective enough for the prospective engineers to correctly incorporate themselves into industrial companies.

Some other didactical modules for this purpose are known, but we needed a more versatile bench, which could be modified rapidly, in order to be updated and adapted to new demands. In addition, it is not possible for any commercial hardware to be directly plugged into our laboratory infrastructure. This pushed us to design our own educative module.

2. EDUCATION IN DISCRETE-TIME CONTROL FOR ESTIA ENGINEERS

Five years of studies are needed in France to obtain the Engineer Degree. The two first years are generally used in order to prepare the access to the High Schools of Engineering, where the students will continue with the three remaining years. According with that, students spend the three last years of Engineering in ESTIA. In other words, the third year in ESTIA is the last year of engineering studies (fifth year). In addition, as shown in Fig. 1, there are three different curricular options in ESTIA: OGI (Industrial Organization and Management), MPA (Control of Automated Processes), and CGP (Generalized Design of Products).

2.1 Courses in Control Engineering

In ESTIA, the students have courses of Control Engineering the three years of the education programme.

The first year, Control in Continuous Time is studied in the three curricular options, under the classical point of view of transfer function, in contrast to state representation. The contents are: modular representation of systems, Laplace transforms, modelling systems of different engineering areas, stability, static precision, dynamics, first and second order linear systems, PID correctors, and identification by simple graphical methods.

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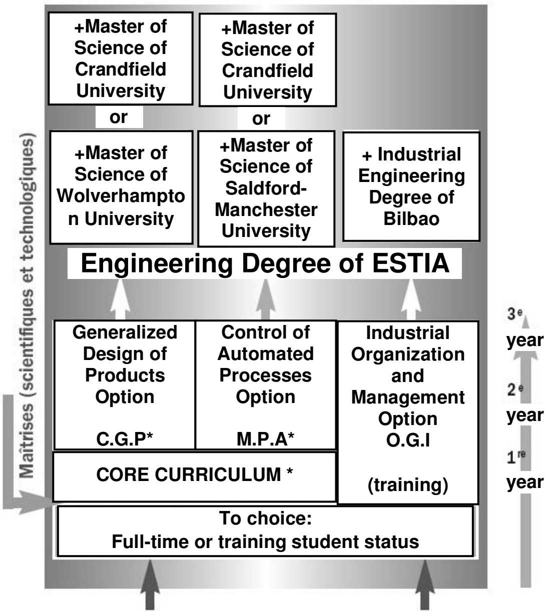

Fig. 1. The education programme in the ESTIA

In the second year, students of CGP and MPA have a course about Discrete Time Control where they learn in particular about the sampling of continuous signals and systems, systems representation using discrete-time transfer functions, and discrete time controllers design methods (Landau, 1993; Ksouri *et al*., 1999). In addition, there are courses of microcontrollers and micro-programmed systems.

Finally, in the Third Year, students of MPA complete their formation with courses of Systems Identification and Advanced Regulation, particularly considering the robustness of R-S-T discrete time controllers against system parameters variations (Landau *et al*., 2006).

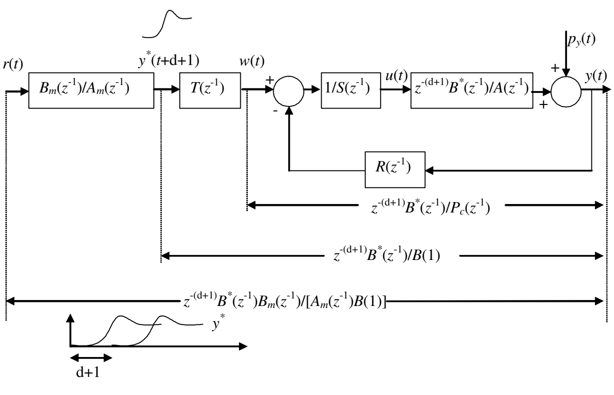

Fig. 2. Bloc diagram of a digital R-S-T closed loop control structure

Fig. 2 displays a block diagram of a typical linear Single Input Single Output (SISO) closed-loop sampled system, as studied by MPA students in the third year. $B(z^{-1})$ ($B^*(z^{-1})$, when specified without the sampling delay) and $A(z^{-1})$ are the numerator and denominator of the transfer function which represents the sampled process to be governed (it is assumed that they do not share common factors). d is the delay expressed as an integer number of sample times. The digital controller is defined by the polynomials $R(z^{-1})$, $S(z^{-1})$ and $T(z^{-1})$, while $B_m(z^{-1})$ and $A_m(z^{-1})$ correspond to the numerator and the denominator of the reference transfer function which generates the desired tracking trajectory $y^*(t\text{+d+1})$.

2.2 Teaching Way in ESTIA

In ESTIA, all the courses are divided in three parts: theoretical classes, practical classes and practical works.

Until last year, the practical works in Control courses were made in simulation, with Matlab / Simulink. But analysing the results of the surveys which evaluate the teaching quality, and talking with the students, it has been detected that there are difficulties for them to make the relationship between theory and real problems. Therefore, it was decided to equip the practical works with experimental setups from Alecop for the academic year 2006 / 2007. The experimental setups were selected in order to teach control in several engineering fields with different dynamics such as in hydraulic, thermal and mechatronic process.

At the end of the first year using these setups, the surveys and the students have said that the interest in this subject has grown. In addition, the results in the exams have been better than in the precedent years. Of course, it is necessary to put this results into perspectives, because the comparison is only based on three years, the students are not the same from one year to another and the exams either (but similar).

Improvements of Alecop setups were necessary to teach the subjects of the second and third years by experimental setups. They have been developed in the frame of BANCO project. Several students have participated in the development of those improvements, aiding them to understand the control engineering problems in real process.

3. IMPROVEMENTS INTRODUCED IN THE EXPERIMENTAL SETUPS

A new module has been made in order to add it to the workbench of Alecop. This module allows controlling in discrete-time the three processes mentioned above (hydraulic, thermal and mechatronic). In addition, in the future, the processes will be improved in order to be able to change their behaviour, and like this to test the controllers' robustness.

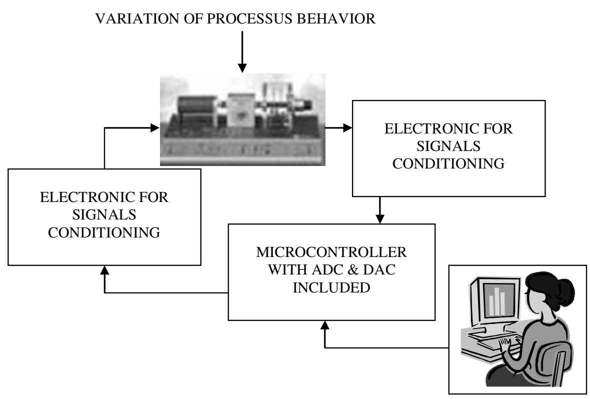

Fig. 3. Functional diagram of the workbench

Thanks to the new module, the user can program the control algorithm in the PC and load it in the microcontroller. As is shown in Fig. 3, the microcontroller sends the command signals to control the processes, and take measurements from the processes. Between the microcontroller and the processes, a stage adjusts the signal into the correct electrical values.

One of the reasons to design and build the module in ESTIA in collaboration with Alecop, instead of buying one existing in the market is didactical. ESTIA students have already worked with other Alecop modules and they have taken this habit, so it is easier for them to use these tools. Thus, it is not necessary to spend time teaching how to use or connect each module, focusing only on the Discrete Time Control concepts.

3.1 Existent Modules Description

Fig. 4 shows the appearance of one workbench of Alecop. There are several modules, and it is possible to remove them easily from the structure and plug new ones, so the physical position does not care. The plugs in the structure provide supplying voltage for the modules and the user can interconnect the outputs and the inputs of different modules using wires. Thus, it is easy for the students to change the controller structure (P, PI, PID…) and evaluate them.

Beside the processes, the available modules are: power supply, reference generator, signals conditioning, comparator, signals adding and proportional/integral/differential actions. Moreover the Kaptoris acquisition module in connection with a PC can generate references and acquire any existing signal.

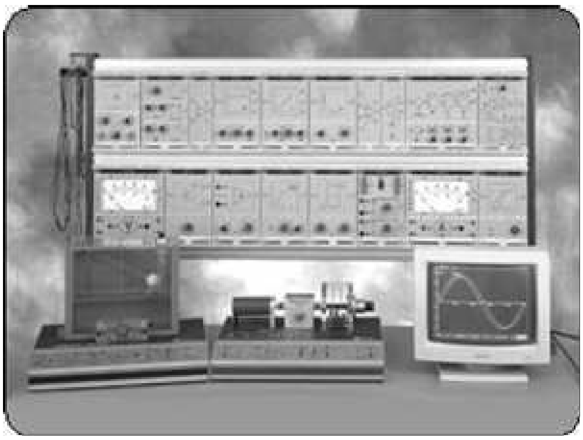

Fig. 4. Educational workbench acquired by ESTIA in 2006 from Alecop

3.2 BANCO Module Added to the Experimental Setup

The basic interactions between each element of this new module are described in Fig. 5. Inside the dotted rectangle are the blocks that make up the BANCO module: the microcontroller card and the signal shaping card which are described in next sections.

The students use the PC to include the control algorithms into the program and to compile it. After that, the program is ready to be loaded into the microcontroller. To make this, a RS 232 serial interface is used.

The microcontroller applies the command signal to the process, to control it. There is a feedback signal from the process to the microcontroller in order to close the control loop. The set point can be fixed from the analog reference generator module or from the PC via the Kaptoris module. All the signals between the microcontroller and the process pass by the signal shaping card to adjust the voltage levels and apply some filtering.

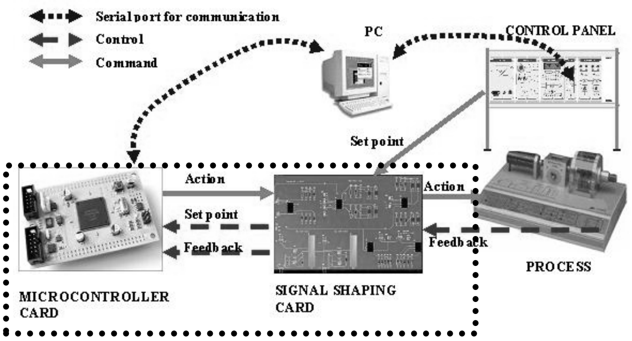

Fig. 5. Physical parts of the complete system

3.2.1 Program Description

This section presents a functional description of the program which implements the R-S-T controller (Adaptech, 2001). This program is implemented on a MC9S12E128 microcontroller.

Sensor and set point signals, after a scaling and filtering stage, go to the microcontroller Analog to Digital Converter (ADC), in order to obtain r and y sampled signals (Fig. 2). These signals and the command signal u are needed to implement the difference equation which defines the R-S-T controller.

At this point, the use of a Real Time Interrupt (RTI) is necessary. It is generated by an internal timer and is used by the microcontroller to fix a sampling time. This is crucial to ensure a correct operation, because the Discrete Time Control must pick up samples with a fixed period.

The procedures performed by the microcontroller for each sample time are:

- start the AD conversions for r and y signals, pick up the results and store the values in temporary memory locations;

- shift the previous r values and put the new value in the attached vector;

- compute y^* using the reference model;

- shift the previous y^* and y values and put the new values in the attached vectors (y^*, y and u vectors are used by the difference equation);

- compute the difference equation to obtain the *u* current value;

- shift the previous *u* values and put the new value in the attached vector;

- the *u* current value becomes the input of the Digital to Analog Converter of the microcontroller (DAC), to deliver the analog signal to the rest of the circuit, where it will be scaled.

The DA and AD converters and the RTI configuration is made in the program initialisation sequence.

3.2.2. Hardware Description

In terms of hardware, BANCO module consists of two parts: the signal shaping card and the LVCS12 module which contains the Motorola MC9S12E128 microcontroller.

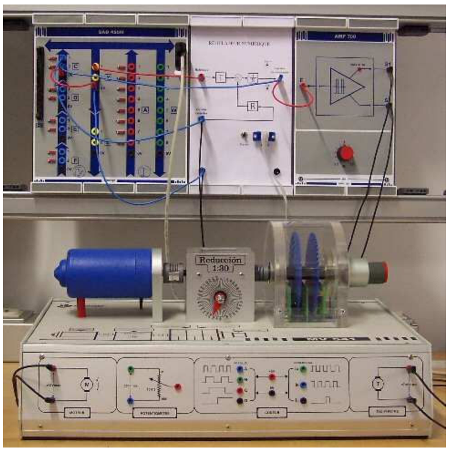

Fig. 6. BANCO module operating in Alecop workbench (in white)

Signal shaping card

In this point, there is a general description of the signal shaping card. The system has three main blocks: the filtering block, the signal scaling block and the power block.

The filtering block is an anti-aliasing filter used before the signal sampler to restrict the bandwidth of the signal to approximately satisfy the Shannon sampling theorem. It is necessary to filter separately the three existing process (hydraulic, thermal and mechatronic), because of the different dynamics of each one. The dynamics of the process is directly related with the filter cut-off frequency. The three filters are hardware implemented and their outputs are connected to three analog inputs of the microcontroller. The analog input (so the filter) and the associated sampling time are selected in the program according to the desired dynamics.

The signal scaling block must adjust the electrical signal magnitude. There are three signal scaling parts, two for the sensor and set up signals going to the microcontroller. They are originally in the range -10 V / +10 V and they are scaled into the 0 / +5 V range. The third part scales the signal from the microcontroller to the actuator, spreading the 0 / +5 V range into a -10 V / +10 V range.

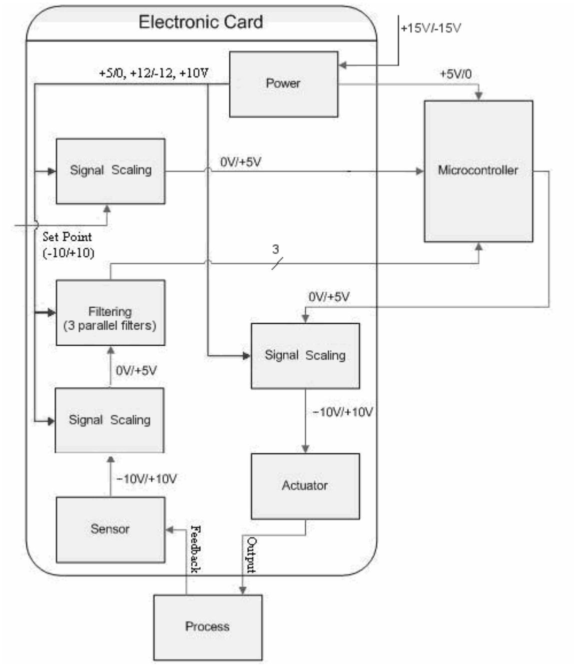

Fig. 7. Signal shaping card block diagram

The power block adapts the power supplying to the microcontroller, the operational amplifiers and provides specific voltages. The operational amplifiers supplying power is -12 / +12 V which is given by voltage regulators. The supply voltage for the microcontroller (+5 V) is given by a voltage regulator too. A 5 V voltage given by a precision voltage reference is amplified to obtain the desired 10 V reference.

The LVCS12 module

LVCS12 is an easy applicable, credit card-sized Controller Module, based on the 16-bit HCS12 microcontroller family from Motorola (MCT Elektronikladen GbR, 2003-2004).

The LVCS12 has a 16 MHz crystal clock and it is equipped with a powerful MC9S12E128 microcontroller unit (MCU).

The microcontroller contains a 16-bit HCS12 CPU, 128 KB of Flash memory, 8 KB of RAM and a large amount of peripheral function blocks, such as SCI (3x), SPI, IIC, Timer, PWM, 10 bit ADC, 8 bit DAC and General-Purpose-I/Os. The MC9S12E128 has full 16-bit data paths throughout (Motorola Inc., 2005). An integrated PLL-circuit allows adjusting performance vs. current consumption according to the needs of the user application.

The LVCS12 module is also equipped with rail-to-rail output amplifiers for the DAC channels and RS 232 transceivers for two serial interfaces (e.g. for PC connection).

Students of ESTIA make practical works with LVCS12 module in Second Year in micro-programmed systems course, so, it is easy for them to use it.

3.3 Changing of the Processes Parameters

In the future it will be possible to change some parameters of the processes in order to prove the robustness of the controller. The students will be able to modify the size of the escape opening in the hydraulic process, to modify the oven volume for the thermal process and to change the axis inertia in the mechatronic process.

4. PRACTICAL WORKS AND RESULTS

The improvements already included and those which will soon be included in the Alecop experimental setups will allow the student to do the complete work of a control engineer, from the study of the controlled process until the test of the designed control laws on a real system. The new experimental setups will be used in the lab works of Advanced Regulation from 2007-2008 university year which will be a transitional year. From 2008-2009 university year, they will also be used in Discrete Time Control and Systems Identification courses.

4.1 Lab Works of the Discrete Time Control Course

Some continuous models of the different processes have been obtained from simple graphical methods in the lab works of the Continuous-Time Control courses of the first year. These models will be used from the second year student to obtain a discrete-time transfer function in Matlab / Simulink. The student will then have to design and test in simulation discrete-time controllers by methods exposed in lecture. Then, the difference equations corresponding to the designed control algorithms will be introduced in the prepared program written in C language. The program will be compiled and loaded in the BANCO module. Finally, the behaviour of the discrete-time controller will be tested in tracking and in regulation mode on the experimental setup. Results will have to be commented by comparing them to those obtained in simulation.

4.2 Lab Works of the Advanced Regulation Course

For this transitional year, these lab works will be similar to the lab works of the Discrete-Time Control course explained previously. Nevertheless, the controllers will be designed with methods explained in the Advanced Regulation lecture. Thus, on top of designing a R-S-T controller, B_m and A_m, polynomials of a reference model (Fig. 2) will also have to be designed and implemented in the BANCO module.

In the following years, the model used to design the controller will be obtained by an identification process. Moreover, the robustness of the designed control laws will have to be tested by changing some process parameters values as explained in section 3.

4.3 Lab Works of the Systems Identification Course

These lab works will be carried out from 2008-2009 university year. The hydraulic, thermal and mechatronic process will have to be identified experimentally.

The fist step of the lab works will be related to the preparation of data acquisitions. The desired sample time, PRBS signal amplitude and number of sequences will be chosen and programmed in the BANCO module in this step. Then the data acquisition will be carried out. These data will be used by the Identification Toolbox of Matlab / Simulink to obtain, by a parameters identification algorithm, the experimental model. The process will have to be made again if the model can not be validated.

4.4 Some Results

As explained before, no lab works have still be carried out by students on these new experimental setups. Nevertheless trials have been made and some results concerning the mechatronic setup are presented here. The results have been caught with the Kaptoris module and software. The controllers corresponding to these results have been designed from the following model of the process which was obtained by a simple graphical identification method:

$$G(p) = e^{-0.009p} \frac{0.79}{0.061p+1} \quad (1)$$

Fig. 8 shows the axle rotational speed behaviour when a step set-point occurs at t = 0.1 and the controller is an analog PI. The PI has been designed from the first order control model, without taking into account the delay. The pole of the system is cancelled out and the closed-loop pole is placed to have a theoretical closed-loop response time of 0.1 s.

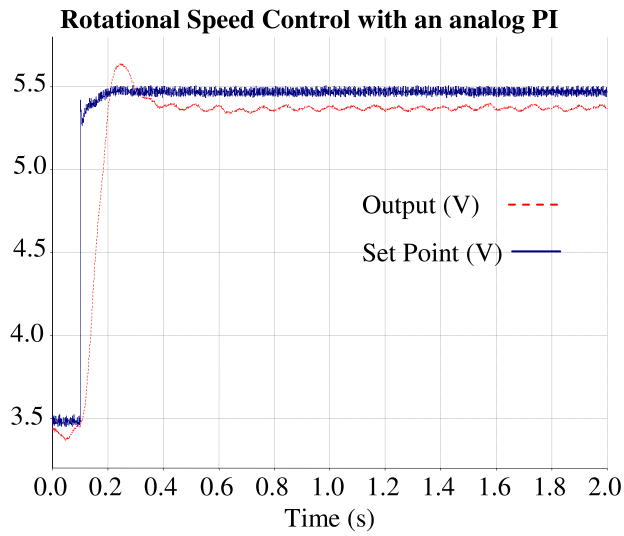

Fig. 8. Step response of the mechatronic process obtained with an analog PI controller

The response in the experimental setup does not correspond to a first order system. An over-shooting and some oscillations are present. Moreover, there is a small static error. These differences with the theoretical and simulation results have different causes. The DC motor axle is not perfectly aligned and thus the friction torque is not really proportional to the rotational speed. Some frictions occur periodically. Concerning the static error, it can be explained by the fact that the electronic components used for the signals scaling and for the integral action and comparator construction are not the best.

A digital R-S-T controller has been designed with the *pole placement with sensitivity function shaping* method (Landau *et al.*, 2006) (Fig 2). The chosen sampling time is of 3 ms. The following control model, obtained from the continuous model of (1) has been used to design the digital controller:

$$H(z^{-1}) = \frac{0.03791 z^{-4}}{1 - 0.952 z^{-1}} \quad (2)$$

A second order dynamics, with a response time of 0.1 s and a damping factor of 0.9 has been chosen for the regulation and reference model (B_m/A_m, Fig 2) dynamics. Fig 9 shows the step response of the system with this digital controller. As for the analog controller, the obtained response is a bit different of that foreseen in theory and that obtained in simulation. An overshooting and some oscillations are observed. On the other hand, here, the static error is nearly nil. We can imagine that results would be better with a discrete-time control model obtained directly by a parametric identification process.

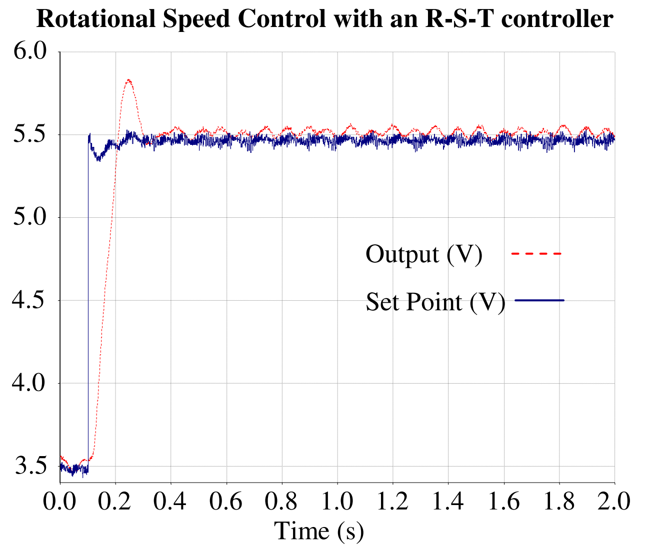

Fig. 9. Step response of the mechatronic process obtained with a digital R-S-T controller

5. CONCLUSIONS AND PERSPECTIVES

Last year, ESTIA equipped itself with some experimental setups from Alecop in order to improve the control engineering courses and thus make easier to understand this subject to the student. The lab works prepared by ESTIA's professors for the Continuous-Time Control course of the first year have been a success. Students understand better the relation between the theoretical aspects learned in lecture and their application on a real system.

The courses of second and third year related to control in discrete-time are still more difficult to assimilate for the student. On the BANCO project, improvements have been made in the Alecop experimental setups (especially the design and the construction of the BANCO module) in order to be able to use them also for the application of discrete-time control theory. Even if students have still not make lab works on this new setups, some trials realized show that the BANCO module works well.

Some tasks are still in progress to finish the BANCO project. For one part, processes are being modified to be able to change the value of some parameters, and like this to be able to test the robustness of the controller. Moreover, the program of the BANCO module's microcontroller is being completed to apply systems identification process on the setups. Alecop will integrate all these new functionalities in their commercial setups next year, beside a wireless communication system.

6. ACKNOWLEDGMENT

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