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An Approach for Improving Student Performance in a Feedback Systems Course for Process Control Education

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Abstract: This paper describes a new approach that has been applied since 2011 with the students of the Feedback Systems course to increase not only the control knowledge and approval rate but also to improve their hands-on practical skills and to prepare them for the industry. Alongside the theoretical lessons and laboratory activities, the students complete their activities with the design and implementation of a physical homemade plant where they make case studies in modeling, calibration, sensor and actuator electronic circuits, simulation, PID tuning and real-time control code under a step by step collection schedule. As result of this laboratory activity, significant progress is observed in the quality, motivation and learning (students feels so good in understanding control topics). The forth experiment of the final practical laboratory task is discussed and it is based on a PID tuning when applied to the fan-and plate, process to be built. Student evaluation is based on a questionnaire to obtain a useful measurement linked to the gain of the final performance.

Keywords: education, laboratory techniques, control equipment, educational aids, PID control.

1. INTRODUCTION

The teaching of control engineering has witnessed over many years the insertion of many pedagogical methodologies with the inclusion of educational platforms in order to motivate, to clarify the concepts, to decrease the abstraction level of the control theory and also to prepare the students for the industrial world (Bernstein, 1999; Leva, 2003; Luntz and Messner, 1997; Cook and Samad, 2009; Rossiter, 2013; Padula and Visioli, 2013).

Extensive usage of technological tools and packages to be used in classroom or laboratory (experimental and numerical setups) has been applied in control education (Dormido, 2004). This means that numerical and hardware-in-the-loop simulations, experimental laboratories with transfer function or control code, web technology and interactive learning modules, have been used for teaching process control systems. In addition, videos, portable hardware platform, interactive books, Arduino devices and Tablets are modern challenges coming towards maximizing the learning and skills of students in automatic control. All these contributions have been reported in specialized books, journals and magazines and, more recently, were well discussed in 2013 in the city of Sheffield in UK at the 10th IFAC Symposium on Advances in Control Education (Guzman et al., 2008; Vargas et al., 2011; Garpinger et al., 2012; National Instruments, 2012; González et al., 2013; Sobata et al., 2013; Taylor et al., 2013).

The Automation and Control Engineering at Undergraduate Program, at Federal University of Santa Catarina in Brazil, has many control courses such as Signal and Systems I and II, Feedback Systems, Instrumentation, Multivariable Control, Nonlinear Systems and Control, Identification, Digital Control and Adaptive Control, to prepare students for the industrial market.

Specifically, although the Feedback Systems course is well structured and integrated in terms of theoretical ideas and experimental laboratory essays, students have difficulties in understanding the standard and control concepts which implies in bad grades or a large number of exam failures. Aware of these results, the course educators have been seeking alternative ways to maximize the knowledge and motivation and also to increase the success of students for the end of each semester (a semester in Brazil is ranging from March to July and from August to December).

In this way, the educators elaborated since 2011 a special control activity: a final practical laboratory task. The student must build their own control apparatus for the semester and apply some of the course concepts in real-time control activities. The main electronic components are provided to groups, each group with four students to assembly and to integrate the controlled process apparatus with a PC, that is conducted by a data acquisition board developed in our department. With these overall equipment sets some tasks in modeling, PID design, anti-windup technique and control code implementation are performed according to a schedule month by month in the semester. As a result of this integrative procedure (conceptually and practically), the learning and motivation curves not only increased but also the quality of the success of the students at the end of the semester improved (Neto et al., 2012; Albeyrurriaga et al., 2013).

This paper is organized as follows. Section 2 discusses the contents of both theory and laboratory activities of the course. Section 3 provides details of the control design of the final practical laboratory task. Section 4 presents a project evaluation looking at the opinion of the students and the knowledge rate. Finally, section 5 gives some conclusions about this new approach for connecting control education with performance and motivation.

2. THEORY AND LABORATORY OF THE FEEDBACK SYSTEMS COURSE

Feedback Systems is the third course in the process control area of undergraduate program, Automation and Control Engineering at Federal University of Santa Catarina in Brazil. The content encompasses classical concepts of the control theory and is presented in a similar way in many engineering universities around the world. For this course the students must have knowledge from calculus, physics, chemistry, transport phenomena, electronic circuits, numerical calculus and signals and systems. Two introductory courses that come before Feedback Systems, Signal and Systems I and II, reinforce the control ideas such as know how to interpret a block diagram, consisting of the process and its control system; obtain the static and dynamic representations of the various system components, the manipulation of Laplace and Z transforms, series, parallel and cascade block diagrams, system responses of 1st and 2nd orders, and to appropriately relate the properties of systems in the time and frequency domains.

Feedback Systems is the central course of the control area and also deals with the most common problems encountered in the process industry. The student must complete the class as a minimum understanding on how to configure and tune traditional control loops (lead, lag and PID in temperature, level, pressure, flow and position processes) and how to use a stand-alone device of an industrial PID controller. The course comprehends continuous/discrete concepts and the final practical work aids the students to understand similar control concepts, e.g., the root-locus analysis tool.

2.1 Theoretical Part of the Course

As general objective the course must provide control tools in classical methods of design and to solve monovariable control problems. As specific objectives the students will understand the analysis, stability aspects and classical design methods of single-input and single-output control systems. Also, it includes the principles and operation of industrial controllers. Various configurations of control structures are discussed like feedback, cascade, ratio and anti-windup in order to understand the proprieties of each one. In addition, the ideas of the importance of modeling for analysis and design of control systems and problems associated to modeling errors are discussed. Applied concepts of analysis and design both in discrete and continuous systems are shown simultaneously. Understanding operating modes of industrial controllers and configuring them are important to give the students practical experience (students spend four hours per week for these theoretical activities).

The theoretical contents of the course are described, by chapter, as follows:

1) Introduction. Discrete and continuous systems. Description of the control problem. Goals of the controller. Two degrees of freedom of a closed-loop control system.
2) System response in the continuous and frequency domains. Systems with dominants zeros. Analyzing non-minimum phase and time-delay systems.
3) Classical stability. Root-locus graphical method. Stability assessment of closed-loop systems. The root-locus method as a tool for lead and lag control synthesis. Control design of discrete and continuous systems.
4) Disturbance rejection and setpoint tracking in control systems. Cascade, feedback and feed-forward control configurations.
5) PID controllers: structures, tuning methodologies and control code for practical implementations. Industrial PID controller.
6) Stability, lead and lag designs of continuous control system in the frequency domain. Discretization of the controller. Numerical examples.
7) Introduction of robust control.
8) Time-delay compensator. Smith predictor and control modifications.

2.2 Practical Part of the Course

Laboratory activities comprise two hours every week and are developed by two students per each of six control workstations. The basic equipment of each workstation includes a computer, data acquisition board and a motor+tacho+generator plant (to deal with practical essays). Specific software packages are also used like computer aided design under Matlab/Simulink environment to support some numerical essays. A report that includes the solutions obtained by each group for the laboratory tasks associated with each experiment is used for evaluation purposes (this contributes to half of laboratory grade).

The following main control experiments are developed by the students:

1) Experiments in identification and digital control in a velocity control system (practical essay).
2) Analysis of poles and zeros in a continuous closed-loop control system (numerical essay).
3) Analysis of poles and zeros in a discrete closed-loop control system (numerical essay).
4) Control code for PI and I+P controllers in a velocity system: regulatory and tracking tests (practical essay).
5) Analysis of the root-locus method (numerical essay).
6) Design of lead and lag controllers by the root-locus method (numerical essay).
7) Disturbance rejection and setpoint tracking with PI controller under cascade, feedback and feed-forward control structures (numerical essay).

8) Evaluation of a industrial FUJI PID controller in a velocity control system (practical essay).
9) Saturation behavior and anti-windup control technique in a velocity control system (practical essay).
10) Hardware in the loop activity: from the numerical simulation to the real-time PID control code and FUJI PID controller implementation (practical essay).
11) Control design of lag controllers in the frequency domain (numerical essay).
12) Control design of lead and lead-lag controllers in the frequency domain (numerical essay).
13) Controller design in the frequency domain: robustness aspects (numerical essay).
14) Time-delay compensator and Smith predictor control structure (practical essay).

3. FINAL PRACTICAL LABORATORY TASK: DESIGN AND SCHEDULE

The application of a physical prototype, as control didactical resource for the students of the Feedback Systems course, must be built and comprises all final laboratory activities. Reports from literature, like Balchen et al. (1981) and Wellstead (1990) characterized that control laboratory equipment must be relevant with the pedagogical objectives, realistic and simple enough to make it understandable in a limited time, adequate from a scale-model plant with less danger and for the student perception be safe, showing visual effects and be audible. Second, Bernstein (1999) stated that education must be both conceptual and experimental. In a recent survey, Cook and Samad (2009) declared that the universities must improve their hands-on practical teaching in order to better prepare their control systems graduates for careers in industry. Lastly, a recent case study by the University of Manchester (National Instruments, 2012) revealed that within a single year of introducing more practical course work into their curriculum, student satisfaction within their School of Electrical and Electronic Engineering rose from 67% to 98% (Taylor et al., 2013). Paving in this same way, for this semester, the classical homemade plant (low-cost platform) called fan-and-plate (FAP) process was selected to be assembled by students. Figure 1 exhibits a version of the FAP implemented by the educator, as a proposal, however the hardware and physical set implementations ideas can be changed by students.

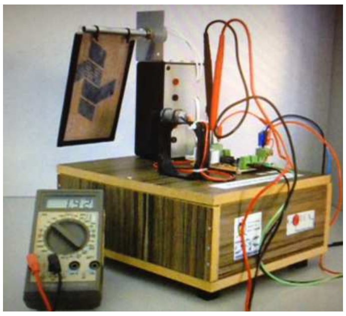

Fig. 1. Experimental setup: FAP process.

This experimental setup is purposed to demonstrate for the course students that the standard components, provided to each group, are enough to build and to encourage all of them. The educators have already applied the final laboratory activity with the students since 2011. Next, a brief description of the control system design, to guide students on implementation, is described:

1) Objective: design, physical assembly, implementation of real-time code for the PI and PID controllers and evaluation of the closed-loop dynamic of the position system for step setpoint changes.
2) Tips of the physical prototype: it can be made of acrylic, wood, styrofoam, aluminum or cardboard. The shape can also vary. To regulate the angular position of the plate the air flow developed by the DC motor and propeller set must be controlled (control variable - CV). The position measurement is performed with a precision potentiometer that is ideal for dealing with small increments of resistance variation (resolution) relative to the rotation angle of the plate (process variable - PV).
3) Calibration of the measurement or actuator circuits: to facilitate the implementation of digital control codes with the data acquisition board it is necessary to calibrate the electronic circuits of the measurement and actuator devices to operate from 0 to 5 V. Do not forget to assess if the inclusion of filters for the measurement or actuator circuits is necessary to decrease noise levels.
4) Suggestion to implement the electronic circuits for the measurement and actuator parts: Resistors and capacitors, with operational amplifiers in the subtract, gain and buffer configurations, are used for assembling the Wheatstone bridge and drive power for measurement and actuator electronic circuits (see Figure 2).

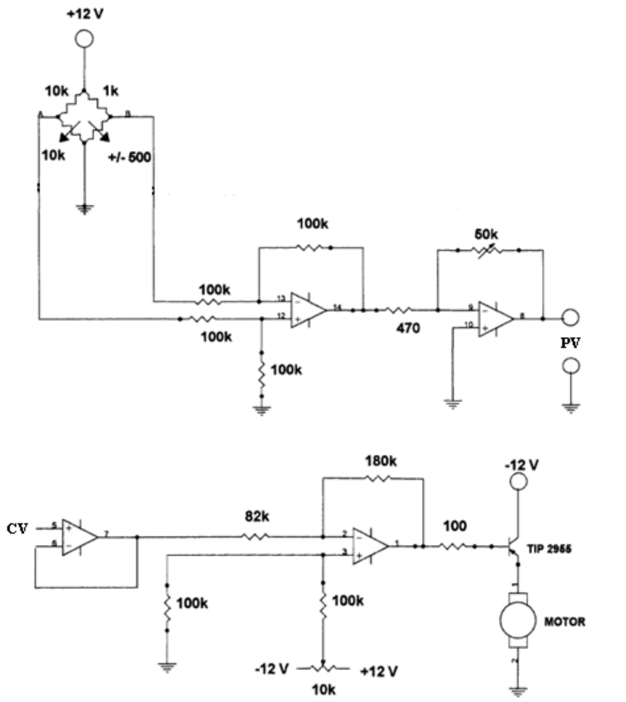

Fig. 2. Standard electronic diagrams for measurement and actuator circuits.

5) Composition of the working group: the implementation must be done in groups of four students. Activities will be undertaken in the second semester of 2013, with the deadline of each partial activity according to the schedule shown in Table 1.

For all steps of Table 1, the students must write a short report concerning the control assignment, including the auto-evaluation of the group and dedicating at least three hours a week. The practical work extends over a period of four months (one semester) and students have the freedom to put others ideas and skills into practice in the different phases of the project. The evaluation of the final practical laboratory completes the other half of the laboratory grade for course.

Table 1. Steps for elaborating the final practical activity.

Week	Subject to be discussed	Weight
9/2-6	Provide the built prototype. Analysis and features of the position process.	1
9/16-20	Physical setup with the electronic circuits of PV and CV. Preliminary tests with the DAQ board.	1
10/7-11	Open-loop identification and validation of continuous FOPDT and SOPDT models.	2
10/21-25	Digital control code implementation of PI and PID controllers with benchmark tuning rules.	2
11/4-8	PI and PID control codes with root-locus design, with and without anti-windup technique.	2
11/25-29	Handover the final report with oral and experimental presentation at the course laboratory. The presence of all group members is required.	2

As an incentive and motivation for students, once the FAP control system developed by the educator has been designed and built, it is possible to illustrate the philosophy and to test the proposal of the fourth essay described in Table 1. The digital PID simulation considers the implementation of two PID loops for the FAP process, PID and I+PD control algorithms with the IMC tuning, which nowadays is a standard tuning and of interest to the industry. For the PID implementation the proportional, integral and derivative bands are multiplied by the system error. This has an implication on the performance of the controller because abrupt changes in the reference, also in error, instantaneously, produces control actions with excessive magnitudes. This loop behavior can degrade the life time of the actuator and process dynamics. To avoid practical problems, including loop saturation, the error is removed from the proportional and derivative terms and receives only the negative output signal. This controller loop characteristic is called I+PD (Åström and Hägglund, 2006; Padula and Visioli, 2013). The real-time PID programming code (MATLAB) to address this control activity is illustrated in Table 2.

Figure 3 shows the experimental results for the implementation of PID (top) and I+PD (bottom) control structures with five step setpoint changes. This digital control essay provides an understanding not only of the theoretical fundamentals but also the dynamic effect of the setpoint tracking in the presence of practical proportional and derivative kicks and noise. Additionally, the students can observe how the behavior of the response, position of the FAP system, changes by increasing or decreasing the closed-loop time constant (*taumf*).

Table 2. Control codes for PID and I+PD structures.

```
%  Initial conditions
nit = 400; ; umax = 4.9; umin = 0; ts = 0.1;
y(1:5) = 0;  u(1:5) = 0; erro(1:5) = 0;
%  SOPDT estimated model of the FAP
kp =1.2; tau1 = 0.2; tau2 = 0.3;
%  IMC tuning set
taumf = 4.5*tau1;    % closed-loop time constant
kc  = (tau1+tau2)/(taumf*kp);
ti = tau1+tau2; td = tau1*tau2/(tau1 + tau2);
%  Setpoint
yr(1:80) = 2; yr(81:160) = 4; yr(161:240) = 1;
yr(241:320) = 3; yr(321:nit) = 2;
%  Selection of the controller
controller = menu('Controller','PID','I+PD');
%  Initialize DAQ board
inicializa_placa(5);
%  Closed-loop simulation
for k = 5:nit
%  Get the output and error
    y(k) = recebe_dado(1); erro(k) = yr(k) - y(k);
%  Get the control law
switch controller
   case 1
%  PID loop
   u(k) = u(k-1) + kc*(1+(td/ts))*erro(k) - ...
   kc*(1+(2*td/ts)-ts/ti)*erro(k-1) + kc*(td/ts)*erro(k-2);
   case 2
%  I+PD loop
   u(k) = u(k-1) + kc*(-y(k) + y(k-1) + (ts/ti)*erro(k-1) …
      + (td/ts)*(-y(k) + 2*y(k-1)-y(k-2)));
end
%  Loop saturation
    if u(k) >= umax; u(k) = umax;
    elseif u(k) <= umin; u(k) = umin;
    end
%  Send the control signal
    envia_dado(1,u(k)); atraso_ms(1000*ts);
end
%  Terminate DAQ board
finaliza_placa;
%  Results
t = 0:ts:(nit-1)*ts;
subplot(2,1,1), plot(t,y,'r',t,yr,'--k','linewidth',2), …
       ylabel('output and setpoint (V)'), xlabel('time (s)');
subplot(2,1,2), plot(t,u,'b','linewidth',2), …
       ylabel('control (V)'), xlabel('time (s)');
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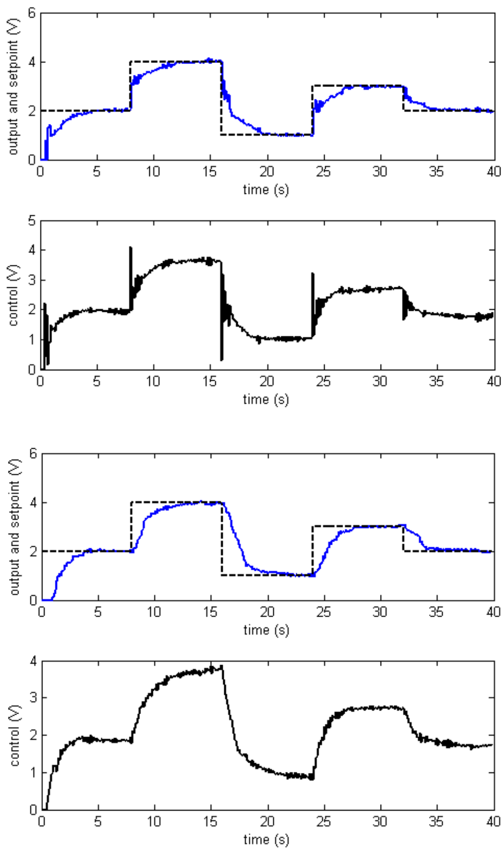

Fig. 3. The system response and the corresponding control variable for PID (top) and I+PD (bottom).

4. APRECIATION BY STUDENTS AND EDUCATORS

In order to observe the real student interest and to determine whether, the effort of elaborating this final practical laboratory task definitely can contributes to the learning and success purposes of the students and provides satisfaction by educators of the Feedback Systems course, they are asked to fill out an inquiry form. Ten questions are applied as follows:

1) What is the degree of difficult in the development of the physical prototype?
2) What is your involvement in the assembly of the physical prototype?
3) What is your satisfaction level in carrying out the laboratory activities in terms of calibration, filtering, modeling, linearization, simulation, identification and implementation of digital control code?
4) Is the set of experimental tests suitable to improve learning and consolidate the theory presented in the classroom?
5) Through this practical task was it possible to review and/or expand your knowledge in process control?
6) In the absence of a commercial equipment, how suitable is the physical prototype learning, for example, to application of the PID controller in terms of topologies, tuning, programming, design and anti-windup scheme?
7) Do you prefer to develop the practical laboratory task in simulation software?
8) Is it a good idea to use this equipment at home to perform the tasks of laboratory practice course?
9) Do you believe that the practical laboratory task provides and adds other skills and training as an engineer?
10) Do you think that the final laboratory task aggregates control educational aspects for your success in the course at the end of the semester?

Figures 4 and 5 show the student evaluation results for questions 1, 2, 3, 6, 8, and 4, 5, 7, 9, 10, respectively, concerning the quality, contribution and success of the final laboratory task of the Feedback Systems course.

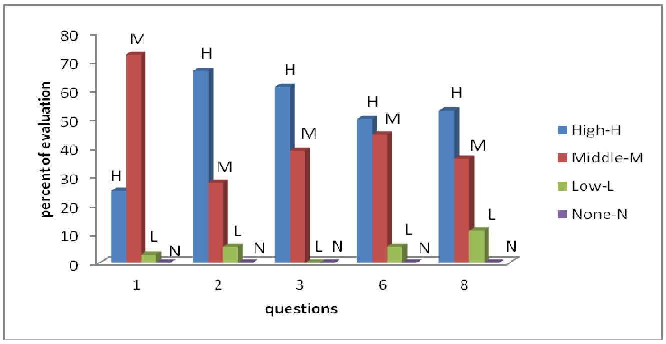

Fig. 4. Evaluation of the final lab task, questions 1,2,3,6,8.

From the results shown in Figure 4 it can be observed that the students approve this laboratory task because they have a smart opportunity to embrace enough knowledge/background, involvement, demonstrations of the control theoretical ideas and experimental essay, and, therefore, agreeing and finding this resource to be helpful for learning purposes.

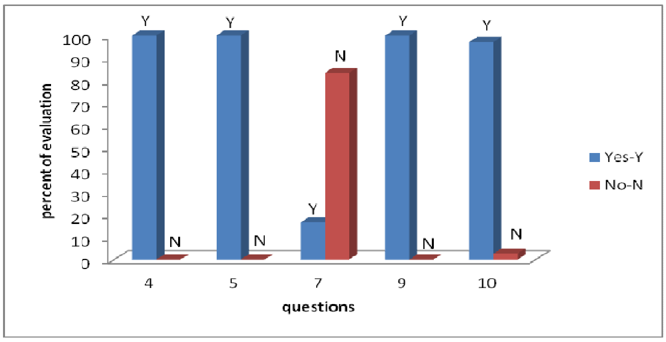

Fig. 5. Evaluation of the final lab task, questions 4,5,7,9,10.

Figure 5 shows that the experience of elaborating this laboratory task is very useful and is an important challenge to encourage the authors to maintain this direction. Aspects of investigation, confidence, understanding and without the possibility of give up of experimental essays are encouraging the students to put their hands on in this practical idea. As a strong factor, preparing all of them not only for the success on the course and control undergraduate program but also for an adequate transition to industry.

Finally, Figure 6 focuses on the potential application of this laboratory task and demonstrates clearly that the success of the students, at the end of the semester, is increasing and therefore, achieving the educational purposes. These results are supported by forty students enrolled per semester.

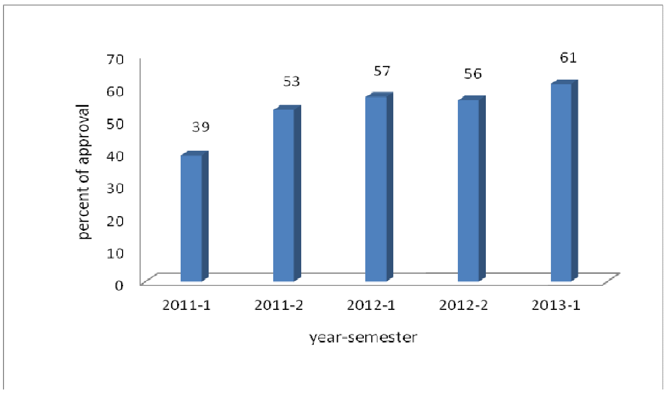

Fig. 6. Performance of students for five semesters.

This paper concentrated the educational ideas in 2013-2 (as Table 1), although others home-made plants like temperature and liquid level were utilized at the corresponding semesters of 2011 and 2012 to achieve the same objective. These low-cost apparatus are shown in Figure 7.

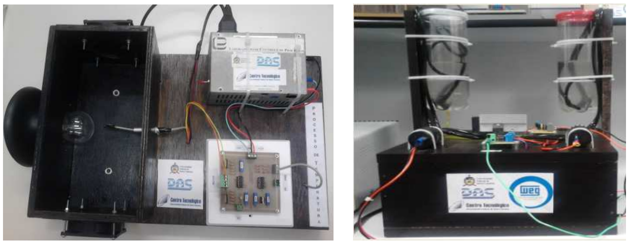

Fig. 7. Photos of the temperature and liquid level apparatus.

5. CONCLUSIONS

Any classical or modern technology is important to improve the quality and education aspects in courses of control engineering.

This paper has discussed the potential of applying a final practical laboratory task into the Feedback Systems course as a new approach to learning and teaching for educational purposes. The idea of a hands-on experimental apparatus, built by students to be used over a semester, seems very interesting concerning the quality, integration, motivation, skills and learning of students in automatic control concepts. From the student point of view it represents a good earning resource, linked to student performance and knowledge. From the educator point of view it gives the opportunity to solve simple control problems and integrate theoretical knowledge obtained at lectures with practical experiments,

The authors inform that details of the control apparatus, including the FAP process and DAQ board discussed this paper, are available to the academy.

REFERENCES

Aldeyturriaga, R.G.; Junior, C.A.; Silveira, A.S. and Coelho, A.A.R. (2013). Low Cost Setup to Support PID Ideas in Control Engineering Education, *IFAC Symposium on Advances in Control Education*, Sheffield, UK.

Åström, K.J. and Hägglund, T. (2006). *Advanced PID Control*, ISA.

Balchen, J.G.; Handlykken, M. and Tysso, A. (1981). The Need for Better Laboratory Experiments in Control Engineering Education, *Proc. of the 8th World Congress of IFAC*, Kyoto, Japan.

Bernstein, D.S. (1999). Enhancing Undergraduate Control Education, *IEEE Control Systems*, pp. 40-43.

Cook, J.A. and Samad, T. (2009). Controls Curriculum survey. A CSS Outreach Task Force Report, *IEEE Control Systems Society*.

Dormido, S. (2004). Control Learning: Present and Future, *Annual Reviews in Control*, pp. 115-136.

Garpinger, O.; Hägglund, T. and Cederqvist, L. (2012). Software for PID Design: Benefits and Pitfalls, *IFAC Conference on Advances in PID Control*, Brescia, Italy.

González, J.C.; Guzmán, J.L., Dormido, S. and Berenguel, M. (2013). Development of Interactive Books for Control Education, *IFAC Symposium on Advances in Control Education*, Sheffield, UK.

Guzman, J.L.; Åström, K.J.; Dormido, S.; Hägglund, T.; Berenguel, M. and Piguet, Y. (2008). Interactive Learning Modules for PID Control, *IEEE Control Systems Magazine*, pp. 118-134.

Leva, A. (2003). A Hands-On Experimental Laboratory for Undergraduate Courses in Automatic Control, *IEEE Transactions on Education*, pp. 263-272.

Luntz, J. and Messner, W. (1997). Web Technology for Controls Education, *36th Conference on Decision and Control*, pp. 3798-3803.

National Instruments (2012). Education Impact Case Study; The University of Manchester, *NI News Academic Edition*.

Neto, A.M.S.; Damo, T.P. and Coelho, A.A.R. (2012). Laboratory Essay with Online Back-calculation Anti-windup Scheme for a MTG System, *IFAC Conference on Advances in PID Control*, Brescia, Italy.

Padula, F. and Visioli, A. (2013). An Approach for Teaching Automatic Control in a Laboratory of Mechatronics, *IFAC Symposium on Advances in Control Education*, Sheffield, UK.

Rossiter, J.A. (2013). Using Online Lectures to Support Student Learning of Control Engineering, *IFAC Symposium on Advances in Control Education*, Sheffield, UK.

Sobata, J.; Pisl, R.; Balda, P. and Schlegel, M. (2013). Raspberry Pi and Arduino Boards in Control Education, *IFAC Symposium on Advances in Control Education*, Sheffield, UK.

Taylor, B.; Eastwood, P. and Jones, B.L. (2013). Development of a Low-Cost, Portable Hardware Platform for Teaching Control and Systems Theory, *IFAC Symposium on Advances in Control Education*, Sheffield, UK.

Vargas, H.; Sanchez, J.; Jara, C.A.; Candelas, F.A.; Torres, F. and Dormido, S. (2011). A Network of Automatic Control Web-Based Laboratories, *IEEE Trans. On Learning Technologies*, pp. 197-208.

Wellstead, P.E. (1990). Teaching Control with Laboratory Scale Models, *IEEE Trans. on Education*, pp. 285-290.