On Teaching Digital Control Systems in a Generic Engineering Degree

Eneko Lerma* Ramon Costa-Castelló*,** Robert Griñó*,***
Carlos Sanchis**** Sebastián Dormido†

*Dep. d'Enginyeria de Sistemes, Automàtica e Informàtica Industrial
(ESAII), Universitat Politècnica de Catalunya (UPC). E-mails:
eneko.lerma@estudiant.upc.edu, ramon.costa@upc.edu,
roberto.grino@upc.edu.
**Institut de Robòtica i Informàtica Industrial, CSIC-UPC. Llorens i
Artigas 4-6, 08028 Barcelona, Spain.
***Institut d'Organització i Control de Sistemes Industials (IOC),
UPC.
****Mathworks. (e-mail: Carlos.Sanchis@mathworks.es)
†Universidad Nacional de Educación a Distancia (UNED) (e-mail:
sdormido@dia.uned.es)

Abstract: In this work, the subject of digital control taught in a generic engineering degree is described. In particular, the contents of the course, the experimental environment and the interactive tools used in teaching are discussed. This work collects the teaching experience obtained during the past twenty years by the teaching team of this subject at the Barcelona School of Industrial Engineering of the *Universitat Politècnica de Catalunya* .

Keywords: Digital Control, Automatic Control, Hands on laboratories, Interactive applications

1. INTRODUCTION

Automatic control is a transversal material which each day is taking more relevance; due to this, most technical engineering studies include an introduction to automatic control. Most of these courses focus on continuous time systems, using a Laplace transform based approach (Guzmán Sánchez et al., 2012). Although this approach is quite natural and consistent with other subjects in the same studies, like the electrical and electronic engineering, shows a viewpoint which is not directly connected with the controller implementation methodologies. Nowadays, almost every controller is digitally implemented.

Most development platforms like MATLAB/Simulink and Labview contain components which allow to automatically generate code for most relevant implementation platforms. These mechanisms hide the discretization procedures and require powerful hardware and small sampling time to approach the designed continuous-time behavior. Although these tools are continuously improving, sometimes the implementations obtained present fragility problems, especially in the case of sophisticated controllers.

Consequently, from our point of view it is very important to introduce students in discrete-time control concepts and techniques. This is the main reason why at the industrial engineering degree (*Grau en Tecnologies Industrials*) at *Escola Tècnica Superior d'Enginyeria Industrial de Barcelona* (ETSEIB) from *Universitat Politècnica de Catalunya* (UPC) are taught a course on discrete-time control (*240172 - Control Automàtic*). The spanish industrial engineering degree is usually described as a generic

engineering since the general principles of engineering are shown without going into any of them. That is, a bit of mechanical, electrical, chemical and operations management engineering is studied simultaneously. This is a study of long tradition and success in Spain.

Automatic control and, discrete-time control in particular, is a difficult topic. Many students have problems to catch most relevant concepts. Interactivity has proven to be a very useful tool to introduce people, and students in particular, to difficult topics and automatic control in particular(Dormido et al., 2005; Dormido, 2004).

The proliferation of high level development tools like Easy Java Simulations(Esquembre, 2004), Sysquake(Piguet, 2009) and MATLAB apps which allow to develop graphical applications with a great degree of interactivity has increased the number of interactive tools designed for control design or teaching purposes (Costa-Castelló et al., 2018; Diaz et al., 2017; Guzmán et al., 2016).

In order to take profit from the nice properties of interactivity and the new development frameworks a set of interactive tools to illustrate most relevant concepts in the discrete-time control course has been designed and implemented using Sysquake. These tools have been integrated in a textbook (Costa Castelló and Fossas, 2014).

In engineering teaching, the realization of experimental practices continues to be of vital importance for the correct formation of students. Unfortunately, the acquisition of equipment that allows experimental practices implies an important economic cost that is not always easy to be assumed by the teaching centers. The emergence of low-

cost hardware platforms like Arduino and Rasberry Pi has favored the development of hands on laboratories that can be used in almost every topic, and in particular in the field of automatic control (Reguera et al., 2015; Candelas et al., 2015; Barber et al., 2013; Sobota et al., 2013; Ishikawa and Maruta, 2010). This type of devices can be programmed with their own development environments or using automatic code generation environments such as those incorporated in MATLAB/Simulink (Barber et al., 2013; Reguera et al., 2015). All this has substantially reduced the costs of the data acquisition, signal generation and processing equipment, as well as the cost in time necessary to prepare practices. In order to take profit from this, at the ETSEIB a project to develop a low-cost platform, based on an Arduino board and MATLAB/Simulink environment, has been initiated. This platform will allow to develop a complete set experimental practices regarding discrete control analysis and design.

This paper describes the discrete-time control subject taught at ETSEIB and all its framework and it is organized as follows, section 2 describes the course theoretical concepts and most relevant books used as bibliographic references, section 3 describes a set of interactive applications which are used to help professors during the lectures and students during their learning process, section 4 describes a low-cost experimental setup which has been developed to perform experimental works, finally section 5 contains some conclusions and future works.

2. SYLLABUS OF THE SUBJECT

In this section the subject (240172 - *Control Automàtic*) is presented in detail, Subsection 2.1 shows the concrete topics described in the course while Subsection 2.2 describes the suggested books.

2.1 Program of the subject

The purpose of the course is to introduce the students to the control of single-input/single-output (SISO) linear sampled-data systems from an input/output approach. To this end, and following a classical approach such as that set out in the main textbook (Kuo, 1995), a program divided into six chapters has been structured: One chapter is devoted to the introduction to sampled-data systems, another to the sampling in the time domain, three more chapters to the analysis (main mathematical tool, time domain and frequency domain) and a last one to the design and implementation of controllers. The details of this chapters are as follows.

Ch. 1: Introduction to digital control
   (1) Digital control systems.
   (2) Digital controllers and control algorithms.
   (3) Architecture of a digital control system.
Ch. 2: Sampling of signals
   (1) Sampling and holding.
   (2) A/D and D/A converters.
   (3) Mathematical study of sampling.
   (4) Properties of the Laplace transform of a sampled function.
   (5) Sampling Theorem.
   (6) Reconstruction of sampled signals.

Ch. 3: Discrete-time systems
   (1) Definition of z-transform.
   (2) Properties of the z-transform.
   (3) Correspondence between the s-plane and the z-plane.
   (4) Calculation of z-transforms.
   (5) Calculation of inverse z-transforms.
   (6) z-domain transfer functions.
   (7) Block diagrams. Simplification.
   (8) Closed-loop systems. Open-loop transfer function (L) and closed-loop transfer functions (S, T).
Ch. 4: Time-domain analysis
   (1) Time response of discrete-time systems.
   (2) Configuration of poles in the z-plane and temporal response.
   (3) Stability.
   (4) Jury's stability criterion.
   (5) Precision. Steady-state error and type.
   (6) Comparison of responses of continuous and discrete time systems.
   (7) The root locus (RL). RL tracing rules. Interpretation of the RL.
Ch. 5: Frequency domain analysis
   (1) Frequency response of discrete-time systems.
   (2) Nyquist and Bode plots.
   (3) Nyquist's stability criterion.
   (4) Simplified Bode criterion. Gain and phase margins.
Ch. 6: Design and implementation of digital controllers
   (1) Control algorithms and digital controllers.
   (2) Digital PID controllers.
   (3) Frequency domain design of lead and lag controllers.
   (4) Root locus design of lead and lag controllers.
   (5) Root locus design of PI and PD controllers.
   (6) Algebraic design of digital controllers: Pole assignment and other specifications, general structure controllers and PID controllers.
   (7) Control algorithms programming.
   (8) Selection of the sampling period.
   (9) Quantification and computation time effects.

It is worth to remark that, during the teaching of the course, a strong emphasis is done in direct digital design techniques comparing them with the approximation of continuous-time designed controllers to discrete time.

The theory and problems' teaching of the program of the subject described in this section lasts 45 hours at the rate of 2 sessions of 1.5 h per week during 15 weeks. In these sessions theory and problems are combined to illustrate theoretical results with problems and examples. The theory and problems sessions are complemented with 15h of experimental laboratory in which the students put into practice the theoretical concepts in an experimental plant. This plant is a dc servo system of the brand LJ Systems.

2.2 Bibliography of the subject

The book "Digital Control Systems" (Kuo, 1995), by B. Kuo, is the main text for the follow-up of the subject by the students. This book follows a classic approach to the control of SISO sampled-data linear systems. This book is complemented by a textbook (Basañez and Caminal, 2002) of solved problems of digital control that includes
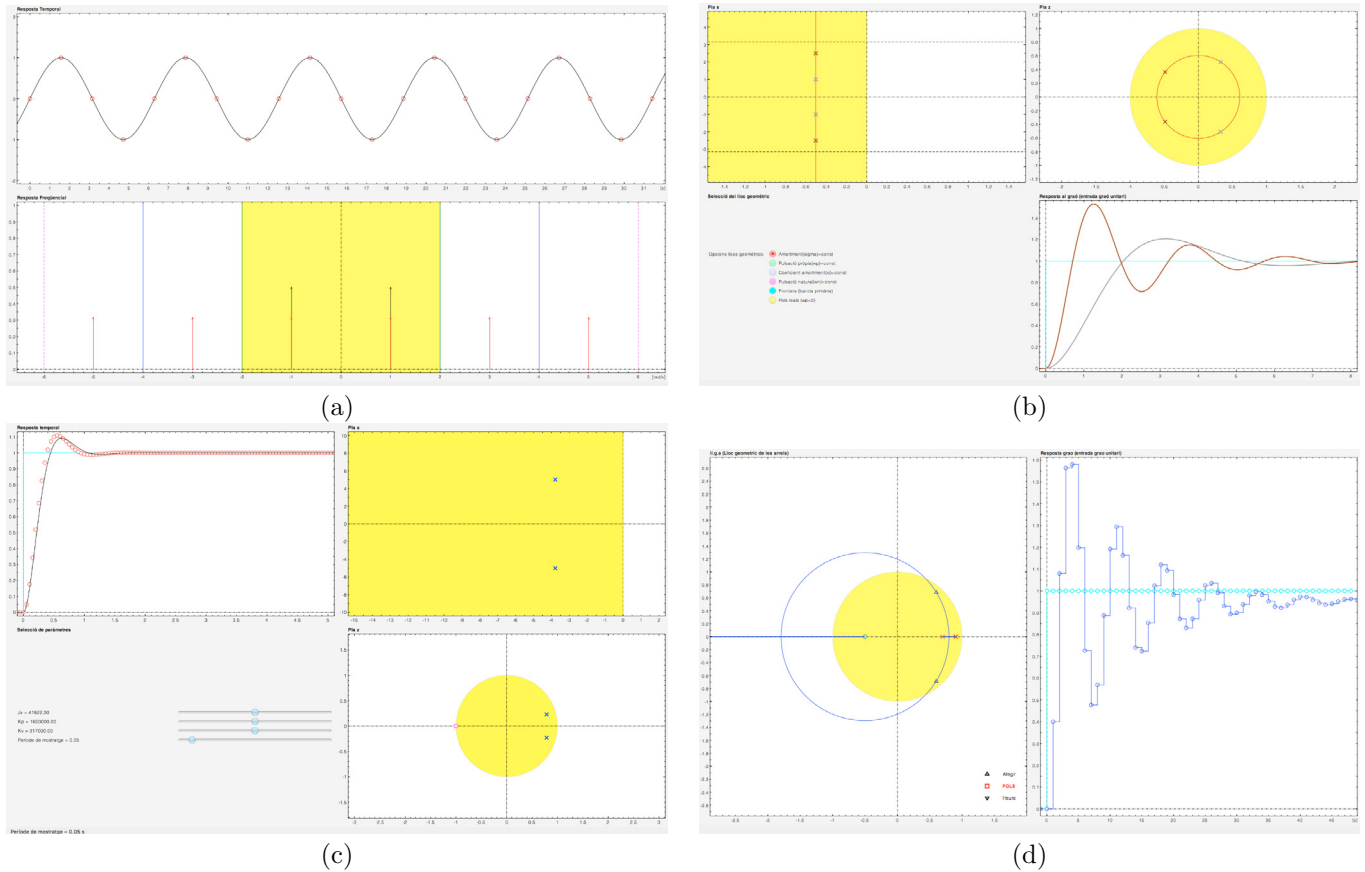
(a)

(b)

(c)

(d)

Figure 1. Main view of the some of the interactive tools used in the course (Costa Castelló and Fossas, 2014).
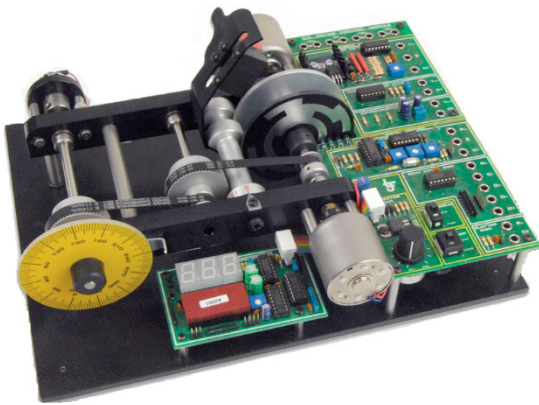

Figure 2. LJ Technical Systems' servosystem

Figure 3. Arduino programming Simulink sheet used for open-loop experiments

a significant number of analysis and design problems that come from final examinations of previous years. In addition, the students have access to the lecture notes (Basañez et al., 2013) that describe the tasks to be carried out in the experimental laboratory sessions.

The texts (Phillips et al., 2014; Ogata, 1994) are recommended as possible alternatives to the main book (Kuo, 1995). These books have a content and follow a similar approach, even in notation, to the main book and are therefore suitable for the follow-up of the subject. Besides, for those students who wish to review or need to settle their knowledge of continuous-time classical control is recommended, in addition to attending the tutoring hours of professors, the reading of certain chapters of the book (Ogata, 2015). It is also important to note that the book (Åström and Wittenmark, 2011), while following a different approach from that of the course, is of great interest to the analysis and design of digital control systems. For this reason, the commentary on the recommended bibliography at the beginning of the course mentions it as a complementary text.

Finally, for certain theoretical aspects that may be of interest to certain students, the seminal texts (Jury, 1958; Tou, 1959) are recommended. In this sense, the book (Jury, 1973) also serves as a reference to deepen in the theory associated with the z-transform which is the basic mathematical tool of the course.

3. INTERACTIVE TOOLS FOR DISCRETE-TIME CONTROL SYSTEMS

Taking profit from previous experience in designing interactive applications (Guzmán et al., 2016; Guzmán Sánchez et al., 2012), it was decided to design a set of interactive applications to support the teaching and students self-
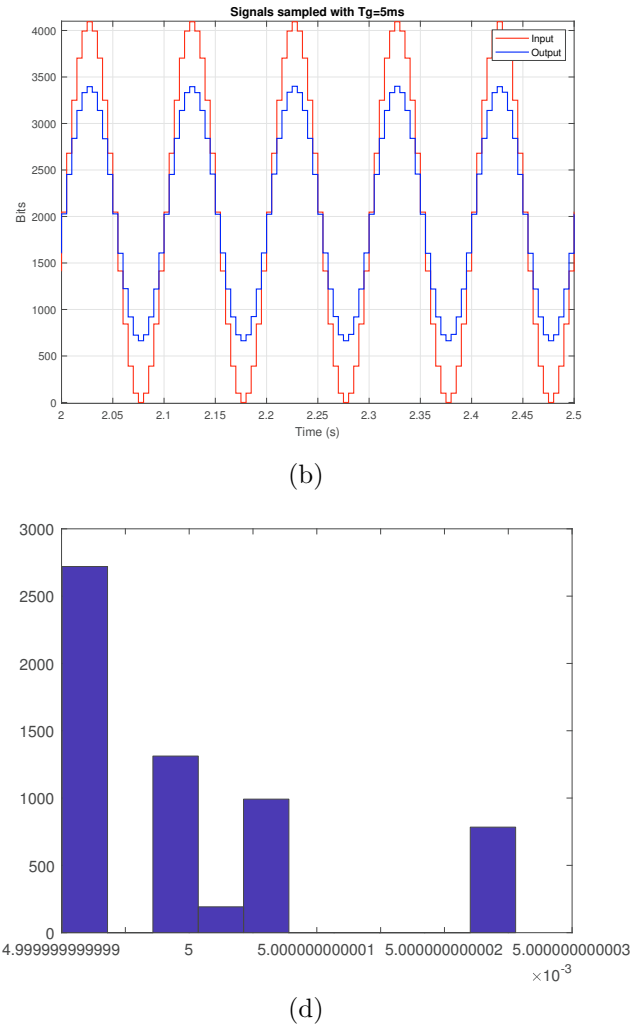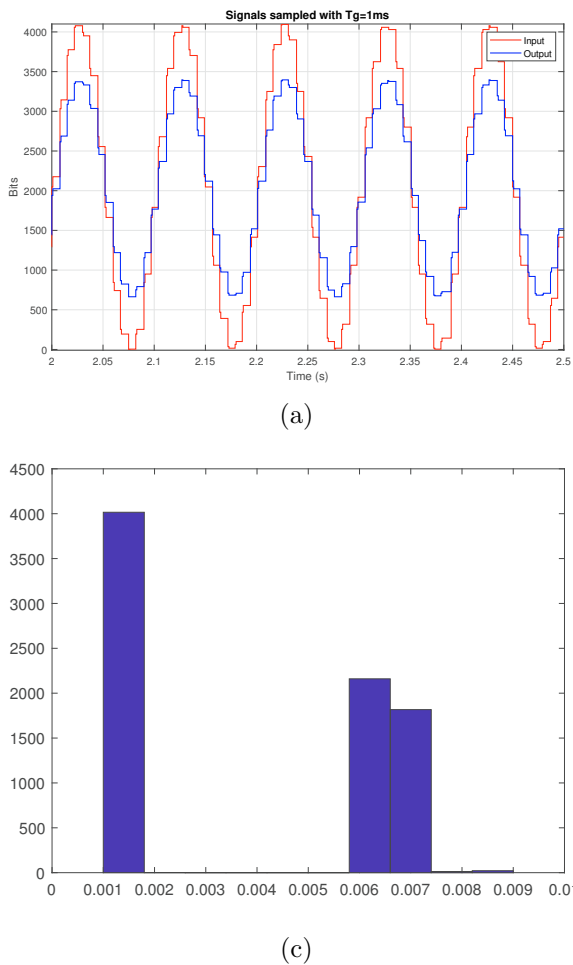
Figure 4. Arduino Simulink sheet, Figure 3, Real Time analysis. (a) Signal Reconstruction for $T_g = 0.001$s, (c) sampling time period histogram for $T_g = 0.001$s, (b) Signal Reconstruction for $T_g = 0.005$s, (d) sampling time period histogram for $T_g = 0.005$s

learning. All this applications have been integrated in a textbook to support the students learning(Costa Castelló and Fossas, 2014). Interactive applications are structured as in the following topics:

- Sampling and discretization.
  · Sampling theorem. Aliasing concept.
  · Signal reconstruction.
  · Plane s-plane z relationship.
  · System discretization : z-transform, Tustin transform, Euler transform.
- Discrete-time systems
  · Time response.
  · Root Locus.
  · Nyquist criteria.
- Controller design
  · Lead Controller. Design of lead controllers in the frequency domain. Design of lead controllers in the root locus.
  · Lag Controller. Design of lag controllers in the frequency domain. Design of lag controllers in the root locus.

· PID controller. Design of PID controllers by placing closed-loop poles.
· Examples
- Technological aspects
  · Windup and antiwindup concepts.
  · Switching between controllers. Bumpless transfer algorithms.
  · Quantification effect in linear filters
  · Structure implementation effect.

All developed applications are freely available in :

https://sites.google.com/site/sicotedi.

As an example, Figure 1 shows the main view of four of the developed interactive tools. Figure 1.a shows the sampling theorem tool, in this tool a continuous sinusoidal signal and its sampled version are shown in the upper figure, below their spectrum is shown. The user can interactively modify the sampling time and see the change effect immediately. Aliasing effect can be easily visualized both in the time and frequency domains.

Figure 1.b shows the tool showing the relationship between plane s and plane z for a fixed sampling time. The tool
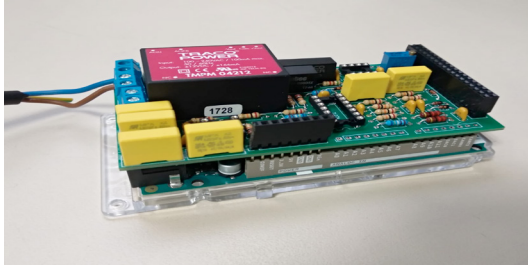
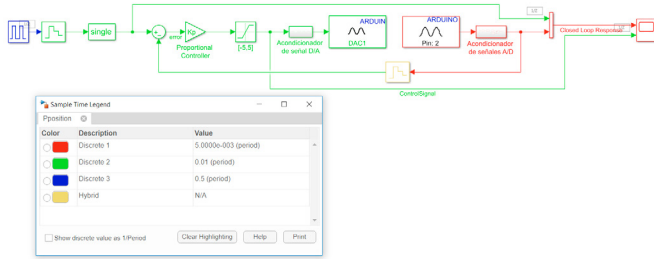Figure 5. Signal conditioning board placed over the Arduino Due board.

Figure 6. Simulink block diagram for position control

shows the poles in plane s and its equivalent ones in the plane z, these poles can be interactively modified and everything is updated. The most relevant geometric locus are shown in both planes and the time response related with the concrete analyzed poles is also shown.

Figure 1.c shows the closed-loop time response of a continuous time system and its sampled equivalent version. The effect of sampling time and parameter changes can be easily visualized.

Figure 1.d shows the root-locus of a discrete-time system and its step response, both the plant poles/zeros and the proportional gain can be automatically updated. The tool also includes hints to analyze the root-locus like showing the centroid, singularity points or the asymptotes.

4. HANDS ON LAB SETUP

The ETSEIB automatic control laboratory has 12 workplaces composed by a plant, a dc-motor plus required power stages (LJ Technical Systems, Figure 2), and a PC which is equipped with AD/DA cards connected through the PCI bus. The use of the PCI bus is becoming less and less common and this increases the price of the required PC.

In order to reduce the cost of each workplace and being able to use low-cost modern PC which allow to run current MATLAB/Simulink version a project to replace the PCI AD/DA cards by low-cost Arduino board was initiated. The first step was analyzing the real-time performance of the new environment, to do this a Simulink sheet, shown in Figure 3, was developed. In these sheet two sampling times are defined:

- T_g : sampling time used plot visualizing sampled data. The Arduino card is also playing the role of an oscilloscope, used to display continuous time signals.
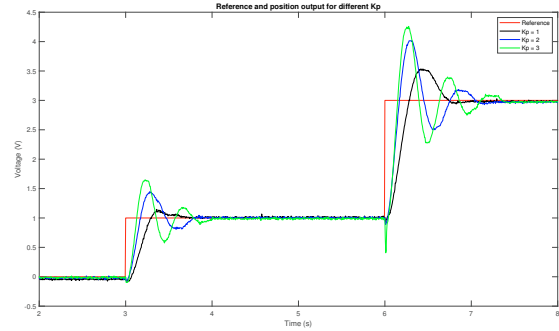- T_s : closed-loop sampling time, used to close the loop.

Figure 7. Position control experimental results for different k_p values, using the Simulink sheet shown in Figure 6

To perform this analysis, the DA output signal is physically connected to the AD input, so that it is possible to read, using the AD, what it is written on the DA channel, the sampling is fix and the sampling period variability is analyzed. Figure 4 shows the results obtained for $T_g = 1\,\text{ms}$ and $T_g = 5\,\text{ms}$ respectively. For the case of $T_g = 1\,\text{ms}$ it can be stated that the period variability, jitter, is important including sample looses; for $T_g = 5\,\text{ms}$ the period variability is very small. In both cases, the signals reconstruction is qualitatively good. Consequently, I was concluded that for visualization purposes, sampling times greater or equal to $T_g = 5\,\text{ms}$ where appropriate.

There exist several Arduino boards which could be used, all of them have a similar price but different computational burden. In the project, the Arduino Due board was selected due to its high computation performance and the fact that it has real DA converters[1] .

Another step that was addressed, was the electrical compatibility. Our plant, has inputs and outputs in ± 5 v range while the Arduino Due board can only handle signals in the $[0, 3.3]$ v range. In order to avoid this problem a signal conditioning board has been designed. Figure 5 shows a prototype of the commented board.

Currently, a set of basic MATLAB/Simulink applications is being developed. All these applications are freely available in:

https://github.com/DuinoBasedLearning/Lab

As an example, Figure 6 shows a MATLAB/Simulink sheet designed to implement proportional controllers. Figure 7 shows the achieved closed-loop response obtained in our system using the proportional controller to control position with different values of k_p.

5. CONCLUSIONS AND FUTURE WORKS

In this work the contents and teaching material used in a discrete-time control course has been presented. All material is available and can be freely used.

The use of interactive tools allows to transform traditional theoretical classes becoming more attractive to the students. Additionally, this tools allow students to develop intuition on most relevant concepts improving the students knowledge. Some of the students do not use the interactive

---

[1] Most Arduino boards only have PWM outputs.

tools because they do not see the realization between its use and the evaluation processes. Currently, work is being done to incorporate its use in these processes.

From a technological point of view, we are working to take advantage of the new features of Sysquake to make them more attractive. Additionally, its transformation is being analyzed in applications that can be executed on mobile devices.

Although the effort necessary to adapt the Arduino board to the available laboratory equipment has been important, its use supposes a significant reduction of the experimental setup economic cost. This allows to increase the number of workplaces. Both the software and the schemes of the circuits are available so that they can be used by other universities.

Currently, several videos are been developed to support the hands on laboratories so that they can be used as a complement to students and other universities. The first of them is available in:

https://www.youtube.com/watch?v=eIqY125xZE0

We are also working on the development of very low cost plants, this will allow the students to carry out their experiences in their homes.

ACKNOWLEDGEMENTS

REFERENCES

Åström, K. and Wittenmark, B. (2011). *Computer-Controlled Systems: Theory and Design*. Dover Pubs.

Barber, R., Horra, M., and Crespo, J. (2013). Practices using simulink with arduino as low cost hardware. *IFAC Proceedings Volumes*, 46(17), 250 – 255. doi: 10.3182/20130828-3-UK-2039.00057.

Basañez, L. and Caminal, P. (2002). *Control digital: problemas (in Spanish)*. Edicions UPC.

Basañez, L., Costa, R., Fossas, E., Mañanas, M.A., Puig, V., Riera, J., Rosell, J., and Villá, R. (2013). *Treballs pràctics de control digital (in Catalan)*. CPDA.

Candelas, F., García, G., Puente, S., Pomares, J., Jara, C., Pérez, J., Mira, D., and Torres, F. (2015). Experiences on using arduino for laboratory experiments of automatic control and robotics. *IFAC-PapersOnLine*, 48(29), 105 – 110. doi:10.1016/j.ifacol.2015.11.221.

Costa-Castelló, R., Carrero, N., Dormido, S., and Fossas, E. (2018). Teaching, analyzing, designing and interactively simulating of sliding mode control. *IEEE Access*, 6(1), 16783–16794. doi:10.1109/ACCESS.2018.2815043.

Costa Castelló, R. and Fossas, E. (2014). *Sistemes de Control en Temps Discret*. Edicions UPC. ISBN: 978-84-9880-492-8.

Diaz, J.M., Costa-Castelló, R., Muñoz, R., and Dormido, S. (2017). An interactive and comprehensive software tool to promote active learning in the loop shaping control system design. *IEEE Access*, PP(99), 1–1. doi: 10.1109/ACCESS.2017.2712520.

Dormido, S. (2004). Control learning: Present and future. *Annual Reviews in Control*, 28(1), 115–136.

Dormido, S., Dormido-Canto, S., Dormido, R., Sánchez, J., and Duro, N. (2005). The role of interactivity in control learning. *Int. J. Eng. Educ.*, 21(6), 1122–1133.

Esquembre, F. (2004). Easy java simulations: a software tool to create scientific simulations in java. *Comput. Phys. Commun.*, 156(2), 199–204.

Guzmán, J.L., Costa-Castelló, R., Dormido, S., and Berenguel, M. (2016). An interactivity-based methodology to support control education: How to teach and learn using simple interactive tools [lecture notes]. *IEEE Control Systems*, 36(1), 63–76. doi: 10.1109/MCS.2015.2495092.

Guzmán Sánchez, J.L., Costa Castelló, R., Berenguel Soria, M., and Dormido Bencomo, S. (2012). *Control automático con herramientas interactivas*. Pearson. ISBN: 9788483227503.

Ishikawa, M. and Maruta, I. (2010). Rapid prototyping for control education using arduino and open-source technologies. *IFAC Proceedings Volumes*, 42(24), 317 – 321. doi:10.3182/20091021-3-JP-2009.00060.

Jury, E. (1958). *Sampled-data Control Systems*. John Wiley and Sons.

Jury, E. (1973). *Theory and Application of the z-Transform Method*. Krieger Pub. Co.

Kuo, B. (1995). *Digital Control Systems*. Oxford University Press.

Ogata, K. (1994). *Discrete-time Control Systems*. Prentice Hall.

Ogata, K. (2015). *Modern Control Engineering*. Pearson India.

Phillips, C., Nagle, T., Brickley, J., and Chakrabortty, A. (2014). *Digital Control System Analysis & Design*. Pearson Education Ltd.

Piguet, Y. (2009). *SysQuake 5: User Manual*. Calerga Sàrl,, Laussane, Switzerland.

Reguera, P., García, D., Domínguez, M., Prada, M., and Alonso, S. (2015). A low-cost open source hardware in control education. case study: Arduino-feedback ms-150. *IFAC-PapersOnLine*, 48(29), 117 – 122. doi: 10.1016/j.ifacol.2015.11.223.

Sobota, J., PiSl, R., Balda, P., and Schlegel, M. (2013). Raspberry pi and arduino boards in control education. *IFAC Proceedings Volumes*, 46(17), 7 – 12. doi: 10.3182/20130828-3-UK-2039.00003.

Tou, J. (1959). *Digital and Sampled-data Control Systems*. McGraw-Hill Inc.