

An interactivity-based methodology to support control education

How to teach and learn using simple interactive tools

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Modern engineering projects are multidisciplinary and involve the integration of diverse elements. Within this context, automatic control plays a crucial role. Automatic control is an area of knowledge with significant mathematical content, including differential equations, linear algebra, differential geometry, and/or complex variable among others [1]. Consequently, in many cases, automatic control is difficult for most students to grasp, especially in those cases where students have only an introductory control course in their engineering curriculum. Thus, teachers look for ways to introduce and make automatic control attractive for the students [2]. From the very beginning, graphical representation has been used as support in automatic control teaching. Looking back to pioneer books in automatic control [3]-[11], it can be seen that there are plenty of schematics and figures. Graphical abstraction was used to contributed to theoretical understanding [12]. Most of the relevant automatic control concepts, such as systems interconnection, frequency response, stability analysis, time response, and/or root locus, have been displayed graphically [13]. This type

of representation has been considered for years an excellent route to introduce automatic control concepts.

A natural way to go on with these graphical methods is to use computers. Modern computers have excellent graphical capabilities, which can be employed to represent most relevant control concepts easily. Personal computers have been used for many years to display control concepts; CC can be considered a pioneering tool. Later, more-sophisticated tools as Matlab, Scilab, Matrixx, and Labview were introduced. Computers are powerful tools that can be deployed for teachers to support automatic control education. In addition to their capability for displaying control concepts, computer use is also an inherently attractive activity for engineering students [13]. Computers can be used anywhere, and smartphones or tablets devices are something most people, including students, are using everyday and everywhere. Although smartphones and tablets have a reduced computation capacity in comparison with computers, they offer impressive graphical display; consequently they are serious candidates to become pedagogical tools in engineering studies (actually, some recent experiences are already available [14], [15], [16]).

Although visualization is a relevant pedagogical tool, other aspects, such as interactivity, are even more powerful. Interactivity can be defined as the action performed mutually by two or more objects that allows information exchange between each other [17]. Different from visualizing a figure or reading a book, interactivity implies a bidirectional information flow that improves the learning process of the involved agents. Interactivity in learning is a necessary and fundamental mechanism for knowledge acquisition and the development of both cognitive and physical skills [17].

In the past, teachers combined different transparent slides or used a compass or a *spirule*

[18], [19] to show how a figure was drawn from information and parameters. Although these techniques did not generate interactive figures, they were better than simple visualization.

When personal computers gained the capability to produce graphical output, it became possible to develop programs that could (re)generate graphical output in response to user input. Initially, user inputs were limited to menus or keyboard elements, but now the options for interactivity have increased a lot. Increase computational performance and additional types of input have allowed the development of amazing interactive environments that can be used in almost any pedagogical context.

The automatic control community has tried to employ interactivity and graphical representation in a learning-by-discovering paradigm [20]. In automatic control, there exist many concepts that are hard to grasp via analytic development but are quite easy to understand through graphical visualization or interactive manipulation.

The development of graphical and interactive applications might be a time-consuming task (notice that teachers are usually the ones who develop these applications) and requires high knowledge of programming languages and integrated development environments (IDEs). Fortunately, in recent times several IDEs, such as Sysquake [21] and Easy Java Simulations (EJS) [22], among others, have appeared, allowing to considerably reduce both the time and required programming capabilities to develop graphical and interactive applications. The use of these kinds of environments is convenient for professors interested in developing this type of material. Notice that Matlab (and other software used in automatic control courses) does not include the interactive behavior of Sysquake and requires the installation of the core software and corresponding licenses. That is, the user needs to have Matlab installed in his/her computer, while Sysquake-based programs

can be used as stand-alone applications.

The authors have been working for many years in the development of graphical and interactive applications as educational aids to learning several topics in the automatic control field [23]; see “ILM and ITSIE.” ILM and ITSIE provide good interactive experiences for users that are knowledgeable about control topics. However, in a basic course the programs have too many options for students to derive fundamental theoretical understanding by haphazardly ‘playing’ with the inputs. Thus, informed by years of experience and after working for some time with new ideas on interactivity [23], [24], it was decided to develop a set of simple and specific applications to support to basic concepts of classical control theory. Effort is focused on how to graphically visualize the main concepts and what kind of interactivity should be introduced in their representation. Additionally, a set of activities is designed to lead to the understanding of the concepts.

The core idea of this project is to develop a set of applications that serve to structure an introductory course on classical control theory. However, notice that the idea is not to force teachers or students to follow a whole course based on interactive tools. Since each tool is associated with a particular independent concept, it can be used separately or the tools can be grouped to combine several concepts based on their contents. In fact, the way in which the project was organized allows different audiences to use the developed *learning cards* (see next section). The tools are standalone applications that can run on PC, Mac, and Linux. The tools have been implemented in Sysquake, which is a Matlab-like language with fast execution and excellent facilities for interactive graphics [21].

For details of the use by beginner students and lecturers, see “Using Interactive Tools in a Control Course,” as an example of how the developed tools are being used to courses with

excellent academic results and relevant interest by the students. During the course, the tools are used in lectures as support to a traditional blackboard, and also as a self-study way for the students where exercises are provided and motivated based on the use of the interactive tools.

Using the tools in educational videos that can be part of distance learning courses or a MOOC [25] is currently under study. The following sections briefly describe the main ideas of the project and illustrate some of the developed applications.

Interactivity-based methodology

As mentioned, most engineering students take an introductory course on control, and in most engineering curricula this is a one-semester class. There is usually short time to obtain a deep knowledge in any material, and particularly in control. Introductory courses contain many new concepts to be learned, so teaching all these concepts is a challenging task for most teachers. The goal of this project is to provide tools for teachers and students to succeed in learning.

Interactivity and graphical visualization can contribute to shortcut the learning process and can help to make traditional lectures more attractive and interesting for students. Thus, according to the authors' experience, an interactive-based methodology is presented to prepare an introductory course on classical control designed from scratch. This new course design is focused on how to teach every concept more than on a full and detailed description of each concept. First, relevant concepts are identified, and then, how to visualize them and how to formulate *learning-by-example* problems around them are analyzed. After the analysis of a complete basic course, a set of computer applications is provided.

On the other hand, one of the secondary objectives of this project is to enhance the lifelong study and to promote individual student work. A set of interactive materials can contribute to this goal, so the applications have been designed trying also to achieve this aim. In this way, the key educational component of the project is called a *learning card*, which is composed of:

- A graphical and interactive application (almost self-explained) that visualize the concept(s). All elements are completely interactive to potentiate the interaction with it. The application contains predefined examples especially designed to illustrate some particular phenomena behind the concept(s) or particular cases.
- Each application is accompanied by a small dossier describing the concept(s) in a formal and analytical way. It is not the goal of the dossier to replace the textbook; as a consequence the theoretical concept is the minimum that allows understanding the application behavior. The dossier contains links to specific textbooks (indicating chapter and pages) so the students can improve their knowledge in the field.
- Although the application functionalities can be understood by playing with the application, the dossier contains a brief user manual that describes in detail all the application capabilities.
- The learning card contains different exercises to be performed using the application. The goal of these examples is to guide students' learning, avoid spending too much time, and force him/her to look at the important points. The exercises try to follow a *learning-by-discovery* paradigm and to combine *qualitative knowledge* obtained by interacting with the tools with *quantitative knowledge* obtained by solving selected exercises.

For details of how a learning card is used see “Material to understand the effect of adding a real zero in a second-order process” as an example.

As was previously mentioned, the way in which the project has been organized allows different audiences to use the learning cards. For *Beginner students*, where the learning cards can be used as a support by the teacher in lectures. The interactive tools can be used by the students to graphically understand concepts (relating interactively equations with their graphical representations) and even to check results of exercises. In the authors' experience, the provided interactive tools highly contribute to assimilating concepts faster than using classical methods (blackboard, sliders, or static simulations). For *Advanced students and professionals*. In this case, the learning cards can be used as a dictionary or collection of fundamental control concepts that can be consulted independently. Finally, for *Lecturers*. The short theory included in the learning cards can be used in basic courses in combination with the interactive tools to improve the learning process. Interactive tools can be used in two ways: at lectures to easily show the theoretical aspects, and to propose homework exercises. The use of interactive tools opens a wide range of possibilities from a teaching point of view, since many different kinds of situations and simulations can be easily tackled.

The course contents are designed based on those concepts needed for an introductory course on classical control techniques, especially those that can be easily displayed. Table I contains the list of applications grouped by topics. The applications can be grouped in the following sets: *From nonlinear physical model to linear models*, which is composed of an application that describes how to relate a nonlinear physical model with the corresponding linear model used in basic control techniques. Additionally, this application is used to describe the linear behavior concept around an operating point; *Time response*, which contains a set of applications intended to illustrate the time response of linear models. An application that shows how to fit time-based models to experimental data is also included; *Frequency response*, which includes a set of applications

developed to illustrate the frequency-response concept, how it is displayed, and the frequency response of linear models. Moreover, an application that shows how to fit frequency-based models to experimental data is included; *From physical model to model parameters*, which provides an example to illustrate the relationship of the physical system to some elements of models such as poles, zeros, time-response and frequency-response; *Closed-loop systems: Stability*, where fundamental stability analysis techniques are introduced in this group of applications; *Control system design*, where different controller design techniques are introduced in this group; and *Controlling physical systems*, where controllers for a physical system are analyzed with this group of learning cards.

An example of how these learning cards are used in a basic control course can be seen in “Using Interactive Tools in a Control Course”. The following section briefly describes several groups of interactive tools.

Teaching and learning concepts: examples

This section briefly summarizes several illustrative examples of the use of learning cards in the classroom. Notice that all the concepts, ideas, and graphics included in the tools are interactively interconnected. Thus, each modification on a parameter, curve, or diagram will show immediately the effect of that modification (concept) on the rest of the elements (concepts) of the tool. Sliders, textboxes, and direct dragging of pole and zero locations and relevant points of the time or frequency responses permits direct interaction. One consideration that must be kept in mind is that the tools’ main feature, interactivity, cannot be easily illustrated in a written text. Nevertheless, some of the advantages of the applications are shown below. Furthermore, demo version of the tools are

available at the project website [26].

Process dynamics

The understanding of concepts around linear process dynamics is the starting and key point of any introductory process control course. So, the first set of interactive tools is developed and focused on learning and understanding basic linear process dynamics in the time domain and frequency domain. Thirteen different tools have been created using Sysquake to study concepts such as first- and second-order dynamics, effects of adding zeros, high-order dynamics, dominance, nonminimum phase systems, frequency response concepts, or fitting models to experimental data. As an example, Figures 1 and 2 show two interactive tools of this set. Figure 1 shows an interactive tool to learn about second-order dynamics, where, among other options, geometric loci can be used interactively to understand the effect of damping factor, natural frequency, and imaginary and real parts of the poles. Different exercises to understand the effect of the characteristic parameters of these processes are provided together with the corresponding learning card. On the other hand, Figure 2 presents an interactive tool to understand the frequency response concept. Bode, Nyquist, and Nichols diagrams are plotted together with the time response and the information about the process transfer function that is being evaluated. Magnitude and phase concepts can be easily understood with this tool. In this case, exercises about the result of the response for several frequencies, the analysis of the results for different process dynamics (real poles, complex poles, zeros, and/or integrators), or the calculation of the crossover frequency and phase shift are suggested.

Stability and Control System Design

This set of tools deals with concepts related to stability, control system limitations, and control system design. Thus, the main techniques for stability analysis of linear systems in closed loop are introduced: root locus, Nyquist criterion, and phase and gain margins. Moreover, an interactive tool that illustrates the limitations imposed by a time delay in a feedback loop is included. On the other hand, the analysis of steady-state errors in unitary feedback systems and the main controller design techniques used in introductory courses (lead-lag compensators, and/or PID controllers) are presented both in the frequency and time domains. Figures 3, 4, and 5 show examples of interactive tools for gain and phase margins, time-delay limitations, and lead-lag compensator concepts, respectively. The interactive tool shown in Figure 3 is helpful for understanding the concepts of gain and phase margins, as well as gain and phase crossover frequencies and bandwidth. The learning card associated to the tool shown in Figure 3 includes exercises where the user has to interactively modify the controller gain in the interactive tool and to observe how those metrics are modified and the system stability is affected. On the other hand, it is well known that time delays have a negative influence on closed-loop systems. Hence, Figure 4 presents an interactive tool focused on understanding the closed-loop system limitations because of time delays. The tool includes a system with and without time delay, in such a way that the limitations on the delayed systems can be interactively compared with the free-delay case. For this purpose, time domain and Nyquist diagram representations are provided and gain and phase margins are calculated and shown continuously. Finally, as a third example of this group of tools, Figure 5 shows an interactive tool to understand lead-lag controllers. This tool is just to learn about lead, lag, and lead-lag controllers, their differences, and their advantages and disadvantages. It is really useful to ask

students interacting with the tools and looking for the contribution of a lead-lag compensator to low or high frequencies. With this tool, it is really straightforward to understand the differences among lead, lag, and lead-lag compensators, and afterwards there are other five complementary tools to design these controllers in the frequency domain and based on the root locus method. Moreover, four interactive tools are also provided to understand PID controllers and classical PID control design methods (Ziegler-Nichols, pole placement, and pole cancellation). Finally, as supplementary material, an additional interactive tool about basic ideas on state-space representation is introduced. This tool aims to provide a first contact with the concepts underlying the use of internal description, which would be subject of a full text. In fact, the application focuses on second-order systems to facilitate the visualization of these concepts.

Guide example

In addition to the different groups of interactive tools described above, a tank system is used through the class as a case study. So, a new group composed of three different interactive tools is available to facilitate the learning of concepts related to linearization and control of nonlinear systems (from nonlinear physical models to linear models, from physical model to model parameters, controlling physical systems) using the tank system as example. In these applications, a tank with liquid that discharges to the atmosphere is provided to describe how to relate a nonlinear physical model with a linear model used in basic control techniques. Additionally, this example is used to describe the concept of linear behavior around an operating or equilibrium point (see Figure 6). The concept of transfer functions and the relationship between physical models and the main elements of the models used in controllers design (such as poles, zeros, and time response) are also illustrated with these tools. Finally, controller design and simulation of closed-loop systems

concepts are also evaluated for the example of a tank with discharge to the atmosphere (see Figure 7).

Conclusions

After more than 10 years of experience in the use of interactive tools and interactive material in teaching activities, the authors of this article present a new methodology on how interactive tools combined with suitable educational material can be used to support control education. The key point of this project is a set of *learning cards* that combine interactive software applications, a short theoretical description about the different concepts to learn/teach, a new kind of exercises to motivate students by a learning-by-discovery paradigm, and references to well-known books.

This methodology and this new educational material is a powerful tool to transmit theoretical abstract concepts that are quite common in control theory. The resulting material is open for different user levels, in such a way that it can be used by beginner students, advanced students or professionals, and/or lectures. An example of how this methodology has been used in a basic control course in the University of Almería has been summarized, where a positive feedback was obtained from students and lecturers. Based on this experience, a book is being developed that will include the tools.

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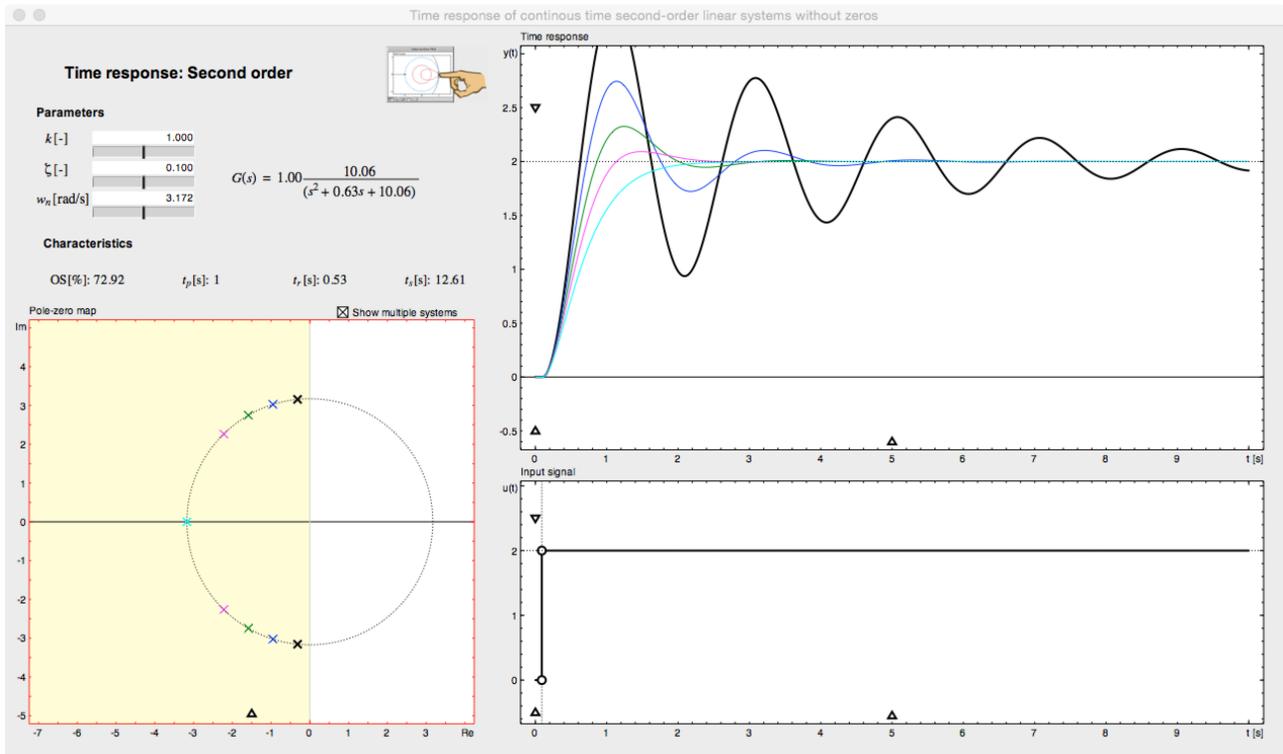
Competitiveness and EU-ERDF funds). The authors would like to thank Yves Piguet for his continuous support and effort in improving Sysquake.

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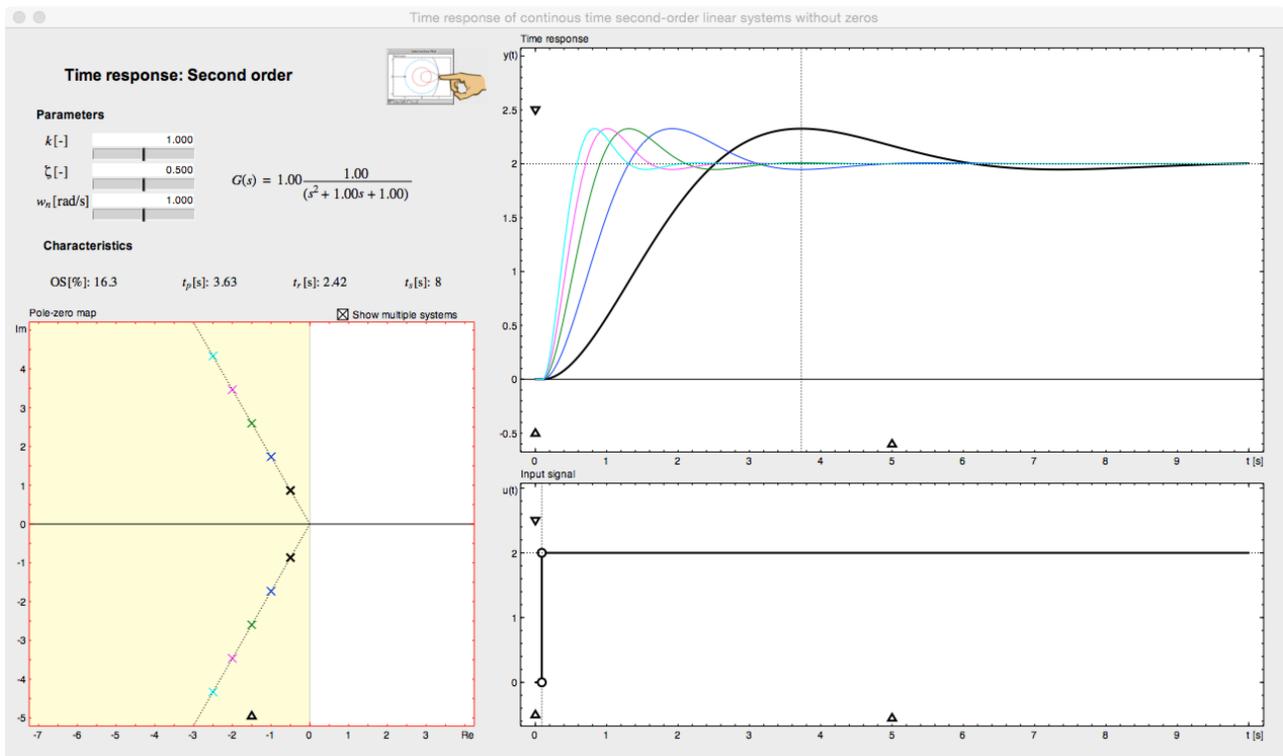
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(a) Analysis on the effect of the relative damping factor



(b) Effect of the natural frequency

Figure 1. Interactive tool to understand second-order dynamics. The tool includes display areas about the process transfer function, pole-zero map, process output, and input signal, which are interactively interconnected by including values in textboxes or changing them using sliders, dragging on poles and zeros on the pole-zero map representation, modifying time and amplitude of step input signal, or moving the overshoot or peak time directly in the time response.

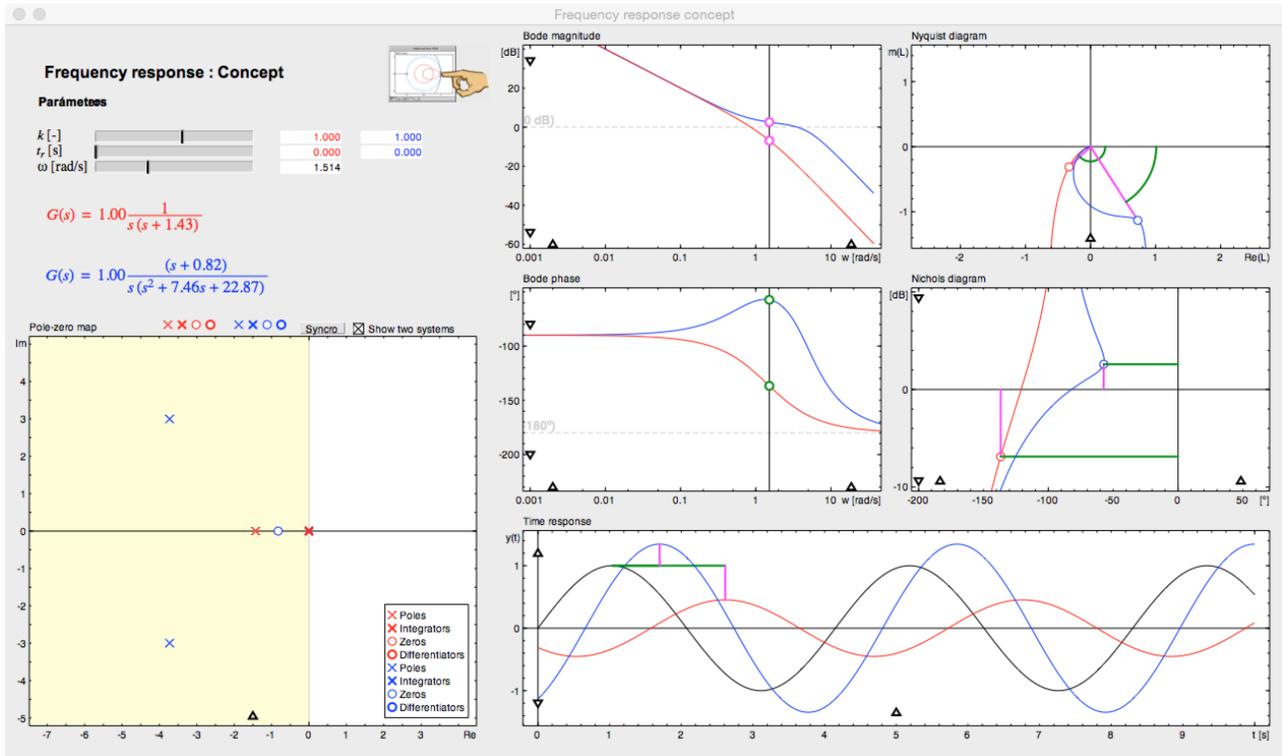


Figure 2. Interactive tool to understand the frequency response concept, involving: concept of frequency response (graphic at the bottom), logarithmic scales, decibels (dB) and decades, graphical representations such as Bode plots, Nyquist and Nichols, relationship with the pole-zero representation and parameters of the transfer function, low pass filters, cutoff frequency and bandwidth, minimum phase and nonminimum phase systems, and influence of time delay. Moreover, the user can change the frequency or magnitude of the input signal in time domain and observe its effect and representation in the different frequency diagrams. A pole-zero map editor can be used to configure the system transfer function to be studied. In the graph there is a legend stating that the poles are drawn using the symbol \times , the integrators with the same symbol, a bold \times , the zeros are drawn using the symbol \circ , and the differentiators use the same symbol, a bold \circ . The system configuration can be defined by interacting with the elements placed in the repository (\times , \times , \circ , \circ) next to the figure title Pole-zero map. When these elements are placed over the real axis they correspond to a real pole or zero, alternatively, if they are placed in other locations, they are assumed to be imaginary poles or zeros. Dragging an integrator or a differentiator onto any area of the graph, automatically located it at the origin ($s = 0$). The elements can be removed from the system by dragging the element towards the repository.

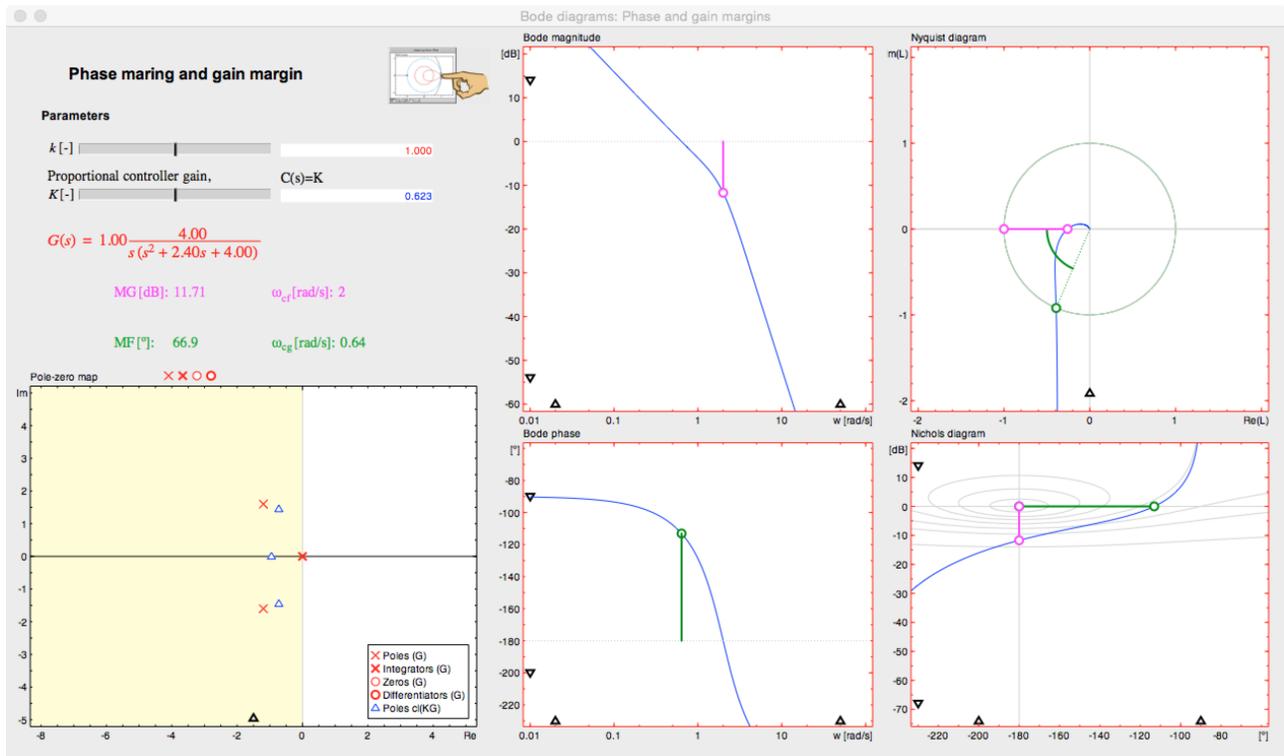


Figure 3. Interactive tool to learn about phase and gain margins and corresponding crossover frequencies. Margins are simultaneously represented in Bode, Nyquist, and Nichols diagrams, being also possible to select step responses. Twelve predefined examples are included in the tool plus the possibility of including a generic one.

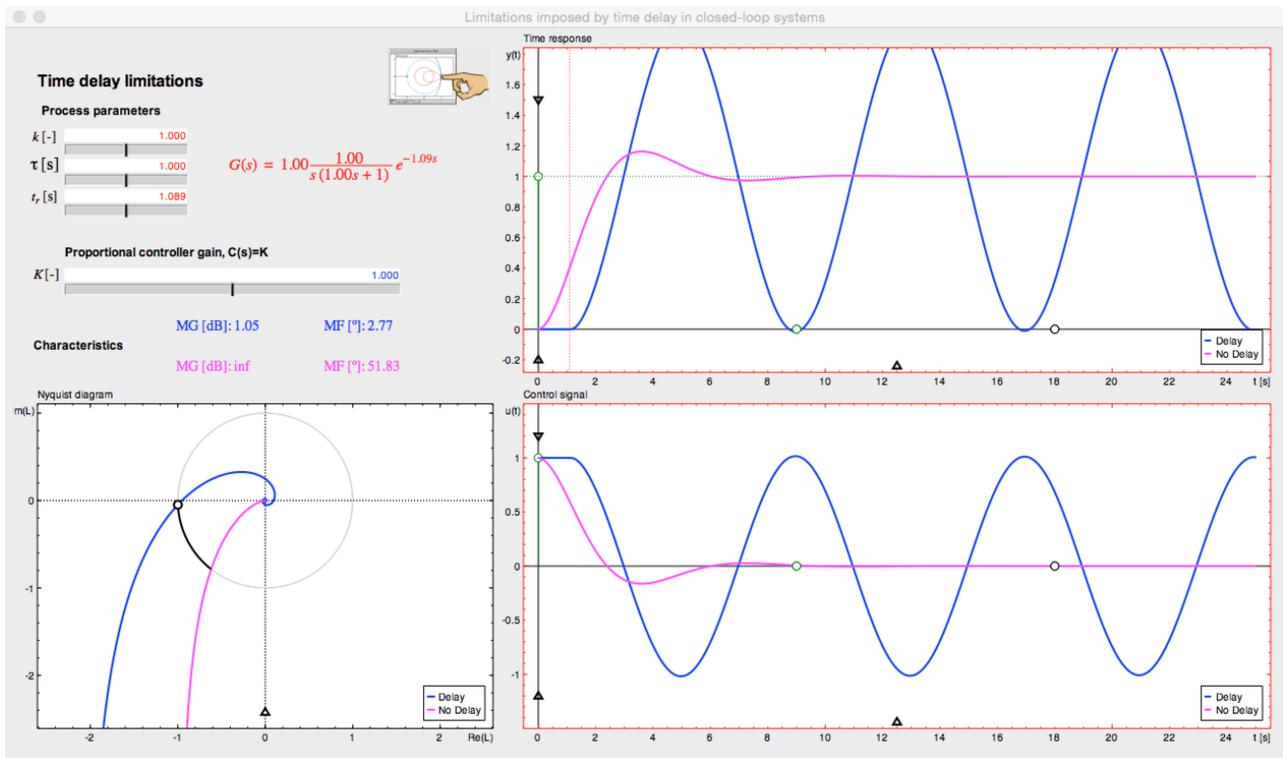


Figure 4. Interactive tool to understand time delay limitations, helping to analyze the effect of time delay in closed-loop performance and stability using the Nyquist diagram as frequency response representation.

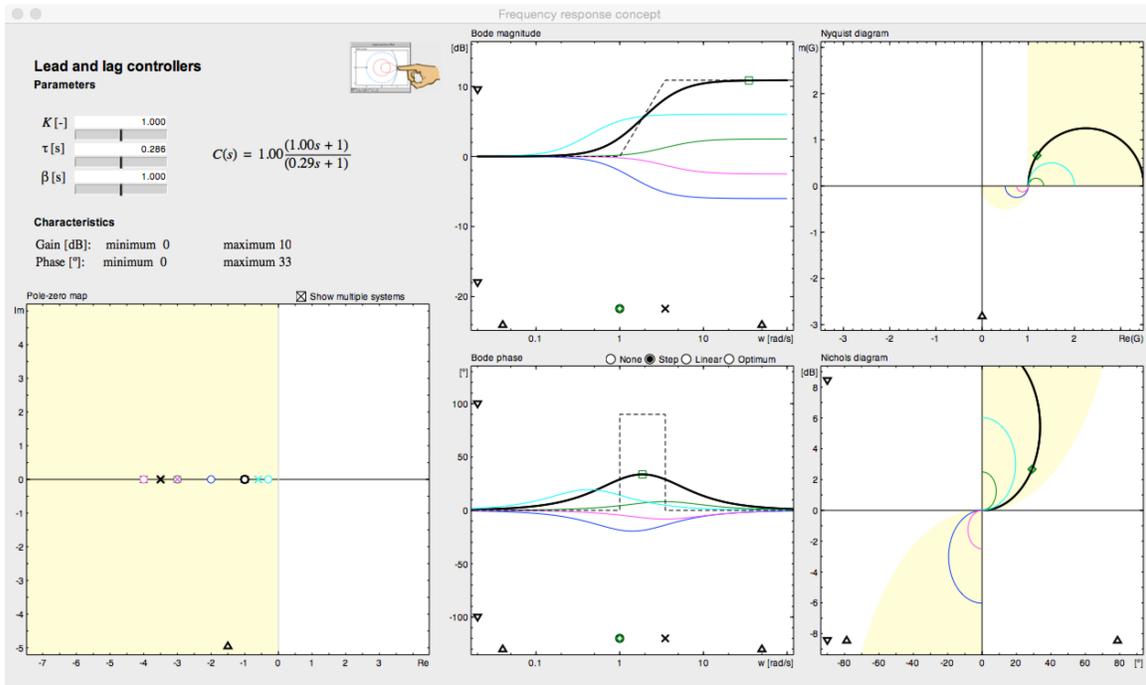


Figure 5. Interactive tool to study lead-lag controller related concepts and its effect in the frequency-response of the compensated system. Bode, Nyquist, and Nichols diagrams are used to represent the controller characteristics. Asymptotic representations of the system are provided in the Bode plots, and Nichols and Nyquist diagrams include shading areas to show the geometric loci where there exist lead-lag networks for the positive interval of their parameters. The tool permits analyzing up to five different controller configurations (pole-zero locations) at the same time.

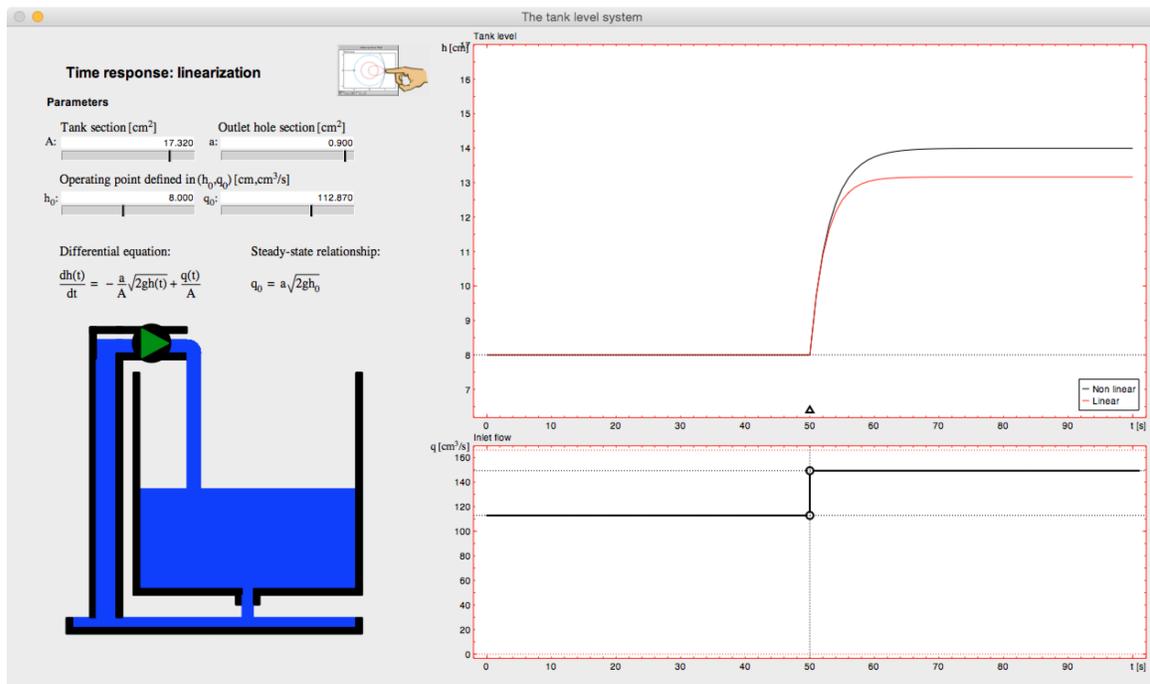


Figure 6. From nonlinear physical models to linear models. An example of a tank process is used to help students understanding how to obtain system models from mass balances, linearization of nonlinear models, definition of operating point, and effect of parameters of the physical system in dynamic response.

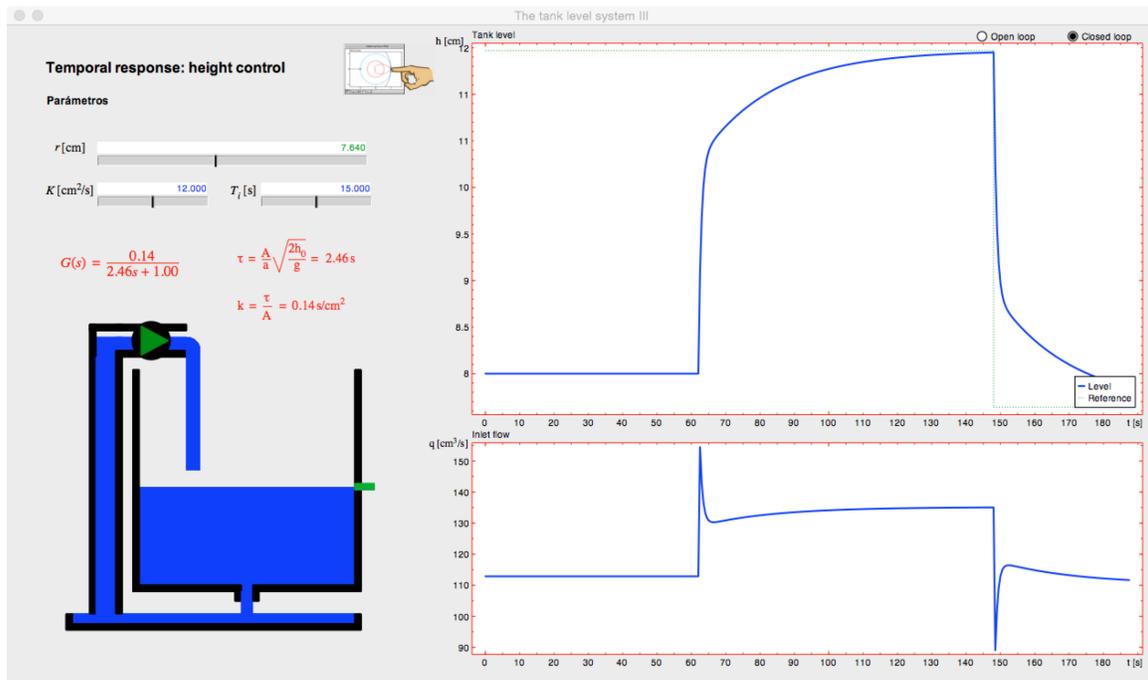


Figure 7. Level tank control as an example of controlling physical systems. The students can tune PI controllers based on the response of the system around an operating point and analyze the effect of changing the operating point on the closed-loop response.

TABLE I
List of interactive tools contained in the learning cards

1 From nonlinear physical model to linear models

1.1 The tank system.

2 Time response

2.1 First-order system without zeros.

2.2 Second-order systems without zeros.

2.3 The effect of zeros in first- and second-order systems.

2.4 Time response in generic systems.

2.5 Time response dominance.

2.6 Fitting models to experimental data in the time domain.

3 Frequency response

3.1 Concept of frequency response.

3.2 First-order system without zeros.

3.3 Second-order systems without zeros.

3.4 The effect of zeros in first- and second-order systems on the frequency response.

3.5 Frequency response in generic systems.

3.6 Frequency response for nonminimum-phase systems.

3.7 Fitting models to experimental data in the frequency domain.

4 From physical model to model parameters

4.1 The tank system II.

5 Closed-loop systems: Stability

5.1 Root-Locus diagram.

5.2 Nyquist criteria.

5.3 Bode criteria. Gain and phase margin.

5.4 Time-delay limitations on closed-loop systems.

6 Control system design

6.1 Steady-state errors for closed-loop systems.

6.2 Lead-lag controller concept.

6.3 PID controller concept.

6.4 Lead-lag controller in the frequency domain.

6.5 Lead-lag controller in the root locus.

6.6 PID design by pole placement.

6.7 PID design by pole-zero cancellation.

6.8 PID design by open-loop Ziegler-Nichols rules.

7 Controlling physical systems

7.1 The tank system III.

8 Introduction to control in state space

8.1 State-space basic concepts.

Sidebar 1: ILM and ITSIE

The Interactive Learning Modules (ILM) project [S2] is a set of interactive tools developed to support the well-known book *Advanced PID Control* by K. J. Åström and T. Hägglund [S1]. These tools are intended mainly to include interactivity in the visual content of *Advanced PID Control*. The modules focus on PID control, studying feedback fundamentals from the standpoint of the time and frequency domains, including robustness issues, filtering measurement noise, load-disturbance rejection, windup phenomenon, feedforward design, and so on. Furthermore, motivating exercises have been developed to support theoretical ideas presented in *Advanced PID Control*. The user is invited to use the interactive tools to find solutions and combine them with the analytical analysis. Some examples can be found in [S2].

ITSIE is an Interactive Tool for System Identification Education [S3]. The tool supports the open-loop identification using classical prediction-error methods of 1) a SISO fifth-order system and 2) a fluidized-bed calciner example characterized by a quasi-rational distributed system, both systems subject to multiple noise sources. The ability to evaluate externally-provided datasets is available in the interactive tool as well. The various stages of system identification, ranging from input signal design using pseudo-random binary sequence (PRBS) and multisine signals through model validation, are evaluated simultaneously and interactively in one screen. The highly visual and strongly coupled nature of system identification is amenable to interactive tools, and the tool enables students to discover a myriad of important identification topics with a much lower learning curve than existing methods. Plans for additional tools in the series are considered.

These applications have been downloaded thousands of times (more than 15,000 downloads)

and from the received feedback both from lecturers and students, they found them really useful for their teaching/learning process.

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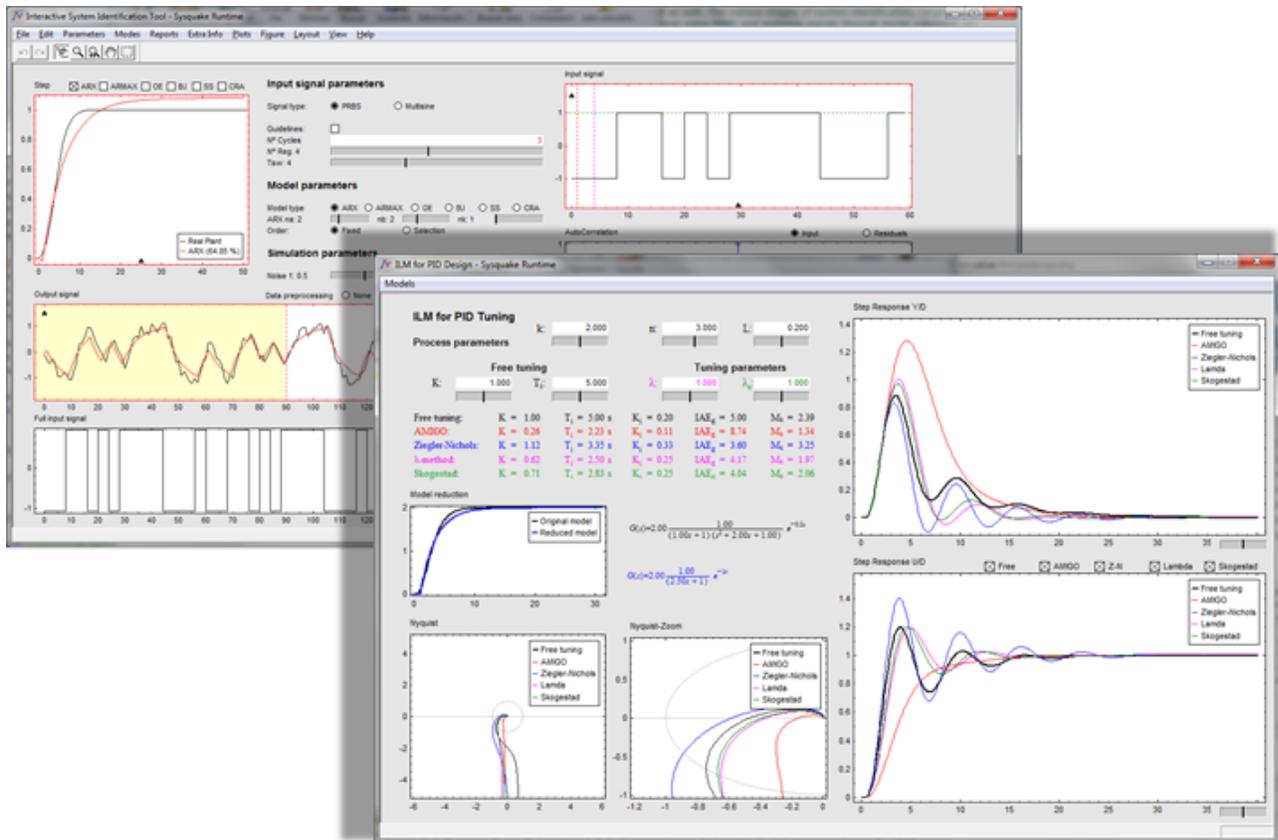


Figure S1. ILM and ITSIE interactive tools. ILM and ITSIE have been implemented in Sysquake from Calerga [S4]. The main reasons for choosing Sysquake was its power to develop interactive graphical tools and the possibility to generate executable files that can run independently and be distributed without any licences. Hence, the modules are available for Windows, Mac, and Linux operating systems and can be freely downloaded.

Sidebar 2: Using Interactive Tools in a Control Course

From 2012, the tools have been used to support a basic continuous-time automatic control course at the University of Almería (Spain). The course is taken in first semester of the third year of the Industrial Electronics Engineering program. It has 9 credits with a total of 225 hours (lectures: 38.5 hours, laboratory sessions: 29 hours, independent work of students: 157.5 hours). It addresses the fundamental theory of continuous-time dynamical systems. The goals and results of learning are: (1) To understand the concept of dynamic systems, being able to model and simulate its behavior, (2) To acquire the ability to analyze the time and frequency response of a dynamical system, both in terms of stability and performance, (3) To acquire the ability to analyze and design feedback control systems. The skills gathered when passing the course are:

- Generic: Ability to solve problems, skills in the use of Information and Communication Technologies (ICT).
- Specific: Knowledge and competence for modeling and simulation, knowledge of automatic regulation, control techniques and their application in industrial automation, capability to design control systems.

The students accessing the course have previously completed an introductory course of *industrial automation*, where basic concepts related to automation, PLC programming, and industrial robotics are covered, providing some introductory aspects of dynamical systems and feedback. After the course described in this section, students take four more courses related to automatic control: *Computer-controlled Systems*, *Industrial Control Techniques*, *Industrial Informatics*, and *Robotics*.

The course is supported by a learning management system (LMS). Specifically, Blackboard Inc is used. In this LMS, all the information of the subject is available to students: syllabus, calendar, readings, lecture notes, laboratory and exercises assignments, exams, and course materials (including interactive tools). Lab sessions are developed using a typical DC motor kit in groups of two students.

Learning cards including interactive tools help introducing and understanding underlying concepts and solving interactivity-based exercises. Exercises are also proposed in each theory module. Both lab sessions and exercises are based on the use of the developed interactive tools and MATLAB environment. The contents of the course, number of hours, and their relationship with the interactive tools (IT) are the following:

Module 1. Analysis of dynamic systems in open loop

Topic 1. Fundamentals of dynamic systems [5.5 h].

Topic 2. Systems representation [5 h] - IT 2.4, 8.1.

Topic 3. Modeling and simulation [5 h] - IT 1, 4.

Topic 4. Continuous time linear dynamic systems [10 h] - IT 2, 3.

Module 2. Closed-loop control systems design

Topic 5. Analysis of feedback systems [5 h] - IT 5.

Topic 6. Control design [8 h] - IT 6.

The bibliography recommended to students comprises classical books like [S5], [S6], [S7], [S8], [S9], [S10] and learning cards (as presented in this paper) supplied by the teachers where main theory is summarized and the graphical interpretation is done using interactive tools facilitating the

understanding of underlying theory and proposing exercises to be developed using the tools.

The evaluation of the subject and skills is done based on: 60% theory exam, 15% exercises (done using interactive tools) reports, 20% laboratory sessions reports (also done with the help of interactive tools) and practical (hands on) exam, 5% active participation in class.

Each year a survey of students is performed (about 30 responses are obtained), where the students are asked about several aspects related to the development of the subject, among which the use of interactive tools to support student learning is included. Table II provides figures of merit for some of the questions.

TABLE II

Table S1. Mean values (of 57 answers) for the most-relevant questions covering the survey filled by the students, where the use of interactive tools is highlighted. The scale used ranges between 0 (strongly disagree) and 5 (strongly agree). From the surveys and the authors' experience, it can be concluded that the method used to conduct the lectures been well received by students.

Learning outcomes: theory + LMS + interactive tools	Mean [0-5]
1. The method (slides + blackboard + interactive tools) was successful	4.40
2. Materials placed on the LMS are enough for learning	4.47
3. Teachers are committed to the results of our learning	4.80
4. I can easily follow the schedule of the classes	3.73
5. Overall I am satisfied with the lectures	4.20
Learning outcomes: solving exercises with support of interactive tools	
1. Ease of use of the interactive tools	4.07
2. Layout of interactive objects in the tools	4.00
3. Easiness to understand the involved concepts	4.13
4. I learned more in comparison with "traditional methods"	4.20
5. I learned faster than with "traditional methods"	4.13
6. Overall usefulness as complement to lectures	4.47
7. Overall usefulness as complement to MATLAB	4.20
8. Overall I am satisfied with doing exercises using interactive tools	4.33
Learning outcomes related to lab sessions	
1. Simulation helps understanding the goal of laboratory sessions	3.87
2. Engineering practice using real equipment is better than simulation	4.20
3. Lab sessions helps consolidating theory	4.13
4. Overall I am satisfied with lab sessions	4.07

References

- [S5] K. J. Åström, R. M. Murray. *Feedback systems: an introduction for scientists and engineers*. Princeton University Press, 2nd edition, 2014.
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- [S9] F. Golnaraghi, B. C. Kuo, *Automatic control systems*, 9th edition, Wiley, 2010.
- [S10] K. Ogata. *Modern control engineering*, 5th edition, Pearson, 2010.

Sidebar 3: Material to understand the effect of adding a real zero in a second-order process

Short theoretical description of the concept and references to well-known textbooks

Interactive tool: [2.4. t_second_order_zero](#)

Concepts analyzed in the card

- Effect of a zero in the time response to a step input of a linear time-invariant second-order system. Effect of a right-half s -plane zero.

Theory

The main objective of this card is to analyze and understand the influence exerted by the presence of a zero on the step response of a second-order system. The generic transfer function of a second-order system is given by

$$G_2(s) = \frac{Y_2(s)}{U(s)} = \frac{k\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \quad (S1)$$

where k is the *static gain* or canonical gain of the system, ζ is the *relative damping factor* of the system, and ω_n is the *natural undamped frequency* (explained in previous sections).

When considering in the above transfer function (S1) the presence of a zero with related time constant β (and therefore located in the complex plane in $s = -1/\beta$), the following transfer

function is obtained

$$G(s) = \frac{Y(s)}{U(s)} = \frac{k\omega_n^2(\beta s + 1)}{s^2 + 2\zeta\omega_n s + \omega_n^2}. \quad (\text{S2})$$

Analyzing this new transfer function $G(s)$ it can be separated into two terms based on the transfer function of the system without the zero, $G_2(s)$

$$G(s) = G_2(s)(1 + \beta s) = G_2(s) + \beta s G_2(s) = \frac{k\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} + \beta s \frac{k\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}. \quad (\text{S3})$$

Considering that the time response when the input signal is a step of amplitude U_e for the system represented by $G_2(s)$, the step response of the system described by $G(s)$ can be obtained from $Y_2(s) = G_2(s)U(s)$ as follows

$$Y(s) = G(s) \frac{U_e}{s} = \left(G_2(s) + \beta s G_2(s) \right) \frac{U_e}{s} = G_2(s) \frac{U_e}{s} + \beta s G_2(s) \frac{U_e}{s} = Y_2(s) + \beta s Y_2(s), \quad (\text{S4})$$

$Y_2(s)$ being the Laplace transform of $y_2(t)$, which is the step response of the system without the zero, represented by equation (S1). Applying the inverse Laplace transform and taking into account that $y_2(0) = 0$

$$y(t) = y_2(t) + \beta \frac{dy_2(t)}{dt}. \quad (\text{S5})$$

That is, based on the result obtained in (S5), it can be interpreted that the influence of a zero in the time response of a second-order system is given by the original time response plus the time derivative of that response weighted by a constant β when the input signal is a step.

If the system is overdamped, the representation of the transfer function of the second-order system with a zero is

$$G(s) = \frac{k(\beta s + 1)}{(\tau_1 s + 1)(\tau_2 s + 1)}, \quad (\text{S6})$$

where τ_1 and τ_2 are the time constants associated with the real poles (explained in previous sections). In this case, the response is affected by the relative position of the zero with respect to the two real poles. It should be remembered that when a zero is located near a pole, the effect of the two elements in the response is largely cancelled. If $\tau_1 \neq \beta$, $\tau_2 \neq \beta$ and $\tau_2 > \tau_1 > 0$, the response to a step input can be obtained

$$y(t) = kU_e \left(1 - \frac{\tau_2 - \beta}{\tau_2 - \tau_1} e^{-\frac{t}{\tau_2}} + \frac{\tau_1 - \beta}{\tau_2 - \tau_1} e^{-\frac{t}{\tau_1}} \right), \quad t \geq 0. \quad (\text{S7})$$

Both in the underdamped and the overdamped cases, the derivative of the output is not zero at $t = 0$, a fact that does occur in second-order systems without zeros. The responses influenced by the presence of a zero are classified into two types according to the sign of the zero. When $\beta > 0$, the zero is in the left-half s -plane and the response is known as *minimum phase*, where the time response is affected in the form of an increase in the response speed and in the overshoot. On the other hand, when $\beta < 0$, the zero is located on the right-half s -plane, and the response is known as *nonminimum phase*, where now the term that accompanies the derivative $dy_2(t)/dt$ in (S5) is subtracted from the time response $y_2(t)$, causing an *inverse response* to the original direction of the system response during a given period of time. In [S8] the following cases are distinguished:

- 1) $\beta < 0$: The system has an *inverse response*, which is more pronounced the closer the zero $-1/\beta$ is to the origin of the complex plane.
- 2) $\beta > \tau_2 > \tau_1$: The response presents an *overshoot* even more pronounced the closer the negative zero is to the origin with respect to the location of the poles.
- 3) $\beta \approx \tau_2 \gg \tau_1$: In this case, the output evolution can be approximated by $y(t) \approx k(1 - \exp(-t/\tau_1))$, $t \geq 0$ and the system can be treated like a first-order one, although due to the

pole-zero pair proximity, a transient behavior of small magnitude is generated, producing a slow drift of the output to the steady-state value.

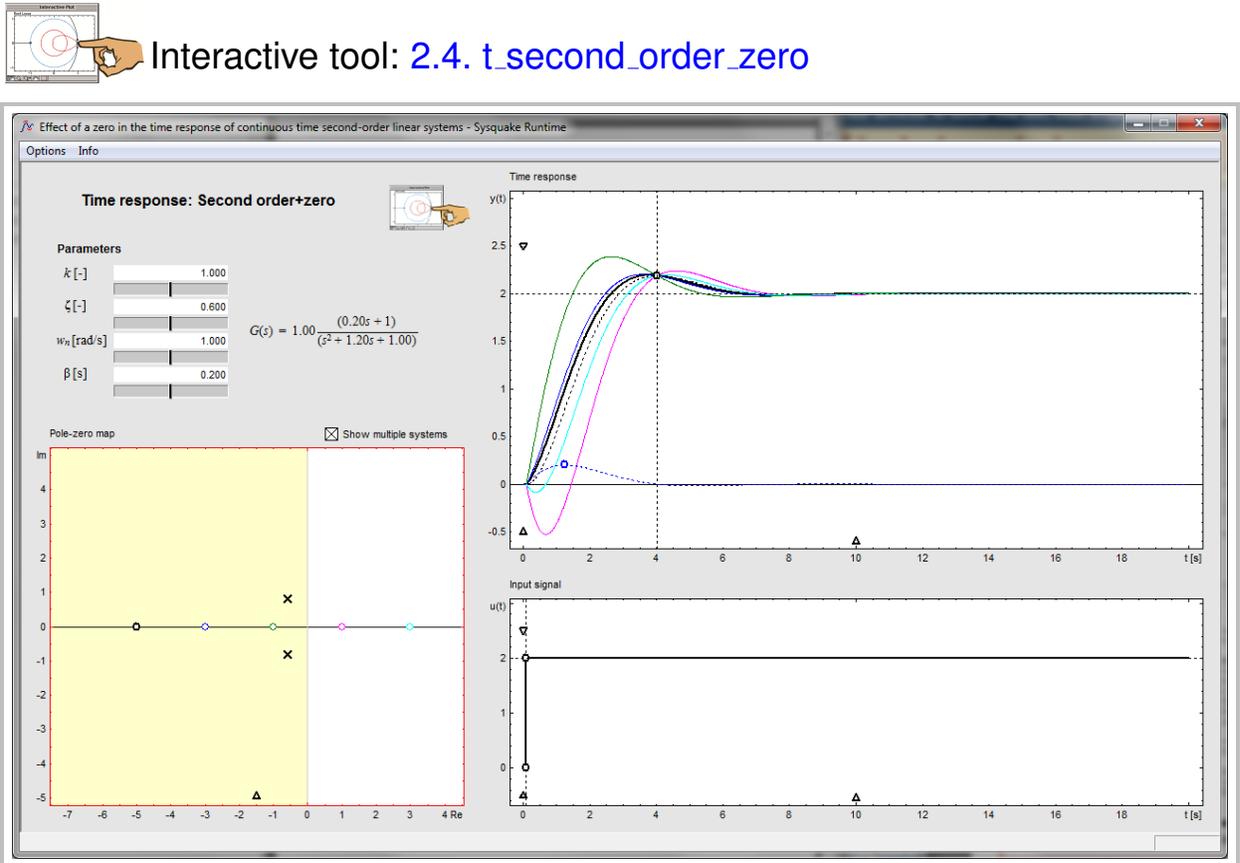
- 4) $\tau_2 > \beta > \tau_1$: The presence of the zero tends to speed the response when compared to the case without zero. If the zero is near the pole furthest from the origin, the response increasingly approaches that of a first-order system with a time constant τ_2 . In this case, there is not a slow drift of the output towards the steady-state value because the negligible dynamics vanishes quickly.
- 5) $\tau_2 > \tau_1 > \beta$: When moving the zero away from the origin of the complex plane (and from the poles), the response tends to be that of a second-order system with the same poles but without zero.

References

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Example of Interactive tool description

Application



Time response: Second order + zero

The main objective of this tool consists of studying and analyzing the effect of a zero on the time response of a continuous second-order system in an interactive way.

The left part of the tool is dedicated to display the **Parameters** that define the transfer function of the system, for the underdamped (k , ζ , ω_n , and β) and for the overdamped (k , τ_1 , τ_2 , and β) cases. The values of these parameters can be modified numerically by using the text boxes or the sliders appearing in this area. These values are also affected by the modification of the poles and/or zero locations from the Pole-zero map graphic. Moreover, the **Parameters** section includes a symbolic representation of the system transfer function (according to the nomenclature used in equation (S2)), whose coefficients are updated after any change produced in the tool.

The tool loads only one second-order system with zero by default. However, it is possible to load several systems by using the Show multiple system option. In this case, five systems with different zeros and with the same poles are represented.

The zeros are represented by circles of different colors (the active system being represented by **black**, \circ), while the two poles are represented using the symbol \times . The tool includes two conjugated poles by default, but these poles can be changed to be real poles moving their location to the abscissas axis.

... continue ...

Proposed learning-by-example exercises

Exercises (only a few are displayed)

- 1) Study and describe the difference observed in the time response when the system zero is positive or negative, that is, when the zero is in the right-half s -plane or in the left-half s -plane, respectively. Use the Show multiple systems option for a better analysis of the results.
- 2) Enter an example in the tool using a value of the time constant associated with the zero equal to $\beta = 0.1$ s. Interactively modify its value increasing it to $\beta = 4$ s and after decreasing its value to $\beta = 0.1$ s. What effect can be observed in the time response of the system? How do these changes affect the time response of **blue** represented by a dashed line?
- 3) Enter an example in the tool with $\beta = -0.2$ s. Interactively decrease its value to $\beta = -1$ s and then increase it to $\beta = -0.2$ s. What effect can be observed in the time response of the system? How do these changes affect the time response of **blue** represented by a dashed line?
- 4) For the configuration of poles and zeros that appears by default when starting the tool, analyze (in relation to the real part of the poles of the system given by $\sigma = -\zeta\omega_n$) from which value of β the effect of the zero is not appreciable. Perform this analysis for different configurations of poles and zeros.
- 5) Using the configuration of poles and zeros that appears by default when starting the tool, indicate what value of β makes the overshoot twice that of the original system without the zero? Is the peak time affected? Justify the answer. Perform this analysis for different configurations of poles and zeros.
- 6) Using the pole-zero configuration loaded by default and only changing the value of $\beta = 1$, justify what condition defines the point in which there is an intersection between the original

system response without the zero (dashed line) and that of the system including the zero (thick solid line) for the first time. Justify the answer.

- 7) In the case of inverse response (nonminimum phase systems), justify in the underdamped case if it is possible to obtain an overshoot greater than that of the original system without a zero. If so, does the maximum overshoot take place at a peak time greater or less than that of the original system?
- 8) For a configuration with two real poles (corresponding to $\tau_1 = 0.5$ s and $\tau_2 = 1$ s), find the value of β from which the response is similar to that of the original system without a zero. Modify the location of the poles and perform the analysis again. Justify the obtained results.
- 9) For a configuration with two real poles (corresponding to $\tau_1 = 0.5$ s and $\tau_2 = 1$ s), comment on the response obtained when $\beta = 0.5$ s and when $\beta = 1$ s. Justify the answer.
- 10) Check the analysis performed in the summary of theory with equation (S7) with the interactive tool. Take adequate values of β , τ_1 , and τ_2 that allows the analysis of the time response obtained in the five cases considered in terms of the relative position of the poles and the zero:

- a) $\beta < 0$: $\beta = -1$ s.
- b) $\beta > \tau_2 > \tau_1$: $\beta = 3$ s, $\tau_2 = 2$ s, $\tau_1 = 1$ s.
- c) $\beta \approx \tau_2 \gg \tau_1$: $\beta = 2$ s, $\tau_2 = 1$ s, $\tau_1 = 0.1$ s.
- d) $\tau_2 > \beta > \tau_1$: $\tau_2 = 10$ s, $\beta = 5$ s, $\tau_1 = 1$ s.
- e) $\tau_2 > \tau_1 > \beta$: $\tau_2 = 10$ s, $\tau_1 = 5$ s, $\beta = 1$ s.

Verify that the comments made in the summary of theory are true.

- 11) Using the default configuration when starting the tool, calculate the value of β that produces:
 - a) An overshoot of 50 %.

- b) A peak time of 2 s.
- c) An inverse response whose maximum absolute value coincides with the maximum of the direct response.

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