

Early Introduction of Robust Control Concepts: Hands-On Experience and CAD

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Abstract—This paper presents an educational experience in an initial course in feedback control. The purpose is to introduce the concepts of robust design not included in the regular curriculum. The problem of designing a controller for a simple mechanical system without knowing the true value of the parameters is proposed in a laboratory class. The task is performed on the real system with the aid of Computer-Aided Design freeware. The combination of practice and software tools encourages the development of autonomous learning and favours the apprehension of the concepts of uncertainty and robustness. A perception survey shows promising results indicating that the strategy of learning by doing is very well accepted by the students.

Index Terms—Action learning, computer aided instruction, control engineering education, freeware tools, QFT.

I. INTRODUCTION

MOST of the control systems design techniques require a plant model during the tuning stage of the controller parameters. While it is known that mathematical models are only an approximation of real systems, fixed structure models with known parameters values are considered in the first control courses. Modeling errors are not taken into account under the assumption that the model can be accurately determined and that feedback reduces the sensitivity to possible parameters variations.

In an initial degree course, addressing the problems associated with uncertainty in the parameters, stabilization and robust tracking are hampered by the complexity of the mathematical treatment involved. These courses cover the classical content in analysis and design of controllers in both time and frequency domains for single-input and single-output (SISO) linear systems modeled by transfer functions.

If the concept of robustness is to be treated, then it is presented superficially by considering stability margins

and sensitivity. Similarly, if the latest bibliography on classical control is analyzed, only a few authors introduce robust design and if so, they do it in a rather intuitive way. This reflects the difficulty of finding a balance among the time required to introduce the formal framework of robust control, conceptual clarity and practical applicability in the context of these subjects. The result is that the issue is left to be dealt with in specific courses, usually of optional or even graduated character. For the student, the idea that obtaining a well-defined model is not only possible but sufficient for the control purposes is misleadingly rooted.

This paper presents a didactic experience that aims to introduce the concept of uncertainty in general, as a way to include inaccuracy in the system model, and also offers tools to address the corresponding control design. By taking into account uncertainties, the controller performance complies with the specifications, even in the presence of imperfections, modeling errors and possible disturbances.

The experience is designed so that the parametric uncertainty arises naturally in a practical laboratory activity when different groups of students identify a simple system and compare their results.

The situation enables a discussion on the reasons and consequences of the clear disparity in the obtained results, the way of looking at this fact in the model, the effects on the design of a PID controller and the limitations of classic methodologies to address the problem.

An alternative approach is to use a freely distributed CAD tool, ISOQFTIT [5], which implements the quantitative feedback theory methodology, QFT, leading to the design of a “robust” controller and allowing the comparisons with a classic design.

Without going deeply into the associated theory, it is intended that from an experimental and natural point of view students become aware of the real issues involved in the processes of modeling, identification and control and that there are accessible approaches to address them.

The proposal is implemented in the first theoretical course in the area of feedback control systems, Fundamentals of Feedback Control, belonging to the fourth year (the penultimate) of the Electronic Engineering career at the Universidad Nacional del Sur. During and after the experience, a simple survey allows verifying the fulfillment of the proposed objectives on the topic according to the perception of the students.

In section II, the basics of QFT are presented along with a brief description of the CAD tool adopted SISO-QFTIT. Section III describes the experiment, the model identification,

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the motivation for introducing QFT, the specifications and a typical design result. Section IV details the results of the experiment and finally in Section V, conclusions are elaborated.

II. CONTEXT AND GENERAL CONCEPTS

A. Application Context

The experience takes place in the course of Fundamentals of Feedback Control (FFC), taught in the first term of the fourth year in a five-year curriculum corresponding to Electronic Engineering at Universidad Nacional del Sur. This career is accredited by the National Commission of Evaluation and Accreditation of the Argentine Education Ministry. When students attend FFC, they have already accumulated 640 hours of mathematics including Complex Variable Theory, 384 hours of Physics, 128 hours of Methods and Numerical Simulation in Electrical Engineering. Also, they have 128 hours of Circuits and Systems theory attended at third year, where they acquired skills in time and frequency characterization and analysis of linear systems including Bode plots.

The FFC course has a total workload of 128 hours, considering 4 hours of theory and 4 hours of practice per week including problems and laboratories. The course core addresses three major issues in the automatic control discipline: development of dynamic models, evaluation and analysis of the dynamic behavior of linear systems with open loop and with feedback, and evaluation and analysis of behavior of these systems in the complex plane and frequency response methods. Each of these laboratories has particular thematic blocks, conforming a total of five experiences of two hours each.

The experience described in section III is performed during the third block, where they have already covered contents in modeling and temporal behavior and is contemporary with the presentation of frequency methods. Students have the usual problem solving practice and perform this comprehensive laboratory that includes modeling and identification, analysis of time and frequency behavior, controller design and performance analysis of the entire system. The work is done in two stages of 4 hours each, 2 hours in the lab and (estimated) 2 hours of homework for design and processing.

QFT is adopted as an alternative to the classic design due to its relative simplicity and its direct relationship with the frequency design. This methodology effectively reinterprets Bode's ideas in a quantitative manner, reinforcing the concept that the feedback is necessary depending on the existence of uncertainty or no measurable disturbances on the plant model [8]–[10]. Although a theoretical explanation of the subject is not taught, basic guidelines are given to relate Bode graphics and Nichols charts using the CAD tool during the execution of the labs.

Both this laboratory and this experience also allow students to reinforce relations between frequency and time response, phase margin and crossover frequencies with overshoot and rise time in the step response.

B. Overview of the QFT Design Concept

The Quantitative Feedback Theory was conceived by Pahuja and Rai [11] as a frequency domain design

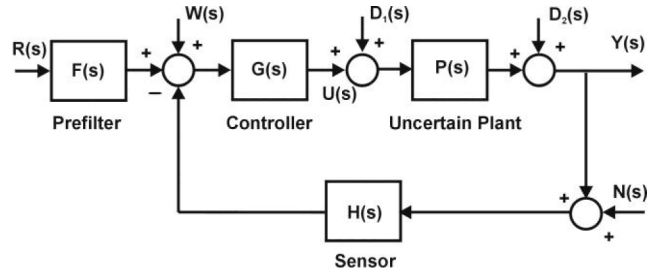


Fig. 1. Control system configuration with two degrees of freedom.

methodology for feedback control systems. It proposes a transparent design methodology that has been and continues to be used. So, the design procedure becomes really dynamic with very good results in diverse applications [12]–[17].

Figure 1 shows a typical feedback control system configuration where $P(s)$ represents the uncertain plant model, the external disturbances are described by the processes W , D_1 and D_2 , N is the measurement noise, R is the reference signal and Y is the system output signal. The sensor dynamics in the feedback loop is represented by $H(s)$. Due to the uncertainty, the plant is characterized by a family of frequency responses. That is, the dynamics at each frequency is described by a set of points that constitutes the so-called template [18]. An arbitrary member in the plants set is chosen as the nominal case.

The goal of QFT design is to synthesize the simplest possible controller in the loop, $G(s)$, with minimum bandwidth meeting simultaneously all specifications for the plants family established by the uncertainty. The general setting may eventually include a prefilter, $F(s)$, which allows achieving the desired frequency response once the uncertainty has been controlled.

The specifications concerning the desired performance in terms of stability, temporal tracking, disturbance rejection and limits on control action combined with plant templates are translated into allowed regions in the Nichols chart delimited by contours known as Horowitz-bounds. Intersection of all such contours at the same frequency points yields the worst case bounds that are the guide to determine the nominal open loop transfer function $L_0(j\omega) = G(j\omega)P_0(j\omega)$ that is the basis to the controller design $G(j\omega)$. For this purpose, classical loop shaping is used such that $L_0(j\omega)$ does satisfy the bounds in the Nichols chart. This ensures that the other loop functions in the templates will also do so.

Particularly in this experience, the design of the controller $G(j\omega)$ is based on robust stability and temporal specifications only.

C. Control Design Software Tool: Selection Criteria and Features

One feature of the newer generations of students is the easy way they interact naturally with technological devices through menu-based interfaces. These allow selecting different options and settings. Many accessible software tools available in Internet are very suitable for this purpose encouraging students to involve in their own learning process. Such tools

enable a quick and efficient introduction of relatively complex concepts.

From a pedagogical point of view, two different strategies for the incorporation of the design software can be distinguished [19]:

- as an auxiliary tool, considering two stages. The first one called synthesis consists in determining the design parameters set. The second stage is the analysis or validation of the results obtained in relation to the specifications. This usually leads to a new iteration in a procedure of trial and error;
- as an interactive tool [20], which combines both stages and immediately shows the effects of changing the parameters. So, the design procedure becomes really dynamic and the users perceive how each parameter change affects the system behavior. This interactive feature guides the design to obtain an acceptable compromise between all the requirements, generates an intuitive criterion related to expert knowledge, and quickly identifies if the specifications can be achieved.

In the field of automatic control, Matlab is the software tool most widely adopted because of both its extensive set of library functions and its graphical user interface (GUI), which allows the easy implementation of the different techniques used in feedback control systems. In particular, there are different CAD tools implemented in this environment [21]–[24] to assist in applying the QFT controller design methodology. Among them, the commercial QFT Frequency Domain Control Design Toolbox (FDCDT) [22] and the user friendly QFT Control Toolbox (QFTCT) [23] are mentioned as the most widespread and complete. In both cases, it is necessary to have installed the Matlab software so a costly license is required and not always accessible.

On the other hand, in the field of freely available software, instructors count on the QFTIT-SISO program (Single Input Single Output Quantitative Feedback Theory Interactive Tool) characterized by high interactivity at every stage of the process and its ease of use. This interactive tool, developed in Sysquake environment [6], is available in the form of an executable file for Windows- or Mac-based platforms providing high portability.

It sequentially presents a series of windows that respond to the concept of “dynamics pictures” [25] which facilitate the understanding of the involved concepts, the development of fundamental design skills, and provide practical support for the theoretical basis. SISO-QFTIT adapts perfectly to the proposed objectives, incorporating the added value of being freely available and accessible to the student who wants to experience outside the scope of the classroom. Specific details are described in [26]. These features led to the decision to adopt the SISO-QFTIT software as the CAD tool for the development of experience.

D. Description of the Control System

The system consists of a DC permanent magnets motor (Liotton C23, 24 volts) with a flywheel that acts as a load (Fig. 2). An integrated tachometer generates a measurable signal for identifying the associated parameters.



Fig. 2. Motor-wheel-position sensor system.

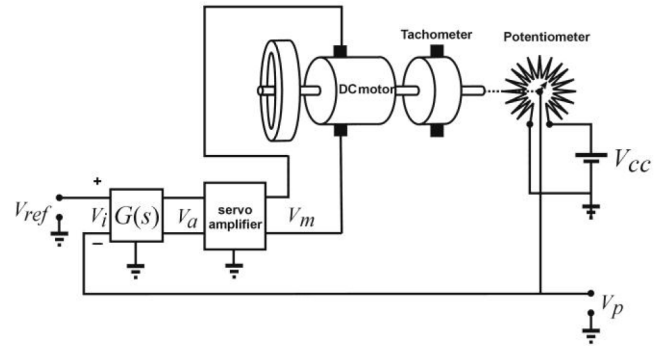


Fig. 3. Control system scheme.

The control action is conditioned by a servo amplifier and converted into a PWM signal (Advanced Motion Controls, model C25AB, 22 KHz). The aim is to position the flywheel. A linear potentiometer of 10 K Ω is used as a position sensor and is coupled directly to the motor shaft (Fig. 3).

The controller is a PID (proportional+integral+derivative), implemented with operational amplifiers [27]. The servo amplifier motor assembly is modeled with the transfer function:

$$\frac{\theta}{V_a} = \frac{K}{s(s+a)} \quad (1)$$

where θ represents the angular position and V_a is the control signal on the servo amplifier. For the controller, the transfer function is:

$$\frac{V_a}{V_i} = k_p \left(1 + k_i \frac{1}{s} + k_d \frac{s}{0.022s + 1} \right) \quad (2)$$

with possible variation of the gains in the range $0 < k_p < 7$; $0 < k_i < 10.64$ and $0 < k_d < 0.1$. The two poles of the controller are fixed, one at the origin (the integrator), and the other at high frequency, $s_0 = \frac{1}{0.022} = 45.454$ [rad/sec]. Both zeros are tuned at the design stage.

The block diagram of the feedback control system can be seen in Figure 4.

III. IMPLEMENTED METHODOLOGY

A. Experience Description

The experience is proposed as laboratory work consisting in the design of the position control described in the

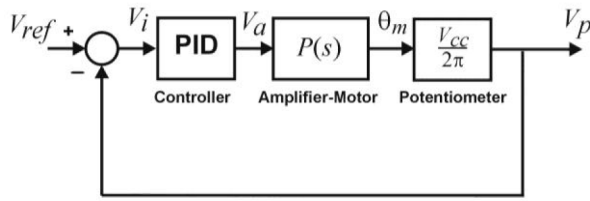


Fig. 4. Block diagram of the control system.

previous section, adapted to the learning objectives of the course [27]. It is performed in two stages of four hours each, assisted with an activity guide. The former uses knowledge of the first two blocks of the subject, which already have the system models obtained from previous practices and laboratories. The model is identified, the uncertainty is highlighted and the debate is established. In the latter stage, which is contemporary with the development of the third block of the subject, the design of the conventional control is performed first. Then, taking into account the effects of uncertainty, the robust control is subsequently performed.

The detailed description of these stages is:

1) *Stage 1a (2 Hours in Laboratory)*: The identification consists in the determination of the two parameters associated with the plant model in Eq. (1), the gain K and the real pole a . This is done using the responses to steps of different amplitudes. Although the experimental kits have similar characteristics, the dispersion in the results naturally arises due to small constructive differences, measurement errors, limitations of the linear model and identification methods (measurement of the time constant, least squares). The concept of structured uncertainty is elaborated from the comparisons of the results obtained with different sets of measurements and methods implemented by the different teams. The idea that the model represents an approximation of the actual physical system and that in practice it is not possible to determine the exact values of its parameters is reinforced. It is emphasized that this dispersion can be eventually quantified and considered in the design process.

2) *Stage 1b (2 Hours Post-Laboratory)*: The teams must select among the parameters identified in the previous stage what they consider to be the set that defines the nominal plant. The selection criteria range from adopting average values to simply retain the most representative parameters comparing simulations with experimental data. This set of parameters defines the nominal model which is the basis for the design.

3) *Stage 2a (2 Hours Pre-Laboratory)*: A PID controller must be designed using classical frequency methods. The performance specifications are determined based on the desired characteristics for the step response. These are interpreted as properties of the frequency response: rise time and damping translated as stability margin and 0 dB crossover frequency. At this stage, students should review the influence that the model uncertainty could have in the expected results and the possibility of considering it in the design process.

4) *Stage 2b (1 Hour in Laboratory)*: The control system is implemented and its behavior is analyzed according to the nominal design.

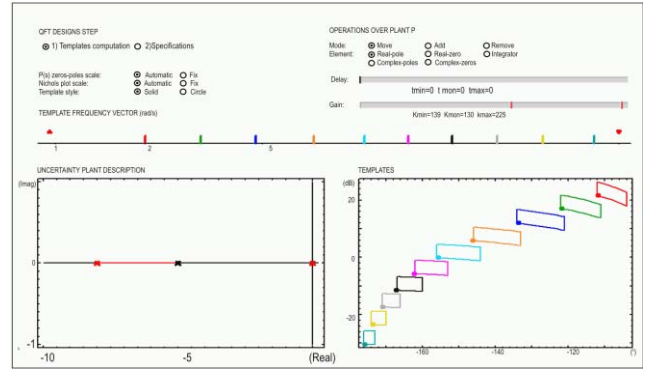


Fig. 5. Window for the first stage: input of plant parameters and working frequencies, and computation of templates.

5) *Stage 2c (1 Hour in Laboratory)*: The QFT is shown as an alternative methodology which allows the design of a robust controller. The SISO-QFTIT CAD program is described, stressing that this software is freely available, with a user-friendly graphical interface and very interactive design features. This CAD requires a sequential data load:

- the plant model with parametric uncertainty;
- the working frequency range;
- the specifications.

Type 1 specification, “Robust Stability Bounds”, for a desired stability margin is selected. A robust control scheme with a single degree of freedom, without prefilter, is considered. Finally, the controller is synthesized and tuned interactively. When the process finishes, the software presents the results with time and frequency graphics considering the worst cases.

The implemented system is modified with the robust controller gains. The behavior with various excitations is used to compare both the classic and robust design. At this point, the student must verify that the robust controller implemented in any of the kits available in the laboratory fulfills the specifications despite the differences detected in *Stage 1a* (uncertainty).

B. Design Example

A set of typical results for the above stages is presented.

According to the scheme of Figure 4, after identification, the nominal plant (including position sensor) is adopted as

$$P_0(s) = \frac{V_p}{V_a} = \frac{V_{cc}}{2\pi} \cdot \frac{\theta}{V_a} = \frac{10}{2\pi} \cdot \frac{117.46}{s(s+5.46)} = \frac{187.04}{s(s+5.46)} \quad (3)$$

where the supply voltage of the sensor was fixed in $V_{cc} = 10$ volts. The response is fast with little damping, corresponding to a phase margin of 22.6° . It is desired to design a PID controller to bring this margin to 50° . One possible parameter set resulting from the classical design is $k_p = 0.735$; $k_i = 1.208$ y $k_d = 0.059$.

Using the software the robust design is performed considering the nominal plant along with the uncertainty described as $K \in [79.36, 158.73]$ and $a \in [4, 7]$, thus $126.37 \leq K V_{cc} \frac{1}{2\pi} \leq 252.75$. Successive interactive windows allow

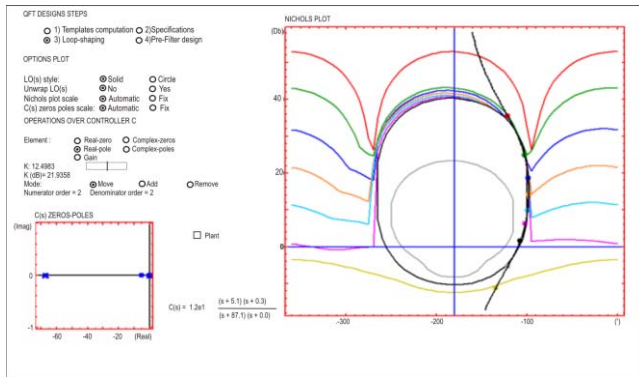


Fig. 6. Window for the third stage: Loop-shaping based on the nominal transfer function and bounds for robust stability and tracking.

advancing through different stages of the QFT methodology as shown in Fig. 5 and 6. For this example, the working frequencies used are: 0.1, 0.5, 1, 2, 5, 13.3, 50, 100 [rad/sec]. Specification type 1 was selected, $W_{s1} = 1.18$, which corresponds to a phase margin of 50.19° . Associated contours or bounds are generated immediately and automatically.

The next step, known as loop-shaping, is to synthesize the robust controller. The components (gain, poles and zeros) are set graphically with immediate visualization of the effect on the nominal open loop frequency response. First, fixed poles are incorporated: $p_1 = 0$ and $p_1 = 45.454$. Then, interactively, two real zeros and the gain are selected so as to satisfy as closely as possible the bounds, in order to avoid over-design.

This process concludes with a transfer function for the controller such as:

$$G(s) = 2.8407 \frac{(s + 8.964)(s + 0.424)}{s(s + 45.454)} \quad (4)$$

Figure 6 shows the printscreen of this design window for a conventional PID structure. Finally, in the validation stage of the design, the results of the simulation for the final system are shown. Compliance with specifications can be checked with the performance in time and frequency. Each graph shows the most restrictive situations, taking into account both uncertainty and the limits set by the specifications. An image of the system used is presented in Figure 7.

Each team implements the same controller on their system, verifying proper operation. Then, integrating and comparing the results, the robustness of the design is checked: the same controller works properly in all cases. In Figure 8, a temporal response of the actual system is compared with a simulation. The presence of a “dead zone” is detected. This non-linearity is due to frictions and has not been modeled affecting the settling time and the steady state response.

IV. RESULTS

The experience is designed to be developed autonomously by the students with ongoing assistance from teachers. It was implemented in two regular courses along two consecutive years with the participation of twenty students. Although the number of students is small, it is considered to be applicable to larger courses working in shifts with teams of few members, to ensure adequate teacher-student interaction.

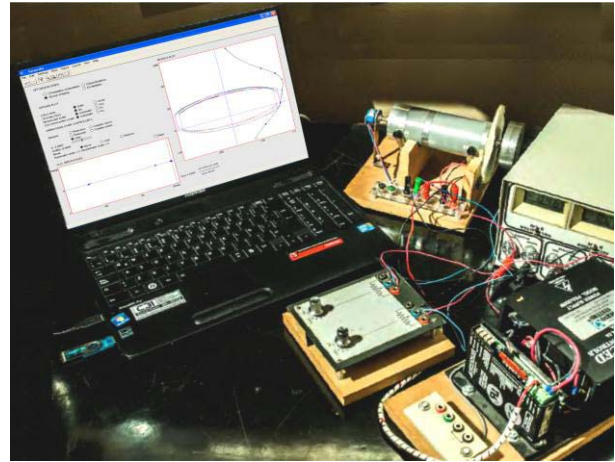


Fig. 7. Mechanical system with robust PID controller implemented in the laboratory.

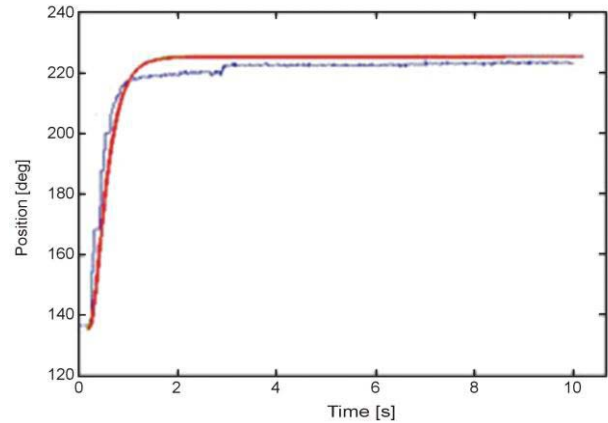


Fig. 8. Experimental and simulated temporal responses of the system with the designed controller.

The results were evaluated from the students’ perspective by perception and opinion surveys. These surveys are conducted during and after the experience with the following results:

- 1- 100% of the students detect the uncertainty and recognize that dispersion in the results as a consequence inherent to the experimental determination of a model.
- 2-a 70% of the students believe that the maladjustment and dispersion of values are due to errors in the measurement procedure, modeling and nonlinear effects.
- 2-b 30% of the students consider that the maladjustment between the model and the system is not necessarily due to the measurement process, but to modeling errors and nonlinear effects.
- 3-a 45% of the students believe that this uncertainty can affect the performance of the system and should be considered in the design process.
- 3-b 55% of the students consider the effects of uncertainty on the performance of the system irrelevant and should not be taken into account in the design.
- 4-a After completing the design, 35% of the students do not consider the improvement obtained significant.

4-b After completing the design, 65% of the students believe the improvement obtained by taking into account the uncertainty in the design process to be significant.

5- 100% of the students believe that the QFT software package is intuitive and user friendly according to their skills and knowledge.

The results suggest that the pedagogically non-structured introduction of the uncertainty and robustness concepts, naturally through laboratory experiences, is positively accepted by the students. After the practice, most of the students recognize the potential benefits of this type of design and understand the concepts involved, although they may not initially appreciate the advantages of the methodology. Both the user friendly software and the natural ease with which the current generation of students handle these tools play a very important role, even though the students do not know the underlying theory.

From the instructional point of view and according to the opinion of the educators, the following advances are recognized:

- Through the discovery learning paradigm, most students recognize the uncertainty of any modeling process, and in this case they associate it with the dispersion in the parameters of the model.
- A robust methodology conceptually simple and basically graphical is naturally introduced, expanding the students' view with respect to the limitations of the classical control.
- Learning is geared towards expert knowledge.
- Students observe that the robust design, not necessarily optimal, behaves reasonably well in all systems. On the other hand, the simulations show that the performance of the conventional design is satisfactory when the parameters are close to their nominal values. But the performance rapidly degrades when the parameters deviate from the nominal values—in some cases it even violates the restrictions. Behavioral differences obtained from both approaches are emphasized.
- This effective teaching style engages students in the learning process and helps them develop critical thinking skills. Students recognize the worth of learning through observation and experience since it facilitates the understanding of the ideas and concepts involved.
- The use of interactive freeware software is encouraged. It raises awareness in relation to the importance of incorporating this type of tools into the teaching process.

V. CONCLUSIONS

In this paper, a teaching methodology implemented for a first degree course in feedback control systems which combines a laboratory experience with an interactive CAD tool was presented. It is shown that this alternatively pedagogical strategy enables the introduction of concepts not usually covered, such as modeling with uncertainty and its inclusion in the design process. It was presented as an accessible alternative to address some of the limitations of classical control that clearly arise in practical situations.

The adopted strategy allows students to take greater independence and responsibility for their own learning process,

favoring autonomy, strengthening the skills to use design tools, and to appreciate the limitations of a single model.

While there are many authors who have designed interactive tools to facilitate this learning [7], [26], in this paper an interactive tool is applied and integrated as part of a specific experience based on both action and discovery learning paradigms in an undergraduate course.

Classical control theory with the assistance of CAD serves as sufficient basis for the informal introduction of QFT and also helps to strengthen the underlying concepts of frequency response.

The interactivity level of the SISO-QFTIT software greatly favors a broader and faster understanding of the subject. The proposal is incorporated without difficulty since the students are naturally trained and acquainted with the use of such interactivity.

A perception survey was performed and the results indicate that the students recognize the effects of uncertainty and show good general acceptance of the experience. Furthermore, it can also be interpreted that the simplicity of the system allows acceptable results even with the classic design. However, the potential of the presented method is evident.

Finally, it is worth emphasizing the importance of freeware software, very well designed for improving the teaching and learning process and the development of specific skills.

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