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A Lean Path for Learning Control in Undergraduate Electronics Programmes

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Abstract: In recent years, the development and spread of machine learning, robotics and other novel application areas, made indispensable to include such topics in undergraduate programmes for students in the area of electrical and computer engineering. However, this entails that traditional subjects must be covered in less time while maintaining their relevant topics for getting an engineering diploma. In this paper, one presents an approach to streamline the learning and teaching of automatic control. As surveyed in the paper, many universities divide the study of control theory in an initial course with system theoretic concepts followed by two other dedicated to linear systems. Various approaches appear on how to divide the topics over these two units. The study of single-input single-output systems defined by differential equations and the study of transfer functions can be argued to be mainly rooted on the need to introduce the Proportional Integral Derivative (PID) controller. In this paper, motivated by the concept of differential observation, we propose a new organization of the control curricula where a first course on systems theory gathers all relevant general tools and a second course, specific to automatic control, presents both continuous and discrete-time linear control systems in the state-space formulation together with ways to get working control systems in face of actuator saturation, measurement noise and parametric uncertainty. In this approach, PID controllers are presented as a special case of state feedback. The structure can also be useful for Universities developing their curricula in countries where control theory teaching is still being developed.

Keywords: Teaching curricula developments for control and other engineers; Balance issues of theoretical-versus-practical training; Control education using laboratory equipment.

1. INTRODUCTION

The increasing need to diversify the curricula of electronics undergraduate programmes requires reducing the number of curricular units targeted to traditional subjects as control. This creates the challenge to design a minimal sequence of courses that provides effective formation on automatic control, i.e., whose graduates can integrate a control engineering team producing useful work. For this to be possible, besides specific knowledge on control, the graduate must have obtained capabilities in mathematics, physics, analog and digital electronics and microcomputer programming. The main proposal in this paper is to have a sequence of two semester courses with laboratory support devoted to: i) systems modeling and dynamics; ii) Linear Time-Invariant (LTI) control.

Upon reflection, it becomes clear that to achieve the proposed goals, students must be exposed to other topics apart from linear control. The current paper is proposing a set of shortcuts and deviations from the usual learning path in control that is expected to allow students acquire the learning objectives aligned with (Rossiter et al., 2020) within two semester courses, supported with laboratory practice. The remainder of this paper is organized as follows. Section 2 reviews current methodologies for teaching control, with samples from several schools. The shortcuts and the rationale underpinning what is termed a lean learning path for automatic control are explained in Section 3. In Section 4, the syllabi for the courses in dynamic systems modeling and in LTI control are given. Section 5 details the laboratory practice supporting the LTI control course with an example in the underlying paradigm. Section 6 offers some concluding remarks and gives some perspectives of development.

2. REVIEW OF METHODOLOGIES TO TEACH CONTROL

Current curricula for teaching control are spread over several courses, with sometimes overlapping topics. The typical approach is characterized by first having a course related to systems and signals to explore Laplace transform and other tools transversal to other areas, followed by two courses of control and possibly others of advanced topics.

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Recently, there have been proposals to reformulate the path to teach automatic control either by changing the organization of theory presentation or by showcasing problems found in applications. In (Yang, 2018/05), one of the main conclusions is to reduce the root locus teaching and the closed-loop system frequency analysis accompanied by a larger focus on discrete-time models and in-depth state space analysis. The article (Yang, 2018/05) follows a similar idea to the current proposal in dividing the topic into two courses and teaching both state-space and differential equations in tandem with the introduction of transfer functions being derived for both cases. The main difference to the current proposal is that there is little attention to PID controllers, which we consider to be indispensable to present (and frame as a special case of state-space controllers) given its widespread use.

Other researchers have focused on reformulating the laboratories offered to students in order to showcase implementation issues that are not covered in initial curricular units. The work in (Vargas et al., 2011) has proposed a set of laboratories that can be accessed remotely by students at Spanish universities. A similar approach has already been followed in (Valera et al., 2005) at a shorter scale. In order to have students working beyond simulations, it requires a deeper introduction to discrete-time models and robustness margins, which further reinforces the proposal in this paper.

In the reviewed literature, proposals fostering the use of simulators like the work in (Granado et al., 2007) draw attention to the need to further include concepts from digital control within the laboratory practice. This case is even more pressing within areas such as mechatronics as the authors of (Padula and Visioli, 2013) refer. A concern regarding the use of experimental setups could be the higher cost for departments to have kits for the various groups in the curricular units. However, in the literature, cheap examples using a DC motor (Cook et al., 2020) have been presented, similar to the proposal of the laboratory practice in this paper.

In the remainder of this section, we sample some specific cases to illustrate how control is taught at BSc and MSc levels to get a picture of how this proposal relates to actual teaching practice. At Instituto Superior Técnico, University of Lisbon, in the second year, students follow a course on signals and systems covering the topics common to other areas such as antenna transmission or signal processing. In the third year, within the subject of control, undergrads finish the BSc level with the knowledge of continuous-time systems with a single input and output. Only at the fourth year (already a MSc level), are they exposed to state space systems and later to computer control devoted to digital control.

At Faculty of Engineering, Porto University, the BSc degree in electrical and computer engineering follows a similar path with a course on signal theory being the introductory one, followed by a course named Control Theory. Inside these two courses, all topics of LTI systems and control in continuous time are presented. At the MSc level a course named Digital Control goes from Z transforms to linear quadratic optimal control. The MSc in Systems and Control of Delft University presents an introductory course named Signals and Systems, followed by other two entitled Systems and Control and Control Theory. These lay the topics related to linear systems. At the MSc level, advanced courses include Optimization in Systems and Control related to model predictive control and optimal control; Control Engineering devoted to digital control; and Robust Control as a final one.

The Eidgenössische Technische Hochschule (ETH) in Zurich, starts with Signal and System Theory I and II as introductory courses, followed by Control Systems I and II and Linear Systems Theory for the one dimensional continuous-time theory and state space representation.

Cambridge University has Linear Systems and Control along with Control Systems Design to address linear systems with a single input and single output, followed by advanced courses including Aircraft Stability and Control, Robust and Nonlinear Control and Optimization based Approach to Control.

Even in the United States, where degree curricula have more optional courses, the Stanford University divides the subject of linear control systems into Introduction to Control Design and Feedback Control Design, followed by more applied topics such as Vehicle Dynamics and Control.

The mentioned programmes differ from the current proposal by dividing the teaching and learning of linear control systems into two courses: one for single input single output systems represented by a differential equation and another for state space representation. In this paper, one proposes to eliminate this distinction. In the next section, we outline the key observations that motivate this proposal.

3. RATIONALE FOR THE LEARNING PATH

This section presents the underlying reasoning to design the learning path as it will be made concrete in Sections 4 and 5.

3.1 Control in continuous- and discrete-time at once

Nowadays automatic controllers are implemented mainly through digital electronics, if only because:

- One requires that automatic controllers should connect to a communications network, as in the emerging Internet of Things (Madakam et al., 2015) and cyberphysical systems (Zanero, 2017) emerging worlds.
- Affordable microcontrollers have sampling frequencies in the kilohertz range (Marciniak et al., 2020).

Proper design of digital controllers requires discrete time models of the systems to be controlled. The obvious way to generate these in the LTI framework is to depart from the general continuous time model:

$$\begin{aligned} \frac{dx(t)}{dt} &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned} \tag{1}$$

Given the ubiquitous zero-order hold output characteristics of the command signal, discrete time models are obtained as zero order samplings of (1) with period h:

$$\begin{aligned} x(kh+h) &= Fx(kh) + Gu(kh) \\ y(kh) &= Cx(kh) + Du(kh) \\ F = e^{Ah} \quad G &= \int_0^h e^{A\tau} d\tau B \end{aligned}$$

These models share similarities as expressions for pole-placement or the transfer functions can be related albeit with a reinterpretation of the symbols. On the basis of the above, one may present LTI systems as being representable either with null sampling time (continuous time) or non-null sampling time (discrete time). This concept can be exploited to considerably shorten the required learning time and effort for LTI control, in both time domains. Other authors also take advantage of this property to present linear systems in both time domains at once, rather than going through the more inefficient method of presenting all the theory for continuous time first and then repeating the exposition for discrete time. The book (Hespanha, 2018) is a case in point.

3.2 State space primacy, differential observation and the PID special case

Introductory courses in control usually lead the student through the classical transfer function formalism and dedicate a significant effort to PID type controllers. Here, a radically different approach is taken. State space models are presented practically from the start as the way to analyze systems and design controllers through pole placement.

For this to be possible, the treatment of state estimation, rather than being made through full and reduced order observers, will be limited to differential observation (Garrido, 2021), i.e., understanding differentiation as a method for an approximate observation of a controlled system state variable. In this way, the lengthy and somehow difficult path to learning state observation through full and reduced order observers is cut to a simpler, widely used, approach while maintaining the concept of full-state feedback.

While the performance of differential observers cannot be made as good as the performance of full or reduced order observers, (they do not use the available information on command values generated by the controller), they give an excellent benefit. They allow framing PD or PID controllers as special cases of state-space controllers with differential observation.

3.3 Separation into the regulation and servo problems and integral action

As there is no way to represent an initial disturbed state with transfer functions, this representation complicates understanding the separation into regulation and servo control problems.

That is not the case in the state space approach. In this one, it makes sense to introduce first the fundamental regulation problem of driving the state to the null value from a disturbed initial condition resulting from an impulse disturbance. This problem is easily solved through full-state feedback with pole placement establishing the internal dynamics of the feedback system (Åström and Wittenmark, 2013). First, it is addressed the full-state measurement case followed by using differential observation for the estimation of the unmeasured states. Then, it is a natural step to introduce servo signals intended to track a given nonzero reference.

3.4 Actuator saturation, measurement noise and model uncertainty

LTI control gives a very useful paradigm to design feedback controllers with a large applicability, but three issues outside deterministic linear modeling must be properly dealt with to obtain working control systems. First, actuators are always amplitude limited, i.e., actuators saturate. When an actuator saturates, the fundamental assumption of control system linearity is no longer valid. This is critical in the control of unstable systems. Second, measurements of state variables will always contain some errors due to sensor noise. The third issue to consider is model uncertainty when parameters may vary given the system operating range. This means that a pole placement design based on a nominal model must be checked for robustness in face of parameter variations. A completely proper treatment of this issue is possible through robust control (Zhou and Doyle, 1998). Unfortunately, it is not viable to include it in a lean learning path and we limit to checking the design robustness through the classical measures of gain and phase margin.

3.5 The role of transfer functions

While not having a primary role, transfer functions (in the z domain) do have two important uses in the proposed LTI digital control course:

- Obtaining analytical expressions for the steady-state errors.
- Calculating the frequency response of the loop transfer function in order to determine the gain and phase margins.

3.6 The systems foundation

Learning of LTI control rests on capabilities to understand and use systems modeling and analysis, which are intended for the first proposed course in systems theory. The starting point is the concepts of system and its models both in continuous and discrete time, in state-space, with time invariant or time varying dynamics. The goal of this first module is:

- To get students acquainted with examples of dynamic models,
- To develop understanding of their meaning,
- To develop capabilities for using as well as simulating them.

Grounded on the above, one can proceed to establish the types of input responses and the most important concepts of trajectory stability and system stability, from which one is ready to introduce the overarching concept of system and model linearity.

From this point, one will focus on LTI models and dynamics study through the use of Laplace and Z transforms. Main learning goals will be impulse and general responses of linear systems, their decomposition in modes leading to the well-known stability criterion based on pole positions either in the s or z plane and sinusoidal frequency response. The last one can be completed with the Nyquist stability criterion for feedback systems.

To complete the foundation for the LTI control course, students should learn the sampling of a continuous time model under a zero-th order hold and the resulting discrete time model, as well as relating poles and zeros and frequency responses in continuous and discrete time.

4. THE PROPOSED SYLLABI

In this section, the proposed syllabi is split into two modules (each with 6 ECTS) with learning outcomes and nominal week duration. Whenever applicable and not said explicitly, the items refer to both continuous and discrete time. The syllabus for the Systems Theory and Control courses are given in Table 1 and Table 2, respectively.

Table 1. Syllabus for the Systems Theory course with content and allocated time.

Systems theory course		
Module	**Contents**	**Weeks**
1	**Introduction to systems and models; functions.** Concepts and examples of system, subsystem, supersystem, interior and frontier of a system. Definition of a model. Structural and behavioral models. Behavioral models: variables and parameters. Examples. Evolution of variables. Continuous and discrete time functions, definition and properties. Important function families. Sampling of a continuous time function. Programming the calculation of functions in discrete time.	2
2	**Time operators and behavioral models.** Time operators as higher order functions mapping time functions into time functions. Programming operators in Matlab and Scilab. Static and dynamic, causal and non-causal operators. Simulation of operators. Obtaining models through the connection of operators. Differential and difference equations as scalar descriptions of models composed of operators. Vector models. The concept of state. State space models. Examples.	3
3	**Systems responses, stability, linearity, time variance.** Concepts of free, forced and impulse response. Definition of stability for system trajectories. Definition of linear models. Importance of linearity. The superposition principle. Composition of linear models. Recognition of linear and non-linear models. Definition of time varying and time invariant models. Practical importance. Examples.	2
4	**Complex variable analysis of linear systems.** Laplace and Z transforms. Definitions and properties; common transforms. Transformation of state-space models. Expressions of inputs and responses. Transfer functions. Free and forced responses; the impulse response. The stability criterion for linear systems deduced from pole positions. Decomposition of the forced response; transient and steady-state responses. Responses to the step and the sinusoid. Steady-state gain to the step. Frequency dependent gain and phase shift: the frequency response or frequency transfer function. Plotting the frequency response in polar coordinates (Nyquist) and Bode diagrams; effects of poles and zeros in the diagrams. First and second-order systems equations and transfer functions. Model parameters and their meaning and associated frequency responses. Observation parameters.	5

Table 2. Syllabus for the Control Course with content and its allocated time.

Control course		
Module	**Contents**	**Weeks**
1	**Introduction.** Concept of control and examples. Subsystems in a control system: plant, actuators, controller, sensors. Variables in a control system: controlled, actuation, disturbance, command and measurement variables. Control actions: feedback, reference and disturbance feedforward. Examples of on-off and proportional control of a house temperature.	2
2	**Modeling and simulation of the subsystems and the control system.** Sensors: continuous, pulse and sampled output; measurement errors. Actuators: continuous and pulsed, commanded through a zero-order hold; linearity and saturation; amplifiers and motors. Plant: the continuous and the discrete time model under periodically sampled zero-order hold actuation; choice of sampling period; joint models of actuator, plant and sensor. Analog and digital implementation of controllers, model of an analog control system, structural model of a digital control system and its principle of operation.	3
3	**Designing the control rule 1: full-state feedback and pole-placement.** Revision of poles determining behavior characteristics of linear systems; response to an impulse disturbance provoking a disturbed initial state. Full-state feedback and its pole-placement property; obtaining the feedback gains for intended poles. Choice of closed poles: effects on speed of response, actuator saturation and measurement errors sensitivity. The concept of controllability and how plant controllability can be tested.	2
4	**Designing the control rule 2: state observation and differential estimation.** Observing unmeasured states: types of observers. Differential observation: expression, frequency response, sensitivity to measurement errors, expression of estimation error. Introduction of additional poles and checking the shift of intended poles.	1
5	**Designing the control rule 3: servo signals and disturbance rejection through integral action; the PID control rule.** The regulation and the servo problems in control design. Introducing servo signals. Steady-state errors provoked by references and non-impulse disturbances and their expressions obtained through transfer functions. The nullifying error property of integral action. Introducing integral action and setting its gain. Interpreting PID controllers as full-state feedback controllers with differential observation and integral action. Tuning experimentally a PID controller.	2
6	**Designing the control rule 4: checking robustness, gain and phase margins.** Revision of frequency response of linear systems in continuous and discrete time. The Nyquist stability criterion for feedback systems. Gain and phase margins and their evaluation in Bode diagrams. Relating gain and phase margins to the controller gains and chosen poles.	2

5. THE LABORATORY PRACTICE

In this section, one presents a laboratory practice aimed at providing the students with hands-on experience in designing and implementing a digital control system along the rationale presented in the previous sections. The objective is to control the angular position of a rotating disk. Students are invited to go through a three stage process: i) qualitatively understanding the control system and its operation, ii) designing the controller and simulating the system using a computer program coded in Scilab or Matlab, iii) implementing and testing the control system.

Figure 1 shows a schematic of the device used in the laboratory practice. The disk and its shaft are mounted on two bearings attached to a u-shaped support. A DC motor that incorporates a reduction gearbox and a Hall effect pulse generator drives the shaft. The pulse generator is connected to a microcontroller board.

The microcontroller keeps a measure of the disk rotation angle by counting impulses and periodically runs a routine to calculate the average voltage to be applied to the motor through a PWM amplifier made up by a power supply and a H-bridge. The calculation is made on the basis of the current disk rotation angle and the internally kept reference value for the disk rotation angle. These are the key points to understand qualitatively about the system.

The design and simulation stage encompasses eight steps:

(1) Modeling the system to be controlled in continuous time.
(2) Getting parameter values.
(3) Analysis and simulation in continuous time.
(4) Choice of the sampling period.

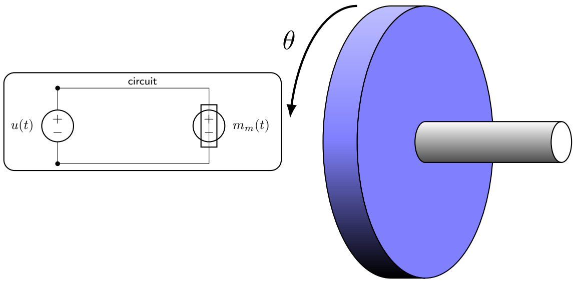

Fig. 1. Schematic representation of the mechanical model used in the laboratory practice.

(5) Choice of closed loop poles and obtaining the full state feedback gains for the regulator.
(6) Measurement analysis and choice of an estimation method.
(7) Introducing servo action, check steady-state errors and the need for integral action.
(8) Checking design robustness against parameter variations.

To begin the design, students should get the following model for the mechanical load, actuator, and sensor:

$$\begin{bmatrix} \frac{d\omega(t)}{dt} \\ \frac{d\theta(t)}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \omega(t) \\ \theta(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{J} & \frac{1}{J} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} m_m(t) \\ m_d(t) \end{bmatrix} \quad (2)$$

$$m_m(t) = \frac{K_m}{R}\left(u_a(t) - K_m\omega(t)\right) \quad (3)$$

$$u_d(t) = K_w u(t) \quad (4)$$

$$-u_{\max} \le u \le u_{\max} \quad (5)$$

$$\theta_m = nq, n \in \mathbb{Z}, q = 2\pi/N \quad (6)$$

In (2), ω and θ are the angular velocity and position of the disk, m_m and m_d are the motor and disturbance torques, J and B are the moment of inertia and linear friction coefficient of the rotating body. In (3), u_a is the (average) motor supply voltage, K_m is the motor plus gearbox electromechanical constant (referred to the disk shaft) and R is the rotor resistance. In (4), u is the command value determined by the microcontroller and K_w is the gain of the PWM amplifier. The nominal value of K_w is assumed to be 1, but the distinction between u_a and u allows one to account for variations of the supply voltage in the PWM amplifier. Nominally, this one should saturate at a maximum voltage equaling the motor rated voltage. These constraints are incorporated in the calculation of u through equation (5) where $u_{\max}$ equals the motor rated voltage. Conditions in (6) translate to the available measurements of angular position being restricted to be integer multiples of the angle quantum defined by the number N of generated pulses by revolution.

Having got the model and compressed equations (2), (3) and (4) in a state space model, students should understand the available methods to get nominal values for the parameters in the model. They should also understand the need to estimate intervals around the nominal values. The design will proceed based on the following determined or assumed nominal parameter values:

$J = 0.02$ kg/m$^2 \pm 0\%$
$B = 0.02$Nm/(rad/s) $\pm 20\%$
$K_m = 0.40$Nm/A or V/(rad/s) $\pm 10\%$
R $= 13\Omega \pm 10\%$
$u_{\max} = 6$ V $\pm 0\%$
$K_w = 1 \pm 5\%$
$N = 760$

The next step is simulation in Scilab or Matlab, assuming perfect measurements of angle and velocity. It turns out that the model poles are at $s = 0$ and $s = -1.6$, therefore the time constant associated to the last one is $T = 0.62$ s.

Having checked the model consistency through simulation, it comes the important determination of the sampling period to use. Following the rule that the sampling period h should be such as to get 4 to 10 samples in the time constant interval (associated to the fastest pole) (Åström and Wittenmark, 2013) one gets that it must belong to $[0.06, 0.15]$, from which one chooses a comfortable $h = 0.08$. Having defined the sampling period, one may program the calculation of the state space discrete model relating the command variable u to the angular velocity and position, ω and θ, of the disk.

Students then determine the gains for a full-state feedback assuming perfect measurements of both angular velocity and position, where it becomes handy to specify not the closed loop poles in the z-plane but their corresponding s-plane poles. As a benchmark, one wants that the response to an initial state equal to $[0\ 1]^\intercal$ (disk at rest deviated 1 rad from the reference position) exhibits good settling time without exceeding too much the motor rated current 0.16 A. While setting both s-plane poles at -2 (z-plane poles at 0.85) gives a settling time of 4 seconds, setting both s-plane poles at -4 (z-plane poles at 0.73) gives a settling time of 2 seconds with an acceptable exceeding (during 350 ms) of the motor rated current. So, the gains to get closed loop poles at $z = 0.73$ are selected.

Now students must face the fact that measurements of angle and velocity are far from perfect. To get values for the angular velocity with this hardware, one must calculate an estimate for $\omega(k)$. The estimate can be calculated by approximating it using observation differentiation of position through the rate of variation of measured position:

$$\hat{\omega}(k) = \frac{\theta_m(k) - \theta_m(k-1)}{h}$$

So, the control law is in fact:

$$u(k) = -k_1\hat{\omega}(k) - k_2\theta_m(k)$$

Furthermore, quantization error happens due to the number of pulses per revolution (N in (6)) being finite. These real conditions can be introduced in the simulation of the above response yielding the results depicted in Figure 2. Although not visible in the figure, a further effect of quantization error is the existence of an offset or of a limit cycle in the angular position near 0.

Going on, one introduces servo action by changing the control law to introduce a reference term:

$$u(k) = -k_1\hat{\omega}(k) - k_2\theta_m(k) + k_2\theta_r(k)$$

Analysis of steady-state behavior shows that this system will exhibit 0 steady state error to step references, 0.54 rad steady-state error to a unit ramp reference and 0.04 rad to a step, 10 mNm, disturbance torque. To zero the errors one may introduce integral action through:

$$u(k) = -k_1\hat{\omega}(k) - k_2\theta_m(k) + k_2\theta_r(k) - k_3\sigma(k) \quad (7)$$

In (7), σ is the sum of errors, a state to add to the model in order to calculate a new set of gains to place the, now three, poles of the system at -4 (s-plane) or equivalently at 0.73 (z-plane). Steady-state (linear) errors become in fact null while limit cycles with severity increasing with decreasing resolution will be observed. To end the design stage, gain and phase margins should be calculated. For

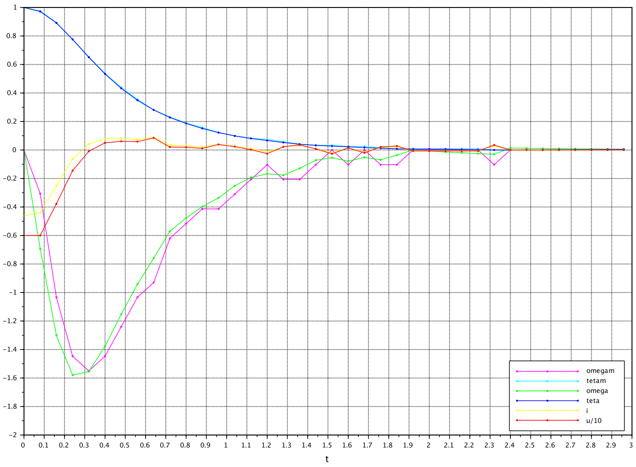

Fig. 2. The evolutions of the state variables, measured state variables subject to quantization error, voltage and current in the motor are shown for an initially disturbed state.

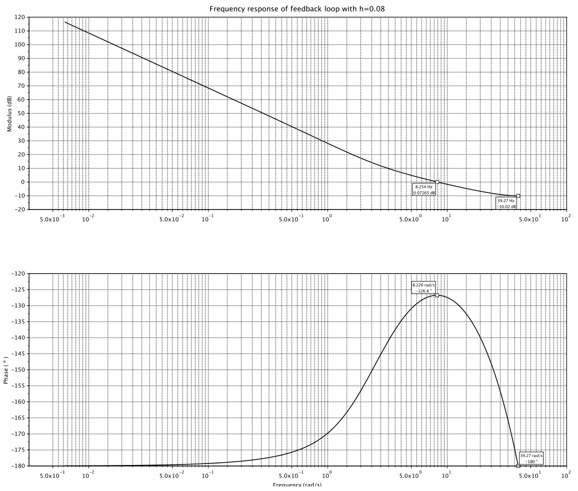

Fig. 3. Calculation of gain and phase margins for the control system with integral action and poles placed at $z = 0.73$.

integral action added and according to Figure 3, they have the comfortable values of 10 dB and 53.2 degrees.

6. SUMMARY AND PERSPECTIVES

In this paper, a new methodology to teach the fundamentals of LTI control is presented. It was motivated:

- By the aim to get a leaner and cleaner presentation of LTI control;
- By the need to reduce the number of control curricular units in undergraduate electronic engineering programmes in order to include emerging topics.

The state-space formulation provides a solid basis to develop a systematic approach to design linear controllers. The difficulty to integrate the PID controller in the state-space formalism is overcome with the concept of differential observation, thus connecting the study of the PID controller with that of an equivalent full state feedback of a linear system in state-space. The paper includes the description of a laboratory work. One argues that the flow of concepts is suitable for engineers that are to practice in a control team within the industry.

Implementation of the proposal has been by now a multi-year effort. Actual viability of the systems theory course has been verified after three editions in the second year of the Telecommunications Engineering programme at University of Minho, Portugal. The same happens for the laboratory course, which supports a classical theoretical course in digital control at the third year of the Industrial Electronics Engineering programme.

REFERENCES

Åström, K.J. and Wittenmark, B. (2013). *Computer-controlled systems: theory and design*. Courier Corporation.

Cook, M.D., Bonniwell, J.L., Rodriguez, L.A., Williams, D.W., and Pribbernow, J. (2020). Low-cost dc motor system for teaching automatic controls. In *American Control Conference (ACC)*, 4283–4288. doi:10.23919/ACC45564.2020.9147781.

Garrido, P. (2021). Differential Observation and Integral Action in LTI State-Space Controllers and the PID Special Case. In J.A. Gonçalves, M. Braz-César, and J.P. Coelho (eds.), *CONTROLO 2020*, 425–434. Springer International Publishing, Cham.

Granado, E., Colmenares, W., Strefezza, M., and Alonso, A. (2007). A web-based virtual laboratory for teaching automatic control. *Computer Applications in Engineering Education*, 15(2), 192–197. doi:10.1002/cae.20111.

Hespanha, J.P. (2018). *Linear systems theory*. Princeton university press.

Madakam, S., Ramaswamy, R., and Tripathi, S. (2015). Internet of things (IoT): A literature review. *Journal of Computer and Communications*, 03No.05, 164–173. doi:10.4236/jcc.2015.35021.

Marciniak, T., Podbucki, K., Suder, J., and Dabrowski, A. (2020). Analysis of digital filtering with the use of stm32 family microcontrollers. In A. Bartoszewicz, J. Kabziński, and J. Kacprzyk (eds.), *Advanced, Contemporary Control*, 287–295. Springer International Publishing, Cham.

Padula, F. and Visioli, A. (2013). An approach for teaching automatic control in a laboratory of mechatronics. *IFAC Proceedings Volumes*, 46(17), 214–219. doi:10.3182/20130828-3-UK-2039.00051. 10th IFAC Symposium Advances in Control Education.

Rossiter, A., Serbezov, A., Visioli, A., Žáková, K., and Huba, M. (2020). A survey of international views on a first course in systems and control for engineering undergraduates. *IFAC Journal of Systems and Control*, 13, 100092. doi:10.1016/j.ifacsc.2020.100092.

Valera, A., Diez, J., Valles, M., and Albertos, P. (2005). Virtual and remote control laboratory development. *IEEE Control Systems Magazine*, 25(1), 35–39. doi:10.1109/MCS.2005.1388798.

Vargas, H., Sánchez, J., Jara, C., Candelas, F., Torres, F., and Dormido, S. (2011). A network of automatic control web-based laboratories. *IEEE Transactions on Learning Technologies*, 4(3), 197–208. doi:10.1109/TLT.2010.35.

Yang, M. (2018/05). Teaching reform and practice of ”automatic control theory”. In *Proceedings of the 8th International Conference on Social Network, Communication and Education (SNCE 2018)*, 878–880. Atlantis Press. doi:10.2991/snce-18.2018.180.

Zanero, S. (2017). Cyber-physical systems. *Computer*, 50(4), 14–16. doi:10.1109/MC.2017.105.

Zhou, K. and Doyle, J.C. (1998). *Essentials of robust control*, volume 104. Prentice hall Upper Saddle River, NJ.