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Evidence-Based Control Engineering Education: Evaluating the LCSD Simulation Tool

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ABSTRACT The advance in control engineering education needs well-designed studies that validate what methods and tools work best. This paper addresses the lack of empirical evidence supporting innovations in control engineering education by proposing a methodology that works at different abstraction levels. Hence, innovations' impact on students' performance can be statistically analyzed either globally or locally by examining competencies or fine-grained indicators, respectively. The article reports the application of the methodology for evaluating an interactive simulation tool, named LCSD, on 101 students at the Pontifical Catholic University of Valparaiso in Chile. According to the experimental results, LCSD is an effective free alternative to enhance the student's skills on control system analysis for our automatic control course. Also, some improvements have been identified for future LCSD versions.

INDEX TERMS Control engineering education, simulation, interactive tools, evidence-based education.

I. INTRODUCTION

Learning the fundamentals of automatic control requires acquiring a solid base on maths and physics to understand the theory thoroughly. Also, students need to learn how to interpret a variety of inter-related diagrams, whose trade-offs are crucial for the analysis and design of control systems [1]. For example, *time-response plots*, *pole-zero map*, *root locus*, and *frequency domain diagrams (e.g., Bode, Nyquist, and Nichols)*. Unfortunately, students frequently struggle to interpret the control information these diagrams depict and to link it with theory [2] correctly.

Although several *Interactive Learning Tools* (ILT) have been proposed to boost students' understanding on these topics [2]–[15], their real effectiveness has not been validated in most cases. This problem has been pointed out by several authors [16]–[22], who claim that decision making on pedagogical interventions to enhance the students' academic performance should be supported by empirical evidence.

This paper seeks to overcome this problem by proposing a methodology for evaluating educational innovations in control engineering. The basic idea is to structure the assessment hierarchically, from competencies and learning outcomes to low-level measurement indicators. This way, the teaching innovation effectiveness can be examined at various abstraction levels.

The paper reports the application of the proposed methodology for evaluating an interactive simulation tool called *Linear Control System Design* (LCSD) [2], [3], which has been specifically designed for teaching the fundamentals of control engineering. LCSD is free[1] and is distributed as lightweight portable binaries for Microsoft Windows and Mac OS (not requiring the installation of additional software). We do not use LCSD as a replacement for actual laboratories but to prepare our students for the second semester, where they work with real hardware. Working with both simulations and actual labs also helps students to recognize that mathematical models are simplifications that do not always mimic hardware's behavior adequately.

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[1] `https://www2.uned.es/itfe/LCSD/LCSD.html`

LCSD evaluation was conducted on two groups of 44 and 57 students taking an automatic control course at the *Pontifical Catholic University of Valparaiso*, in Chile. The former group used LCSD, and the latter Matlab. The results (i) validate LCSD as a suitable tool for teaching control concepts, especially the topics related to results' interpretation and validation, and (ii) identify some aspects that need to be improved in future LCSD versions.

The remainder of this paper is organized as follows. Section II shows the shortage of empirical validations in control engineering education by analyzing a sample of 19 articles published in 2019. Section III introduces our methodology and describes the context where it was applied. Section IV reports our evaluation results. Finally, Section V provides some concluding remarks.

II. RELATED WORK

Initial research on the use of computer simulations for assisting control engineering education dates from the early seventies [23]–[25]. Since then, the literature on this topic has grown incessantly. To get an idea about up to what point the pedagogical value of this approach has been validated, let us review the research published in 2019.

In general, collecting the whole population of articles that fall into the scope of a literature review is unrealistic [26]. Accordingly, instead of performing an exhaustive analysis, let us examine a paper sample that represents the population. To gather such sample, we queried Elsevier Scopus that, together with Clarivate Analytics-Web of Science (WoS), is the highest-quality bibliographic databases for research literature [27], [28].

The query in Figure 1 was run. Lines 1-4 set the scope of the search, where $\texttt{TITLE-ABS-KEY}(X)$ means "seek for X in the article's title, abstract, and keywords". Line 5 limits the results to articles published in 2019. Line 6 specifies that we are interested only in papers published in conference proceedings and journals. Finally, Line 7 restricts the subject area to *engineering*.

Table 1 lists the documents obtained with the query, indicating whether they report any empirical evaluation and, in the affirmative case, how the evaluation was carried out.

Figure 2 summarizes the results. 68.42% of the 19 papers in the sample do not report any validation at all, 26.32% briefly summarize students' answers to questionnaires, and just one paper provides some descriptive statistics about students' marks. It is worth noting that no paper provides any statistical inference test.

```
1 TITLE-ABS-KEY(
2   "control engineering"  AND  (education  OR  teaching)
3   AND  (simulation  OR  virtual  OR  computer)
4 )
5 AND LIMIT-TO(PUBYEAR, 2019)
6 AND (LIMIT-TO(DOCTYPE, "cp") OR LIMIT-TO(DOCTYPE, "ar"))
7 AND LIMIT-TO(SUBJAREA, "ENGI")
```

FIGURE 1. Query to retrieve from Scopus a sample of educational control engineering articles published in 2019.

TABLE 1. Scopus sample (19 papers published in 2019).

Article	Type of evaluation
De Brito et al. [29]: Thermosolar plant with didactic potential for study in modeling, simulation and control applications	✗
De la Torre [30]: A Master Course on Automatic Control with Remote Labs	✗
Farias et al [31]: Development of an Easy-to-Use Multi-Agent Platform for Teaching Mobile Robotics	Questionnaire
Gazdos [32]: Using real-time laboratory models in the process of control education	✗
Gonzalez-Vargas et al. [33]: A low-cost, free-software platform with hard real-time performance for control engineering education	Questionnaire
Hinov et al. [34]: LabVIEW Based Control System for PWM DC-DC Converter	✗
Kagami et al. [35]: A weblab control experiment using the ball and beam system and multiobjective optimization	✗
Kaluz et al. [36]: Flexy2: A Portable Laboratory Device for Control Engineering Education	✗
Kuczmann201927 [37]: Linear state space modeling and control teaching in maxwhere virtual laboratory	✗
Kuczmann et al. [38]: State Space Model Based Control in Virtual Laboratory	✗
Lei et al. [39]: Combining MOOL with MOOC to Promote Control Engineering Education: Experience with NCSLab	Descriptive statistics
Morales-Menendez et al. [40]: Virtual/Remote Labs for Automation Teaching: A Cost Effective Approach	Questionnaire
Nevaranta et al. [41]: Interactive Learning Material for Control Engineering Education Using Matlab Live Scripts	Questionnaire
Rabek et al. [42]: Integration of new control experiments to online environment	✗
Saenz et al. [43]: A new architecture for the design of virtual/remote labs: The coupled drives system as a case of study	✗
Samuelsen et al. [44]: A Holistic View on Engineering Education: How to Educate Control Engineers	✗
Takacs et al. [45]: OptoShield: A Low-Cost Tool for Control and Mechatronics Education	✗
Vasquez et al. [46]: Curriculum change for graduate-level control engineering education at the Universidad Pontificia Bolivariana	Questionnaire
Wakitani et al. [47]: Design of an educational hardware in the loop simulator for model-based development education	✗

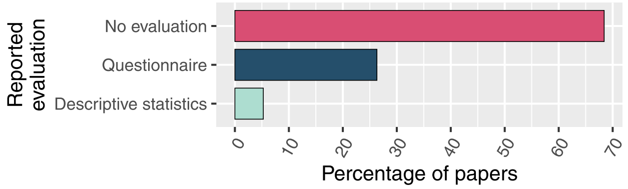


FIGURE 2. Educational evaluations reported in the article sample.

SUMMARY

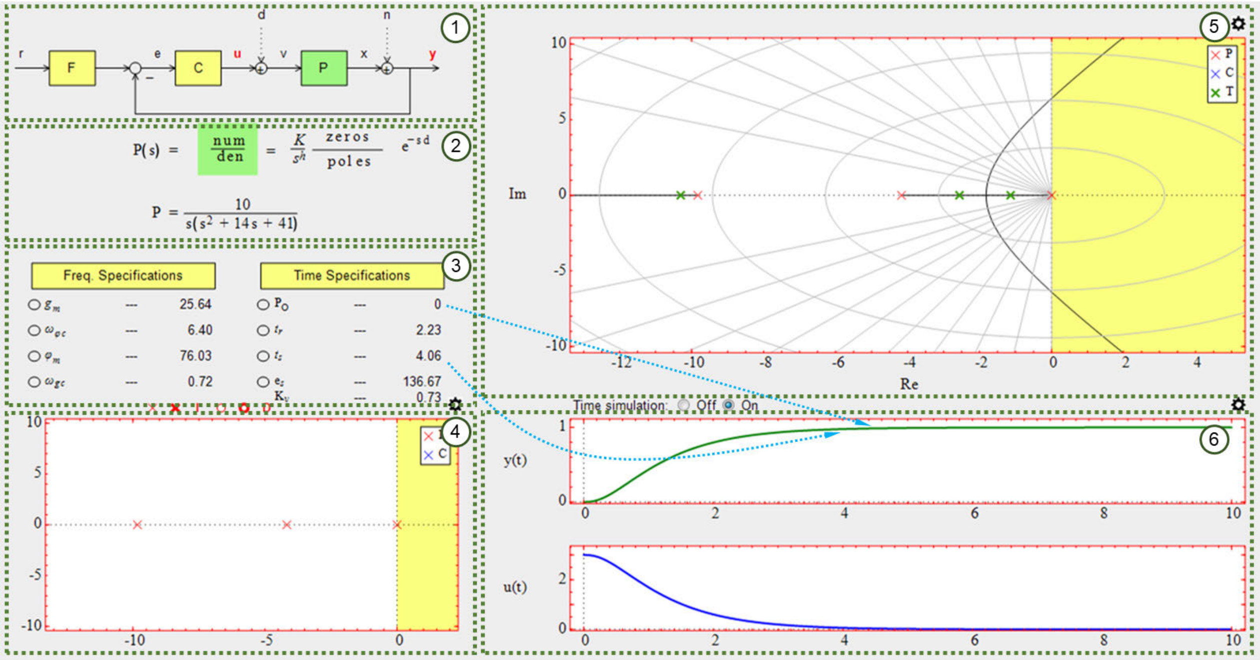
According to the article sample, there is a lack of empirical evidence supporting the educational value of control engineering simulations. This paper's contributions are (i) a framework that combines qualitative and quantitative statistical analyses to perform the needed experimental validations systematically, and (ii) a report obtained with the mentioned framework that accredits the effectiveness of the LCSD simulation tool for teaching automatic control in a university introductory course.

III. MATERIALS AND METHODS

This paper proposes a methodology to assess the effectiveness of innovations in control engineering education. Data are organized hierarchically in a competency-based model

TABLE 2. Course contents on which LCSD application was evaluated.

Competency	**Solving open and complex problems of Electrical Engineering.**	
Learning outcome	**Indicators**	**Low-Level Indicators**
The student will be able to apply methodologies of control system analysis to solve electrical engineering problems.	The student analyzes the transient and stationary response of control systems.	**TR-C**: The student determines the transient response specifications of a control system.
		SS-C: The student determines the steady state error of a control system.
	The student analyzes stability of control systems using Root Locus, Bode and/or Nyquist diagrams.	**RL-C**: The student determines and plots the control system root locus.
		BD-C: The student determines the control system phase and gain margin.
	The student interprets and validates the results obtained from the analysis of control systems.	**TR-I**: The student interprets the Transient Response of a control system.
		SS-I: The student interprets the Steady-State Response of a control system.
		RL-I: The student interprets the control system stability using the Root Locus technique.
		BD-I: The student interprets the control system stability using a Bode plot.
		ND-I: The student interprets the control system stability using a Nyquist diagram.



$$P(s) = \frac{num}{den} = \frac{K}{s^h}\frac{zeros}{poles}e^{-sd}$$

$$P = \frac{10}{s(s^2+14s+41)}$$

Freq. Specifications

○ g_m --- 25.64
○ $\omega_{\varphi c}$ --- 6.40
○ φ_m --- 76.03
○ ω_{gc} --- 0.72

Time Specifications

○ P_O --- 0
○ t_r --- 2.23
○ t_s --- 4.06
○ e_s --- 136.67
K_v --- 0.73

Time simulation: ○ Off ● On

FIGURE 3. Graphical user interface of the LCSD interactive tool (graphics obtained for a simple gain controller $K = 3$).

[48]–[50] to enable instructors to analyze information at different abstraction levels. Whereas the highest levels provide a panoramic view of the results, fine-grained analyses help to identify the innovation effects accurately. We will motivate and illustrate the use of the methodology by assessing the educational value of LCSD in a control engineering course.

A. A BRIEF INTRODUCTION TO LCSD

LCSD is an interactive simulation tool created by researchers at the Universidad Nacional de Educación a Distancia of Spain [2]. LCSD assists students in learning the analysis and design of linear Single-Input Single-Output (SISO) control systems using the loop shaping methodology. Through its interactive interface, students can change the value of various parameters and immediately visualize the effects on the control diagrams.

Figure 3 presents the user interface of the LCSD tool, in which 6 sections can be seen:

1) The ***block diagram*** section allows selecting the control structure (open or closed loop) and the type of input filter (F), controller (C) and process (P) to analyze. Students can either select and customize a transfer function among a set of predefined templates available for each control diagram block (F, C, and P), or define their own functions from scratch. Besides, it can enable a disturbance (d) at the input to the process and white noise (n) to the control system's output.

2) The ***parameter selection*** section supports the selection of the parameters related to the input filter, compensator, process, and input signals (r, d, n).
3) The ***performance Specifications*** section allows configuring the performance specifications in the time domain, such as overshoot and settling time, and frequency domain, like phase and gain margins.
4) The ***map of poles and zeros*** section shows the process poles and zeros. In this section, the user can modify the process roots.
5) The ***graphics*** section visualizes different analysis plots: Root locus, Bode, Nichols, Nyquist.
6) In the ***temporal response*** section, the user observes the different temporal signals of the block diagram: input, error, actuation and output, depending on which one is selected.

Once the process and the control type are set, the student can modify various system parameters in the LCSD interface, receiving immediate visual feedback of these changes on the system. For example, the user can change the controller parameters with the keyboard, through numeric fields established for this, or dragging a slider with the mouse. Furthermore, he/she can make changes in the dynamic behavior of the system, sliding with the mouse the poles of the closed control loop, which correspond to the green x observed at the root locus in Figure 3. With this change, the student observes a new controller gain and new performance parameters in the "Frequency Specifications" and "Time Specifications" areas.

LCSD has different color indicators that show whether the controller design meets the specifications, both in the frequency and time domain. For instance, in Zone 3 of Figure 3, there are small circles in green or red, depending on whether the performance specification is met or not, respectively. Also, in the graphics area, tinted yellow areas will appear, representing spaces outside the specifications defined for the system performance.

B. COURSE OF AUTOMATIC CONTROL

We have evaluated LCSD on an *automatic control* course of the master degree on *Electrical Engineering* at the *Pontifical Catholic University of Valparaiso* (PUCV), in Chile. The master follows the competency-based pedagogical paradigm [51], encompassing a total of twenty competencies. In the automatic control course, students develop two of them: ($C1$) solving open and complex problems of electrical engineering, and ($C2$) simulating electrical systems to represent its behavior, optimize its parameters, and improve its operating conditions. Competencies are subsequently decomposed into learning outcomes, and the latter into assessment indicators. Students' marks are obtained in a bottom-up fashion, from indicators to competencies, computing each element's mark as the weighted average of its descendants' marks.

We proposed and applied this competency assessment model in [50] on the same course, but with a different purpose. Table 2 summarizes the course contents on which our evaluation was focused. In previous course editions, students showed low performance on these contents, specifically when required to analyze and discuss their results in the applied assessment tools. In this context, instructors decided to incorporate LCSD to improve this situation, thus taking advantage of the *continuous improvement scheme* also proposed in [50].

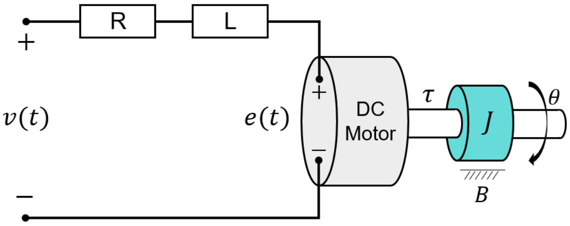


FIGURE 4. Scheme of an armature-controlled DC motor.

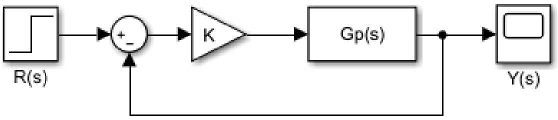


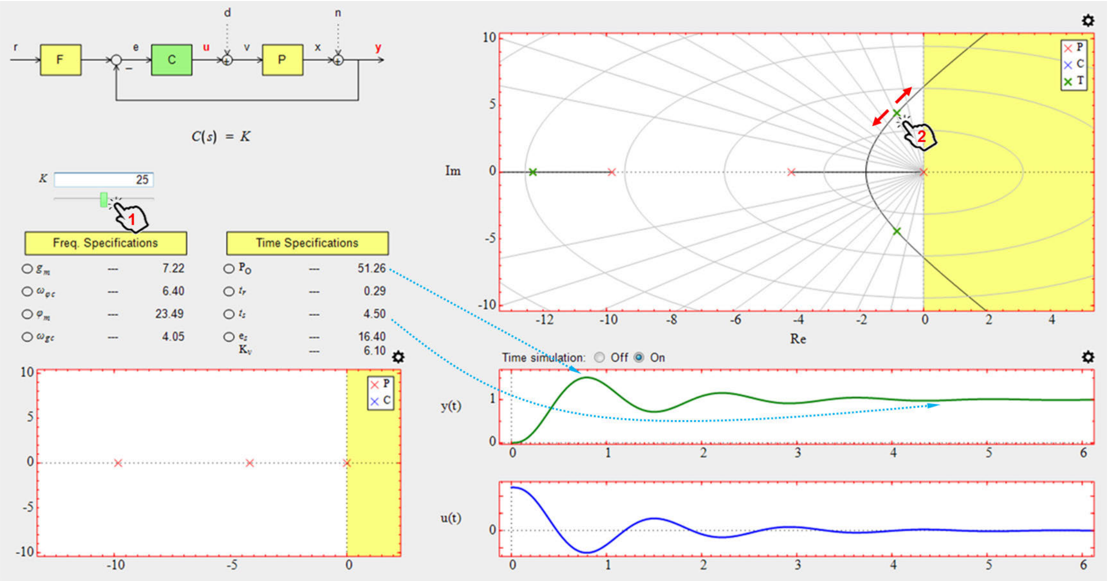
FIGURE 5. Closed-loop control scheme.

To complement our initial proposal, a new evaluative element was included to validate LCSD. The following lower-level indicators were defined for measuring the learning outcome under analysis: TR-I and TR-C (Transient Response of a control system), SS-I and SS-C (Steady State), RL-I and RL-C (Root Locus), BD-I and BD-C (Bode diagram), and ND-I (Nyquist diagram); where I and C correspond to interpretation and calculus, respectively. This allowed checking accurately if LCSD helps students to interpret and validate the results obtained from the analysis of a control system. Particularly, we targeted the following research questions:

- **RQ1: Educational value of LCSD**. *Is LCSD useful to enhance analysis and interpretation skills of control systems*?. In previous course editions, the Control System Toolbox (CST) of Matlab was used. Given that LCSD is free and provides a higher level of interactivity, we were interested in measuring the extent to which LCSD is comparable to what has been done previously, or even more appropriate for our educational purposes.
- **RQ2: LCSD melioration**. *What LCSD improvements do students demand?*. LCSD authors have expressed their commitment to support and improve the tool. Our validation could help developers by detecting bugs and new features that LCSD should incorporate.

To answer the questions above, two groups of students were compared in the first semester of 2019-2020. The content, instructors, and laboratory practices were the same for both groups. The only difference was the tool students used to carry out the practices: the *control group* utilized Matlab CST and the *treatment group* used LCSD.

To give an idea of the kind of laboratory practices our students undertook, the following section presents a summarized example of one of them by using the LCSD tool. A varied



$C(s) = K$

K 25

Freq. Specifications

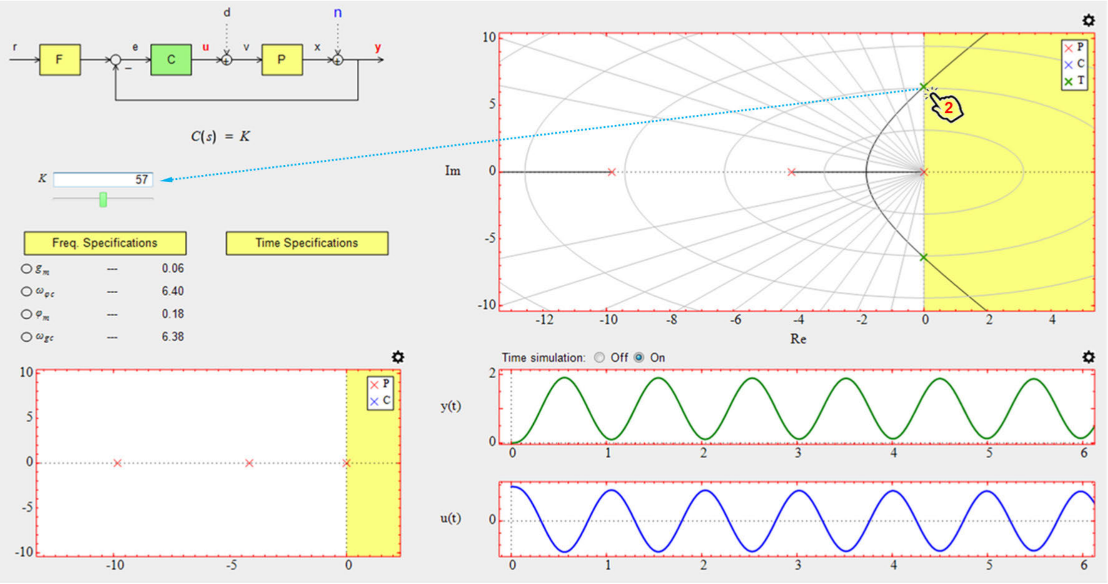
○ g_m --- 7.22
○ ω_{pc} --- 6.40
○ φ_m --- 23.49
○ ω_{gc} --- 4.05

Time Specifications

○ P_O --- 51.26
○ t_r --- 0.29
○ t_s --- 4.50
○ e_s --- 16.40
K_v --- 6.10

Time simulation: ○ Off ● On

(a) Root locus and performance specifications for $K = 25$.



$C(s) = K$

K 57

Freq. Specifications

○ g_m --- 0.06
○ ω_{pc} --- 6.40
○ φ_m --- 0.18
○ ω_{gc} --- 6.38

Time Specifications

Time simulation: ○ Off ● On

(b) Critical stability point reached for $K = 57$. As expected, time specifications are not observed in this case.

FIGURE 6. Using LCSD to analyze the time response in closed-loop control systems.

set of examples illustrating the LCSD use for control system analysis and design can be found in [2].

C. THE DC MOTOR LABORATORY PRACTICE

DC motors are mechanisms typically used for teaching basic control concepts. The following subsections describe some of the learning activities students face to analyze a DC motor's closed-loop behavior by using the LCSD tool.

1) MODELING

In this practice, students work on the armature-controlled DC motor that Figure 4 sketches, with inertia J and viscosity B.

The motor electromechanical model is described by Equations 1-4 (a complete discussion can be found in [52] and [53]).

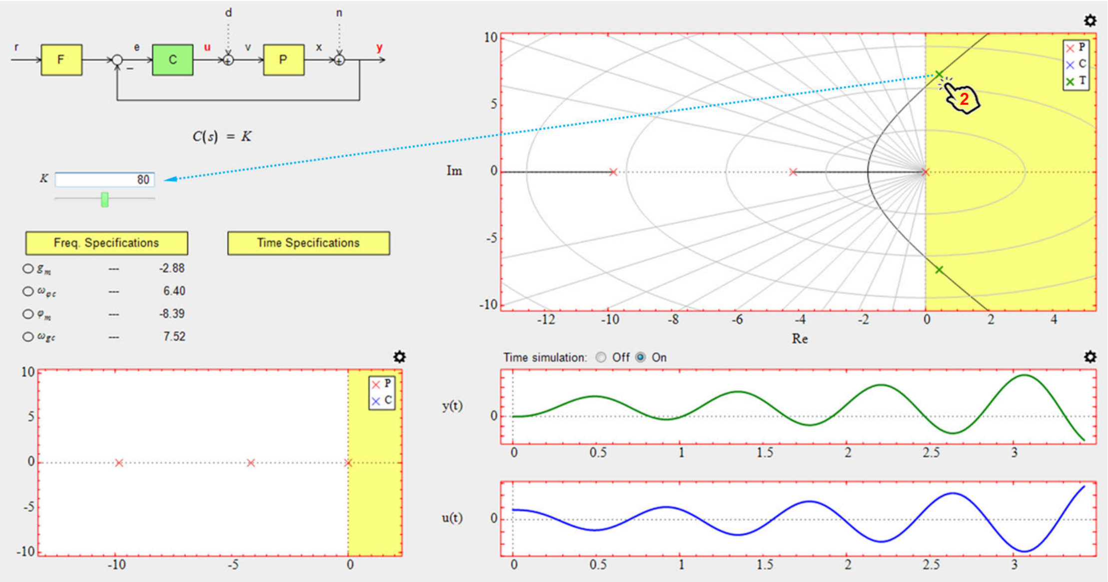
$$v(t) = Ri(t) + L\frac{di(t)}{dt} + e(t) \tag{1}$$

$$e(t) = K_b\frac{d\theta(t)}{dt} \tag{2}$$

$$\tau(t) = K_m i(t) \tag{3}$$

$$\tau(t) = J\frac{d^2\theta(t)}{d^2t} + B\frac{d\theta(t)}{dt} \tag{4}$$

Since the model is described by a set of linear differential equations, these can be transformed into the *Laplace domain*, thus simplifying its analytical treatment. Equation 5 shows the *transfer function* obtained for the motor position θ when



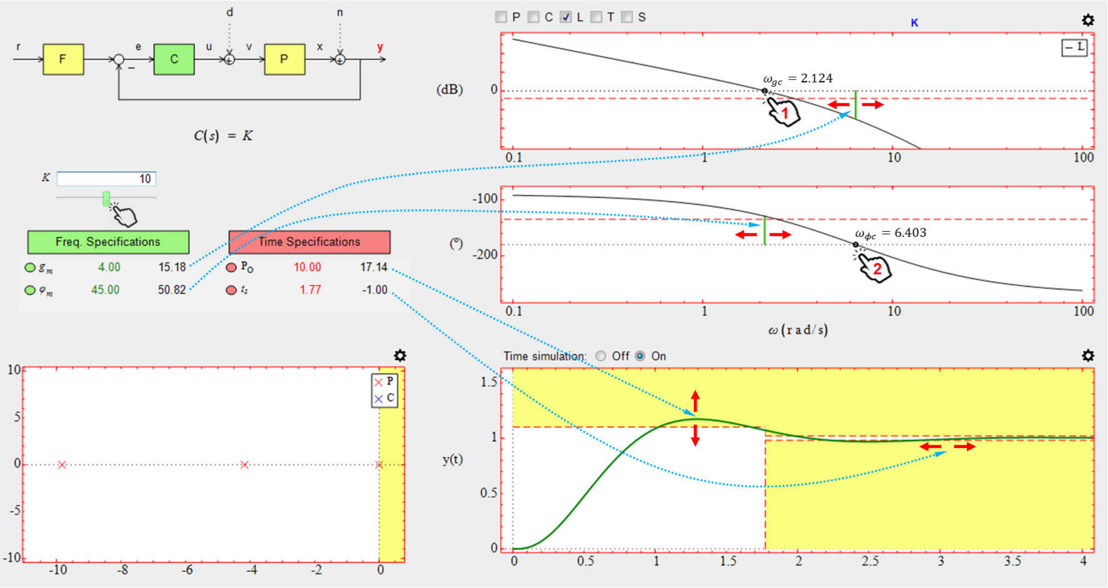
$C(s) = K$

K 80

Freq. Specifications		
○ g_m	---	-2.88
○ ω_{gc}	---	6.40
○ φ_m	---	-8.39
○ $\omega_{\varphi c}$	---	7.52

Time simulation: ○ Off ● On

FIGURE 7. Instability is manifested when the student drags the closed-loop pole beyond the stability zone (inside the yellow area for $K = 80$).



$C(s) = K$

K 10

Freq. Specifications		
● g_m	4.00	15.18
● φ_m	45.00	50.82

Time Specifications		
● P_O	10.00	17.14
● t_s	1.77	-1.00

☐ P ☐ C ☑ L ☐ T ☐ S

$\omega_{gc} = 2.124$

$\omega_{\phi c} = 6.403$

Time simulation: ○ Off ● On

FIGURE 8. The Bode diagram for stability analysis.

an input voltage V is applied.

$$\frac{\Theta(s)}{V(s)} = \frac{K_m}{s(LJs^2 + (JR + BL)s + BR + A^2)} \tag{5}$$

Each student has to determine the transfer function for a particular DC motor parameter. For example, Equation 6 would be the transfer function that corresponds to:

- $R = 2\ [\Omega]$
- $L = 0.5\ [\mathrm{H}]$
- $J = 0.02\ [\mathrm{kgm}^2]$
- $B = 0.2\ [\mathrm{kgm}^2/s]$
- $K_m = 0.1\ [\mathrm{Nm}/A]$
- $K_b = 0.1\ [\mathrm{Vs/rad}]$

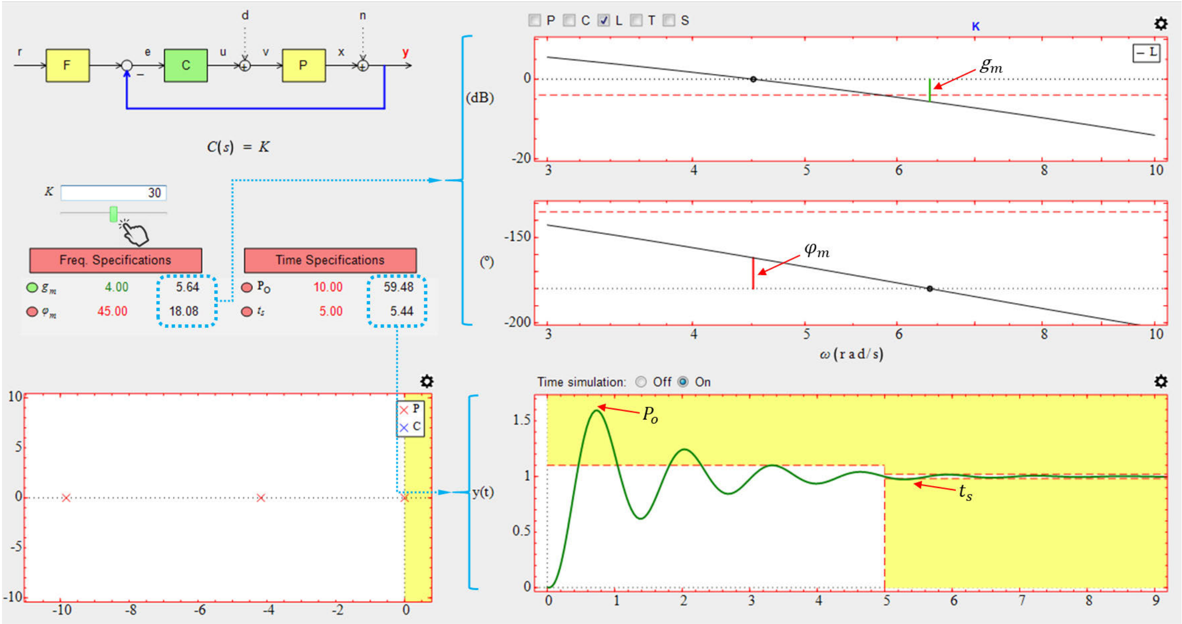
In this case, and as expected for a DC motor, the transfer function has a *pole* at the origin of the *Z-P diagram*, being its closed-loop behavior especially interesting for pedagogical purposes.

$$G_p(s) = \frac{\Theta(s)}{V(s)} = \frac{10}{s(s^2 + 14s + 41)} \tag{6}$$

2) TIME RESPONSE

Based on the process transfer function $G_p(s)$, students analyze the control diagram in Figure 5, whose closed-loop transfer function is specified with Equation 7.

$$G(s) = \frac{Y(s)}{R(s)} = \frac{10K}{s^3 + 14s^2 + 41s + 10K} \tag{7}$$



☐ P ☐ C ☑ L ☐ T ☐ S

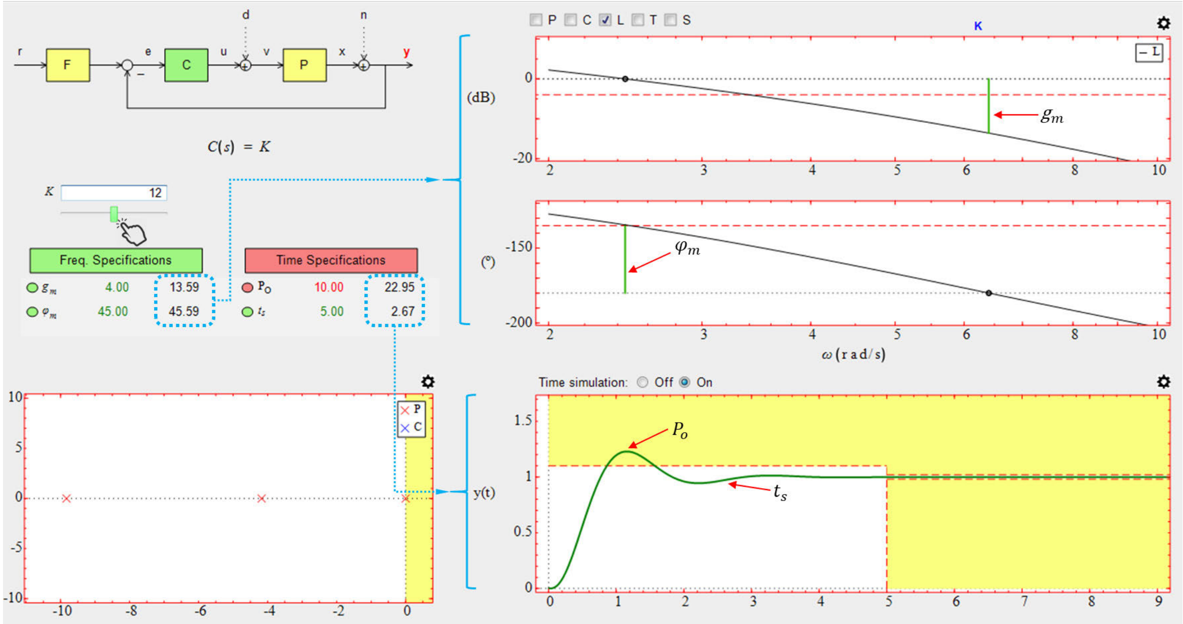
K 30

Freq. Specifications		
g_m	4.00	5.64
φ_m	45.00	18.08

Time Specifications		
P_o	10.00	59.48
t_s	5.00	5.44

Time simulation: ○ Off ● On

(a) Phase and margin margins for $K = 30$.



☐ P ☐ C ☑ L ☐ T ☐ S

K 12

Freq. Specifications		
g_m	4.00	13.59
φ_m	45.00	45.59

Time Specifications		
P_o	10.00	22.95
t_s	5.00	2.67

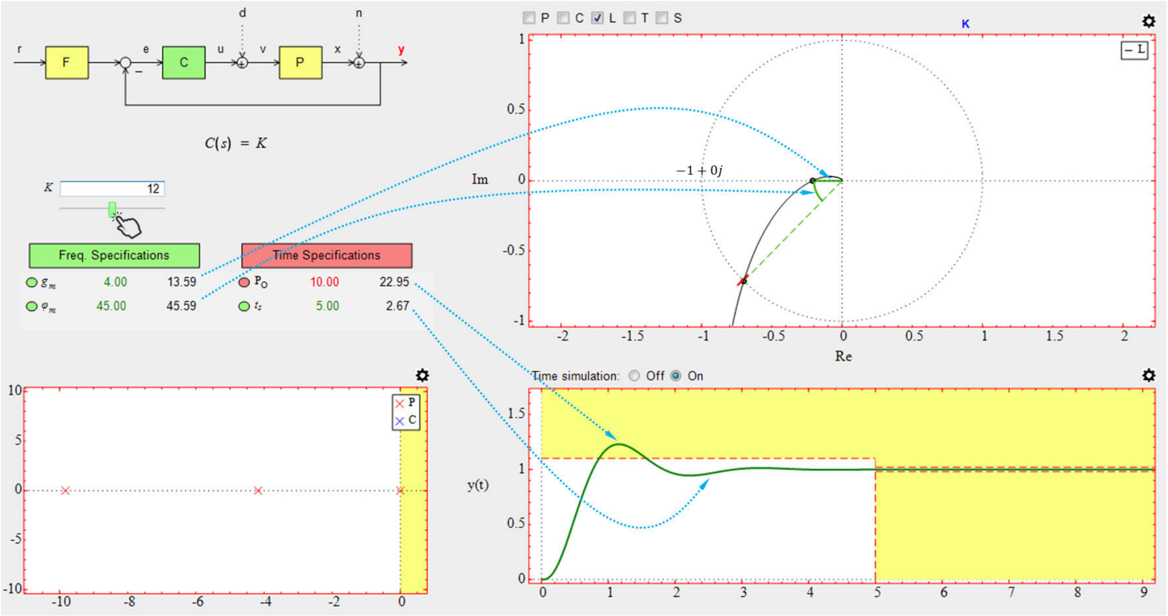
Time simulation: ○ Off ● On

(b) Phase and margin margins for $K = 12$.

FIGURE 9. **Example of stability analysis with *Bode diagrams.***

Students use LCSD to analyze the stability of the closed-loop system, varying K from 0 to ∞, and observing the corresponding changes in the *Time Specifications* area and *Root Locus* and *Time Response* diagrams. Figure 3 shows the results obtained for $K = 3$, where an overdamped response is obtained (as expected for two dominant closed-loop real poles) without overshoot and a settling time of 4.06 seconds.

Likewise, LCSD adapts the diagrams dynamically as the student changes the gain K interactively, either modifying the numeric field or slider (hand-click 1 in Figure 6a) or dragging a closed-loop pole on a *Root Locus* branch (hand-click 2 in Figure 6a). Figure 6a also shows the diagrams obtained after the student has dragged the real closed-loop pole closer to the imaginary axis in Figure 3 until a new placement on the *Root Locus* branch for $K = 25$. In this case, an underdamped response is observed (as expected for two dominant closed-loop complex poles) with an overshoot $P_o = 51.26\%$ and a settling time of 4.5 seconds. If the student follows dragging the closed-loop pole on the *Root Locus* branch, the critical stability point is reached for $K = 57$ (see Figure 6b) and going



$C(s) = K$

K 12

Freq. Specifications

○ g_m 4.00 13.59

○ φ_m 45.00 45.59

Time Specifications

● P_O 10.00 22.95

○ t_s 5.00 2.67

Time simulation: ○ Off ● On

FIGURE 10. Nyquist diagram for stability analysis.

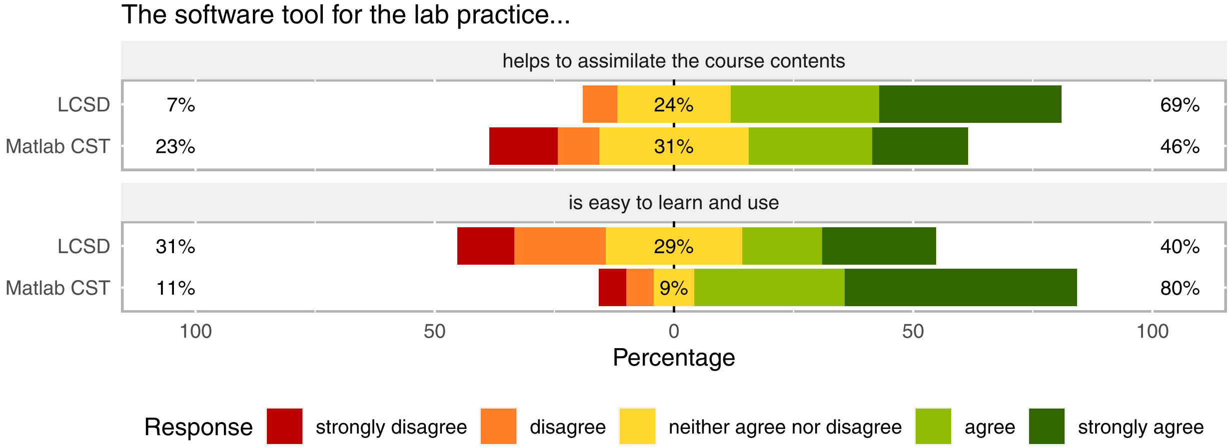


FIGURE 11. Students' response frequencies to the closed questions.

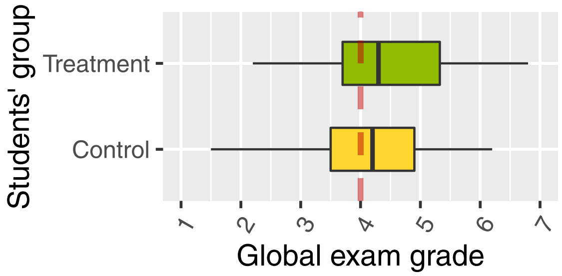


FIGURE 12. Treatment and control groups' global exam grades.

beyond, the imaginary axis is crossed getting the instability of the system (see Figure 7). Since LCSD displays all diagrams jointly in runtime, students easily relate changes on the *Root Locus*, *Time Response*, and *Performance Specifications* to gain changes, thus improving their insight on control system analysis in both time-response and stability concepts.

3) FREQUENCY RESPONSE

To study control systems in the frequency domain, students use the LCSD tool for stability analysis, primarily by looking at the phase and gain margins (φ_m and g_m) using *Bode* or *Nyquist* diagrams as K varies.

Figure 8 shows the plots that LCSD generates for $K = 10$ for the same transfer function $G_p(s)$ of the DC motor. Firstly, *Root Locus* plot is replaced by the *Bode* plot keeping the *Time Response* graph below so that students can observe the time and frequency response relationship.

Subsequently, students explore the *Freq. Specification* area to get the specific values of phase and gain margins. Likewise, two vertical lines in the *Bode* plot represent such values as well. Additionally, LCSD allows setting the desired stability requirements, displaying different colors depending on whether the system meets them, which is used for controller design purposes. On the other hand, they can see the relationship between the numerical value of the margins and the time specifications on runtime as they change the gain K interactively through the corresponding slider.

The student is also required to obtain the value of the gain crossover frequency ω_{gc} and the phase crossover frequency $\omega_{\phi c}$. This is done by moving the mouse over the points where the gain crosses the 0 dB, and the phase crosses the -180°, respectively, such as shown in Figure 8. After that, the student is required to obtain the phase and gain margins analytically in order to check their theoretical results with those obtained through the simulation.

Figure 9 explains how LCSD helps to recognize the time and frequency response dependency. For example, for $K = 30$ the phase margin is $\varphi_m = 18.8$, showing a time response with high oscillation ($P_o = 60\%$). When the student decreases the gain, the phase margin increases, and the time response presents fewer oscillations ($K = 12$, $\varphi_m = 45.6$, and $P_o = 23\%$ in Figure 9b).

Finally, by using the *Nyquist diagram*, the student can also observe the system stability visually. Figure 10 shows how the phase and gain margins are deployed in LCSD for $K = 12$. The student can change the gain and observe the effects instantaneously, helping him/her to relate different aspects such as margins, frontier stability point $(-1 + 0j)$, and time response.

IV. RESULTS AND DISCUSSION

This section reports the results of our evaluation. The treatment and control groups were composed of 44 and 57 students that used Matlab CST and LCSD, respectively.

The evaluation material (exam, questionnaire, and students' answers) is available at:

https://github.com/rheradio/LCSDAssessment

A. QUALITATIVE ANALYSIS

To gather students' opinions regarding the usability and usefulness of LCSD and Matlab CST, we asked them to fill a straightforward two-item questionnaire in the last laboratory session. Responding to the questionnaire was voluntary. The participation ratio was 42/44 and 52/57 students for the treatment and control groups, respectively.

Also, to encourage them to express honest and personal comments about LCSD, we proposed two more open-ended questions. Following Oppenheim's recommendations [54], open-ended questions were formulated as sentence-completion items to center students' responses. For example:

> Please complete the following sentence in your own words:
> *LCSD strengths to learn the analysis of control systems are ...*

1) CLOSED QUESTIONS

Figure 11 summarizes the obtained frequencies for two questions that inquire students about the usefulness and usability of LCSD and Matlab CST. Responses are rated on a five-point Likert scale.

TABLE 3. Students' responses to the open-ended questions.

LCSD strengths	
Versatility to represent multiple plots (temporal response, root locus, Bode, etc.).	88.1%
Ability to simulating both open and closed loop systems.	50%
High interactivity.	38.1%
LCSD weaknesses and suggested improvements	
Documentation needs to be improved; there should be video-tutorials with examples.	26.19%
The user interface is rigid and excessively complex; a more simplified version should be available.	23.81%
Some plots are too small; the user should be able to re-scale graphical elements.	21.43%
There are runtime errors that produce unexpected results and fault codes.	14.29%

TABLE 4. Descriptive statistics of the global exam grades.

	Sample size	**Mean**	**Std. dev.**	**1st Qu.**	**Median**	**3rd Qu.**
Treatment	44	4.484	1.065	3.700	4.300	5.325
Control	57	4.068	1.134	3.500	4.200	4.900

TABLE 5. Null hypothesis significance testing for the global exam grades. Statistical significance: $p \leq 0.05(*)$. Effect size: $d \sim 0.2$ (small $\star$).

Levene's Test			**Welch's adj.**	**One-tailed t-Test**		**Cohen's d**
Df	F	p**-value**		t	p**-value**	
99	0.309	0.580	✗	1.875	0.032 (∗)	0.376 (⋆)

2) OPEN-ENDED QUESTIONS

Table 3 summarizes the responses of the treatment group students to the open-ended questions. Note that the total number of participants in this group was 42 students. The right-hand column indicates the percentage of students that agree with the response in the left-hand column. The table only summarizes opinions supported by at least two students.

SUMMARY

According to the closed-questions, LCSD is as appropriate as Matlab CST for our introductory automatic control course, but less usable. The open-ended questions concerning LCSD reinforce this. Students appraise LCSD interactivity, diagrams, and simulation capabilities; however, they think LCSD needs to be polished in various aspects that affect its learnability and usability.

B. QUANTITATIVE ANALYSIS

All students from both the control and treatment groups undertook the same final exam. This section compares the exam marks of those groups.

1) GLOBAL EXAM

Table 4 and the box-plot in Figure 12 summarize the total scores, i.e., considering all exam questions. It is worth noting that, in the Chilean education system, students are graded from 1 to 7. The red dashed line in Figure 12 shows the threshold to pass the exam.

The treatment group scores look slightly above the control group ones. To verify if the difference is statistically significant, a *one-tailed independent t-test* was performed (see Table 5). First, a *Levene's* test was used to assess the groups' equality of variances. As the Levene's p-value ≥ 0.05, the equality hypothesis holds, and thus the t-test does not requires *Welch's adjustment*. The t-test p-value is 0.032; so, the group difference is statistically significant. Finally,

TABLE 6. Null hypothesis significance testing for the exam indicators. Statistical significance: $p \leq 0.05(*)$, $p \leq 0.01(**)$, and $p \leq 0.001(***)$. Effect size: $d \sim 0.2$ (small $\star$), $d \sim 0.5$ (medium $\star\star$), and $d \sim 0.8$ (large $\star\star\star$).

	Levene's Test			Welch's	One-tailed *t*-Test			Bonferroni's	Cohen's
	Df	***F***	***p*-value**	**adj.**	**Df**	***t***	***p*-value**	**adj. *p*-value**	***d***
TR-I	99	0.421	0.518	✗	99	3.407	4.747e-4 ($***$)	0.0043 ($**$)	0.684 ($\star\star$)
TR-C	99	5.201	0.024 ($*$)	✓	98.665	0.271	0.541	$\sim$1	0.1181
SS-I	99	0.194	0.661	✗	99	6.288	4.37e-09 ($***$)	3.933e-08 ($***$)	1.262 ($\star\star\star$)
SS-C	99	0.391	0.533	✗	99	0.626	0.266	$\sim$1	0.125
RL-I	99	1.165	0.283	✗	99	1.682	0.478e-1 ($*$)	0.430	0.338 ($\star$)
RL-C	99	0.106	0.745	✗	99	0.325	0.373	$\sim$1	0.0652
BD-I	99	4.260	0.041 ($*$)	✓	97.248	2.650	4.696e-3 ($**$)	0.0423 ($*$)	0.506 ($\star\star$)
BD-C	99	0.004	0.947	✗	99	0.144	0.443	$\sim$1	0.029
ND-I	99	0.399	0.530	✗	99	1.469	7.255e-2	0.653	0.294 ($\star$)

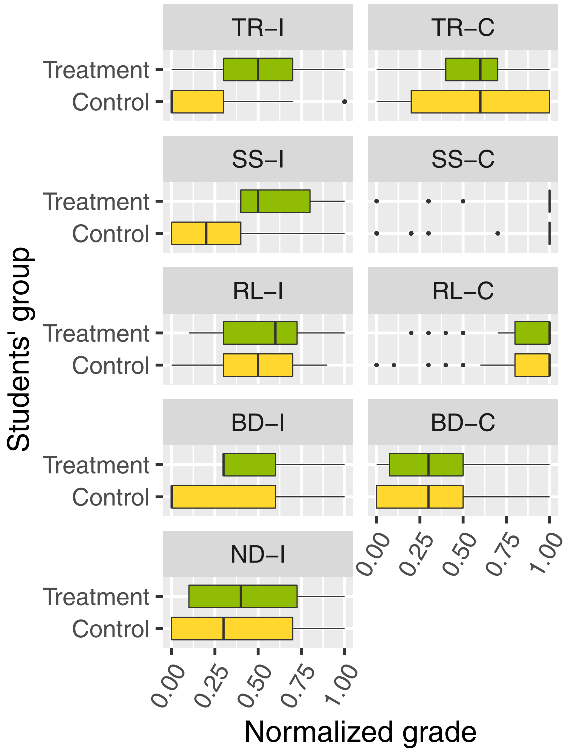


FIGURE 13. Treatment and control groups' indicator grades.

the last column reports the *effect size*. According to the rule of thumb given in [55], a *Cohen's d* around 0.2 indicates a small effect.

2) LOW-LEVEL INDICATORS

We were particularly concerned about whether LCSD helps students to fulfill the learning outcome in Table 2. Accordingly, this section focuses on the fine-grained indicators TR (Transient Response of a control system), SS (Steady State), RL (Root Locus), BD (Bode diagram), and ND (Nyquist diagram).

Table 7 and Figure 13 summarize the exam scores for these specific indicators. The notation INDICATOR-I and -C distinguishes between the scores that students obtained interpreting and calculating the indicator, respectively. For instance, TR-I stands for the students' scores on the interpretation of TR, and TR-C stands for the students' scores on TR calculation. It is worth noting that the course includes the interpretation of Nyquist diagrams, but not their calculation.

Table 6 summarizes the results of the null hypothesis significance tests for all the exam indicators. To counteract the Type I error inflation due to the multiple comparisons, the Bonferroni corrections of the *p*-values are reported. Accordingly, only TR-I, SS-I, and BD-I show statistically significant differences in favor of the treatment group.

TABLE 7. Descriptive statistics of the exam indicators.

		Mean	Std. dev.	1st Qu.	Median	3rd Qu.
TR-I	**Treatment**	0.479	0.327	0.300	0.500	0.700
	Control	0.247	0.349	0.000	0.000	0.300
TR-C	**Treatment**	0.602	0.257	0.400	0.600	0.700
	Control	0.565	0.355	0.200	0.600	1.000
SS-I	**Treatment**	0.604	0.234	0.400	0.500	0.800
	Control	0.259	0.300	0.000	0.200	0.400
SS-C	**Treatment**	0.852	0.305	1.000	1.000	1.000
	Control	0.810	0.352	1.000	1.000	1.000
RL-I	**Treatment**	0.564	0.237	0.300	0.600	0.725
	Control	0.489	0.205	0.300	0.500	0.700
RL-C	**Treatment**	0.848	0.230	0.800	1.000	1.000
	Control	0.832	0.261	0.800	1.000	1.000
BD-I	**Treatment**	0.477	0.250	0.300	0.300	0.600
	Control	0.312	0.374	0.000	0.000	0.600
BD-C	**Treatment**	0.332	0.309	0.075	0.300	0.500
	Control	0.323	0.315	0.000	0.300	0.500
ND-I	**Treatment**	0.466	0.327	0.100	0.400	0.725
	Control	0.367	0.344	0.000	0.300	0.700

The explanation regarding how to perform the calculations is theoretical, i.e., students learn them in a traditional classroom session. Consequently, there is no meaningful difference between the treatment and control groups concerning the calculation indicators (TR-C, SS-C, RL-C, and BD-C). This comparison verifies that both groups are similar in cognitive terms. In contrast, there are differences between LCSD and Matlab CST in all interpretation indicators, being statistically significant the ones in TR-I, SS-I, and BD-I.

SUMMARY

Concerning the global exam scores, there is a small but statistically significant difference between the control and treatment groups. Analyzing the exam scores at a more fine-grain level, there are statistically significant differences in the TR-I, SS-I, and BD-I indicators with medium, large, and small effect sizes, respectively.

V. CONCLUSION

The methodology presented in this paper guides researchers and practitioners to perform evaluations for collecting evidence about the strengths and shortcomings of innovations in control engineering education. This information is fundamental to advance toward better tools and methods.

On the other hand, we have identified LCSD's most useful features (e.g., high interactivity, multiple and simultaneous inter-related plots, etc.) and drawbacks (e.g., bugs, improvable documentation, interface rigidity, etc.), thus orienting LCSD future development.

The use of low-level assessment indicators allows a fine-grained analysis regarding students' academic performance in the different sub-topics studied, thus observing their strengths and weaknesses. This information plays a crucial role in continuous academic improvement. However, we are aware that gathering the sub-scores in assessment tools requires a significant effort. Our future research will seek to take advantage of the automatic assessment paradigm to collect indicators in a fast and effective way, thus reducing the effort required in this process.

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