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An Interactive and Comprehensive Software Tool to Promote Active Learning in the Loop Shaping Control System Design

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ABSTRACT The classical loop shaping is a design procedure that explicitly involves the shaping of the open loop transfer function $L(s)$, within a desired frequency spectrum by manipulating the poles, zeros, and gain of the controller $C(s)$. Interactive software tools have proven as, particularly, useful techniques with high impact on control education. This kind of interactive tools has demonstrated in the past that students learn in a much more active way. This paper presents the basic functionality of the linear control system design (LCSD), an interactive tool for analysis and design of linear control systems with special emphasis on the classical loop shaping design. The software tool is implemented in Sysquake, a MATLAB-like language with fast execution and excellent facilities for interactive graphics, and is delivered as a stand-alone executable that is readily accessible to students and instructors. Several design problems are used to illustrate the main features of the LCSD tool to perform classical loop shaping.

INDEX TERMS Control engineering education, educational aids, interactive software tools, loop shaping design.

I. INTRODUCTION

Conventional teaching procedure based on classical components formed by textbook-blackboard-lecture-homework and evaluation test for student learning has received much criticism in recent years. Many studies have shown that the use of lecturing paradigm produces a passive learning atmosphere. Today there is a clear consensus that engineering students learn much better by participating and interacting, instead of by watching and listening [1].

In this sense, the use of techniques that promote higher order critical thinking skills such as analysis, synthesis, and evaluation has been shown to be highly effective in improving students' learning [2]. Several innovative methodologies have been proposed to promote active learning among engineering students. Examples include the use of computer-based instructional tools [3]; self-paced computerized tutorials [4]; multi-media presentations [5]; cooperative learning [1]; hands-on demonstrations [6]; computer simulation models [7]; project/problem-based learning [8], [9]; internet-based instruction [10] and use of interactive software tools [11].

Control engineering is a multidisciplinary subject that is part of the curriculum of aerospace, industrial, mechanical, electrical and chemical engineering students. Typically, an introductory undergraduate course on fundamentals of control systems includes the following contents [12]–[14]: mathematical models of dynamic systems, analysis of the time-response of dynamic systems, analysis of the root locus, analysis of the frequency response of dynamic systems, design of basic feedback control systems using lead compensators, lag compensators, lag-lead compensators, and PID controllers.

Most of these contents have a nice an intuitive graphical representation: time series plot, poles-zeros map, root locus, and frequency domain plot (Bode plot, Nyquist plot, or Nichols plot). These diagrams are related to each other. For example, a change in the position of a pole of a linear system in the poles-zeros map produces a modification of its time response, root locus and frequency response. Likewise, a change in the corner frequency of a pole in a frequency plot produces a change in the time response, poles-zeros map and root locus.

The knowledge of the tradeoff between the different types of diagrams is fundamental in the analysis and design of control systems. However, some students have difficulties to grasp them. Our experience in teaching introductory undergraduate courses in control systems tells us that the best way to teach and learn these dependencies is using interactive software tools, [15]–[29].

The most popular software in control systems education is MATLAB, due to its power and versatility. From an educational point of view, however, to illustrate the dependencies between the different types of diagrams, it would be useful to have some supporting software with a graphical user interface that displays better interactivity than the one found in MATLAB, and which could be used by both instructors and students.

The idea of interactive design procedure presents two important differences in relation to the conventional scheme (non-interactive design):

1) The interactive approach introduces a feedback loop of iterative design from the outset. In this way, the users can identify the tradeoff of their designs in a systematic way and modify the controller to satisfy the specifications involved.
2) Not only the effect of the manipulation of the design parameters is visualized, but also the gradient of the changes becomes immediately clear. The control engineer learns quickly which parameter to use and how to push the design in the direction of fulfilling better satisfaction of the specifications. Fundamental limitations of the system and the type of controller are revealed [30], giving a way to find an acceptable settlement between all the performance criteria.

Using the interactive approach the students can learn to recognize when a process is easy or difficult to control. In summary, the distinctive features of the interactive control design procedure are the following:

1) The modifications of the parameters or other elements, such as the poles-zeros diagram, immediately produce an update of the overall graphical elements in the interface.
2) The design process is completely dynamic.
3) Students feel in a very natural way the gradient of the performance change in relation to the elements they are handling.
4) This interactivity makes easier to identify the tradeoff that can be reached.

Many design control methods are based on the open loop transfer function $L(s)$, which is related to the controller transfer function $C(s)$ through $L(s) = C(s)P(s)$, where $P(s)$ is the plant. It is thus simple to inspect how the controller $C(s)$ affects the open loop transfer function $L(s)$. This straightforward idea is the foundation of several different design methods collectively called *loop shaping* [31]–[33]. These methods are based on selecting a compensator that gives a loop transfer function with a desired shape.

In the classical loop shaping, the designer must decide how to modify the parameters, such as poles, zeros and gain, in such a way that the loop transfer function meets the specifications. This means that the procedure is an indirect design technique where the closed loop transfer function is designed using the open loop transfer function as an intermediate step. This way of working is very suitable for the use of interactive tools because classical loop shaping design is typically an iterative procedure where the designer shapes and reshapes $|L(j\omega)|$ to meet all specifications. This is the reason why the loop shaping technique fits like a glove with an interactive design using the software tools available today. The graphic image is as if the loop gain $|L(j\omega)|$ were an elastic band that it is possible to bend in the desired frequency range to meet the specifications given.

This paper deals with a new way to use interactive software tools in the teaching and learning of classical loop shaping in control system design. At present, the analysis and design tools have very well developed intuitive man-machine interface. Students can manipulate system parameters and structure directly using the mouse and instantly see the results on system behavior. Compared with the conventional simulation, the effectiveness of using such tools is drastically increased.

An interactive control system tool for control education should satisfy at least the following requirements to fulfill the needs of any user [34]:

- *Interactivity through the graphical user interface* (GUI). The text type interaction should be reduced as much as possible and the student should be able to interact with the system simply using mouse dragging in the GUI or "short-cut" keys.
- *Simplicity*. An interactive tool should be simple and focus on the specific concept that is trying to transmit, without overloading the content. The virtue of simplicity is a priority objective. The interaction should be intuitive and clear. What students need is to be able to start to act easily, and to reach the result as soon as possible.
- *Easy to understand and use*. An interactive tool cannot, and should not be used as a replacement of textbooks. Its main virtue is to help the students to deepen in their understanding of the fundamental concepts in control.
- *Accessibility*. The students should be able to easily access the interactive tool when necessary to study on his/her own pace not being dependent on the schedule of the computer room at the university campus.
- *Extendable.* The interactive tool should be designed in such a way that when necessary, a new module can be easily attached and used.
- *Self-contained*. The interactive tool can be accessed as an independent study unit that provides all that is necessary for learning.

Considering these ideas, we decided to develop the Linear Control System Design (LCSD) tool, an interactive software tool for teaching and learning the design of

Single-Input Single-Output (SISO) linear controllers using the loop shaping methodology.

The structure of this paper is as follows. First, basic ideas of the manual loop shaping methodology are summarized. Second, the functionality and use of LSCD are described. Third, different illustrative examples showing the use of LCSD are included. Finally, conclusions are presented.

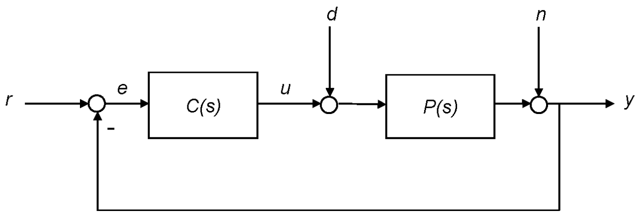

FIGURE 1. Classical 1-DOF control system.

II. BASIC IDEAS OF MANUAL LOOP SHAPING METHODOLOGY

Let be the typical one degree of freedom (1-DOF) single-loop control system shown in Fig. 1. Where u is the control signal, y is the output signal, e is the error signal, r is the reference signal, d is the disturbance signal, and n the noise signal. The plant and the controller are linear and time-invariant with transfer function given by $P(s)$ and $C(s)$ respectively. The plant is fixed and the controller is to be designed.

The goals of a control system are tracking references $R(s)$ and rejecting disturbances $D(s)$, while trying to be as much insensitive as possible to measuring noise $N(s)$.

The closed loop relationship between these signals and the output $Y(s)$ can be written as

$$Y(s) = \frac{L(s)}{1+L(s)}R(s) + \frac{P(s)}{1+L(s)}D(s) + \frac{1}{1+L(s)}N(s), \quad (1)$$

where

$$L(s) = C(s)P(s) \quad (2)$$

is the *open loop transfer function*. Let be

$$T(s) = \frac{L(s)}{1+L(s)} \quad (3)$$

the *complementary sensitivity function*,

$$S(s) = \frac{1}{1+L(s)} \quad (4)$$

the *sensitivity function*, and

$$P(s)S(s) = \frac{P(s)}{1+L(s)} \quad (5)$$

the *load sensitivity function*.

To achieve the desired performance, $T(s)$ should be equal to 1, while $S(s)$ and $P(s)S(s)$ should be identically 0. Clearly, this cannot be globally achieved by selecting a controller $C(s)$. Additionally, it is important to note that

$$S(s) + T(s) = 1, \quad (6)$$

so all the closed loop transfer functions are related and cannot be independently fixed.

Regarding the input signals, reference $|R(j\omega)|$, disturbance $|D(j\omega)|$, and noise $|N(j\omega)|$, it is normal to make certain assumptions of their frequency content. In most common applications references and disturbances are constant or slow-varying signals while noise is a rapidly-varying signal. In other words, $|R(j\omega)|$ and $|D(j\omega)|$ are relevant variables in the low-frequency range and tend to zero as frequency increases while $|N(j\omega)|$ takes small values in the low-frequency and becomes relevant in the high-frequency range.

Considering this scenario, it is possible to reformulate the objective that a controller must achieve. If in the low-frequency range, or *control band*, it is verified that $|T(j\omega)| \approx 1$ and $|P(j\omega)S(j\omega)| \approx 0$ signal references would be tracked and disturbances would be rejected while if $|S(j\omega)| \approx 1$ in the high-frequency range, or *cut-off band*, noise would not be amplified. These conditions could be achieved by selecting a controller $C(s)$ which guarantees that $|L(j\omega)| = |C(j\omega)P(j\omega)|$ is high enough in the low-frequency range and $|L(j\omega)|$ is small enough in the high-frequency range.

An additional necessary condition is closed loop stability and robustness which in classical control is measured in terms of the gain and phase margins. For a stable $L(s)$, this implies that $|L(j\omega)|$ must be small (less than 1) when $\arg(L(j\omega))$ is more negative than -180° (*gain margin*) and that $\arg(L(j\omega))$ must be greater than -180° when $|L(j\omega)| \approx 1$ (*phase margin*). In summary, a typical set of loop shaping specifications [34] are the following:

$$\begin{array}{ll} |L(j\omega)| \geq l(\omega) & 0 \leq \omega \leq \omega_B \\ |L(j\omega)| \leq u(\omega) & \omega \geq \omega_C \\ 150^\circ \leq \arg(L(j\omega)) \leq 30^\circ & \omega_B \leq \omega \leq \omega_C \end{array} \quad (7)$$

where interval $[0, \omega_B]$ defines the control band and interval $[\omega_C, \infty]$ is the cut-off band. Crossover specifications are imposed between both bands, in particular, in the crossover band between ω_C (where $|L(j\omega_C)| = 1$) and ω_{180} (where $\arg(L(j\omega_{180})) = -180^\circ$). At these frequencies, the main issue is to maintain $L(j\omega)$ at a safe distance from the critical point -1 (closed loop stability).

By loop shaping [31]–[33] we mean a design procedure that involves explicitly shaping the loop transfer function $L(j\omega)$ in order to meet the specifications. The loop shaping design is usually done in a Bode, Nyquist, or Nichols plot. In each representation, the specifications can be associated to different geometric shapes. The most relevant properties of these representations are:

- *Bode plot*. In this diagram (see Fig.2), the evolution of $|L(j\omega)|$ and $\arg(L(j\omega))$ against frequency are drawn. To meet the required behavior, it is necessary that in the control band, $|L(j\omega)|$ is over a certain value defined taking into account the allowed error. While in the cut-off band, $|L(j\omega)|$ must be below a given value fixed according to the required noise attenuation. Additionally, care must be taken with respect to the evolution

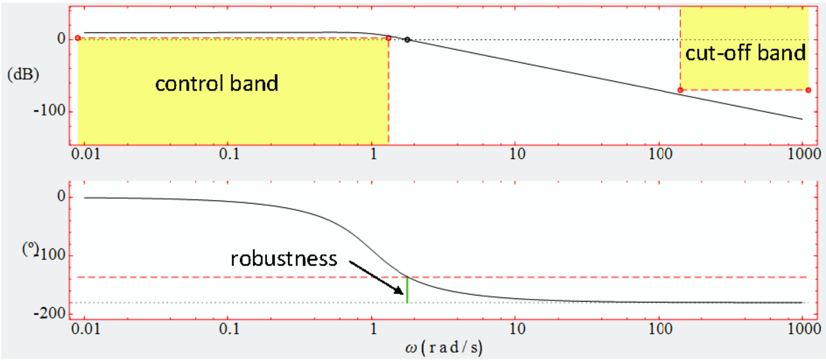

FIGURE 2. Frequency response of $L(s)$ and specifications in a Bode plot.

of arg($L(j\omega)$) to guarantee the closed loop stability and robustness through the gain and phase margin. In this diagram, it is possible to display the corner frequencies of the controller poles and zeros, and modifying them it is possible to shape $|L(j\omega)|$ as required. The asymptotic nature of $|L(j\omega)|$ helps to have a clear cause-effect intuition.

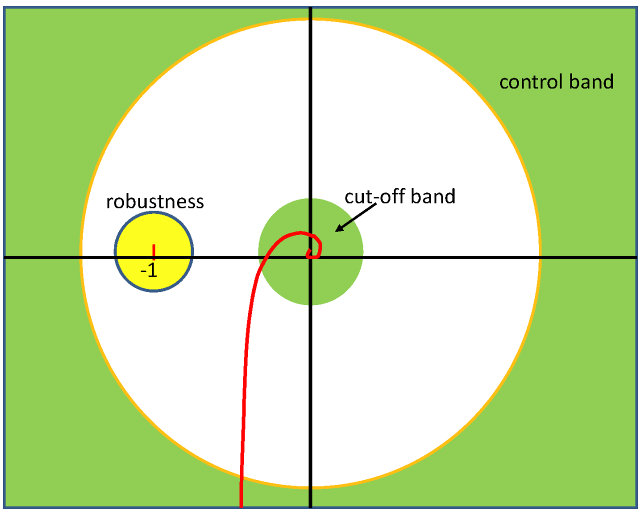

FIGURE 3. Frequency response of $L(s)$ and specifications in a polar (Nyquist) plot.

- *Polar plot* (*Nyquist plot*). In this diagram (see Fig.3), the evolution of $\Re\{L(j\omega)\}$ against $\Im\{L(j\omega)\}$ is drawn, so frequency ω is not given explicitly. In the polar plot those points that have the same module are over the same circle centered in the origin, accordingly to meet the specifications in the control band $L(j\omega)$must be out of a big circle of radius defined by the allowed error in the frequency operation range, $0 < \omega \leq \omega_B$, while in the cut-off band $L(j\omega)$ must be inside a small circle with a radius defined by the required noise attenuation. Regarding to robustness, $L(j\omega)$ must be out of a circle centered in (-1,0) of radius defined according to the robust specification.
  As the polar plot combines phase and gain in one diagram it is possible to simultaneously consider closed loop stability and robustness, $L(j\omega)$ must combine high gain with a reduced phase to guarantee performance in a robust manner. Additionally, it is possible to compute those points that would correspond to the same value of $|S(j\omega)|$. This directly connects the open loop system with the closed loop one, and it is a very interesting hint during the loop shaping procedure.
  One drawback about using the Nyquist plot for loop shaping is that there is no straightforward connection between the movements of the poles and zeros of the controller and the changes in the curve at a given point. Additionally, it needs to display values of $L(j\omega)$ with big modules, in the control band, and others with small modules, in the cut-off band. This is, in general, difficult to be done because of the linear nature of the Nyquist plot.
- *Nichols plot*. In this diagram (see Fig. 4), the evolution of $|L(j\omega)|$ in dB, in the vertical axis, against arg($L(j\omega)$) in degrees, in the horizontal axis, is shown, so frequency ω is not given explicitly. To meet the control band (cut-off band) specifications, $L(j\omega)$ must be over (below) a horizontal line fixed according to the allowed error (noise attenuation). Additionally, gain and phase margin can be easily identified by looking at the intersection between $L(j\omega)$ and a horizontal line corresponding to 0 dB (phase margin) and the intersection of $L(j\omega)$ with a vertical line corresponding to -180^{o} (gain margin). As this diagram contains all information from $L(j\omega)$ in some cases the curves corresponding to equal values for $S(j\omega)$ are automatically drawn which can be of great help during the loop shaping procedure.
  In addition, like the gain is drawn in dB, both big and small values of $|L(j\omega)|$ can be displayed with no problem.

As a conclusion, the Bode plot and the Nichols diagram are the two most popular scenarios to perform the loop shaping, the first one has the advantage to show the frequency in a natural manner while the second offers a complete and intuitive formulation in just one diagram.

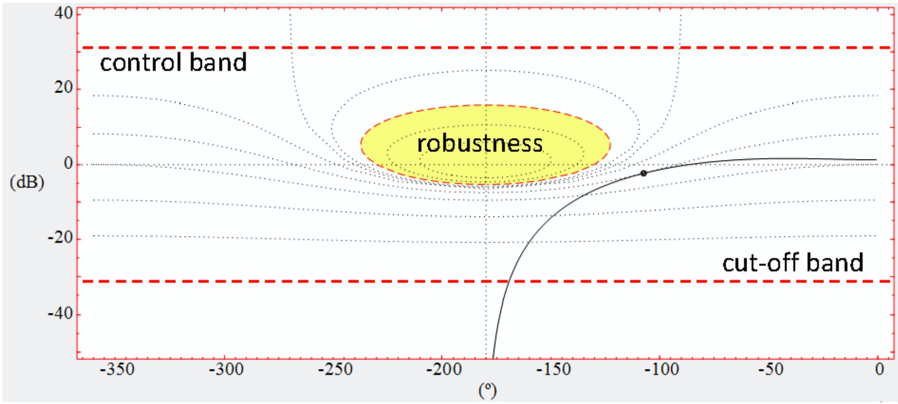

FIGURE 4. Frequency response of $L(s)$ and specifications in a Nichols plot.

In the manual loop shaping, first, the designer has to select a frequency response diagram (Bode, Nyquist or Nichols) to work. Second, the frequency specifications have to be drawn in the selected diagram. Third, the designer has to select a controller structure (lag compensator, lead compensator, lag-lead compensator, PID compensator,...). Fourth, it is necessary to adjust the controller elements (gain, poles, and zeros) in a poles-zeros map, or their corner frequencies in the selected frequency response diagram, to shape the open loop transfer function $L(s)$, and meet the specifications. If the specifications cannot be met with the controller structure selected in step 3, the designer has to try another control structure. Thus, the manual loop shaping design is an iterative procedure. Obviously, the performance of this design technique requires the use of software tools with adequate GUIs.

III. LCSD TOOL DESCRIPTION

LCSD is a free of charge stand-alone executable for Windows and Mac OS computers. The tool has been developed using Sysquake [35], an integrated development environment with a programing language like the one used in MATLAB. Sysquake has excellent facilities for developing tools with interactive figures. This interactivity allows users to visually perceive the effects of their actions, and as a result is very useful to grasp the concepts that want to be taught/learnt.

LCSD main features are simplicity, ease of use and interactivity. Users can interact with the tool by menus, text fields, sliders, buttons and different items in the figures displayed on the main window of the tool. Any action carried out on these elements is immediately reflected on all the figures on the screen. Obviously, the interactive capabilities of the tool can only be appreciated by testing it and cannot be fully conveyed through text. The best way to do that is to download and test the tool [36]. The LCSD main window (see Fig. 5) is organized in six zones: *block diagram*, *parameters setting*, *performance/specifications*, *poles-zeros map*, *root locus/frequency response*, and *time response*.

The *block diagram* zone is a block diagram of two degrees of freedom. This block diagram consists of three blocks (prefilter F, controller C, and plant P), three inputs (reference r, plant input disturbance d, and plant output disturbance n), one output (y), and four intermediate signals (error signal e, controller output u, plant input v, and plant output x). In this area, users can perform the following actions:

- Select the block or the input whose structure and parameters wants to configure in the rest of zones of the tool. The block or input selected is represented in light green color. LCSD has implemented several predefined structures of transfer functions: first order, first order with an integrator, second order, etc. The tool also allows the user to define the structure of its own transfer function. Besides, LCSD has implemented six types of inputs: pulse, step, ramp, parabola, sinusoid, and white noise.
- Select the signals that are represented in the *time response* zone. The selected signals are represented in red color.
- Enable feedback. If the feedback is enabled the associated line of the block diagram is plotted in solid line, otherwise the line is plotted in dotted line.
- Enable disturbances d and/or n. The arrow associated to an enabled disturbance is plotted in solid line. If the disturbance is disabled, then it is plotted in dotted line.

The *parameters setting* zone contains several text fields and sliders to configure the parameters of the block or input selected in the *block diagram* zone. Besides, this zone shows the symbolic transfer function of the selected block or the mathematical expression of the selected input. It helps the user to remember the meaning of the configurable parameters.

The *performance/specifications* zone contains two buttons (Frequency specifications and Time specifications) to enable and configure the specifications in both domains: time and frequency. When there are no specifications enabled in a certain domain, the associated button is represented in yellow color. If the enabled specifications are all met the button is represented in green color, otherwise the button is represented in red color.

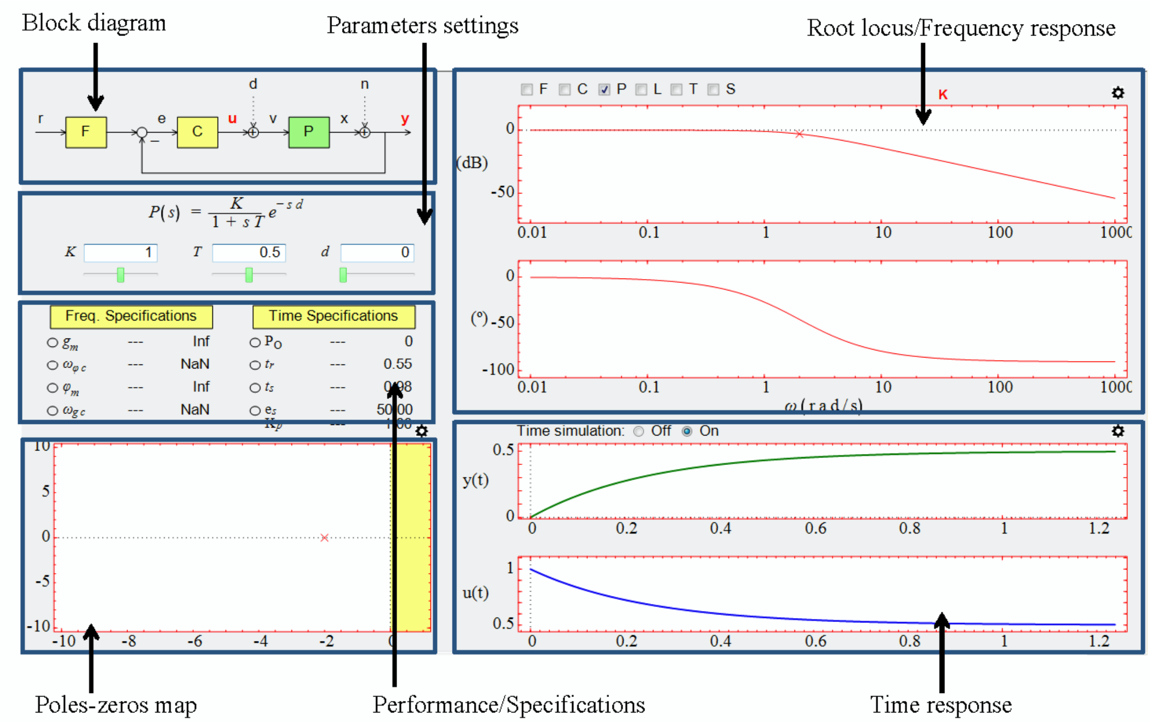

FIGURE 5. **Graphical user interface of the LCSD interactive tool.**

The central area of this zone contains a table with the main characteristics of the system in the frequency domain (gain margin, phase crossover frequency, phase margin, and gain crossover frequency) and in the time domain (overshoot percentage, rise time, settling time, and steady-state error). If there is some enabled specification, then this table is replaced with the enabled specifications and the system values for these specifications. Each specification has associated a small circle whose color indicates whether (green color) or not (red color) the specification is being met for the system.

The *poles-zeros map* zone plots the poles ('o') and zeros ('x') of prefilter (light blue color), controller (blue color), and plant (red color). For the selected block in the block diagram zone, the user can set the position of a pole or a zero by dragging the associated interactive element ('o' for a zero and 'x' for a pole). When the user finishes the dragging of an element, all the information and graphs of the LCSD main window are updated.

The *root locus/frequency response* zone shows one of the following interactive diagrams: root locus, Bode diagram, polar diagram, and Nichols diagram. The different diagrams appear by pressing the short-cut key "R", "B", "P" and "N", respectively. The enabled specifications are also represented in the diagrams. In the case of the root locus, the user can configure the position of the closed loop poles. Likewise, in the case of the frequency response diagrams (Bode, polar, or Nichols), the user can configure the corner frequencies of the poles and zeros for the selected block. Besides, LCSD allows the user to add and remove poles and zeros in the poles-zeros map zone, and in the root locus/frequency response zone.

The *time-response* zone contains one or two subplots with the time response of the signals that are selected in the block diagram zone. The enabled time specifications are also represented in the diagrams.

LCSD can be used by the instructor to teach the design of SISO linear controllers using the loop shaping methodology. Once the plant $P(s)$ has been defined, and the specifications have been set, LCSD allows loop shaping in a very easy way. First, the user must select the type of controller: gain, lead compensator, lag compensator, lag-lead compensator, PID compensator, or user-defined compensator. Then, in the frequency diagram (Bode, Nyquist or Nichols), the user must drag the gain or the frequency corners of the compensator poles and zeros to modify the shape of the open loop function $L(s)$. The user can see immediately what specifications are met because LCSD validates the specifications each time the user modifies $L(s)$. In the main window, there are circular indicators associated to each specification. If an indicator is in green color that means its associated specification is met, otherwise the indicator is in red color.

Besides, LCSD can be used by the teacher to generate exercises (and their solutions) of control systems design by the loop shaping methodology because the tool allows saving and loading the work sessions. Note that LCSD allows formulating a problem and its corresponding solution as a visual image that contains all the time and frequency specifications given and showing if every specification is verified.

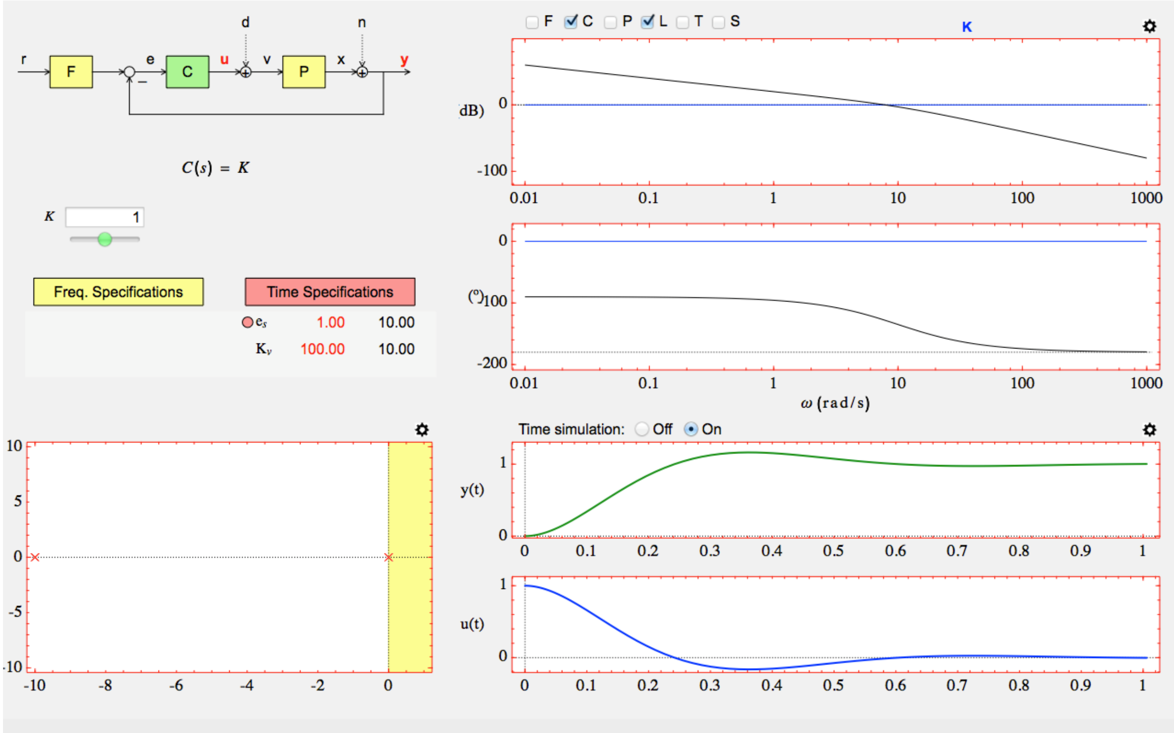

FIGURE 6. Formulation of example 1 with specification 1.

The students can also use LCSD to solve these exercises. The tool has implemented an automatic checking of the fulfilment of the specifications that help the students to know whether the design is correct or not. When a student finishes an exercise, LCSD allows generating a report of the design and saving the work session. These files could be sent directly to the teacher to be evaluated or can be used by the student as self-correction exercise if the teacher provides them with the right solution.

IV. ILLUSTRATIVE EXAMPLES OF USING THE LCSD TOOL

A. EXAMPLE 1: LOOP SHAPING USING THE BODE DIAGRAM

As a first example to illustrate the classical loop shaping methodology using the Bode diagram, we are going to solve the following problem [37], [38]: Design a series compensation for a unity-feedback with a plant:

$$P(s) = \frac{10}{s(1+0.1s)}. \tag{8}$$

The compensated system must meet the following specifications:

1) The velocity-error constant K_v must be 100.
2) Phase margin should be approximately 45°.
3) Sinusoidal inputs of up to 1 rad/s should be reproduced with ≤ 2 percent error. This means that:

$$\left|\frac{E(s)}{R(s)}\right| = \left|\frac{1}{1+C(s)P(s)}\right| \leq 0.02 \Rightarrow |C(s)P(s)| \geq 50$$
$$\Rightarrow |C(s)P(s)| \geq 34\,dB,\ \forall\omega \leq 1. \tag{9}$$

4) Sinusoidal inputs with frequency greater than 100 rad/s should be attenuated at the output to 5 percent of their value at input. This means that:

$$\left|\frac{Y(s)}{R(s)}\right| = \left|\frac{C(s)P(s)}{1+C(s)P(s)}\right| \leq 0.05 \Rightarrow |C(s)P(s)| \leq 0.05$$
$$\Rightarrow |C(s)P(s)| \leq -26dB,\ \forall\omega \geq 100. \tag{10}$$

In this example, the solution will be obtained in a step by step procedure using the LCSD tool, beginning from the first specification and continuing consecutively until the last specification.

1) SPECIFICATION 1

The velocity-error constant of the given plant is only 10, as can be shown in Fig. 6. To meet this specification K must be equal to 10 to ensure the desired low-frequency asymptote of $KP(s)$. Fig. 7 shows the solution to this simple problem that verifies specification 1 with a proportional controller (P-controller).

2) SPECIFICATIONS 1 AND 2

If the phase margin specification is included, it is observed that the proportional controller obtained in the previous step does not satisfy it (see Fig. 8). The phase margin is not adequate and there is a compromise between the value of the velocity-error constant and the phase margin. If K decreases, then the phase margin increases and the velocity-error constant decreases. In the same way, if K increases then the phase margin decreases and the velocity-error constant increases.

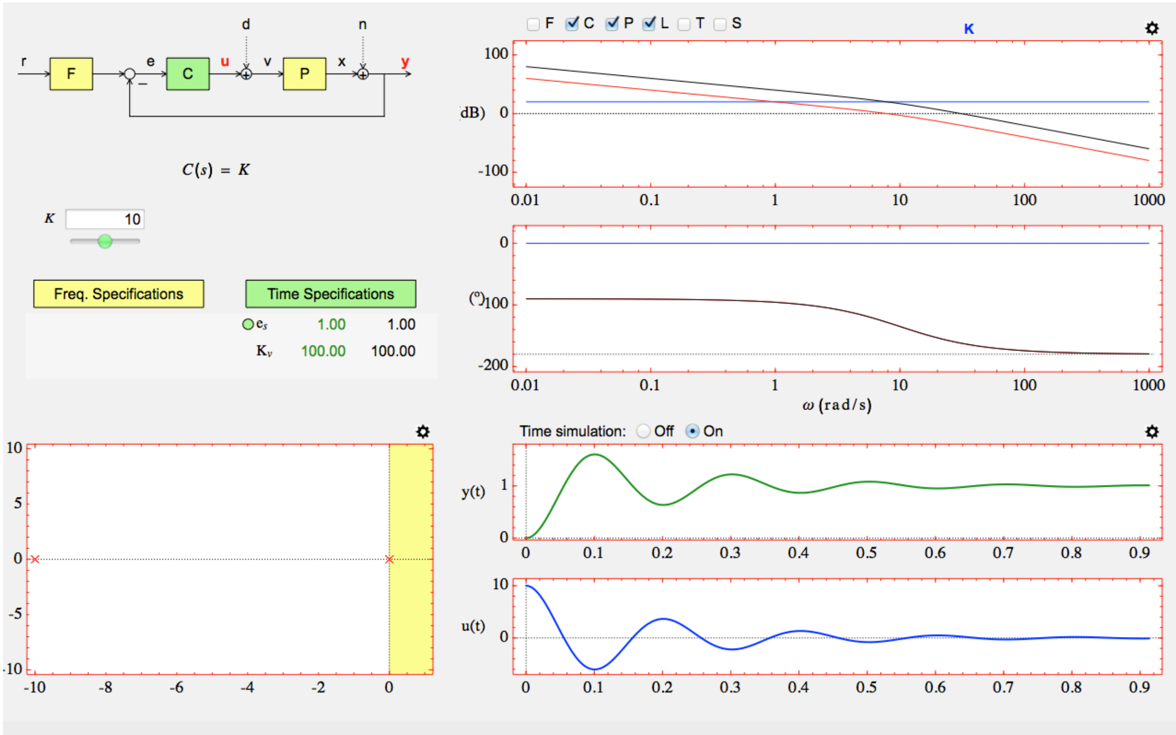

FIGURE 7. Solution of example 1 with specification 1.

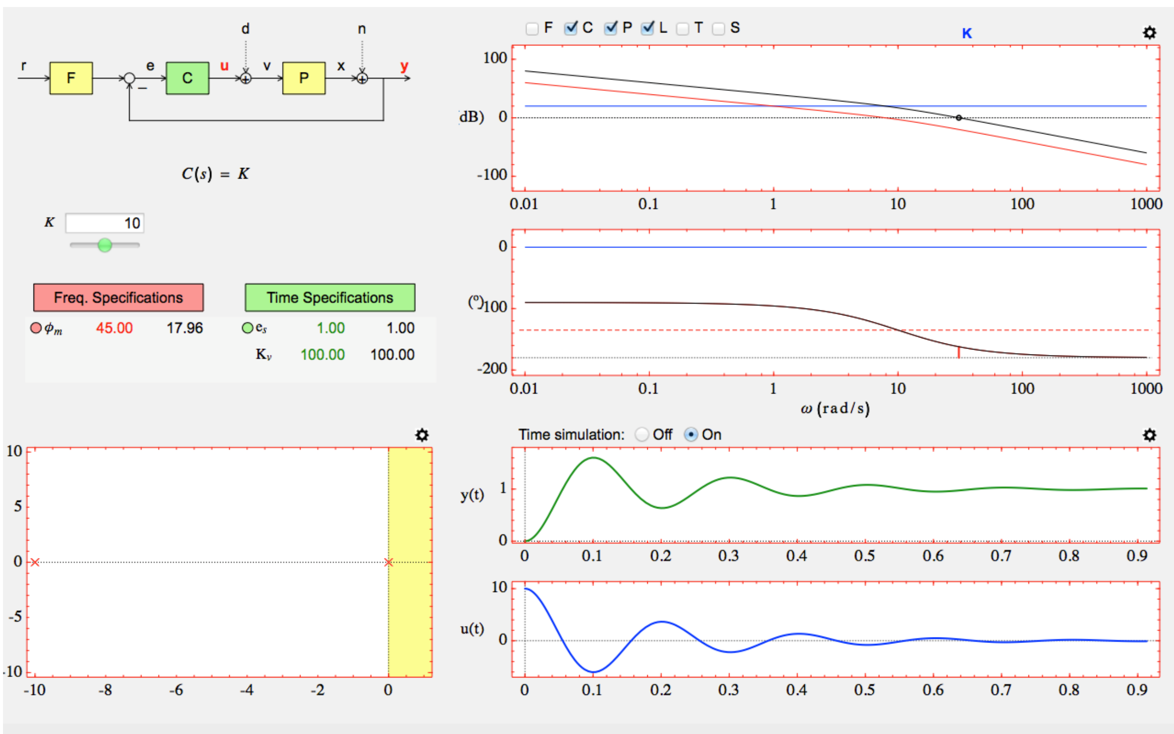

FIGURE 8. Formulation of example 1 with specifications 1 and 2.

This means that it is not possible to satisfy both specifications with a P-controller.

One possibility is to use a lag compensator. By retaining the same low-frequency asymptote as the plant compensated only in gain, the low-frequency accuracy, and the velocity error constant of the system is maintained at its high value of 100. At the same time, the use of attenuation before crossover permits the phase margin to be raised to the desired

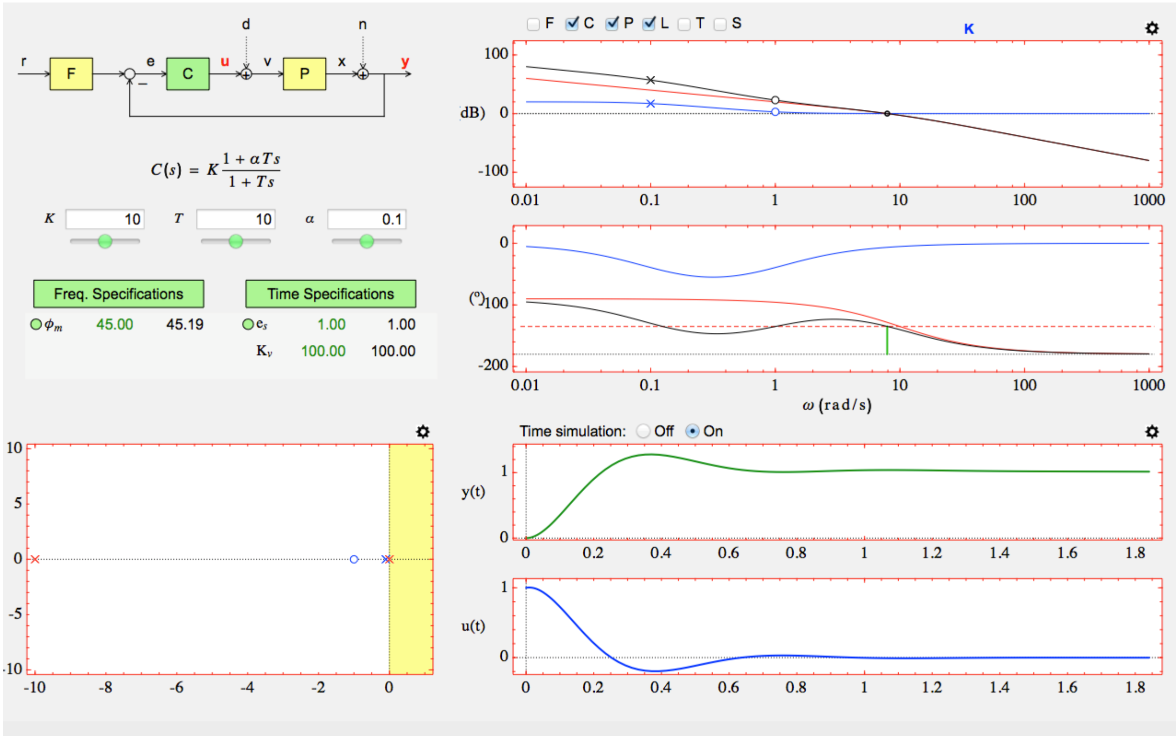

FIGURE 9. Solution of example 1 with specifications 1 and 2.

value of 45°. Fig. 9 shows the solution of both specifications with the following lag compensator:

$$C(s) = 10\frac{1+s}{1+10s}. \tag{11}$$

3) SPECIFICATIONS 1, 2, AND 3

The specification of a middle frequency gain requirement needs that the open loop transfer function, $L(s)$, verifies that $|L(j\omega)| \geq 34$ dB for $\omega \leq 1$rad/s. This constraint is indicated by the yellow shaded area in Fig. 10 and the use of a lag compensation implies that $|L(j\omega)|$ enters always in this forbidden region. The student can assure this by moving the location of the pole-zero pair of the lag compensator.

This situation is almost ideal for the application of lead compensation because no high frequency attenuation specification is included and the phase lag of the uncompensated plant increases slowly after the crossover frequency. Fig. 11 shows the solution of specifications 1, 2 and 3 with the following lead compensator:

$$C(s) = 10\frac{1+0.1s}{1+0.01s}. \tag{12}$$

4) SPECIFICATIONS 1, 2, 3, AND 4

Specification 4 requires that $|L(j\omega)| \leq -26$ dB for $\omega \geq 100$rad/s. The high-frequency attenuation specification rules out the use of lead compensation since no high frequency gain may be used (see Fig. 12).

However, this problem can be solved quite easily with the use of lag-lead compensation. We need to move the plot of $|L(j\omega)|$ in the high-frequency range as far to the right as possible consistent with the high frequency attenuation specification. The completion of the design procedure requires that specifications 3 and 4 of the open loop transfer function $L(j\omega)$in the low and high frequency range be joined in such a manner to maximize the phase margin. In terms of this problem it means to join the low and high frequency shape of $L(j\omega)$with a segment of -20 dB/dec slope so that the phase margin is maximized. One way to perform this action in a direct and interactive way is to introduce a lag-lead compensator. In the tool, all the requirements can be examined visually to shape $L(j\omega)$ to meet all the specifications. Finally, Fig. 13 shows the solution of all specifications 1, 2, 3 and 4 with the following lead-lag compensator:

$$C(s) = 10\frac{(1+0.25s)}{(1+2s)}\frac{(1+0.1s)}{(1+0.025s)}. \tag{13}$$

B. EXAMPLE 2: LOOP SHAPING USING THE NICHOLS DIAGRAM

As a second example to illustrate the classical loop shaping methodology using the Nichols diagram, we are going to solve the following problem [39]: Design a series compensation for a unity-feedback with a plant:

$$P(s) = \frac{2340}{s(s+10)(s+20)}. \tag{14}$$

The compensated system must meet the following specifications:

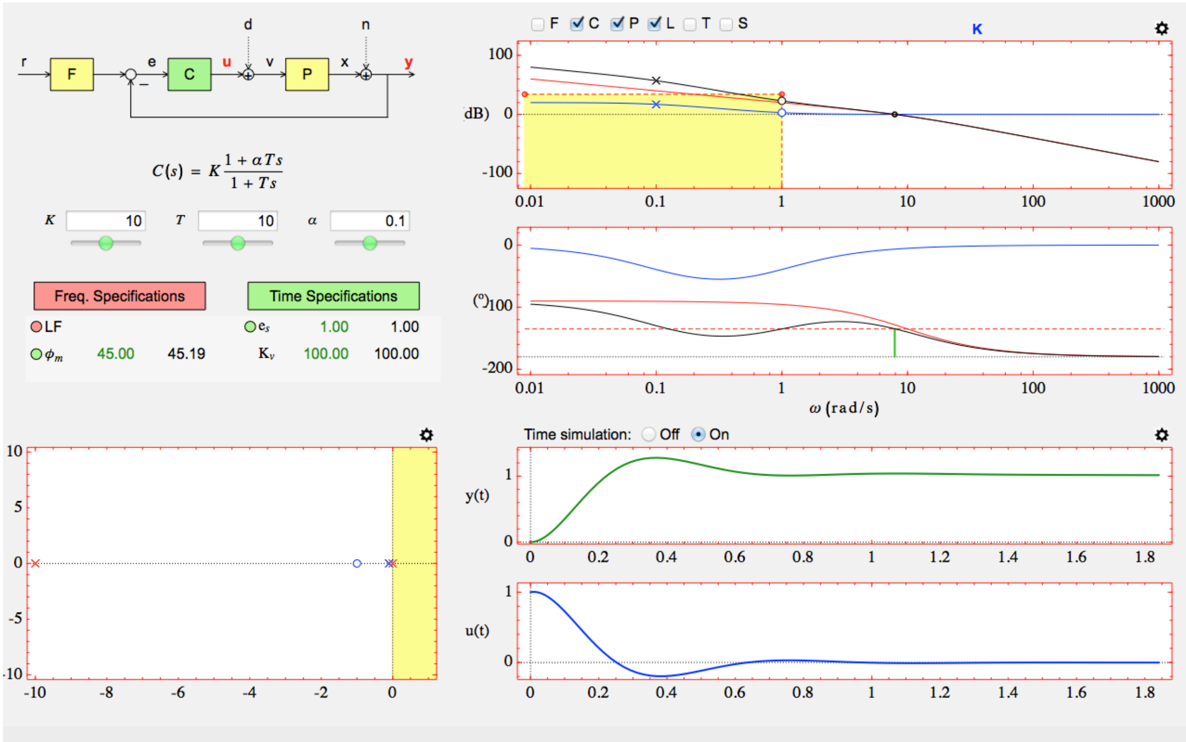

FIGURE 10. Formulation of example 1 with specifications 1, 2 and 3.

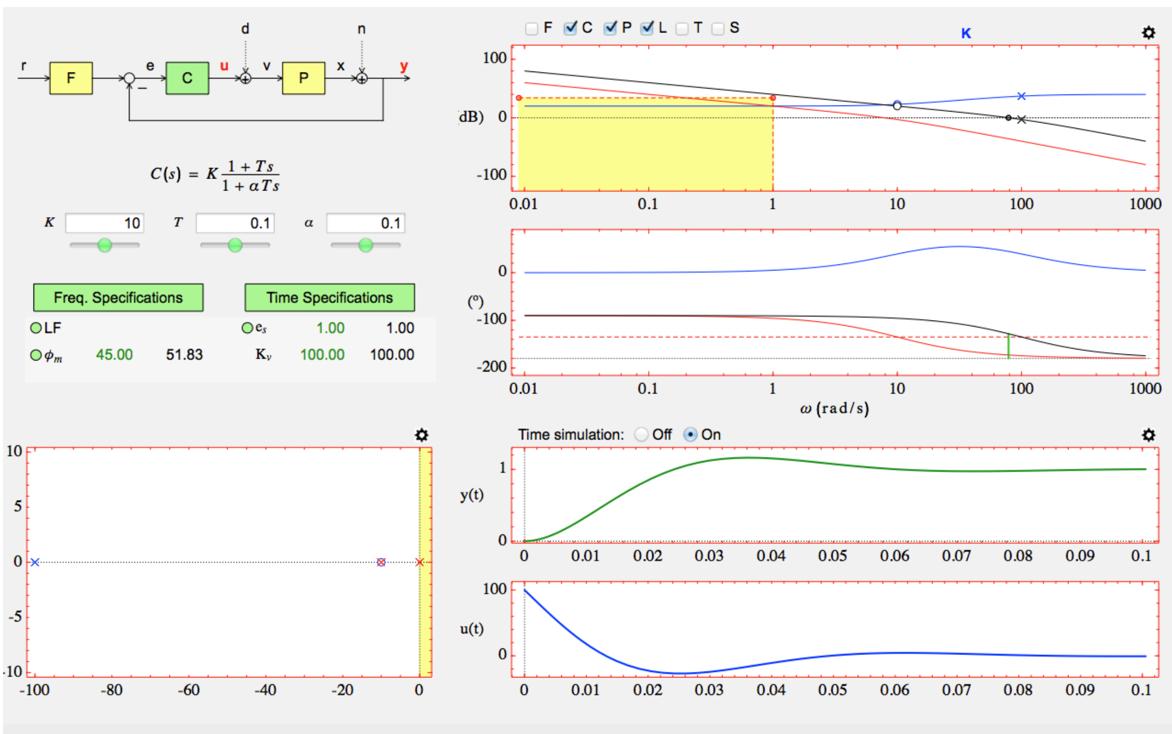

FIGURE 11. Solution of example 1 with specifications 1, 2 and 3.

1) The velocity-error constant K_v must be greater than 11.5.
2) Overshoot must be less than 10%.
3) Settling time must be less than 0.5 s.
4) The maximum magnitude of the sensitivity complementary function must be less than 1.4.

In this case, we are going to present only the formulation of the problem (see Figure 14) and a possible

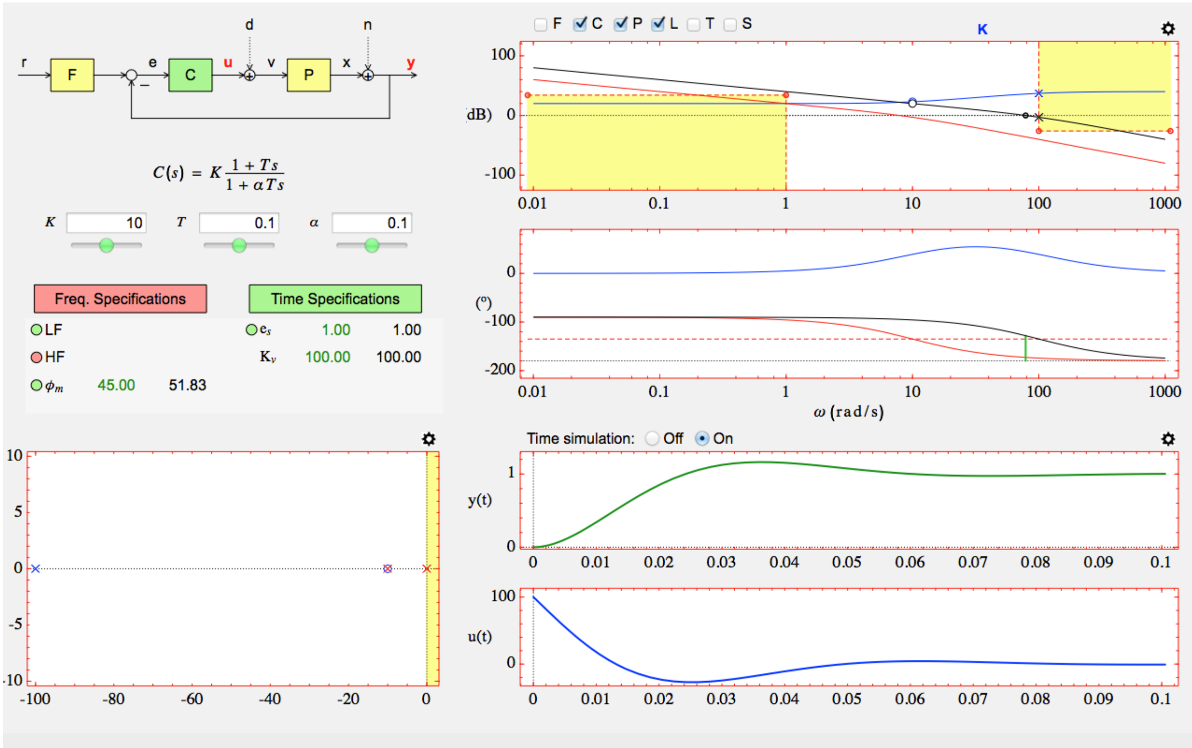

FIGURE 12. **Formulation of example 1 with specifications 1, 2, 3 and 4.**

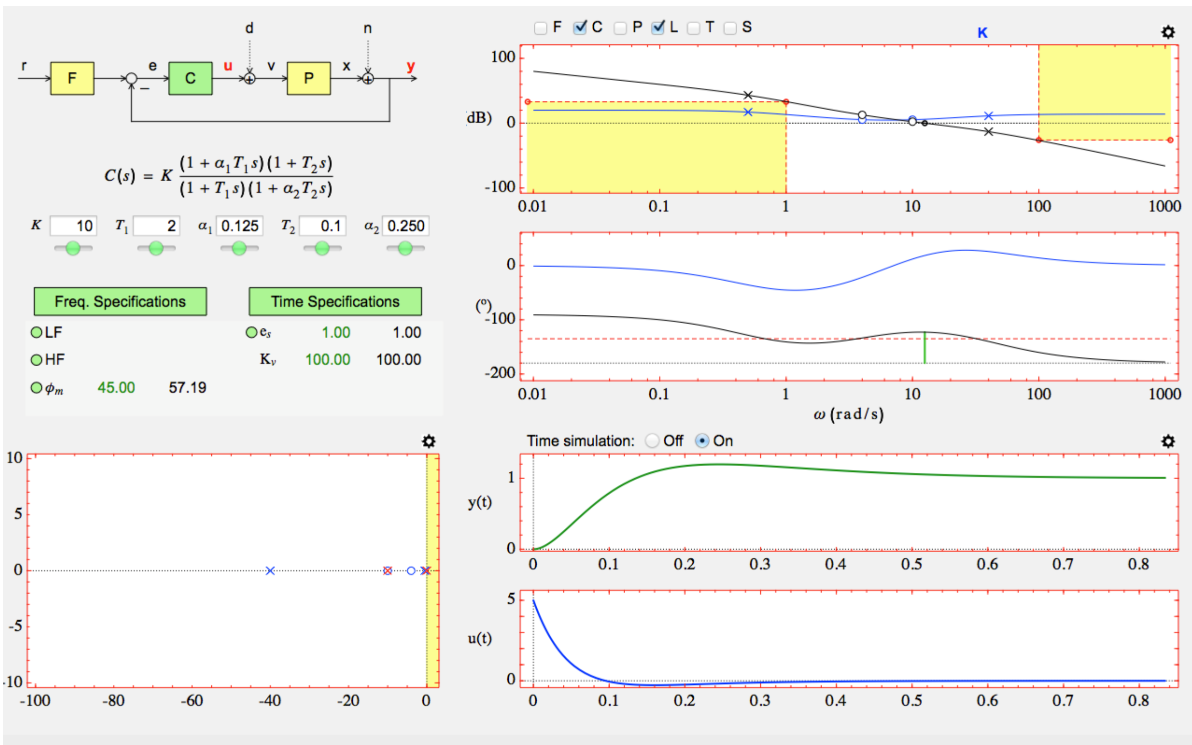

FIGURE 13. **Solution of example 1 satisfying specifications 1, 2, 3 and 4.**

solution (see Figure 15). Figure 11 shows that the initial controller is a P-controller with gain $K = 1$. It is easy to follow from this figure that specifications 2, 3 and 4 are not met. In the same way, Figure 15 shows that using the following lead compensator:

$$C(s) = \frac{1 + 0.1s}{1 + 0.005s}, \tag{15}$$

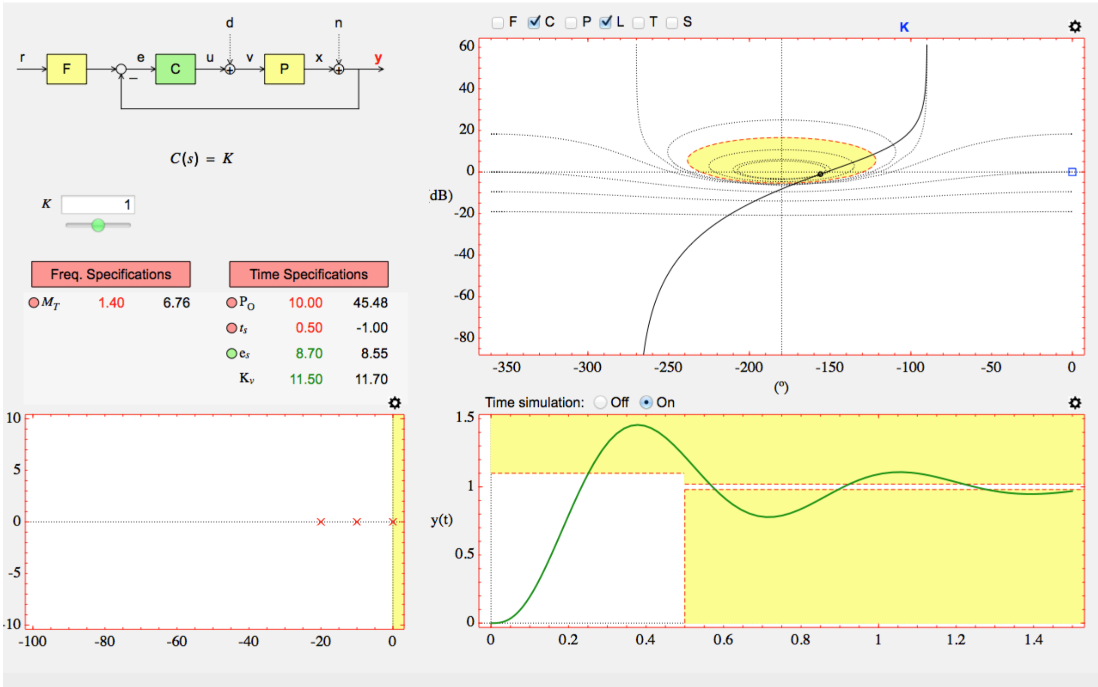

FIGURE 14. Formulation of example 2.

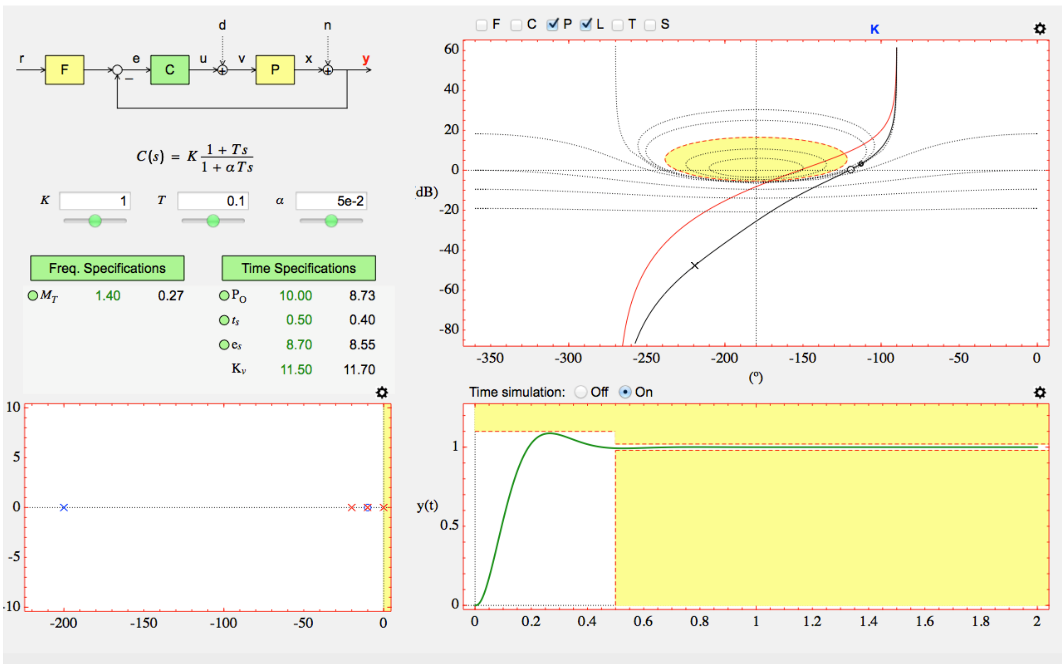

FIGURE 15. Solution of example 2.

all the specifications are verified (they are represented in green color in the figure).

C. EXAMPLE 3: LOOP SHAPING USING THE POLAR DIAGRAM

Consider a process with the transfer function:

$$P(s) = \frac{1}{(1+s)^4}. \tag{16}$$

It is desired to maximize the integral gain k_i of a PID controller subject to the following robustness constraint: the maximum magnitude of the sensitivity function must be equal to or less than 1.4.

This example taken from [40] shows that for the case of PID controller the optimization of the integral gain k_i often provides controllers with undesirable properties. The performance is very sensitive to variations in the controller

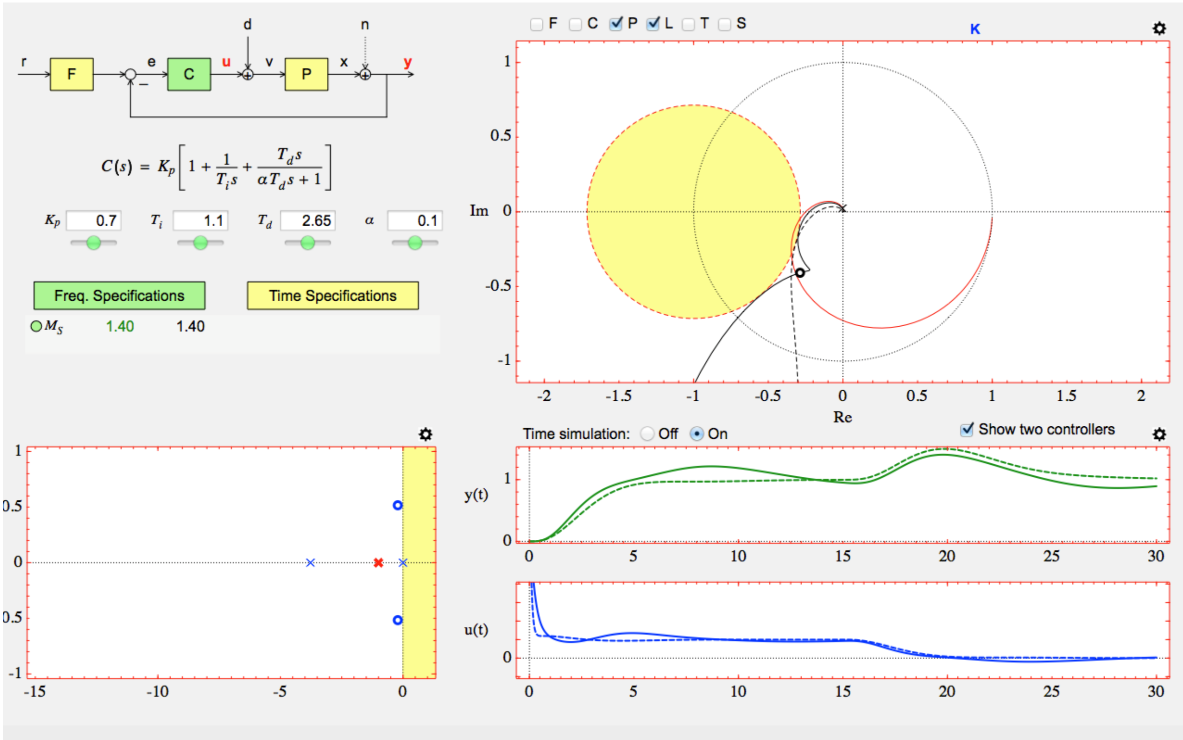

FIGURE 16. Solution of example 3.

parameters at the maximum. Also, the controller that maximizes k_i has other drawbacks: the derivative cliff. This problem of loop shaping modifying the three controller PID parameters can be solved in a very easy way using the interactivity capability of LCSD. Using the tool the following parameters are obtained: $K = 0.7$, $T_i = 1.1$, and $T_d = 2.65$. It can be noticed that the polar curve of the open loop transfer function (solid line) has a loop as can be seen in Fig. 16. The controller obtained has excessive phase lead which is obtained by having a PID controller with complex zeros, $T_i < 4T_d$. For comparative reasons we have shown Nyquist plots and time plots for a PID controller where $T_i = 4T_d$ (dashed lines). The controller parameters are $K = 1.1$, $T_i = 3.2$, and $T_d = 0.8$. The responses of this controller are better, even if the peak in the response to load disturbances is larger.

V. CONCLUSIONS

The use of interactivity on education provides a wide range of possibilities to both teachers and students. Teachers can use interactive presentations where not only the meaning of the concepts is provided, but also how these concepts are related with others, or how such concepts are affected by some input modifications. On the other hand, students can use interactive web sites or interactive computer-based tools, to study theoretical concepts abstracted by means of interactive elements. This paper has focused on describing the main features and functionality of an interactive software tool called LCSD developed by the authors in support of control education. The tool provides an excellent means of enhancing the standard 'textbook' design approach for linear design compensators using the classical loop shaping paradigm. The images and the immediate feedback enable students to gain insight into the linear control design very quickly and with a deep understanding.

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