Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Project-based Learning for Control Education during COVID-19 Pandemic

Aiman Najeeb * Junaid Ahmed Memon *

* Habib University, Karachi 75290 Pakistan,
(aiman.najeeb@sse.habib.edu.pk; junaid.memon@sse.habib.edu.pk)

Abstract: The paper presents a project-based learning approach for the undergraduate level first course on control systems in the context of electrical and computer engineering program. We share the experience of a complex engineering project model that assumes no access to lab facility due to the COVID-19 pandemic but targets learning outcomes of a fundamental control system course, i.e., system modeling, performance investigation, analysis, design of analog or digital controller for a selected open-loop unstable system. The project utilizes Tinkercad Circuits which is a free online circuit simulator. The approach provides a solution to one of the challenges of remote or virtual engineering labs, i.e., a requirement of having high-performance expensive hardware and resource-intensive software support. Results are presented in terms of student samples and learning outcomes achieved at the end of the project.

Keywords: Control Engineering Education, Online experiments, Educational Innovation, Changes in control Education due to the COVID-19 pandemic, Remote learning and teaching.

1. INTRODUCTION

Due to Corona Virus Disease 2019 (COVID-19) pandemic, numerous challenges were faced by education in general and engineering education in particular. For an undergraduate-level control systems course, hands-on experience to controller design problem is very important for developing the understanding of control theory concepts. Generally, this experience is provided to students through hardware setups, trainer boards, or hardware-in-loop-based plant models available in laboratories of campus. But during COVID-19, access to laboratory facilities was either limited or completely revoked which badly affected the lab work of students. To avoid compromise on the learning outcomes of the labs in the situation, numerous virtual, online, and remote-control laboratories are available in the literature, see Heradio et al. (2016), Sanchez-Herrera et al. (2019). Most of such labs function for a limited time and for general audience. Often such setups provide limited data on experiments and do not provide any open ended control problems to study and investigate. Also, the setups require either good internet connection or good configuration personal computers which are not always available to a majority of the student population in developing countries, Waheed (2021). Another approach available in the literature is the development of control test-beds at home Chacon et al. (2019) or providing students necessary equipment at home or showing video recordings of lab experiments Gamage et al. (2020).

We present here a project-based learning approach to work on complex engineering problem for the undergraduate students taking first course on control systems in an Electrical and Computer Engineering (ECE) program. The proposed methodology exposes students to the key principles of mathematical modeling, time-domain and stability analysis. The approach provides students an opportunity to apply classical control theory for controller design problems in order to satisfy system constraints for an open-loop unstable system. For this, we utilize Tinkercad Circuits for engineering system simulations, Abburi et al. (2021). Tinkercad Circuits is a free web browser-based online circuit simulation platform that provides a lightweight interface that can be used easily in a web browser of a personal computer or a smartphone. Our contribution is providing an approach for using Tinkercad Circuits in conjunction with numerical computing environment like MATLAB Simulink for plant modeling, analysis, and testing of analog and digital controllers. The approach addresses many complex engineering problem attributes like having range of conflicting requirements, depth of analysis, exposure to practical issues of systems like saturation and student teamwork as identified in Antsaklis et al. (1999).

Section 2 and 3 provide the lab curriculum and the project details of the Principles of Feedback Control (PFC) course offered at Habib University (HU) in Fall 2020. Results are discussed in terms of student samples in section 4 followed by conclusion of study.

Table 1. CLOs of the PFC Lab

| CLO No. | Course Learning Outcomes |
|---------|--------------------------|
| CLO 1   | Ability to build simulation models of physical systems on MATLAB and Simulink |
| CLO 2   | Ability to investigate the impact of system parameters on response characteristics |
| CLO 3   | Ability to design feedback controllers for regulating the control variable of a system |

2. LAB CURRICULUM

The curriculum of the PFC lab is designed to provide students ability to achieve three Course Learning Outcomes...
(CLOs) as summarized in Tab. 1. In PFC lab, students perform 12 experiments as listed in Tab. 2 and a lab project to achieve the CLOs. Project details are given in following section.

Table 2. List of experiments of the PFC Lab

| Lab 01: Introduction to feedback control systems |
| Lab 02: Simulating dynamic models using MATLAB |
| Lab 03: Simulating dynamic models using Simulink |
| Lab 04: Bang-bang control |
| Lab 05: Grey-box modelling of DC Motor |
| Lab 06: Transient response of 1st and 2nd-order systems |
| Lab 07: PID control of DC motor speed and position |
| Lab 08: Tracking and disturbance rejection |
| Lab 09: Design of analog controllers |
| Lab 10: Design of digital controllers |
| Lab 11: Frequency-based system identification |
| Lab 12: Set-point weighting and integrator wind-up |

3. LAB PROJECT

This section describes project problem, requirements, and assessment criteria utilized to evaluate the project outcomes. An open-loop unstable system was selected as a plant to practice controller design for regulating control variables. Details of the system and the thought process behind system selection are discussed in the following sections which provide further details for the study.

3.1 Plant

Control of the "double integrator" has been of interest since the early days of control theory when it was used extensively to illustrate minimum-time and minimum-fuel controllers, see Franklin et al. (2018), Rao and Bernstein (2001). Since several important control problems are characterized by a process with double integrator transfer function, therefore the electrical system shown in Fig. 1 was selected to be the plant of study with resistors \((R_1, R_2)\) of 2.2 k \(\Omega\) and capacitors \((C_1, C_2)\) of 470 \(\mu\)F. The system ideally forms a double-integrator circuit as given by the transfer function of system in Eqn. (1).

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{1}{R_1 R_2 C_1 C_2 s^2} \tag{1}
\]

![Double integrator circuit](image)

Fig. 1. A double integrator circuit as plant

The plant being unstable system makes an interesting example that subtly exposes students to the most of classical control theory ideas. Nonetheless, any complex transfer function can be constructed using different combination of impedances for feedback amplifiers using op-amps, see Nise (2000).

3.2 Project Constraints and Requirements

For the plant in Fig. 1, the students were given following design constraints to come up with a suitable feedback controller that regulates system output for step input such that:

1. Percentage Overshoot (POS) remains less than 20%
2. Settling-time \((T_s)\) does not exceed 4 seconds

The problem was further divided into steps to elaborate on the requirements of the project. This helped students in adopting a systematic approach to solve the problem by applying control theory. The steps are illustrated below.

a. Modeling and Stability Analysis of Plant

The first step toward solving a control problem comprises obtaining an accurate mathematical model of the plant. As the students were only given a system schematic, they were required to identify the system by deriving the plant’s transfer function using first principles. The system model was useful to predict the time-domain response and to carry out the stability analysis for an open loop.

Since students at HU have access to MATLAB online and were already familiar with MATLAB environment through Lab 01-03 (see Tab. 2), MATLAB simulation and time domain analysis results were made one of the requirements. To verify the mathematical model and practical system response, it was further required to simulate the given plant schematic using electronic components on Tinkercad.

b. Analog Controller Design

This step was made open-ended step which involved designing an analog controller to meet the given specifications. Through the course lectures and labs, students were beforehand exposed to Lead/Lag compensators, Proportional-Integral-Derivative (PID) controllers and any other combinations. The approach to designing the controller was also not specified. Students were familiar with root-locus-based design, pole-zero placement method, time-domain-based calculations, and Ziegler–Nichols tuning of PID controller gains. The controller design approach was to be verified with closed-loop system simulations. For this, students were allowed to design any controller and use any approach that would meet the given specifications.

c. Analog Controller Testing

The operational amplifiers-based analog PI (Proportional-Integral) controller implementation was introduced in the lab 09 (see Tab. 2). In this step, the simulation for the physical realization of the designed controller for the double-integrator through electronic components and operational amplifiers was required. Students were required to identify the arrangement of components (like capacitors and resistors with operational amplifiers) for the realization of the controller transfer function and their exact values required for setting the controller gains. Verification of the analog controller circuit was required by simulating the closed-loop system us-
ing electronic component modules on Tinkercad. The comparison of the closed-loop system response obtained through transfer function simulation on Simulink with the ones obtained through circuit realization of the controller was required for interesting observations like actuator saturation providing motivation for actuation amplitude optimization.

d. **Discrete Controller Design and Simulation**
The knowledge of discrete controller implementation learned in lab 10 (see Tab. 2) was applicable in this step. It was required to convert transfer function of the analog controller obtained in the previous steps, to a discrete equation through the approach of controller emulation. A comparison was to be made between the performance of an analog controller and a digital controller for closed-loop system response.

e. **Digital Controller Implementation**
Tinkercad allows to integrate Arduino UNO microcontroller board with an electronic circuit. A digital controller can be implemented with the Arduino development board. This step required the replacement of the analog controller with an Arduino-based digital controller in the Tinkercad environment. This part was kept optional due to the complexity of modelling of PWM signal from Arduino output pins which affects the control effort for the analog plant.

### 3.3 Assessment Criteria

The labs contributed 70% while the project contributed 30% to the complete lab grade of a student. For the project, the students were allowed to work in group of 02. Rubrics developed for the assessment of project work are shown in Fig. 2. Students submitted project outcomes in the form of a report. The report was required to contain modeling, analysis, design and discussion of all the simulation results. Excerpts from those reports are discussed in next section. Each of the listed tasks in the rubrics contributed to the achievement of a CLO given in Tab. 1. Task 1 is mapped with CLO1, Task 2, 3, and 4 are mapped with CLO3 and Task 5 is mapped with CLO2.

![Fig. 2. Rubrics for assessment of project](image)

![Fig. 3. Simulink model of the plant from sample student submission](image)

**Fig. 3. Simulink model of the plant from sample student submission of Fig. 3 where p(t) is unit step response to step input r(t)**

### 4. RESULTS

Following are the task-wise results submitted by students in their project reports. The figures and equations in the following sections are given as received with slight modification in axes labels to improve readability.

#### 4.1 Mathematical Model and Open Loop Response of Plant

The given system was modeled using circuit theory for the operational amplifier in an inverting configuration for given values of resistors and capacitors. This resulted in the transfer function given in Eqn. (2) whereas time-domain unit step response was reported as given by Eqn. (3).

\[
\frac{V_{out}}{V_{in}} = \frac{1}{1.07s^2} \quad (2)
\]

\[
v_{out}(t) = \frac{1}{2.14}t^2 \quad t \geq 0 \quad (3)
\]

![Fig. 4. Response of uncompensated system from sample student submission of Fig. 3](image)

**Fig. 4. Response of uncompensated system from sample student submission of Fig. 3 where p(t) is unit step response to step input r(t)**

![Fig. 5. Tinkercad model of the double-integrator circuit](image)

**Fig. 5. Tinkercad model of the double-integrator circuit, implemented using operational amplifier Integrated Circuit (IC) LM-741, along with the time-domain response. The response from circuit implementation looks different from the transfer function output from Simulink as the amplifier IC gets saturated at the supply voltage of 12V. The unstable response of the double-integrator system is verified in both cases.**
4.2 Controller Design

From the given response specifications (i.e., $\text{POS} < 20\%$ and $T_s < 4\text{ sec}$, given in section 3.2), the required damping ratio $\zeta$ and natural frequency $\omega_n$ were found to be in the range $\zeta > 0.456$ and $\omega_n > 2.193$ for second order system approximation. To meet the response specifications for the double-integrator circuit, different approaches to designing controllers were adopted by students. A few are discussed in this section.

a. Pole-Zero placement method

One of the adopted approaches was the placement of poles and zeros to meet the design specifications. For given system, the placement of a zero at origin canceled one pole at origin and an addition of another pole at the left side of the s-plane resulted in a second-order closed-loop system. The controller transfer function, in this case, is given by Eqn. (4).

$$C(s) = \frac{bs}{cs + 1} = \frac{2.4s}{0.4s + 1}$$

The exact values of $b$ and $c$ were obtained by comparing the closed-loop system transfer function with the standard second-order system characteristic equation using the calculated values of $\zeta$ and $\omega_n$. The response of a compensated system is shown in Fig. 6. The obtained response meets the required specifications with $\text{POS}$ of $11.4\%$ and $T_s$ of $3.14 \text{ sec}$.

b. Controller Design via Root Locus

One approach to the controller design found in student samples was based on the root locus of the system. MATLAB SISO tool was utilized to obtain the root locus of the lead compensated system as shown in Fig. 9 and the selection of pole, zero, and gain of the lead compensator were based on the region where the constraints of $\zeta$ and $\omega_n$ were met. This is shown in Fig. 10. The designed lead compensator is given in Eqn. (5).

$$C(s) = \frac{s+1}{s+20}$$

The Simulink model and response of the designed controller are given in Fig. 11. For the realization of the proposed controller through Fig. 7, a parallel combination of resistor $R_s$ and capacitor $C_s$ with values of $400k\Omega$ and $1\mu F$, respectively where as for the feedback impedance $Z_f$, a resistor $R_d$ of $2.4 \text{ M\Omega}$ was selected. Fig. 8 shows the snapshot of the designed analog controller implementation in the Tinkercad environment. This results in $\text{POS}$ of $15\%$ and $T_s$ of $3.55 \text{ sec}$.

c. Proportional-derivative (PD) controller

For the given time-domain specifications, proportional-derivative controller was designed based on a comparison of the characteristic equation of the closed-loop as a series combination of resistor $R_s$ and capacitor $C_s$ with values of $400k\Omega$ and $1\mu F$, respectively where as for the feedback impedance $Z_f$, a resistor $R_d$ of $2.4 \text{ M\Omega}$ was selected. Fig. 8 shows the snapshot of the designed analog controller implementation in the Tinkercad environment. This results in $\text{POS}$ of $15\%$ and $T_s$ of $3.55 \text{ sec}$.
4. Controller Design

4.1 Pole-Zero placement method

One of the adopted approaches was the placement of poles and zeros based on the root locus of the compensated system. For the input impedance $Z_i$ of $500\,\Omega$ and $T_i$ of $3.5$ sec, respectively were used values of $10k\,\Omega$ and $100\,\Omega$, respectively where the constraints of $\omega_n$ and $\zeta$ were met. This is important for the analog circuit implementation in Tinkercad. The analog PD controller was realized by connecting a parallel combination of resistor and capacitor as input impedance and a resistor for feedback impedance as shown in Fig. 12. The response obtained through Tinkercad is shown in Fig. 13. The deviation in overshoot was due to an added zero introduced by the PD controller which is absent in the standard second order transfer function. The controller was further tuned by increasing $K_d$ and decreasing $K_p$ to $2.45$ each to reduce the overshoot. After this, the $POS$ was reduced to $19.8\%$ and $T_s$ turned out to be $3.8$ seconds. This was verified by the Simulink model as well as the analog circuit implementation in Tinkercad.

4.2 Proportional-derivative (PD) controller

The Simulink model and response of the designed controller through emulation of controller approach. The analog controllers designed were converted to discrete controllers through emulation of controller approach. The obtained discrete equations were simulated through Simulink models for different values of the sampling time $T$. This is illustrated by considering the example of Lead Compensator given in Eqn. (5). Eqn. (6) is the discrete equation for controller output $u(t)$. Simulink model for the closed-loop system with the discrete controller of Eqn. (6) is shown in Fig. 14.

$$u[k] = \frac{e[k] - e[k - 1] + T[e[k] + u[k + 1]]}{1 + 20T}$$ (6)

The model was tested for different values of sampling time, $T$. In Fig. 15, the closed-loop system response of the analog control system is compared with the digital.
like MATLAB/Simulink. The study can further be enhanced and adapted for the different plant models e.g. DC-DC converters, automatic voltage regulators (AVR) for generators, and inverters. Scilab or Octave GNU can be considered as free and open-source alternatives for MATLAB for numerical computations. Based on the requirements and features needed, other software packages like Online Multisim for circuit simulation and LabVIEW for simulation of mathematical models can be considered as an alternative to Tinkercad.

**ACKNOWLEDGEMENT**

Authors thank **Habib University** for the support to present this work.

**REFERENCES**

Abburi, R., Praveena, M., and Priyakanth, R. (2021). Tinkercad—a web based application for virtual labs to help learners think, create and make. *Journal of Engineering Education Transformations*, 34(SP ICTIEE), 535–541.

Antsaklis, P., Basar, T., DeCarlo, R., Mcclamroch, N., Spong, M., and Yurkovich, S. (1999). Report on the nsf/css workshop on new directions in control engineering education. *Control Systems, IEEE*, 19, 53 – 58. doi: 10.1109/MCS.1999.793442.

Chacon, J., de la Torre, L., and Dormido, S. (2019). The air levitation system. *IFAC-PapersOnLine*, 52(9), 33–35. doi:https://doi.org/10.1016/j.ifacol.2019.08.119. 12th IFAC Symposium on Advances in Control Education ACE 2019.

Franklin, G.F., Powell, J.D., and Emami-Naeini, A. (2018). *Feedback Control of Dynamic Systems (8th Edition)*. Pearson, 8th edition.

Gamage, K.A.A., Wijesuriya, D.I., Ekanayake, S.Y., Rennie, A.E.W., Lambert, C.G., and Gunawardhana, N. (2020). Online delivery of teaching and laboratory practices: Continuity of university programmes during covid-19 pandemic. *Education Sciences*, 10(10). doi: 10.3390/educsci10100291.

Heradio, R., de la Torre, L., and Dormido, S. (2016). Virtual and remote labs in control education: A survey. *Annual Reviews in Control*, 42, 1–10. doi: https://doi.org/10.1016/j.arcontrol.2016.08.001.

Nise, N.S. (2000). *Control Systems Engineering*. John Wiley Sons, Inc., USA, 3rd edition.

Rao, V.G. and Bernstein, D.S. (2001). Naive control of the double integrator. *IEEE Control Systems Magazine*, 21(5), 86–97.

Sanchez-Herrera, R., Mejías, A., Márquez, M., and Andújar, J. (2019). The remote access to laboratories: a fully open integrated system. *IFAC-PapersOnLine*, 52(9), 121–126. doi: https://doi.org/10.1016/j.ifacol.2019.08.135. 12th IFAC Symposium on Advances in Control Education ACE 2019.

Waheed, A., .M.A.D. (2021). Investigating the undergraduate students’ readiness to participate in online classes amid covid-19 outbreak: A survey of shahheed benazir bhutto university, sindh, pakistan. *PAKISTAN. Journal of Education Amp; Humanities Research, University of Balochistan, Quetta-Pakistan*, 11(1), 47–54–126.