Digital Twins Enabled Remote Laboratory Learning Experience for Mechatronics Education

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***Abstract*—Laboratory intensive assignments and hands-on skills are important components in Mechatronics and Control Engineering by their nature. Like many other educational services, lots of the contents including laboratory studies are switched to remote learning due to COVID-19. In this work, the need for remote laboratory assignments is transformed into an opportunity to use Digital Twins in the education effectively. Laboratory assignments are designed on top of the concept of Digital Twin applications for the course "ME-142: Mechatronics" at the University of California, Merced. Basic mechatronics simulation skills are enhanced using the foundational applications in MATLAB/Simulink. After students reached high confidence level in the simulation environment, the concept of Digital Twins is introduced for subsequent laboratory assignments consisting identification, modeling, analysis, controller design and validation. Through the end of the semester, students are expected to work in groups of six for the course project to create their own applications of Digital Twin for a variety of systems. Finally, Digital Twin applications are posted online using MATLAB Web App Server to enhance accessibility and compensate the lack of hardware interaction.**

***Index Terms*—Digital Twins, Engineering Education, Mechatronics, Remote Laboratory**

I. Introduction

Laboratory experiences play a considerable role in the engineering education and learning experience. For the undergraduate level courses of Mechatronics and Control Engineering, hands-on experience with a hardware creates huge impact on the learning process as defined in Model, Analysis, and Design (M.A.D) methodology [1]. However, the COVID-19 pandemic had a huge influence on the educational processes. Universities all over the world switched to remote learning experiences, resulting a challenging adaptation problem for the students especially for the laboratory intensive courses. These courses require hands-on applications that are key to understand and utilize the concepts. In this concept, there are different applications of remote applications for mechatronics and control engineering [2]–[7], remote laboratory [8]–[10], robotics [11]. All of these remote applications enable users to interact with real applications with a remote connection. However, almost all of them require time scheduling for users to dedicate hardware, server or connection to limited number of users. In this scenario, this time management is also another problem for courses with high number of students.

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In order to ensure remote learning experience for high volume of users, considerable number of plants should be active at the same time. There are high end commercial products that enable remote laboratory applications such as Roboholics Maniacs [12] and Quanser [13]. Although the interaction with the hardware is remote, having a limited number of physical plants can not satisfy the demand for the educational process. Furthermore, the overall prices for remote laboratory is above $200/hour for 8 student maximum. This eliminates the extensive usage of these products due to both time management problems and cost.

Considering the situation with a need of remote access laboratories and undesirable hardware issues, a very strong candidate for the remote laboratory applications is the Digital Twin. The concept of Digital Twin corresponds to virtual twin of the real physical application which enables users to interact with detailed real-time model [14], [15]. Digital Twins are highly utilized for different aspects of modeling, analysis and design processes of mechatronics applications [16].

This manuscript introduces a remote laboratory design for Mechatronics course utilizing the concept of Digital Twins as a remote interactive educational infrastructure. The remote laboratory of the course ME-142: Mechatronics taught in the University of California, Merced is designed in a structure consisting three main parts. The first part enables students to create solid foundation in simulation concepts using MATLAB/Simulink. In the second part, Digital Twin applications are introduced in order to perform fundamentals of M.A.D. methodology [1]. Thus, students are able to apply different aspects of the mechatronics course like identification, modeling, system analysis and controller design in the remote learning process. Lastly, students are expected to form groups of six and create their Digital Twin applications using the learning outcomes from the previous parts. Lastly, Digital Twin applications designed by students can be posted online using MATLAB Web App Server [17] to enhance the accessibility of different applications and compensate the lack of hardware interaction during the remote learning process. The main contribution of the work is introducing all remote laboratory design for mechatronics education based on the concept of Digital Twins, to propose a suitable alternative for in-person laboratory learning experience.

The paper is structured as follows. Section 2 describes the

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laboratory experience for both in-person laboratories before COVID-19 and remote laboratories. Section 3 introduces Digital Twin development framework utilized throughout the course and delivers a case study. Section 4 presents the results for Digital Twin applications developed by the students and final questionnaire. Finally, conclusions are in Section 5.

II. Laboratory Learning Experience

Mechatronics is an upper-division course offered annually each Spring semester in the Department of Mechanical Engineering of the University of California, Merced. The context of the cources includes both theoretical background and hands-on experience for modelling, analysis and design of the electro-mechanical systems. In this context, the laboratory experience plays a key role on the successful completion of the course.

A. In-Person Laboratory

ME-142 Mechatronics is one of the most lab-intensive courses with 150 min lectures and 180 min laboratory sessions per week for 16 weeks. Each year, around 60 students are registered for taking the course which is a considerable work for laboratory coordination. Before COVID-19 pandemic, in-person laboratory design of the course was based on intensive laboratory focused on hardware application for real-time mechatronics systems. In-person laboratory design was also using MESABox, a low-cost hardware development kit developed by [18].

B. Remote Laboratory

Due to the impact of COVID-19, all learning experiences including laboratory processes are switched to remote access. In this scenario, the role of simulation environments like MATLAB/Simulink increased dramatically. Therefore, first part of the remote laboratory is dedicated to functional capabilities of students for computational skills in MATLAB/Simulink. Since the access to hardware is not available by the nature of remote laboratory design, the idea of Digital Twins was leveraged for the educational purposes. In the beginning of the course, a questionnaire is designed to understand the background knowledge of students. Results in TableI and Table II indicates that most of the students have entry-level knowledge and skills for both theoretical and computational background.

TABLE I: Questionnaire for theoretical and computational backgrounds.

Question	Yes	No
1) Have you ever used Matlab/Simulink before?	71.93	28.07
2) Did you hear the concept of filter before in the sense of signals and systems?	50.88	49.12
3) Did you hear any of the filter types: Lowpass, Highpass, Bandpass, Bandstop (Notch)?	68.42	31.58
4) Do you know what are Fourier Transformation and Bode Plot?	36.84	63.16

TABLE II: Questionnaire for confidence level on Simulink

If you used Simulink before, how confident you feel about it?	Students
0 to 25%	35.09%
25 to 50%	33.33%
50 to 75%	21.05%
75 to 100%	10.53%

In order to design a remote laboratory program that is comprehensive and effective in terms of fundamentals of engineering instructional laboratories introduced in [19], learning objectives are defined as *Instrumentation, Models, Experiment, Data Analysis, Design, Learn from Failure, Creativity, Psychomotor, Safety, Communication, Teamwork, Ethics in the Laboratory, Sensory Awareness*. These learning objectives enable students to reach high-level hands-on learning experience in a remote laboratory of the mechatronics course.

The first part of the remote laboratory includes the foundations of signals and systems to obtain background knowledge and skills in MATLAB/Simulink. This foundation is constructed with the aid of dynamical systems response analysis with RC and RLC circuits, first and second order system simulations, Fourier and Bode techniques and a variety of filter types used in signal processing.

The second part of the remote laboratory introduces Digital Twin applications with MATLAB/Simulink and Simscape. Students first meet with the idea of Digital Twin as a virtual representation of real electro-mechanical systems. Then, they applied the concepts of identification, modeling, analysis and controller design using benchmark Digital Twin applications.

The last part of the remote laboratory introduces focused group study. Students are asked to form groups of six. Each group selected their own specific Digital Twin application to model, analyze and control using the M.A.D. methodology [1]. Finally, all the applications are posted online using MATLAB Web App Server [17] in order to increase the accessibility.

All the laboratory assignments are assigned to students along with a corresponding background and tutorial video. Therefore, students are enabled to go over and prepare for the theoretical and practical load of each assignment. Recorded tutorials are also posted online on the YouTube channel of Prof. YangQuan Chen [20] available at https://www.youtube.com/user/yqchen1.

III. Digital Twin Development Procedures & An Example

In order to implement a workflow in the development of the Digital Twin applications a benchmark framework proposed by [21] is utilized. The five DT development steps are defined as target system definition, system documentation, multidomain simulation, assembly and behavioral matching, and lastly validation and deployment. The overall framework is shown in Fig. 1. The framework is utilized in the definitions of the remote laboratory assignments in order to enable students to engage with the development process of the Digital Twin concept.

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Fig. 1: Digital Twin 5-step development framework [21]

A. Case Study

In order to enable students to grasp the essential idea of applications with Digital Twin concept, a case study for motion control system is provided. In order to refer in the later studies, each step in the overall framework described in [21] is addressed.

1) Target System Definition: The target system for the case study is defined as a position and velocity control in a real-time application as shown in Fig.2. Real system consists of a 12V DC motor of 600 RPM, a L298 H-bridge and Arduino Mega 2560 in Hardware in the loop setup with a PID controller in MATLAB/Simulink.

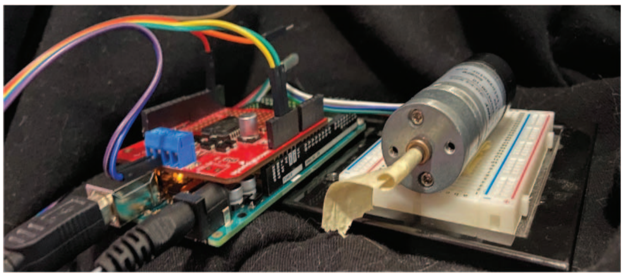

Fig. 2: Case study: motion control system.

2) System Documentation: The documentation for the components defined in previous step is given in Table III.

TABLE III: Motion system documentation

Component	Features
TSINY(TS-25GA37OH-10) DC motor	12V, 600RPM,2.5W Quadrature encoder 460 CPP
Hall effect encoder	460 CPR
Arduino Mega 2560	54 digital IO,16 analog inputs SRAM 8KB,EEPROM 4KB
Ardumoto Shield	Dual motor controller up to 2A based on L298 H-bridge

3) Multidomain Simulation: Multidomain structure of the Digital Twin application is considered in three subdomains namely Digital, Electrical and Mechanical. The Digital domain consists of the controller structure where the Electrical domain consists of motor and H-bridge structures. Finally, the Mechanical domain consist of the motion sensor and corresponding structures.

4) Behavioral Matching: After obtaining the multidomain simulation, the parameters of the Digital Twin can be obtained using behavioral matching. In this step, a set of stepped reference signals are utilized along with the datasheet specs as the initial values for behavioral matching. Using the Simulink Design Optimization (SLDO) Toolbox, the best parameters for Digital Twin can be obtained automatically. Results for behavioral matching are presented in Table IV.

TABLE IV: DC motor parameters.

Parameter	Manufacturer Specs	Value After SLDO
Armature Inductance [H]	1.2577e-11	1.2304e-11
Armature Resistance [Ohm]	0.075922	0.091449
Back EMF Constant [V/rpm]	0.0012462	0.041662
Rotor Damping [Nm/(rad/s)]	0.0004682	0.000405
Rotor Inertia [g*cm^2]	1.8747e-13	1.8747e-13

5) Digital Twin Validation and Deployment: After the behavioral matching, Digital Twin is deployed online using MATLAB Web App Server (MWAS) [17]. MWAS enables to create a server for deployed applications and access online with the aid of a web browser. Final deployed Digital Twin for case study is shown in Fig 3.

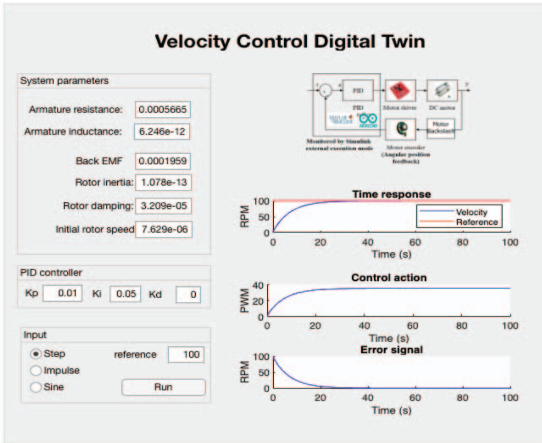

Fig. 3: Deployed Digital Twin web application using Matlab Web App Server

IV. Results

The outcomes of the designed Digital Twin based remote Mechatronics laboratories are defined in two aspects. Initial contribution of the offered laboratory design is the resulting Digital Twin applications deployed to Web App Server. Then, students are expected to participate in final laboratory evaluation survey in order to understand the impact of the offered remote laboratories.

A. Digital Twin Web Applications

In order to increase the accessibility of remote laboratory outputs, Digital Twin applications created by the student groups are deployed to MATLAB Web App Server. Compiling different applications can allow any user to utilize the Web App Server in their further remote mechatronics application. Main screen of MATLAB Web App Server is shown in Fig. 4.

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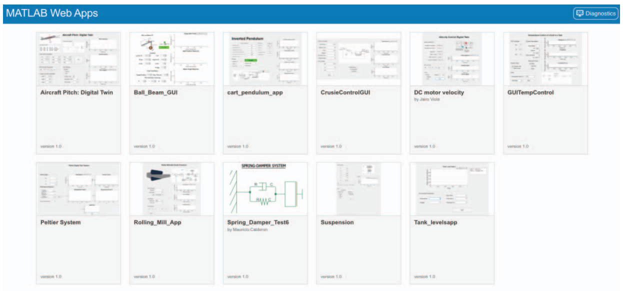

Fig. 4: MATLAB Web App Server including 11 Digital Twin applications implemented by the ME-142 class

At the end of the semester, ME-142 Mechatronics course Digital Twin Web App Server had 11 different Digital Twin applications namely, Aircraft Pitch Control, Ball and Beam, Inverted Pendulum, Cruise Control, Room Temperature Control, Peltier System, Rolling Mill Control with Smith Predictor, Suspension, Tank Level Control, Mass-Spring-Damper and DC Motor Velocity Control.

B. Final Survey

For the final evaluation of the remote learning using Digital Twin concept, students are expected to answer three questions. Out of 42 total answers, only 7.1% of the students answered "Yes" to the question of "Before the first day of instruction of ME-142, Have you ever heard the concept of Digital Twin?". Rest of the results for the Digital Twin survey is given in Table V.

TABLE V: Final survey results on Digital Twin

Questions (1.Lowest 5.Highest)	**1**	**2**	**3**	**4**	**5**
After take ME-142, how confident do you feel about Digital Twins?	7.1%	21.4%	31%	33.3%	7.1%
From your perspective, how much relevant is the Digital Twin for control systems design?	4.8%	0%	11.9%	40.5%	42.9%

Results of the survey indicate that the overall confidence levels of the students about the Digital Twin concept are above satisfactory.

V. Conclusion

This paper introduces a novel contribution for the utilization of the Digital Twin concept in remote mechatronics laboratory. The proposed remote laboratory design is offered for the ME-142 Mechatronics course in the University of California, Merced for Spring 2021 semester. This program enables students from entry level technical and computational skills to enhance their abilities in mechatronics as well as simulation and Digital Twin development capabilities. A case study for the Digital Twin development process is presented. At the end of the semester, groups of six students created their own Digital Twin applications and deployed them using MATLAB Web App Server. The utilization of Digital Twin concept in remote laboratory education had great influence on the educational progress of the students despite of the drawbacks of the remote learning.

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