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Digital Twin Based Laboratory for Control Engineering Education

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***Abstract*—The Covid-19 pandemic has made online learning the main choice in learning modes. For control engineering education that requires substantial laboratory practices as part of the learning process, online learning is a challenge in itself. It is difficult for students to gain experience and understanding of physical phenomena through online learning. Two approaches are commonly used to provide learning experiences that resembles practices in a traditional laboratory, namely virtual laboratory and remote laboratory. The drawback of virtual laboratory is that simulation eliminate the interaction aspect with physical devices make students miss the mental experiences of dealing with physical objects that important for engineering students, while the remote laboratory requires high cost and less flexible. This paper proposes another approach to overcome the shortcomings by utilizing a technology known as Digital Twin. Digital Twin based laboratory provides digital or virtual twin of a physical system that are interconnected with one another via the internet. The interconnection of the physical system and its virtual twin preserve the physical interaction and also increase the flexibility of the laboratory. Preliminary implementation and experiments show that the propose approach works properly. Users are able to manipulate the real plant remotely, and to observe almost identical dynamics of the real plant and the 3D visualization of the virtual plant.**

***Index Terms*—Digital twin, remote lab, virtual lab, control engineering, cloud technology**

I. INTRODUCTION

The Covid-19 pandemic has had a major impact on the education process. Many universities in the world, including in Indonesia, choose online learning as a mode of learning. This learning mode has challenges in terms of adaptation, especially for students and lecturers in engineering, because there are many courses that require laboratory practices as part of learning processes. For courses in engineering such as control engineering, laboratory practices have large impacts on instilling an understanding of concepts where learning begins with the modeling stages, analyzing and realizing designs and applying them to real physical systems [1]. Online learning can be used to convey facts, concepts and theories, but does not help students to apply theories and concepts into real practice in order to gain a deeper understanding of concepts [2].

One approach to provide practical experiences in online learning is to use a virtual laboratory [3]. Virtual laboratories allow students to interact with simulated versions of physical devices in the form of virtual representations of devices such as machine, robots, controllers and other materials through computers. Virtual laboratories provide an advantage in improving learning understanding through time-scale changing facilities, namely speeding up or slowing down a process so that some physical phenomena that are difficult to observe can be slowed or accelerated so that easier to observe. Another advantage is that it provides a safer and cheaper environment [4]. On the other hand, there is a fundamental shortcoming of virtual laboratories, namely that the visualization of physical device is often simplified by adding assumptions to eliminating interference factors so that they do not represent the reality. As a result, students often fail to understand mentally the phenomena that should appear in the real environment [5].

Another approach is to use a remote laboratory [6–9]. In this approach, students directly access and control or manipulate hardware remotely through a network so that students can really feel working with the system for real and more motivated in learning. This approach is more complex than the virtual laboratory approach and is more expensive. Therefore, the use of this approach is still limited to large universities in developed countries.

On the other hand, advances in several technologies such as sensors, networks, standards, big data, and artificial intelligence have driven the emergence of the Internet of Things (IoT) which allows almost unlimited interactions between physical and virtual things. One of the IoT technologies that is widely used in the industrial world is Digital Twin which integrates the cyber world and the physical world [10]. Digital Twin is a digital reflection of a physical system where changes that occur in the physical system are directly visible on the digital equivalent and vice versa manipulations carried out on the digital part of the cyber world will immediately be felt on the physical system.

Digital Twin has the potential to be applied to laboratories to realize a combination of virtual laboratories and remote laboratories. The characteristics of Digital Twin that combine the cyber world and the physical world interactively will meet the needs of online laboratory practices that still provide a physical experiments experience. In this paper, the concept of Digital Twin based laboratory that allows students to interact with physical devices remotely via the internet and the preliminary implementation and experiments are discussed. The rest of the paper is organized as follows. Section II describes the concept of education in control engineering, the objectives of laboratory in engineering education, the classification of laboratory based on the physical nature of the equipment and location, and the concept of Digital Twin. In Section III, the proposed Digital Twin based laboratory operation mechanism and implementation steps are discussed. Section IV discusses the preliminary implementation of the concept and the

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experiment results, and in Section V the conclusion is given.

II. LITERATURE REVIEW

A. Education in Control Engineering

Control Engineering is the fundamental of the more general concept automatic control. It is an interdisciplinary in nature, because the theoretical formalism of this field is given by system theory which is applicable to many different fields of engineering such as mechatronics, mechanics, process control, chemical, transportation, etc. Although it is an engineering field which demands practical experiences, however, the general theory behind this field is fundamentally based on mathematics and physics [11]. That fact became one of the reasons why control engineering is considered to be a difficult topic to teach [12].

Traditionally, Control Engineering is taught in a pattern which can be described as [13]:

Mathematics ➔ theory ➔ analysis ➔modeling ➔ design

Potential problems with that approach are: i) there is a tendency that theory and analysis dominate the practice and synthesis which drift the “professional engineering” into “applied science”, and ii) students cannot comprehend the fundamental theory, and are failed to relate the theory to practical engineering problems which in turn will demotivating to students. The possibility of the potential problems is supported by the fact that the basic skills in physics and mathematics of students are varied depend on their background, and also by the indication that the mathematics skills of students are generally decreased [14]. Engineering schools students often argue that they come to study engineering not mathematics, therefore, it is difficult to persuade them to learn mathematics as part of their study in engineering schools. Students want to immediately start doing practical things without feeling the need to understand the theoretical basis.

Accrediting bodies for engineering education, however, require students to acquire adequate understanding of both practical and theoretical aspects as the student outcomes. ABET, for example, set “an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, sciences, and mathematics” and “an ability to develop and conduct appropriate experimentations” as student outcomes criteria for undergraduate program [15]. Therefore, a balanced teaching curriculum between theoretical notions and practical training is necessary in order to lead to highly qualified engineers as required by accrediting bodies. Practical experimentation in a laboratory is then a vital part to reduce the gap between theory and practice in control engineering education.

There is no general agreement about the objectives of engineering laboratories. A colloquy convened in San Diego on January 2002 suggested the following thirteen abilities as objectives of engineering laboratories [16]: i) apply instrumentation, ii) understanding modeling as predictors of real-world behaviors, iii) experiment to characterize an engineering material, component, or system, iv) data analyze, v) design to meet requirements, vi) learn from failure, vii) independent thought, creativity and problem solving, viii) use appropriate engineering tools and resources, ix) identify health, safety, and environmental issues, x) communicate effectively both orally and in writing at levels ranging from executive summaries to comprehensive technical reports, xi) work effectively in teams, xii) ethics in the laboratory, and xiii) sensory awareness. The objectives cut across three domains of knowledge, namely, cognitive, psychomotor, and affective, and can be used as guidance for laboratory experiments designer.

Control engineering laboratory usually provide experimental devices that can be used to demonstrate system dynamics, and can be used as vehicles for controllers design. Experimental devices can be purely hardware or combination of hardware and software. Devices for control engineering laboratory is reasonably expensive so that a laboratory usually only provides a limited number of devices, makes access to laboratory a challenge in itself [17].

To increase laboratory accessibility and reduce laboratory operating costs, two approaches, namely virtual laboratory and remote laboratory are utilized. With the advent of the Covid-19 pandemic, both approaches have almost completely replaced traditional laboratories.

B. Remote and Virtual Laboratory

Numerous definitions of remote laboratory definition are found in literature [18–23]. Nevertheless, there is no definitive definition are agreed. Several different terms such as e-labs, web-labs, online-labs, tele-labs or virtual-labs are used to define the very same concept. To establish a clear classification of lab, two criteria based on location and the physical nature of equipment are widely used [18, 19, 21, 22]. Based on the location labs are divided into local and remote, and based on the physical nature labs are divided into physical or hands-on lab and virtual lab. From the two criteria the following four labs can be classified as shown in Fig. 1, i) traditional hands-on lab, where students directly access real equipment, ii) local virtual lab or software lab, where simulated plants in a stand-alone computer fully replace the real equipment, iii) remote lab, where student access real equipment through internet, and iv) virtual remote lab, where the simulated plants in the computer are accessed remotely via internet. From this classification, virtual laboratory and remote laboratory become new concepts within the distance education framework. Virtual remote laboratory is more powerful than the local virtual lab, allowing the simultaneous use of remote simulation modules by the students.

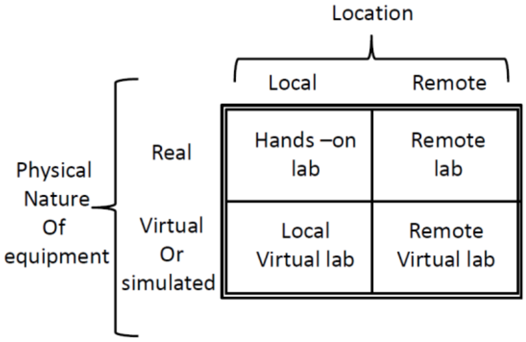


Fig. 1. Laboratory classification.

Remote laboratory is much more flexible and accessible allowing students to access real equipment and perform laboratory activities remotely 24 hours a day at anytime and anywhere.

The combination of remote lab and virtual remote lab is known as Virtual and Remote labs (VRLs) or web-based lab. Several initiatives in the development of VRLs are emerged from different universities, some of them are [23]: iLab (MIT, USA), Labshare (UTS, Australia), VISIR (BTH, Sweden), WebLab-Deusto (University of Deusto), LiLa (European), and NetLab (Unisa, Australia).

One of the drawbacks of VRLs is the lack of convergence and interoperability between the virtual and the physical elements. Many efforts have been made to integrate the virtual and the physical elements in remote labs. Torre et al. [24] proposed a solution that combines both elements using Easy Java Simulation (EJS) and tested it on the ball and beam module as the physical element. The EJS lab is then deployed into Moodle as the LMS. Through this approach the processes become simpler and faster, and improve the VRLs by adding lab management features such as saving data files, automatic language detection and booking system.

Vargas *et al*. [25] proposed an approach to combine remote and virtual lab by dividing into two layers, namely the experiment layer and e-learning layer. For the experiment layer, Labview is used and for the e-learning layer eMersion is used. Several devices such as heat-flow module, three tanks system and servo motor are used as the physical elements. The proposed method has the advantage of effectively switching between simulation and actual operations of a real system.

It can be seen that the approaches taken to combine virtual and physical elements have not fully utilized the interoperability between virtual and physical elements. The data obtained from physical element are simulated in virtual element, but virtual element has not been used optimally to obtain information that can be used to manipulate physical element. Meanwhile in the context of design in control engineering, dynamic manipulation of the physical system by a controller is very important.

Along with the development of Internet of Things (IoT) technology, a method that combines physical objects and virtual objects known as the Digital Twin gains the popularity. Digital Twin has been widely used in Industrial Internet of Things (IIoT) where interoperability between physical elements and virtual elements runs very optimal. In this paper, utilization of Digital Twin to develop VRLs is discussed.

C. Digital Twin

The concept of Digital Twin was first introduced by Grieves in 2003 who in his 2014 paper [26] defined Digital Twin as a combination of three main components: i) virtual twin, ii) physical objects that can be in the form of a system, a model or other physical component, and iii) data flow cycle that supplies data from the physical object to the virtual twin, and subsequently feeds back information from the virtual twin for manipulation or control purposes. The virtual twin is an algorithm that replicates the character and dynamics of a physical object or a system so that it will produce the same input and output pairs.

Although it has been almost 20 years since it was first introduced, it only less than the last 10 years that there has been an increasing interest in Digital Twin, especially in intelligent manufacturing applications and industry 4.0 [27]. In its development the following definitions provide a clearer picture of the Digital Twin concept [28]:

- Digital Twin is a virtual representation of a system or a physical object that uses data, machine learning, and IoT to assist a company in optimizing, innovating and generating new services [29].
- Digital Twin is a virtual representation of a system or a physical object in the entire system life cycle using real-time data that allows learning and thinking process to occur [30].
- Digital Twin is a virtual representation that simulates the dynamics of a system or a physical object and works in parallel together changing when the object or system changes [31].

From the definitions above, it can be seen that Digital Twin is growing rapidly due to the encouragement of several technologies that support it such as wireless sensor networks, IoT, machine learning, deep learning and big data so that interconnection between the physical domain and digital or cyber domains can occur properly [32]. This interconnection is able to provide in-depth and broad information for a complex system that previously would have been very difficult to achieve [33].

The process of physical and virtual interconnection in Digital Twin is achieved through technologies that enable the transfer of information from physical environment to its virtual twin such as cellular technology, web services, and WiFi. Virtual twins are gradually set to match their physical twins through a measurement and correction process. The difference between the physical environment and the virtual environment becomes data that is fed back to the virtual twin for correction process. Measurement of the real condition takes place in the physical environment while the intervention for correction occurs in the virtual environment. Through this mechanism, virtual or digital twins will always reflect the status of their physical twin in real time [34].

Virtual-physical interconnection represents the flow of information from the virtual environment to the physical environment. This information is not only used for monitoring processes but can also be used to change or manipulate physical system parameters for control and optimization purposes. Data and information from physical and virtual domains can be stored and analyzed on servers or the cloud where decisions regarding optimization, diagnosis and prediction are made.

The main components of Digital Twin can be depicted as in Fig. 2 [35]. It can be seen that the main components of Digital Twin consist of three parts, namely: i) the physical side which can be in the form of sensors and infrastructure with their specific functions, ii) the virtual side with the main function is to collect, process, and analyze data. In general, the virtual side is made up of a number of models with different functions, and iii) connections in the form of data transmission and human-machine interface. Generally, there are three connections: i) the connection between the virtual and physical sides, ii) the connection between the virtual side and humans which can be in the form of visualization techniques such as virtual reality, augmented reality or 3D simulation, and iii) the connection between humans and the physical side for example connections with hardware such as sensors, actuators, controllers and plants to be controlled.

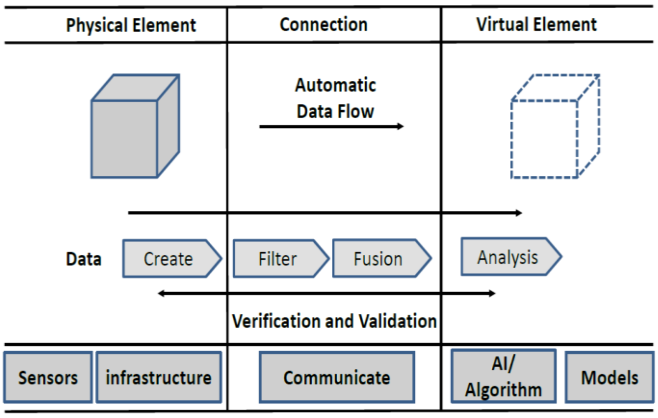


Fig. 2. Digital twin components.

Digital Twin is applied in various industries such as [27, 36–38]:

- Manufacturing, in the manufacturing industry Digital Twin is believed to be the main technology to realize smart manufacturing, fault diagnosis, robotics, quality control, health monitoring and process maintenance. The use of Digital Twin can increase productivity, shorten production time and increase efficiency.
- Health, the application of Digital Twin in the healthcare industry includes the maintenance of medical equipment and optimization of its use. The main purpose of using Digital Twin in the healthcare industry is to assist authorities in managing patients as well as medical devices for diagnosis and intervention so that the quality of services can be improved.
- Transportation, in the transportation industry Digital Twin is used for example for unmanned vehicles, for traffic management, for congestion prediction and also for energy use optimization purposes.
- Education, in the world of education Digital Twin can be used for implementation of online learning for example in virtual laboratories, but not much research has been done on the use of Digital Twin in the education domain.

III. DIGITAL TWIN BASED CONTROL ENGINEERING LABORATORY

A. Operation Mechanism

The operating mechanism of the Digital Twin based laboratory is shown in Fig. 3. There are three main components of the Digital Twin based laboratory, namely, physical components, virtual components, and connections. Physical components are the real plants for experiments including sensors and actuators. Virtual components are models that have characteristics and properties that are identical to physical components so that they can be used for the controller design. In the Digital Twin based control engineering laboratory, the controller is included in virtual components.

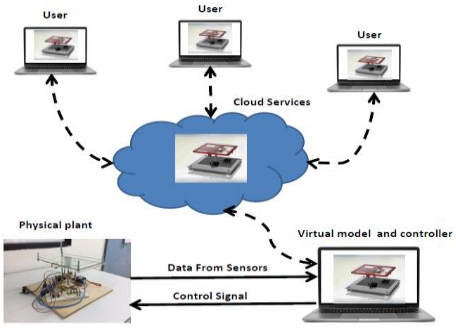


Fig. 3. Operation mechanism of digital twin laboratory.

Virtual components are spread in several locations, namely on a computer close to the physical components, in the cloud, and on each user's computer. The virtual components in the computer close to the physical components are physically connected to the physical components either through wire or wireless. The physical components send data through sensors and receive control signal from controller. The data from sensors will directly affect the virtual model so that the virtual model will describe the current conditions of the physical plant in real-time. The virtual components are connected with other virtual components in cloud and in the users' computers via internet network.

B. Implementation Steps

Implementation steps for a Digital Twin based control engineering laboratory are as follows:

1) Physical system set-up. For learning purposes, it must be ensured that the selected plant has dynamics that are sufficiently complex so that it can accommodate wide spectrum of controller design strategies from classical control design such as PID controller or lag and lead compensators to modern control design such as Robust, Adaptive, Fuzzy or Neural Network controller.
2) Modeling of Virtual Plants. Modeling is a very crucial part of Digital Twin based laboratory. To model dynamics of a system adequate knowledge in differential equations are required. Low interest of students in mathematics may hinder them in the modeling process. Therefore, modeling using Simscape, a MATLAB toolbox, will be a good approach. Simscape is a multi-domain modeling with the capability to model a combination of different domains such as mechanical, electrical, hydraulic or multi-body system based on direct physical connections of fundamental elements. Simscape and Simulink provide good visualization support for 3D simulation, and support hardware in the loop system.
3) Controller design. Controller designer apps in MATLAB can be used as control design tool which provide graphical visualization to give students design intuition and improve the analytical skills. The controller is then implemented in the Simulink block to be able to access both physical and virtual plants.
4) Connection with the cloud. Currently, three are major cloud services provider: Amazon, Microsoft, and Google. Several choices of cloud platform integration protocols like AMQP, MQTT, and REST can be used.
5) Connection to users. After the virtual models are deployed in the cloud, users can access the virtual and

physical components through internet.

After all the steps are completed, the laboratory is ready to use. Students can start the experiments in a more flexible time.

IV. EXPERIMENTS AND RESULTS

A. Experiments Set up

In accordance to the implementations steps a preliminary system is implemented as follows:

(i) Physical system set-up. Ball and plate system is chosen as the plant. This system is chosen because the underlying concept of the system has wide applications such as active suspension of a car, Segway, active vibration control, multi-terrain wheelchair etc. This system also has challenging dynamics, allowing a wide range of control laws to be tested to control the system. The implemented plant is shown in Fig. 4. The objective of the system is to place a ball at desired positions on the plate regardless the presence of disturbance. An iron ball with mass of sixty seven grams is placed on the resistive touchpad. The touchpad also serves as a sensor that will send out analog voltage with the amplitude depending on the position of the ball. Two servo motors are used to move the plate. One servo rotates around the x axis and the other one around the y axis. Arduino microcontroller is used to connect the plant to a computer, and to connect wirelessly to the internet ESP8266 Wifi shield is used.

(ii) Modeling of virtual plant. The model of the ball and plate is built using Simscape and Simulink. The visualization of 3D model of the virtual ball and plate is shown in Fig. 5. This virtual model will simulate the dynamics of real plant in real time. The building blocks to realize the model is shown in Fig. 6. The model consists of five components which are the ball, the plate, the linkage that connect the servo motors to the plate, the servo motor and the stand that support the other components.

(iii) Controller design. In this experiment Proportional Derivative (PD) controller is designed and built in Simulink. Since the two servo motors are independent, the coupling between the two motors are can be neglected, therefore two PD controller are used.

(iv) Connection to the cloud. In this experiment the system is not connected to the cloud, however, the real plant and the virtual plant are connected through internet. Therefore, the deduction that if the system work through internet connection then the system will also work in the cloud is valid.

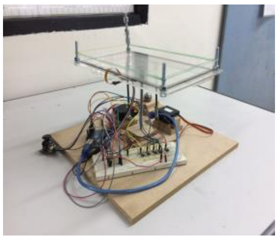


Fig. 4. Implemented ball and plate plant.

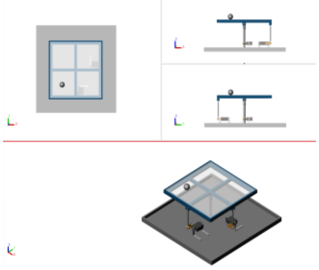


Fig. 5. 3D model visualization of ball and plate.

(v) Connection to users. Using ESP8266 the real plant can connect to up to four virtual plants, however, in this experiment only one virtual plant is connected to the real plant.

The realization of digital twin laboratory is shown in Fig. 6. The system is divided into two different domains namely, the digital or virtual domain and the physical domain. The digital and physical domains are connected through internet as indicated by the thin dashed line. The real plant and the digital plant will receive the same signals control, ux and uy, from controllers, and the real plant generate the output signals, x and y, that will be send as feedback signals to the controllers. A dashboard is provided in the digital domain where users can manipulate the reference source, set point, and controllers' parameters. Users will be able to observe all the signals for analysis purpose through a scope.

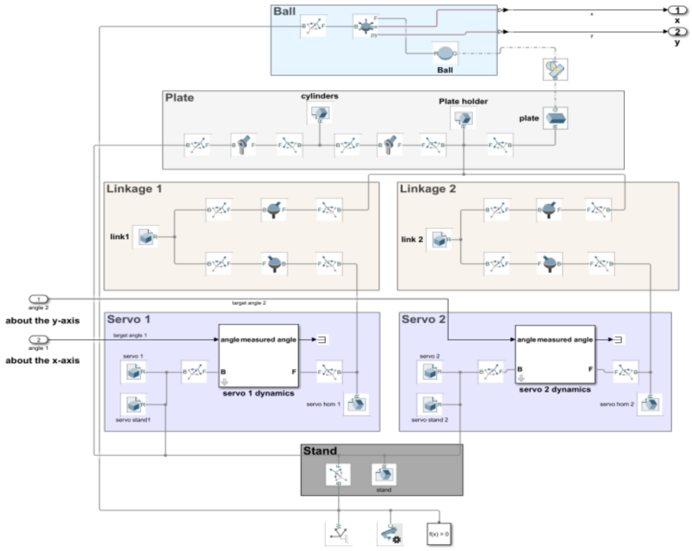


Fig. 6. Building blocks of virtual model of the ball and plate system in Simscape-Simulink.

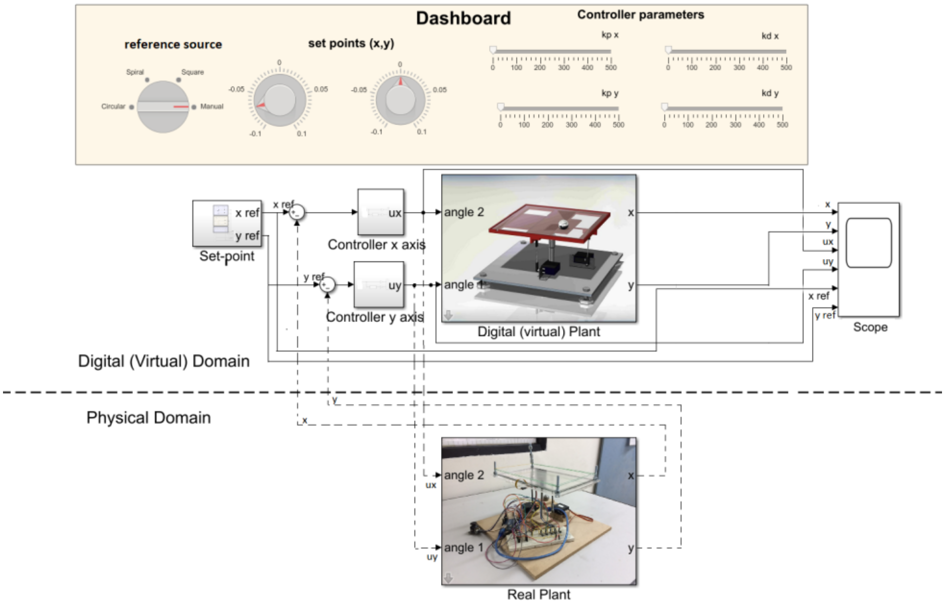
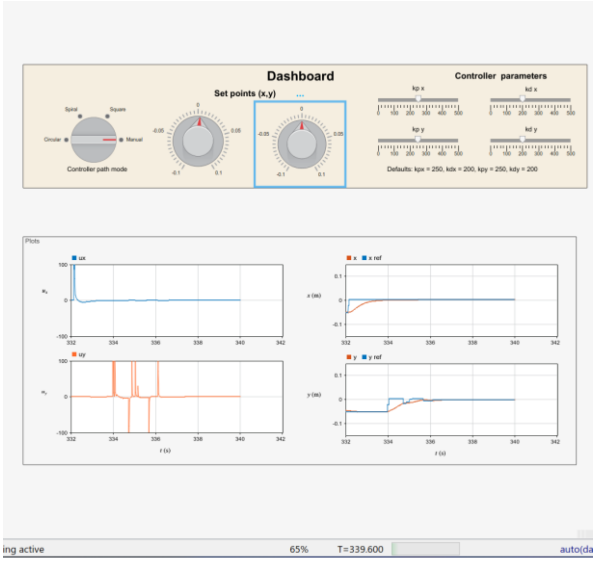


Fig. 7. Interconnection of digital twin laboratory.

Several experiments are run to observe the connectivity of the two domains and whether there is agreement between the virtual model dynamics and the real plant dynamics. Two of the results are discussed in the following subsection.

B. Experiments Results

Two experiment results are shown in Fig. 8 and Fig. 9. The two figures consist of three parts. The top part shows the dashboard and the signals graphs from the scope, the middle part shows the 3D visualization of the virtual plant, and the bottom part shows the real plant. In Fig. 8, the set point is set at (0,0) as indicated by the knob at the dashboard. It can be seen that the control signals, ux and uy, go to zero as the ball reached the desired position. The 3D visualization and the real plant are in agreement as shown at the middle and the bottom of the figure, respectively. In Fig. 9, the set point is changed to (0.05,0.05) that is to place the ball close to the corner of the plate. The figure shows that the controller give the signal control ux and uy to drive the ball to reach the desired position, and the control signals go to zero once the ball reach the set point. The figure also shows that the 3D simulation is in agreement with the real plant.



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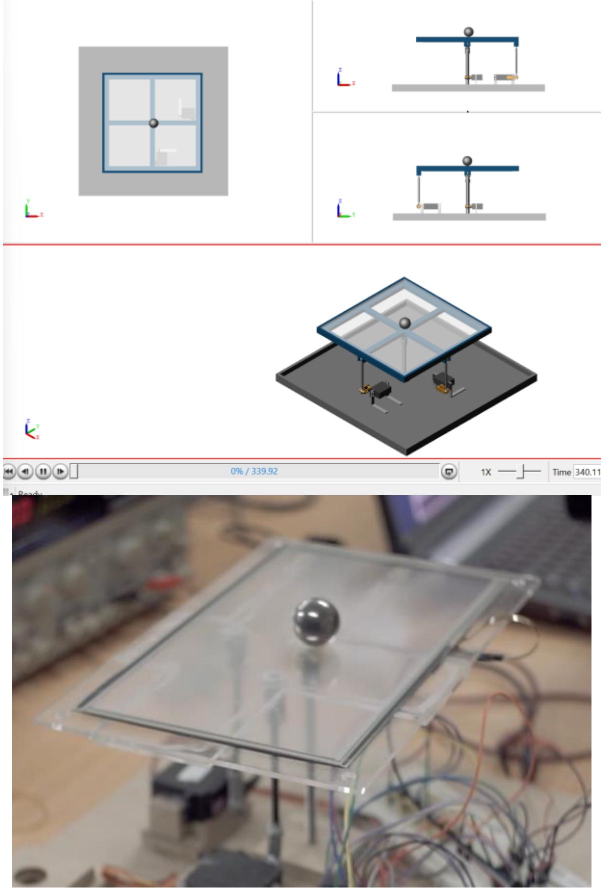

Fig. 8. Experiment 1.

The experiments demonstrate that the digital twin based laboratory is work properly. Users are able to control the real plant remotely through internet, and at the same time are able to observe both the 3D visualization and the signal graphs at their own computers.

As previously mentioned, in this preliminary experiments the proposed digital twin based laboratory is not connected to the cloud yet. However, since the system is already interconnected through internet then it can be deducted that there will be no technical problems to connect the system to the cloud. Placing a virtual model in the cloud enables the utilization of cloud services such as analytics or diagnostic decisions. The cloud can also provide virtualization software so that it can run multiple instances of software efficiently which results in reduced costs without sacrifice performance. Using their own computers with lower specification, users are able to design and run advance controllers that require strong computation power. Users will also able to access the laboratory from their own computers remotely in a more flexible time.

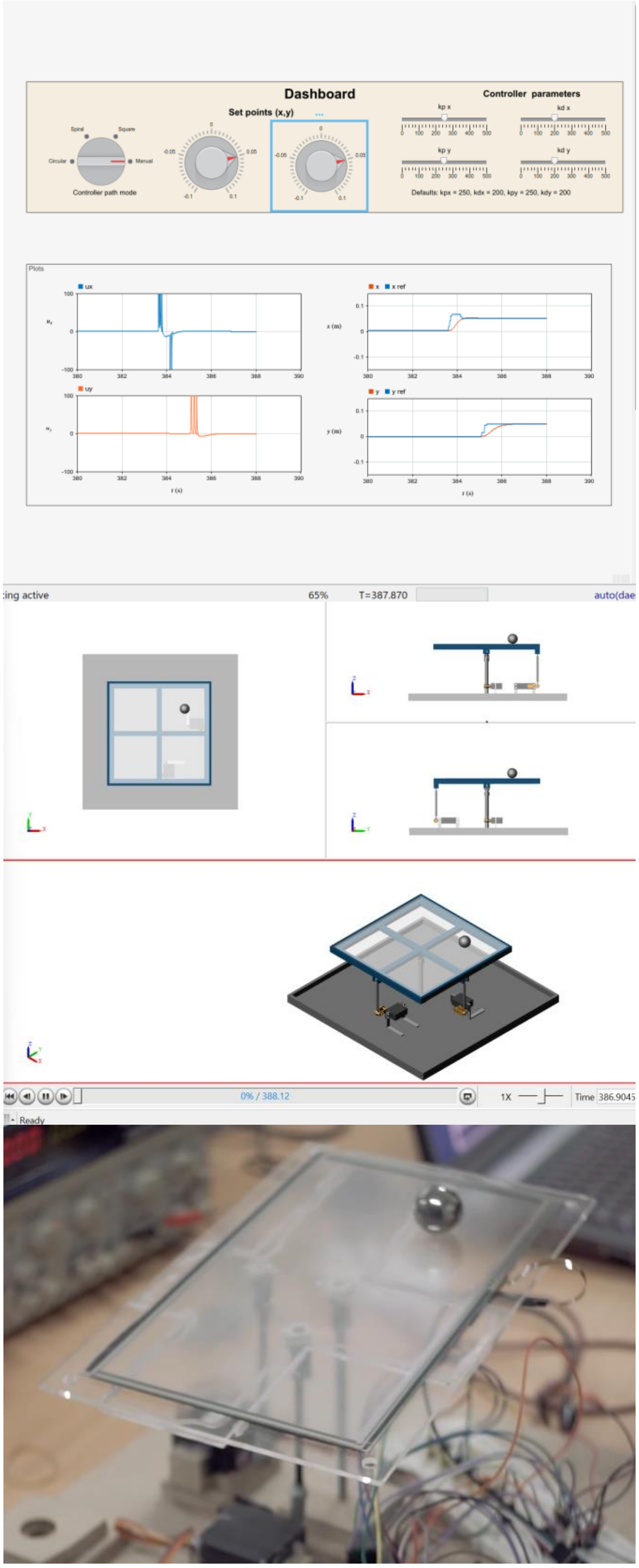

Fig. 9. Experiment 2.

V. CONCLUSION

In this paper, the concept of a Digital Twin based laboratory which is the unification of remote and virtual laboratory is presented. Preliminary experiments show that the unification works properly. User is able to manipulate the real plant remotely and observe the same dynamics of the real plant and the 3D visualization of the virtual plant. The propose system demonstrate the convergence and interoperability of the real plant and the virtual plant. In the midst of the Covid-19 pandemic where distance learning is the main choice of learning methods, digital twin based laboratory provides a promising alternative solution to achieve the objectives of engineering laboratory. In the future, the implementation of learning and the analysis of student experiences in using the Digital Twin based laboratory will be explored.

VI. FUTURE DIRECTIONS

One of the challenges that need to be considered in the implementation of the Digital Twin based control engineering laboratory is the latency time. Although with the development of internet and cloud technology the latency time is getting shorter, however, in the control system latency is a crucial factor that affected the performance of the system. In the future, evaluations of the effects of latency time to the system performance and to the students' experiences when using the Digital Twin based laboratory will be explored.

Furthermore, although the purpose of this paper is to propose an approach that provides students with learning experiences that resembles practices in a traditional laboratory using Digital Twin technology, the focus of the paper is on the implementation side. Future studies will be more focus on the pedagogical aspects. Statistical analysis that measure the students' interest, motivation, learning efficiency and academic performance when using the Digital Twin based laboratory in comparison to the traditional one will be investigated.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Hendra Tjahyadi did the literature review of the remote and virtual laboratory and the Digital Twin, the hardware implementation, preliminary experiments, and contributed to the writing of the whole paper. Kusno Prasetya and I. Made Murwantara contributed to the research and literature review of modeling and cloud technology, and the implementation of virtual model. All authors had approved the final version.

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