

Augmented Reality and Digital Twins in Engineering Education: Technological Enhancements and Applications

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Abstract—This research explores the advantages of real-time simulation in augmented reality (AR), focusing on the simultaneous interaction with both physical and virtual environments. AR enables an intuitive understanding of simulated phenomena, offering more natural controls and reducing nausea compared to virtual reality (VR). By integrating AR simulations with physical models and digital twins (DT), the differences between simulation and reality are accentuated, allowing for further refinement of simulation models. These benefits are particularly impactful in engineering education, where students can engage with both theoretical and practical aspects simultaneously. The integration of AR, DT, and physical models can enhance the learning experience, providing a deeper understanding of complex concepts. Additionally, these advancements are applicable to various fields, including engineering design and validation, medical training, and construction planning. This research aims to demonstrate the significant potential of combining AR and DT in educational and professional settings, ultimately bridging the gap between simulation and reality.

Index Terms—Augmented Reality, Digital Twins, Real-Time Simulation, Engineering Education.

I. INTRODUCTION

AR has many advantages when applied to real time simulation. One of the biggest advantages is the simultaneous interaction between physical and virtual environments - unlike a purely virtual environment, such as a desktop simulation software, AR environments allow the user to see the real world and any overlaid simulation environment. This configuration enhances the user's ability to both intuitively understand and manipulate the system, as well as detect any discrepancies that may pose a problem down the line. This is due to the natural 3D environment, as well as visualizations of forces and typically unseen and abstract dimensions of a physical model. One of the

other benefits provided by an AR environment is that it has more natural controls than a mouse, keyboard, or touchscreen can offer. When interacting with AR, you can both interact with the physical environment as usual, as well as utilize familiar physical movements for interaction with the digital simulation. In contrast, VR does not offer the same physical interaction that AR does - only providing natural controls for the simulation environment. AR is also less nauseating than VR for many users, and keeps them aware of their surroundings to a greater degree. AR for real-time simulation is an evolving landscape, and in an effort to stay up-to-date with any recent developments, we have conducted a thorough literature review of recent publications in the AR space. These are our findings, a summarization of relevant and recent papers regarding AR and its uses in real time simulation. Augmented Reality (AR) has transformed real-time simulation across various domains by merging the physical with the virtual, enhancing both understanding and interaction. This integration enables simultaneous interaction between environments, which is particularly advantageous over virtual-only settings like desktop simulations. AR's ability to overlay simulations on the real world not only facilitates intuitive manipulation of systems but also aids in detecting discrepancies early in the process. The natural controls offered by AR, such as gestures and movements, surpass traditional interfaces like mouse or keyboards, providing a more immersive experience. Moreover, AR tends to be less disorienting than virtual reality (VR), helping users maintain awareness of their surroundings [7].

Recent advancements in AR technology further exemplify its potential in education and engineering. For instance, integration of AR in a Mechanical Vibra-

tions Lab allows real-time interaction with MATLAB simulations, enhancing hands-on learning experiences despite challenges such as latency [4], [9]. Similarly, AR's application in structural modal identification, despite a delay caused by data buffering, offers valuable real-time insights by utilizing FFT analysis and accelerometer data [1]. The educational sector benefits as well, with systems like the one utilizing the Open Dynamics Engine to simulate physical phenomena in 3D spaces, thereby increasing interactivity and realism in learning environments [2]. Engineering analysis and simulation have also been revolutionized by AR. Techniques like OpenGL and Java3D improve the rendering of simulations in fields ranging from biomedical engineering to thermal and fluid transfer. Despite limitations in simulation speed and data accuracy, solutions like marker-based tracking have been proposed to enhance the reliability of complex simulations [7], [8]. The practical application of AR in power systems design highlights the necessity of parallel computing to handle demanding simulations effectively, leveraging graphical user interfaces for user-friendly operation [5]. In educational contexts, AR proves highly beneficial by enhancing student engagement and understanding of complex concepts. Systems developed for physics education employ GPU acceleration to improve performance, demonstrating AR's capability to deliver immersive and interactive educational content [10]. This is supported by other educational AR applications that utilize game engines for fast and accurate simulations, making learning more accessible and appealing [6]. Manufacturing and production processes have also embraced AR to streamline operations. By integrating AR with virtual reality, manufacturers can simulate and visualize entire processes and supply chains, significantly reducing the time and cost associated with system planning and error mitigation [3]. Collectively, these studies underscore AR's broad applicability and transformative potential in real-time simulation. By enhancing interactivity, reducing errors, and improving comprehension, AR continues to offer significant advantages over traditional methods and technologies, shaping the future of simulation in various disciplines. The primary goal of this project is to simulate a dynamic system in real time and visualize it using AR. The project aims to create a system that is accurate, responsive, and user-friendly. When evaluating the success of an AR simulation environment, many parameters must be kept in mind. Latency and update rate are key factors, as high latency or low update rate can induce nausea, as well as provide out of date or inaccurate information to the user. Tracking

accuracy and simulation accuracy are also critical, as the origin of the simulated and virtual environment must be identical. Failing to maintain tracking can result in a shift in size or position of the simulation model visualization in relation to the physical system. A final metric is the ease of use - the environment must provide intuitive controls to the user, including moving their head to change simulated camera positioning, and pausing or restarting the simulation without removing the headset. Ease of use can also apply when outside the environment, as adapting the environment to different models is essential for it to be useful in a range of scenarios.

II. METHOD AND SETUP

As part of the Mechanical Engineering Undergraduate course in the Vibrations Lab (ME-318), a set of linked pendulums was erected to serve as a physical system that could be modeled in simulation. These pendulums are linked by springs, creating a two-degree-of-freedom system. Traditionally, students derive the governing equations of motion using either Newton's method or the Energy method, resulting in two second-order differential equations. By employing the state-space method to reduce the order of these differential equations, students can solve them numerically and compare the simulation results with the measurement data.

1) *Physical System:* The current lab setup features a combination of double pendulums where students can read the angular position of each arm using potentiometer sensors and an oscilloscope (Figure 1). The double pendulum system consists of two mass pendulums connected by a spring between the two rods. The spring could be adjusted up and down to produce varying results, but we kept the spring at the middle location about halfway up the rod. The first procedure asked us to offset each pendulum the same number of degrees and in the same direction to see the effect that each pendulum had on each other throughout its motion. We connected one of the pendulums to an oscilloscope to observe the natural frequency and solve for the spring constant. The second procedure consisted of releasing each pendulum from equal degree offset but in opposite directions. Again, we observed the natural frequency and solved for the second frequency and spring constant. We then performed a modal analysis of beat phenomenon of the system by providing an initial angular displacement to only one of the pendulums. We observed the constructive and destructive interference patterns of the system.

The schematic of the double pendulum system can be found in Figure 2. The system, which has two

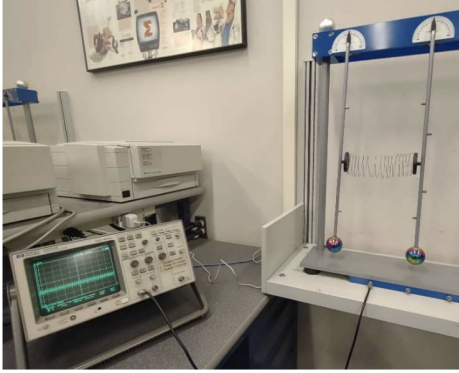


Fig. 1. Double pendulum setup with potentiometer sensors and oscilloscope

degrees of freedom, is governed by the following equations of motion:

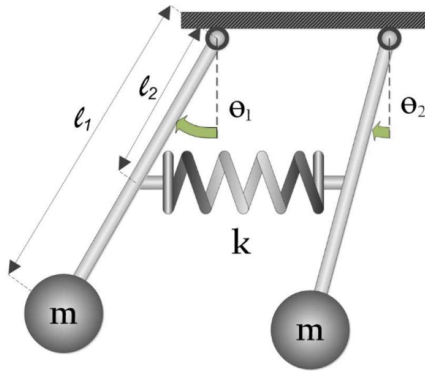


Fig. 2. schematic of the double pendulum system

$$-mgL_1\theta_1 - k(\theta_1 - \theta_2)L_2^2 = mL_1^2\ddot{\theta}_1 \quad (1)$$

$$-mgL_1\theta_2 + k(\theta_1 - \theta_2)L_2^2 = mL_2^2\ddot{\theta}_2 \quad (2)$$

2) *Matlab Simulation:* The double pendulum experiment performed by students in the ME 318 lab will be simulated. This experiment examines the movement of a double pendulum with a spring between at different initial conditions. The simulation in MATLAB uses the derived equations of motion for this double pendulum system in an 'ode45' solver to produce an animation that replicates the experiment. The provided code served as the basis for this study. To achieve a real-time simulation, a pause function was incorporated into the for loop that creates the animation, and the value of the spring constant was modified. While it is impossible for this simulation to be accurately real-time without advanced software, these code alterations

allow for the simulation to appear as though it is real-time. To properly align the simulation with the real-life experiment, additional code was added to display a line symbolizing the spring, and the lengths of the pendulums were adjusted to ensure accurate overlay. Students can then adjust the initial conditions in the MATLAB code and run the experiment simultaneously with the simulation in the headset.

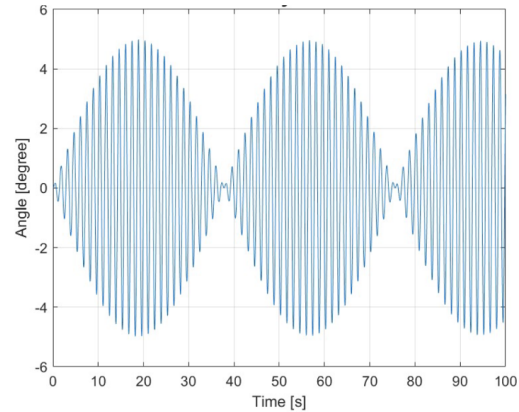
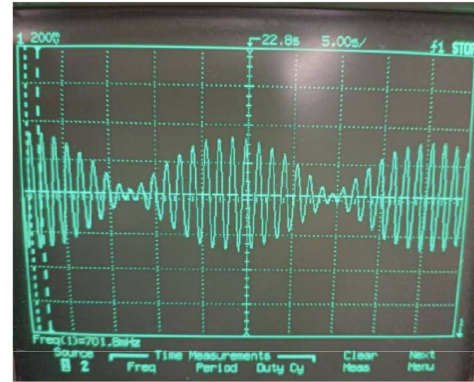


Fig. 3. Oscilloscope and Simulation output

3) *Implementation of Augmented Reality:* There are numerous choices for consumer AR headsets, including the Microsoft HoloLens 2 and the Apple Vision Pro. We chose to use the Meta Quest 3 for its ease of use, high performance and quality, as well as its excellent software support. The Quest 3 has cameras on the outside, allowing for vision passthrough, as well as hand tracking and controller support for a variety of control options. Another advantage to the Quest 3 is the ability to use it wired or wireless. Wired has the advantage of the lowest latency, but our chosen software for PC casting is limited to wireless operation. Wireless on the Quest 3 can be used from a Mac, Windows, or Linux host, and paired with the Virtual Desktop application, AR passthrough can be achieved

with high performance and low latency, as passthrough is done on the headset. Wireless on the Quest 3 also does not require any base stations, which minimizes setup time and allows for portability.

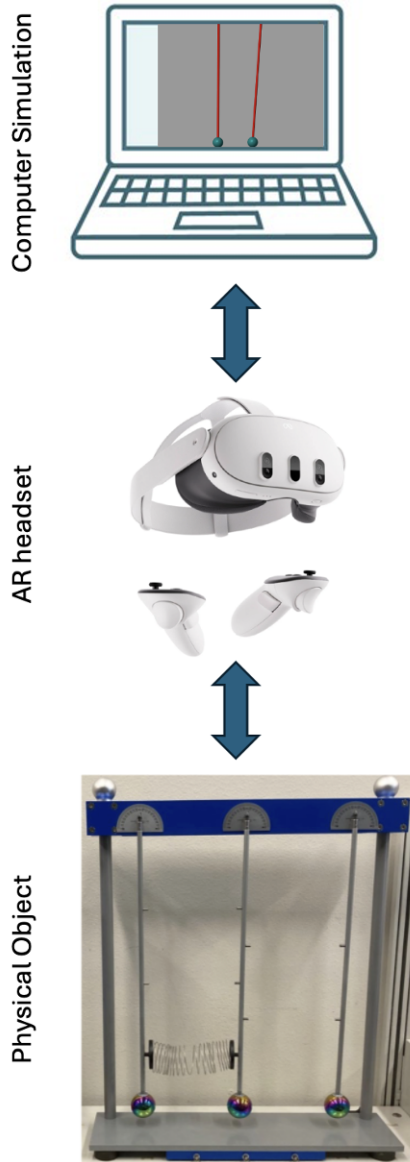


Fig. 4. Digital twins, mapping computer simulation on the physical object using Augmented Reality

III. FINAL OUTPUT

The inclusion of AR proved successful in the Vibration lab with the double pendulum experiment. Mapping the simulation over the physical setup was completed and all requirements were met. A day was set aside to demonstrate the progress to a class of 30

students. The response of the class was excitement and strong interest as this headset transformed the lab and engaged the curiosity of the audience. The headset proved to have limitations in terms of processing power and during changing of the headset crashes were frequent. Although covering a sensor on the nose bridge which controls the state of headset wearing fixed this issue. Each student was able to interact with the pendulum and experience the interface between the real world and simulation. The headset and associated program took less than five minutes to set up.

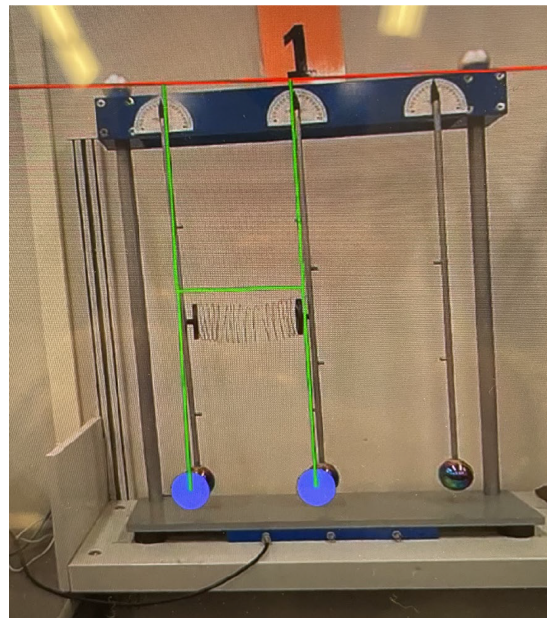


Fig. 5. Double pendulum simulation as seen through headset.

IV. CONCLUSIONS AND FUTURE DEVELOPMENTS

The inclusion of augmented reality (AR) and digital twin (DT) technology in the laboratory environment represents an exciting innovation in the engineering curriculum. This project has laid the groundwork to demonstrate the potential of new technologies in the classroom. AR and VR headsets have become highly sought after in both the consumer and professional industries. The Meta Quest 3 headset successfully met our initial requirements of smooth overlay and minimal usage errors. However, limitations include poor resolution when viewing screens, frequent crashing without alterations to the headset, and a limited battery life of 2 hours. Despite these challenges, the rapid advancements in this field suggest that with further investigation, AR and VR can be highly beneficial for all aspects of the vibrations lab.

While our results were well-suited to the project scope, several improvements could enhance performance and usability. One proposed enhancement is the incorporation of a dedicated 3D environment for simulations, allowing for better mapping of the simulation system onto the physical environment, and enabling more precise visualization and interaction. Additionally, faster simulation runtimes or running the simulation entirely on the headset with a more condensed software stack could be explored. Utilizing a game engine like Unity would provide performance benefits and well-supported software for handling simulations, although it may reduce simulation accuracy and require knowledge of more complex programming languages than MATLAB.

Integrating sensor input from the physical system could also improve accuracy and enable automatic detection of discrepancies between the simulation and the physical system. Live sensor input is natively supported by MATLAB and could facilitate physical interactions from the user being reflected in the simulation environment. Sensors such as potentiometers, accelerometers, gyroscopes, or strain gauges could provide real-time data to enhance simulation accuracy.

If tracking issues persist or sensor integration proves challenging, marker-based tracking is a reliable method for using the existing cameras on the headset to model the physical system. This approach is more accurate than machine learning/object detection methods and can be implemented with ease. Overall, integrating AR, VR, and DT technologies holds significant promise for advancing engineering education and providing students with a deeper, more interactive learning experience.

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