Science-Twins: Digital Twins for Interactive Lecture Demonstrations

Davide Rigoni[1], Dilek Düştegör[1,*]

[1]University of Groningen, the Netherlands

Abstract

Digital twins are increasingly utilized across various sectors, including industry and education, due to their significant advantages in our increasingly digital world. Particularly in education, digital twins offer interactive and comprehensive learning experiences. This paper explores the benefits of integrating digital twin technology into classroom settings and proposes a proof-of-concept application suitable for both in-person and online learning environments. The application aims to enhance student engagement by providing interactive tutorials and experiments with the ability to replay digital twin simulations. By offering real-time data observation alongside simulation-based learning, the application enriches the learning experience. Moreover, the paper also provides a brief literature review on the topic of digital twins in smart classrooms.

Keywords

Digital Twins, Smart Classroom, Education, Active Learning

1. Introduction

In the midst of the COVID-19 pandemic and rapid digitalization, education is swiftly moving to virtual platforms. To enhance student focus and understanding, the educational sector is embracing engagement-boosting technologies.

Digital twin technology, facilitating bidirectional data exchange between digital and physical objects, is gaining prominence in smart classrooms. These classrooms utilize technology to enrich the educational experience for both students and instructors.

While the integration of digital twins in smart classrooms is still in its early stages, new applications have demonstrated efficacy in online tutorials [1] and student attendance monitoring [2]. To enhance the smart classroom experience and further explore digital twins, this paper proposes a proof-of-concept application. This application utilizes digital twins to augment laboratory and experimental activities, offering students a realistic representation and deeper insight into experiments, whether in online or in-person formats. Students, through the digital twin interface, can actively engage with experiments, transforming from passive observers to active participants. Consequently, the application transcends mere data simulation, enabling students to interact with real-time data and observe genuine changes in data exchange. The proposed application holds significant promise for educators, facilitating the conveyance of complex concepts and the design of interactive demonstrations (ILDs) , which have been demonstrated to enhance student learning of theoretical concepts [3].

Accordingly, this study seeks to address the question ”*How can the integration of digital twins enhance scientific experiments in smart classroom environments?*”. Additionally, the study will provide a concise literature review to offer insights into the current state of digital twin technology in smart classrooms.

2. Background

This section investigates the intersection of smart classrooms and Digital Twins through a literature review, exploring their current understanding and potential applications in education.

DiDit 2024: Fist International Workshop on Distributed Digital Twins, June 17, 2024, Groningen, the Netherlands

*Corresponding author.

d.dustegor@rug.nl (D. Düştegör)

0000-0003-2980-1314 (D. Düştegör)

2.1. Smart Classroom

The term `smart classroom` is used to describe a classroom that avails itself with the use of technology to improve its educational process for both students and lecturers. The degree of technology present in a smart classroom varies greatly, from the presence of computers or projectors to enrich the learning activity, to the usage of IoT devices used to conduct a more in-depth analysis of the learning environment, up to the possibility of using artificial intelligence such as Nestor AI during in online classroom environment [4].

2.2. Digital Twins

The concept of Digital Twins, initially introduced by Michael Grieves in 2002 [5], refers to a virtual representation of a physical object connected to its real-world counterpart via a bidirectional stream of sensor data. This continuous exchange of information distinguishes Digital Twins from concepts like digital shadow and digital model [6], where data exchange is unidirectional or absent, respectively.

Although the term ”digital twins” was coined in 2002, the first practical implementations emerged around 2010 [7], notably with NASA’s efforts to replicate and test aircraft functionalities. Since then, fueled by the proliferation of Internet of Things devices, Digital Twins have found application across various sectors, including education and the smart classroom environment

2.3. Related Works

Although digital twins are a relatively new concept, they are already finding applications across various sectors. Notably, they are utilized within Industry 4.0 for testing and model validation, in smart cities as a traffic flow-regulation tool [6], and in the healthcare system as a possible tool to improve patients’ diagnostics and treatments [8]. Importantly, digital twins serve as educational tools, particularly in smart classroom environments. The use of digital twins in classrooms has the potential to yield several positive outcomes, such as aiding teachers in better understanding the learning needs of individual students and optimizing the learning process [9]. The theoretical use of digital twins for aiding education has been discussed in studies by Zacher et al. [10] and Balyakin et al. [11], where the authors identify possible positive outcomes that can derive from their utilization for education. Among the discussed positives are the ease of utilization, cost reduction, and the possibility of bringing educational activities to people and institutions that do not have the financial capabilities to afford them. These points are all considered in this project as driving forces behind our decision to pursue it. Furthermore, the use of digital twins can aid the Symbiotic Education paradigm, fostering closer collaborative efforts between teachers and learners, as suggested by the study from Kinsner et al. [12]. Similarly, Furini et al.’s study [13] employs a combination of Digital Twins and Artificial Intelligence techniques to devise personalized learning models for students. This approach is of particular interest and presents a potential avenue for enhancing our proof-of-concept application, as will be discussed in Section 4.

Furthermore, recent studies indicate high student satisfaction with their learning experiences in smart classroom environments. For example, students who encountered smart classroom technology during their physiology course provided positive feedback on their learning experiences afterward [14]. Additionally, Ahuja et al. developed an application utilizing digital twins to analyze students’ eye gaze patterns during classes, providing instructors with feedback and insights into student interest during lectures [15]. Moreover, digital twins find successful application in online classroom environments, which have seen increased demand during the COVID-19 pandemic. The ’DeepClassRooms’ project by Razzaq et al. employs a digital twins framework to monitor student attendance effectively and perform content monitoring checks [2]. Similarly, Pitelinsky et al. aim to utilize digital twins to create digital student profiles, enabling analysis of academic achievements, behavior, and student needs [16]. Both projects contribute to enhancing the overall teaching and learning processes in education through the utilization of digital twins technology.

Moreover, an intriguing application of digital twins technology lies in laboratory experiments and tutorials, offering potential for enhancing remote teaching in these environments and facilitating online experiment replication. This presents an opportunity for students to better comprehend experiments while enabling institutions to replicate experiments that may surpass their financial constraints. For example, Xie et al. introduced the 'Telelab' application in chemistry, where instructors utilize a thermal camera as a sensor to upload experiments to the cloud, allowing students to recreate experiments at home [1]. Other research endeavors focus on utilizing digital twins for experiment replication and interaction, albeit in different domains.

Deniz et al. utilize digital twins to recreate laboratory experiences entirely online, encompassing fluid mechanics, thermodynamics, and turbomachinery experiments [17]. Similarly, Abdullah et al. develop a digital twin model of the High-performance liquid chromatography (HPLCs) instrument, aiming to provide students with a realistic, interactive, and immersive learning environment [18]. Additionally, Johra et al. utilize digital twins to enhance mechanics-based experiments, catering more to engineering students [19]. Likewise, Orsolitis et al. pursue a similar objective but focus on robotics experiments [20]. In the realm of engineering education, Gonzalez et al. describe the educational benefits of constructing a low-level digital twin based on an ERP simulator, complemented by mixed reality lessons to support Industrial Engineering learning [21].

Lastly, Lei et al. employ digital twins to enhance student learning and interactivity in networked control system laboratories [22].

In summary, the increasing utilization of digital twins in classroom environments in recent years is evident, with a focus on online tutorials and laboratories. To our knowledge, the study by Xie et al. [1] stands out as it explores the use of digital twins for scientific experiments, employing a thermal camera as the primary sensor. While innovative, this approach could be enhanced by leveraging the full capabilities of digital twins. For instance, the Telelab application lacks bidirectional data exchange, limiting student interaction with experiments. Moreover, its reliance on a thermal camera may restrict the range of applicable experiments. A more effective solution could involve connecting sensors to a versatile platform like Arduino, enabling support for experiments requiring specific sensors.

This approach, coupled with active experimentation interaction, forms the core concept behind **Science Twins**, the web application developed for this study.

3. Application Overview

The web application created to address the research question of this study is named *Science-Twins.* Its objective is to incorporate digital twins technology to enhance demonstrative scientific experiments.

As previously mentioned, the web application is designed to enhance experiment interactivity and replayability, fostering student learning and engagement during demonstrations. The application must support active participation for both online and in-person tutorial attendees and be easily adaptable to accommodate additional sensors and experiments across various courses and tutorials.

The website's core functionalities center around leveraging digital twins to enrich laboratory experiences. This is achieved through live streaming of experiments, wherein the stream creator can interface the application with Arduino or Raspberry Pi-based sensors, enabling real-time data display for all users. Additionally, the stream creator (e.g., professor) can pose multiple-choice questions regarding data changes in experiment variables, such as actuators. All connected users (e.g., students) receive these questions and can utilize a simple simulation tool within the application to visualize data changes based on their answers. Importantly, students can simulate various answer values and observe corresponding data changes, submitting their answers for review by the professor. Such simulation is based both on previously collected data from the same experiments as well as theoretical results obtained from it.

The professor can save student answers, selecting one at a time to influence the experiment's state accordingly. Thus, the application transcends mere simulation, allowing students to impact experiment outcomes and compare real-time data with simulated values. Notably, students cannot directly interact with the experiment due to the one-to-many relationship; therefore, the professor determines which answer influences the experiment's actuator, particularly in live sessions. Digital twins of experiments are created and uploaded to the website, enabling online learning through student interaction with previously saved experiment twins. This interaction relies on data acquired during experiment setups, across multiple runs if necessary.

The interaction flow is illustrated in Figure 1, showcasing online engagement with experiment digital twins and in-person interaction with experiments guided by lecturers' decisions on different actuators.

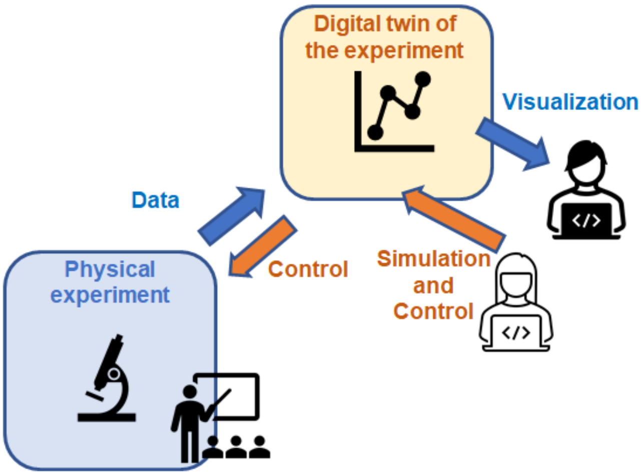


Figure 1: Different flows of the application

3.1. Application Design

The primary goal of the proof-of-concept application "Science Twins" was to create a foundational framework that could be further developed, as discussed in section 4. The digital twins functionality of the application was designed to be versatile, supporting not just a single experiment, sensor, or set of actuators, but providing a framework that can easily incorporate others. This requirement, already expressed in the previous sections, is the base guideline with which the application was built.

The application is built on a NodeJS runtime environment with a MongoDB database. Python and C++ allow for the communication between the experiment and the application. The choice of these two languages is deliberate. C++ is used primarily to interface with Arduino devices, while Python has a broader role. Currently, Python supports RaspberryPi-based sensors and actuators, and it can also serve as a bridge to other types of sensors commonly used in advanced scientific experiments, such as Vernier sensors [23], which are compatible with Python.

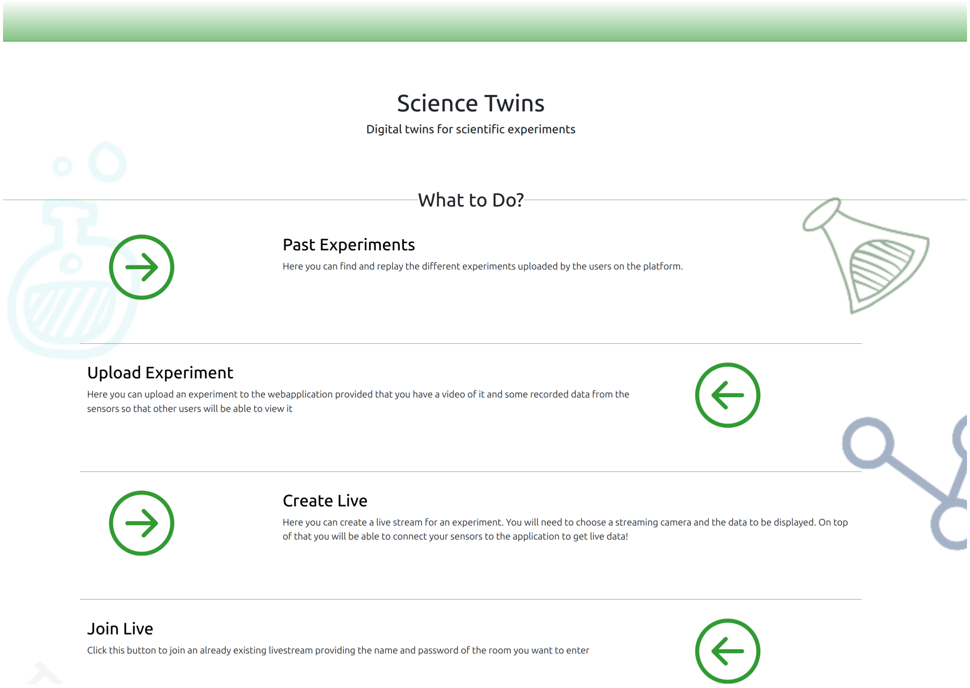
Despite the availability of Vernier sensors, we chose to use Arduino and RaspberryPi for their affordability, making the application accessible in various countries and situations where budget constraints exist. This decision allows nearly anyone to use the web application for their experiments. Additionally, Arduino and RaspberryPi offer a wide range of affordable sensors and actuators.

Compared to the related works discussed previously, this project provides a more general implementation that can be extended to a variety of sensors and actuators. It also supports interactive simulations if the experiment involves actuators. Moreover, the website allows for interactions through custom questions posed by the lecturer, bridging the gap between theoretical and practical work in online experiments.

Figure 2 shows a screenshot of the application's landing page.

4. Future Works

As this application serves as a proof-of-concept, one of its primary objectives is to pave the way for future enhancements toward achieving an optimal version. Firstly, its versatility allows for the



Science Twins

Digital twins for scientific experiments

What to Do?

Past Experiments

Here you can find and replay the different experiments uploaded by the users on the platform.

Upload Experiment

Here you can upload an experiment to the webapplication provided that you have a video of it and some recorded data from the sensors so that other users will be able to view it

Create Live

Here you can create a live stream for an experiment. You will need to choose a streaming camera and the data to be displayed. On top of that you will be able to connect your sensors to the application to get live data!

Join Live

Click this button to join an already existing livestream providing the name and password of the room you want to enter

Figure 2: Homepage of the application

integration of various technologies, such as diverse sensor sets and tracking devices, as well as the potential adoption of a more distributed architecture.

Designed with scalability in mind, the application is primed for future expansion into a microservices-based architecture. The selection of Arduino and Raspberry Pi stems primarily from their suitability for demonstration purposes and provides a straightforward starting point for incorporating different sensor and actuator classes, aligning with the application's adaptable nature.

Furthermore, the question-and-answer mechanism is reserved for refinement in subsequent iterations. This foundational setup can serve as a repository for student responses, with each student having a personalized set of answers using the question-answer system described in the previous section. As examined in Section 2.3, this framework can be further enhanced through the integration of learning analytics to develop each student's learning digital twin (in a sense, an instance of their cognitive twin within the scope of the course), thus enabling the development of personalized learning plans.

Therefore we can say that this proof-of-concept application serves as the baseline for future works on digital twin technology in the context of smart classrooms. Figure 3 shows the future enhancement planned for the application.

5. Conclusion

This study aimed to explore how digital twins can enhance scientific experiments in a smart classroom setting, while also examining existing implementations of this concept. The developed application, *Science Twins*, accomplishes this on a theoretical level by integrating digital twins into experiments and demonstrations for both online and in-person instruction. Nonetheless, extensive research will be required to validate the improvements this application offers in a real-life classroom setting. Moreover, the application can enhance the current state of digital twin usage by enabling more interactive tutorials and providing a versatile framework for various experiments. We believe that this proof-of-concept application can be further enhanced and expanded, as outlined in Section 4.

Consequently, this application holds significant potential to foster more inclusive and accessible learning experiences for all students, irrespective of circumstances, highlighting the potential of digital twins to enhance scientific experiments in smart classroom environments.

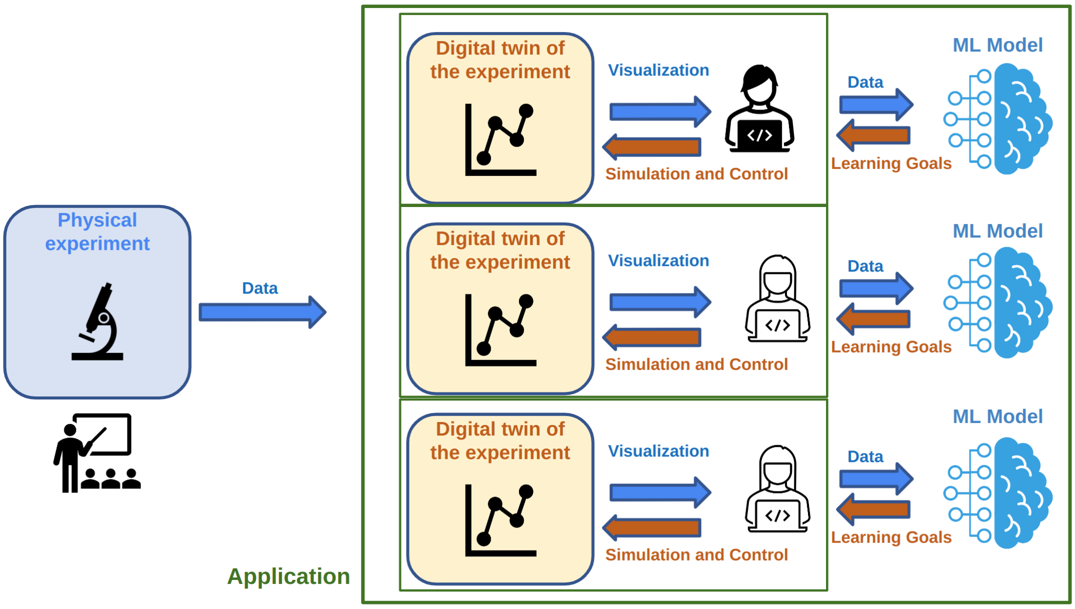


Figure 3: Future enhancement to the application architecture

References

[1] C. Xie, C. Li, X. Ding, R. Jiang, S. Sung, Chemistry on the cloud: From wet labs to web labs, Journal of Chemical Education 98 (2021) 2840–2847. doi:`https://doi.org/10.1021/acs.jchemed.1c00585`.

[2] S. Razzaq, B. Shah, F. Iqbal, M. Ilyas, F. Maqbool, A. Rocha, DeepClassRooms: a deep learning based digital twin framework for on-campus class rooms, Springer Science and Business Media LLC, 2022. doi:`https://doi.org/10.1007/s00521-021-06754-5`.

[3] D. R. Sokoloff, R. K. Thornton, A interactive lecture demonstrations: Active learning in introductory physics, John Wiley Sons, 2004.

[4] M. Kweta, P. Prinsloo, The ‘smart’ classroom: a new frontier in the age of the smart university, Teaching in higher education 25 (2020) 501–526. doi:`https://doi.org/10.1080/13562517.2020.1734922`.

[5] E. Brucherseifer, A. Fay, Digital twins, Automatisierungstechnik, 69 (2021) 1023–1025. doi:`https://doi.org/10.1515/auto-2021-0155`.

[6] A. Tello, V. Degeler, Digital Twins: An enabler for digital transformation, Groningen Digital Business Centre, Groningen, Netherlands, 2021.

[7] E. Negri, L. Fumagalli, M. Macchi, A review of the roles of digital twin in cps-based production systems, Procedia Manufacturing 11 (2017) 939–948. doi:`https://doi.org/10.1016/j.promfg.2017.07.198`.

[8] B. Björnsson, C. Borrebaeck, N. Elander, et al, Digital twins to personalize medicine, Genome Medicine 12 (2019). doi:`https://doi.org/10.1186/s13073-019-0701-3`.

[9] X. Chen, Research on the reform of hybrid teaching mode based on digital twin, International Conference on Computer Science Education (2021) 672–675. doi:`10.1109/ICCSE51940.2021.9569412`.

[10] S. Zacher, Digital twins for education and study of engineering sciences, International Journal on Engineering, Science and Technology 2 (2021) 61–69. URL: http://dx.doi.org/10.46328/ijonest.40. doi:`10.46328/ijonest.40`.

[11] A. A. Balyakin, N. N. Nurakhov, M. V. Nurbina, Digital twins in contemporary education: Virtual workshop, in: A. Mesquita, A. Abreu, J. V. Carvalho (Eds.), Perspectives and Trends in Education and Technology, Springer Singapore, Singapore, 2022, pp. 473–483.

[12] W. Kinsner, R. Saracco, Towards evolving symbiotic cognitive education based on digital twins, in: 2019 IEEE 18th International Conference on Cognitive Informatics & Cognitive Computing (ICCI* CC), IEEE, 2019, pp. 13–21.

[13] M. Furini, O. Gaggi, S. Mirri, M. Montangero, E. Pelle, F. Poggi, C. Prandi, Digital twins and artificial intelligence: as pillars of personalized learning models, Commun. ACM 65 (2022) 98–104. URL: https://doi.org/10.1145/3478281. doi:`10.1145/3478281`.

[14] H. Su, A research-based smart classroom in an exercise physiology course, Int. J. Emerg. Technol. Learn 16 (2021) 97–112. doi:`https://doi.org/10.3991/ijet.v16i18.25339`.

[15] K. Ahuja, D. Shah, S. Pareddy, F. Xhakaj, A. Ogan, Y. Agarwal, C. Harrison, Classroom Digital Twins with Instrumentation-Free Gaze Tracking, Association for Computing Machinery, New York, NY, USA, 2021. doi:`https://doi.org/10.1145/3411764.3445711`.

[16] K. Pitelinsky, V. Britvina, A. Aleksandrova, Digital twins and basic digital student profiles, Automatic Documentation and Mathematical Linguistics 58 (2024) 51–62.

[17] S. Deniz, U. C. Müller, I. Steiner, T. Sergi, Online (remote) teaching for laboratory based courses using “digital twins” of the experiments, Journal of Engineering for Gas Turbines and Power 144 (2022) 051016.

[18] N. B. Abdullah, M. Taylor, A. Al-Dargazelli, M. B. Montaner, F. Kareem, A. Locks, Z. Cao, B. Bowles, S. Schafhauser, J.-C. Sarraf, et al., Breaking the access to education barrier: Enhancing hplc learning with virtual reality digital twins (2023).

[19] H. Johra, E. A. Petrova, L. Rohde, M. Z. Pomianowski, Digital twins of building physics experimental laboratory setups for effective e-learning, in: Journal of Physics: Conference Series, volume 2069, IOP Publishing, 2021, p. 012190.

[20] H. Orsolits, S. F. Rauh, J. G. Estrada, Using mixed reality based digital twins for robotics education, in: 2022 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), IEEE, 2022, pp. 56–59.

[21] C. A. Gonzalez Almaguer, B. Murrieta Cortés, V. Saavedra Gastélum, N. Frías Reid, A. Acuña López, C. Zubieta Ramírez, The power of digital twins, erp simulator based in virtual and augmented reality, to increase the learning for industrial engineers students in the educational model tec21, in: International Conference on Remote Engineering and Virtual Instrumentation, Springer, 2023, pp. 961–973.

[22] Z. Lei, H. Zhou, W. Hu, G.-P. Liu, S. Guan, X. Feng, From virtual simulation to digital twins in online laboratories, in: 2021 40th Chinese Control Conference (CCC), IEEE, 2021, pp. 8715–8720.

[23] 2024. URL: https://www.vernier.com/.