WIP: A Review of Digital Twin Technology in Undergraduate Control Engineering Education: Applications, Challenges, and Future Directions

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***Abstract*—*Contribution:* This research, WIP paper describes a domain-specific, literature review on the use of Digital Twins (DTs) in undergraduate, Control Engineering Education (CEE). Such a body of work is currently absent from the scientific literature. The existing DT reviews were quantitatively assessed, and then the CEE applications, implementation possibilities, emerging opportunities, challenges, and future directions identified.**

***Background:* DTs are cutting-edge technologies, touted for their wide range of applications and services. As a result, domain-focused, DT reviews are often found in the scientific literature, to address the individual needs and challenges of various application domains. However, there is a need for such reviews in education and even CEE, which is itself tightly coupled to DT technology.**

***Research Questions:* 1. To what extent is education represented in recent, domain-specific, literature reviews on DTs as compared to other DT application domains? 2. What opportunities exist for the incorporation of DTs and their services into undergraduate, CEE and how can the challenges associated with their integration be addressed?**

***Methodology:* The methodology involved conducting a systematic literature review of peer-reviewed, domain-specific reviews published between 2019 and 2024 and then quantitatively assessing the representation of education and other application domains. Subsequently, peer reviewed, primary sources were synthesized into an integrative review on available DT services, CEE applications, emerging opportunities and challenges associated with DT implementations.**

***Findings:* This work has established that 1) there is a lack of application-focused, DT reviews in the field of education and its subdomain CEE 2) manufacturing and energy systems have the greatest prominence in existing DT reviews. 3) opportunities exist in learning theory-based DT design, novel enabling technologies, interacting DTs and sustainable education, and 4) challenges include the management of curricula, data, finances, change, and ethical issues, and 5) future works should develop frameworks that capitalise on the above opportunities.**

***Index Terms*—control engineering, digital twins, educational technology, engineering education, engineering fields, laboratory, learning environment, technology applications, undergraduate.**

I. Introduction

The digital twin (DT) is a disruptive, technological system, that incorporates many Industry 4.0 enabling technologies. It is a synchronised, digital replica of a physical entity that also imparts a degree of intelligence and agency to its physical counterpart [1]. This synchronization allows the updating of the DTs with real-time data, creating high fidelity replicas, capable of evolving over the life cycle of the real twin [2]. Furthermore, the intelligence and agency of DTs can facilitate analytics, decision making, automation and optimization of the physical systems [3]. It is anticipated that DTs for the Industry 5.0 era are expected to enhance human-technology collaboration and incorporate solutions for sustainability and human-centric challenges [4].

Since DTs can be considered advanced feedback control systems, modern CEE must incorporate DT education as part of its curricula and should benefit from employing DTs as a supportive technology. CEE is a cross-disciplinary branch of engineering education that is heavily influenced by technological advancement and changing industry demands. Therefore, CEE students need to develop technological literacy and a wide range of skills, behaviours, and competencies to increase their employability [5]. In addition, there is a need for modern learning environments to be flexible, adaptive, accessible, innovative, relevant, multi-disciplinary, and engaging [6]. DTs can be used to achieve these goals by providing remote access to costly or restricted equipment, managing assets or facilities, facilitating safe student exploration, and by providing timely feedback and personalised learning experiences.

The diverse application domains and design variations in DT research have led to significant standardization challenges and the need for systematization in the scientific literature [7]. DT designs often vary based on the complexity of the real twin, the life cycle phases, functional objectives, and enabling technologies. Despite the growing body of DT primary sources and reviews, to the best of this author's knowledge, as of May 2024, there were no reviews that specifically address the application of DTs in education. This paper aims to quantitatively evaluate application-focused DT reviews to ascertain the representation of education and other domains. Additionally, it has identified existing DT applications in undergraduate CEE, considered DT incorporation possibilities, identified emerging opportunities, and has provided suggestions for addressing potential challenges.

TABLE I
RESEARCH QUESTIONS, GOALS AND APPROACHES USED

Research Questions	Goals	Approaches used
RQ1. To what extent is education represented in recent, domain-specific, literature reviews on DTs as compared to other DT application domains?	A. Assess the distribution of application-focused DT reviews to identify areas of interest and under-represented areas.	Quantitative assessment of application-focused, review articles published in reputable databases between 2019 and 2024.
	B. Evaluate the extent to which education is represented application-focused DT reviews.	Quantitative assessment of education-focused, review articles between 2019 and 2024 without database restriction.
RQ2. What opportunities exist for the incorporation of DTs and their services in undergraduate, CEE and how can the challenges associated with their integration be addressed?	C. Summarise the documented applications of DT in undergraduate CEE as well as CEE related fields.	Consolidation of the contributions of primary sources found in reputable databases that describe applications of DT in education as well as CEE.
	D. Explore the possible ways in which DT services can be incorporated in undergraduate CEE.	Review of the various DT services used across the application domains. Review of CEE and DT articles to investigate opportunities for the application of DT services.
	E. Identify the emerging opportunities associated with use of DTs in CEE.	Consolidate DT opportunities and research gaps as discussed in general DT reviews and primary sources on education DTs
	F. Identify and address the potential challenges associated with DT in CEE.	Consolidate DT challenges and their associated solutions as discussed in general DT reviews and primary sources on education DTs.

II. BACKGROUND

A. Trends in the scientific literature

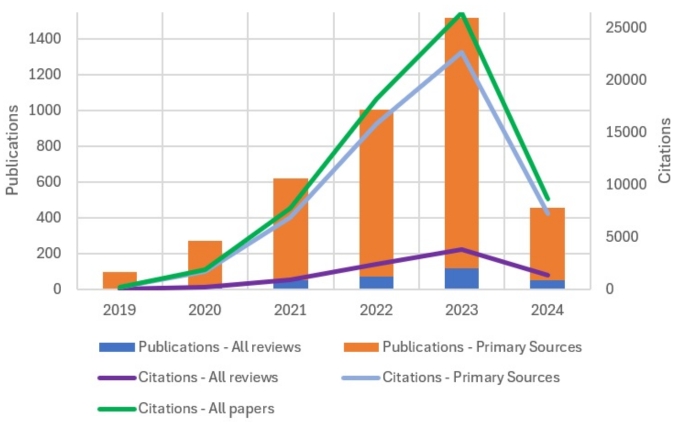

Fig. 1. Web of Science publications of DT articles (both primary and review articles) and their citations over time.

A preliminary search containing *digital twin* in the title, yielded 3,963 papers in the Web of Science research platform, for papers from 2019 to May 2024. After categorizing the publications and citations into reviews and primary sources, Fig. 1 was generated. 1) The rising trends in the number of publications and citations for both DT reviews and primary sources, and 2) the corresponding increase in DT reviews as the number of primary sources rises, indicate that there is growing interest in DT research and DT knowledge synthesis.

B. Importance of application-focused, DT reviews

In [7], DT reviews are categorised according to 31 dimensions, with 1) DT value benefits and 2) DT application domains being the top two dimensions. Application domain DT reviews are prevalent because they allow for the consolidation and transfer of DT knowledge in specific application contexts to researchers, practitioners and decision makers in both academia and industry. Such reviews identify research gaps, potential challenges, opportunities, trends, technological advancements, and direct the development of conceptual frameworks, practical implementations, and future research in the application domain.

C. Related work

A previous work used metadata searches to find application-focused DT reviews from 2015 to 2021 and clustered them into 10 application domains [7]. However, some of the DT reviews were not exclusively dedicated to a specific application domain as alluded to in [7]. Fig. 1 shows that there were less primary sources and reviews available at the time of the previous work, and that the current values are growing. Therefore, in an effort to limit the number of search results and to ensure research relevance, future reviewers should consider screening DT articles by titles and keywords, rather than broader metadata searches.

D. Education-focused, DT reviews

As DT implementations become more accepted in both industry and education, there is a need to extensively review education as a DT application domain. However, to the best of the author's knowledge, as of May 2024, there have been no DT reviews explicitly dedicated to the use of DTs in education. In addition, although there exists sufficient primary sources that document the DT applications in education, such works have not been exclusively reviewed and synthesized.

Of the three DT reviews identified in [7], two discussed multiple application domains, rather than education exclusively [8], [9], while the third only made a passing mention of education as an application. Aside from these, there are other general DT reviews in the scientific literature that partially discuss the use of DTs in education [10], [11].

III. METHODOLOGY

For this paper, the approach shown in Table I was utilised. First, a Google Scholar Search of review articles with the title words *digital AND (twin OR twins OR twinning)* was conducted using Harzing's Publish or Perish software to identify publishers of DT review articles. The following reputable publishers were identified using the search results: 1) ScienceDirect/Elsevier, 2) IEEE Xplore, 3) SpringerLink, 4) Taylor and Francis Online, 5) Wiley Online Library, 6) Emerald Publishing Limited, 7) American Society of Mechanical Engineers (ASME), 8) Association for Computing Machinery (ACM), and 9) American Society of Civil Engineers (ASCE).

A site-restricted, Google Scholar search using the above publishers and the review articles filter, was conducted using the search string: *allintitle:digital (twin OR twins OR twinning)*. Then, a Clarivate Web of Science search, that excluded the previous publishers, was performed to extend the search to peer reviewed articles outside the previous databases to minimise questionable or fraudulent, scientific literature. Then, the review articles filter was disabled and the search modified to incorporate the string segment *(education OR educational OR "learning factories" OR "learning factory" OR teaching OR student OR students OR "experiential learning" OR "active learning")* to search for primary sources on DTs in education.

Prospective papers from Google Scholar and Web of Science were screened to exclude review articles that were 1) not oriented towards a specific application-domain or subdomain post-review of their titles and abstracts, or 2) where the primary content of the work was not in English or 3) search result is not a conference or journal paper e.g. books or posters.

IV. Findings

A. Representation of the various application domains in review articles

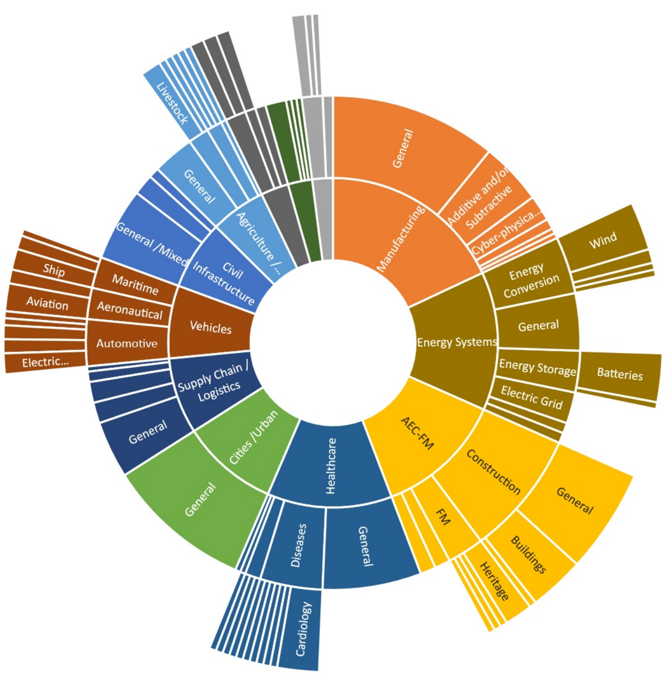

Fig. 2. Sunburst diagram grouping DT reviews found between 2019-2024 by application domain.

The Sunburst diagram shown in Fig. 2, categorised the DT reviews published in journals and conferences between 2019 and May 2024, into 12 different application domains and several subdomains. The ranking of the application domains from highest to lowest representation in DT reviews was as follows 1) manufacturing, 2) energy systems, 3) AEC-FM (i.e. architecture, engineering, construction and facility management), 4) healthcare, 5) cities and urban areas, 6) supply chain and logistics, 7) vehicles for land, sea or air, 8) civil infrastructures, 9) agriculture or farming, 10) extractive Industries (i.e. mining, oil and gas, process industries), 11) humans, and 12) machinery (e.g. fluid machinery and machine tools). Despite the adequate numbers of primary sources available for synthesis, DT reviews for domains like communication systems, water resources and education, were under-represented in the identified databases. No education-specific, DT reviews were resulted from these searches.

B. Representation of education in DT reviews

To ascertain whether, the site database restrictions imposed on the previous searches, were responsible for the lack of results, an unrestricted Google Scholar search for education DT reviews was conducted. This returned only 4 search results. One of these results was excluded because it was a poster, and the three remaining articles required further investigation to verify whether they belonged to predatory publishers or were fraudulent in nature. Nevertheless, these findings confirmed the absence of DT reviews in education from 2019 to May 2024 in the more reputable scientific databases, with a minimal number of studies found outside these publishing spaces.

C. DT applications in CEE and related fields

A primary source search for education-based DT papers was conducted in both Google Scholar and Web of Science, yielding 81 non-duplicated results. From these search results, examples of DT implementations in CEE and related fields were screened. These DTs were further classified as individual learning experiments, learning factories [12], skill training centers [13], instructional avatars [14], equipment maintenance systems, facility management systems [15], and administrative systems.

A variety DT laboratory experiments exist in the literature. These include the ball plate system [16], motors [17], robotic experiments [18], flexible manufacturing systems [19], conveyor systems [20], overhead crane experiments [21], fluid mechanics, thermodynamics, and turbomachinery [22], energy systems [23], and embedded systems [24].

In the scientific literature, DTs in education have also been used for personalised learning [25] and lifelong learning [26]. However, such DT applications are less numerous, probably because they are auxiliary services rather than actual course content. Personalized learning has allowed educators to accommodate different learner starting points and progressions. Whereas lifelong learning, has been used for skill and career development, qualification tracking and continuous professional development recommendations.

D. Ways in which DTs and their services can be incorporated into CEE

DTs can provide a variety of services [7] to the human beings that operate in CEE learning spaces. These include 1) real-time monitoring and supervision, 2) data integration, dissemination, and analytics, 3) model and data visualisation, 4) simulation 5) emulation, 6) gamification, 7) performance evaluation, 8) diagnostics, 9) prognostics and prediction, 10) decision support and recommender systems,11) control and system configuration management, 12) optimization, 13) life cycle support and management, 14) remote access, and 15) user collaboration. In addition, real twins can range from equipment, learning spaces, processes, and humans.

In [27], five DT interactions for learning spaces were listed, namely human-human, human twin self-evolution, human-thing twin, physical twin self-evolution, and human twin-physical twin. However, after considering the human roles (i.e. staff and students) and the physical facilities (i.e. equipment and learning spaces), this list can be expanded to nine (9) DT purposes in CEE. These include 1) student-resource interaction for student learning exercises, 2) staff-resource interaction for equipment status monitoring and maintenance, 3) staff-learning space interaction for supervisory monitoring and optimisation, 4) staff-student interaction for support and feedback services, 5) staff-staff interaction for administrative activities, 6) student-student interaction for collaborative learning and networking activities, 7) student self-evolution for self-reflection, learning performance, career development etc., 8) staff self-evolution for self-reflection, teaching performance, career development etc., and 9) resource-resource interaction for fleet based self-evolution. It should be noted, that some of these DT interactions do not have working examples in the scientific literature, and it may be impractical to implement all of them in a single CEE setting.

E. Emerging opportunities

1) Learning theories, learning outcomes and lean engineering as the basis for educational DT design: Given the complexity of DT implementations, practitioners can develop cost-effective designs that align with the needs of stakeholders, by using learning theory and learning outcome-driven design [7], and lean engineering approaches. Innovative teaching strategies and learning theory should also be incorporated.

2) Innovative applications of DT enabling technologies for engagement, accessibility, and feedback: Novel immersive experiences for CEE, can be developed through visualization, haptic technologies and diverse human-interface devices [7]. DTs should switch between a variety of modalities (e.g. in-person, remote, collaborative, online and offline experimentation etc). Formative assessments and personalised feedback can be provided through gamification and AI strategies [28] (e.g. Explainable AI).

3) Comprehensive, learning environment monitoring and management: DTs can extend staff's ability to monitor and manage learning spaces and their activities. Such DTs should integrate facility management, asset management, equipment monitoring, student monitoring, predictive maintenance, and energy conservation features [15].

4) Innovative DT services and the facilitation of DT to DT interactions: Individual DTs can be developed for novel or innovative services [7], [9]. In addition, as DTs become more mainstream, DT to DT interactions and the transfer of data between DTs should be incorporated.

5) Industrial and academic collaboration: DT systems used in industrial and academic collaboration, can be used to facilitate remote access to cutting-edge, or even cost-intensive equipment. They can also support CEE or even interdisciplinary research and projects. Experiences from such initiatives should be documented for the benefit of future practitioners.

6) DTs for Sustainable Development Education: Due to the UN 2030 SDG Agenda [29], equal access education, energy conservation, environmental management, quality monitoring, and responsible consumption and production, have become of high importance. Manufacturing and energy DTs [30] are recommended for sustainable development education in CEE, as Fig. 2 has shown that they are high interest DT application domains, and also because they are tightly coupled to the CEE, industry and sustainability.

F. Challenges and Solutions

1) Lack of standards, best practices and frameworks: Potential solutions include the adoption of widely accepted standards for the individual elements of the DT, or the adaptation of standards utilised in manufacturing for other domains. Use of interoperability protocols where possible, development of frameworks and practices based on experiences from other practitioners [15].

2) Curriculum, resource, and financial management: Formation of partnerships with industry and academia can address issues pertaining to curricula relevance and resources such as time, money, and expertise [2]. If available, the use of open source and low-cost tools can reduce financial burdens.

3) Data management, cyber-security, and ethical concerns: Incorporation of solutions that manage data privacy, data ownership, intellectual property (IP) [9], and provide protection from cyber-threats. Development of ethical guidelines and regulations to treat with sensitive data and prevent potential discrimination [2]. Careful selection of data management architectures.

4) System performance, safety, and reliability: Solutions include commissioning and testing procedures [12], standardized frameworks, supporting documentation and media, system accuracy and latency checks, development of trouble shooting procedures.

5) Change management and Technology preparedness: Solutions should consider future upgrades in the design process and use modular and open-source implementations where possible. External expertise should be sought for technological and curricula advice, and resources from academia, industry, product vendors should be incorporated wherever possible. Staff training for management of all stages of the DT life cycle and incorporation of change management practices. Pre-lab tutorials should be facilitated for student familiarization [19].

V. Conclusions and Future Directions

As of May 2024, there are no DT reviews in the education application domain, despite numerous primary sources in CEE and related fields. This paper has identified various DT applications in education, DT services, and 9 potential DT interactions than can be incorporated into CEE. However, these approaches need to be cost-effective, maintainable, upgradeable, secure, and safe for them to be feasible. In addition, many of the potential DT interactions are theoretical, lacking working examples in the literature.

Therefore, future efforts should develop experimental examples of these approaches to assess the value, impact, and conceptual frameworks for DT implementations in educational environments. Designs based on learning theories, learning outcomes, lean engineering, sustainable development education, should also be leveraged. The complete list of references and analyses for DT reviews in different application domains, inclusive of CEE, will be included in the extended version of the paper.

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