A three-tiered architectural model for Digital Twins in Education

Valéria Farinazzo Martins[1], João Eduardo Cosentino Bachmann[1], Alexandre Cardoso[2], Ismar Frango Silveira[1]

[1]Programa de Pós-Graduação em Computação Aplicada, Faculdade de Computação e Informática, Universidade Presbiteriana Mackenzie

[2]Universidade Federal de Utajubá

valeria.farinazzo@mackenzie.br, joao.cosentino@gmail.com, alexandre@ufu.br, ismar.silveira@mackenzie.br

Abstract. *The advent of Digital Twins, integrating technologies such as Mixed Reality, the Internet of Things, Machine Learning, Big Data, and Cloud Computing, is increasingly demonstrating its potential across various domains. These technologies enable the creation of accurate simulations of real objects, processes, and systems based on real-time data. This capability supports a wide range of applications, including hypothesis testing, design and prototyping, process optimization, among others, which makes this solution strongly suitable to applications in education, training and skills development. To effectively implement Digital Twins in the educational context, this paper proposes a three-tiered software architecture, comprising a Data Acquisition Tier, another tier for Processing and Analysis and the last one for Visualization and Interaction. The paper finishes presenting a case for technical training in an energy provider company.*

Keywords. *Digital Twins, Mixed Reality, Architectural Patterns, Education*

1. Introduction

Grieves (2023) presented in 2002 the embrionary definition for Digital Twins (DT), as virtual instances of physical elements capable of continuously mirroring them. At that time, technological advances were not capable of obtaining real-time big data processing and transmission, as well as the visualization and manipulation of virtual elements were limited, compared to nowadays.

With the recent technological advances, related to high-speed bandwidth, cloud-like storage and processing, IoT (Internet of Things) sensors and actuators, besides the current visualization and manipulation devices for VR (Virtual Reality) brought a completely new scenario. In this context, the blend of MR (Mixed Reality) - which put together VR and AR (Augmented Reality) and DT represent a significant evolution in human-machine interaction and physical environment simulation, especially when dealing with component, asset and environment DT - whose types will be explained later.

There is a vast panorama of potential MR-based DT applications, each one with its idiosyncrasies. One of these areas is Education and Training, in which the expanded possibilities for experimentation, visualization and interaction could generate powerful learning experiences.

In this sense, this study proposes a robust and scalable architecture to support the implementation and integration of MR and DT systems in the context of Education, also bringing a case study in a MR-DT application for workforce training in the context of Energy Industry.

The proposal, in fact, by emphasizing the flexibility and scalability of the architecture, allows its adaptation for various other sectors such as manufacturing, healthcare, logistics, and entertainment. Implementing such an architecture promises to revolutionize how we interact with the digital and physical worlds, offering new opportunities for innovation and operational efficiency. The blend of MR and DT represent a significant evolution in human-machine interaction and physical environment simulation, especially when dealing with component, asset and environment DT - DT types will be explained later.

This article is structured as follows. Section 2 presents the necessary concepts for understanding the remainder of the work. Section 3 proposes an architecture that supports Digital Twins (DT) in the context of Education. Section 4 features a case study in the Energy Industry sector. Finally, Section 5 presents the conclusions and future work.

2. Background

2.1. DT Types

There are several types of digital twins, each with specific characteristics and applications in different areas. Extending the four types proposed by Khang e Hong (2015), and based in previous works of Grieves et al. (2021) the seven current main types include:

● Component DT (CDT): it refers to individual components, machine units or parts of some complex object. They are generally used to monitor the health and performance of critical components, predict failures, and optimize maintenance in Engineering and Architecture using BIM (Building Information Modeling)- as shown in Zhao et al. (2022), and also to represent body organs in Health and Medicine applications, as can be seen in Tang et al. (2024).

● Asset DT (ADT): it could represent physical components of some object, or the object itself - here called as “asset”, but also “aggregate”, “object” or “product Moreover, they could also be digital counterparts of processes or systems, thus extrapolating the original definition of DT, since these representations could not need VR or MR visualizations or interactions [Siqueira et al., 2024]. It could be used to design, test, and improve products before manufacturing. Allows monitoring of product performance in use and predicting maintenance needs.

● Process DT (PDT): it represents manufacturing, operational, administrative, social and economic processes. This DT not necessarily is related to a MR-based interface, and it is currently used to optimize production processes, identify bottlenecks, improve efficiency, simulate scenarios and reduce costs [Onaji et al. 2022][Siqueira et al. 2024].

● System DT (SDT): it integrates multiple assets (potentially with many components) and processes into a complete system. It is being used in sectors like infrastructure, energy, and transportation to manage and optimize the operation of complex systems, but also to represent educational systems. It allows complex visualization and analysis of entire system performance [Semeraro et al. 2023] [Backmann, Silveira & Martins 2024].

- Environment DT (EDT): it represents physical environments such as buildings, cities, or geographical regions. Used in urban planning, environmental management, virtual campi, buildings and infrastructure monitoring. Enables simulation of environmental changes, planning of new constructions, and efficient resource management, as well as it allows immersive walkthrough experiences [Vallée 2023].
- Organization DT (ODT): represents business and administrative processes and operations within an organization. It is generally used to optimize business operations, improve resource management, and support strategic decision-making. It could help organizations to change and innovate, thus enhancing their organization's sustainability [Caporuscio et al. 2020].
- Human DT (HDT): it is an emerging technology with significant potential in various fields, such as healthcare and sports to personalize medical treatments, predict reactions to medications, and monitor health in real-time. Unlike traditional Digital Twins, HDTs represent humans, leading to challenges like ambiguous definitions and lack of design guidance [Lauer-Schmaltz et al. 2024]. According to Zalake et al. (2020), it represents individuals or groups of people.

For simplicity and clearness, Fig. 1 synthesizes these seven types in a mental map (left), showing the DT hierarchy, and a concept map showing the relationships among DT types (right).

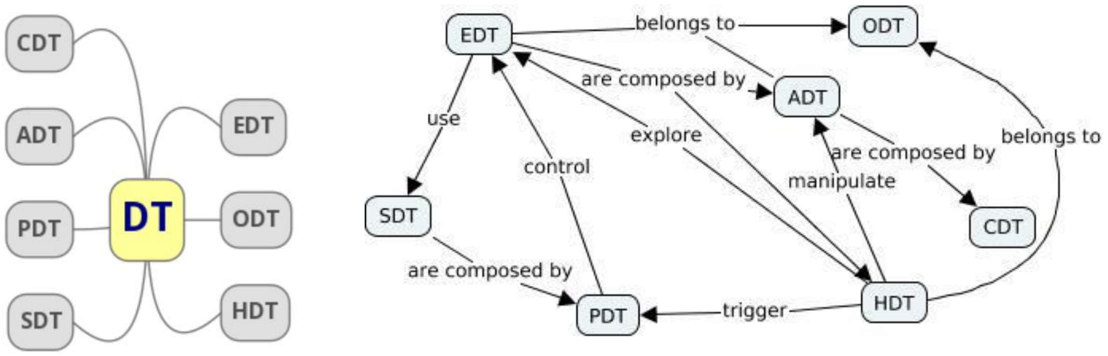

Figure 1. Mental Map with DT types (left) and Concept map with relationships among different DT types (right)

Each type of digital twin offers specific benefits depending on the application and sector. Choosing the right type is crucial to maximize the benefits of implementing digital twins. A discussion should be done regarding the main differences between DT types. Whilst the differences between CDT and ADT are obvious, being the second one a potential aggregate of elements characterized as the first one, having to work together, the main differences between ADTA and EDT must be elicited.

ADT presents a collection of interconnected CDT that model a complex product, but EDT goes beyond the simple aggregation of ADT. EDT provides a virtual environment, infrastructure, and tools to develop, deploy, and manage ADT, thus encompassing the entire ecosystem and infrastructure required to create, simulate, and operate digital twins.

Together with a MR-based visualization layer, it allows virtual exploration of 3D environments through walkthroughs and ADT manipulation.
Some misconceptions and blurred definitions make confusing the differences among PDT and SDT. Both are used to simulate, monitor, and optimize different aspects of physical entities and their operations and dynamics. However, they focus on different elements: while SDT include models of all physical components, their interactions, and overall system behavior, PDT represent specific operational processes within a system, such as manufacturing workflows, supply chain operations, or business and administrative processes. Often, the entire lifecycle of a PDT could encompass design, manufacturing, quality inspection, simulation, operation, maintenance, and disposal (Liu et al., 2022). Both can benefit from real-time data obtained from sensors, other systems, data sources and IoT devices to provide real-time monitoring, experimentation and control. Both are not always dependent on the MR layer for interaction.
On the other hand, employing an ODT would help enterprises to change and innovate, thus enhancing their organization's sustainability. However, the lack of best practices for developing and operating an ODT makes it difficult for enterprises to fully benefit from it, given that most companies, especially in the Latin American context, have not yet adopted Industry 4.0 practices [Eliseo et al. 2022] and will likely face difficulties in implementing both meanings of DT: Digital Transformation and Digital Twins. Many companies are currently investigating the potential use of it, but available solutions are often context-dependent or system-specific, and challenging to adapt, extend, and reuse. Therefore, digitalization is perceived as a slow, resource-demanding, and extremely expensive process whose outcome is uncertain. To this extent, enterprises seek solutions allowing them to gently introduce an ODT into their organization and to evolve it according to the changing needs and situations [Caporuscio, et al., 2020].
About HDT, it is a computer-generated character that interacts with the real and virtual worlds simultaneously. These virtual entities are designed to simulate human appearance, behavior, and communication, often using advanced technologies such as AI, motion capture, natural language processing (NLP), voice recognition and synthesizing, besides using LLM to interpret and generate humanized dialogs. In MR environments, HDT can interact with physical surroundings and real users, providing a seamless blend of real and digital experiences. They are employed in various applications, including training, education, health, entertainment, and customer service, to enhance user engagement and immersion.

2.2 Related Works

The work of Berko et al. (2022) points out that the lack of widely accepted reference architectural solutions for DT often leads to their construction using a combination of n-tiered and service-oriented patterns. These patterns address key quality attributes such as maintainability, performance efficiency, and compatibility. For instance, the work of Malakuti et al. (2019) proposes an abstract four-tier architectural pattern that is used to construct DT and integrate information from various sources. Based on microservices, this proposal is designed to be flexibly extensible with new information sources and can support new types of proprietary or standard information.

General architectural models for DT are capable of giving support to common elements, scenarios and dynamics, as in the work of Tekinerdogan and Verdouw (2020), which proposes a catalog of DT architecture design patterns that can be broadly reused in systems engineering. Nonetheless, considering that DT are highly dependent on their specific use cases, resulting in a wide variety of configurations, it makes sense to have specific architectural patterns and models for each area of application. In this sense, Van der Valk et al. (2022) present a set of DT archetypes tailored for individual use cases.

Kovacs and Mori (2023) provide an overview of Digital Twin architectures, highlighting a general system architecture based on various usage scenarios. It traces the evolution of Digital Twins, starting with their application in production lifecycle management (PLM), progressing through 3D visualization (AR/VR) and product usage simulations. The integration of Internet-of-Things (IoT) technology captures the dynamic state of real assets. In today's connected world, cloud-based Digital Twins leverage broadband networks for enhanced functionalities. Emerging data spaces like GAIA-X and IDSA enable secure data sharing, forming the basis for distributed Digital Twin Worlds to address global challenges such as decarbonization.

As presented by Crespi, Drobot & Minerva (2023), DT is being used in various domains of digital applications, including production (manufacturing and automotive area), energy (oil and gas, nuclear reactor design), buildings (construction), IT applications (IoT systems, smart cities), health sciences (health care, life sciences), education (physics, education in manufacturing, VR), and society (personal DT, cultural heritage).

3. Proposal of an Architecture to Support MR and DT for Education

The proposed architecture is composed of three main tiers, from the inner to the shallower: the data acquisition and storage tier, the processing and analysis tier, and the visualization and interaction tier. These tiers are presented as follow, and after depicted in Figure 2:

- Data Acquisition and Storage Tier: This tier is responsible for real-time data collection and storage from IoT sensors and monitoring devices, which are already present in Multimodal Learning Analytics (MLA) [Ochoa et al, 2022] and other data sources, as Virtual Learning Environments (VLE), Learning Objects Repositories (LOR), administrative and other educational systems used by educational institutes. Combining speed and security, it utilizes communication technologies such as 5G/6G and IoT protocols to ensure fast and secure data transfer.
- Processing and Analysis Tier: The collected data is sent to cloud, edge, fog and/or dew computing platforms, where it is processed and analyzed using Artificial Intelligence (AI) and Machine Learning (ML) algorithms. This tier is crucial for creating accurate digital twin models and implementing mixed reality interactions, which includes the possibility of automatically generating trustworthy 3D avatars, objects and scenarios using LLM (Large Language Models), for instance (Song et al., 2023; Hu et al., 2024). This tier is also responsible for intensive data processing of educational batch or real-time applications, like Educational Data Mining (EDM) and MLA.
- Visualization and Interaction Tier: This tier is eligible to use AR and VR, resulting in a MR-based interface that allows students and professors to visualize and manipulate DT - but this interaction can be performed otherwise, especially for PDT and SDT. It could support VR glasses, mobile devices, controllers and holographic displays to provide an immersive learning experience, but also other types of conventional and non-conventional User Interfaces (UI). It allows for the visualization of DT and interaction

with MR environments or other UI, facilitating decision-making, hypothesis tests and the simulation of complex scenarios.

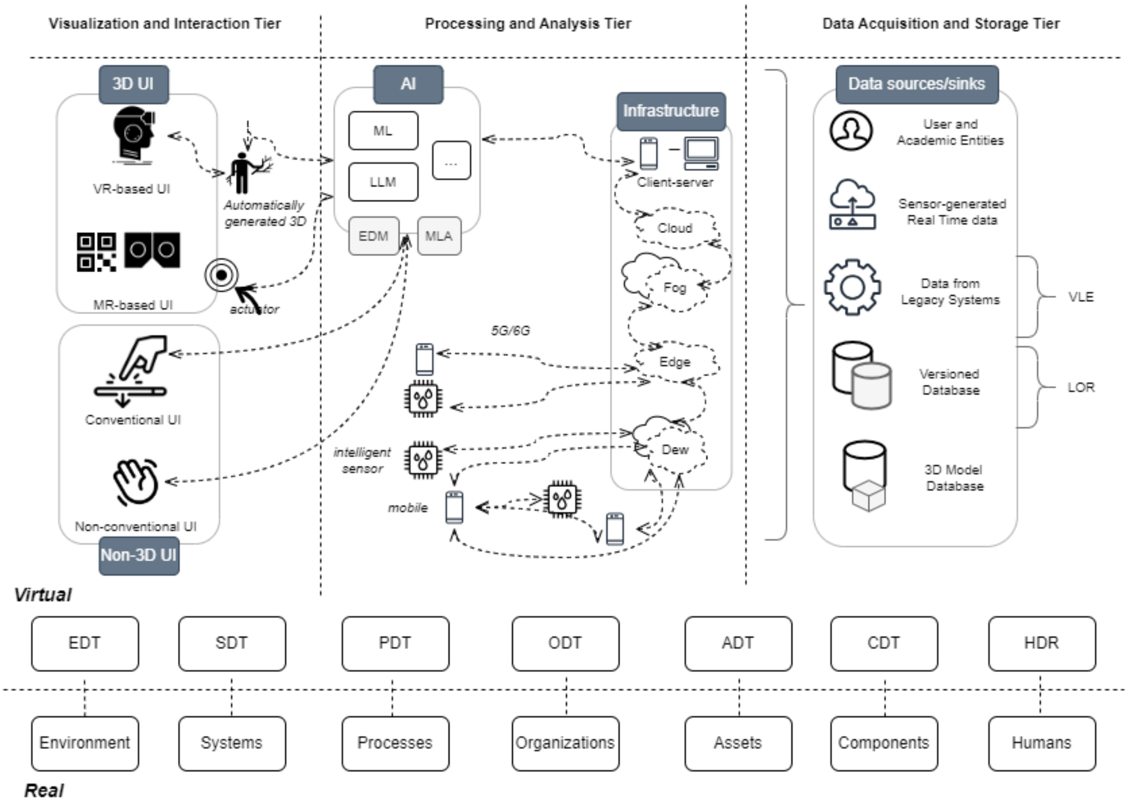

Figure 2. Architecture to Support MR and DT for Education

The integration of these layers is facilitated by a low-latency, secure and high-throughput network infrastructure, essential for ensuring synchronization between the physical world and digital twins. The architecture also incorporates cybersecurity mechanisms to protect sensitive data and ensure user privacy.

4. DT in Training: a Case Study

This study is part of a larger project between a public university research group to which one of the authors belongs and a regional electric power supplier in a Latin American country. It involves a MR-based solution for the operation, maintenance, and training of operators managing high-risk equipment. The case is better detailed in [Backmann, Silveira & Martins 2024].

It is known that power systems require continuous operation for safety, emergency management, security, and business continuity [Siqueira et al. 2024]. Companies typically use 2D diagrams for control, which do not accurately represent the physical properties and complexities of the systems. Training in real substations poses significant safety risks, leading to operators often being unfamiliar with real environments, which reduces performance.

To address this, the project modeled the entire 3D environment of electrical substations as an EDT, as shown in Figures 3 and 4, which show the real environment of the electrical substation and its EDT with MR interface. Most assets, being old, lacked datasheets, so they were modeled using photogrammetry or 3D drawings, thus configuring CDT and ADT. Initially, the EDT was VR-based, allowing only walkthroughs, but it evolved to provide ADT real-time information, incorporating a MR layer, using VR glasses and manipulators, besides AR. The entire solution followed the steps shown in the three-tiered architecture and was a source of inspiration for improvements in the model.

Figure 3. Real arrangement of Electrical Substation

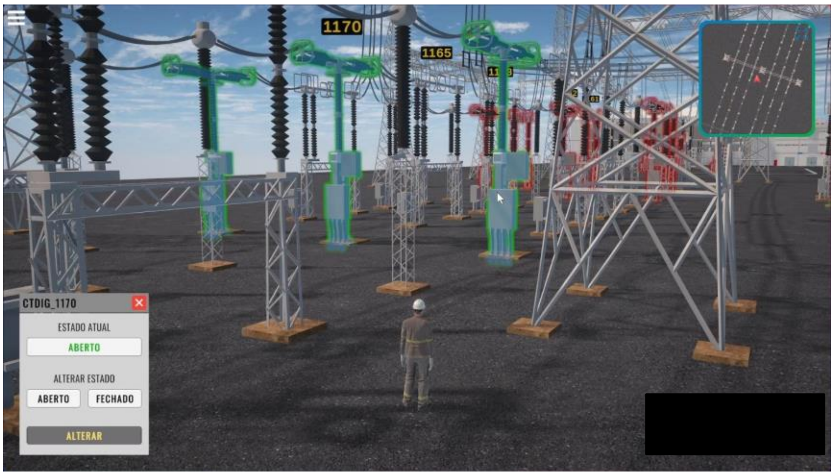

Figure 4. EDT with MR interaction (information in Portuguese)

5. Conclusions and further work

This paper presented a three-tiered software architecture for design and implementation of DT in the field of Education and training. These three layers are: the data acquisition layer, the processing and analysis layer, and the visualization and interaction layer. The construction of an EDT for workforce training in the context of the energy sector benefited from the three-tiered software architecture proposed here.

The modular nature of the architecture allows for easy scalability and customization. Training programs can be tailored to specific needs and scaled up to accommodate a larger workforce without compromising the quality of training.

The case studies an enhanced immersive and interactive training experience, improved safety, real-time data utilization, scalability, cost-effectiveness, operational efficiency, and better knowledge retention. By simulating real-world environments and operations, trainees can gain practical knowledge and skills without the associated risks of real-life scenarios. This leads to higher engagement and retention rates compared to traditional training methods. By allowing trainees to interact with up-to-date information, this enhances their understanding of current operational conditions and improves their decision-making skills. By using the EDT, they could practice and make mistakes in a controlled, risk-free setting, leading to better preparedness and safer operations in the field.

Although the initial setup of the shown RDT required a significant investment of funds, people and time, the long-term benefits include reduced training costs, minimized downtime, and lower risks of operational errors. Over time, these savings can outweigh the initial expenditures. Thanks to the modularity provided by the three-tiered architecture, changes, updates, and adaptations of the EDT are facilitated, reducing time and cost. As the technology continues to evolve, its potential to revolutionize training in high-risk industries becomes increasingly evident, as well as in other educational contexts and diverse areas of application.

For future work, several critical directions can be identified. One direction involves expanding the architecture to support generic use across various domains such as industry, healthcare, and other applications. Another significant focus is on proposing and developing Digital Twin Patterns. This is essential for documenting best practices and reusable design solutions, which can significantly streamline the development process and ensure consistency and efficiency across various DT projects. Additionally, applying the DT architecture in a purely educational context, separate from training applications, is crucial. This involves utilizing DT technology to create immersive and interactive educational experiences that enhance learning outcomes. Finally, proposing a detailed development process for DT, encompassing all steps from the initial concept and design through to deployment and maintenance, is necessary.

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