From Virtual Reality to Digital Twins: The Long and Winding Road

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ABSTRACT
Considered an evolution of Virtual Reality systems, Digital Twins, which integrate technologies like Mixed Reality, Internet of Things, Machine Learning, Big Data, and Cloud Computing, and it is proving its potential across various domains. These technologies facilitate 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, and process optimization. As a result, Digital Twins are highly suitable for applications in diverse areas. This paper will discuss its types, applications and forecast future directions for research and development, as well as a supporting architecture.

CCS Concepts
• Software and its engineering ➝ Software notations and tools ➝ System description languages ➝ Architecture description languages

• Human-centered computing ➝ Interaction design ➝ Interaction design theory, concepts and paradigms.

Keywords
Digital Twins; Virtual Reality; Architecture; Concept Maps.

1. A LONG, LONG TIME AGO
The advent of Digital Twins (DT), which blend technologies such as Mixed Reality (MR), Internet of Things (IoT), Machine Learning (ML), Big Data, and Cloud Computing, is increasingly demonstrating its potential in various fields. Digital Twins provide trustworthy simulations of real objects, processes, and systems based on real-time data. This capability allows for applications ranging from hypothesis testing, design and prototyping, and process optimization to training and skill development.

Initially present in the fields of industry and manufacturing, DT are now finding potential applications in other spheres. Although the concept of DT has gained traction in recent years, its origins date back to the 2010s when it was first introduced by NASA. At that time, the term referred to multiphysical and multiscale simulations of a vehicle or system using the best physical models, sensors, flight history, etc., to mirror the life of its real counterpart. This concept was initially closely connected to the aerospace industry.

Recent technological advancements have made the concept of Digital Twins evolve. They are now defined as replicas of physical and non-physical entities that respond to real-time data variations and enable the prediction of future scenarios. The current, more comprehensive concept of Digital Twins refers to sensitive, intelligent models capable of evolving, optimizing processes, and continuously predicting future states. These models can represent physical components, complex objects, processes, systems, environments, organizations, and even humans, as stated by [1], and later extended by [2].

In this sense, the present paper discusses the evolution of embryonic, walkthrough-only Virtual Reality (VR) systems to nowadays' DT solutions, forecasting future advances and potential new applications.

This paper is organized as follows: Main concepts are presented in section 2; section 3 brings a proposal of a three-tiered architecture and a development process for DT; applications and use cases are seen in section 4; challenges and perspectives are discussed in section 5; finishing. section 6 brings some final considerations and further works.

2. LET ME KNOW THE WAY

2.1 Characteristics of DT-Compatible Modeling
There are some characteristics that should be considered in almost all DT systems. Digital Twins (DT) integrate real-time data from sensors, actuators, and devices to accurately reflect and act on the current state of physical entities. Challenges include processing, storing, retrieving, and avoiding data loss [3]. DTs must handle the complexity and size of systems ranging from small components to large-scale systems [4]. They must be compatible with various data formats, communication protocols, and platforms to ensure seamless interaction between systems and devices [3]. DTs should provide accurate representations of their

physical counterparts, focusing on critical components for simulation based on system requirements [5]. They should also adapt to changes in the physical entity's structure, behavior, and operating conditions over time [4]. Robust security measures must protect data integrity and confidentiality [6], with blockchain being a valuable tool to enhance security, especially in finance-related DTs. DT models should support predictive analytics to forecast future states and behaviors, aiding proactive decision-making [7]. Advanced mixed reality (MR) visualization techniques should be used for intuitive representations of DTs, although for broader DT applications, non-VR/MR visualization may be necessary [8]. The DT framework should allow for easy maintenance and upgrades to stay current with the latest technologies [7]. Finally, DT solutions should be cost-effective, improving life cycle cost (LCC) by optimizing manufacturing efficiency and reducing maintenance expenses [9].

2.2 Types of DT (MM e MC)

There are several types of digital twins (DT), each with specific characteristics and applications. Building on the types proposed by [1] and [2], the seven main types are: Component DT (CDT) represents individual components or parts of complex objects, used to monitor health and performance, predict failures, and optimize maintenance in fields like Engineering and Medicine [10][11]. Asset DT (ADT) represents physical components or entire objects, and can also be digital counterparts of processes or systems. It is used to design, test, improve products, monitor performance, and predict maintenance needs [8]. Process DT (PDT) represents manufacturing, operational, and administrative processes, used to optimize production, identify bottlenecks, improve efficiency, simulate scenarios, and reduce costs [5] [12]. System DT (SDT) integrates multiple assets and processes into a complete system, used in sectors like infrastructure, energy, transportation, and education for managing and optimizing operations [5][13]. Environment DT (EDT) represents physical environments such as buildings or cities, used in urban planning, environmental management, and infrastructure monitoring. It enables simulation of environmental changes and immersive walkthroughs [14]. Organization DT (ODT) represents business and administrative processes within organizations, used to optimize operations, improve resource management, and support strategic decision-making [15]. Human DT (HDT) is an emerging technology representing humans, used in healthcare and sports for personalized treatments and real-time health monitoring. It faces challenges like ambiguous definitions and lack of design guidance [16][17]. For simplicity and clearness, Fig. 1 synthesizes these seven types in a concept map showing the relationships among DT types (right), according to [18].

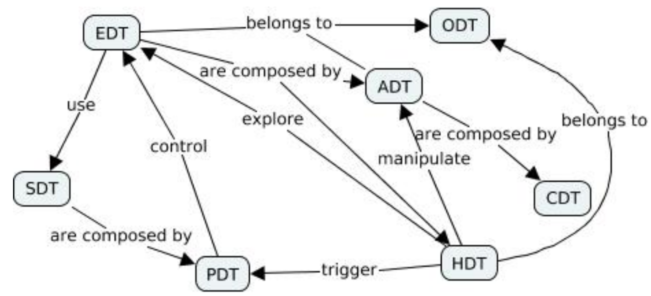

Fig. 1 - Concept map showing the relationships among DT types [18]

2.3 Continuum

Although not a mandatory relationship, VR and DT often complement each other, particularly in representing component and asset twins. In many areas, VR-based visualizations have been utilized—despite known limitations—to provide immersive (or less immersive) user experiences previously impossible due to physical constraints, risks or costs. Therefore, it is essential to view DT as an ongoing evolution of VR, even when considering processes, systems and organizations twins, which frequently do not require VR or MR-based visualization. Figure 3 illustrates the VR-DT continuum, highlighting some technologies that have supported this evolution [5].

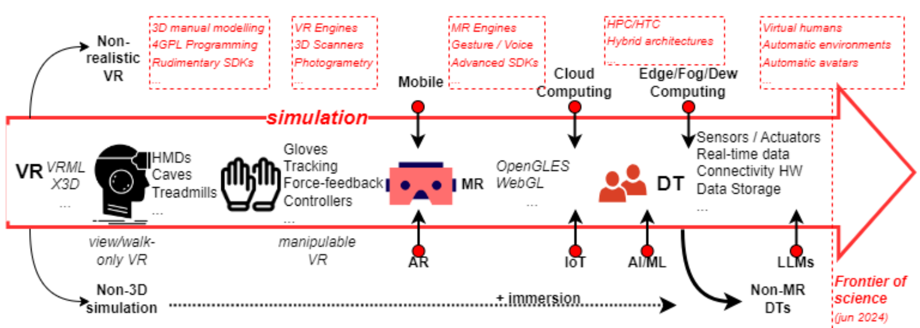

Fig. 2 - The VR-DT continuum [5]

This continuum can be viewed as a timeline, but it's also crucial to recognize the technologies integrated along the way, enabling transformations and introducing new possibilities for data processing, storage, transmission, and visualization. As shown in Figure 2, despite being a continuum, it can be divided into four main landmarks: the very beginning of VR-related technology; the development of manipulation devices enabled users to move beyond basic walkthroughs—though these were technically complex due to synchronization and processing issues, especially in VR caves—to environments that allowed for the reasonable manipulation of elements; the combination of VR and AR technologies; and the current possibility of integrating IoT sensors, having access to real-time data and using the possibilities of cloud / edge / fog / dew computing, over high-speed secure wireless connections.

3. I'VE SEEN THAT ROAD BEFORE

In this section, it will discuss an architectural proposal for general-purpose DT and some development processes. This is an adaptation of the DT architecture presented in [8], now for general purpose.

The proposed architecture consists of three main tiers, from the innermost to the outermost: the data acquisition and storage tier, the processing and analysis tier, and the visualization and interaction tier. These tiers are described below and depicted in Figure 3.

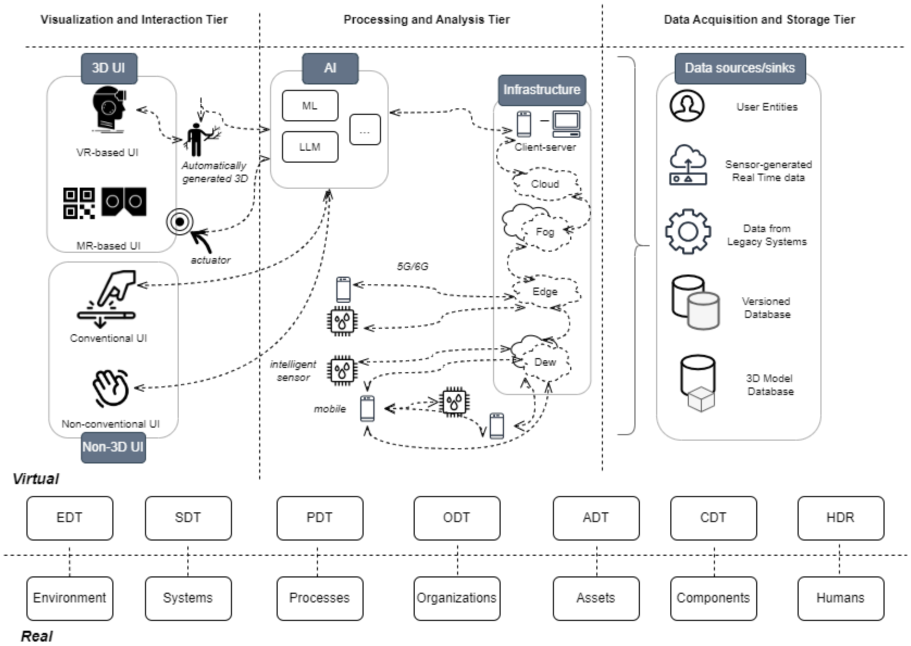

Fig.3 - A general-purpose three-tiered architecture for DT (adapted from REF)

- **Data Acquisition and Storage Tier:** This tier manages real-time data collection and storage from IoT sensors and monitoring devices. It combines speed and security by using communication technologies like 5G/6G and IoT protocols for fast and secure data transfer.
- **Processing and Analysis Tier:** The collected data is sent to cloud, edge, fog, and/or dew computing platforms for processing and analysis using AI and ML algorithms. This tier is crucial for creating accurate digital twin models and implementing mixed reality interactions, including the automatic generation of trustworthy 3D avatars, objects, and scenarios using Large Language Models (LLM). It also handles intensive data processing for batch or real-time applications.
- **Visualization and Interaction Tier:** This tier supports AR and VR, resulting in a mixed reality (MR)-based interface that allows users to visualize and manipulate digital twins. Interaction can also be performed through other means, especially for PDT, SDT and ODT. It supports VR glasses, mobile devices, controllers, and holographic displays to provide an immersive user experience, along with other conventional and non-conventional user interfaces (UI). This tier aids in decision-making, hypothesis testing, and simulating complex scenarios.

4. LEAD ME TO YOUR DOOR

In this section, some areas of applications and use cases will be presented.

In the field of Science, Technology, Engineering, Arts, and Mathematics (STEAM), Digital Twins (DT) are utilized for simulations of scientific experiments, process simulations, modeling of complex systems, digital art, and visualization of abstract concepts. These applications leverage real-time data and interact with the physical counterparts of a DT. For example, universities adopt DTs to virtualize campus environments, enhance learning processes, provide technical training, improve student market readiness, incorporate gamification into disciplines, and reduce costs associated with equipment and laboratories [18][19].

In healthcare, the use of Digital Twins (DTs) is still emerging. DTs in a health context can be defined as visualizable digital replicas containing specific multidimensional patient information, classified into simulation and monitoring types for personalized predictions and continuous care optimization. AI-enabled DTs, using Virtual and Augmented Reality, can facilitate healthcare professional training. Three-dimensional models can be used for studying medical anatomy and surgical procedures, promoting interactive learning and reducing cadaver use. Medical schools can leverage DT solutions to teach surgical techniques via simulation.

In Architecture, Engineering, and Construction (AEC), user experiences can benefit significantly from real-time data-based virtual modeling of buildings and infrastructure. This includes integration with Building Information Modeling (BIM) systems, project simulation, and analysis of structural, soil, and thermal comfort factors, enabling hypothesis testing and experimentation. However, the concept of Digital Twins (DTs) is still in the prototype phase in the AEC sector, with real applications being rare.

For Technical Training, DTs are well-established in the automotive sector, where they serve as accurate virtual representations of a vehicle's mechanical and aerodynamic parts. Workforce training processes can significantly improve in efficiency and safety by using DTs for simulating equipment maintenance, industrial operations, and technical procedures.

5. CRYING FOR THE DAY

This section will discuss some perspectives and challenges for current and future research and development in DT.

5.1 Ethics

Many of the ethical issues involved with Digital Twins are the same as those associated with the use of technology in general, [18][20]. Determining responsibility for Digital Twins (DT) remains a challenge due to their complexity, making it difficult to clearly define accountability. The responsibility may fall on the companies developing DTs, raising questions about ownership of the specific system model and how to ensure the models' safety and effectiveness [18]. The potential for data and DT model abuse is significant, as the integration of multiple data sources and analysis of medical functions hold substantial financial value for both legitimate and illegitimate stakeholders. The risk of hackers and abuse of sensitive data is substantial, underscoring the need to protect DTs and carefully weigh potential benefits against risks.

Inequities in technology access can restrict the reach of DT solutions, particularly in developing or underdeveloped countries and regions with high social vulnerability, which is a significant issue in Latin American countries (blind review). Additionally, the diverse media involved in DT solutions necessitate consideration of the limitations faced by students with physical and cognitive disabilities. Insights from other educational contexts on content creation (blind review) could provide valuable guidance.

5.2 New Interaction Devices

The technological evolution of recent years has led to the creation of a range of devices, which have enabled the emergence of new interface modalities, such as touch screens, voice command recognition, gesture recognition, and Virtual and Augmented Reality interfaces [21]. In this context of Digital Twins, these technologies can excel in various areas, for example, MR, together with body and IoT sensors, and wearable devices, is proving to be particularly effective in training, simulations, and design, providing a user experience that closely resembles interaction with real physical objects.

The future promises even greater integration between the physical and digital worlds, with advanced interaction devices and Digital Twins playing a central role in creating intelligent and connected environments. Continuous research and development in this area are essential to overcoming challenges and fully exploring the possibilities offered by these emerging technologies.

5.3 Advances in connectivity and security

The Internet of Things (IoT) connectivity is integral to 5G wireless communication systems, which are currently being deployed. This deployment is driving a surge in research efforts and visions for 6G wireless systems, further enhancing the capabilities of Digital Twins [22][23]. With 6G, both Digital Twins and the real world could be continuously updated using multi-modal sensing data from distributed infrastructure and user devices. This data would be utilized to make informed communication and sensing decisions.

On the other hand, security is a crucial aspect of DT, given their reliance on real-time data from various sources, including IoT devices, cloud platforms, and other interconnected systems. Ensuring the integrity, confidentiality, and availability of this data is vital to the effective functioning of DT. Blockchain technology offers a promising solution to enhance the security of DT [24].

6. WILL NEVER DISAPPEAR

This article explored the evolution of Virtual Reality (VR) technologies to the current state of Digital Twins (DT), highlighting their application in various fields. We presented the main concepts related to DT, such as essential characteristics like real-time data integration, scalability, interoperability, accuracy, flexibility, security, predictive analytics, visualization, and cost-effectiveness.

We proposed a three-tier architecture for DTs, comprising data acquisition and storage, processing and analysis, and visualization and interaction. The architecture aims to ensure data efficiency and security, utilizing technologies such as cloud, edge, and fog computing, as well as artificial intelligence and machine learning for complex analyses. Regarding DT applications, we covered the fields of Science, Technology, Engineering, Arts, and Mathematics (STEAM), healthcare education, architecture, engineering and construction, technical training, and business management.

We also discussed the ethical and accessibility challenges associated with DTs, emphasizing the importance of addressing issues of legal responsibility, privacy, digital divide, and accessibility to ensure inclusion and equity in the use of these technologies. Additionally, we explored how new interaction devices, such as VR, AR, haptic interfaces, motion sensors, and wearable devices, integrate into the context of DTs, providing more immersive and intuitive experiences.

For the future, research should focus on the continuous updating of models and architectures that support new devices and AI models. Another point of attention is how to make DT systems easier for users to manipulate. The implementation and development of DTs should also consider advancements in security and privacy, such as the use of blockchain, and explore interoperability between different systems and devices to maximize the potential of these technologies. With the advancement of connectivity and greater integration between the physical and digital worlds, DTs and advanced interaction devices will play a central role in creating intelligent and connected environments, promoting digital democratization and inclusion.

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