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DIGITAL TWIN TECHNOLOGY: FOUNDATIONS, APPLICATIONS, AND RESEARCH TRENDS

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Abstract: Digital Twin technology offers a virtual representation of real-world systems, facilitating simulation, evaluation, and operational optimization. This paper provides an introductory overview of Digital Twin, tracing its historical development and highlights important research advancements across various domains specifically in areas of healthcare Aerospace Systems, and Smart Cities. Additionally, it summarizes emerging methodologies and areas of ongoing research that contribute to the future potential of this technology. Rather than presenting an exhaustive survey, the intention is to offer a foundation for readers new to the field and to encourage further exploration.

Index Terms - Digital Twin, Virtual Simulation, Product Lifecycle Management, Predictive Analytics, Healthcare, Aerospace Systems, Smart Cities.

I. INTRODUCTION

A digital twin, as originally proposed by Grieves [1], is a Virtual representation of a complex physical asset in the digital space for the purpose of closely characterizing the operations of the original physical process or system (as shown in Figure 1). In a 2012, Edward H. Glaessgen [2] at NASA's Langley Research Centre and David S. Stargel at the U.S. Air Force Office of Scientific Research gave the first specific definition of digital twin in the aerospace domain as: Digital Twin is an integrated Multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.": The concept of Digital Twin has revolutionized the way physical systems are designed, monitored, and managed in the digital era.

Initially conceptualized by NASA for spacecraft monitoring, Digital Twin technology has since expanded into diverse industries, such as manufacturing, healthcare, energy, smart cities, and aerospace [3]. The growth of Internet of Things (IoT) devices, advancements in Artificial Intelligence (AI), and the growing need for real-time decision-making have driven the adoption of Digital Twins. By bridging the physical and digital worlds, they empower us to predict failures and optimize performance. The core concept of the Digital Twin is a system that couples physical entities to virtual counterparts, leveraging the benefits of both the virtual and physical environments. System information is captured, stored, evaluated. As envisioned by Grieves, this process in essence enables the application of a knowledgeable, data driven approach to the monitoring, management, and improvement of a system process throughout its life-cycle. The value Digital Twin brings to any sector, by reducing time to market, optimizing operations, reducing maintenance cost, increasing user engagement, technologies, etc. is indisputable.

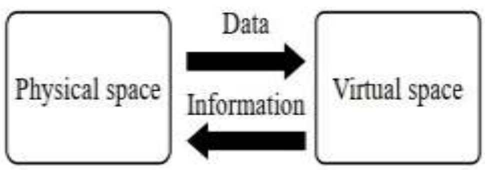


Figure 1. Three-dimensional digital twin (Grieves, 201

4)

II. LITERATURE REVIEW

The concept of Digital Twin came into being in relation to Product Lifecycle Management (PLM) in 2002 [8] at the University of Michigan by Michael Grieves. The proposed model has three components: real space, virtual space, and linking mechanism for the flow of data/information between the two; the model was then referred to as 'Mirrored Spaces Model'. A similar concept in which software models mimic reality from information input from the physical world was imagined by David Gelernter in 1991 [6] and was called 'Mirror Worlds'. In 2003, Kary Framling et al. [7] also proposed "an agent-based¨ architecture where each product item has a corresponding 'virtual counterpart' or agent associated with it" as a solution to the inefficiency of transfer of production information via paper for PLM. By 2011 [9], the name of the conceptual model proposed by Grieves was changed from 'Mirrored Spaces Model' to 'Information Mirroring Model'. The model put emphasis on the linking mechanism between two spaces being bidirectional and having multiple virtual spaces for a single real space where alternate ideas or designs can be explored (Figure 2). Due to the limitations of the technologies, such as low computing power, low or no connectivity of devices with the internet, data storage and management, underdeveloped machine algorithms, etc., Digital Twin had no practical applications at the time. The name 'Digital Twin' first appears in NASA's draft version of the technological road map in 2011 [10]. In the NASA road map, Digital Twin was also referred to as 'Virtual Digital Fleet Leader'. NASA was the first association to forge the definition of Digital Twin; it was described as

"An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin". Since the first-ever definition published by NASA, different authors have described Digital Twin in their own terms and based on its application.

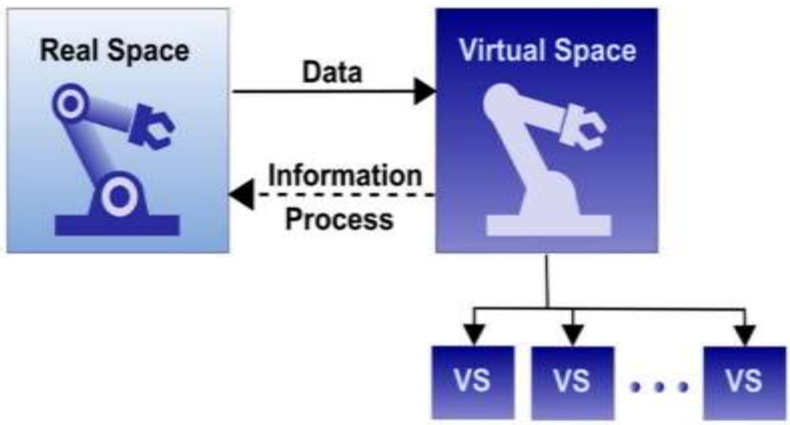


Figure 2. Mirrored Spaces Model as proposed by Michael W. Grieves.

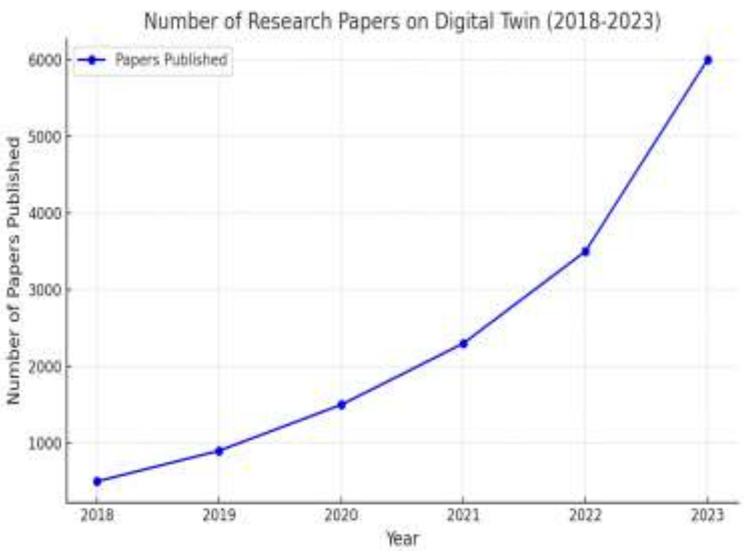


Figure 3. Number of research work published on Digital Twin technology in recent years.

The Digital Twin is a "virtual or digital model", "layout", "counterpart", "doppelganger", "clone", "footprint", "software analogue", "representation", "information constructs", or "simulation" of its physical counterparts. One thing that binds most definitions of Digital Twin other than being a virtual representation of a physical object is the bidirectional transfer or sharing of data between the physical counterpart and the digital one. Using these data, Digital Twin can perform such tasks as [5]:

- In-depth analysis of physical twin;
- Simulate the health conditions;
- Increase safety and reliability;

- Optimization;
- Track the status of physical twin throughout its lifetime;
- Predict the performance;
- Real-time control

III. . APPLICATIONS OF DIGITAL TWIN TECHNOLOGY

3.1 First Digital Twin: Apollo 13

Apollo 13 was the third crewed mission intended to land on the Moon as shown in figure 4. On April 13, 1970, an oxygen tank in the Service Module exploded, crippling the spacecraft. NASA engineers used a combination of physical simulators, real-time communication, and problem-solving approaches that closely resemble the modern Digital Twin process. 15 simulators were used to train astronauts and mission controllers. The spacecraft continuously transmitted telemetry data, including environmental conditions, power levels, and system statuses. Engineers on Earth used this data to replicate the spacecraft's exact condition and performance. Full-scale simulators of the Apollo Command and Lunar Modules were housed at NASA's Mission Control in Houston. These simulators acted as the "virtual twin" of the spacecraft, modeling its behavior under the same constraints and damage conditions. Using the simulators, NASA engineers recreated the spacecraft's damaged state, including limited power, oxygen, and propulsion. Key Innovations Inspired by the Simulators were: i) CO_2 Scrubber Solution; and ii) Power Budgeting.

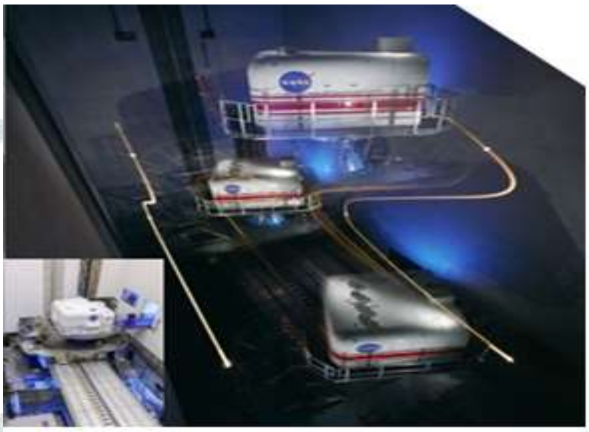


Figure 4. Simulation model of Apollo 13.

3.2 Earth Science Systems

Digital Twin technology is transforming Earth science systems by providing powerful tools for simulating, monitoring, and predicting natural phenomena. By integrating real-time data and predictive analytics, Digital Twins enable scientists to better understand and manage Earth's complex systems, such as climate change, natural disasters, and resource management. Key Technologies include: Remote Sensing and IoT, High-performance Computing (HPC), AI and Machine Learning and 3D Visualization.

Figure 5. NASA's Earth System Digital Twin (ESDT) concept

- The European Union's Destination Earth (Destin E) initiative aims to create high-precision Digital Twins of the planet to simulate climate change impacts and test mitigation strategies.
- Cities like Singapore use Digital Twins to monitor air quality, predict urban heat islands, and manage water resources sustainably.
- The Earth System Digital Twins (ESDT) shown in figure 5, thrust is an initiative by NASA's Earth Science Technology Office (ESTO) under the Advanced Information Systems Technology (AIST) program. It aims to use Digital Twin technology to enhance understanding, prediction, and management of Earth's processes.

3.3 Aviation Systems

By creating virtual replicas of physical assets and integrating real-time data, Digital Twins improve efficiency, safety and cost-effectiveness throughout the aviation life cycle. Applications of Digital Twin in the Aviation Industry include:

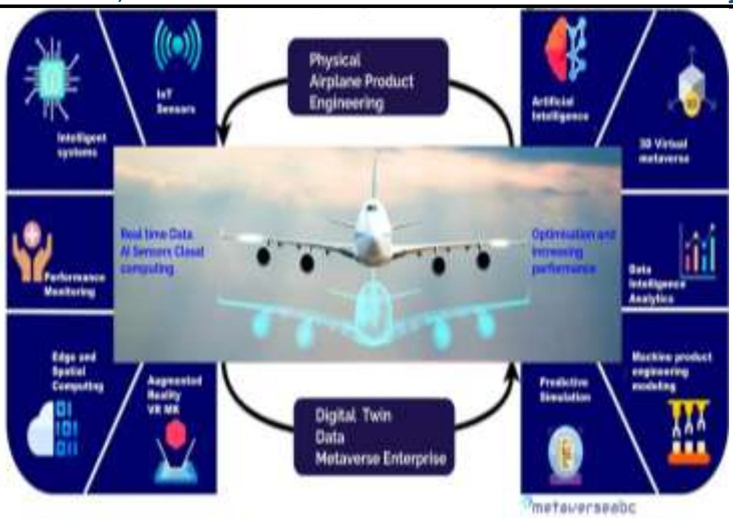


Figure 6. Future-Proofing Aerospace by Indian Aerospace and Defense Bulletin.

- Aircraft Design and Manufacturing
- Virtual Prototyping
- Predictive Maintenance
- Real-Time Monitoring
- Flight Operations Optimization
- Route Planning
- Flight Simulation
- Airport Operations Management
- Infrastructure Monitoring
- Process Optimization; Example: Boeing uses Digital Twin technology to enhance the design of aircraft components and reduce production lead times.
- Failure Prediction; Example: Rolls-Royce employs Digital Twins for its engines to optimize maintenance schedules and improve engine reliability.

Examples of Digital Twin Use in Aviation:

- **Airbus:** Uses Digital Twins to monitor and analyze aircraft performance throughout their lifecycle.
- **GE Aviation:** Employs Digital Twins to track engine health and predict maintenance needs.
- **Heathrow Airport:** Has developed a Digital Twin of its operations to optimize passenger flow and reduce delays.

3.4 Digital Twin in Healthcare

In the field of health, Digital Twin relates to ideas like detecting and diagnosing diseases before they appear by looking at organs in the body or symptoms.

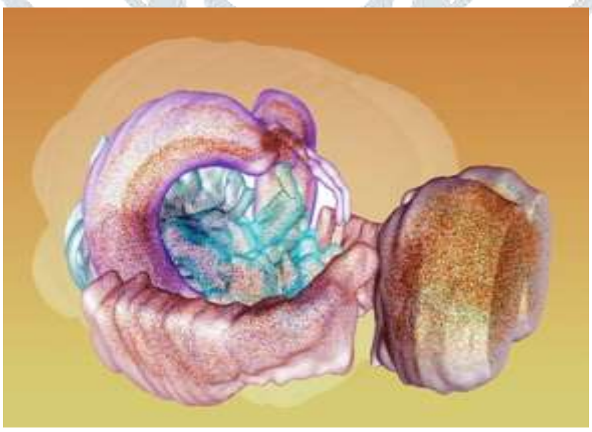


Figure 7. A digital twin of a brain image from the Blue Brain Project.

3.4.1 Brain: Chinese researchers released a paper in 2018 to better understand how neural networks and memory are connected and to build a three-dimensional brain map of the human brain. In America, two initiatives called Human Brain Project and Brain Initiative were launched at the same time to analyse the connections and structure of the human brain and transfer them to a computer. The Blue Brain Project at Hewlett Packard Enterprise collaborated with Ecole Polytechnique Fed´erale de Lausannes (EPFL) is Swiss brain research´ initiative run by Professor Henry Markram, its founder and director and the main objective of the Digital Twin of Brain is to link a human brain with an artificial brain.

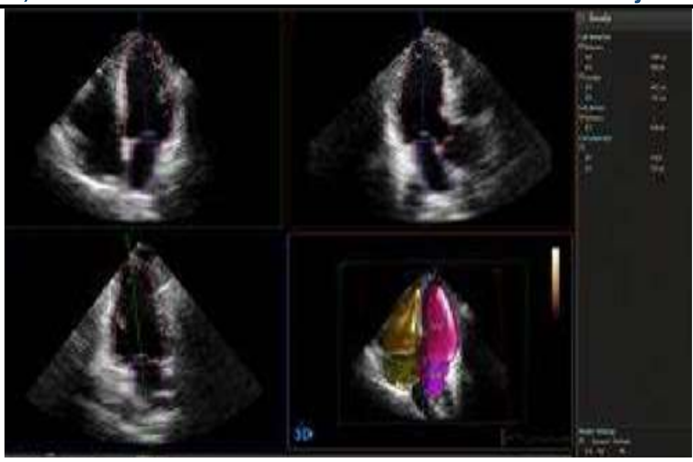


Figure 8. An Example Heart Image from Philips Heart Model.

3.4.2 Heart: A cardiac research study named Echos, directed by Frank Rademakers of University Hospitals Leuven in Belgium, is where the concept of producing digital heart twins originated. A digital twin of the whole heart will enable the simulation of the treatment of a specific individual for many other conditions. doctors will benefit from a new depth of knowledge about how their patients' hearts are working. Cardiac digital twins of human electrophysiology are digital representations of patient hearts created from clinical data that match all available clinical findings like for like. The software company "Dassault" recently unveiled "Living Heart," the first accurate virtual representation of a human organ that takes into consideration blood flow, mechanics, and electricity. A 2D scan of a person may be converted by the programme into a precise, three-dimensional representation of that person's heart. Developed by Philips, the "Heart Model" An essential step towards the concept of the digital patient is the creation of a personalised Digital Twin of the heart.

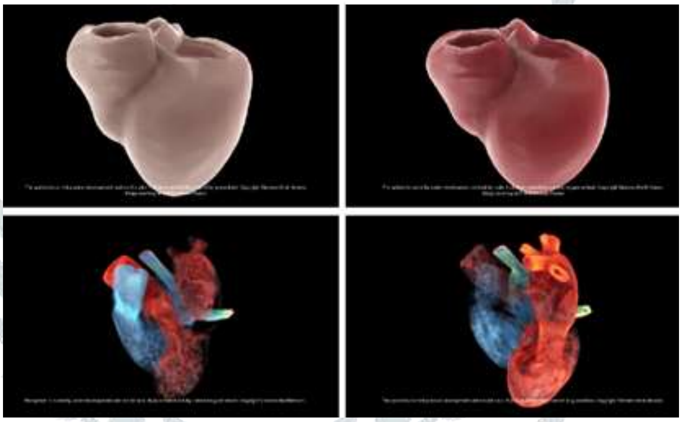
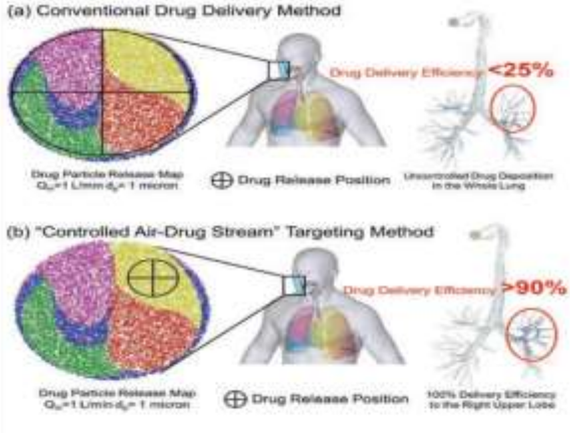


Figure 9. Siemens Digital Twin visualization of the human heart.

3.4.3 Cancer: "A digital twin allows us to make a better assessment of the situation," says Professor Michael Uder, deputy medical director of university at sklinikum Erlangen. IBM, together with the supercomputer Watson, has a goal simulate biochemical processes in the body using artificial intelligence techniques to detect cancer cells in health data acquired from the past. The National Cancer Institute (NCI) and the U.S. Department of Energy (DOE) have formed a strategic interagency collaboration, with Frederick National Laboratory (FNL) serving as a lead organization. FNL has played a key role in the development of novel technologies for building a digital twin of a cancer patient. Future applications for a cancer patient's digital twin include personalized medicine, cancer research, preclinical development, clinical trials, diagnostics, and therapy simulations. The Harvard Medical School, the Broad Institute of MIT and Harvard, the Dana- Farber Cancer Institute, and other organizations are working together on Project DRIVE (Digital Reasoning for Cancer Evolution). To analyze tumor growth and treatment response, the research will make digital twins of specific cancer patients.



Fiure. 10. Digital twin technology for cancer treatment.

3.4.4 Digital Twin of Hospitals: Due to the rising patient demand, growing wait times, etc. at the radiology department of Mater Private Hospitals in Ireland, a Digital Twin study was conducted with Siemens Healthineers to enhance hospital procedures. A Digital Twin of the radiology department was constructed as part of the project and was fed actual data. A number of predictions were made using the digital twin, and a number of situations were tested on it. The smart hospital digital twin can provide the following advantages: Improved patient experiences improved healthcare results, reduced facility running expenses, increased safety, and reduced energy use. After deploying digital twin technology to eliminate bottlenecks in patient flow and bed management, one hospital saw a 900 percent increase in cost savings. More lives can be saved by using digital twins to forecast and prevent patient crises like cardiopulmonary or respiratory arrest, often known as code blue events.

Figure 11. Realistic 3D Animation of Hospital.

IV. Conclusion

The growth in Digital Twin use has seen a shift in recent years, facilitated by an increase in the number of published papers and industry leaders investing heavily in developing Digital Twin technology. It would not be possible without the same growth in the AI and IoT fields, which are becoming key enablers for Digital Twins. The majority of the Digital Twin research is focused on the healthcare and autonomous field, as evidenced through the large proportion of papers in this area reviewed above. Digital Twins may evolve as a tool, not constrained by domains and contribute to economic growth of digital world. The impact from Digital Twins, digital proxies and digital duplicates may be only limited by our imagination.

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