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Digital Twins in Automotive Industry

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ABSTRACT

The automotive industry is currently navigating one of the most disruptive periods in its history. To remain competitive, manufacturers must move away from sequential, siloed development pipelines toward integrated, data-driven frameworks. Digital twin (DT) technology has emerged as a cornerstone of this transition, bridging the gap between physical reality and virtual simulation. It creates a real-time virtual replica of a vehicle, component, or system. It is a key tool influencing how cars are designed, built, tested, and maintained. A digital twin is essentially a virtual replica of a physical product or system. It is not merely a static computer-aided design (CAD) model; it is a dynamic, virtual replica of a physical object, process, or system that is continuously updated with real-time data from its physical counterpart. In the automotive sector, this physical-digital convergence is driving a paradigm shift, offering unprecedented benefits across the entire vehicle lifecycle. This paper explores the emergence of digital twin (DT) technology in the automotive industry.

KEYWORDS: *digitalization, digital twin, automotive industry.*

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INTRODUCTION

For over a century, the automotive industry has been defined by mass production, lean manufacturing, and global supply chains. The dramatic increase in software and electronic complexity, combined with the urgent pressure to transition to electric vehicles (EVs) and autonomous vehicles (AVs), has forced manufacturers to rethink traditional product development and manufacturing paradigms. As vehicles evolve into complex cyber-physical systems, traditional methods of design, manufacturing, and maintenance are proving increasingly inadequate to handle the staggering volumes of data and rapid development cycles required. Digital twin technology has emerged as a revolutionary capability. By creating a high-fidelity, real-time virtual replica of physical vehicles, components, or entire production lines, digital twins bridge the gap between the physical and digital realms [1].

A digital twin is a digital representation of a physical object or space that spans the lifecycle of the physical object and uses simulation and machine learning to enable informed decision-making. It represents a living, dynamic bridge between physical assets and virtual environments. Figure 1 shows a typical digital twin [2]. It is regarded as the next generation of digitalization for decision making support. The current development of digital technologies has dramatically increased the adoption of digital twin (DT) systems into the automotive sector, turning conventional manufacturing practice into a smart and data-driven model. Figure 2 shows the conceptual model of a digital twin [3].

CONCEPT OF DIGITAL TWIN

The concept of the digital twin was introduced in 2002 by Michael Grieves of Florida Institute of Technology. He applied the concept in manufacturing and proposed the digital twin as the conceptual model underlying product lifecycle management (PLM). The concept was being practiced since the 1960s by NASA. The concept of digital twin consists of three distinct parts: the physical product, the digital/virtual product, and connections between the two products [4]. Figure 3 shows the historical evolution of DT technology [5].

A digital twin is much as it sounds: creating a digital duplicate of the physical entity.

It has two sides, one pertaining to a physical device and the other to a digital rendition of this device. DT is a real time digital replica of a physical device using 3D modeling and sensors. The DT is an emerging paradigm focusing on an enterprise asset such as a system, product or process. Its core goal is to virtually represent this asset as close to reality as possible. A digital twin may exist before its physical counterpart is made. Technologies enabling DT include AI, IoT, 5G, virtual reality, augmented reality, wearables, and cloud computing. Figure 4 shows some of the fundamental technologies [6]. Realizing the full potential of DTs requires a convergence of these technologies. Digital twins integrate AI, IoT, machine learning, and software analytics with spatial network graph to create living digital simulation models that change as their physical counterparts change.

The three main pillars of the digital twin technology are visualization, emulation, and simulation. The foundation of DT is the physical world, which may consist of devices/products, physical systems, process, or an organization. Service is an essential component of DT in view of the paradigm of everything-as-a-service. DT-related services include application service, resource service, knowledge service, and platform service. The process of implementing DT can be divided into four steps: digital representation, synchronous mapping, simulation and prediction, and virtual and physical fusion. Figure 5 depicts the digital twin conceptual architecture [7].

There are numerous requirements to describe "digital twin." To be considered a digital twin, the model must have some specific characteristics such as [8]:

1. Data is the carrier of information and the key driver of DT. Real-time data is important for knowing the status of the product. Data-driven digital twin can perceive, respond, and adapt to the changing environment.
2. Integration of the different nodes is essential for creating valuable data. Sensors communicate the data to the digital world through integration technology between the physical world and the digital world, and vice versa.
3. Scalability (ability to analyze different scales of information);
4. Interoperability (ability to convert, match and establish equivalence between representation models);
5. Expansibility (ability to integrate models);
6. Fidelity (ability to conform to the physical model); the core of any DT is a high-fidelity virtual model.
7. Connectivity that indicates the level of communication with its physical counterpart; connectivity by design through IoT which is a paradigm for ubiquitous connectivity. Connect the products/services to a central location with streaming, big data, in-memory, and analytic capabilities to capture sensor data and enrich it with business and contextual data.

These are the most frequent requirements of digital twins. Figure 6 shows the top applications of digital twins [9].

DIGITAL TWIN IN AUTOMOTIVE INDUSTRY

The automotive industry is undergoing a profound paradigm shift, driven by electrification, software-defined architectures, and the transition toward autonomous driving. As vehicle complexity escalates and product development cycles contract, traditional physical prototyping and linear manufacturing workflows are increasingly inadequate. A rapid advancement in technology has ushered in a paradigm shift in the automotive industry, transitioning it from traditional hardware-centric engineering to software-defined, data-driven manufacturing. At the core of this transformation is digital twin (DT) technology—a virtual representation of physical assets, systems, or processes that continuously synchronizes with their real-world counterparts via real-time data loops. Digital twin technology is unique in its capacity to add value at every stage of the automotive value chain, from initial vehicle concept to end-of-life recycling. Figure 7 is a representation of DT in automotive sector [10].

An automotive digital twin is characterized by a three-pillar framework: the physical entity (the actual vehicle, component, or factory floor), the digital counterpart (the high-fidelity computational model), and the bi-directional data connection that binds them together. Unlike traditional simulations, which operate on historical assumptions and run in isolation, a digital twin relies on a continuous stream of operational data collected from Internet of things (IoT) sensors, onboard telematics, and environmental monitors. Pioneers like Tesla, Renault, BMW, and Ford have demonstrated that digital twins can slash vehicle development times by up to 25%, optimize production line efficiency, and enable predictive maintenance through real-time fleet monitoring [1].

APPLICATIONS OF DIGITAL TWIN IN AUTOMOTIVE INDUSTRY

Digital twins have played a vital role in the digitization of manufacturing processes by completely transforming the industry's approach to optimization, design, maintenance, safety, decision-making, and remote access and training methods. DT has become highly valuable in the automotive industry, especially in the domains of virtual prototyping, electric vehicles, autonomous vehicles, smart manufacturing, battery management systems, and product innovation. Other applications of DT in automotive industry include the following [1,11,12]:

- *Virtual Prototyping:* In traditional automotive development, engineering followed a sequential, linear path where design, structural analysis, thermal testing, and manufacturing planning occurred in isolated silos. Digital twins enable a transition to simultaneous engineering, where multiple development phases run in parallel. For example, French automaker Renault utilized digital twins during the design stage to conduct extensive virtual testing, which successfully compressed the timeline required to design a new vehicle from an entire year to just one quarter. In the design phase, Ford creates virtual prototypes to refine aerodynamics and structural integrity long before building a physical model. Figure 8 shows some prototypes of automobiles [13].
- *Vehicle Design:* Traditionally, designing a new vehicle model takes five to six years, and any design oversight discovered late in the process can lead to catastrophic financial losses and brand erosion. The design required the creation of multiple physical prototypes, which was an expensive, labor-intensive, and time-consuming process. Digital twins enable virtual prototyping, allowing engineers to test and refine designs digitally. Aerodynamics, crashworthiness, and thermal management can be simulated under extreme environmental conditions in virtual wind tunnels and crash laboratories. Digital twins mitigate risks by enabling simultaneous engineering, where design, aerodynamics, crash safety, and manufacturing planning overlap and run in parallel. Designers and engineers interact with a unified virtual model that simulates physical behavior in real time.
- *Smart Manufacturing*: The manufacturing of modern vehicles is a marvel of complexity. Modern automotive assembly lines are highly complex, producing a vast array of customized vehicle variants on a single line. To manage this complexity, leading automakers are deploying factory digital twins to orchestrate shop-floor operations. The transition to customized vehicles, deep personalization, and diverse powertrains (hybrid, battery electric, and fuel cell) has introduced immense complexity to the factory floor.
- *Autonomous Vehicle*: The development of autonomous vehicles (AVs) represents one of the greatest engineering challenges of the 21st century. Proving that an autonomous driving algorithm can navigate the real world more safely than a human driver requires validating the system across billions of driving miles and millions of complex, unpredictable scenarios. Validating the safety of autonomous vehicles (AVs) is arguably the greatest engineering hurdle in modern mobility. Physical road testing alone is too slow, expensive, and dangerous to achieve this scale of validation.
- *Electric Vehicles:* DT technologies have revolutionized the electric vehicle (EV) technological realms in various aspects. For instance, DTs are now widely used for virtual testing, parameter optimization, and predictive maintenance. As the application of DT streamlines the design process by reducing the financial and time losses of manufacturing, the acceptability of DT in the EV domain is rapidly increasing. As technology continues to evolve, DT is expected to play a crucial role in the advancement of development and operations. Figure 9 shows DT application along EV ecosystem [12].
- *Battery Management:* The battery pack is the most expensive, complex, and safety-critical component of an electric vehicle. The global shift toward electrification has introduced new engineering challenges, particularly regarding electric vehicle (EV) battery packs. Battery performance, aging, and thermal safety are highly non-linear processes that are difficult to monitor using traditional, onboard battery management systems due to computational constraints. A virtual model of the battery pack runs in parallel with the physical vehicle, utilizing machine learning algorithms and physics-based electrochemical models to analyze battery health. In the rapidly growing EV sector, battery design is a primary differentiator. Automakers like Volkswagen utilize digital twins to model and simulate the complex electrochemical and thermal behaviors of battery packs under diverse charging and driving conditions.
- *Predictive Maintenance:* Rather than waiting for a component to fail or relying on arbitrary mileage-based service intervals, the digital twin analyzes real-time wear-and-tear data to predict when a specific part (such as a battery cell, coolant pump, or brake pad) is approaching the end of its operational life. The utility of a digital twin does

not end when a vehicle is sold; rather, it enters its most valuable phase. By maintaining individual digital twins for every vehicle in operation, manufacturers can transition from reactive service models to proactive asset management. By analyzing real-time wear-and-tear data on components like brake pads, engines, and gearboxes, the twin generates timely service reminders that reflect the actual driving style and environmental exposure of the vehicle, preventing unexpected breakdowns and reducing fleet operational costs. For example, General Motors uses digital twins for predictive maintenance, allowing them to monitor vehicle performance and anticipate issues before they escalate.

BENEFITS

Digital twin technology represents a fundamental paradigm shift in the automotive industry, serving as a powerful catalyst for innovation, efficiency, and sustainability. Digital twins are indispensable for the safe validation of autonomous driving algorithms, while also driving resource efficiency and supporting the transition to a circular economy. Other benefits of DT in automotive industry include the following [1,10]:

- *Collaboration:* The integration of digital twins with the Industrial Metaverse is redefining collaborative engineering. In this shared virtual space, multidisciplinary teams from around the globe can collaborate in real time on a single, photorealistic virtual vehicle or factory model. Any geometric change made by a designer instantly updates the physics-based simulation parameters and manufacturing layouts, eliminating manual synchronization and dramatically accelerating the pace of innovation.
- *Sustainability:* Sustainability has become a new trend in the manufacturing domain by the end of 2021, advocating optimized energy usage and precise manufacturing processes to reduce waste. In an era of tightening environmental regulations and growing consumer demand for eco-friendly products, sustainability has become a core business imperative for the automotive sector. DT has been integrated into the manufacturing industry to achieve sustainable production. It helps cut costs and support sustainability goals. Digital twin technology plays a vital role in helping manufacturers minimize their environmental footprint and transition toward a circular economy. During the manufacturing phase, digital twins optimize energy and resource consumption across the factory floor. Moreover, digital twins contribute to the circular economy by tracking and optimizing the entire lifecycle of critical vehicle components, particularly EV batteries.
- *Battery Digital Twin* (BDT): This represents the future of battery intelligence. By combining physical electro-chemical models with real-time operational data (voltage, current, and temperature) and machine learning algorithms, a BDT running in the cloud can construct an incredibly precise model of internal battery dynamics.
- *Streamlined Production*: Toyota has embraced digital twin technology to enhance visibility and efficiency across its supply chain. By creating virtual replicas of its European manufacturing plants, Toyota can simulate and plan changes to production lines without disrupting actual operations. This approach allows for better analysis of inventory levels, transport routes, and potential bottlenecks, leading to more informed decision-making. The integration of digital twins has enabled Toyota to respond more swiftly to market changes and reduce the risk of costly delays.
- *Proactive Maintenance*: Predictive analytics make maintenance proactive rather than reactive. General Motors, for example, uses digital twins to simulate production lines before construction, optimizing planning, scaling faster, and tracking component health to schedule repairs before failures occur.
- *Enhanced Decision-making*: Digital twins allow designers to quickly test different configurations, materials, and components in a virtual environment. This facilitates better decision-making early in the design phase, saving both time and resources.

CHALLENGES

In spite of its transformative potential, the widespread adoption of digital twin technology in the automotive industry is hindered by several significant technical, economic, security, and organizational challenges. Substantial challenges remain regarding data synchronization, data interoperability, data fragmentation, high initial costs, legacy system integration, and cybersecurity risks. Other challenges of DT in automotive industry include the following [1,10]:

- *High Initial Investment:* Building a comprehensive digital twin ecosystem requires substantial capital expenditure. Organizations must invest in advanced 3D simulation tools, high-performance computing infrastructure, IoT sensor arrays, and specialized engineering talent. Automakers must invest in extensive IoT sensor networks, high-performance cloud computing infrastructure, advanced simulation software licenses, and robust data storage solutions. For smaller automotive suppliers and niche manufacturers, these high upfront costs can be prohibitive, delaying the widespread democratization of the technology across the entire automotive supply chain.

- *Data Quality:* The predictive accuracy of a digital twin is strictly bounded by the quality of its input data. Building a cohesive digital twin requires integrating data from highly disparate software ecosystems, including CAD. Ensuring seamless data flow and maintaining high data quality across legacy silos remains a major technical bottleneck. If a digital twin is fed corrupted or drifted sensor data, its internal state estimation will diverge from physical reality, leading to false alarms or missed critical failures.
- *Data Synchronization:* Achieving high-fidelity synchronization across millions of connected vehicles requires solving immense data-management bottlenecks. A true digital twin requires real-time or near-real-time synchronization to enable dynamic closed-loop feedback. A digital twin is only as valuable as its alignment with the physical asset. Maintaining bidirectional real-time synchronization between a physical vehicle and its digital replica requires high-bandwidth, low-latency communication networks. In remote areas with poor cellular connectivity, data delay or packet loss can cause the virtual model to drift from the physical reality, leading to inaccurate predictions or faulty control commands.
- *Cybersecurity:* As vehicles and factories become increasingly connected, they present a broader attack surface for cybercriminals. Digital twins contain highly sensitive intellectual property, including proprietary vehicle designs, manufacturing process parameters, and customer telematics data. Connecting physical vehicles and manufacturing plants to cloud-based digital twins dramatically expands the cyber-attack surface. Because a digital twin is an exact, high-fidelity replica of a physical vehicle or factory, it represents a goldmine of highly sensitive intellectual property and operational data.
- *Intellectual Property:* Because a digital twin is a high-fidelity replica containing proprietary designs, material properties, and manufacturing parameters, a data breach of a digital twin database represents a catastrophic loss of intellectual property.
- *Legacy Systems:* Connecting new digital twin technology to decades-old systems is often the hardest step. Disconnected data and siloed teams can stall adoption if integration is not carefully planned. Automotive OEMs operate vast, highly fragmented software ecosystems. Integrating disparate, legacy data stacks into a single, cohesive digital twin is exceptionally difficult. The lack of standardized data formats often leads to data silos, preventing the seamless bidirectional flow of information required for high-fidelity synchronization.
- *Interoperability*: The automotive manufacturing ecosystem is incredibly fragmented, relying on a vast array of proprietary software tools and legacy hardware systems. This fragmentation creates an interoperability crisis that severely limits the scalability of digital twins.
- *Talent Shortage:* The successful implementation of digital twins requires overcoming deep-seated organizational inertia and a severe shortage of specialized engineering talent. Engineers must possess expertise not only in traditional mechanical and automotive engineering but also in advanced data science, machine learning, cloud architecture, and 3D simulation engines. There is currently a critical global shortage of skilled professionals who can bridge these domains.
- *Latency:* A true digital twin requires real-time or near-real-time synchronization to enable dynamic closed-loop feedback. However, in high-speed automotive applications, even a millisecond of latency can render the virtual simulation obsolete or, worse, lead to catastrophic physical failures if the twin sends delayed control commands back to the vehicle. This latency is introduced at multiple stages: sensor data acquisition, network transmission, cloud simulation processing, and command execution. Achieving the low-latency, deterministic communication required for real-time cyber-physical interaction remains a major technical barrier.

FUTURE OF DIGITAL TWINS IN AUTOMOTIVE INDUSTRY

The concept of the digital twin represents one of the most profound paradigm shifts in modern industrial engineering. The future of the automotive industry is undeniably cyber-physical. As vehicles transition into highly connected, autonomous, and electric platforms, the traditional boundary between physical hardware and digital software is dissolving. Digital twin technology is the bridge that spans this divide. Over the next decade, the automotive digital twin will evolve from a competitive advantage into an absolute operational necessity. The digital twin is no longer merely a tool for simulation; it is the architectural foundation upon which the future of mobility will be built [1]

The future of the digital twins is in the automotive industry. The next wave of digital twin innovation will bring AI, IoT, AR, and blockchain into tighter integration. In the future, one should expect to see the expansion of the IoT, and with it, some version of digital twin technology. As more and more products in our homes and workplaces evolve into smart devices, we will also see an increase in the availability of digital twin technology [14].

CONCLUSION

Digital twin technology represents a fundamental convergence of the physical and digital worlds, permanently altering how vehicles are designed, manufactured, validated, and operated. It is no longer a futuristic concept; it has become an indispensable strategic tool driving the digital transformation of the automotive industry. The market for digital twins in the automotive sector is experiencing explosive growth. Real-world implementations by pioneers like Tesla, Renault, BMW, and Volvo demonstrate that digital twins are no longer a theoretical concept but a commercial necessity that drives immense value, reduces time-to-market, and enhances vehicle safety.

Digital twin technology offers the automotive sector unprecedented opportunities to merge the physical and virtual realms across the entire vehicle lifecycle. The modern automotive digital twin is not a singular entity but rather a continuous thread that runs through the entire lifecycle of a vehicle. By establishing real-time, bidirectional data flows between physical vehicles and their virtual counterparts, automotive original equipment manufacturers can optimize vehicle design, streamline manufacturing, and enable proactive, post-sale services. More information about digital twin in the automotive industry can be found in the books in [15,16].

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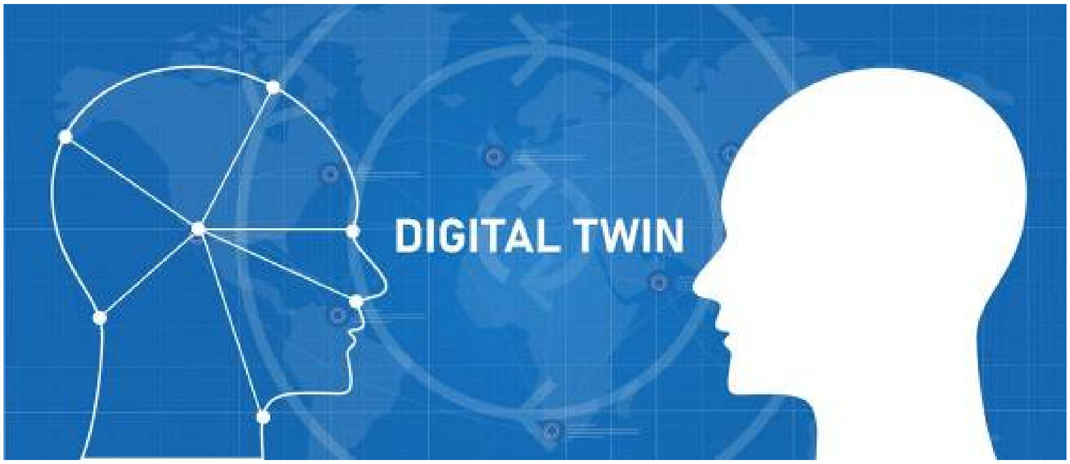

Figure 1 A typical digital twin [2].

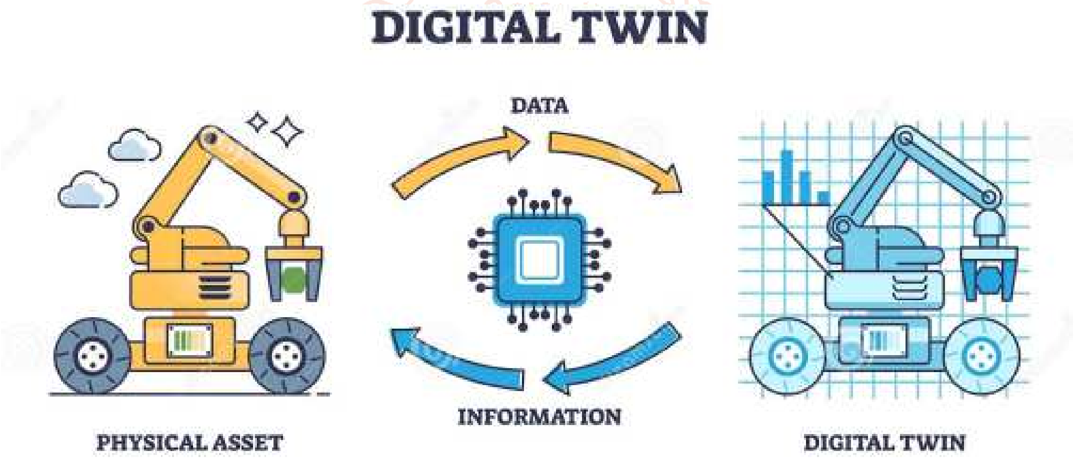

Figure 2 Conceptual model of a digital twin [3].

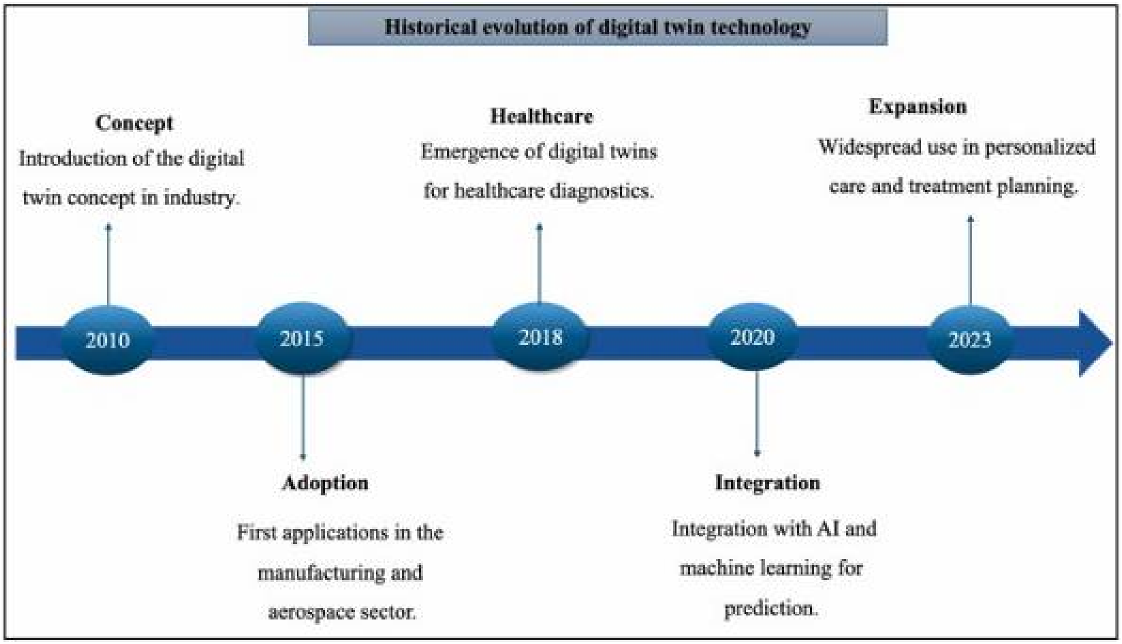

Figure 3 The historical evolution of DT technology [5].

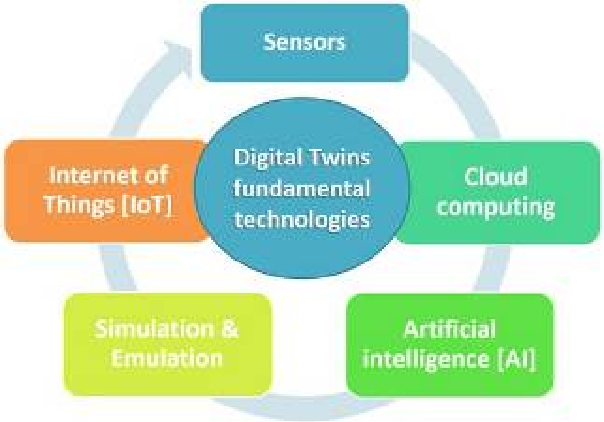

Figure 4 Some of the fundamental technologies [6].

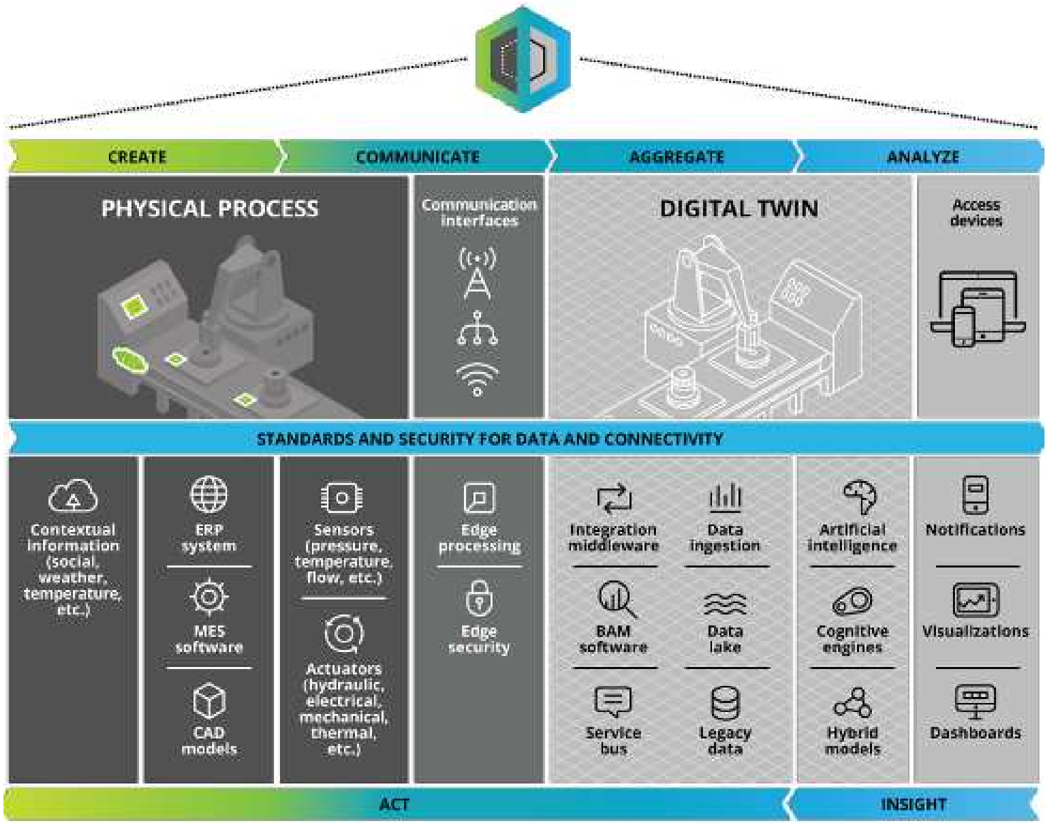

Figure 5 The digital twin conceptual architecture [7].

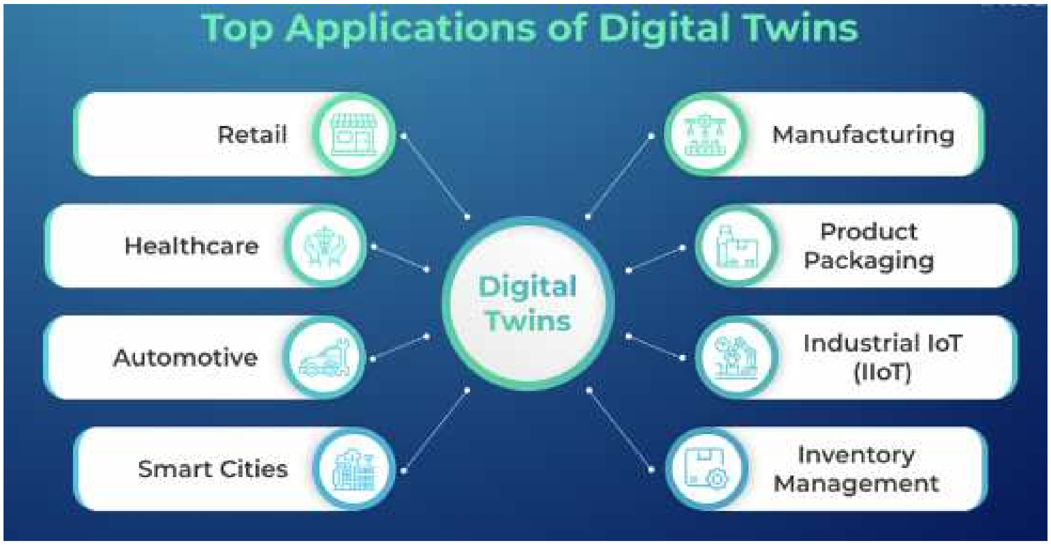

Figure 6 Top applications of digital twins [9].

Figure 7 A representation of DT in automotive sector [10].

Figure 8 Prototypes of automobiles [13].

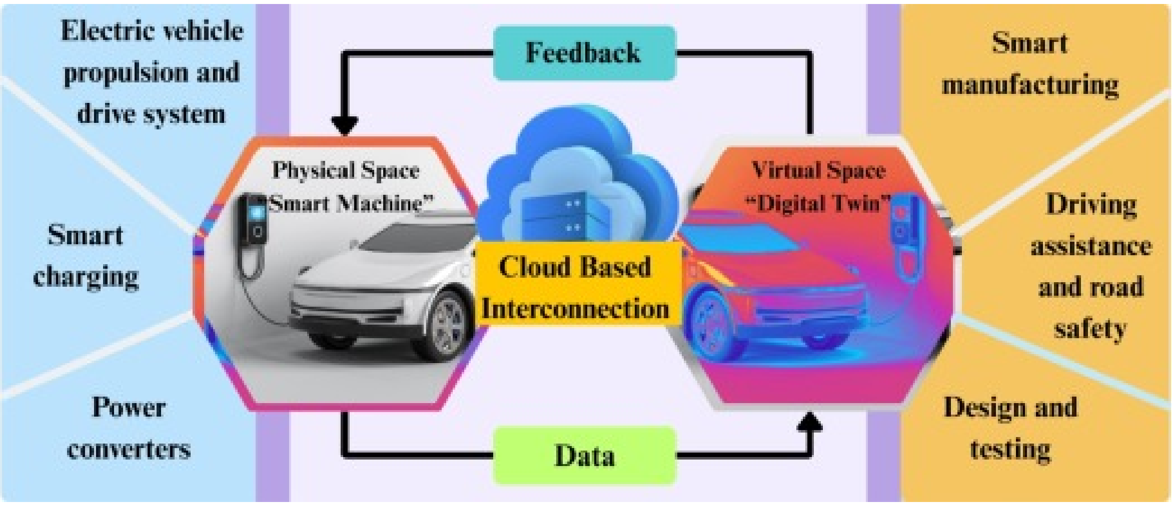

Figure 9 DT application along EV ecosystem [12].