

Review

Digital Twins in the Automotive Industry: The Road toward Physical-Digital Convergence

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Abstract: A newly introduced term in the field of simulating an artificial or physical system is that of the “Digital Twin” concept method. It employs a digital representation and modeling method, capable of expanding and improving the life cycle of complex items, systems, and processes. Nowadays, digital twin technology has become a key research field worldwide. In this context, it is applied and utilized in various fields. One such field is the automotive industry, a technological field that has great implications in users’ everyday life. Digital twin technology not only has great contributions from the initial stages of design until the final construction stages of vehicles, but also during its use, drawing useful information from its daily functions and making the driving experience more enjoyable, comfortable, and safe. It is worth noting that the vehicles that can greatly benefit from the use of digital twins are electric vehicles, which has tended to acquire greater shares in the last decade.

Keywords: digital twin; cyber-physical systems; simulation; automotive industry; vehicle; 4th industrial revolution



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1. Introduction

1.1. Definition of a Digital Twin

A digital twin is a nonphysical model that has been designed in order to accurately reflect an artificial or physical system, where sensors are placed to acquire a variety of data regarding different aspects concerning the performance of the system. These data are then transmitted to a data-acquisition system and applied to the digital copy. When the digital copy is updated with the relevant data, the virtual model may be used for the implementation of various simulations, which can lead to potential improvements, by creating valuable information that can then be applied back to the original system existing in the physical world. In this way, physical processes and products together with their accompanying elements can be digitally transferred and described in a cyber-world context [1–4].

While digital twins have great potential, their use is not a necessity for every fabricated product. Not all objects can be considered as complicated enough in order to need the intense and tactic flow data sensors required by digital twins, neither is it always worth it from a financial point of view to invest important resources for the creation of a digital twin. Therefore, the industrial sectors that have a need to employ digital twins are those that develop and produce products of the niche sector. The rapidly growing digital twin market suggests that while digital twins are already used in many industries, their demand will continue to escalate in the immediate future [5–8].

The major benefits of a nonstatic and highly realistic digital model of a physical object are practically unlimited. Understanding individual aspects of real-life objects as well as designing new ones are endorsed and the competence to simulate and optimize is elevated. Via recording and digitally acquiring the operating data of the model (digital twin), in a

real-time situation, the recording of behavioral patterns of the real-world system becomes more achievable. Therefore, users can predict them in a greater degree.

In order to utilize “digital twin” technology, three distinct steps are basically needed. At first, the digital twin prototype should be made, taking into account data along with processes carried out in the real-world system. After that stage, a digital twin of the properties of every object must be compiled. At the end, every relevant systemic property should be attributed, so that, via all the data acquired, a further understanding and prognosis can be achieved. In conclusion, the digital twin should be able to realistically represent its physical real-world twin and be able to show its condition in real-time. In order for this to be feasible, the employment of innovative technologies is requested, which are considered as the foundations of today’s industrial revolution context. These can be viewed in Figure 1.

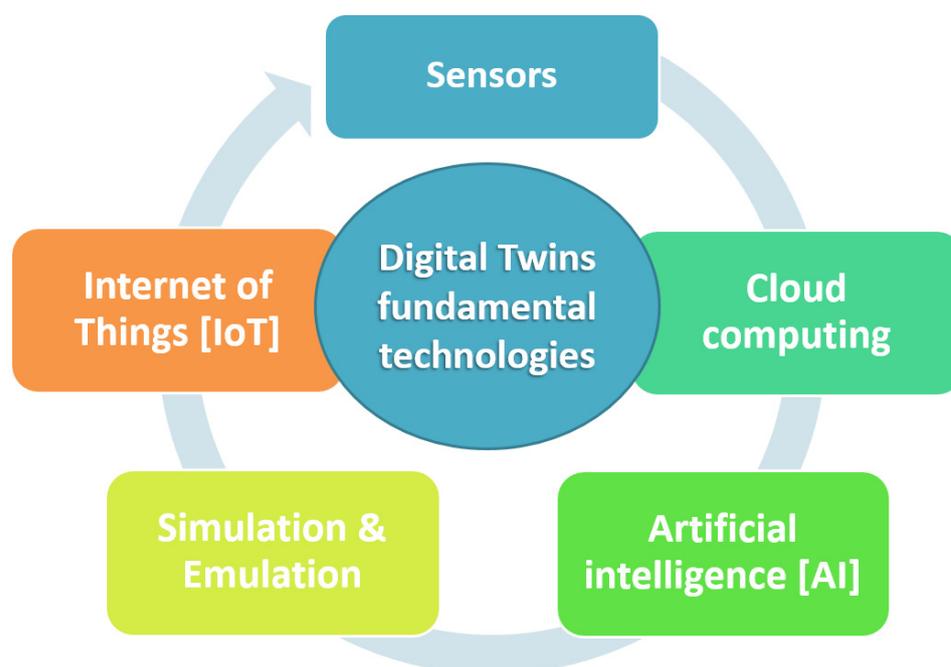


Figure 1. Digital twin fundamental technologies.

1.2. The Historical Background of the Digital Twin Technology

The “Digital Twin” idea arose in 2002 when Challenge Advisory presented the idea from Michael Grieves from the University of Michigan regarding contemporary technological developments. The presentation had to do with the development lifecycle management center regarding products. This presentation included all the core details relevant with the “Digital Twin” technology such as physical space, virtual space, and the exchange of relevant data and information between physical and virtual worlds. Even though the used terms have been altered since then, the basic idea has remained the same. Even though it is generally believed that the concept was first been presented in 2002, it has been well-known since the 1960s. NASA has been using basic similar technology ever since, for space programming. What they actually did was fabricate physical twins at their facilities to simulate the physical mechanical assemblies operating outside of the Earth’s environment. A relevant case was setup in the case of Apollo 13 when it was placed in orbit [9].

When Apollo 13 was launched in April 1970, it was statistically unthinkable that the crew would fight for their own survival when oxygen tanks malfunctioned midflight. It is one of the most well-known rescue missions attempted, while technicians on Earth tried to come up with a solution while being on the Earth. What turned the rescue mission into a success, however, was the fact a digital twin of the spaceship was set-up on Earth, which enabled ground crews and scientists to come-up with a rescue plan. However, nowadays,

such system layouts have apparently become virtual rather than physical. Figure 2 depicts a characteristic systemic layout of a digital twin [10,11].

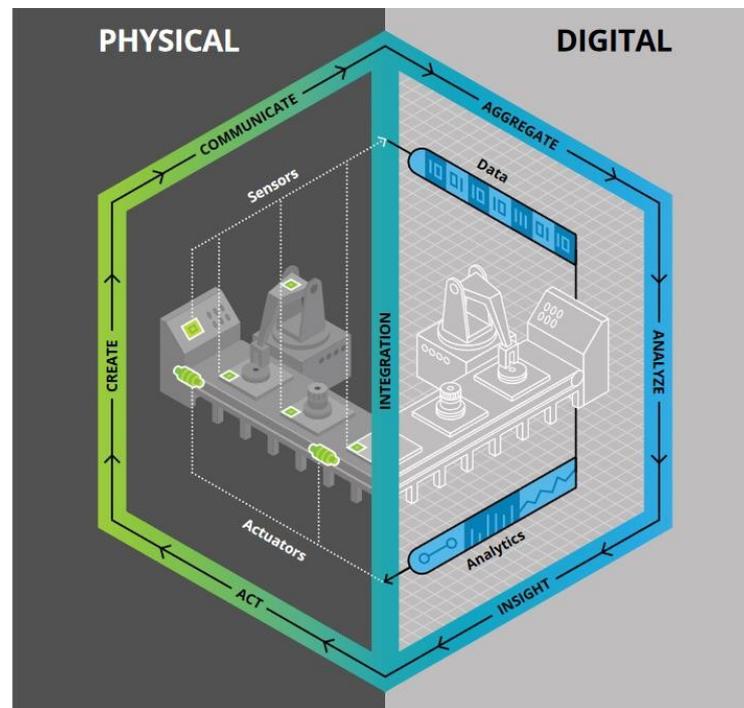


Figure 2. Characteristic systemic layout of a digital twin.

Accordingly, the main contributions of this article are given as follows:

- Describe the modus operandi of the Digital Twin.
- List published literature works about Digital Twin category applications, Digital Twin process functions, and Digital Twin application domains.
- Quote cases where Digital Twin technology is already applied in the automotive sector.
- Include suggestions about further applications in this domain such as the vehicle's meta-life as the tools that support this transition (i.e., IoT, AI, and ML) progress as well.

2. Utilization Fields and Applications

A further classification of the Digital Twin technology regarding its category application that it will potentially utilize is depicted in Table 1.

In order to further describe and understand the concept of Digital Twin functions, a number of relevant process functions are depicted in Table 2.

Digital Twin technology features a wide range of applications. It has penetrated in many technological domains, and it is expected to do so in many other fields as the technology progresses. Thus, the Digital Twin concept has become increasingly important for a number of business sectors [2]. The most predominant ones can be viewed in Table 3.

Table 1. Digital Twin category application.

Digital Twin Category Application	
Product Twins	Operators compile a nonphysical prototype of an object before creating the actual production line to investigate how it will function under various scenarios and what potential malfunctions may arise. Thus, all necessary alterations can be made that will lead to an optimized design.
Process twins	Virtual and simulated processes can lead to different cases and depict the outcome under varying conditions. In order to develop an optimized production planning, twin products for each piece of equipment involved can be made in this context.
System Twins	Virtual systems of real-world integrated systems. They acquire a large number of systemic information generated by systems, obtain information, and create opportunities to optimize processes and the greater system.

Table 2. Digital Twin process functions.

Digital Twin Process Functions	
Design	Visualization processes can be used during design for verification and inspection of the overall 3D design assembly of the product in order to verify that their matching and fitting are the desired ones.
Diagnostics	The simulations along with their various sensor readings can analyze some nonaccessible data such as various forces and stresses applied in different parts of the product.
Prediction	With engineering and deep learning algorithms, forecasting can be conducted accurately and in a timely manner for the purpose of the longevity of the equipment or unit. In addition, all the information is available in real-time operation and assists in the design of rational maintenance plans for the reduction of potential nonscheduled operation interruptions.
Maintenance	A digital twin can analyze performance data collected within a certain time interval and under various conditions. Combined analysis provides the required information for the users, in order to proceed with the appropriate maintenance actions.

Table 3. Digital Twin application domains.

Digital Twin Application Domains	
Industrial production	Facilitates activities such as monitoring, coordination, and control of industrial systems in production lines. Its main function lies in the reduction of errors and production delivery time [12–21].
Health sector	Revolutionizes the healthcare sector by enhancing clinical procedures and hospital management, with digital monitoring and advanced modeling of systems of the human body. These tools are very helpful to researchers in the study of various diseases, novel drug formulas, and medical devices [22–27].
Automotive	Used in the design of new products as well in the production lines. At the same time and after the completion of the product manufacturing, it can measure specific patterns and functional information of the vehicle with the purpose of aiding in its performance increase [28–31].

Table 3. Cont.

	Digital Twin Application Domains
Smart cities	Combined with the Internet of Things, it can increase the efficient design of a smart city. This can be achieved by reinforcing its financial indicators, improving its management resources, and reducing the environmental impact of each citizen [32–35]
Agriculture	The monitoring of land assets by installing various tools and sensors, i.e., in water, temperature, and humidity, for crop protection, maximization of profits, and reduction of failures [36–41].

In this context, a continuously growing number of enterprises has started to utilize digital twin technology. For example, Bosch has supported the technology by creating “Bosch IoT hub” along with other products, such as the “Eclipse Ditto”. Ditto is a tool that assists companies to collaborate, organize, and analyze digital twins. With Bosch subscriptions, this tool bridges the gap between real-world IoT devices and their digital twins. Another proposed product is the “Eclipse Hono” that assists in connecting and interacting with large numbers of IoT devices in a single way, regardless of the device’s communication protocol [42].

In addition, another major enterprise that closely follows the developments in Digital Twin technology is IBM. Their proposed solutions assist companies to create digital twins and eliminate the various mishaps between design and operation. Data provided in real-time also aid in troubleshooting situations in order to eliminate the product-to-market interval [43].

In another case, Ansys, which is the largest company in the field of finite element analysis, also offers products that allow the compilation of digital twins. Engineering simulations, virtual tests, and innovative product design workflows assist companies in testing new developments in a cost-effective way. The ANSYS well-known simulation tools coupled with digital twin technology assist companies toward introducing optimized products and production lines workflows [44].

In addition, PTC, an American software and computer services company founded in 1985 and headquartered in Boston, Massachusetts, is considered a pioneer in the field. Combined with high-capacity simulation and analytics capabilities, their proposed tools help companies toward incorporating customized and highly optimized products. In addition, PTC regularly provides information on digital twin technology and its case studies [45].

In addition, Oracle is another enterprise involved in this sector. With Oracle, businesses can create digital twins and operate them in a cloud-based user-friendly environment. Oracle additionally introduced digital twin tools for use throughout a product’s life cycle, along with products targeted in the IoT sector [46].

A platform developed by Microsoft, named “Microsoft—Azure Digital Twin”, consists of an integrated solution that allows users to create models of products and processes. By using Azure, enterprises can create spatial intelligence charts that model all the synergies between systems, locations, and individual users. Users can use the tool to create high-scalability, spatial knowledge [47].

In addition, Siemens uses digital twin technology in many cases, such as the “Digital Enterprise Suite” tool dedicated to the Defense-in-Depth strategy. By using digital twins, enterprises can have a greater overlook of their R&D processes. This allows for a minimized failure rate percentage and greater versatility in introducing new product lines. The “Mind Sphere” platform creates services and processes based on data from the actual production lines, consisting of a remarkable integrated solution [48].

3. Digital Twins in Automotive Industry

The automotive industry has changed dramatically over time as consumer needs grow and new technologies are constantly entering the field. The industry retains some of its traditional infrastructure while being constantly enriched with emerging digital services based on sensors and devices utilizing artificial intelligence, which operate mainly after the product enters the market. The involvement and importance of Digital Twins in the improvement of the vehicle aid in its life cycle-added value and also in the optimized design of future vehicles [49,50]. Figure 3 depicts a typical Digital Twin arrangement applied in the automotive industry.

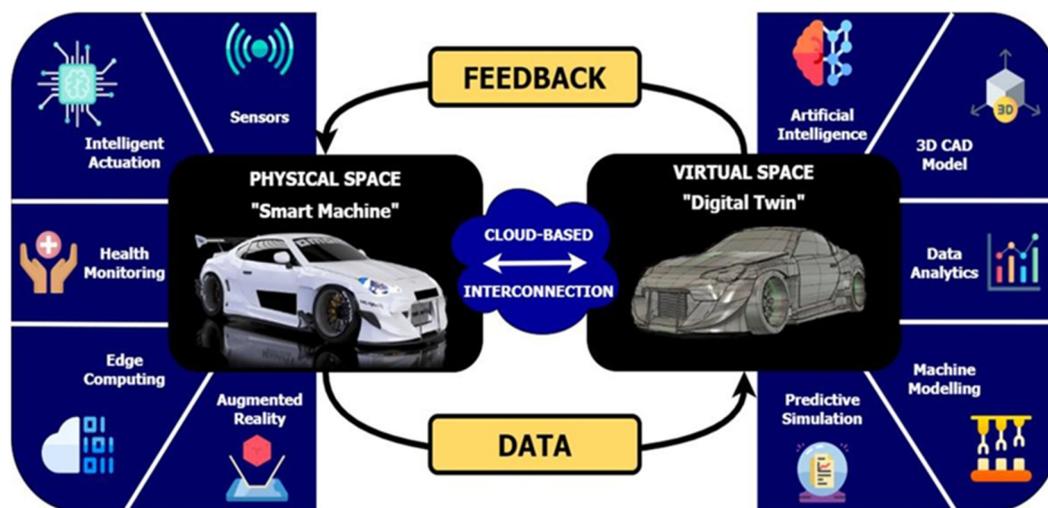


Figure 3. A typical Digital Twin arrangement applied in the automotive industry.

In order for a vehicle to enter the market, it should undergo a number of obligatory design and control stages. The first stage concerns the initial design of the vehicle's exterior surface in a relevant CAD design software package. At that point, designers start with a simple exterior and interior modeling and then proceed with the design of the vehicle's individual components. Physical prototyping has also evolved nowadays with the introduction of 3D printing technology that allows designers to fabricate physical prototypes of their designs rapidly for testing operations [50–55]. However, while physical prototyping is essential, the simultaneous presence of a Digital Twin is of paramount importance for the automotive companies. In the initial stages of product development, the Digital Twin can collect the vehicle's behavioral information in performance terms, thus providing valuable information to the designers and system engineers. The continuously increasing number of various components existing and functioning in a car can be a real challenge for the product development team. As it can be very time consuming to actually test each individual system, a Digital Twin can simulate the existence and function of various systems and provide valuable information about their suitability, interoperability, and performance. In this context, and by employing artificial intelligence technology, failure rates can be forecasted, saving a lot of unpredictable expenses [56–58].

Upon the vehicle's market introduction, in the case of test conduction or a potential recall campaign, via a Digital Twin, vehicle test data can be simulated to determine their quality and performance, such as the use of a new component under various conditions to implement design improvements and to experiment with substantially different elements that may lead to its optimization. Product performance may be predicted along with changes made in real time, determining the optimal configuration. By tracking key components, no recall is required for tens of thousands of products in the event of a problem. Those directly affected can be identified immediately by locating a consignment of corroded components during transport from abroad [59].

In the sales field, the digital twin of a vehicle with 3D vehicle reconstruction and visual representation can make a possible buyer alter its color when visiting an automotive manufacturer's site. The same applies to different vehicle aesthetic elements such as the interior, allowing for a customized product tailor-made for the customer. In the case of used cars, buyers often have no other option but to speculate about the condition of a vehicle. A used vehicle with digital identity assists with the tracking about its maintenance record with the digital twin containing all relevant data [60,61].

Digital Twin technology also has great potential in electric vehicles. The modus operandi in this case suggests that an electric vehicle should be linked with its customized digital twin. Via installed IoT sensors on the vehicle, the sensors can exchange data with the vehicle's digital twin. This information gathered as feedback enables the manufacturer to maintain a digital record of the working condition of the car and also detects potential problems at an early stage before they evolve in order to avoid potential repairs. For example, the American automotive manufacturer Tesla utilizes Digital Twin technology in every vehicle they produce. The partner company that developed Tesla's Digital Twin application (called "Thinkwik") states that real-time mechanical issues in Tesla Motors, regardless of their magnitude, are being fixed by simply downloading over-the-air (OTA) software updates. The uninterrupted continuous transmission of the relevant data between the vehicles and the manufacturer aids toward improving the quality of its products. The use of Digital Twins along with pioneering technologies such as the Internet of Things (IoT) and artificial intelligence (AI) has made feasible such processes that were thought to be unachievable [30,62–68].

A Vehicle's Meta-Life

There is a variety of elements that form a customer's view of an automotive product, such as fuel savings, comfort while driving, and performance, but safety is always a factor of paramount importance. Advanced Driver Assistance Systems (ADASs) is the terminology used regarding the safety supplements designed to increase the driver's, passengers', and pedestrians' safety by minimizing the number and seriousness of automotive accidents. The purpose of an ADAS is to notify users when potential impending hazards are identified, to intervene when necessary in order for the user to achieve proper control of the automobile, and to prevent accidents or to reduce the severity of an accident when it might happen [69]. ADASs rely heavily on Digital Twin technology because they use sensors to detect future threats. The system works in conjunction with the cloud in which all data are stored and recalled if needed. The knowledge obtained from these data may increase the ability to respond to or detect threats from existing ADAS architectures [70].

An attempt is made to use Digital Twin technology by incorporating fuzzy cloud-based logic to draw conclusions to elevate the efficiency of telematics-based user aid. Employing fuzzy logic in ADAS Digital Twin systems is considered crucial for facilitating the transition from manned to autonomous vehicles. To achieve the goal of flawless human–computer interaction while taking into account greater standards and regulations [71], a complex architecture is created where the Digital Twin can aid toward achieving user safety by analyzing real-time sensor data from the real-world car along with the knowledge base of the relevant protection regulation context. This leads to a smart ADAS that respects personal data within the laws' limits, enhancing public perception and market shares [72]. Figure 4 depicts a driver's assistance system architecture.

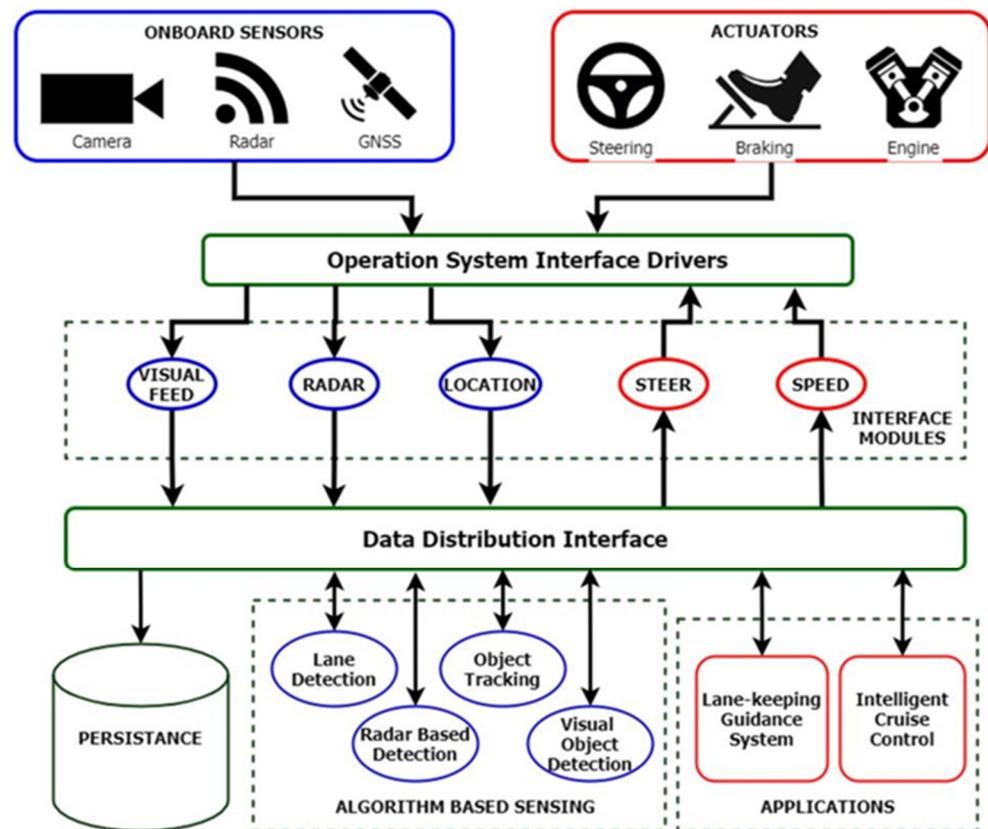


Figure 4. Driver’s assistance system architecture.

This technology can be used to facilitate Maintenance Repair Operations (MROs) by creating a smart interface between the car company and the driver. Using relevant data, the twin can perform an evaluation of the vehicle’s health state while predicting future maintenance requirements. The compiled twin simulates electronics, electromagnetic effects, brake pad wear levels, and vehicle dynamics data detection to provide meticulous information of the vehicle’s state [73]. A system that is subject to a gradual and inevitable degradation in electric vehicles is the electric motor, making health monitoring essential [74]. Figure 5 depicts a Digital Twin system diagram embedded within the Maintenance Repair Operations system.

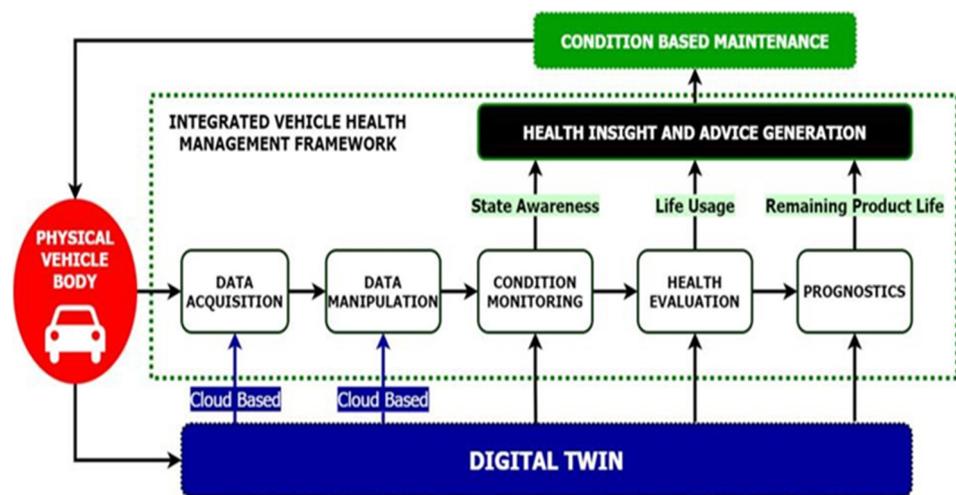


Figure 5. Digital Twin technology embedded within the MRO.

4. Conclusions

Even though the field of digital twin technology is very promising, the compilation of such systems is equally difficult due to the challenges often faced in terms of engineering, technology, and big data [75]. This technology is inextricably linked with the IoT and Industry 4.0, making it very versatile. In addition, the inclusion of the IoT might lead to a great amount of data and potential system security concerns [75]. Taking into account the case of a smart vehicle, where its users are human, the security of the data created by this human–computer interaction is of paramount importance.

When employed in real-time vehicle cases, especially in the cases of health monitoring, a number of issues can arise due to lost connectivity and sudden power losses/outages. The discontinuance of information flow from the embedded sensors and the consequent loss of connectivity with the twin might have implications on the accuracy of a prediction model. Therefore, the global infrastructure regarding wireless technologies and signal transmission must also evolve at the same time. Even though certain elements of this technology have simple purposes, the infrastructure needed is vast. Accurate installation and rigorous data logging are probably the main obstacles found by developers of digital twins. A digital twin's theoretically infinite reuse will not only minimize the cost of complex physical test settings but also help develop safer and more efficient vehicles. In addition, the potential for continuous data analysis makes it possible to acquire a large number of accurate vehicle performance measurements, leading to the creation of smart electric vehicles.

Starting from the initial R&D stage to the final production and vehicle's meta life, digital twin technology is a powerful tool in order to achieve the fabrication of sustainable vehicles. The concept has not yet been widely adopted by the majority of the automotive industry, due to the fact that its core supporting technologies such as the IoT and Artificial Intelligence have not yet matured up to the stage that allows their flawless use by the users. However, their continuous evolution along with the need for smarter, more efficient, and sustainable vehicles indicate that the contribution of digital twin technology will be immense.

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