Review


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Abstract: This article explores the transformative potential of digital twin (DT) technology in the automotive sector, focusing on its applications in enhancing propulsion drive systems. DT technology, a virtual representation of physical objects, has gained momentum due to its real-time monitoring and analysis capabilities. Within the automotive industry, where propulsion systems dictate vehicle performance, DTs offer a game-changing approach. Propulsion drive systems encompass electric motors, transmissions, and related components, significantly impacting efficiency and power delivery. Traditional design and testing methods need help addressing these systems’ intricate interactions. This article aims to investigate how DTs can revolutionize propulsion systems. The study examines various applications of DTs, ranging from predictive maintenance to performance optimization and energy efficiency enhancement. The article underscores the technology’s potential by reviewing case studies and real-world implementations. It also outlines challenges tied to integration and validation. In unveiling the capabilities of DT technology for propulsion systems, this article contributes to a comprehensive understanding of its role in shaping a more data-driven and efficient automotive industry.

Keywords: digital twin; propulsion drive system; automotive; vehicle propulsion; powertrain; virtual modeling; simulation; performance optimization; real-time monitoring; vehicle modeling

1. Introduction

The automotive industry has undergone a transformative shift in recent years driven by technological advancements. One of the most promising innovations to emerge is the concept of DT technology [1]. A DT is a virtual representation of a physical object, system, or process created and maintained in real time [2]. It enables a bidirectional flow of information between the physical entity and its digital counterpart, allowing for continuous monitoring, analysis, and optimization. The application of DT technology can potentially revolutionize various sectors, including the automotive industry [3].

The concept of DTs draws inspiration from aerospace, manufacturing, and simulation, where they have already demonstrated remarkable benefits [4]. DTs have gained traction in the automotive sector due to their ability to address complex challenges associated with vehicle design [5], production [6], operation [7], and maintenance [8]. Manufacturers can gain insights into real-time performance, anticipate issues, and make informed decisions by creating a digital replica of an entire vehicle or its components.

At the heart of every electric vehicle’s performance lies its propulsion drive system, which encompasses the electric motor, transmission, and related components [9]. Propulsion systems determine a vehicle’s efficiency, power delivery, and overall driving experience [10]. The battery powers a control unit that oversees the electric motor. At the same time, the transmission facilitates the transfer of this power to the wheels, allowing the vehicle to accelerate, decelerate, and maintain different speeds.
Optimizing propulsion drive systems is essential for achieving various performance objectives, including efficiency and enhanced drivability. However, the complexity of these systems, with numerous interconnected components and intricate interactions, presents significant challenges for manufacturers and engineers [11]. Traditional design, testing, and analysis approaches may need to address these challenges comprehensively.

This research aims to delve into the applications of DT technology for enhancing propulsion drive systems within the automotive sector. The objective is to explore how DT technology can address the challenges and complexities associated with propulsion systems, ultimately leading to improved vehicle performance, efficiency, and reliability. Specifically, in this study, an exploration is conducted into the diverse applications of DT technology within propulsion drive systems, encompassing its potential for predictive maintenance, performance optimization, and energy efficiency augmentation. The investigation encompasses a comprehensive overview of case studies and instances wherein DTs have notably propelled advancements in propulsion systems. Furthermore, this research delves into the recognition of prospective hurdles and constraints that may arise during the practical integration of DT technology into real-world scenarios for propulsion drive systems.

By shedding light on the capabilities and potential of DT technology in the context of propulsion systems, this research aims to contribute to a deeper understanding of how the automotive industry can leverage this innovative approach to drive performance improvements, streamline development processes, and embrace a more data-driven and efficient future.

The manuscript is organized as follows. In the subsequent sections of this article, we will delve into the fundamental principles of DT technology and its historical evolution and explore the various facets of propulsion drive systems and the complexities they entail. By systematically examining relevant literature and case studies, we will illuminate how DTs are already making a difference in enhancing propulsion systems’ design, operation, and maintenance.

2. DT Technology: Fundamentals and Evolution

A DT represents a virtual counterpart of a physical object, system, or process. It is a dynamic and interactive digital model replicating real-world entities’ behavior, characteristics, and interactions [12]. Not only does this technology enable a bidirectional flow of information, exchanging data between the physical entity and its digital counterpart in real time, but also new ideas might be introduced. A DT goes beyond mere simulation; it continuously captures and updates data from the physical world, providing insights into its performance, status, and behavior [13]. The DT evolves alongside its physical counterpart, reflecting changes and responding to inputs like a real-world object.

As presented in Figure 1, the core components of a DT include the following [14]:

1. The DT represents the physical object, system, or process. In the automotive context, this could be a vehicle, its propulsion drive system, or specific components like the engine and transmission.
2. The virtual model is the digital representation of the physical entity. It includes geometry, attributes, behavior, and interactions. The accuracy and fidelity of the virtual model are critical for achieving meaningful insights.
3. DTs rely on data collected from sensors embedded within the physical entity. These sensors monitor temperature, pressure, vibration, and performance metrics.
4. The DT and the physical entity are connected through data networks, enabling real-time data exchange and communication.
5. Advanced analytics, machine learning algorithms, and simulations process sensor data and model interactions within the virtual counterpart.
6. Visualization tools visually represent the DT’s behavior, making complex data understandable to users.
The concept of DTs has its roots in aerospace and manufacturing. NASA pioneered DTs for spacecraft design and operation while manufacturing industries used them to optimize production processes [15]. Recent computing power, data analytics, and connectivity advances have propelled DT technology into new domains.

For instance, the authors in [16] present the design methodology, mathematical analysis, simulation study, and experimental validation of a DT approach for fault diagnosis distributed photovoltaic systems. In [17], the authors introduce a technique where the online diagnostic analysis of power electronic converters utilizing real-time, probabilistic DT technology is proposed. The authors in [18] offer an approach based on the Internet of Things and the DT of the cyber-physical system that interacts with the control system to ensure its proper operation. In [19], the authors propose a novel methodology for predicting the remaining useful life of an offshore wind turbine power converter in a DT framework as a strategy for predictive maintenance. The authors in [20] present a new architecture and its associated supporting implementation technologies in the DT framework and its application of online analysis of power grids. In [21], the authors introduce a DT of distribution power transformers for real-time monitoring of medium voltage from low voltage measurements.

Nonetheless, the DT has attracted particular attention in the automotive industry [22,23], which is shown in Figure 2.
DTs are becoming increasingly relevant in the automotive sector due to their potential to address challenges at various stages of a vehicle’s lifecycle. In the design phase, virtual prototyping and testing via DTs enable engineers to identify issues before physical prototypes are built [24]. During manufacturing, DTs optimize production processes, predict equipment failures, and reduce downtime [25]. In the operational phase, DTs provide real-time insights into a vehicle’s performance, enabling predictive maintenance, optimizing fuel efficiency, and enhancing safety [26].

In general, there can be highlighted numerous benefits of the usage of DTs in domestic and industrial applications:

- Predictive maintenance [27];
- Performance optimization [28];
- Efficient design and development [29];
- Data-driven decisions [30,31];
- Improved safety [32].

DTs allow rapid prototyping, testing, and iteration, reducing design time and cost. Real-time insights enable engineers to fine-tune propulsion systems for optimal efficiency and power delivery. DTs can predict and prevent breakdowns by monitoring components’ health, reducing maintenance costs and vehicle downtime. Real-time data from DTs empower manufacturers to make informed decisions, from production to operations. Monitoring and analyzing real-time data can enhance vehicle safety, prevent accidents, and aid in designing safer vehicles.

At the same time, there are several practical challenges:

- Computational demands [33];
- Data integration [34];
- Accuracy and fidelity [35];
- Privacy and security [36];
- Validation and calibration [37].

It can be complex to gather and integrate data from various sources and sensors and to integrate them into a coherent DT. The accuracy of the virtual model is crucial; any discrepancies between the DT and the physical entity can lead to misleading insights [38]. Handling sensitive vehicle data raises concerns about privacy and cybersecurity. Running real-time simulations and analytics requires significant computational resources. Ensuring that the DT accurately reflects real-world behavior can be challenging. Table 1 shows the strengths, weaknesses, opportunities, and threats of using DT in the automotive industry.
Table 1. SWOT analysis about using DT technology in the automotive industry.

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<th>Description</th>
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<tr>
<td><strong>Strengths</strong></td>
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<tr>
<td>Efficient Design and Development: DTs allow for rapid prototyping, testing, and iteration, reducing design time and cost.</td>
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<td>Performance Optimization: Real-time insights from DTs enable engineers to fine-tune propulsion systems for optimal efficiency and power delivery.</td>
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<td>Predictive Maintenance: DTs can predict and prevent breakdowns by monitoring components’ health, reducing maintenance costs and vehicle downtime.</td>
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<tr>
<td>Data-Driven Decisions: Real-time data from DTs empower manufacturers to make informed decisions, from production to operations.</td>
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<td>Improved Safety: Monitoring and analyzing real-time data can enhance vehicle safety, prevent accidents, and aid in designing safer vehicles.</td>
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<th><strong>Weaknesses</strong></th>
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<tr>
<td>Data Integration: Gathering and integrating data from various sources and sensors into a coherent DT can be complex.</td>
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<td>Accuracy and Fidelity: The accuracy of the virtual model is crucial; any discrepancies between the DT and the physical entity can lead to misleading insights.</td>
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<td>Privacy and Security: Handling sensitive vehicle data raises concerns about privacy and cybersecurity.</td>
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<tr>
<td>Computational Demands: Running real-time simulations and analytics within DTs requires significant computational resources.</td>
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<tr>
<td>Validation and Calibration: Ensuring that the DT accurately reflects real-world behavior can be challenging.</td>
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<th><strong>Opportunities</strong></th>
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<td>Broader Industry Application: The concept of DTs originated in aerospace and manufacturing, indicating potential applications beyond the automotive sector.</td>
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<tr>
<td>Technological Advancements: Ongoing advances in computing power, data analytics, and connectivity can expand the capabilities of DT technology.</td>
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<td>Innovation in Fault Diagnosis: Opportunities exist for developing advanced fault diagnosis techniques using DTs, enhancing system reliability and maintenance efficiency.</td>
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<th><strong>Threats</strong></th>
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<td>Complex Implementation: The complexities of integrating DTs into existing automotive processes and systems could slow down widespread adoption.</td>
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<td>Lack of Standardization: A lack of standardized approaches and frameworks for DT implementation could lead to compatibility issues and hinder collaboration.</td>
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<tr>
<td>Competitive Landscape: As DT adoption grows, competition among automotive companies and technology providers in implementing effective DT strategies could intensify.</td>
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Furthermore, Table 2 shows the pros and cons of different DT development methods. In conclusion, DT technology represents a groundbreaking approach with the potential to revolutionize the automotive industry. By creating a dynamic virtual counterpart of physical entities, DTs offer real-time insights, enabling efficient design, performance optimization, predictive maintenance, and more. While benefits are promising, data integration, accuracy, security, and validation challenges must be addressed for the technology’s successful implementation. As the automotive sector continues to evolve, DTs stand poised to play a pivotal role in shaping their future.
Table 2. Subdivision of DT methods.

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<th>DT Method</th>
<th>Advantages</th>
<th>Shortcomings</th>
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<tr>
<td>Data-Driven DTs</td>
<td>- Utilizes real-world data for accurate modeling.</td>
<td>- Highly dependent on data availability and quality.</td>
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<td>- Suitable for predictive maintenance applications.</td>
<td>- May struggle to capture complex physical behaviors.</td>
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<td></td>
<td>- Enables anomaly detection and predictive analytics.</td>
<td>- Requires extensive computational resources.</td>
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<td>Physics-Based DTs</td>
<td>- Offers a deep understanding of system dynamics.</td>
<td>- Relies on comprehensive and accurate physics models.</td>
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<td>- Suitable for complex simulations and virtual testing.</td>
<td>- Development and validation can be time-consuming.</td>
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<td></td>
<td>- Provides transparency in modeling physical phenomena.</td>
<td>- Complexity can limit real-time capabilities.</td>
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<td></td>
<td>- Supports optimization of system performance.</td>
<td>- May require specialized expertise for modeling.</td>
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<tr>
<td>Hybrid DTs</td>
<td>- Combines the strengths of data-driven and physics-based models.</td>
<td>- Integration can be complex and challenging.</td>
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<td>- Offers versatility and adaptability to different scenarios.</td>
<td>- Balancing model components may require effort.</td>
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<td></td>
<td>- Enables accurate modeling using limited data.</td>
<td>- Development and maintenance can be resource-intensive.</td>
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<td></td>
<td>- Suitable for complex systems with uncertain dynamics.</td>
<td>- Proper validation of hybrid models can be tricky.</td>
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3. Propulsion Drive Systems in the Automotive Sector

The automotive sector is undergoing a seismic shift, marked by the rapid advancement of propulsion drive systems [39]. At the heart of every vehicle’s performance lies its propulsion system, a complex assemblage of components working harmoniously to convert energy into motion [40]. This article delves into the intricacies of propulsion drive systems, highlighting their features, complexities, interactions, and challenges in optimizing their performance.

Propulsion drive systems encompass the mechanisms that generate and transmit power to propel a vehicle [41]. Traditionally, internal combustion engines (ICE) have been the mainstay of propulsion. However, the surge towards sustainability and energy efficiency has led to the proliferation of electric propulsion systems, particularly electric motors [42].

Figure 3 presents a view of the main components of the electric vehicle propulsion drive system. Electric motors are at the forefront of the electric vehicle revolution, functioning as the primary source of propulsion. These motors convert electrical energy from the battery into mechanical energy, propelling the vehicle [43]. Electric motors boast simplicity, compactness, and instantaneous torque delivery, unlike their ICE counterparts, enhancing driving dynamics and efficiency [44]. Complementing the electric motor or internal combustion engine are transmissions, responsible for transmitting power to the wheels and optimizing performance across various driving conditions. Transmissions enable the vehicle to transition through gears smoothly, adjusting torque and speed for optimal efficiency and power delivery [45].

Within propulsion systems, an array of components, such as power inverter, differentials, and clutch systems (in the case of conventional transmissions), further contribute to the system’s functionality. These components ensure torque distribution, manage power flow, and facilitate smooth transitions between different modes of operation. The complexity of propulsion systems arises from the intricate interactions among their components.
Electric propulsion systems, for instance, require sophisticated power electronics to manage the energy flow between the battery and the electric motor [46]. Thermal management systems are critical to prevent overheating, optimize efficiency, and prolong the lifespan of components.

Optimizing propulsion drive systems hinges on key performance metrics, each influencing the vehicle’s overall efficiency, power delivery, and environmental impact. Some of the critical metrics include:

1. Efficiency [48,49]: The efficiency of propulsion systems determines how effectively they convert energy into motion. Electric propulsion systems, particularly electric motors, often exhibit higher efficiency than traditional internal combustion engines due to fewer energy conversion steps.

2. Power-to-Weight Ratio [50,51]: This metric reflects the power generated by the propulsion system relative to the vehicle’s weight. Higher power-to-weight ratios lead to better acceleration and overall performance.

3. Energy Consumption [52]: Energy consumption of propulsion systems directly impacts the vehicle’s range and operational costs. Electric propulsion systems tend to be more energy-efficient, contributing to longer electric vehicle ranges.

4. Emissions [53]: For internal combustion engines, emissions play a crucial role in environmental impact. Efforts to reduce emissions while maintaining performance are central to propulsion system optimization.

5. Reliability and Durability [54]: Propulsion systems must be reliable and durable, minimizing maintenance requirements and enhancing the vehicle’s lifespan.

While DT has the potential to be utilized across various electric propulsion drive elements, it is evident from Figure 4 that transmission and battery are the most widely adopted ones. Figure 4 presents search results for publications related to DT components in automotive applications.

Figure 3. Main components of electric propulsion drive system.

Conventional powertrains’ interactions between engines and transmissions are intricate, affecting power distribution, fuel efficiency, and vehicle responsiveness [47]. Achieving seamless transitions between gears necessitates meticulous engineering to avoid power loss and improve overall driving comfort.

Main components of electric propulsion drive system.

- **Battery**: Store energy, High-capacity power source, Chemical energy to electrical energy conversion, Provides energy for propulsion, Enables electric operation.
- **Inverter**: Controls motor speed and torque, Variable frequency and voltage output, Efficient power distribution to the motor, Enables smooth control and regenerative braking.
- **Electric Motor**: Converts electrical energy to mechanical energy, Generates torque and rotational motion, Drives the vehicle’s wheels, Enables efficient and direct propulsion.
- **Transmission**: Matches motor performance to load requirements, Optimizes power transfer to wheels/protractors.
Challenges in optimizing propulsion drive systems are multifaceted. Integrating components within the system, balancing performance with efficiency, and addressing thermal management and energy storage pose significant hurdles. Battery technology advancements and infrastructure development are vital for electric propulsion systems to address range anxiety and charging concerns [55].

In conclusion, propulsion drive systems are the beating heart of modern vehicles, evolving to meet the demands of efficiency, performance, and sustainability. Electric propulsion systems are gaining prominence for their simplicity and eco-friendliness, while conventional powertrains continue to improve through meticulous engineering and innovation. The intricate web of components, interactions, and metrics defines the landscape of propulsion systems, and navigating this complexity is essential for unlocking their full potential in shaping the future of transportation.

4. Applications of DTs for Electric Propulsion Drive Systems: Pioneering Efficiency and Sustainability

The automotive landscape is profoundly transforming, with electric propulsion systems taking center stage in the quest for cleaner, more efficient transportation [56]. At the forefront of this transformation is integrating DT technology into electric propulsion drive systems, heralding a new era of performance optimization, predictive maintenance, and sustainable energy consumption. This section delves into the multifaceted applications of DTs within electric propulsion drive systems, spotlighting their role in predictive maintenance, performance optimization, energy efficiency enhancement, and emissions reduction.

4.1. Predictive Maintenance and Condition Monitoring

DTs revolutionize maintenance strategies by offering real-time insights into the condition of components within electric propulsion systems. Through embedded sensors and continuous data collection, DTs create a dynamic virtual representation that mirrors the behavior of their physical counterparts [57]. This real-time monitoring equips manufacturers and operators to detect anomalies, irregularities, and potential failures before they escalate into costly breakdowns [58].

Many cases highlight instances where DTs have prevented breakdowns and optimized maintenance schedules. In [59], there is a case study where DT was combined with deep transfer learning to detect faults in a car body-side production line. Authors in [60] address a verified DT model of life-cycle rolling bearing for fault diagnosis. In [61], a data-driven DT model is proposed for preventing incipient inter-turn short-circuit faults in permanent magnet synchronous motors. In [62], the authors outline a methodology
for monitoring and diagnosing the degradation of power electronic converters based on DTs. In [63], an approach for the early-stage degradation of fuel cells and its prediction is addressed using DT, which is tolerant to different degradation patterns and can achieve real-time degradation prediction. The authors in [64] propose a novel wind speed-sensing methodology for wind turbines based on DT technology.

Case studies serve as compelling testaments to the efficacy of DTs in predicting and preventing failures. For instance, a DT of an electric motor can monitor variables such as temperature, vibration, and power consumption. Anomalies detected in these parameters trigger alerts, allowing maintenance teams to intervene proactively, preventing motor failure and minimizing downtime [65]. Such interventions can also lead to optimized maintenance schedules, reducing operational disruptions and costs [66].

4.2. Performance Optimization and Virtual Testing

DTs offer a virtual laboratory for engineers to explore design variations, simulate scenarios, and predict performance outcomes. In electric propulsion drive systems, virtual prototyping using DTs expedites the iterative design process. Engineers can explore diverse configurations and evaluate their impact on performance metrics, narrowing down the most promising design iterations for physical implementation.

There are numerous illustrative examples of using DTs to optimize engine efficiency, transmission responsiveness, and overall drivability. For instance, in [67], a DT-based optimization procedure is presented for an ultraprecision motion system, subject to backlash and friction. The authors in [68] present a development case study of a DT for an electric motor based on an empirical performance model. In [69], the DT concept is applied to electric motors. It is used to solve general problems related to the application of electric motors in the automotive industry, such as estimating the driving torque or the rotor temperature to improve cooling control. The authors in [70] introduce how motor dielectric aging can be prevented. In [71], the authors present a DT-based optimization for optimally adjusting parameters in ultraprecision motion systems.

DTs open avenues for optimizing propulsion systems’ efficiency and responsiveness. Consider an electric propulsion system’s motor controller. Engineers can fine-tune control algorithms to maximize efficiency, torque delivery, and response to driver inputs via simulating various control strategies and motor performance scenarios using a DT. Moreover, DTs optimize transmission gearing ratios for optimal power delivery across different driving conditions, contributing to enhanced drivability and energy consumption.

4.3. Energy Efficiency Enhancement and Emissions Reduction

DTs are potent tools for energy efficiency and emission reduction. For electric propulsion systems, accurate modeling of battery behavior within DTs aids in optimizing energy usage. This includes predicting the battery state of charge, discharge rates, and overall performance under varying conditions. Accurate simulations help engineers design battery management systems that enhance efficiency, extend battery life, and minimize energy waste.

Numerous case studies showcase DTs’ role in achieving regulatory compliance and sustainability goals. For example, DTs are widely used in the oil and gas industry to enhance their operations’ productivity, efficiency, and safety while minimizing operating costs, health, and environmental risks [72]. In autonomous transportation, a DT is a promising tool as the safety and security of vehicles have obvious advantages of reducing accidents and maintaining a cautious environment for drivers and pedestrians [73]. In [74], the authors explore a potential approach based on DT that aims to achieve optimization and automation systems for energy management meeting the near-zero energy buildings through the Internet of Things and machine learning. The authors in [75] demonstrated the applications based on DTs for sustainability and vulnerability assessments that enable the next-generation risk-based inspection and maintenance framework. Smart manufacturing is also addressed in many cases [76–78].
DTs also play a pivotal role in aligning propulsion systems with regulatory and sustainability objectives. Consider the challenge of reducing emissions in internal combustion engines. Engineers can virtually explore combustion strategies, timing adjustments, and exhaust after-treatment systems by creating a DT that models combustion dynamics and emissions generation. This proactive approach enables the development of strategies to meet stringent emission standards while optimizing engine performance.

In conclusion, integrating DT technology into electric propulsion drive systems is poised to redefine automotive engineering and propel the industry toward unprecedented efficiency and sustainability. DTs provide a multifaceted toolkit for engineers to design, test, and operate propulsion systems with unmatched precision, from predictive maintenance and performance optimization to energy efficiency enhancement and emissions reduction. As the automotive sector embraces this digital transformation, the possibilities for innovation and progress are boundless, promising a future of greener, more innovative, and more efficient transportation.

5. Practical Implications of DTs for Automotive Advancement

Integrating DT technology into the automotive sector heralds a new era of possibilities, reshaping how vehicles are designed, developed, and operated. This section explores the practical implications of DTs for automotive manufacturers, designers, and engineers. It delves into how DTs expedite design iterations, reduce development time, and enhance product quality. Moreover, it identifies areas where DTs can stimulate innovation and drive transformative changes within the automotive landscape.

Numerous practical implications for automotive manufacturers, designers, and engineers can be found in the literature. The authors in [79] present a new embedded system that provides a complete set of self-driving modules, including localization, detection, prediction, planning, and control. In [80], an overview of existing inverter designs from several production vehicles across multiple manufacturers is presented from the perspective of industrial demands and future trends. An overview of additive manufacturing for automotive branches is presented in [81] to make production more sustainable and reliable. In [82], the author discusses a DT demonstrator for privacy enhancement in the automotive industry.

DTs serve as a common ground for collaboration among multidisciplinary teams. Designers, engineers, and manufacturers can collectively visualize, simulate, and assess vehicle components and systems. This collaboration fosters a shared understanding, expedites decision making, and enhances communication throughout development. DTs provide real-time insights into the behavior and performance of components and systems. This enables manufacturers and engineers to make informed decisions and identify design flaws, optimization opportunities, and potential failures early in the development cycle [83]. Traditional design cycles involve multiple iterations and physical prototypes. DTs streamline this process by enabling virtual prototyping, assessment, and refinement. Designers can explore various configurations, simulate performance outcomes, and optimize designs without the need for costly physical prototypes. Engineers can leverage DTs to develop predictive maintenance strategies. Monitoring real-time data from the DT can anticipate potential maintenance issues, allowing for timely interventions and minimizing vehicle downtime.

DTs dramatically accelerate the design iteration process. Engineers can swiftly modify and test design parameters in the virtual environment, assessing their impact on performance metrics [84]. This agility allows for rapid adaptation and refinement, reducing the time required to iterate through design alternatives. Integrating DTs shortens the development lifecycle by reducing the need for physical prototyping and testing. Simulating performance outcomes and conducting virtual tests eliminates time-consuming phases, leading to faster time-to-market for new vehicle models and innovations. DTs contribute to higher product quality by facilitating thorough testing and optimization before physical
manufacturing [85]. Design flaws, inconsistencies, or inefficiencies are identified early in development, minimizing the risk of costly recalls or post-launch modifications.

DTs facilitate the design of integrated vehicular systems. Rather than treating components in isolation, engineers can optimize the interactions between propulsion, chassis, and connectivity systems, leading to holistic vehicle performance and efficiency improvements [86]. With DTs, engineers can explore the effects of different materials on performance, durability, and weight. This encourages innovation in materials selection, enabling the development of lighter, more efficient, and sustainable vehicle components. DTs would allow manufacturers to create tailored vehicle configurations based on customer preferences and needs. Manufacturers can refine designs by analyzing real-world data collected from vehicles in operation to align with customer expectations and usage patterns [87]. As DTs collect data from connected vehicles, machine-learning algorithms can identify patterns, anomalies, and optimization opportunities [88]. Manufacturers can then apply these insights to drive continuous innovation, resulting in evolving and improving vehicles over time.

In conclusion, the practical implications of DTs for the automotive industry are profound and far-reaching. From streamlining design iterations and reducing development time to enhancing product quality and fostering innovation, DTs offer a paradigm shift in how vehicles are conceived, developed, and operated. As manufacturers, designers, and engineers embrace this transformative technology, the automotive landscape stands poised for unprecedented advancements, efficiency gains, and a future where innovation flourishes like never before.

6. Challenges and Future Directions

As DT technology continues to reshape EV industries, its integration into propulsion drive systems within the automotive sector is poised to unlock transformative potential [89,90]. However, this journey has its share of challenges [91–95]. This section delves into the intricacies of implementing DTs for propulsion systems, discussing hurdles such as data integration, accuracy, computational demands, and real-world validation. Looking forward, it also speculates on the future of DT technology in the automotive industry and the potential advancements that lie on the horizon.

6.1. Exploration of Challenges in Implementing DTs for Propulsion Drive Systems

One of the primary challenges in implementing DTs for propulsion systems is the seamless integration of data from various sources [96]. Propulsion systems are comprised of many components, each generating a data stream. Ensuring these data streams converge into a coherent and meaningful DT can be complex. In addition, the effectiveness of a DT hinges on the accuracy of its virtual representation. Achieving accuracy entails a comprehensive understanding of the physical system’s behavior. Deviations between the DT and the physical system can lead to inaccurate predictions and insights. At the same time, creating and operating a DT entails substantial computational demands [97]. Real-time monitoring, data processing, simulation, and analysis necessitate robust computing infrastructure [98]. This can pose challenges regarding resource allocation, scalability, and managing computational costs. The success of a DT is contingent on its ability to replicate real-world behavior faithfully. Validating a DT’s accuracy against the physical system involves extensive testing and validation. Ensuring that predictions generated by the DT align with real-world outcomes requires meticulous verification.

6.2. Discussion of Data Integration, Accuracy, Computational Demands, and Real-World Validation

Successful data integration requires a standardized data collection, storage, and transmission approach. Ensuring compatibility among different data sources and formats is essential for creating a holistic DT that accurately represents the propulsion system. Achieving accuracy entails a comprehensive understanding of the physical system’s behavior.
Accurate modeling of components' characteristics, interactions, and responses to various inputs is crucial for generating reliable insights [99]. Also, meeting the computational demands of DTs involves a trade-off between processing power, scalability, and resource allocation. Cloud computing, edge computing, and distributed computing models are potential solutions to manage computational requirements effectively [100]. Rigorous real-world validation involves subjecting the DT to various operating conditions and scenarios that mirror real-world situations. This process verifies the accuracy of the DT’s predictions and its ability to respond accurately to changes in the physical system.

6.3. Speculation on the Future of DT Technology in the Automotive Industry and Potential Advancements

The potential of DT technology in the automotive industry is vast, promising a future characterized by innovation and efficiency. As technology evolves, several potential advancements could shape the trajectory of DT integration:

1. Advanced Machine Learning [101]: Integrating advanced machine learning algorithms within DTs can enhance their predictive capabilities. Real-time anomaly detection, fault prediction, and prescriptive maintenance recommendations can empower manufacturers to optimize vehicle performance.

2. Holistic Ecosystem Integration [102]: Future DTs may encompass the entire vehicular ecosystem, extending beyond propulsion systems to include chassis, sensors, communication networks, and road infrastructure. This holistic approach could comprehensively understand vehicle behavior in diverse contexts.

3. DT Interoperability [103]: The development of standards for DT interoperability could facilitate seamless collaboration and information exchange across various stakeholders in the automotive value chain. This could lead to improved decision-making, faster innovation cycles, and enhanced operational efficiency.

4. Autonomous System Collaboration [104,105]: DTs could play a pivotal role in developing and testing autonomous driving systems. They could serve as a safe and controlled environment for simulating complex scenarios and validating the behavior of autonomous vehicles.

In conclusion, integrating DT technology into propulsion drive systems promises to reshape the automotive industry. However, data integration, accuracy, computational demands, and real-world validation must be navigated thoughtfully. The future of DT technology in the automotive industry holds immense potential for transformation, with advancements in machine learning, ecosystem integration, interoperability, and collaboration with autonomous systems offering a glimpse into an exciting era of innovation and progress.

7. Conclusions and Discussion

In conclusion, the integration of Digital Twin (DT) technology into the automotive industry represents a major shift in how vehicles are conceptualized, manufactured, and operated. This revolutionary approach provides real-time insights, and it changes various aspects of propulsion drive systems. DTs hold the promise of forecast refinement, better performance, increased energy efficiency, and reduced air pollution, all while fostering innovation and cross-sector collaboration.

The practical implications of DT are profound. Automakers, manufacturers, and engineers are empowered to optimize rework, reduce production time, improve product quality, and drive innovation. Virtual prototyping enabled by DT accelerates the process, allowing rapid optimization and optimization without the need for expensive physical prototypes, providing real-time insights that facilitate informed decision-making from system improvements to maintenance options. DTs encourage integrated vehicle design and innovation, resulting in lighter, more efficient, and sustainable products.

But the journey to full DT integration is not without challenges. Ensuring seamless integration of data from multiple sources, maintaining accuracy in virtual representations,
managing computational requirements, and verifying DT predictions against real-world results are necessarily obstacles that need to be addressed.

The potential advancements of DT technology are exciting. Advanced machine learning algorithms, holistic ecosystem integration, DT interoperability standards, and collaboration with autonomous systems are all areas that could shape the future of DT technology in the automotive industry. As the automotive sector continues to evolve, DTs stand at the forefront of innovation, poised to drive efficiency, sustainability, and a new era of automotive excellence.

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