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Review Article

Digital twins for internal combustion engines: A brief review

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Abstract. The adoption of digital twin technology in the realm of internal combustion (IC) engines has been attracting a lot of interest. This review article offers a comprehensive summary of digital twin applications and effects in the IC engine arena. Digital twins, which are virtual counterparts of real-world engines, allow for real-time monitoring, diagnostics, and predictive modeling, resulting in improved design, development, and operating efficiency. This abstract digs into the creation of a full virtual depiction of IC engines using data-driven models, physics-based simulations, and IoT sensor data. The study looks at how digital twins can potentially be used throughout the engine's lifespan, including design validation, performance optimization, and condition-based maintenance. This paper emphasizes the critical role of digital twins in revolutionizing IC engine operations, resulting in enhanced reliability, decreased downtime, and enhanced emissions control through a methodical analysis of significant case studies and innovations.

Keywords: Digital twins; IC engine; Predictive maintenance; Sustainability; Reliability

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1. Introduction

The rapid development of digital technology has brought about dramatic shifts across many sectors, especially in the world of IC engines. The incorporation of digital twin technology into the realm of IC engines has created new opportunities for innovation and optimization. A digital twin is a virtual clone of a physical thing, in this case, an IC engine, which operates beside its physical counterpart (Xu et al., 2021). As a result of this symbiotic relationship, real-time data synchronization is possible, enabling continual monitoring, evaluation, and simulation. IC engines are critical in transport, energy production, and manufacturing. However, the requirement for greater economy, lower emissions, and increased performance mandates the use of advanced engineering, creation, and operational management techniques (Lim et al., 2020)(Stoumpos et al., 2020). Digital twins alleviate these kinds of problems by offering a full platform for holistic engine analysis, allowing researchers to acquire insights into complex behaviors and interconnections that are often complex or expensive to investigate experimentally. The essential ideas of digital twin technology as employed in IC engines are addressed in this review study. It looks into the critical role that data integration, sensor networks, and simulation approaches play in producing a dynamic digital representation of an IC engine. The sections that follow go into the many uses of digital twins, which range from design validation to real-time diagnosis, performance optimization, and predictive maintenance. Furthermore, the study analyses current issues and suggests prospects in this developing discipline. In essence, this analysis highlights digital twins' transformational potential in revolutionizing IC engine-related operations, opening the way for a more effective, dependable, and sustainable engine technology.

2. Digital Twins: Concepts and Fundamentals

The advent of digital twin technology has brought about an entirely novel phase of innovation in a variety of sectors, particularly in the realm of IC engines. The digital twin serves as a virtual counterpart of a physical entity, whether it's a machine, a process, or an entire system. Digital cloning in the context of IC engines entails generating a virtual replica that accurately represents the geometry, dynamics, and behavior of the motor in the digital realm (Cheng et al., 2020). This revolutionary approach goes beyond mere replication by combining real-time data from a wide range of sensors with advanced simulation models to generate a dynamic, realistic, and practical picture of engine function (Tao et al., 2019). The aggregation of data from different sources is essential to the digital twin idea. Consolidation of real-time data from sensors, activity records, performance measurements, and ambient variables

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creates a full, real-time perspective of engine operation. This multimodal method assures that the digital duplicate is a constantly evolving model while the engine operates (Stoumpos et al., 2020)(M. Liu et al., 2021)(Singh et al., 2021). The digital twin is built on physics-based and model-based simulation. The digital twin replicates the complex operations that occur inside an engine employing the fundamentals of thermodynamics, combustion kinetics, fluid dynamics, and heat transfer equations (Zaccaria et al., 2018). This physics-based technique allows engineers to get a thorough understanding of engine performance under an array of operating circumstances. As a result, reliable predictions and optimization techniques can be developed, enhancing effectiveness and reducing emissions (Söderäng et al., 2022)(Tsitsilonis et al., 2023). A typical schematic of a digital twin for an IC engine is depicted in **Figure 1**.

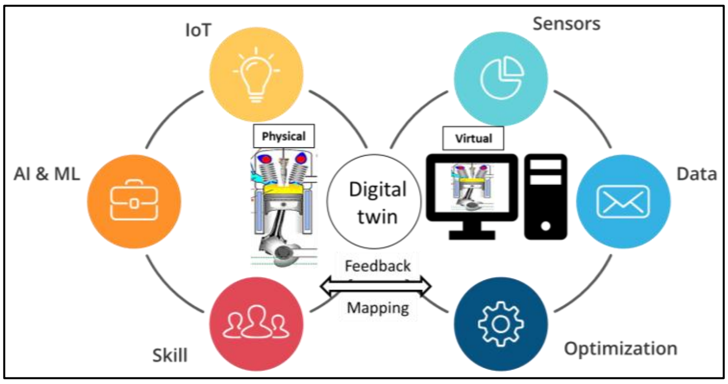

Figure 1. Schematics for digital twin of IC engine

The ability to track and analyze digital twins in real-time is critical to realizing their full potential. Real-time evaluation of engine conditions is possible because of the dynamic synchronization of real-world data with digital twin simulation. Deviations between expected and actual behavior are promptly discovered, enabling the early discovery of potential abnormalities and failures. This preventive maintenance technique minimizes unplanned downtime and increases operational reliability (Lim et al., 2020)(Xiong et al., 2021). The ability of digital twins to learn iteratively is a distinguishing feature. As the engine works and collects data, this information is given back to a digital copy, enriching and improving its comprehension and accuracy. The digital twin gets increasingly sensitive to engine behavior over time, allowing for more accurate forecasts and better decision-making. The value proposition of digital copy is built on this iterative learning and refinement loop (Xiong & Wang, 2022)(Singh et al., 2022).

To summarize, grasping the concepts and principles of digital twins is critical to realizing their promise for IC engines. Engineers and operators may revolutionize development, design, and implementation models by combining varied data sources, physics-based modeling, real-time monitoring, and iterative learning. The internal combustion engine will reap the rewards of greater efficiency, dependability, and reduced environmental impact as a result of this integration. As digital twin technology advances, its revolutionary impact on IC engine performance has the potential to redefine industry norms and expectations.

3. Digital Twins in IC Engine Design and Development

The employment of the digital twin encompasses its transformative impact early in the IC design and development process. The employment of digital twins at this stage opens up a new dimension of accuracy, efficiency, and innovation.

- Virtual prototyping and iterative design: Researchers may explore and refine designs in a virtual playground before building a physical prototype using digital twins. This feature expedites the design phase by allowing for rapid iteration and modification based on simulation performance findings. The investigators may experiment with various settings, setups, and materials to optimize efficiency and performance (Sørensen et al., 2022)(Y. Wu et al., 2022).
- Performance prediction and optimization: By merging physically-based modeling with real-time sensor data, the digital twins provide an unprecedented picture of engine performance under different operating conditions. This allows researchers to simulate and optimize performance parameters such as fuel efficiency, power, and emissions. Iterative testing in a virtual environment identifies design options that provide the best compromise between performance, efficiency, and environmental impact (Xu et al., 2021)(Söderäng et al., 2022).
- Emissions strategy: In an era of stringent emissions laws, digital twins can play an important role in creating and enhancing emissions control techniques. Designers can test the performance of various emission reduction strategies by simulating combustion and governing emissions in a virtual replica. This enables engines to be designed to comply with or exceed emissions limits while remaining as efficient as possible (Xu et al., 2022)(Zhao et al., 2021).
- Sensitivity and durability structural analysis: A digital twin enables engineers to undertake sensitivity analysis and investigate how design parameter changes affect performance. This aids in identifying crucial design aspects that have a major impact on performance or dependability. This data can be employed to make sound design decisions that maintain consistent engine operation under varying conditions (Söderäng et al., 2022)(Qi et al., 2021).
- Save time and development costs: Integrating digital twins substantially decreases IC engine development time. By optimizing designs in practice, fewer actual prototypes are required, saving time and money. Dual digital development's

iterative nature also makes the design process more efficient, enabling faster validation and refinement (Lim et al., 2020)(Tsitsilonis et al., 2023).

- Personalization and personalized solutions: Digital twins allow for easier-to-design IC engine solutions that are tailored to specific applications. Engineers can modify engine settings to satisfy the specific needs of various industries, vehicles, or power generation systems. This level of personalization guarantees that the tools produced are optimized for the tasks at hand.

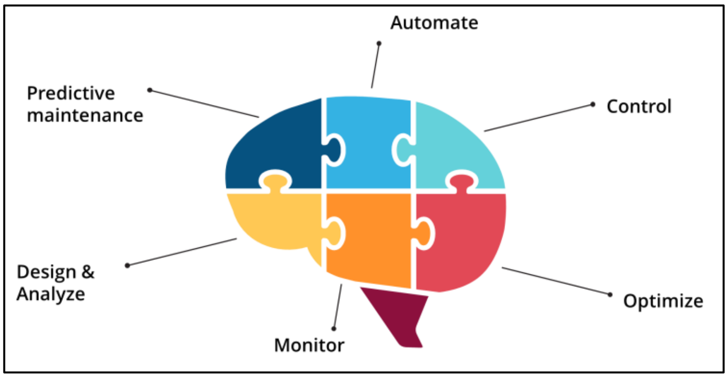

Figure 2. Digital twins for IC engines

In essence, as depicted in **Figure 2**, the utilization of digital twins in IC engine design and development is causing a paradigm shift regarding the way engines are developed, refined, and implemented. Digital twins enable engineers to create engines that are not just efficient but also environmentally friendly through the use of virtual prototyping, performance forecasting, emissions monitoring, sensitivity analysis, and customization. & adapted to unique requirements. As this technology advances, the bounds of innovation in IC engine design are constantly pushed, offering a future in which engines are designed rather than produced.

4. Real-time Monitoring and Diagnostics

The debut of digital twin technology in the realm of IC engines is ushering in an entirely novel phase in real-time monitoring and testing. The dynamic merging of real data and virtual simulations is at the heart of this accomplishment, allowing for a complete and fast assessment of the engine's state and performance.

- Predictive insight through real-time data integration: Digital twins have transformed how an IC engine is monitored while running. The digital replica provides a synchronous depiction that simulates the engine's functioning in real time by flawlessly integrating data from numerous sensors. It provides engineers and operators with instant access to crucial information including temperature, pressure, efficiency of combustion, and emissions. Any discrepancies between actual and simulated processes are promptly identified, suggesting potential issues or performance anomalies (Stoumpos et al., 2020)(Xiong & Wang, 2022)(Lo et al., 2021).
- Anomaly detection and predictive analysis: The real-time nature of digital twins is critical for discovering anomalies that may go undetected until maintenance or an outage occurs. Digital twins can detect even the smallest differences by constantly comparing real data to predictions from virtual models. This early detection of abnormalities enables maintenance staff to step in and address issues before they become critical. Furthermore, the integration of historical data and ML algorithms provides predictability to digital twins, allowing them to forecast probable errors according to patterns and trends (Xu et al., 2021)(Tsitsilonis et al., 2023).
- Condition monitoring and health assessment: The digital twin delivers a complete view of the engine's state as well as relevant information about the engine's condition to the user. Digital twins enable researchers to assess engine performance by providing real-time data and simulated performance (Jiang et al., 2022). This enables educated decisions about maintenance routines, component replacement, and performance optimization strategies to be undertaken. Furthermore, remote engine monitoring allows for more effective troubleshooting and decision-making, particularly for engines placed in remote or hazardous areas (Stoumpos & Theotokatos, 2022).
- Improve data decision-making: By combining real-time monitoring and diagnostics with digital twins, operators, and engineers may arrive at more informed decisions. Instead of depending on reactive measurements, digital twin data enables informed decisions that can improve efficiency, prolong component life, and reduce downtime (Z. Wu & Li, 2021). This transition to proactive decision-making shifts maintenance techniques from scheduled to condition-based operations, optimizing resource utilization and lowering operational costs (Li et al., 2022)(Granacher et al., 2022).

Essentially, employing digital twins to combine continuous monitoring and diagnostics enhanced the IC engine operating model. Digital twins allow stakeholders to dynamically monitor, analyze, and optimize engine performance by giving immediate, precise, and predictive knowledge of engine performance. The shift from reactive service to proactive, data-driven tactics not only increases reliability and efficiency but also illustrates the digital dual model's potential to revolutionize the future of IC engine control.

5. Performance Optimization through Digital Twins

The Digital Twins have heralded a new phase of IC efficiency optimization, offering previously untapped information on how to optimize efficiency, capacity, and performance as a whole. Researchers can adjust engine characteristics and operating settings employing the capabilities of digital depiction and real-time data assimilation.

- Virtual testing and iterative tweaking: Digital clones enable engineers to undertake risk-free virtual tests. The engine reaction may be easily analyzed by altering several settings in the digital dual system, such as ignition timing, the fuel injection rate, and air-fuel ratio. any physical change. This iterative improvement approach aids in determining the best settings for improving fuel economy and lowering emissions (Xu et al., 2021)(Tsitsilonis et al., 2023).
- Actively improve performance: Digital twins provide predicted knowledge of how performance might be enhanced by integrating sensor data with physical-based modeling in real time. The digital twin keeps track of engine functioning and can make real-time modifications to keep it running at top performance. This proactive strategy reduces performance deterioration while optimizing operating parameters (Lim et al., 2020)(Xiong et al., 2021).
- Emissions Control and Compliance: In conjunction with efficiency, enhancing heat engine performance requires efficient emission control. Modifications in operational conditions can be predicted by the digital twin. Engineers can devise ways to reduce harmful emissions while retaining optimal engine performance in the face of stringent environmental requirements (Zhao et al., 2021).
- Adaptive learning and AI integration: Digital twins possess the capacity for development into intelligent systems that can adapt to changing conditions. The digital twin may gain insight from historical data and automatically optimize engine performance by combining machine learning and AI. Even in changing operating situations, this adaptive technique assures consistent optimization (Söderäng et al., 2022)(Tsitsilonis et al., 2023).
- Faster development cycle and lower cost: Traditional engine optimization necessitates significant physical modification and testing, which consumes time and money. By allowing rapid virtual testing, digital twins accelerate the optimization process. This reduces development cycles and results in substantial cost savings, making innovation more accessible.

In short, digital twins have revolutionized heat engine efficiency optimization. These replicas provide researchers with a full set of tools for fine-tuning engines to achieve maximum efficiency, decreased emissions, and peak performance through modeling engine behavior, analyzing scenarios, response prediction, and adding adaptive learning. The importance of digital twins in defining the next phase of IC engine optimization will become clearer as technology enhances and digital twins become more complicated.

6. Condition-based Maintenance Strategies

Condition-based maintenance (CBM) solutions are being developed across sectors to increase operational efficiency and reduce downtime. Whenever applied to IC engines, these strategies attain new levels of efficacy and precision, boosted by digital twin capabilities:

- Real-time health assessment: Real-time evaluations of health are among the most amazing features of integrating digital twins in microchip engines. Deviations and deviations can be promptly recognized by regularly evaluating virtual performance estimates with real engine operating data. This real-time monitoring provides for the early detection of anomalies, possible breakdowns, or reduction in performance (Tsitsilonis et al., 2023).
- Forecasting abnormality detection: Employing effective algorithms and physics-based models, digital twins can foresee potential troubles before they appear in the physical engine. Digital twins can detect the need for prompt maintenance by analyzing data patterns and departures from expected behavior. This proactive strategy enables maintenance employees to address emergent issues as they arise, avoiding costly problems and unanticipated downtime (Aghazadeh Ardebili et al., 2023)(Ma et al., 2023).
- Optimal maintenance schedule: Conventional maintenance schedules sometimes adhere to defined intervals or utilization constraints, resulting in resource underutilization or premature part replacement. Digital twins, on the contrary, enable maintenance to be conducted precisely when it is required. Maintenance can be performed at the optimal time by analyzing actual engine running data and performance trends, optimizing component life, and avoiding inefficient operations (Abbate et al., 2022)(Z. Liu et al., 2019).
- Replace component based on state: Researchers can use the digital clone to accurately evaluate the condition of each component in an IC engine. Rather than replacing every component, digital twins can identify individual components that require repair or substitution due to wear, stress, or breakage. This targeted strategy saves not only money but also important resources by reducing unnecessary exchanges (Li et al., 2022)(Ma et al., 2023).
- Activity trend analysis: By dynamically integrating real-time operational data, digital twins provide complete IC engine performance patterns. These graphs show how different running conditions affect component wear and overall engine performance. By examining these trends, maintenance programs can be fine-tuned to ensure optimal efficiency in specific scenarios, thereby extending engine life (Y. Wu et al., 2022)(Jiang et al., 2022).
- Informed decision-making: The digital twin's plethora of information gathered and analyzed allows the maintenance crew to adopt data-driven decisions. They have an in-depth knowledge of engine behavior, allowing them to make educated decisions about maintenance procedures, spare parts stock, and resource allocation. This information-centric strategy boosts operational efficiency while lowering maintenance risk (Fuller et al., 2020)(van Dinter et al., 2022).

In conclusion, the deployment of digital twins in IC engines heralds a new era of strategic monitoring of the condition. Real-time condition evaluations, proactive identification of anomalies, optimal maintenance planning, condition-based part replacement, efficiency trend analysis, and data-driven decision-making are all provided. Data and twin technologies have elevated maintenance operations to previously unheard-of levels of precision and effectiveness. These tactics not only help to extend the life of the

IC engine, but they also help to save money, enhance dependability, and improve performance. As digital twin technology progresses, the possibility for advanced and efficient IC engine status monitoring technologies grows.

7. Challenges and future trends

7.1. Challenges

While digital twins have demonstrated significant promise to transform the landscape of internal combustion engines, they are not without problems and prospects for further development. This section explores the key obstacles in adopting digital twin power in microchip motors and offers potential future research prospects.

- Complexity and data integration: Among the most challenging assignments is merging disparate data sources into a single digital copy. Data collection from multiple sensors, records, and engine components necessitates the application of strong data integration and aggregation algorithms. Maintaining data accuracy, reliability, and real-time synchronization remains a critical challenge (Qi et al., 2021).
- Model Accuracy and Validation: The precision of the physically-based models incorporated in digital twins is important to their success. The development and refinement of such models that represent the complicated dynamics of internal combustion engines is a continuous effort. Establishing the reliability of these models against the engine's real behavior is critical for boosting the reliability of the digital twin's forecasts (Lim et al., 2020)(Lo et al., 2021).
- Scalability and complexity: The digital twin should evolve as microchip-controlled IC engines become more complex and networked. The goal is to keep the digital twin scalable while not requiring extra IT resources. The significance of combining realistic simulations with computational economics cannot be emphasized (Singh et al., 2021)(Haag & Anderl, 2018).
- Sensor reliability and maintenance: For precise depiction, digital twins rely considerably on real-time data from sensors. It is critical to ensure the long-term reliability and functionality of these sensors. Corrections of sensor faults, calibration mistakes, and maintenance requirements must be performed to preserve the accuracy of the digital twin's predictions (Stoumpos et al., 2020)(van Dinter et al., 2022)(Yu et al., 2021).
- Privacy and Security: The digital twin integration involves the transmission and storage of sensitive operational data. Ensuring data protection, data protection and regulatory compliance is essential. Strong cybersecurity measures should be in place to protect against potential data breaches or unauthorized use (Akbarian et al., 2021)(Varghese et al., 2022).

7.2. Future direction

In the future, the development of digital twins brings exciting opportunities for IC engines:

- Integrating AI and machine learning: Employing AI and ML approaches when combined with a digital twin may improve predictability. AI algorithms can enhance the accuracy of predictions and provide significant insights into optimal engine performance by learning from historical data (Aghazadeh Ardebili et al., 2023)(Yu et al., 2021).
- Full lifecycle management: Digital copies can have a consequence that extends beyond the development and implementation phases to the full engine lifecycle. From original design and prototype to production, operations, and post-processing, digital twins can give full insights for decision-making at all stages (Granacher et al., 2022)(Yu et al., 2021).
- Digital Twin Ecosystem: While diverse stakeholders, including manufacturers to operators, join a shared digital twin, collaborative ecosystems might develop. This method has a chance to improve group understanding, optimize care strategies, and promote innovation (Jianfeng et al., 2022)(Pantelidakis et al., 2022).
- Virtual Testing and Optimization: As processing power rises, digital twins can be used to facilitate large-scale virtual experimentation and optimization. This might eliminate the need for costly physical prototypes, accelerate innovation cycles, and result in more efficient IC engines (Xu et al., 2021)(Zhao et al., 2021).

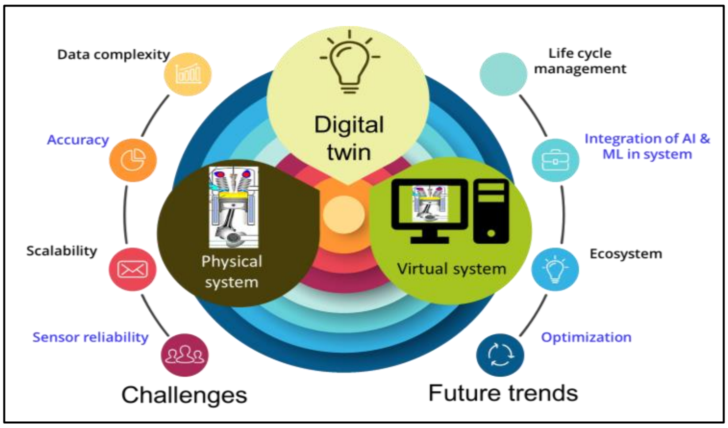

Figure 3. Challenges and future trends

To summarize, although many problems remain, the creation of digital twins for heat engines appears to be encouraging. The IC engine industry could capitalize on the full potential of digital twins by tackling the challenges of data integration, enhancing model accuracy, and embracing new technologies. digital. The digital twins are ready to transform microchip-based IC engines into the smart, adaptable, and efficient power plants of the future as they overcome these difficulties and explore future avenues.

8. Conclusion

The integration of digital twin technology into the internal combustion engine (IC) industry has certainly changed design, development, and operating practices. This review highlights the power of digital twins to enable real-time monitoring, diagnostics, and predictive analytics using virtual replicas of real tools. By combining data-driven models, physics-based simulations, and IoT sensor data, comprehensive digital representations of IC engines have been created. These virtual colleagues improve decision-making, reduce potential errors, and improve work efficiency. As the industry evolves, digital twins promise greater reliability, shorter downtime, and more advanced emissions control.

In short, the digital twins have gone beyond theory and shaped the landscape of the internal combustion engine. Seamless integration of real data and virtual simulation drives the industry towards efficiency, reliability, and sustainability. This transformative journey of the digital twin in the internal combustion engine offers an opportunity to redefine future engine technologies and their role in a dynamic world.

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