International Research Journal of Multidisciplinary Scope (IRJMS), 2024; 5(2): 596-610

Review Article | ISSN (O): 2582-631X DOI: 10.47857/irjms.2024.v05i02.0586

Digital Twin in Fluid Power: Review- Technology Trends

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Abstract

The Digital Twin (DT) is the most modern technology in Industry 4.0, which combines digital and physical components, accurate visualization, and multifaceted perception to represent the digital-physical world in real-time. The use of simulation, monitoring, optimized performance, and projection are crucial and increasingly popular, particularly in the field of industrial automation. Fluid Power Application (FPA) is an essential industrial automation technology that offers accurate monitoring, immense power, flexibility, reliability, cost-effectiveness, and seamless compatibility with pre-existing automated systems through the utilization of hydraulic and pneumatic power. Nevertheless, certain technological elements and emergent DT technology in fluid power systems have not been extensively explored. Based on the conception and constituents addressed in a companion review paper (1), this paper looks into various technologies that allow the seamless integration of both physical and digital representations in diversified FPAs. This article intends to thoroughly examine the crucial role of technological enablers in the successful implementation of digital twin. The paper provides an in-depth review of the technological enablers that support DT, specifically focusing on software used for the simulation of FPA and programmable logic controllers (PLCs) with the accompanying software. This review paper enhances the academic discourse by emphasizing different emerging technologies and acts as a catalyst for DT in current investigation efforts and breakthroughs in FPAs.

Keywords: Digital Twin, Emerging Technologies, Fluid Power Applications, PLC, Simulation Software, Technological Enablers.

Introduction

Implications and contributions statement

This extensive review of the digital twin in fluid power applications promotes scholarly and industry investigation. This study improves scholarly understanding of the digital twin by filling in information gaps and creating a basis for fluid power research. Identifying emerging trends enables academics as well as industry experts to embrace cutting-edge methodologies and propel technological progress. This review aims to consolidate present knowledge and promote future academic research and practical applications in the dynamic field of digital twin in fluid power applications.

Background

Fluid power (FP) systems, which include hydraulic and pneumatic systems, are essential in various industrial applications due to their ability to provide accurate control, significant amounts of power, flexibility, dependability, cost-effectiveness, and seamless integration. Despite their well-established significance, the implementation of DT technology has the ability to transform the control, examination, and optimization of FP systems (1). The digital twin is a virtual replica that is closely linked to physical systems in the real world, and it has the power to bring about significant changes in advanced technology (1). Digital twins are dynamic and synchronized with real-time sensor data, allowing for more than just virtual depiction, and providing extensive ways for interpretation. Their importance lies in their ability to adapt, resulting in significant transformations in numerous fields, such as changing the monitoring and control of complicated engineering systems like fluid power applications.

The previous review paper (1), titled "Digital Twin in Fluid Power: Reviewing Constituents", thoroughly investigated the key constituents of a DT designed for fluid power applications, which include physical representation, virtual representation, and communication frameworks. This necessitated the development of a virtual

(Received 07th February 2024; Accepted 23rd April 2024; Published 30th April 2024)

replica that closely simulates the physical system, integrating both physical and virtual representations along with a robust communication architecture. The DT not only represents information data but also facilitates remote monitoring, simulation, and prediction within the framework of the FP system. The development of the virtual replica involves complex procedures that serve as the foundation for precise simulations as well as real-time monitoring. The digital model, also known as a virtual representation, functions as a dynamic tool that enables predictive analysis and optimal system adaptations. The communication framework plays an equally important role in coordinating a seamless interaction of data between the physical and virtual worlds (1). The assurance of continuous synchronization allows for ongoing feedback loops, facilitating flexible and dynamic reactions. The complex interaction between different elements not only demonstrates the advanced nature of DT technology but also emphasizes its ability to significantly change FP systems.

This article explores the underpinning technological enablers that are driving the development of DT. By examining the elements of these facilitators, which include cutting-edge simulation software and extensive control nexus, the aim is to explore the revolutionary capabilities that these technologies possess for FP systems. This article has a specific emphasis on emerging technologies and attempts to envisage the potential future outcomes. By seamlessly integrating the constituents discussed in the previous studies (1), this paper explores the technological framework that supports the progress, including emerging technologies, in DT applications for FP.

Role of Technological Enablers

The effective implementation of DT in FPAs relies significantly on the role performed by technological enablers, each enhancing the efficiency and transformative capability of this novel approach. The key element of DT deployment is the development of a Virtual Blueprint, which is a dynamic and accurate digital replica of real FP systems. This parameter utilizes sophisticated modeling techniques to provide an up-to-date representation of the system's current state (2). Simultaneously, Data Fusion becomes an essential enabler, smoothly merging various data sources. The merging of these elements not only improves the precision of the digital replica but also allows for a thorough comprehension of the FP system (3). In addition, Simulate Dynamics extends conventional visualization by offering a platform for conducting simulations in real-time. This parameter enables engineers and operators to anticipate system behaviors and enhance performance (4).

Control Nexus serves as the centralized facilitator, enabling online monitoring as well as control of fluid power systems with the help of the digital twin. It establishes a connection between the physical and virtual segments, enabling accurate improvements based on real-time data (5). Furthermore, the Connective Cloud facilitates the smooth transfer of information between real systems and their virtual counterparts (6). This connectivity offers an adaptable and dynamic environment, promoting ongoing enhancement and flexibility in fluid power applications. Sensor Insight is crucial in this process, as it continuously provides an ongoing source of data from physical systems (7). The growing quantity of information improves the precision of the digital twin, hence enhancing its capacity to replicate and optimize the performance of fluid power applications.

Ultimately, the various aspects of technological enablers, represented by factors like Virtual Blueprint, Data Fusion, Simulate Dynamics, Connective Cloud, Control Nexus, and Sensor Insight, highlight their crucial role in effectively implementing DT in FPAs. Collectively, these enablers establish a harmonious structure that not only replicates real-world framework but also enables engineers with the ability to anticipate outcomes and provide quick intervention. The ongoing evolution of FP technology has the potential for not just improved efficiency, but also an essential shift in the comprehension, monitoring, and optimization of FP systems. This shift in approach has the potential to transform the future of applications involving FP, enabling remarkable capacities for adaptability, reliability, and efficiency.

Significance of Comprehending Technology Trends

Gaining a comprehensive understanding of technology trends is highly significant when it comes to DT for FP systems, especially in relation to the technological enablers that facilitate and the novel technologies that are emerging. In the field of FP, where accuracy, effectiveness, and dependability are extremely important (1), it is crucial to keep up with technical progress in order to maximize system efficiency and foster innovation. To fully leverage the potential of emerging technologies for system monitoring, predictive maintenance, and performance optimization, industries need to understand the technology trends that are relevant to DT in FPA.

The advancement of DT in FP systems is being propelled by technological enablers such as real-time data analytics (3), IoT connectivity (6), and enhanced sensors (7). These advancements empower firms to generate virtual replicas of physical assets, facilitating instantaneous monitoring, analysis, and optimization of system performance (1). Moreover, emerging technologies like machine learning, artificial intelligence, and augmented reality are transforming the powers of DT, enabling the industry to anticipate malfunctions, optimize energy usage, and improve the dependability of FP systems (1).

FP researchers must comprehend technology developments to advance DT applications. Researchers can improve DT models, predictive capacities, and FP system performance by staying updated on new technological enablers and technologies. In a nutshell, understanding DT technology trends for FP systems is crucial to unlocking new possibilities, fostering innovation, and advancing research. Industries and researchers can use technological enablers and new technologies to optimize system performance, dependability, and the next generation of FPAs using DT.

In this section, it is crucial to thoroughly examine the knowledge and understanding of industry adoption trends and their possible implications for future research and development endeavors. Gaining insight into the manner in which sectors are adopting and integrating technological enablers and emerging trends offers useful direction for guiding the path of research and development endeavors. Through the analysis of industry adoption trends, experts may pinpoint areas of increased demand and importance. This allows them to concentrate their efforts on creating creative solutions that specifically target the difficulties faced by the FP industry. Furthermore, gaining knowledge about the patterns of industry acceptance allows researchers to predict changing market demands and technological prerequisites, enabling them to develop proactive strategies that lead to significant improvements in the FP sector. This provides vital perspectives on how technology breakthroughs and industry practices interact in the domain of DT for FP systems.

Understanding industry adoption trends helps us discover technology opportunities and constraints, driving future research and innovation. Thus, by linking industry adoption trends to technology trends, one can provide a more complex and comprehensive view of the implications of technological advancements in DT for FP systems.

Review Structure

The paper's organization is illustrated in the following way, as depicted in Figure 1. Section 1, named "**Introduction**", is composed of four subsections: "Background", "Role of Technological Enablers", and "Review Structure". The "Background" subsections provide a concise overview of FP systems and DT, focusing on their integration within FPAs. This subsection further connects conclusions from a prior review paper (1), which clarifies the three fundamental components of DT in FPAs: Physical representation, which serves to bridge the gap between the digital and physical domains; Virtual representation, which models the dynamic behavior; and Communication frameworks, which facilitate smooth data exchange. Ultimately, this subsection describes the aim of the review article, with a particular focus on the framework of technological enablers, including emerging technologies. The "Role of Technological Enablers" subsection explores the significant importance of six technological enablers, which are further examined. This examination highlights the importance of their role in facilitating the effective execution of digital replicas in FP systems. The intricate link between these factors constitutes the core of the paper's significance, offering a thorough examination. The "Significance of Comprehending Technology Trends" subsection, underscores the criticality of comprehending technology trends to effectively guide industry operations and research endeavors as well as the importance of understanding industry adoption trends and their implications for future research and development efforts. The "Review Structure" subsection outlines the structure of the review and gives a methodical framework for conducting the review. Section 2, under " **Systematic Literature Review (SLR)**," provides a concise and comprehensive description of the method used to analyze and aggregate data regarding DT in FPAs. This section not only offers the literature search index but also offers a comprehensive set of assessment questions for each subsequent segment. These questions serve as a structured and thorough approach to assessing the DT in the context of FPAs.

Section 3, entitled "**Technological Enablers**", comprises six subsections. Each subsection focuses on identifying and discussing the crucial technologies that facilitate the development and functioning of DT in FP systems. Virtual Blueprint pertains to the creation of a virtual representation of a product whereas data fusion encompasses the analysis, integration, and visualization of data. Simulate Dynamics involves simulating the behavior of a system and control nexus deals with controlling the behavior of a system. Connective Cloud refers to communication with a virtual product. Lastly, Sensor Insight focuses on the measurement of data. The emphasis is placed on simulation software and the components of the control section, such as PLCs. Section 4, over "**Emerging Technologies**", examines the cutting-edge advancements in technology that have the potential to improve DT in FPAs. The study on emerging technologies examined recent research findings that may influence the future of DT in FPA. This section serves as a proactive perspective, predicting and analyzing the technical advances that have the potential to completely transform the way DT is implemented in the real world. The discussion examines the latest advancements in technology, offering insights into the current state of DT in FP systems and providing a foundation for predicting its future direction. Finally, section 5, named "**Conclusion**", serves as the concluding segment of this comprehensive review. The content provides a concise and thorough summary that encompasses its key findings and ideas by synthesizing the abundant information offered. In addition to summarizing the investigation, this section presents a thoughtful analysis, providing a detailed viewpoint on the consequences of the studied material. The conclusion of the review plays a crucial function in directing readers towards a more profound comprehension of the significance of DT in FPAs by extracting the core content of the review.

Systematic Literature Review (SLR)

The systematic literature review (SLR) approach generally comprises three separate phases: planning the content of the literature review, executing the literature review, and synthesizing and disseminating data (8). The present examination of the study is conducted according to these approaches. This study follows the SLR process and aims to achieve the goal of the review, as demonstrated in Figure 2 (1).

Thematic analysis was employed to discover recurrent themes, patterns, and trends within the chosen research. This process facilitated an enhanced awareness of the multiple aspects associated with technological enablers and emerging trends in the domain of DT for FP systems. Data extraction was essential in the review process as it systematically gathered important information from all the studies.

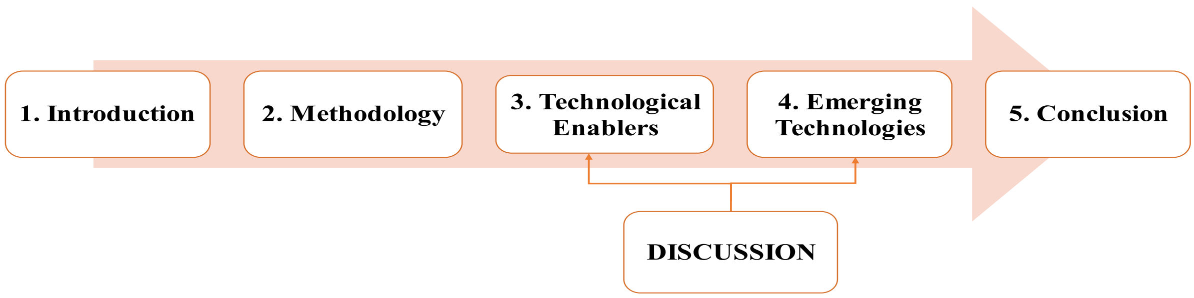

Figure 1: Logical flow of paper

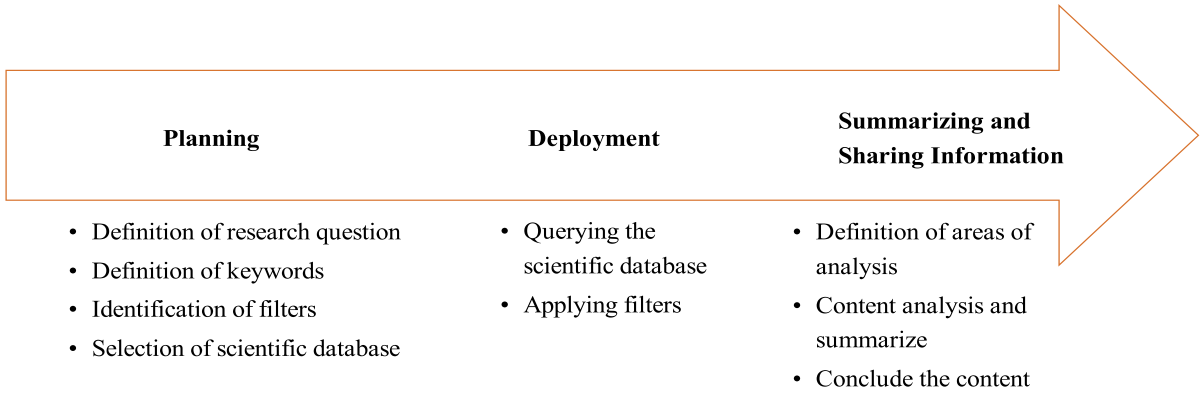

Figure 2: SLR Methodology (1)

This encompassed specific information such as the aims of the study, the approaches employed, notable discoveries, and ultimate conclusions. Through a methodical process of gathering and arranging this material, it enabled a thorough examination and synthesis of the literature (8).

The process of selecting literature was carried out according to predetermined criteria for inclusion and exclusion. This was done to ensure that the sources of information included in the review were both relevant and of high quality. The criteria were created to fit with the study aims and scope of the review. The focus was on selecting scholarly journal papers, conference papers, and other reliable sources from Scopus, IEEE Xplore, and Web of Science databases. Rigorous quality assessment standards were used to evaluate the caliber and relevance of the chosen sources. This entailed assessing the methodological rigor, reliability, and relevance of each work according to acknowledged standards in the field (8).

Ultimately, the process of outcomes synthesis involves the examination and integration of the extracted data in order to construct cohesive descriptions and uncover underpinning trends and patterns. This process facilitated the recognition of crucial observations and emerging patterns, hence leading to a thorough comprehension of technological enablers and new trends in DT for FP systems.

A database search is performed on sources published from 2000 to 2023, including a range of resource types such as journal papers, conference papers, and book series. The publications encompassed search terms such as "Digital Twin", "Fluid Power Systems", "Fluid Power Application", "Hydraulic Systems", "Pneumatics Systems", "Framework", "Future Directions", "Implementation", "Manufacturing", and others. The words were deliberately merged in particular sections of the articles. Figure 3 provides a detailed index for carrying out extensive literature searches in educational resources. More than 150 manuscripts have been subjected to thorough scrutiny based on their ranking in terms of relevance. A total of 52 papers, which are closely aligned with the objective of the review, have been chosen and added to the Mendeley database for comprehensive examination and analysis. The articles encompass a range of topics including the title, abstract, introduction, enablers, emerging technologies, and conclusion. In the literature filtering stage, the investigation examines the chosen articles within the "fluid power applications" domain so as to further pare into the particular study topic for the present review.

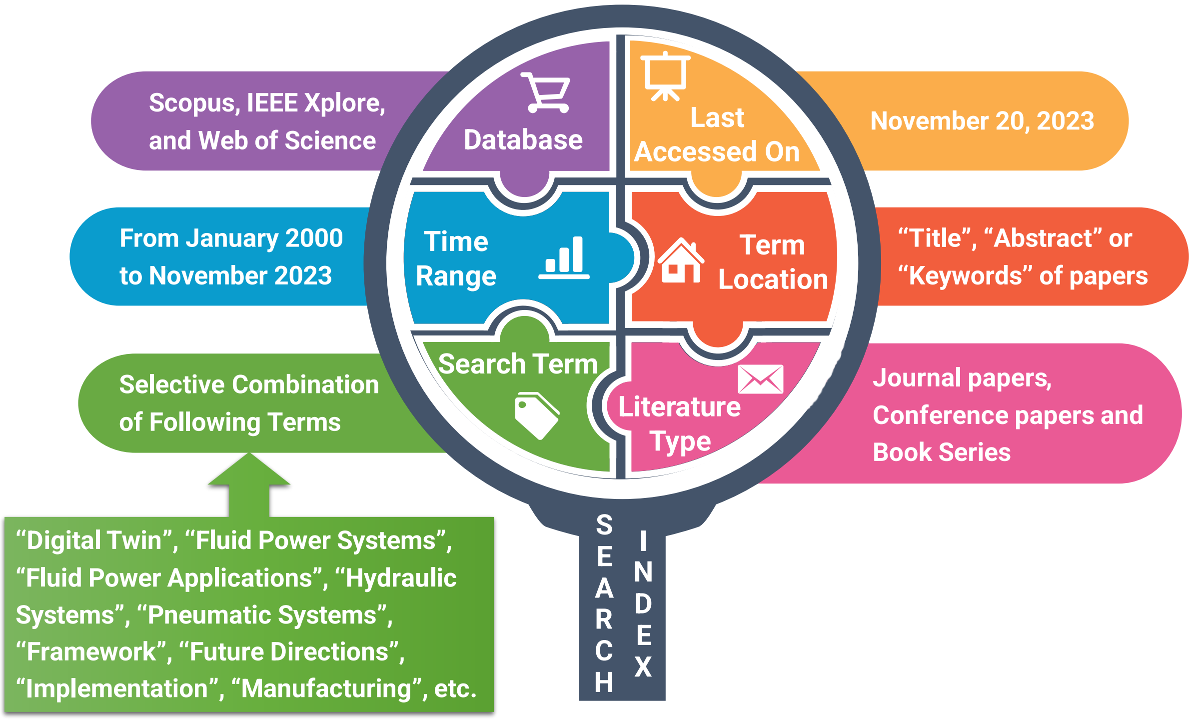

Figure 3: Literature Search Content: Academic Database

The article introduces and analyzes six questions resulting from a thorough assessment of previous studies:

1. What is the DT?
2. What is the importance of FP systems in industry applications?
3. What is the function of DT in FPAs?
4. What is the role of technological enablers in the implementation of DT in FPAs?
5. What are the technological enablers that facilitate it?
6. What are the emerging technologies in the implementation of DT in FPAs?

The utilization of the SLR technique in this study ensures the validity and reliability of the review process in thoroughly investigating the applications of DT. This method guarantees a thorough and organized procedure, starting with well-defined research inquiries and search parameters, which methodically drive toward the discovery and choice of pertinent material. The review procedure reduces bias and guarantees the inclusion of high-quality and relevant studies through adherence to certain inclusion and exclusion criteria.

Moreover, the stringent criteria employed for literature selection enhance the reliability of the review process. The review procedure ensures the inclusion of studies that offer strong and significant insights into DT applications by carefully assessing the scientific rigor, credibility, and relevance of each study. The rigorous selection method ensures the validity of the review conclusions and reduces the possibility of incorporating irrelevant or low-quality papers. Standardized data extraction and analysis improve review validity and reliability. The review method promotes uniformity and accessibility by extracting crucial information from each study and summarizing conclusions (8).

In short, the SLR methodology offers an effective and reliable approach to obtaining comprehensive insights into DT applications. The review method guarantees the integrity and credibility of the conclusions by employing thorough protocols for research selection, data extraction, and analysis. As a result, it makes a substantial contribution to the current state of knowledge in the area of study.

Discussion

In the discussion part, a detailed review of the technological enablers and emerging technologies of DT in FPAs is presented.

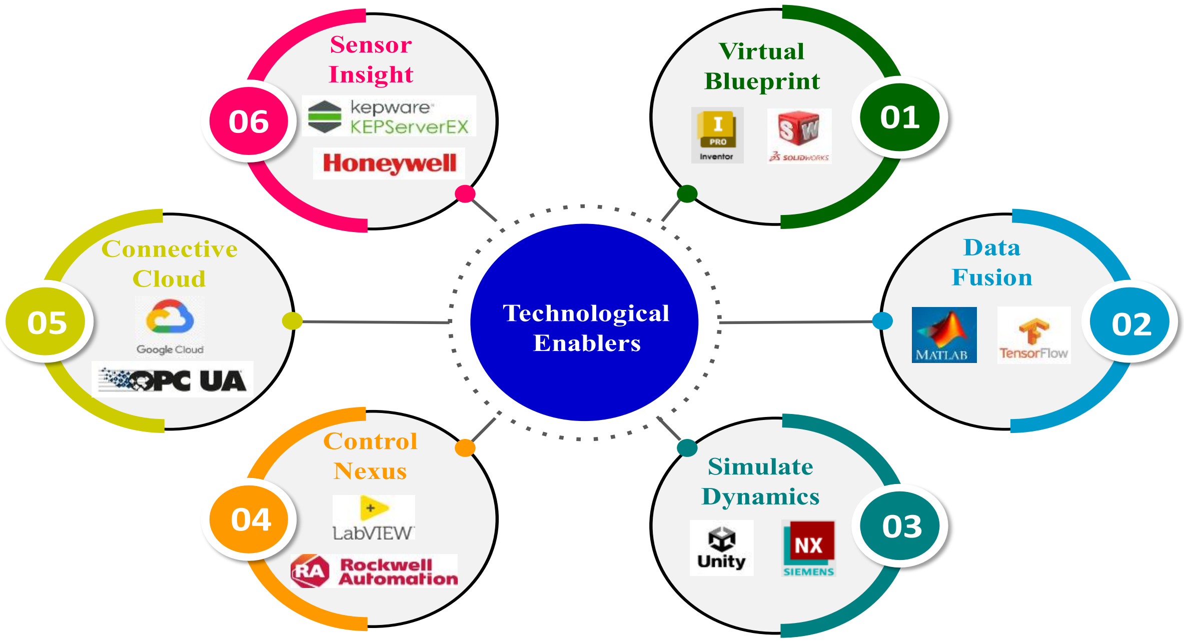

Figure 4: Technological enablers of DT

Technological Enablers

Technological enablers encompass a range of tools, systems, and resources that facilitate the implementation and exploitation of technology across many areas. The development of DT technology has revolutionized the field of FPAs by providing an integrated approach for modeling, monitoring, and enhancing the efficiency of hydraulic or pneumatic components. This review paper explores the fundamental technological enablers that support the development and effectiveness of DT in FP systems. Figure 4 illustrates a well-designed circle that represents the important aspects of a DT, enables the implementation of DT and emphasizes various services related to FPAs at each level.

Virtual blueprint: Virtual blueprint is a virtual model that accurately replicates the design and structure of a physical thing or system. Computer-aided design (CAD) software, such as NX CAD (9), SolidWorks (2), and Autodesk Inventor (10), is essential for generating precise virtual models of actual parts and systems. These technologies facilitate engineers in the virtual design and modeling of components for FPAs. Furthermore, software applications such as Blender (11), Rhino (12), and 3ds Max (9,13) offer the capability to generate three-dimensional models, hence improving the visual appearance of fluid power components. The aforementioned models serve as the fundamental basis for the concept of the DT, offering a comprehensive and precise virtual representation of the corresponding physical system.

Data fusion: The process of data fusion involves integrating and combining multiple sources of data to generate a comprehensive and unified representation. Software applications such as MATLAB (3) and Python modules (14), as well as dedicated data analytics platforms, are utilized to do analysis on the data produced by the fluid power applications. Engineers are empowered to extract valuable insights and enhance the performance of systems by utilizing either real-time or historical data. Platforms such as Apache Kafka (15) or Microsoft Azure (16) integration services play a crucial role in enabling the integration of data from diverse sources, hence ensuring the creation of a cohesive and extensive dataset. The integration is crucial in order to establish a comprehensive DT that precisely mirrors the functioning of the corresponding physical fluid power system. Software tools such as Tableau (17), Microsoft Excel (17), and Power BI (18) enable the generation of dynamic and instructive visual representations. These tools facilitate the interpretation of complex data by engineers and stakeholders, hence enhancing comprehension of fluid power system dynamics and enabling the identification of areas that can be enhanced. Machine learning frameworks such as

TensorFlow (19), PyTorch (20), and the Ethereum blockchain platform (21) have the potential to be utilized for the purposes of predicting fluid power system behavior, detecting anomalies, and optimizing performance. Artificial intelligence (AI) improves the capabilities of DT by facilitating adaptive learning and decision-making processes that rely on developing data.

Simulate dynamics: Simulate dynamics refers to the process of modeling and simulating the behavior of a system over time. Virtual reality (VR) platforms such as Unity3D (22) and Unreal Engine (23) offer immersive simulations that accurately depict the behavior of FP systems. Engineers have the ability to investigate the virtual environment, thereby acquiring valuable knowledge regarding the dynamics of systems and identifying potential difficulties. Virtual reality technology has been found to significantly improve training, design validation, and troubleshooting processes. Engineers can utilize advanced software tools like NX MCD (24), ANSYS (4), Simulink (25), OpenModelica (26), Simumatik (27), Visual Components (28), Tecnomatix Plant Simulation (29), Emulate3D (30), FlexSim (31), and Automation Studio (32), to simulate the behavior of fluid power applications under diverse operating situations. These software tools are summarized based on their various types of capability criteria as outlined in Table 1. Simulations offer a virtual platform for the purpose of evaluating designs, enhancing performance, and detecting potential failures prior to their occurrence in the physical FP system.

Control nexus: The term "control nexus" refers to a central point or system that has power and exerts influence on different aspects or components within a certain context, hence facilitating the control behavior of DT. Augmented reality (AR) applications, such as Microsoft HoloLens (33) or ARKit/ARCore (34) for mobile devices, superimpose virtual information over the physical FP systems. In the domain of FPAs, augmented reality has the potential to enhance maintenance and troubleshooting processes by offering real-time data and instructions that are immediately integrated into the actual environment. Software interfaces, such as LabVIEW (35), EtherCAT (36), or TwinCAT (37) facilitate the real-time control of physical FP systems by connecting with actuators. By integrating this feature, it enables the implementation of dynamic control schemes, hence enhancing the efficiency and agility of the system.

Table 1: Capabilities of simulation software

Simulation Software	Modeling Capabilities	Simulation Capabilities	Integration and Compatibility
Unity3D (22)	3D modeling, Animation, Physics Engine	Limited fluid dynamics simulation, Real-time interactions	API, SDK, Plugins, Support for third-party physics engines
Unreal Engine (23)	3D modeling, Animation, Physics Engine	Limited fluid dynamics simulation, Real-time interactions	API, SDK, Plugins, Support for third-party physics engines
NX MCD (24)	Comprehensive fluid power system modeling	Fluid dynamics simulation, Multi-physics simulations	PLM Integration, Integration with Siemens tools
ANSYS (4)	Advanced fluid dynamics modeling, Multiphysics Modeling	Advanced fluid dynamics simulation, Multiphysics simulations	API, Scripting, CAD Integration, Customization
Simulink (25)	System-level modeling, Block diagrams	Limited dynamic system simulation, Integration with MATLAB	MATLAB Integration, Simulink Desktop Real-Time, Hardware support

OpenModelica (26)	Modelica language modeling	Multi-domain simulation, Equation-based simulation	API, FMI, FMU, Integration with other modeling tools
Simumatik (27)	Fluid power component modeling	Limited fluid power simulation	API, SDK, Support for Python scripting
Visual Components (28)	Multi-Domain Modeling, Realistic Physics Engine	Dynamic system simulation, Virtual commissioning	API, SDK, Integration with PLCs, Support for external physics engines
Tecnomatix Plant Simulation (29)	Manufacturing process modeling	Fluid dynamics simulation, Virtual commissioning	PLM Integration, Integration with Siemens tools
Emulate3D (30)	Dynamic System Modeling, Emulation model	Limited fluid dynamics simulation, Real-time interactions	API, OPC, Integration with PLCs
FlexSim (31)	3D Modeling Environment, Material Flow Simulation	Discrete Event Simulation, PLC Integration	API, SDK, Integration with PLCs
Automation Studio (32)	PLC programming, Fluid power circuit design	PLC Simulation, System-Level Simulation	PLC Integration, Support for IEC 61131-3 programming

Table 2: PLC's DT development tools

PLC	Programming Software	Simulator Software	Communication Software	Communication Protocol
Siemens (5)	TIA Portal	Siemens PLCSim Advanced	SIMATIC Net OPC Server	Siemens Industrial Ethernet, PROFINET
Beckhoff (37)	Beckhoff TwinCAT	TwinCAT 3 PLC Simulation	TwinCAT OPC Server	EtherCAT, OPC UA
Allen-Bradley (38)	RSLogix 500	RSLogix Emulate	RSLinx Classic OPC Server	EtherNet/IP, ControlNet, DeviceNet
Schneider Electric (38)	Unity Pro	Schneider Electric Simulator	Unity Pro OPC Server	Modbus, Ethernet/IP, OPC UA
Mitsubishi Electric (39)	GX Works3	MELSOFT GX Simulator	MELSOFT MX OPC Server	CC-Link, MELSEC
Omron Sysmac (40)	Sysmac Studio	Omron CX-Simulator	Omron CX-Server OPC	EtherNet/IP, EtherCAT, OPC UA

The control behavior in the domain of DT for fluid power applications depends extensively on the choice of specific PLC hardware and its corresponding software. Prominent PLC hardware encompasses the Siemens SIMATIC (5), Allen-Bradley CompactLogix (38), Schneider Electric series (38), Mitsubishi Electric (39), and Omron Sysmac (40). Their associated PLC software are Siemens TIA Portal (5), Rockwell Studio 5000 (38), Schneider Electric Unity Pro (38), Mitsubishi GX Works (39), and Omron Sysmac Studio (40) respectively. These software solutions are specifically designed to complement the functionality of the aforementioned PLCs. The comprehensive examination of a wide range of PLC hardware and software combinations highlights the need to evaluate several alternatives when designing and implementing DT for fluid power applications. Table 2 provides a comprehensive overview of programmable logic controllers and their associated software tools. This approach provides flexibility and adaptability to effectively fulfill unique control needs.

Connective cloud: The Connective Cloud is a technological platform that enables the seamless integration and communication between various devices, applications, and services over a network. Protocols such as MQTT (41), OPC UA (41), and RESTful APIs (42) serve as facilitators for communication between the physical fluid power system and its digital twin. The establishment of connectivity facilitates the seamless exchange and synchronization of data in real-time, thereby enabling the DT to accurately replicate the present condition of the fluid power application. Cloud service providers such as AWS IoT (6), Google Cloud IoT (6), and Microsoft Azure IoT (16) provide cloud-based infrastructures that are both scalable and secure, making them suitable for hosting digital twin. Cloud computing facilitates the efficient handling of extensive datasets, the prompt analysis of data in real-time, and the smooth incorporation of sophisticated technologies such as machine learning.

Sensor insight: The term "Sensor Insight" pertains to the capacity to acquire knowledge and comprehension by means of utilizing sensors. Sensors play a crucial role in facilitating the integration between the physical and digital environments in the domain of a DT for the fluid power applications. The main purpose of these systems is to collect real-time data from the physical fluid power system, generating a continuous flow of information that serves as the foundation for the virtual representation. Multiple sensors, such as pressure sensors (43), flow sensors (44), Ultrasonic sensor (45), and Infrared sensor (46), are utilized to collect real-time data from the physical fluid power system. Sensors produced by manufacturers such as Honeywell (47) or Bosch (7) offer precise measurements, hence facilitating the digital twin's ability to accurately represent the present condition of fluid power components. Middleware tools such as Node-RED (48), Apache Kafka (15), and KEPServerEX (49) play a crucial role in enabling the seamless integration of sensor data into the DT. This software guarantees the precise integration of real-time measurements into the virtual representation of the fluid power applications.

To summarize, the integration of advanced technological enablers for DT in FPAs represents a significant advancement towards a more effective, adaptable, and robust future. As we explore the complicated domain of these technical tools, it becomes clear that DT not only replicate the

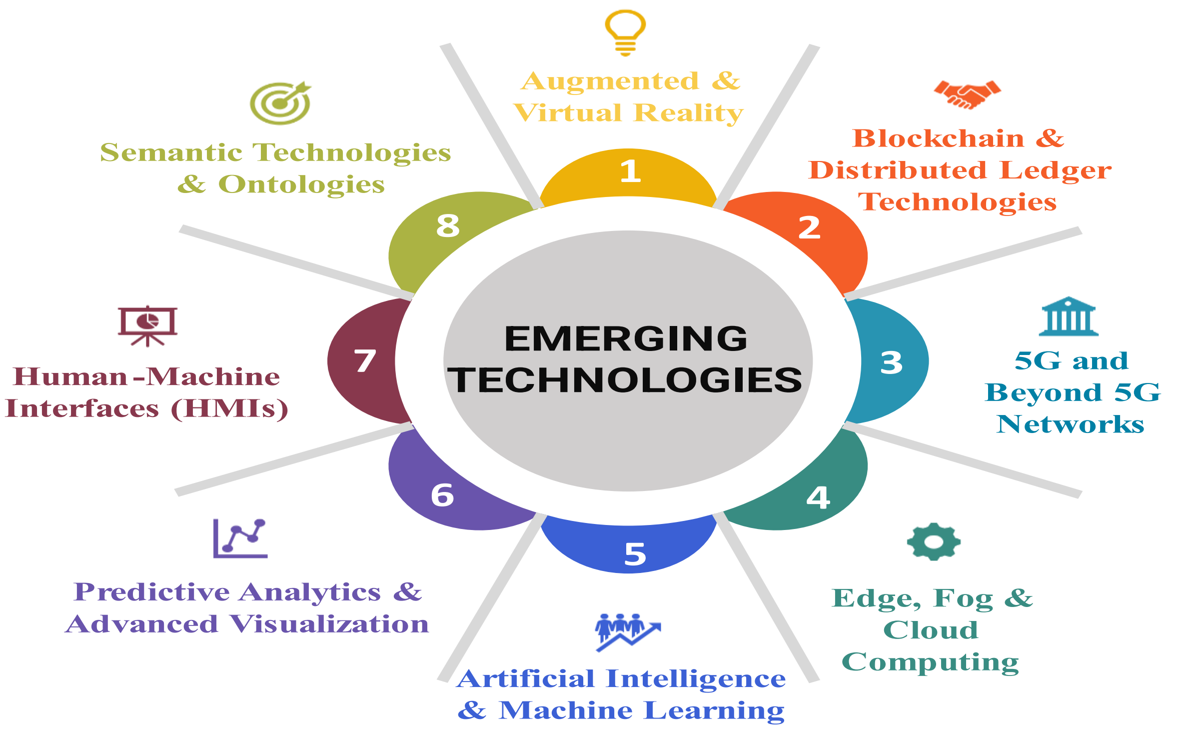

Figure 5: Emerging Technologies in DT

intricacies of FP systems but also act as the driving force for innovation and optimization in this ever-changing sector.

Emerging Technologies

The significance of emerging technologies as shown in Figure 5 is crucial in influencing the trajectory of DT in FPAs when contemplating their future directions. An ongoing revolution is currently underway as emerging technologies are positioned to fundamentally change the nature of virtual replicas in the field of DT. The combination of developing technologies together suggests a future in which DT in FPAs will exhibit increased intelligence, efficiency, and collaboration, hence facilitating breakthroughs in the industrial sector (50). Developments in fields like as artificial intelligence, edge computing, 5G/6G networks, and human-machine interfaces have the ability to tackle present challenges and unveil new opportunities for DT. The following are some of the important technologies that may influence the development of DT in FPAs:

Augmented and Virtual reality: The incorporation of the metaverse into DT architectures offers the potential for engaging virtual experiences and collaborative virtual environments, fundamentally transforming the way these systems are conceived and employed (51). Extended reality (XR), which includes augmented reality (AR), virtual reality (VR), and mixed reality (MR), could improve DT experiences, especially when it comes to training, maintenance, and repair in fluid power applications (51). Augmented and virtual reality technologies have the potential to greatly change the way humans interact with digital representations of themselves. Through the facilitation of direct interaction with virtual representations, these technologies have the capacity to improve remote support, training, and collaborative decision-making (50).

Blockchain and Distributed ledger technology: The integration of blockchain and distributed ledger technology effectively mitigates concerns regarding data security, hence facilitating smooth data interchange inside intricate fluid power supply networks (50). This interoperability has the potential to facilitate novel collaborative operating strategies and applications that encompass the entirety of crucial FP systems. The use of blockchain technology, which prioritizes the security, accuracy, and origin of data, shows potential for creating collaborative digital replicas in fluid power applications (50). The integration of these technologies indicates a future in which digital replicas provide increasingly self-governing, intelligent, and immersive encounters, fundamentally transforming industries in the fluid power domain (51).

5G and Beyond 5G networks: The emergence of sophisticated networks, such as 5G and future generations, guarantees increased data transmission capacity and reduced delay, enabling instantaneous data streaming for highly responsive digital replicas (51). The recent development of 5G networks and the continuous advancement of 6G technology are expected to significantly enhance the adoption of digital twin technology by offering widespread, fast, and reliable connectivity. Terahertz communications, integrated sensing and communications, and reconfigurable intelligent surfaces are advanced features of 6G technologies that have the potential to enhance the sensing and interaction capabilities of DT (51).

Edge, Fog, and Cloud computing: Edge and fog computing strive to enhance data processing by prioritizing it at the network edge in close proximity to data sources such as sensors and devices (51) This minimizes delay and minimizes bandwidth consumption in contrast to transmitting all unprocessed information to centralized cloud servers. The utilization of edge and fog computing facilitates enhanced responsiveness in real-time simulations, specifically in the context of predictive maintenance of DT applications of FP systems (50). Cloud computing has emerged as a crucial technology that significantly enhances the accessibility and scalability of DT applications in FP systems (52). Shifting virtual replicas to the cloud not only facilitates smoother exchange and coordination across functional borders but also corresponds with the field's growing acceptance of cloud-based solutions, leading to improved interaction and productivity.

Artificial intelligence and Machine learning: The use of artificial intelligence and machine learning (ML) brings about a level of self-governance, automating the process of acquiring knowledge and enabling the development of adaptable digital replicas over a period of time (50). AI/ML approaches can be employed to automatically identify trends and extract information from the extensive operational information generated by DT in FPAs. The acquired insights can subsequently be utilized to enhance the efficiency of DT models and simulations by incorporating real-world feedback (50). This has the potential to enhance the autonomy of DT in FPAs gradually, hence reducing the need for extensive professional programming intervention. Machine learning and deep learning are two types of artificial intelligence that are expected to make DT smarter and more independent. This advancement will enable predictive and prescriptive capabilities in several domains such as maintenance and anomaly detection (51).

Predictive analytics and Advanced visualization: The potential of DT capabilities in predictive maintenance and optimization can be significantly enhanced by advancements in predictive analytics and artificial intelligence (52). The notion of "self-defining digital twins" proposes a prospective scenario in which autonomy and flexibility are intrinsic qualities, leading to the optimization of processes with minimal need for human intervention (52). The inclusion of emerging technologies, including data management, and computational capabilities with advanced visualization, is crucial for advancing DT in FP systems to higher levels of intelligence, interoperability, and accessibility (52). The revolutionary capabilities of these technologies will be crucial in fully exploiting the immense benefits of DT in the FP industry and other sectors.

Human-Machine interfaces (HMIs): The progress made in fields such as augmented and virtual reality, haptics, brain-computer interfaces, and multi-sensory feedback holds the possibility of completely transforming the manner in which individuals engage with DT in FPAs. Upcoming immersive interfaces will enhance the usability of DT in FPAs by providing a more natural experience, while also gathering more comprehensive context-sensitive data regarding human decision-making and behaviours. This can, in turn, enhance the human-centricity of DT and improve their ability to accurately simulate real-world human-in-the-loop systems (51).

Semantic technologies and Ontologies: The utilization of semantic technologies, specifically ontologies, offers the potential for enhanced interoperability across DT in FPAs. Ontologies facilitate the establishment of shared definitions and connections among data, hence enabling seamless communication between DT originating from diverse sources. This might become crucial in implementing notions such as the "federation of twins" as stated in the paper (52).

Ultimately, the incorporation of cutting-edge technology is crucial for advancing the intelligence, compatibility, and user-friendliness of DT in FPAs. This will enable them to fully realize their worth and benefits not just within the FP industry but also in other sectors. The combination of AI, edge computing, advanced networks, and human-machine interfaces is set to develop DT in FPAs, overcoming limits and creating new options for application. This integration has the ability to significantly change and influence the future of digital twins in the field of fluid power technology.

Conclusion

To summarize, this article has thoroughly analyzed the crucial role of technological enablers in fostering the use of DT in FPAs. By reviewing the Virtual Blueprint, Data Fusion, Simulate Dynamics, Connective Cloud, Control Nexus, and Sensor Insight, it becomes clear that these elements play a crucial role in facilitating the successful deployment of DT in FPAs. The "Introduction" section provided a clear explanation of the fundamental knowledge of FP systems and DT, enabling an in-depth examination of the role of technological enablers. Every enabler mentioned in this review makes a distinct contribution to the advancement of DT in FPAs. By creating virtual models and ensuring smooth data transfer, these factors collectively promote technological advancement and effectiveness in FP systems. The review has highlighted the fundamental revolutionary capacity of these technology enablers, underscoring the capability to revolutionize the techniques of monitoring, analysis, and optimization within FPAs. Through the utilization of cutting-edge simulation software, sensors, advanced data analytics, and developing technologies, individuals involved can access previously undiscovered knowledge and improvements, leading to increased effectiveness and decision-making in FP systems.

In a nutshell, the integration of emerging technologies addressed in this review offers an opportunity for the advancement of DT, both in different fields and particularly in FP systems.

Digital twin have the potential to shift industry practices by leveraging semantic technologies to improve interoperability and harnessing the transformational possibilities of artificial intelligence, cloud computing, and augmented reality. Their capacity to enhance efficiency, independence, and collaboration highlights their importance as accelerators of growth and transformation. As firms develop the current technological landscape, it is crucial for them to adopt and incorporate innovative techniques in order to fully utilize the endless opportunities of DT. This assessment highlights the crucial significance of emerging technologies for developing the future of DT, placing them as essential assets in driving advancement and success across several industrial sectors, particularly in the FP industry.

Overall, this review offers a significant reference for scholars, professionals, and industry experts who are interested in utilizing DT for FPAs. Stakeholders may confidently and innovatively navigate the changing environment of FP systems by comprehending the vital role of technological enablers, and emerging technologies.

Abbreviation

AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
CAD	Computer-Aided Design
DT	Digital Twin
FMI	Functional Mock-up Interface
FMU	Functional Mock-Up Units
FP	Fluid Power
FPA	Fluid Power Application
HMI	Human-Machine Interface
IoT	Internet of Things
MCD	Mechatronics Concept Designer
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
MR	Mixed Reality
OPC	Open Platform Communications
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
SDK	Software Development Kit
SLR	Systematic Literature Review
VR	Virtual Reality
XR	Extended reality

Acknowledgement

Nil

Author Contributions

All authors contributed equally to the conceptualization, literature synthesis, analysis, and interpretation of this review. All authors critically reviewed and approved the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest pertaining to this review paper.

Ethics Approval

This review publication did not require ethics approval because it did not collect new data from humans, animals, or experiments.

Funding

Nil

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