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Digital Twin in Fluid Power: Reviewing Constituents

Akshay Dattaprasad Khamkar, Sudhir Madhav Patil*

Department of Manufacturing Engineering and Industrial Management, COEP Technological University (COEP Tech), Chhatrapati Shivajinagar, Pune: 411005, Maharashtra, India. *Corresponding Author's Email: smp.prod@coeptech.ac.in

Abstract

The most advanced technology in Industry 4.0 is the digital twin, which utilizes a fusion of virtual and physical elements, precise mapping, and multi-dimensional vision to depict the virtual-physical environment in real-time. It is vital for simulation, control, optimization, and prediction and is growing in popularity, especially in industrial automation. Fluid Power Application is a crucial industrial automation system because it provides precise control, enormous power, adaptability, dependability, affordability, and ease of integration into existing automated systems using hydraulic and pneumatic system's power. However, emerging digital twin technology, robust framework, and applications in fluid power systems emphasize distinct technological aspects at various stages, a phenomenon that has not yet been thoroughly examined. Thus, this article aims to provide a thorough review of digital twin technology in fluid power applications considering their significance in the industrial sector, followed by an in-depth examination of each component necessary for developing digital twin of fluid power applications. This review paper contributes to academic knowledge by emphasizing the fundamental concepts and constituents of digital twin, particularly within the context of fluid power applications, and serving as a driving resource for digital twin in fluid power applications' ongoing research attempts and advancements.

Keywords: Communication framework, Digital twin, Fluid power application, Physical representation, Virtual representation.

Introduction

Within the domain of sophisticated technology paradigms, the notion of a digital twin has arisen as a disruptive influence, encompassing a wide range of viewpoints and interpretations. The digital twin is a concept that refers to a virtual representation of a physical asset. It maintains a continuous synchronization with real-time sensor data in order to properly reflect the current status of the entity (1). However, it is important to note that this particular definition represents only a single aspect of the wider scope of the digital twin domain. In other words, one can understand that it is the digital embodiment of a tangible system, predominantly consisting of structural and behavioral models for fundamental regulation, observation, and assessment. The digital twin can be outlined by three key elements (2). Figure 1 illustrates these three key elements of digital twin. Building upon this concept, the digital twin is depicted as a virtual entity that generates digital reproductions of real entities. This can be achieved by incorporating several simulation methods that encompass multiple disciplines, physical quantities, scales, and probabilities (3). A comprehensive simulation can circumscribe the complete life cycle of the associated physical equipment. It enables many functions like simulation, monitoring, evaluation, prediction, optimization, and control. The digital twin is regarded as a significant technological advancement since it can serve as a replica of actual systems by creating virtual replicas (4). As stated by Barbara Rita et al. as cited in Namita Kumari (5), the approach described is a comprehensive simulation that incorporates several physics, scales, and probabilities. Their simulation utilized the most advanced physical models, sensor updates, and historical data from a fleet to accurately replicate the operational lifespan of an aircraft (5). Considering the aerospace sector, a digital twin refers to a virtual representation of an apparent system that undergoes consistent updates with regard to its performance, maintenance, and overall health status data over its entire lifespan (6). The idea is further underscored by its comprehensive

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nature, as it is characterized as a virtual information construct that provides a complete description of a physically made object, spanning both the micro-atomic level and the macro-geometrical level (7). The digital twin is commonly conceptualized as a virtual manifestation of a substantial system that undergoes regular updates through the flow of data between the physical and virtual domains (8)
In the era of Industry 4.0, the concept of the digital twin has emerged as a paradigm shift. It involves the creation of a virtual clone of physical systems, which is achieved through the integration of sensors, data analytics, and machine learning algorithms (9). The digital replica exceeds its basic purpose of representation, as it possesses the capability to significantly transform the monitoring, analysis, and optimization of various physical elements and systems within the Industry 4.0 framework. In the era of the Industrial Revolution in the Industrial Internet of Things (IIoT), digital twin is additionally defined as the digital representation, achieved by a model, of a physical system, procedure, or any apparatus. This depiction, which emerges from the integration of advanced technologies, serves to connect the physical and digital domains, providing a valuable understanding of the internal mechanisms of tangible entities.

Definition of digital twin: Fluid power applications

Considering the field of fluid power applications, the idea of a digital twin assumes a prominent position. This concept entails the creation of a virtual replica that is intricately crafted to closely resemble its physical counterpart. The comprehensive four-layer design encompasses the multifarious construct, which includes the physical entity layer, data transmission layer, visual interaction layer, and decision-making layer as shown in Figure 2 (10). These layers jointly contribute to the complex construction of a digital replica that surpasses mere depiction and expands to encompass remote monitoring, modeling, and prediction within the framework of fluid power applications. Building upon this conceptual foundation, a digital twin can be more comprehensively defined as a simulated depiction of an entity, that enables the capturing of both its stationary as well as dynamic characteristics and allows for the seamless integration of data in real-time, followed by the visualization and implementation of corrective actions based on empirical data obtained from the physical system, notably in the intricate domain of fluid power systems (11).

Upon further examination, the digital twin is depicted as a comprehensive mathematical model, serving as a potent instrument utilized to recreate and simulate the complex dynamics of fluid power systems to achieve optimization and control objectives (12). A software model can describe a dynamic system that can replicate physical systems in the field of fluid power engineering. A software can enable the performance of predictive analyses and pre-implementation testing in real-time (13). The comprehensive digital replication, encompassing its characteristics and dynamic interactions, provides a strong basis for conducting predictive assessments and controlled experimentation of alterations prior to their manifestation in the physical domain (14). In the domain of fluid power applications, the concept of the digital twin goes beyond a mere static depiction and instead transforms into a dynamic digital replica that is closely linked to and consistently refreshed by real-time data obtained from its corresponding physical entity (15).

Evolution of digital twin

The evolutionary trajectory of digital twin in the field of engineering reveals a captivating chronology characterized by significant milestones. Figure 3 outlines the major milestones from the 1970s to the present in digital twin evolution. During the design phase of the Apollo 13 mission in the early 1970s, the first iteration of the digital twin prototype was developed, demonstrating the early origins of this concept (16). The researchers not only finalized the design of the spacecraft but also constructed a high-fidelity model to faithfully represent its flight circumstances. The aforementioned model played a pivotal part in the course of the mission, specifically when the spacecraft encountered an explosion of an oxygen tank while in orbit. Using the mirror-model as a framework, the National Aeronautics and Space Administration (NASA) ran comprehensive simulations to discover the most effective strategies for addressing the problem.

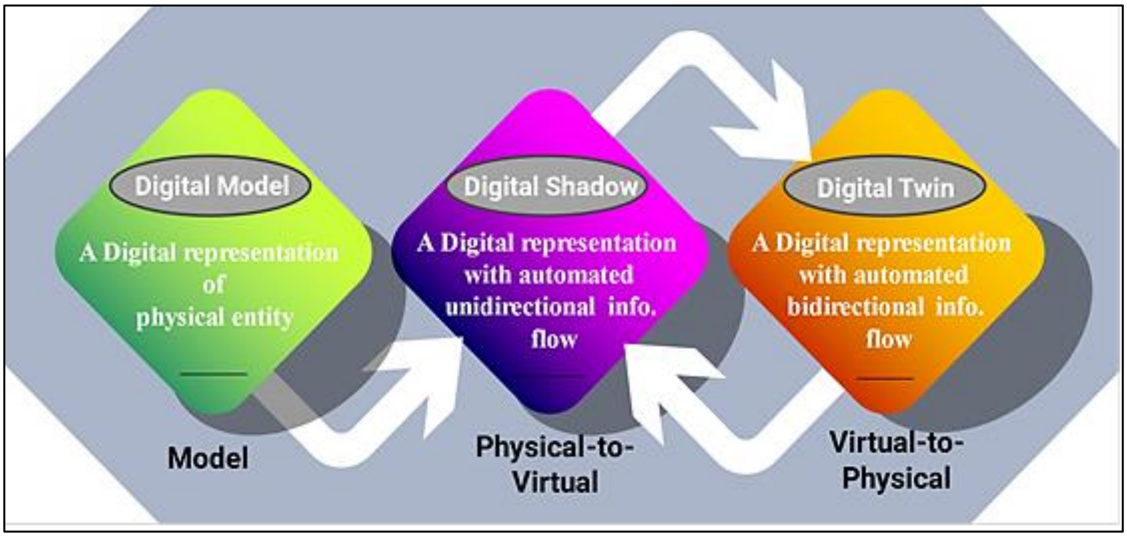

Figure 1: Three key elements of digital twin

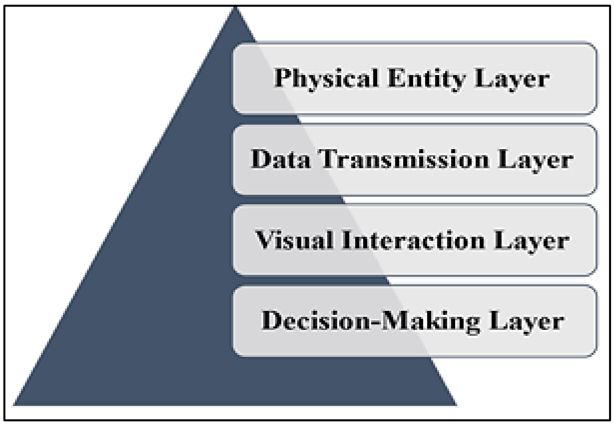

Figure 2: Layers of digital twin

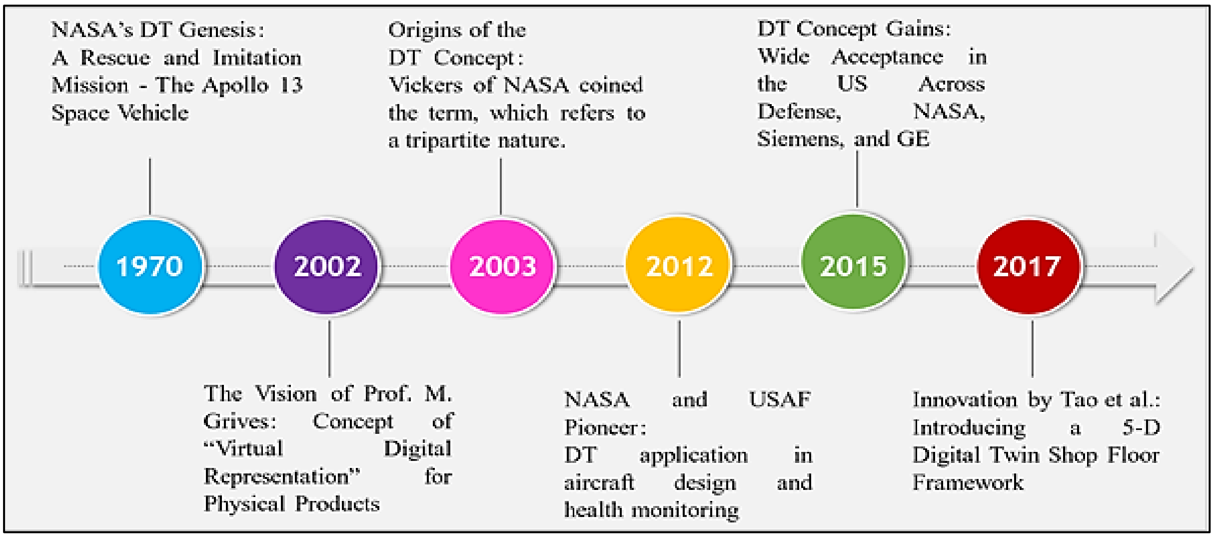

Figure 3: Evolution of digital twin

This initial implementation is in accordance with the fundamental concepts of the digital twin, representing a significant milestone that is widely regarded as the genesis of the digital twin concept (17). The formalization of the notion of digital twins occurred in 2002 when Dr. Grieves presented it within the context of Product Lifecycle Management (PLM) at the University of Michigan (18). The practical implementation of Internet of Things (IoT) technologies was in its early stages, necessitating several years for the emergence of new technologies before a comprehensive industrial framework could be established. During the same time frame, a lecture on project life-cycle management took place in 2003, which is credited with the inception of the digital twin concept. The phrase "Digital Twin" was first introduced by Vickers, an individual affiliated with NASA. Vickers emphasized the three essential components of a digital twin, namely the actual object itself, its virtual counterpart, and the interconnected data streams that provide the real-time transfer of information from the physical to the virtual domain (19).

In 2012, a remarkable advancement took place when NASA and the United States Air Force (USAF) collaborated on a joint proposal, presenting the highly regarded impression of the digital twin. The concept places significant emphasis on the utilization of advanced physical models, sensor updates, historical rapid data, and other relevant aspects to simulate scenarios specifically intended to accurately replicate the complete life cycle of the matching physical entity (20). The aerospace sector initially conceptualized digital twins as the digital representation of a physical system, progressively expanding its scope to deal with the monitoring of complete product life cycles (21). By the year 2015, multiple definitions arose about digital twins, highlighting their significance in diverse industrial domains, specifically about Industry 4.0 and the IIoT (18). Expanding upon this fundamental basis, the technological framework, initially referred to as the "Conceptual Ideal for PLM", underwent a gradual process of development and refinement. Throughout this period, digital twin had several alterations in nomenclature; however, its core elements and ideas remained constant. The model consisted of a real and physical entity, an associated virtual model, and bidirectional data exchange between the physical and virtual domains (22). The progress continues with a major contribution by Professor Tao Fei of Beihang University. In 2017, Professor Tao proposed a five-dimensional architecture for digital twin, which effectively combines service and digital twin data models inside the Grieves framework (23). In conclusion, this historical trajectory showcases the development of digital twins, starting from their initial utilization in space missions and progressing towards their formal conceptualization within engineering settings with application-specific simulators. This progression covers a wide range of definitions and implementations across several industries. Every significant achievement adds to the holistic comprehension and transformative capacity of digital twin techniques.

Background of fluid power applications

The domain of fluid power applications in the industrial sector is extensive and ever-changing, as evidenced by a collection of enlightening scholarly articles. The primary focus lies on the significant significance of fluid power systems within industrial applications. Efficient systems, novel concepts, and optimal designs are prominent areas of focus in the field, as ongoing research initiatives utilize both experimental and computational studies to advance the development of fluid power systems and components (24). A fluid power application has two unique categories of components as shown in Figure 4 power section components, which utilize actuators, pumps, or compressors, and control section components, which encompass various types of control valves. This paper examines significant advancements in the field of fluid power technology, while also emphasizing the need for increased environmental awareness and acceptance.

After conducting a more thorough examination, attention is redirected onto hydraulic systems and their substantial role in the functioning of mobile machinery. Linear actuators are very important in emerging fields like renewable energies, owing to their exceptional power density, cost-effectiveness, and robustness. A significant advancement emerges in the form of a switched displacement hydrostatic transmission specifically built for wind turbines (25), exemplifying the growing field of hydraulic systems and their crucial role in improving energy efficiency across several industrial sectors. Within the aerospace industry, there is a significant focus on the analysis of hydraulic and electromechanical actuation systems. The narrative emphasizes the growing use of electric actuation in turbine engine control systems as a solution to the challenges of integrating adaptive or smart components. Despite the absence of a comprehensive industrial framework, the article (26) extensively explores the complexities associated with aircraft systems, elucidating the delicate interplay between hydraulic and electric actuation technologies. The notion gains more momentum with the introduction of a novel high-speed actuation mechanism that employs magneto-rheological fluid clutch technology (27). The significance of these systems is evident in various fluid power applications in the automotive sector, such as vehicle dynamics, engine air and fuel control systems, industrial robotics, and testing machines. These systems primarily emphasize the crucial link between high-speed actuators and the achievement of optimal functionality in dynamic systems.

When analyzing the broader scope of the United States (U.S.), it becomes evident that there are numerous applications of fluid power technology requiring thorough research. The vital importance of fluid power in many industries such as dentistry, military vehicles, mining, agriculture, construction, and mining equipment is easily noticeable. The notable fact that over 30% of construction and industrial equipment relies on fluid power underscores its substantial impact. The utilization of hydraulic power has become the preferred approach for transmitting power and controlling motion in several industries, highlighting its substantial economic influence. This is apparent from the significant worth of U.S. deliveries, which exceeded $90 billion in 2008 (28). In the field of simulation, the use of Hardware-in-the-loop (HIL) systems has gained significance in evaluating control systems that involve both hardware and software elements. The use of HIL systems could be advantageous for hydraulic actuators, especially in industrial applications like aircraft flight control (29). These systems offer a secure and efficient method for assessing the efficacy of fault-tolerant control algorithms through experimentation. The significance of fluid power systems is elucidated, spanning a diverse array of applications such as automatic control systems, manufacturing processes, soft robotics, and demanding operating circumstances. Hydraulic actuators play a crucial role in controlling and transmitting power, especially in difficult and demanding circumstances. The extensive array of applications highlights the versatility of these technologies across various industrial contexts.

As the continuing conversation continues, attention is once again directed toward hydraulic systems, emphasizing the persistent need to solve shortcomings in energy efficiency. This article (30) explores key topics in hydraulic systems research, such as advanced and reliable components, lightweight and intelligent transmission systems, and the foundational technologies driving digitalization. The pinnacle of the journey entails a thorough analysis of the pivotal role that hydraulic and pneumatic systems plays in various industrial sectors. The application of systems is essential in various domains, such as manufacturing, processing, transportation, and the integration of high-integrity safety systems. These systems play a vital role in the operation, control, and measurement of parameters within diverse equipment, machinery, and plant configurations. In light of broadening the range of inquiry, a scholarly article that examines the obstacles and significance of fluid power systems underscores the necessity of appropriate design, maintenance, and comprehension of design requirements for particular machine applications. The suggested prototype presents a computational support tool that has the potential to significantly transform the design process, followed by a training facility and an empowering tool for engineers at all levels of experience (31). Exploring the domain of cutting-edge technologies, the utilization of neural network technology in hydraulic systems has garnered significant interest. This study (32) advocates for a reassessment of control and circuit design methodologies in order to effectively address the rigorous performance requirements of hydraulic circuits. The utilization of neural networks, in conjunction with other sophisticated technologies such as adaptive, fuzzy, and neural controls, is identified as a pivotal factor in the reconfiguration of the fluid power industry. The study enlightened on the pivotal role of fluid power systems in the Japanese car industry, acknowledging their historical significance and contemporary uses. Hydraulics serve as a fundamental component in the operation of vehicles, encompassing a range of critical systems such as automatic gearboxes, sophisticated suspensions, and brake systems (33). These studies collectively highlight the challenges, potentials, and historical significance of fluid power systems in many industrial environments, demonstrating a seamless synthesis. The synthesis provides a detailed analysis of the dynamic field of fluid power in the industrial sector, encompassing a range of topics including computational support tools, neural network technology, and the diverse uses of fluid power systems.

Significance of digital twin: Fluid power applications

The growing importance of digital twins in the field of fluid power applications demonstrates their ability to bring about significant changes and adapt to the advancing technological environment. As stated in the opening and abstract of the review article, the idea of a digital twin extends beyond a simple virtual representation. It encompasses a dynamic and changing counterpart that is closely connected to real-world physical systems. Within the domain of fluid power systems, where utmost importance is placed on accuracy and effectiveness, digital twins have become essential technologies. The various definitions presented emphasize the adaptability of digital twins, which can range from virtual representations used for simple control and monitoring (2) to extensive simulations that encompass the whole lifespan of actual equipment (3). Due to their wide range, digital twins are able to have a significant impact in various areas such as simulation, monitoring, evaluation, prediction, optimization, and control (3). The significance of digital twin is amplified in the complex domain of engineering systems, specifically in the fields of hydraulics and pneumatics. Digital twin provides a comprehensive method for recreating and interpreting real-world counterparts by utilizing a four-layer architecture as shown in Figure 2. This surpasses the mere depiction of data and allows for distant observation, simulation, and forecasting within the particular framework of fluid power systems (10). In addition, the digital twins generate dynamic digital replicas that constantly receive real-time data from their physical counterparts in fluid power applications (15). Real-time integration is extremely helpful for conducting thorough analysis, as it allows for the visualization and implementation of corrective actions based on empirical data obtained from the physical system.

In the era of Industry 4.0, new technical paradigms are changing industrial landscapes. Digital twins are emerging as revolutionary paradigms (9). In the domain of fluid power systems, this refers to the creation of a highly accurate digital model achieved by the combination of sensors, data analysis, and machine learning algorithms. This digital replica has the potential to completely transform the monitoring, analysis, and optimization of various physical elements and systems within the Industry 4.0 framework. The classification of digital twins as the digital representation of physical systems (34) and the precise mathematical models for recreating and modeling behaviors of fluid power systems (12) further emphasize their significance. These models, created by combining advanced technologies, serve as connectors between the physical and digital worlds, providing a comprehensive understanding of the functioning of real-world things. The importance of digital twin in the field of fluid power applications resides in their capacity to surpass traditional visualizations. They transform into sophisticated digital representations intimately linked to real-time data, facilitating thorough analysis, modeling, and prediction. Among the ongoing digital change in the industrial sector, digital twin has emerged as a leading concept that enables the optimization and management of extensive fluid power systems.

Through the synthesis of these conceptualizations, this review paper aims to provide a valuable contribution to the holistic understanding of digital twin fundamentals in relation to fluid power technology and their applications in fluid power systems.

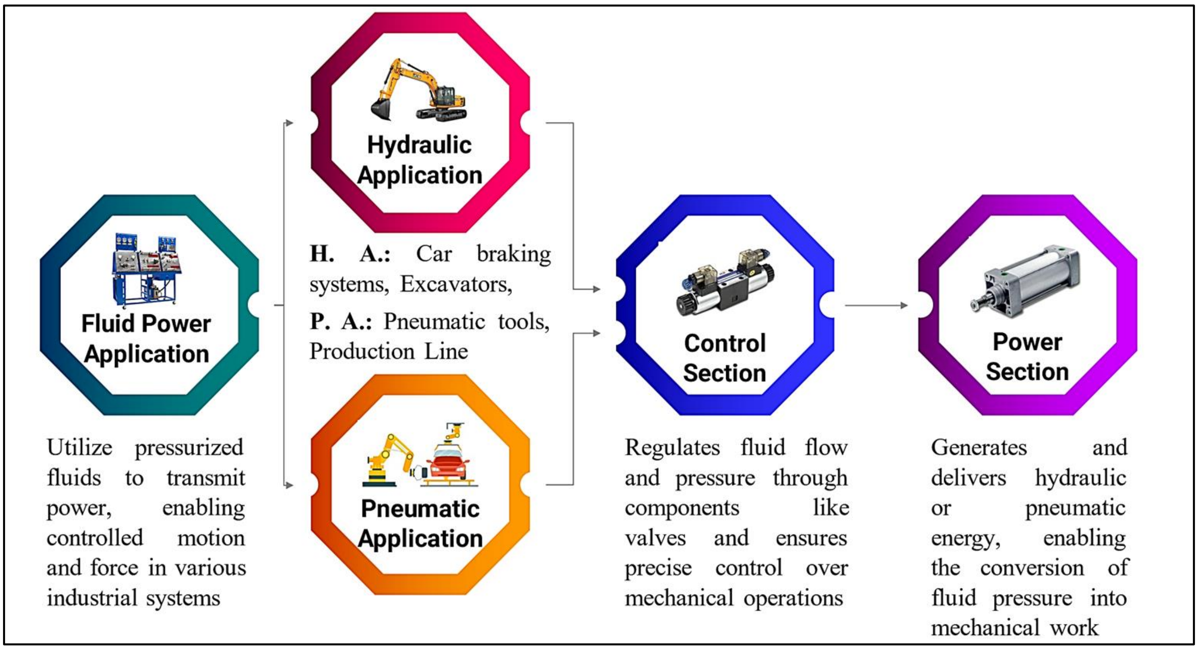

Figure 4: Sections of fluid power application

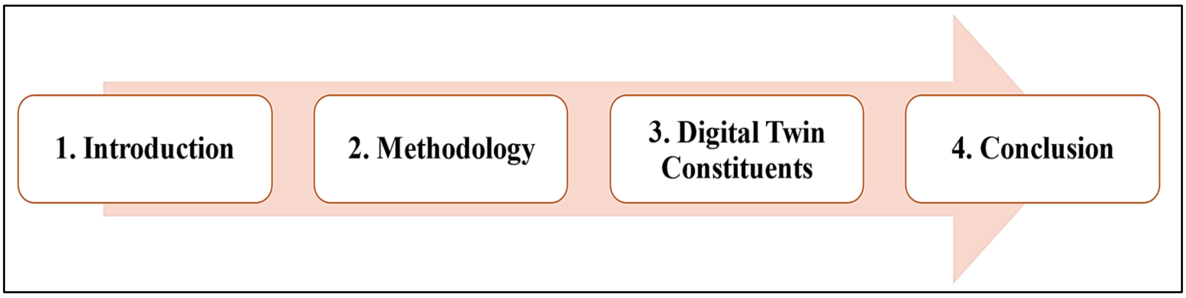

Figure 5: Logical flow of paper

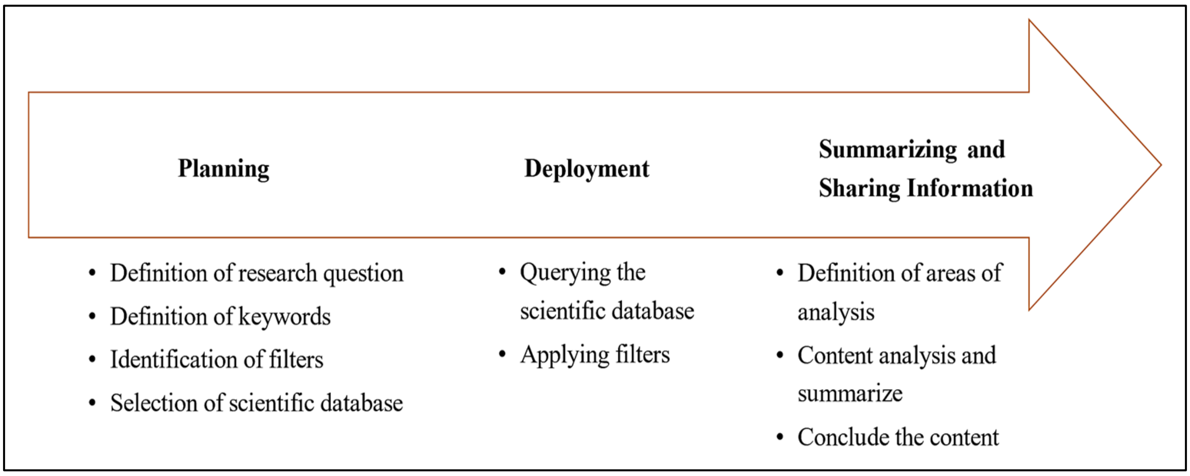

Figure 6: SLR methodology

Review structure

The organization of this paper is structured as follows, as shown in Figure 5. Section 1, titled "Introduction" consists of 6 subsections: "Definition of Digital Twin", "Definition of Digital Twin: Fluid Power Applications", "Evolution of Digital Twin", "Background of Fluid Power Applications", "Significance of Digital Twin: Fluid Power Applications", and "Review Structure". This section offers a concise summary of the digital twin definitions, particularly within the scope of fluid power applications. The article explores the evolution of digital twin, reviewing its historical progress in the field of engineering and highlighting important milestones and technological developments that have facilitated its extensive adoption. Furthermore, it offers a brief overview of fluid power applications, emphasizing their crucial role in several industrial sectors. Ultimately, it highlights the significance of digital twin in the context of fluid power applications and presents an organized structure for the review. Section 2, headed "Methodology", is a clear description of the approach used to review and synthesize information on digital twin in fluid power applications. It also includes the search index of the literature that was used. Additionally, it provides a series of questions for the assessment of each section. Section 3, titled "Digital Twin Constituents", provides a brief description of the main components of a digital twin in the context of fluid power applications. These components include physical representation, virtual representation, and communication framework. Physical representation refers to the replication of the physical components of a fluid power system in digital space. On the other hand, virtual representation encompasses a digital model that represents the physical system, including simulations, algorithms, and real-time data integration. Finally, the communication framework defines the protocols and methods that facilitate smooth data interchange between the physical and virtual elements of the digital twin. Section 4, titled "Conclusion", serves as the last section of this review, providing a summary and final thoughts.

Methodology

The systematic literature review (SLR) approach typically consists of three distinct stages: literature review planning, literature review deployment, and summarizing and sharing information (4). These procedures are followed in order to do the current review research. This study adheres to the SLR methodology and tries to fulfill the aim of the review, as illustrated in Figure 6. A search is conducted on resources published between 2000 and 2023, encompassing various source formats such as journal papers, conference papers, and book series. The publications included search terms such as "Digital Twin," "Fluid Power Systems," "Fluid Power Application," "Hydraulic Systems," "Pneumatics Systems," "Framework," "Implementation," "Manufacturing," etc. These terms were selectively combined in the various sections of the publications. The comprehensive index for conducting thorough literature searches in academic databases is presented in Table 1. Over 150 pieces of literature have undergone meticulous examination based on their relevancy ranking. 58 papers, which are highly relevant to the aim of the review, are selected and included in the Mendeley database for thorough reading and analysis. These papers cover various sections such as the title, abstract, introduction, methodology, constituents, and conclusion. During the literature screening phase, the study focuses on the selected documents for the database confined to the domain of "fluid power applications" in order to narrow down the specific research area of this review. This paper presents and examines the following four review questions derived from a comprehensive evaluation of existing literature.

1. What does digital twin stand for?
2. What is the significance of fluid power systems in industrial applications?
3. What is the role of digital twin in fluid power applications?
4. What are the main constituents of digital twin in the context of fluid power applications?

Discussion

Digital twin constituents

The inherent complexity of digital twin is fostered by three fundamental elements that constitute its core essence: physical representation, virtual representation, and an effective communication framework (35).

Table 1: Literature search content: Academic database

Search Index	Details
Database	Scopus, IEEE Xplore and Web of Science
Time Range	From January 2000 to November 2023
Search Term	"Digital Twin", "Fluid Power Systems", "Fluid Power Applications", "Hydraulic Systems", "Pneumatic Systems", "Framework", "Implementation", "Manufacturing", etc. with selective combination of aforementioned terms.
Term Location	"Title", "Abstract" or "Keywords" of papers
Literature Type	Journal papers, Conference papers and Book Series
Last Accessed Date	November 20, 2023

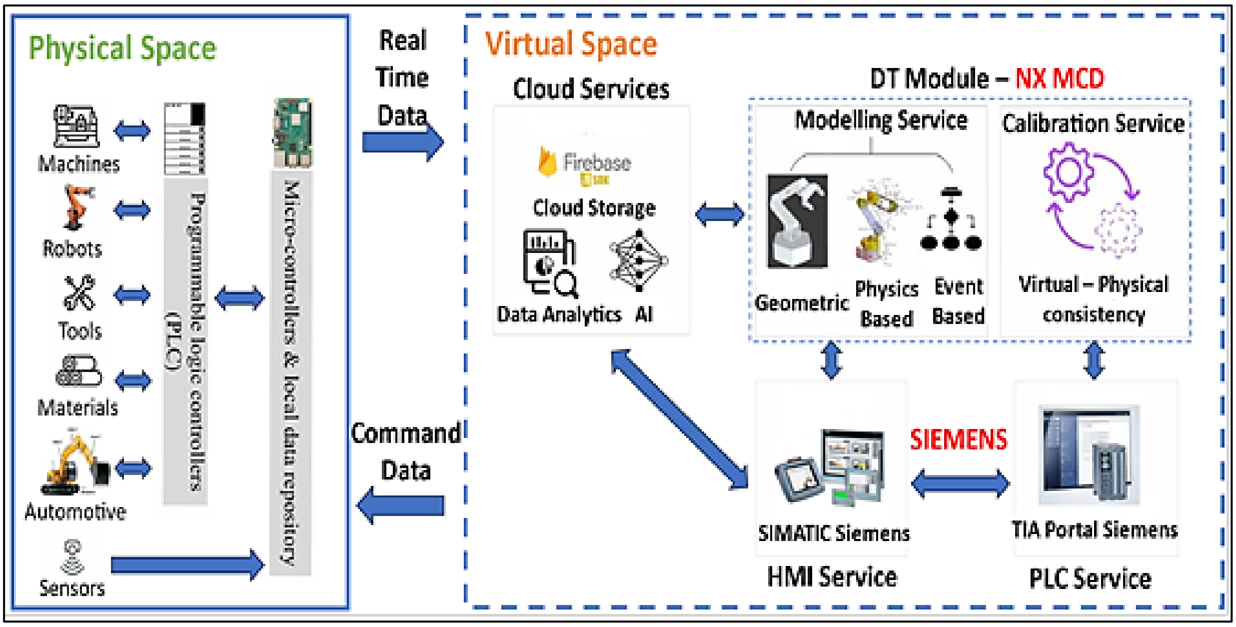

Figure 7: Architecture of digital twin for fluid power applications

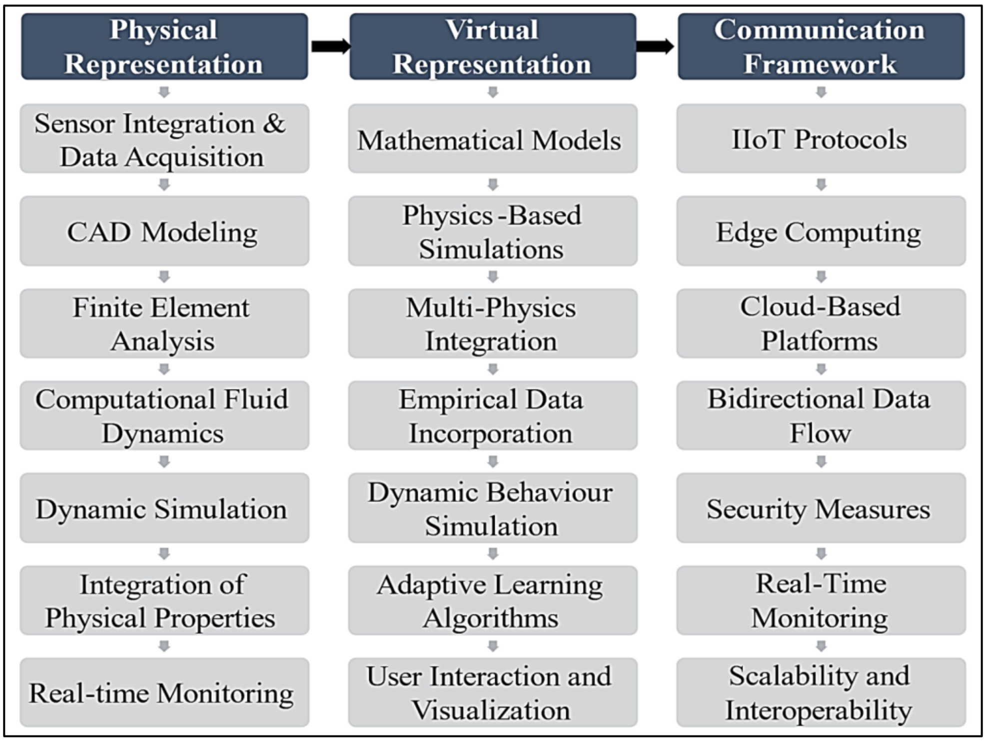

Figure 8: Flow of digital twin constituents

Figure 7 illustrates the typical architecture for fluid power applications based on this three-dimensional digital twin model. These several elements jointly coordinate the complex interaction between the physical and digital domains, encompassing the material aspects, generating a precise digital representation of fluid power systems, and producing an effective conduit for instantaneous data communication. The subsequent section explores the intricate significance of each constituent, elucidating their respective functions in creating the transformative potential of digital twin across several domains, with particular attention to their implications in the field of fluid power applications. Figure 8 illustrates the detailed constituents and their respective flow.

Physical representation

In the domain of a digital twin, the term "Physical Representation" pertains to the meticulous and precise replication of a physical system within a digital environment. This entails the process of capturing and representing the tangible elements, structures, and actions of the fluid power system within a simulated environment. The objective is to develop an accurate and interactive digital representation that accurately reflects the physical counterpart in the real-world.

Sensor integration and data acquisition: The method commences by deploying sensors across the physical fluid power system. The sensors are strategically positioned to collect pertinent data on several factors including pressure, temperature, flow rates, and the condition of individual components such as pumps, valves, and actuators. The data obtained from sensors is consolidated into a centralized data acquisition system. This system collects and combines up-to-date data, offering a complete perspective on the current condition and efficiency of the physical hydraulic or pneumatic system (36).

Computer-aided design modelling: Subsequently, the next phase entails generating a complex three-dimensional representation of the fluid power application. This model includes the geometric configuration, shape, and sensory characteristics of each element (37). CAD technologies are frequently utilized to precisely depict the configuration, dimensions, and interrelationships of fluid power systems.

Finite element analysis (FEA): FEA is employed to simulate and study the mechanical characteristics of the physical fluid power systems (38). It aids in reproducing the structural responses of components in different circumstances, including elements such as material characteristics, stresses, and deformations. This phase guarantees that the virtual representation precisely mirrors the mechanical behaviours of the actual system.

Computational fluid dynamics (CFD)

In the context of fluid power applications, the utilization of CFD plays a vital role in accurately simulating and reproducing fluid phenomena. The virtual model is capable of simulating the fluid flow, temperature gradients, and pressure distributions (39). CFD enables the precise depiction of fluid dynamics, hence guaranteeing that the digital replica comprehensively encompasses the complexities of the hydraulic performance of the physical system.

Dynamic simulation: The physical representation of a fluid power system is not in a state of equilibrium; it is imperative that it accurately reflects the dynamic characteristics of the system. Dynamic simulation techniques are utilized to duplicate the transient responses of fluid power components in response to alterations in operating conditions (40). This encompasses the utilization of simulations to replicate the processes of initiating operations, ceasing operations, and encountering diverse operational circumstances, to verify the realistic behaviour of the virtual model.

Integration of physical properties: The computerized model incorporates the physical attributes of materials, including density, viscosity, and thermal conductivity. This stage guarantees that the virtual representation precisely mirrors the actual properties of the materials employed in the real fluid power systems (41).

Real-time monitoring: The digital twin possesses the ability to continuously monitor the physical fluid power application in real-time. The data collected by the sensors is integrated into the virtual model of the fluid power system, enabling the digital twin to adjust and develop in response to modifications or variations in the actual system's performance (42). The achievement of a high-fidelity physical representation of fluid power applications is made possible by adhering to the prescribed stages, enabling engineers and operators to acquire valuable insights, perform simulations, and make well-informed decisions by using the virtual simulation of the actual fluid power systems.

Virtual representation

Virtual representation, in the domain of the digital twin, entails the creation of a digital representation that precisely replicates the real-world system it is intended to simulate. The digital replica of the fluid power applications serves as the basis for simulations, analysis, and real-time monitoring in the virtual world. The subsequent section provides an in-depth examination of the fundamental components of virtual representation considering fluid power systems.

Mathematical models: Virtual representation is dependent on mathematical models that accurately depict the functioning of the fluid power applications. These models are derived from the fundamental laws of physics, fluid dynamics, and thermodynamics. Equations that govern the dynamics of fluids, including fluid flow, pressure variations, and the transmission of energy are crucial elements of the mathematical model for hydraulic or pneumatic systems (43).

Physics-based simulations: Virtual representation utilizes meticulous physics-based simulations to accurately reproduce the dynamic behaviour of the physical fluid power application. Mathematical techniques are utilized to solve difficult equations, enabling the digital model to represent the dynamics of fluid flow, structural stresses, and heat transfers. This feature guarantees that the digital replica precisely mirrors the system's behaviour in diverse circumstances (44).

Multi-physics integration: Fluid power systems encompass the complex interaction between mechanical and hydraulic or pneumatic elements. The virtual representation incorporates multi-physics modeling to accurately represent these interactions (45). This comprehensive technique guarantees that the digital representation of a fluid power system accurately depicts the system's behaviour across various operating situations, resulting in a more authentic simulation.

Empirical data incorporation: In order to improve precision, empirical data obtained from the actual fluid power applications is integrated into the virtual representation (46). Sensors and monitoring devices collect empirical data that enhances and verifies the accuracy of mathematical models. Continuous improvement is attained by incorporating machine learning algorithms, which enable the digital twin to adapt and enhance its predictive powers progressively.

Dynamic behaviour simulation: Fluid power systems have dynamic characteristics during transitory situations. Virtual representation is specifically engineered to replicate these fluid reactions, providing an instantaneous depiction of the system's performance during the initiation, cessation, and abrupt alterations in load (47). The utilization of dynamic behaviour simulation is imperative in recognizing the robustness of the system and enhancing its performance through optimization.

Adaptive learning algorithms: The integration of adaptive learning algorithms significantly improves the abilities of virtual representation (48). The digital twin enhances its predictive capabilities for the fluid power applications by constantly synthesizing knowledge from both past and present data, thereby enhancing its model and increasing accuracy. By employing adaptive learning techniques, the virtual representation is continuously updated and optimized to maintain its relevance and effectiveness throughout the system's lifespan.

User interaction and visualization: The presence of a user-friendly interface enhances the ease of interacting with the virtual representation (49). Engineers and operators can visually perceive the digital representation, examine variables, and view real-time simulations. Visualization technologies facilitate the interpretation of technical data, enabling users to make well-informed decisions and acquire essential information about the functioning of fluid power applications.

The virtual representation of fluid power applications in a digital twin is a complex synthesis of mathematical models, physics-based simulations, empirical information, and adaptive learning techniques. It functions as an effective tool for operators and engineers to interpret, examine, and enhance the performance of the physical fluid power system within a digital environment, transforming the manner in which hydraulic or pneumatic systems are supervised and controlled. This comprehension enhances the continuous progress in the domain of digital twin and its revolutionary influence on fluid power technology.

Communication framework

The communication framework, within the context of a digital twin for fluid power application, has a crucial function in enabling the smooth transmission of data between the physical and virtual fluid power components. This framework is essential for establishing synchronization, facilitating real-time monitoring, and guaranteeing the exact representation of the physical fluid power system in the digital twin. This article examines the fundamental components of the communication framework in relation to fluid power application.

IIoT protocols: The Communication Framework utilizes standardized IIoT protocols such as message queuing telemetry transport (MQTT) and open platform communications (OPC) unified architecture (UA) to ensure an effective and secure exchange of data (50). These protocols facilitate communication between physical and virtual fluid power components, ensuring the dependable and consistent exchange of data (51). The inherent characteristics of MQTT, such as its lightweight and publish-subscribe nature, improve real-time communication in fluid power systems.

Edge computing: In order to reduce latency and improve responsiveness, the communication framework frequently incorporates edge computing. Edge devices are capable of conducting data processing in close proximity to the physical fluid power system, hence diminishing the need for centralized processing (52). The distributed technique is highly suitable for real-time fluid power applications, enabling faster reactions to dynamic conditions.

Cloud-based platforms: Cloud-based systems function as centralized servers, performing an essential function in the communication framework. They facilitate secure storage, analysis, and exchange of data (53). The physical fluid power system's connectivity to cloud servers enables centralized control of digital twin, allowing for remote usage, interactive analysis, and long-term archiving of past information.

Bidirectional data flow: The communication framework is characterized by its ability to facilitate bidirectional data transmission (54). The physical fluid power system's sensor data is relayed to the digital twin, which can then communicate information derived from the virtual model back to the actual fluid power elements. The bidirectional flow creates a closed-loop feedback system, guaranteeing that the virtual representation stays linked with the physical environment.

Security measures: Due to the sensitive nature of the data being transmitted, it is crucial to implement strong security measures. The communication framework incorporates encryption techniques, secure authentication, and accessibility restrictions to ensure the integrity of data and prevent illegal access (55). Ensuring the confidentiality and reliability of interconnected fluid power systems requires the implementation of several essential security measures.

Real-time monitoring: The communication framework facilitates the instantaneous control of the physical fluid power system. Continuous data transfer enables operators to evaluate performance, identify anomalies, and receive notifications in the event of deviations (56). The ability to operate in real-time improves the system's ability to withstand challenges, allowing for proactive decision-making and reducing the negative effects of prospective problems.

Scalability and interoperability: The communication framework is specifically designed to facilitate adaptation, hence ensuring scalability (57) and achieve interoperability (58). It allows for the incorporation of new sensors or devices without significant alterations. Interoperability is a crucial aspect that guarantees seamless communication between the digital twin and fluid power systems, promoting flexibility and adaptation in the constantly changing environment of fluid power technology.

The communication framework acts as a conduit between the physical and virtual domains of fluid power applications, facilitating a seamless flow of information that allows engineers and operators to actively observe, evaluate, and enhance fluid power systems in real-time. By incorporating secure and two-way communication, the digital twin becomes more efficient and becomes a highly valued tool in contemporary fluid power applications.

Conclusion

This review has explored the evolving technology of digital twin in fluid power applications, providing a more precise perspective on the current research environment. The paper establishes a foundation of knowledge for researchers as well as professionals by presenting a precise conceptualization and definitions within the broader scope of fluid power application. The inclusion of a historical evolution timeline provides a vital chronological viewpoint, which enhances the understanding and recognition of the progression of digital twin. The importance of these digital replicas in enhancing the performance of fluid power systems is emphasized, highlighting their function in enhancing efficiency and maintenance operations. The review structure and SLR methodology approach, which are clear, make the content easily accessible.

This synthesis aims to enhance current understanding and offer details regarding the various elements of digital twin, specifically in the context of fluid power applications. These components encompass the physical representation, virtual replica, and communication framework, which collectively establish the fundamental basis of this revolutionary technology. The complexities of duplicating the physical system in the digital domain (physical representation) establishes the basis for precise simulations and live monitoring. The digital model, also known as the virtual representation, functions as a dynamic perception, enabling predictive analysis and system optimization. The communication framework is of equal importance since it coordinates a seamless exchange of data between the physical and virtual components. This guarantees that the digital replica remains in synchronization with its physical counterpart, allowing for ongoing feedback loops and enabling dynamic responses. The collaboration among these elements not only demonstrates the complexity of digital twin technology but also emphasizes its ability to transform fluid power systems. As we explore the emerging field of digital twin in fluid power applications, it is crucial to understand and enhance these components in order to fully utilize their possibilities in numerous industries. This study is a valuable resource for researchers and practitioners, offering direction on how to shape the future of innovation and implementation in the dynamic field of digital twin for fluid power applications.

Abbreviation

CFD	Computational Fluid Dynamics
CAD	Computer-Aided Design
DT	Digital Twin
FEA	Finite Element Analysis
FPA	Fluid Power Application
H. A.	Hydraulic Application
HIL	Hardware-in-the-loop
IIoT	Industrial Internet of Things
IoT	Internet of Things
MQTT	Message Queuing Telemetry Transport
NASA	National Aeronautics and Space Administration
OPC	Open Platform Communications
P. A.	Pneumatic Application
PLM	Product Lifecycle Management
SLR	Systematic Literature Review
UA	Unified Architecture
U. S.	United States
USAF	United States Air Force

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Conflict of interest

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Ethics approval

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