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Digital Twin Concept and its Applications: A Review

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Abstract

This article reviews the development of digital twin and summarizes the evolution of the concept of digital twin. The key words and abstracts of 1187 relevant papers in recent 5 years are quantitatively analyzed, and 13 key nodes are obtained. Then it analyzes the content of 9 systematic review articles and summarizes 15 core contents. Then select 115 application examples from the articles. Through the above three steps, nine descriptive general characteristics of digital twin system are summarized: Entity object; Virtual object; Twinning degree; Communication; Data; Functionality; Human-computer interaction; systematicness; and Cost control. This paper will explain these features in detail and summarize the application examples of classifying each feature. This paper aims to summarize the development of digital twin in recent years and propose a description method of system characteristics according to the application scenario of digital twin and the increasingly complex situation of the system.

Keywords: Digital Twin Model, Cyber Physical System

1. Introduction

In recent years, the rapid development of industrial digitization has achieved considerable results. The digitization of production equipment, management mode, resources, and so on has greatly improved production efficiency [1]. And with the deepening of the digitization of the existing industrial content, the potential of industrial digitization can be explored and high expectations are given.

As a breakthrough technology in modern industry, digital twin [DT] has great potential and may change the existing industrial pattern and production mode, which has become a consensus [2]. At present, the development of sensor technology, cloud computing, network physical system, big data, industrial software, CAD, CAE, cam, and artificial intelligence has greatly promoted DT [3]. The concept of DT was first proposed by NASA in the Apollo program. The mirror image of spacecraft is built through virtual space, to realize the prediction and Simulation of spacecraft in space using a mirror model on the ground [4]. In 1997, Hern'andez first called the imaging technology of virtual model" digital twin" [5]. Until 2014, NASA gave the original definition of DT and made a detailed explanation [6].

At present, the number of articles published by DT has doubled every year, involving more and more diversified and complex application scenarios, systematic concept development, subdivided fields, and the requirements for DT in industry and scientific research have also been improved compared with the initial stage. Currently, DT systems are widely used in automotive and spacecraft inspection, industrial production monitoring, medical assistance and other fields. And DT system research has changed from a technical problem to a comprehensive one, which includes technology, labor value, economic cost and operation and maintenance, and so on. As an enabling technology, DT has very strong application potential. Therefore, this paper expects to explore some typical cases and general technologies based on research.

Summary of research purpose: 1. Analyze the development status and concept evolution of digital twins. 2. describe the general characteristics of digital twin system. 3. Summarize the key technical tools and application examples in the research and development of digital twin system.

The flow of this paper is as follows: Chapter 1 introduces the concept and development history of DT. Chapter 2 introduces the research methods. Analyzes the development status of DT papers and summarizes the relevant reviews. 9 key features are summarized. Chapter 3 explains the connotation of key features in detail and lists the classification, tools, and examples related to features. Chapter 4 summarizes this paper and discusses the future development and problems of the concept of DT.

2. Research Model

The research method of this paper is a combination of bibliometric analysis and literature content analysis. The DT research literature in the last 5 years is searched, and the key nodes are extracted from the huge amount of literature by the method of bibliometric analysis. Filtering from the DT review literature in the last 5 years, the review literature was content analysis to abstract the key points, main contents and conclusions of the literature. Rapid screening of a huge number of research papers yielded 115 research papers with application examples.

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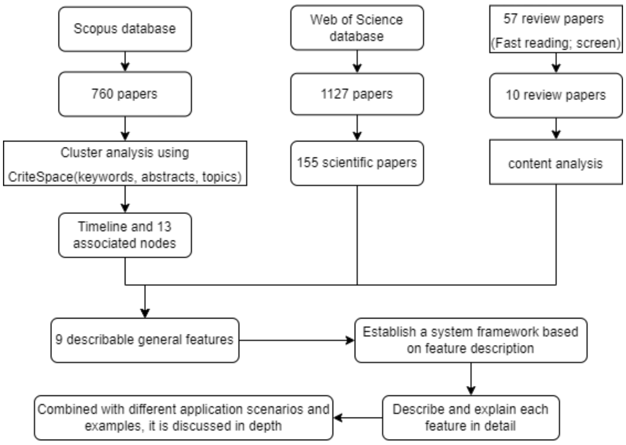


Fig. 1. Research method.

As shown in Figure 1, taking 15 core contents as boundary conditions, 13 related nodes as main analysis items, and 155 scientific kinds of literature as analysis samples. Nine descriptive general characteristics of DT system are summarized. Then, based on the nine descriptive general features, a DT descriptive system is established, and the meaning and application examples of each general feature are explained in detail.

2.1 Bibliometric analysis

Critespace is a kind of document bibliometrics software, which can analyze the information of its title, keyword, abstract, author and so on from the massive document index. Critespace adds time series based on clustering, which can intuitively and accurately reflect the association between data and the development of the time-series dimension. DT-related literature was searched from Scopus and Web of science databases for the last 5 years. Excluding duplicate literature, there were 760 and 1127 papers, respectively. Bibliometric analysis of the research papers was carried out and the items analysis were keywords, abstracts and topics. As shown in Table1, according to the resultsof the timeline, the relevance of keywords can be judged.

Summarized from the timeline, the current research focuses on the man-machine collaborative assembly, intelligent operation, and maintenance, computer control, visual damage detection, algorithm research based on semantic direction, data-driven visualization, good human-computer interaction; DT driven industrial upgrading, and a higher architecture to ensure real-time and energy utilization.

2.2 Content analysis

The keyword retrieval of DT is carried out on the platform of the Scopus database. The limited-time is from 2017 to 2022. The search results are 57 reviews of literature related to DT. Eliminate the overview of specific fields or specific application objects that have no general meaning in the review paper. Get 12 systematic and general review articles and conduct content analysis.

Table 1. Timeline table (Associated node: Related objects with time series obtained from cluster analysis]

Keyword	Associated node		
	2018-2019 year	2020 year	2021 year
Cyber-physical system	Manufacture industry 4.0		Cloud computing; Cyber-physical production system
Operation and maintenance	Maintenance		Production control; Planning; Software test
Assembly	Assembly robot	Automation product design	The human-robot collaboration end effector
Structural health monitor	Machine tool; Monitoring	Optimization	Mixed reality; Computer control system; Modeling
Architectural design	Architectural design; Information management	Forecasting	Digital replica; Physical world; Fault detection
Unmanned aerial vehicle	Data acquisition; Data handling	Optimization	Construction industry
Genetic algorithm	Knowledge-based system	Quality control; Digital transformation	Digital technology; long short-term memory; Numerical model
Human	Human	Computer architecture; Neural network	Iterative method; Prediction
Additive	Electronic data interchange; Real-time		Network architecture; Additive; data model
Scheduling		Virtual representation; Industrial revolution	Reliability analysis; Physical asset; 3D printer
E-learning	Deep learning	Predictive analytics	Competition; Data mining
Energy utilization		Machine learning	Real-time; Edge computing engi- neering education
Virtual reality	Energy efficiency	Data-driven	Energy utilization; Human-computer interaction
Visualization	Dynamics	Smart city; Virtual reality	

Content analysis is a commonly used literature analysis method, data quantitative analysis. The main definition and idea are: the value of content analysis is to classify and count the communication content in a systematic, objective, and quantitative way, and make narrative interpretation according to these categories. The content analysis of the reviewed literature is shown in Table 2.

From the above discussion and review paper table, it can be inferred that the development direction of DT and the challenges faced in recent years. How to unify the description methods and related development tools for models; how to make intelligent decisions more efficiently; how to unify the standards established at the industry standard level; and how to meticulously analysis the efficiencies and costs in industry applications.

2.3 Classification Results

Through the above analysis, nine general features can be described, which are: Entity object; Virtual object; Twinning degree; Communication; Data; Functionality; Human-computer interaction; systematicness; and Cost control. Based on these nine descriptive general indicators and taking

155 papers as samples, this paper will summarize and discuss the general technology, concepts, and application examples. As shown in Table3.

3. Features and Application Examples in Literature

3.1 Entity Object

DT entity objects show different application characteristics in different industries. This paper will list typical application cases in major industries and research fields. As shown in Figure 2. DT is used for digital management of smart cities and building industry operations. A typical case is the European connecting Europe facility; Open and Agile Smart City community; Indian Urban Data Exchange platform; Japanese smart city [16]. DT technology based on building information modeling (BIM) and the Internet of things (IoT) is used to manage various tasks and activities in different construction and operation stages of the AEC industry [17]. DT technology is used to visualize indoor conditions of buildings, such as temperature, brightness, and energy consumption parameters. The platform was tested in a case study in Italy [18].

An energy consumption model was established for the BAIC (Beijing Automotive Industry Corporation) new energy electric vehicle, and then the model is optimized and verified by the energy consumption data of the drum test [19].

Table 2. Summary of review paper (Ref: Reference paper)

Year	Ref.	Review purpose(P) and Content(C)	Conclusion
2017	7	P: From different backgrounds to expounds definition and relevance of DT to the manufacturing industry C: The role of DT for Industry 4.0 industrial	Conduct real-time synchronous simulation of the operation of the production system
2018	8	P: Classification according to the integration degree of DT C:Level of integration; Focused areas in manufac- turing; Key enabling technologies	Establish a common definition
2019	9	Review Purpose: 1. Compare DT models in the literature 2. traced back to the model in recent research C: Discussion of DT models, Purpose of Usage, Model Level, Model Formalism	Three development directions: 1. Reference architecture model with operability 2. Unified description method of DT model 3. Modeling tool software and industrial software
2019	10	P: Application and service of DT in the actual system. Improve the utilization of DT in the existing system C:DT implementation features; DT services; Over- all findings of the review; A case study	Future work should be based on specific decision-making and management rules
2020	11	P: Provide feature description of DT, identifica- tion of knowledge gap, and necessary fields for future research C: Identify, discuss and integrate conceptual States, key terms, and related processes to pro- duce 13 features	Seven knowledge gaps: perceived benefits; Product life cycle; Use cases; Technical realization; Degree of loyalty; Data ownership; Integration between virtual entities
2021	12	P: Future research direction of DT; System architecture for performing all functions of DT C: Describe the commonalities of DT, Explain DT cases and introduce representative case studies	DT core functions: Prototype design; Preliminary test of productivity and investment cost; Monitoring: real-time data synchronization; support decision-making.; Improve productivity
2021	13	P: Integrate different types of DT definitions; Understand the characteristics and types of DT	Three main problems: Lack of cost standards; Data related issues; Life cycle mismatch
2021	14	P: Key technologies required for DT; Summarize the industrial application of DT C:The three enabling technologies and 15 indus- trial applications are introduced	Connotation of DT concept: Individualization; high fidelity: continuous model update; real-time: low latency response; controllable
2022	15	P: DT technology and its applications, challenges, and limitations in engineering and other related fields C: The application of DTS in different fields and its limitations and challenges. Results and findings of enabling technology trends comparison table of enabling technologies in different fields	Data related issues (trust, privacy, network security, integration and governance, access, and large-scale analysis); With the increase in sensor and computing resources required for long-term and large-scale demand, the implementation cost is very high

In the medical field, DT is used for medical assistance and prevention. Computational modelling and simulation of the cardiovascular system can yield very valuable information about new therapies or clinical devices through in-house experiments [20]. A "digital twin" simulator is developed in the hardware in the loop framework. It is specially designed to prevent lymphedema after breast cancer after axillary lymph node dissection (ALND) and to remind them of any symptoms or recurrence to prevent their deterioration [21].

Table 3. Characteristics of DT system

Classification	Definition
Entity Object	In reality, all digital twin systems with physical and physical information exist
Virtual object	Digital description of all entity and physical information in virtual environment
Twinning degree	The adequacy of digital factors (digital objects, information, environment, etc.) to describe entity factors (entity objects, information, environment, etc.)
Communication	Methods of exchanging data information between physical factors and digital factors
Data	Processing, identification, integration, and decision-making process of data and information from entity factors in Digital Environment
Functionality	Degree of digitisation of physical objects

Human-computer interaction	The relationship and cooperation between human and digital factors and entity factors
Systematicness	Systematic description of digital twins
Cost	Cost of digital twin system in the full life cycle

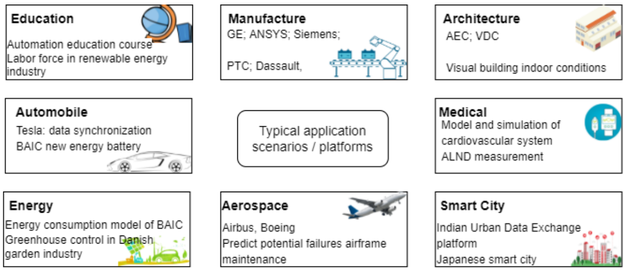


Fig. 2. Entity Object

Table 4. Summary of reference papers in main application fields

Classification	Reference
Manufacture	[24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37]
Architecture	[18], [38], [17], [39], [40], [41]
Automobile	[27], [42], [30], [43], [44], [45], [46], [47], [48], [49], [50], [51], [34], [52], [53], [54], [55]
Medical	[56], [57], [21], [58], [59], [20]
Energy	[60], [25], [61], [62], [18], [63], [64], [65], [66], [67], [68], [69], [19]
Aerospace	[70], [71], [72], [73], [74], [75], [30], [76], [77], [78], [7], [79], [80], [81], [82], [83], [84]
Smart City	[85], [16], [86], [87], [88], [49], [89], [90], [91]
Education	[92],[93], [94]

In aerospace, DT is used to detect defects. Large airlines such as Airbus and Boeing have started to develop and apply DT techniques to reflect actual conditions, identify defects, predict potential failures and address airframe maintenance issues [22, 23]. Reference examples are shown in Table 4.

3.2 Virtual Object

Virtual objects represent the digitization of entity objects, mainly including digital models; Digital workspace; Digitization of physical information, and information of toolboxes, obstacles, and other facilities. As shown in Figure 3.

Geometric information model: It describes the geometric size of the digital model, to preliminarily describe the entity object. For example, traditional CAD software is a very typical geometric modeling software [95, 96]. There are also a series of 3D modeling software, such as Pro-E, Solidworks, and CATIA. The common feature of these tool software is that they can quickly mirror the 3D dimension model of solid objects and establish the assembly relationship of solid objects [97]. Some comprehensive analysis platforms can also establish dimensional models. For example, ANSYS software can not only identify and import various formats of 3D models but also establish relatively simple dimensional information models in its own development environment [98, 99]. There are software platforms independently developed by equipment manufacturers, most of which have their product size information model library. For example, ABB's robot studio software can quickly generate the manipulator model produced by ABB and operate it [100, 101].

Yu Zhou takes free-form blades for five-axis flange milling as the object for geometric modeling and optimization while considering the balance of machinability and aerodynamic performance [102]. IEK man Lei and his team used DT combined with 3D printing technology to model the geometric information of cochlear implant and patient's ear contour [59]. Zheng Xu deeply analyzes the gas exchange system of a 2-stroke heavy fuel aircraft engine and establishes a geometric information model [103].

Logical information model refers to the model representation of physical logic, physical rules, working logic, and working rules that can describe entity objects. For example, the workflow can be used to describe the working rules and logic of entity objects on the MATLAB software platform [104]. In addition, there are integrated text language development environments such as visual studio and Pycharm. C, C + +, Python, and other languages can be used to describe the rules and logic of entity objects and establish the rule information model [105].

Mark Austin, in order to establish a better information model of smart city, uses a semantic description method to establish a logical information model [106]. Asma Ladj uses a knowledge-based framework to establish a logical rule information model for machine tools in machine tool manufacturers' factories [107]. According to the characteristics of DT workshop and machining machine tools, Zhifeng Liu establishes a super network model of logic rules [108].

The dynamic information model is inclined to describe the dynamic information of entity objects. By responding to driving and considering the interference of external factors. For example, the ADAMS software platform can analyze the movement, trajectory, and dynamic torque changes of electromechanical equipment under the condition of considering external factors. The commonly used PLC compiling tool CoDeSys can be linked to the Mworks platform through communication to describe and control the movement of machine tools, manipulators, and other equipment. Simulink integrates a multi-disciplinary toolbox. It can quickly call some dynamic description modules in the development environment to establish the framework of the behavior information model [109].

Gabor Erdos establishes the dynamic model of the industrial robot by digital method and verifies it on grinding and polishing robot [110]. Yang Yi established a dynamic information model for the assembly process and process of complex products [111].

The physical information model refers to the physical information of the entity and its components, including a series of physical factors such as material, wear coefficient, hydraulic and pneumatic parts, battery, motor, calorific value, and so on. The typical physical information model analysis platform is ANSYS, which integrates a rich material library of metallic and non-metallic materials. Simulink, a multi-disciplinary module integration platform, can also quickly build physical information models by calling modules of various disciplines, such as friction, fluid, collision, etc.

Yang Xie established a physical information model for the tool and discussed the problem of tool wear in combination with the DT system [112]. From real devices to DT, Luca Antonini and her team established physical information models in the research of new bioabsorbable scaffolds [56].

Digital workspace requires to accurately mirror the physical workspace. The most important thing is that the digital workspace needs strong compatibility with the model and rich extensible external interfaces. Unity3D has advantages in scene construction and rendering, supports C, Java, and other Chinese programming languages, and has rich interfaces [113]. There are also some modeling workspace development platforms, such as Coppeliasim and Gazebo, which can directly import and identify a variety of model files and have a rich scene module library [114].

The available tools and reference examples are shown in Table 5.

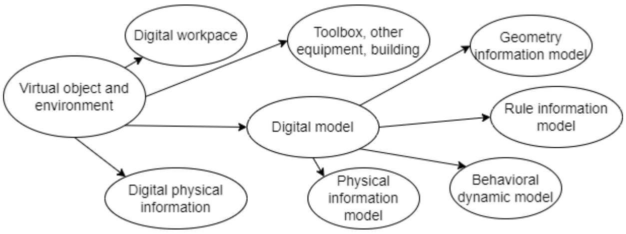


Fig. 3. Digital model and scene classification

Table 5. Digital modeling tools and reference papers

	Classification	Tool	Ref
Digital model	Geometry information model	AutoCAD; CATIA; UG; Solidworks; Pro-E; 3D Max; CAXA	[115], [59], [83], [96], [116], [102], [103], [110], [111], [112], [117], [118], [119], [120], [121], [122], [123], [124], [125]
	Rule information model	Matlab; Pycharm; Workflow; Visual studies; Keras	[16], [37], [57], [75], [81], [86], [102], [103], [106], [107], [126], [108], [111], [122], [127], [128], [129]
	Behavioral dynamic model	Simulink; ADAMS; Matlab toolbox; 3DMax; Mworks; Dymola	[115], [42], [44], [85], [94], [102], [126], [108], [110], [130], [131], [111], [120], [121], [124]
	Physical information model	Simulink; ANSYS; Fluent; Fidap; Ployfolw; Mixsim; Icepak; CFX-TASCflow	[19], [66], [26], [56], [67], [69], [132], [116],[103], [108], [130], [131], [133], [112], [134],[117]
Physical information			
Digital workspace, Toolbox		Unity3D; gazebo; coppeliasim	[126], [108], [118], [119], [120]

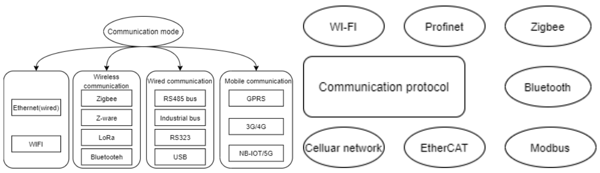
3.3 Twinning Degree

Twinning level refers to the adequacy of the description of physical objects by digital models or information. For example, in order to explore the machining process of centrifugal Impaler, Yu Zhou modeled the geometry of centrifugal Impaler and the change of surface geometry in the machining process in detail, but the digital model did not consider the physical factors that will affect the machining, such as material characteristics, tool state, machining environment, vibration, stress deformation, temperature and so on [102]. The digital model established by Meng Zhang on job shop scheduling describes the entity object and entity space at the policy level. In this case, the object is more unitized than the dynamic characteristics in the unit [125]. The digital model established by Ali vatankhah barenji describes the energy and energy loss of industrial robots in detail, but the digital model lacks description of the structure of industrial robots [121].

Therefore, for this situation, it is necessary to have an index to describe the twinning degree of the system. The concepts of black box, white box and gray box can used to describe the twinning degree of the system. Black box has the lowest degree that means a specific function is output directly according to the model rules without considering the internal structure, characteristics, information and other factors of the entity object. Gray box means to consider or describe the internal structure of a part of an entity object; Modeling output in the case of characteristics or information. White box indicates that the digital object completely and fully describes all the characteristics, structure, information and other factors of the entity.

3.4 Communication

The communication technology of DT technology and IOT equipment communication technology coincide to a great extent, which is different according to the physical link mode and communication limit distance. Common communication methods can be divided into four categories: wired communication, wireless short-range communication, mobile communication, and network communication, as shown in figure 4.



Fig, 4. Communication Type and Protocol

Wired communication is suitable for field type DT systems. Low latency, high fidelity, convenient for centrally deployment. RS485 bus is the most widely used communication mode in the field of automation. RS485 can realize the networking function [135]. PROFINET is widely used in automation solutions to link systems in manufacturing environments [136]. EtherCAT is based on CANopen protocol and Ethernet and is specially designed for the field of industrial automation. It uses any standard PC as the EtherCAT master station in sequence and uses any topology network to communicate with the EtherCAT slave station. It is safe and reliable and can link all equipment in the factory in the shortest time [137].

Wireless short-range communication enables easier deployment of DT systems and reduces energy consumption. ZigBee is a short-distance wireless LAN technology. It is characterized by low speed, low complexity, low cost, and supports network topology. The standard is formulated according to IEEE802.15.4 [138]. LoRa is a local area network technology, which is characterized by low power consumption and can realize long-distance transmission than traditional wireless communication [139]. In the field of short-range wireless transmission, the most commonly used communication protocols are ZigBee and Bluetooth. Bluetooth supports a data transmission rate of up to 1Mbps, with an effective range of 50-100 meters [140].

Network communication enables DT systems to break through spatial constraints and pool more resources. Mobile communication includes 3G, 4G, and NB-IOT/5G. NB-IOT refers to 'narrow band Internet of things' to achieve the carrying capacity of the Internet of things through the ultra-narrow band, repeated transportation, and simplified network protocols [141; 140]. The cellular network protocol is applied in the field of mobile networks, which can realize ultra long-distance transmission, and data can be exchanged up to 23dbm [142].

3.5 Data

The data directly reflects the physical information of entity objects, dynamic change information, and the change of environmental variables. As shown in Figure5, Data processing mainly includes data acquisition, data transmission, data storage, data processing and preprocessing, and data fusion. The available tools and references examples are summarized in table 6

Data acquisition is a complete collection of data measured or obtained from various channels, and then ready for transmission. Yi CAIA, Binil Starry's team researched sensor data acquisition and processing in DT system and verified it on the machine tool [143]. Jinsong Yu established a DT system based on health detection [144].

Data storage: The data storage of the database is the basis for subsequent data calls and data writing. Data storage requires effectively classifying and saving data, and having an efficient data reading and writing mechanism, which can call data quickly and conveniently. Shanghai Mi divides data into device data through an open cloud platform; Environmental data; Resource status data and environmental plan data are stored [128]. Y. H. pan uses edge computing, an open platform, which integrates the core functions of the network, computing, storage, and application close to objects or data sources [129]. Wenjun Xu combines industrial robots and cloud services and encapsulates them into industrial robot cloud services to realize the operation of data [124].

Usually, there are many factors in the collected data, such as noise, missing data, scattered data, irrelevant data, and so on. At this time, the data quality is low and may not be used directly, so the data needs to be preprocessed. Common data preprocessing software, such as hive, Apache spark, impala, Apache storm, etc.

Data fusion usually refers to statistical analysis of data, extraction of features, correlation of feature vectors, target recognition, etc., to obtain preliminary conclusions and judgments on the observation object. Various algorithmic models can also be used to mine, learn and train the data to achieve a more desirable outcome or predictive state. Yi Cai extracts the machining contour features through the data processing of machine tool sensors and puts forward the fusion analysis of data and information in this paper [143]. Qibing LV outputs the processing optimal solution of the assembly system for a large number of data Jinxing operations with different structures and constraints in the assembly process [120]. Ali Vatankhah Barenji realizes the optimization of human scheduling in the scenario of a satellite production workshop by combining data fusion and knowledge management [121]. Xingzhi Wang achieves the effect of data integration through data fusion and Simulation of intelligent customization mode [145].

The available tools and references examples are summarized in table 6.

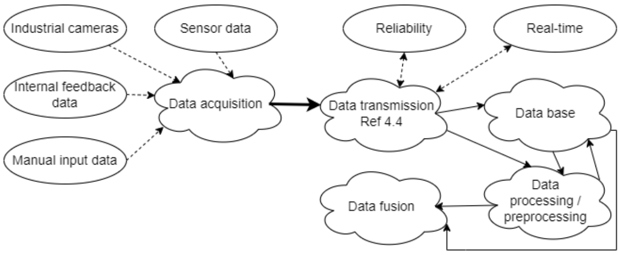


Fig. 5. Data processing induction

Table 6. Data processing tools and reference papers

Classification	Tool	Ref
Data acquisition	Mindspere; Exlab; X-modal; Octoparse; Kepware; KEPServeEX; BasicFinder; Apache Flume	[107], [126], [131], [111], [112], [134], [144], [143], [145], [146]
Data storage	MongoDB; Alibaba cloud relational database; Visual FoxPro; PostgreSQL; DB2; SQL Server; Oracle; MySQL; DynamoDB	[23], [107], [108], [111], [112], [117], [124], [128], [129], [147], [145]
Data processing/preprocessing	Hive; Apache Spark; Impala; Apache Storm Matlab; Pycharm; Visual studio; SPSS; Spyder	[115], [23], [126], [131], [111], [112], [124], [125], [144], [145]
Data fusion	Matlab; Pycharm; Visual studio; SPSS; Spyder	[103], [107], [131], [134], [120], [121]

3.6 Functionality

Functionality have been very important features in the DT system concept, since the DT system concept was proposed. DT system is difficult to cover the functionality and all of functionality of entity objects. Therefore, how to measure the coverage of distributed test system to the life cycle of entity objects is the main content of this sections. The description of the life cycle of entity objects can describe the application characteristics of entity objects in different periods. A complete entity object must go through four stages: design and manufacture, service and retirement. The functionality of auxiliary design, prediction, monitoring and optimization runs through functionality. In the design and manufacturing stage, the auxiliary design function of digital twins is particularly prominent. In the service stage, the monitoring and prediction functions are more obvious. In the retirement stage, it is more convenient to summarize and optimize the whole work information data of the product during its service. It can be seen from the above that the articles in the system design have absolute advantages, but the number of articles in the prediction and simulation stage is still very small. Therefore, to a certain extent, functionality coverage of distributed testing is still a challenging topic.

3.7 Human-computer Interaction

Digital technology upgrading does not mean that the DT system should be isolated from human beings. Man- machine relationship is still a topic worthy of discussion in the research of various fields. The basic requirements of a human-computer interaction system are good data visualization interface, convenient manual operation interface, reading, writing, and sending of data and instructions. At present, there have been many mature human-computer interaction system development platforms. For example, LabVIEW, Matlab GUI (Graphical User Interface), QT and visual studio.

Kendrik Yan Hong Lim integrates robot and working environment through a 'C++'development environment and can realize collision and operator instructions through GUI [119]. Qibing LV deeply discusses the digital driven assembly method from the perspective of man-machine cooperation [120]. Gang Wang integrates user-operable resource management and data visualization in the management platform of shared manufacturing resources [146]. Tian Wang deeply discussed the possibility of the combination of VQA Technology [visual question answering] and DT [148]. Available references examples and tools are shown in Table 7.

Table 7. Human-computer interaction tools and reference papers

Tool	Lab VIEW; Matlab GUI; QT; visual studio; Visual Basic
Ref	[115], [112], [119], [120], [146], [148], [149]

3.8 Systematicness

DT system is a comprehensive complex system, which integrates the functions of data processing, communication, simulation, modeling, and so on. Therefore, it is necessary to evaluate the general performance of the system, including reliability, security, scalability, and compatibility. Among them, scalability requires the expansion ability of DT system in response to future demand changes or increases. Compatibility refers to the ability of the software and hardware of the DT system and the coordination between models. The definitions and references examples are summarized in Table 8.

Table 8. Systematic definitions and reference papers

Classification	Definition	Ref
Extensibility	There are reasonable ways to deal with the growth of digital and physical factors	[130],
Integration	The ability of digital factors, physical factors, and communication to coordinate and cooperate with each other	[124], [143],
Reliability	The ability of digital twin systems to work in difficult situations	[150],
Compatibility	The ability of digital twin systems to be compatible with each other	[149]

3.9 Cost Control

The cost problem is directly related to industrialization and large-scale application. DT is a huge and complex integrated system, involving multi-disciplinary, software development and hardware application. The cost control is directly related to whether the DT system can go out of the laboratory, be widely popularized, industrialized, standardized, and applied on a large scale. Costs mainly include R&D and design costs, labor manufacturing costs, maintenance costs, hardware acquisition costs, and other cost categories. The definitions and references examples are summarized in Table 9.

Table 9. Cost definition and reference papers

Classification	Definition	Ref
Design Cost	Costs of software, creativity, patents, etc. in the design stage	
Hardware Cost	Hardware procurement, loss, and other costs	[17], [66], [21], [26], [29],
Maintenance Cost	Daily maintenance, detection, and replacement cost of system	[30], [34], [38], [42], [56],
Labor Cost	Cost of manual assembly, manufacturing, creativity, etc	[60], [132], [86], [96], [102]

4 Future Prospects

This paper summarizes the development history and current situation of digital twin system. According to the development status of digital twins and the current technological development trend, this paper puts forward the future development direction of 4 digital twins. They are Human-computer interaction upgrading; Multimodal information fusion; Multi terminal data synchronization and sharing.

Human-computer interaction upgrading: The principle of traditional human-computer interaction is to explore the interaction among human, machine and environment. As shown in the figure6 (a). The three achieve a balanced state through mutual influence and interaction, that is, human operate machines with high efficiency, more conveniently and comfortably. The development of DT can broaden the boundary of human-computer interaction principles. The traditional human-computer interaction principle does not involve such a high degree of digitization, although it also takes into account the impact of digitization and virtualization. Therefore, how to highly digitally simulate behaviour of human. How to highly digitally simulate the effects of human-machine influences. This is an exciting challenge.

Multimodal information fusion: With the development of information technology and intelligent algorithms, a variety of sensors are used in industrial fields, such as common vision sensors; Sound sensor; Electromagnetic sensors, etc. Multimodal information fusion refers to the fusion and optimization of information collected by different types of sensors, so as to obtain more comprehensive and accurate information of the tested object. The information usually presents different modes, such as two dimensional mode for images and one-dimensional mode for sound signals. Multimodal information fusion technology is one of the most important research directions in the field of information measurement and fusion. The feature of digital twins is to mirror the information of physical objects and environment as much as possible. Therefore, the integration of DT and multimodal technology is very desirable.

Multi terminal data synchronization and sharing: This paper summarizes the practical communication methods and protocols in the DT system. In fact, in the real production and living, the system usually needs to match different intelligent terminals through a variety of communication methods, as shown in the figure. These different intelligent terminals will be part of the digital environment. It is a huge challenge to achieve data sharing on different intelligent terminals and achieve better data synchronization through different communication methods. The data synchronization and sharing of the digital twin system gives further imagination to the era of industrial intelligence.

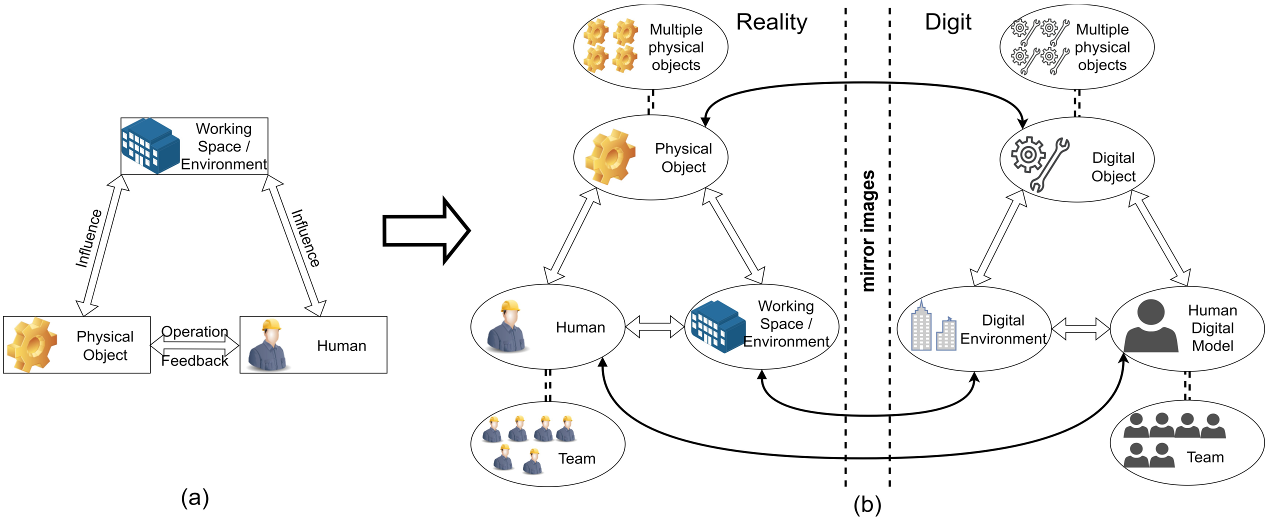


Fig. 6. Human-Computer Interaction in DT System Framework (a) Traditional human-computer interaction, (b) Human- computer interaction under the DT framework

5. Conclusion

The main work of this article is to summarize the key features of digital twins from a large number of literatures using bibliometric methods, and explore their details, trying to elaborate the development status and future direction of digital twins. The author hopes that readers can benefit from this article and express the available digital twin features for readers. There are still many deficiencies in this article. In the process of bibliometrics, there must be some information loss. Digital twins is a very broad concept. In recent years' development, Digital Twin has shown its amazing potential and constantly broadened its application boundaries. It is undeniable that digital twin technology is very promising to play an important role in the future intelligent industry. For the research of digital twin theory and technology, the author believes that the key is to use imagination and boldly explore the possibility of digital twins for the industry.

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