工业数字孪生系统的概念、结构与运行模式

The Concept, Structure and Mechanism of Industrial Digital Twin Systems

摘要：数字孪生（Digital Twin，DT）技术在制造业的研究最早，目前技术应用相对成熟，但是其理论研究和技术应用集中在数字孪生体的表达、基于数字孪生的设计制造一体化、基于数字孪生的产品故障诊断和运行维护等方面，涉及工业产品的数字孪生系统的特点、系统组成、逻辑架构和系统运行模式的研究较少。本文针对这一问题，在对比不同类别的数字孪生系统的基础上，提出了工业数字孪生系统（industrial Digital Twin System，iDTS）的概念，并总结 iDTS 的典型特点，包括以人为中心、“人-机-环境”相互融合、系统保高保真度和孪生模型复杂；iDTS 通过由物理层、感知层、孪生层、应用层和控制层组成的功能结构满足这些特点；另外，提出了 iDTS 的成熟度模型，描述随着产品或系统的生命周期进展，iDTS 的成熟度阶段。最后，针对具体的工业应用场景，论文分析了 4 种 iDTS 的运行模式，并通过典型案例验证所提出 iDTS 的可行性。

Abstract: Digital twin was originally and firstly researched in manufacturing, and is now widely and maturely used for application in industries. Recent theoretical studies and technical applications mainly focus on the definition of the digital twin, the integration of design and manufacture based on digital twin, and the fault diagnosis and operation maintenance of products on the basis of the digital twin. There are very few studies on the characteristics, system composition, logical architecture, and system operation mode of digital twin systems applied on industrial products. To fill the gap above, this paper proposes the concept of industrial Digital Twin System (iDTS) and summarizes the typical characteristics of iDTS, based on the comparison of different types of digital twin systems, including people-centered thinking, "human-machine-environment" mutual fusion, high fidelity of the system and complexity of twin model. iDTS integrates these characteristics with the functional structure composed of physical layer, perception layer, twin layer, application layer, and control layer. In addition, the maturity model of iDTS is developed to describe the maturity stage of iDTS, along with the life cycle progress of products or systems. Lastly, this paper analyzes four iDTS operation modes and verifies the feasibility of the proposed iDTS with typical cases for specific industrial application scenarios.

关键词：数字孪生；工业数字孪生系统；组成结构；功能结构；运行模式

Key words: Digital Twin; Industrial Digital Twin System; Composition Structure; Functional Structure; Running Mode

1 介绍 Introduction

随着云计算、物联网、大数据和 5G 技术等新一代信息技术的兴起，各个行业都在向数字化、智能化的方向发展，例如智慧城市、智能制造、智慧农业、数字建筑和数字电网等的出现。随着新一代信息技术和人工智能技术与制造业深度融合，世界各国均在大力推动制造业的转型升级，例如德国提出的“工业 4.0”战略、美国大力推进的“工业互联网”战略、欧盟部署的人工智能战略和中国重点推进的“中国制造 2025”等。数字孪生技术（Digital

Twin，DT）作为推动实现企业数字化转型、促进数字经济发展的重要抓手，在此背景下迅速成为工业界和学术界的研究热点。

With the rapid development in the new generation information technology, such as cloud computing, Internet of Things (IoT), big data, and 5G technology, various industries are moving towards digitalization and intelligence, including the emergence of smart cities, intelligent manufacturing, intelligent agriculture, digital buildings, and digital power grids. As for the manufacturing industry, its rapid integration with the new-generation information technology pushes countries around the world to vigorously promote transformation and upgrading, i.e. the “Industry 4.0” strategy proposed by Germany, the “Industrial Internet” strategy developed by the United States, the artificial intelligence strategy deployed by the European Union, and the “Made in China 2025” strategy. Digital Twin (DT), as a key driver for accelerating the speed of the transformation and upgrading, has rapidly become a research hotspot in industry and academia.

DT 是以数字化方式创建物理实体的虚拟模型，借助数据模拟物理实体在现实环境中的行为，通过虚实交互反馈、数据融合分析、决策迭代优化等手段，为物理实体增加或扩展新的功能[1]。虚拟模型不仅能对物理实体实际行为进行多维度的刻画，也能达到虚实共生，实现对物理对象的监控、仿真、预测、优化等功能服务和应用需求，应用发展前景非常广阔。

DT is a virtual replication that mirrors the corresponding physical object. It can simulate the behavior of the physical counterpart and add or extend new functions to the physical counterpart through virtual-real interactive feedback, data fusion analysis, and iterative optimization for decision making [1]. The virtual representation can not only depict the actual behavior of the physical object in multi-dimension, but also generate the symbiosis between the virtual and the real to provide the monitoring, simulation, prediction, optimization, and other useful services. As a result, DT has high value in application and considerable potential for development.

早在 19 世纪 60 年代的阿波罗计划中，美国国家航空航天局（National Aeronautics and Space Administration，NASA）就建立了一套与实际航天任务对应的地面半物理仿真系统用于宇航员培训，该系统本质上体现了数字孪生虚实结合的特点。2003 年，美国密歇根大学的 Michael Grieves 教授在产品生命周期管理（Product Lifecycle Management，PLM）课程上首次给出了与 DT 概念等价的“镜像空间模型”，并解释该模型是“与物理产品等价的虚拟数字化表达”，它是一个系统、过程或服务的虚拟模型，由真实空间、虚拟空间和两者的数据与信息交互组成，能够从微观到宏观描述潜在的或实际的物理信息[2]。但是，此后很长一段时间，DT 并未受到广泛关注。近年来，建模与仿真技术、计算机技术、网络技术和通讯技术的快速发展，NASA 能够建立宇航任务中的各种物理实体的仿真模型，并在功能和行为上反映物理实体的真实状态。随着建模仿真工业软件的不断成熟与应用，2010 年 NASA 在其发布的 Area 11 技术路线图中正式提出了 DT 这一概念，并将其定义为“一种集成化了的多种物理量、多种空间尺度的运载工具或系统的仿真，该仿真使用了当前最为有效的物理模型、传感器数据的更新、飞行的历史等等，来镜像出其对应的飞行当中孪生对象的生存状态”[3, 4]。此后，DT 迎来了飞速发展。

In the 1960s, the National Aeronautics and Space Administration (NASA) established a ground-based semi-physical simulation system of actual space missions for astronaut training in the Apollo program, which essentially embodies the characteristics of virtual-real synthesis in DT. Until 2003, Professor Michael Grieves of the University of Michigan proposed the “Mirrored Spaces Model” equivalent to the DT in a Product Lifecycle Management (PLM) course and explained it as “a virtual digital expression equivalent to physical products”. The digital expression can be a virtual model of a system, process, or service, which consists of real space, virtual space, and the interaction of involved data and information[2]. However, DT has not received extensive attention for a long period thereafter. In recent years, the rapid development of modeling and simulation technology, computer technology, network technology, and communication technology has enabled NASA to build simulation models of various physical entities in space missions and to reflect the real state of physical entities in function and behavior. Finally, with the continious development in modeling and simulation industry software, NASA formally proposed the concept of DT in its Area 11 Technology Roadmap in 2010 and defined it as “an integrated simulation of multiple physical quantities, multiple spatial scales of a launch vehicle or system., the simulation used the most effective physical model, sensor data update, flight history at that time, and so on, to mirror the survival state of twin objects in its corresponding flight” [3, 4]. Since then, DT has ushered in rapid development.

目前，DT 已在工业、农业、教育、医疗、运输、能源等领域进行了探索和初步应用，开展了 DT 车间、DT 城市、DT 建筑、数字医疗、数字电网等众多应用研究，涵盖了人们日常生活的方方面面。但是，不同行业对 DT 的应用重点并不完全一致。例如，智能制造通过 DT 能够进行多物理场仿真、产品个性化定制设计、智能生产调度和产品全生命周期运维等[5]；DT 城市强调为城市的建设、运转和规划提供一套完整的数字基础设施，最终实现“城市大脑”，提高人的生活质量[6]；在智能建筑中，DT 强调模拟人们如何与建筑环境互动，改善居住体验[7]；电力系统 DT 的研究对象是高维度、长时间跨度的时空数据块，能够实现电网实时状态监测和异常原因诊断[8]。

At present, DT has been explored and initially applied in industry, agriculture, education, healthcare, transportation, energy, and other fields. Numerous studies in application have been carried out in DT workshop, DT city, DT building, digital healthcare, and digital power grid, covering various aspects of people’s daily life. However, the emphasis on DT applications in different areas is not entirely consistent. For example, smart manufacturing focuses on using DT to achieve multi-physical field simulation, product personalized customization and design, intelligent production scheduling, and product life cycle operation and maintenance [5]. While for the DT city, it aims to provide a complete set of digital infrastructure for city construction, operation, and planning, and ultimately enabling the “city brain” to improve the quality of human life [6]. In intelligent buildings, DT can be used to simulate how people interact with the building environment to improve the living experience [7]. The research object of DT in the power grid is the spatio-temporal data block with high dimension and long period, which can be used to realize real-time status monitoring and abnormal cause diagnosis [8].

基于 DT 在工业产品的生命周期不同场景的功能、成熟度和运行模式的特点，本文提出了工业数字孪生系统（industrial Digital Twin System，iDTS）的概念，为 DT 在制造业领域的发展提供基本理论和技术支撑。论文整体结构如下：第 1 节介绍了论文研究 iDTS 的目的和意义；第 2 节综述了数字孪生的国内外发展现状；第 3 节阐明了通用的数字孪生系统的构成，比较了不同数字孪生系统的区别；在此基础上，第 4 节给出了 iDTS 定义，建立了 iDTS 的功能结构和成熟度模型；第 5 节提出了四种 iDTS 的运行模式，并通过典型案例对所提出的 iDTS 进行了应用分析；第 6 节完成了论文总结。

Based on the characteristics of the function, maturity, and operation mode of DT in the different scenarios of industrial product life cycle, this paper proposes the concept of the industrial Digital Twin System (iDTS), which provides fundemental theoretical and technical support for the development of DT in the manufacturing field. The remainder of this paper is organized as follows. Section 2 summarizes the current development in DT. In Section 3, the composition of the general digital twin system (DTS) is clarified and the features of different DTSs are specified. Section 4 explains the definition of iDTS and establishes its functional structure and maturity model. Four types of operation modes of iDTS and their typical application cases are discussed in Section 5. Finally, conclusions are drawn and directions for future work are indicated in Section 6.

2 国内外现状 State of the art

DT 的技术发展与工程应用起源于制造业，经历了萌芽期、发展期和爆发期三个阶段，如图 1 所示。NASA 在工程实践中首先认识到了建立物体实体对应的数字孪生体的重要性，并在 2010 正式提出了 DT 这一概念，DT 赢来新的发展机遇，由萌芽期进入到了发展期，如图 1 所示。2011 年美国空军研究实验室在研究机体等疲劳及寿命预测时，形成了一个低保真性的“数字孪生体”，并随着技术的发展，进而逐步提升了保真度[9]；2012 年 NASA 和美国空军研究实验室合作并共同提出了未来飞行器的数字孪生体范例，将飞行器等数字孪生体定义成系统的、集成的多物理、多尺度、概率仿真模型，并提出了“机体 DT”的概念[10]；2013 年，美国空军发布的《全球地平线：全球科技愿景》顶层科技规划文件中，将数字总线和 DT 并列视为“改变游戏规则”的颠覆性机遇[11]；2014 年 Grieves 教授发表了关于 DT 的白皮书，并将数字孪生分进行了分类，包括数字孪生样机、实例、集合和环境，同时总结了 DT 能够解决的实际工程问题[2] [12]。

The technical development and engineering applications of DT are originated in the manufacturing industry and can be divided into three typical stages: germination stage, development stage, and explosion stage, as shown in Figure 1. In the germination stage, NASA first recognized the significance of establishing the DT in engineering practice and formally introduced the DT concept in 2010. Then it moves to the second stage when the DT embraced new development opportunities. In 2011, when studying fatigue and life prediction of airframes, models developed by the U.S. Air Force Research Laboratory formed a low-fidelity DT, and the fidelity of it gradually improved with the raising of advanced technologies [9]. In 2012, NASA and the U.S. Air Force Research Laboratory cooperated and described the DT paradigm for future air force vehicles. The flying DT was proposed, which integrated ultra-high fidelity simulation with the on-board health management system, maintenance records, and all available historical and fleet data to ensure unprecedented levels of safety and reliability [10]. Then, in the top-level science and technology planning document “Global Horizons: Global Science and Technology Vision”, the DT and digital thread were considered as a subversive opportunity to ‘change the rules of the game’ in 2003 [11]. In 2014, Professor Grieves published the DT white paper, in which he categorized DT into DT Prototype, DT Instance, DT Aggregate, and DT Environment, and identified typical engineering issues that DT can solve[2] [12].

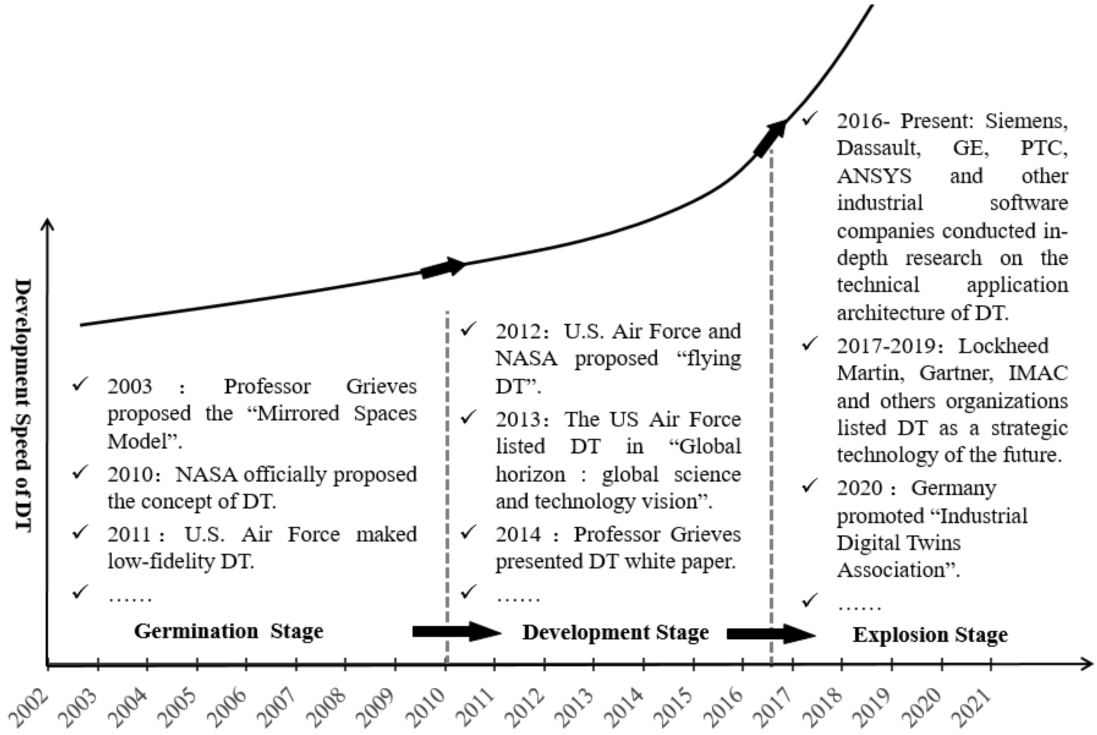

Figure 1. Three stages of digital twin development

2017 年前后，随着不同国家的科研机构和企业将数字孪生作为其未来发展的重要使能技术，数字孪生的发展迎来了爆发期。2017 年 11 月，世界最大的武器生产商洛克希德马丁公司将数字孪生列为未来国防和航天工业 6 大顶尖技术之首；2017 年 12 月，中国科协智能制造学术联合体在世界智能制造大会上将数字孪生列为世界智能制造十大科技进展之一。世界权威信息技术研究咨询公司 Gartner 在 2016、2017、2018 和 2019 连续 4 年将数字孪生列为未来十大战略性技术之一，指出在未来将会出现数以亿计的数字孪生，它们将被企业用于产品设计、生产制造、经营工厂、故障预测和运行维护等[13]。2020 年 2 月，德国工程师协会/德国电气工程师协会（VDI/VDE）发布了《设备生命周期中的仿真与数字孪生》报告；2020 年 9 月，德国各大行业协会深感工业 4.0 平台难以承担其利益，决定在联邦经济与能源部（Bundesministerium für Wirtschaft und Energie，BMWi）支持的体系外发起“工业数字孪生体协会”（Industrial Digital Twin Association，IDTA）[14]。

DT ushered in the explosion stage around 2017, when more and more research institutions and manufacturing companies regarded DT as an essential enabler for future development. Particularly, in November 2017, Lockheed Martin, the world’s largest arms producer, described DT as one of the top 6 technologies in the future defense and aerospace industries. Next month, at the World Intelligent Manufacturing Summit (WIMS), the Chinese Intelligent Manufacturing Alliance of CAST Member Societies (IMAC) considered DT as one of the world's top 10 scientific and technological advances in intelligent manufacturing. Besides, DT was recognized as one of the top 10 future strategy technologies for four continuous years in 2016, 2017, 2018, and 2019 by Gartner, the world's leading research and advisory company, which predicted that hundreds of millions of DTs will emerge and be used for product design, manufacturing, operating factories, fault prediction and operation and maintenance by companies in the future [13]. In addition, in February 2020, the VDI/VDE of Germany published the report “Simulation and Digital Twins in the Equipment Life Cycle”. Moreover, in September 2020, most industry associations of Germany recognized that the Industrial 4.0 platform was difficult to bear their benefits and thus decided to promote the “Industrial

Digital Twin Association” (IDTA) outside the frame of the Bundesministerium für Wirtschaft und Energie (BMWI) system [14].

目前，DT 的发展仍然处在爆发期，由于 Michael Grieves 教授在最初定义 DT 时抛开了具体的工程背景[15]，其理论研究和技术应用从最初的制造业迅速扩展到农业、城市、建筑、电力和医疗等 13 种行业，涉及 50 多种应用场景，涵盖了人们日常生活的方方面面，如图 2 所示。DT 也从概念模型阶段步入初步的规划与实施阶段，西门子、达索、GE、PTC 和 ANSYS 等工业软件公司在 DT 的技术应用架构上进行了深入的研究。例如，德国西门西公司基于开放式物联网操作系统 MindSphere 实现生命周期 DT 应用，法国达索公司建立了基于 DT 的三维体验平台 3DEXPERIENCE，美国 GE 基于 Predix 云计算环境构建了 Genix DT 框架，美国 ANSYS 公司构建了系统级多物理域 DT 平台 Twin Builder，美国 PTC 通过 Thingworx 物联网平台与 Twin Builder 进行 DT 建模，中国阿里巴巴集团建立了阿里云工业大脑 DTwin 平台[16]。

So far, the development of DT is still in the explosion stage. Because the initial definition of DT presented by Professor Michael Grieves left aside the specific engineering background [15], the theoretical research and technical applications of DT expands rapidly from the manufacturing industry to agriculture, cities, construction, electricity, and medical industries, etc., involving more than 50 applications, covering almost every aspect of people’s daily lives, as revealed in Figure 2. Furthermore, the DT development is stepping into the initial planning and implementation period with well-established industrial software companies such as Siemens, Dassault, GE, PTC, and ANSYS, which have carried out an in-depth study on the technical application architecture of DT. For instance, Siemens of Germany implemented lifecycle DT applications based on the open IoT system MindSphere, Dassault Corporation of France has established DT-driven 3D EXPERIENCE. The American corporation GE has established the Genix DT framework under the Predix cloud computing environment. ANSYS has built system-level multi-physical field DT platform Twin Builder. PTC modeled DT with Twin Builder through the IoT platform Thingworx. Alibaba Group of China established the Alibaba Cloud Industrial Brain DT platform[16].

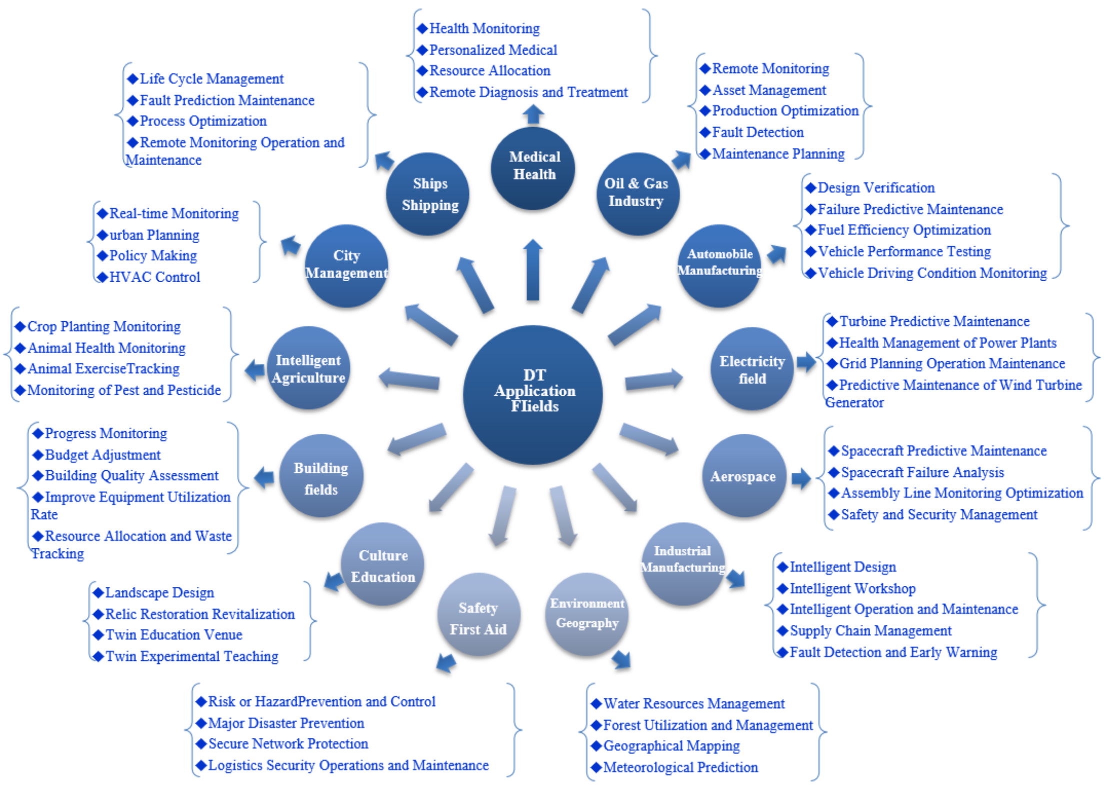

Figure 2 DT application fields and application scenarios [17]

由于不同行业对 DT 的应用重点并不完全一致，形成了具有不同特点的城市、建筑、电网、医疗和工业等 DT 系统。其中，DT 的研究与应用在工业界，特别是制造业中开始最早，研究较深入。DT 技术在产品的概念设计、详细设计、加工制造、使用运维和报废回收全生命周期都发挥着作用。例如，Victor 等给出了产品设计中 DT 的数学定义，用于设计决策[18]；Farid 等提出了基于 DT 的自动流水线个性化设计[19]；为了打通设计和制造的壁垒，Benjamin 等提出了基于表面模型形状的综合参考模型，作为设计与制造阶段物理产品的 DT [20]；Redelinghuys 等构建了支持网络物理生产系统（CPPS）的 DT 六层架构[21]；Aivaliotis 等提出了基于 DT 的机械设备剩余使用寿命预测方法，用来对制造资源进行预测性维护[22]；为了实现车间数字孪生系统，Coronado 等提出了基于云计算工具的 MES 数据和 MTConnect 数据集成方法[23]；Ghosh 等使用隐式 Markov 模型构建了面向制造系统评价的数字孪生模型，该模型包括模型组件和仿真组件[24]。陶飞等提出了 DT 车间的概念，并定义了 DT 五维模型[25, 26]；赵浩然和刘检华等提出了面向 DT 车间的三维可视化实时监控方法[27]；刘强等提出了一种基于 DT 的自动化流水车间制造系统的快速个性化设计方法[28]；胡天亮等在统一平台上建立了计算机数控机床（CNCMTs）的多域虚拟原型，并将 DT 的概念引入原型中，以实现虚拟世界与现实世界的实时准确映射[29]；鲍劲松等提出面向制造的数字孪生建模和操作方法[30]；李浩等分析了基于 DT 的复杂产品设计内涵，提出了基于 DT 的复杂产品环形设计框架，基于此提出了基于 SysML 的统一 DT 模型[5][31]。但是，这些研究是基于某一工业场景、单个产品功能和产品生命周期单一阶段的，缺少面向工业产品的数字孪生系统的特点、系统组成、逻辑架构和系统运行模式的研究。为此，本文提出工业数字孪生系统（industrial Digital Twin System，iDTS），为数字孪生在工业的应用提供理论和技术支撑。

Various DT systems (DTSs), such as DT cities, DT construction, DT power grid, medical DT, and manufacturing industrial DT, have different characteristics, as their application priorities are not completely consistent in each industry. Particularly, in the field of the manufacturing industry, the application of DT started the earliest and was studied more deeply. In short, DT technology plays an increasingly crucial role in the life cycle of an industrial product from conceptual design, detailed design, manufacturing, operation, and maintenance to end-of-life recycling. For example, Victor et al. proposed a mathematical definition of DT in product design for design decisions making [18]. Farid et al. described the personalized design of automatic pipelines relies on DT [19]. To bridge the gap between design and manufacturing, a comprehensive reference model based on the concept of Skin Model Shapes was developed by Benjamin et al., which serves as a DT of the physical product in design and manufacturing [20]. Redelinghuys et al. constructed a six-tier DT architecture supporting the application of cyber-physical production systems (CPPS) [21]. Aivaliotis et al. explained the use of DT for predictive maintenance in manufacturing [22]. To implement shop floor DTS, Coronado et al. proposed the MES data and MTConnect data integration method based on mobile and cloud technologies [23]. Ghosh et al. addressed the construction of DT using hidden Markov models for the futuristic manufacturing systems known as Industry 4.0 [24]. Fei Tao et al. put forward the concept of DT workshop (DTW), and presented the five-dimensional DT model [25, 26]. Haoran Zhao et al. provided a 3D visual real-time monitoring approach for the DT workshop [27]. Qiang Liu et al. proposed a Digital twin-driven rapid individualized designing of an automated flow-shop manufacturing system [28]. Tianliang Hu established a multi-domain virtual prototype of Computer Numerical Control Machine Tools (CNCMTs) on a unified platform and introduced the concept of DT into the prototype to achieve real-time and accurate mapping between the virtual world and the real world[29]. Jinsong Bao et al. proposed a manufacturing-oriented DT modeling and operation method [30]. Hao Li et al. analyzed the connotation of complex product design and illustrated the ring design framework of complex products on DT, and proposed a unified DT model via SysML[5][31].

All the aforementioned DT studies provide some insights into the development of DT in the manufacturing industry, however, most of them are limited to a certain industrial scene, a single product function, or a single stage of the product life cycle. There is a lack of research on the characteristics, system composition, logical architecture, and system operation mode of the digital twin system (DTS) for industrial products. To provide fundamental theoretical and technical support for the application of DT in the manufacturing industry, we propose the industrial digital twin system (iDTS) in this paper.

3 不同类别的数字孪生系统 Different types of DTSs

3.1 数字孪生系统的构成 Composition of a typical DTS

如图 3 所示，一个典型的数字孪生系统通常包括物理对象、测量感知、终端控制器、通信网络、数字孪生运行平台和用户域。这五个部分相互关联，形成正向的数据采集与传输分析，以及反向的数据反馈与决策控制，最终完成信息传递的闭环。

A typical DTS includes physical objects, measurement perception and terminal controller, communication network, DT operating platform, and user domain. In Figure 3, it is shown that the five parts are related to each other, which complete forward data collection and transmission analysis, control the reverse data feedback and decision control, and then complete the closed-loop of information transmission.

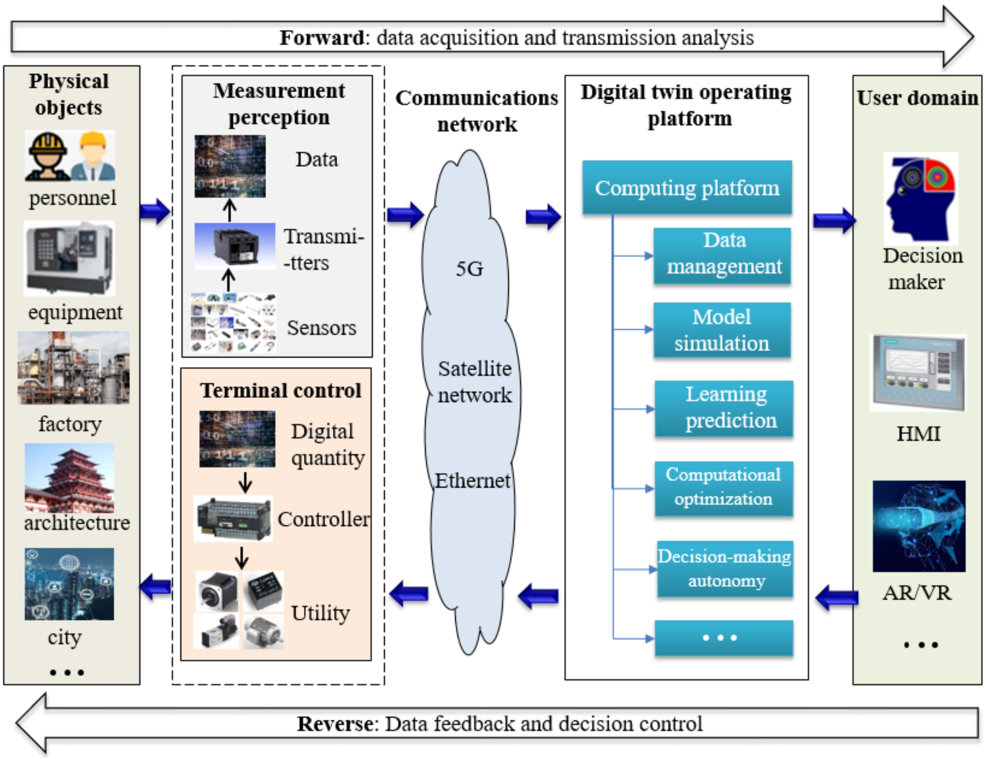

Figure 3. The composition of the DTS

（1）物理对象：物理对象在不同的应用领域具有不同的实体形式。例如，工业领域中的人员、设备、物料、环境；城建领域的城市建筑、交通基础设施、城市能源、水利、电气等设施；农业领域的作物、水利、农田生态系统、农业机具等；建筑领域的人员、建筑结构、空调系统、照明、供水、供气、电梯等。

(1) Physical objects: Physical objects have different entity forms in different application fields, such as labour, equipment, materials, and environment in manufacturing industries; buildings, transportation infrastructure, urban energy, water conservancy, and electrical facilities in urban infrastructure; crops, water conservancy, farmland ecosystems, agricultural machinery in the agricultural field; and building structure, air-conditioning system, lighting, water supply, air supply, elevators in construction.

（2）测量感知与终端控制：测量感知主要实现对物理空间的数字化。一方面，对于物理对象相关的静态数据，通常在数字孪生系统建立之初，通过人工测量得出；另一方面，对于物理对象相关的动态变化的数据，通常借助于传感器将物理对象相关的模拟量转化为电信号，然后由变送器将电信号转化为数字信号，实现对物理对象必要数据的数字化，供上位机处理。终端控制器首先接收上位机传过来的控制信号，然后通过控制器作用于效用器从而改变物理对象的相关状态。例如，对机床铣刀运动轨道参数的修改，首先通过上位机软件编写相应的代码，然后代码传至机床内部控制系统，最后控制系统控制电机做功实现对物理对象的控制。

(2) Measurement perception and terminal control: Measurement perception mainly helps the DTS to realize the digitization of physical objects. On one hand, static data related to physical objects is usually measured manually at the beginning stage when the DTS is established. On the other hand, for the data related to the dynamic changes of physical objects, the corresponding analog quantity is converted into electrical signals via sensors. The electrical signals are then converted into digital signals by the transmitter, to achieve the digitalization of the necessary data for the computer in the upstream to process the result. In terms of the terminal controller, it firstly receives the control signal from the upstream computer and then acts on the utility of the controller to change the relevant state of the physical object. For example, to modify the motion track parameters of the machine tool milling cutter, the corresponding code is developed through the upper computer software. The code is then transmitted to the internal control system of the machine tool. Finally, the control system drives the motor to control the operation of physical objects.

（3）通信网络：它是数字孪生系统的重要组成部分。数字孪生系统需要通过高速、低延时网络通信实现数字孪生体与物理对象的数据交互。因此，数字孪生系统对物理网络、网络接口、通信协议都有更高的要求。例如，在异构系统的联网中，需要对多种系统进行通信接口的统一约定，以实现各种数据接入平台。另外，在低延时方面，需要通信网络具有更高的性能，例如采用 5G 专用通信链路或者使用卫星通信链路。

(3) Communication network: Communication network is an essential part of the DTS, by which the DTS can interact data and information between the DT and the physical object with a high speed and low latency. Therefore, the DTS has an urgent requirement on the physical network, network interfaces, and communication protocols. For example, in the network of heterogeneous systems, it is necessary to implement a unified agreement on communication interfaces for various systems to provide access to different data platforms. In addition, regarding to the low latency, higher speed requirement is important for communication networks, which pushes the adoption of 5G dedicated communication and satellite communication.

（4）数字孪生运行平台：数字孪生运行平台具有数据管理、模型仿真以及基于模型的学习预测、计算优化、决策自治等功能。数据管理功能为仿真模型提供数据服务，包括接收数据采集系统上传的数据，对多种数据的分析、压缩、模式识别等处理，以及为驱动仿真模型运行提供数据伺服等。同时，数据管理功能部分还对模型运行的中间数据以及历史记录等数据进行存储。模型仿真是数字孪生系统核心功能，涉及对物理对象的数字建模和展示，对物理对象的同步驱动和运行管理等。数字孪生系统通常根据要解决的问题不同建立不同类型的系统机理模型，基于人工智能算法进行自学习、系统状态预测、过程优化、结构优化和自主决策等。另外，系统运行需要更高的算力支持，高算力平台是数字孪生系统运行的重要基础设施。

(4) DT operating platform: Significant functions like data management, model simulation, model-based learning prediction, calculation optimization, and decision-making autonomy, etc., can be provided by the DT operating platform. For instance, the data management function provides data services for the simulation model, including receiving the data uploaded by the data acquisition system, processing the analysis, compression, and pattern recognition of various data, as well as providing data servo for driving the simulation model. At the same time, the data management function can store the intermediate data and historical records of the model running. Particularly, simulation is the core enabler of DTS, which involves digital modeling and display of physical objects, synchronous driving and operation management of physical objects, etc. Moreover, the DTS needs to build different types of system mechanism models for specific engineering issues, and carry out self-learning, system state prediction, process optimization, structure optimization, and independent decision-making through artificial intelligence algorithms. In addition, as the effective operation requires higher computing power, the powerful computing platform is a critical infrastructure for the DTS.

（5）用户域：用户域包括人、人机接口、应用层软件以及基于虚拟现实、增强现实的人机交互等。在数字孪生系统中，人是起统筹控制，主导系统调控核心作用的。另外，人的

知识和决策通过人机交互输入给数字孪生体，作为数字孪生体模型仿真、学习预测和优化决策的关键参数。先进的人机接口是数字孪生系统的重要特征，其中虚拟现实技术将可视化的模型以沉浸式的3D显示方式呈现给人，同时通过手柄、穿戴式传感器采集人体动作，实现人与3D画面的人机交互；增强现实更进一步将物理空间和数字空间重叠显示。

(5) User domain: The user domain includes man, human-machine interface (HMI), Apps, and human-computer interaction based on virtual reality (VR) or augmented reality (AR). In the DTS, humans play a central role in the overall control of the system. In addition, knowledge and decisions from engineers and managers are the input to the DT through HMI, which are key parameters for the simulation, learning prediction, and optimal decision-making. Hence, advanced HMIs are more and more significant for the efficient implementation of DTS. For example, VR technology is able to present the visual model to people in an immersive 3D environment, where the data of human movements is collected by the handle and wearable sensors for the human-computer interaction. Similarly, the information about the surrounding physical objects of the user becomes interactive and digitally manipulated through AR.

3.2 不同数字孪生系统特点分析 Analysis of the characteristics of different DTSs

面向不同行业的数字孪生系统虽然都具有精准映射、虚实交互、智能反馈和优化迭代等共性特征，但是它们在研究对象、主要应用场景、数据来源和类别、系统运行的主导因素等方面各不相同，导致不同系统所要解决的关键问题和研究的关键技术有所差别，如表1所示。下面以城市数字孪生系统、建筑数字孪生系统、电网数字孪生系统、医疗数字孪生系统和工业数字孪生系统为例进行比较说明。

Although general DTSs have common features of precise mapping, virtual-real interaction, intelligent feedback, and optimization iteration, they vary greatly in terms of research objects, application scenarios, data sources and categories, and dominant factors of operation in different areas, which leads to differences in critical issues to be solved and key technologies of research, as depicted in Table 1. The following is a comparison of urban DTS, building DTS, power grid DTS, medical DTS, and iDTS.

Table 1. Comparison of the characteristics of typical DTSs

Type	**The research object**	**Application Scenarios**	**Critical issues**	**key technologies**	**Data sources and categories**	**Operating dominant factor**
Urban DTS	Infrastructure such as water, electricity, and transportation, and municipal resources such as police, medical care, and firefighting, etc.	Traffic diversion, energy dispatch, major project cycle management, infrastructure site selection, etc.	City information model (CIM) repeated construction, massive data transmission and aggregation, inadequate data expression, unreasonable allocation of computing resources, and space analysis capabilities need to be improved, etc..	Geographic Information System (GIS), CIM modeling, urban brain, etc.	Source: ubiquitous cameras. Category: Video data.	Man-environment dominated
Building DTS	Water, HVAC, power supply, key facilities, building structure, etc.	Architectural planning and design, construction implementation and control, intelligent operation and maintenance of buildings, etc.	Gap between the building “information – physics”, energy control depends on manual, the prediction accuracy of building safety risks is low, and the early warning and analysis ability of building equipment failure is insufficient, etc.	Building information Modeling (BIM), building safety state warning based on DT, building energy consumption control based on DT, etc.	Source: camera, sensor, terminal auxiliary facilities, power supply and distribution equipment. Category: video data, sensor data.	Environment dominated

Power grid DTS	equipment for power transformation, transmission, and distribution, voltage, energy, electricity costs and other power consumption, and power grid operation, etc.	Power grid design, power system monitoring and analysis, power grid operation optimization, etc.	Power grid state information is difficult to master, power grid operation and maintenance efficiency needs to be improved, power grid operation strategy depends on manual experience, etc.	Power grid DT modeling, power grid state analysis based on DT, intelligent patrol, DT – based load prediction and user behavior analysis, etc.	Source: power transmission and transformation and distribution control system, inspection system. Category: power data, few video date.	User profiles and environment dominated
Medical DTS	Patients, doctors, medical resources, etc.	Personalized medical care, medical and surgical program validation, optimization of medical resource management, etc.	Inaccurate description of patient and medical device mechanisms, and dependence of medical and surgical protocols on physician experience, etc.	Construction of mechanism model of man-machine fusion DT, real-time 3D image navigation of surgery, optimal management of medical resources based on DT, etc.	Sources: medical cards, medical equipment, medical records. Category: medical images, tables.	Man-machine dominated
iDTS	Products, equipment, materials, personnel, energy, etc.	Multi-physical field simulation, personalized customized design, full life cycle operation and maintenance, etc.	The classification of DTs is fuzzy, the co-simulation of different models is difficult, the life cycle of DT is changeable, and the iDTS has many security risks, etc.	DT modeling and evaluation technology, multi-physical field simulation and integration of complex industrial systems, DT life cycle management, security control, etc.	Sources: Manufacturing equipment, sensors, cameras, industrial software systems. Category: multimodal data.	Man-centered, Man-machine-environment integration, high fidelity, complex mechanism model.

（1）城市数字孪生系统 Urban DTS

“智慧城市”的提出和建设让城市发生了翻天覆地的变化，城市数字孪生系统为其落地提供了有效途径。中国信通院发布了《数字孪生城市白皮书（2020 版）》，深入分析了城市数字孪生系统的典型特征、总体架构、核心能力、共性问题和实施策略[32]。城市数字孪生系统通过城市物理世界、网络虚拟空间的一一对应、相互映射和协同交互，在网络空间再造一个与之匹配的“孪生城市”，实现城市全要素的数字化、城市全状态的可视化和城市管理决策的协同化。

The proposal and construction of “smart cities” have brought earth-shaking changes to the city. The urban DTS has provided an effective way for it to land. For example, the China Academy of Information and Communications Technology released the “White Paper on Digital Twin Cities (2020 Edition)”, which comprehensively analyzed the typical characteristics, overall architecture, core capabilities, common issues, and implementation strategies of urban DTS [32]. The urban DTS recreates a matching twin city in the cyberspace through the one-to-one correspondence, mutual mapping, and collaborative interaction between the city's physical world and its virtual space, which achieves the digitization of all elements of the city, the visualization of the entire state of the city, and the coordination of urban management decision-making.

城市数字孪生系统的主要研究对象包括水、电、交通等基础设施，警力、医疗、消防等市政资源，以及洪水、台风和地震等自然灾害。城市数字孪生系统主要用于交通疏导、能源调度和疫情监控等，系统的数据大部分来自布置在道路上的摄像头所采集的海量视频数据，系统的运行是以人和城市环境为主导的。目前，城市数字孪生系统存在着城市信息模型（City Information Model，CIM）重复建设、海量数据传输汇聚、数据表达不到位、计算资源分配不合理等问题，针对这些问题需开展地理信息系统（Geographic Information System，GIS）建模、城市信息模型（CIM）统一建模和“城市大脑”搭建等关键技术研究，其中“城市大脑”是构建城市数字孪生系统的核心使能技术，需要研究视觉认知计算和数字视网膜架构[33]。

The main research objects of the urban DTS include the infrastructure such as water, electricity, and transportation, and municipal resources like police, medical care, firefighting, and natural disasters such as floods, typhoons, and earthquakes. In terms of applications, the urban DTS is usually used for traffic diversion, energy dispatch, and epidemic monitoring, etc. Most of the data of the system come from the massive video data collected by intensive cameras arranged on the road. The operation of the system is dominated by people and the urban environment. At present, the research of the urban DTS has issues such as repeated construction of the City Information Model (CIM), massive data transmission and aggregation, inadequate data expression, and unreasonable allocation of computing resources. It is critical to developing geographic information system (GIS) modeling, city information model (CIM) unified modeling, and "Urban Brain Project" and other researches to address the issues above. Among them, the "Urban Brain Project" is the core enabling approach for the effective application of the urban DTS, which requires the study of sophisticated visual cognitive computing and digital retina architecture [33].

国内外已经开展了城市数字孪生系统的相关研究。例如，雄安新区数字孪生城市、虚拟新加坡平台、法国雷恩 3D 城市、多伦多高科技社区等就是典型的城市数字孪生系统[34]。

In recent years, studies on urban DTS have been carried out. For example, the DT city of Xiongan New Area in China, the virtual Singapore platform, the 3D city of Rennes in France, and the high-tech community of Toronto are typical urban DTSs [34].

（2）建筑数字孪生系统 Building DTS

根据普华永道《2030 年全球建筑业》的预测，到 2030 年，全球建筑业产值将增长 85%，达到 15.5 万亿美元，其中中国、美国和印度处于领先地位，占全球增长的 57%[35]。建筑数字孪生系统已经在组织层面上对商业房地产建筑产生了巨大影响，并且使居住者对自己的工作区和环境条件有更多的控制权。与城市相比，建筑数字孪生系统聚焦建筑物本身，其定义是在物理建筑模型中使用各种传感器全方位获取数据的仿真过程，用来在虚拟空间中反映相对应实体建筑的全生命周期过程[36]。

According to PWC's forecast on "Global Construction Industry in 2030", the global construction industry output value will increase by 85%, reaching 15.5 trillion dollars, of which China, the United States, and India are in the leading position, accounting for 57% by 2030 [35]. The application of the building DTS already has a huge impact on commercial real estate buildings at the organizational level and has offered occupants more control over their working areas and environmental conditions. Compared with the city, the building DTS focuses on the building itself, which is considered as the simulation process of using various sensors in the physical building to obtain data in all aspects, which is used to represent the full life cycle process of the corresponding physical building in the virtual space [36].

建筑数字孪生系统的研究对象主要包括用水、暖通、供电、关键设施、建筑结构等，系统的数据来源于摄像头、传感器、终端辅助设施所采集的视频、传感器数据，系统运行以环境为主导。建筑数字孪生系统的目标是实现建筑规划、设计、施工、运营的一体化管控。但是，目前存在建筑“信息-物理” 不交互、能源管控依赖人工、建筑物安全隐患预测精度低、建筑设备故障预警分析能力不足等问题[37]，需要重点开展建筑信息模型（BIM）建模、基于数字孪生的建筑安全状态预警、基于数字孪生的建筑能耗管控等技术研究。需要注意，建筑数字孪生系统与 BIM 模型有所区别，BIM 专注于建筑物的设计和建造，而建筑数字孪生系统可以在 BIM 的基础上模拟人们如何与建筑环境互动。

The research objects of the building DTS mainly include water, heating, ventilation, power supply, key facilities, building structures, etc. The data of the system comes from the video and sensor data collected by cameras, sensors, and terminal auxiliary facilities. The operation of the system is led by the environment. The goal of the building DTS is to realize the integrated management and control of building planning, design, construction, and operation. However, there are research issues outstanding, such as the gap of "information-physical" of buildings, the reliance on labor for energy management and control, the low accuracy of predicting building safety hazards, and the insufficient capacity for early warning analysis of building equipment failures [37]. Therefore, it is worth to note that there are significant differences in DTS and building information modeling (BIM). BIM focus on building safety state warning, and building energy consumption management and control based on DT.

阿联酋 Bee'ah 公司打造的新总部智慧大楼就是建筑数字孪生系统，该总部大楼基于人工智能的预测和自动化控制系统实现了建筑内部资源利用零摩擦，目标是达成能耗降低 5%，耗水量降低 20%，运营两年内零净碳排放量[38]。另外，“数字巴黎”也是一个建筑数字孪生系统，能够通过数字化建模和仿真完整地还原了巴黎圣母院的原貌和几百年的建造过程，在数字世界中再现了一块砖、一扇门、一扇窗的安装过程，同时也完美的构建了巴黎圣母院的数字孪生体[39]。在中国武汉雷神山医院的设计建造过程中，建筑数字孪生系统帮助设计师进行可视化设计、流线分析、管线综合、装配式设计、室内室外 CFD 模拟等，助力武汉雷神山医院快速建成[40]。

For example, the new headquarters smart building built by Bee'ah in the United Arab Emirates adopts the concept of the building DTS. The headquarters building's artificial intelligence-based forecasting and automated control system realizes zero friction in the use of internal resources in the building. The goal is to achieve a reduction of energy consumption by 5% and water consumption by 20%, with zero net carbon emissions within two years of operation [38]. In addition, "Digital Paris" is also a building with DTS that can completely restore the original appearance of Notre Dame de Paris and the construction process of hundreds of years through digital modeling and simulation, and reproduce a brick in the digital world, a door, a window of the installation process. At the same time, it perfectly constructed the DT of Notre Dame de Paris [39]. In China, during the design and construction process of Wuhan Leishenshan Hospital, the building DTS helped designers to achieve design visualization, streamline analysis, pipeline synthesis, assembly design, indoor and outdoor computational fluid dynamics (CFD) simulation, etc., finally help Wuhan Leishenshan Hospital to be quickly completed [40].

（3）电网数字孪生系统 Power grid DTS

在中国国家电网对标世界一流管理提升行动中，“数字化”扮演了十分重要的角色，并且亟待企业在一个开放的生态圈中相互协作，开展联合创新，而数字孪生技术推动了电网的“数字化”升级。电网数字孪生系统是将物理电网以数字化方式映射至虚拟空间，通过接收来自物理电网的状态信息而同步演化，以实现对物理电网的全面精准检测、并基于物理电网的状态信息，进行诊断和预测等一系列计算分析，并将分析结果反馈给物理电网，从而推动物理电网的优化调整[41]。

In China's State Grid's benchmarking of world-class management improvement actions, "digitalization" has played a crucial position, and companies have to collaborate and carry out joint innovations in an open ecosystem. The DT technology promotes the digital upgrade of the power grid. The power grid DTS digitally maps the physical power grid to the virtual space, and evolves synchronously by receiving the status information from the physical power grid, to realize comprehensive and accurate detection of the real statues. According to the state information of the physical power grid, the power grid DTS performs a series of calculation analyses such as diagnosis and prediction, and feeds back the analysis results to the physical power grid, thereby promoting the optimization strategy [41].

电网数字孪生系统已经能够灵活满足数字化电网内不同场景、不同规模的需求，例如对于单个配电柜、机柜，数字孪生可以支持三维扫描、可视化呈现，实现数字化交付；对于单个配电站、开关站，数字孪生可以支持站点设备全要素数据的连接，实现数字化运维管理；对于区域配电站，数字孪生可以为区域电网实现配电智能管理、按需配电；针对环网数字化，数字孪生则可以助力实现站点联通、快速检测等功能[42]。电网数字孪生系统的研究对象涉及变电、输电、配电等设备，电压、电能、电费等用电情况和电网运行状态，系统的数据来源于输变电和配电控制系统、巡检系统，其运行受用户分布情况和环境影响较大。目前，在电网数字孪生系统中，电网状态信息难以掌握、电网运维效率有待提升、电网运行策略依赖于人工经验，为此需要重点开展电网数字孪生建模、基于数字孪生的电网状态分析、智能巡检、基于数字孪生的负荷预测与用户行为分析等技术研究。

The power grid DTS has been able to flexibly scarify the needs of different scenarios and various scales in the digital power grid. For example, for a single power distribution cabinet, the DT supports 3D scanning, visual presentation, and digital delivery. For a single power distribution station and switch station, the DT can alleviate the complex connection of all-element data of the site equipment, realize digital operation and maintenance management. For regional power distribution stations, the DT can realize intelligent power distribution management and on-demand power distribution. For the digitization of the ring network, the DT provides functions of site connectivity and rapid detection [42]. Accordingly, research objects of the grid DTS involve equipment, power transformation, transmission, distribution, voltage, electric energy, electricity cost, and other electricity consumption and grid operation status. The data of the system mainly comes from the power transmission, transformation distribution control system. the inspection system. Its operation is greatly affected by the distribution of users and the environment. However, at present, in the study of the power grid DTS, it is difficult to represent the real-time status information of the power grid accurately. The efficiency of power grid operation and maintenance needs to be improved, while the power grid operation strategy still relies on manual experience. To this end, the development of technical researches on power grid DT modeling, power grid state analysis, intelligent inspection, load forecasting, and user behavior analysis based on DT has practical significance.

2021 年中国数字孪生体联盟发布了《数字孪生电网白皮书—电力企业数字化转型之道》，给出了数字孪生电网系统的定义、参考架构和典型案例[43]。随着对电力系统运行机理认知的不断提升，电网数字孪生系统对未来的预测将非常接近真实物理世界的变化[44]。

In 2021, the China Digital Twin Alliance released the “Digital Twin Power Grid White Paper—The Road to Digital Transformation of Power Enterprises”, which describes the definition, reference architecture, and typical cases of the power grid DTS [43]. With the continuous improvement of the understanding of the operation mechanism of the power system, the future prediction of the power grid DTS will be extremely close to the changes in the real physical world [44].

（4）医疗数字孪生系统 Medical DTS

2019 年中国国家卫健委首次提出了“智慧医疗”的概念，指出需要将云计算、大数据、人工智能和物联网等技术应用于医疗服务领域，围绕患者就医体验、临床诊疗水平、医院管理三方面，全方位提升医疗服务效率和质量。2020 年，Genome Medicine 刊登了一篇由瑞典数字孪生协会（SDTC）联合多国科学家发表的名为《Digital twins to personalize medicine》的报告，肯定了基于数字孪生技术实现“智慧医疗”的设想[45]。

In 2019, the National Health Commission of China first proposed the concept of “smart healthcare”, pointing out the necessity to apply cloud computing, big data, artificial intelligence, and IoT technologies to medical services to comprehensively improve its efficiency and quality in three aspects: patient experience, clinical diagnosis and treatment level and hospital management. Similarly, in 2020, Genome Medicine published a report entitled “Digital twins to personalize medicine” by the Swedish Digital Twins Association (SDTC) and scientists from multiple countries, which affirmed the vision of “smart healthcare” based on the DT technology [45].

医疗数字孪生系统能够基于数字病历、疾病登记库、穿戴式传感器等获取数据信息，构建患者的数字虚拟状态、剖析结构和医院虚拟环境等数字孪生体，最终实现个性化医疗保健、医疗与手术方案验证和医疗资源管理优化等。医疗数字孪生系统的研究对象包括患者、医生和医疗资源，系统的数据来源于急诊卡、医疗设备和患者病例等。目前，医疗数字孪生系统的研究存在患者和医疗设备机理描述不准确、医疗和手术方案依赖于医生经验等问题，因此需要进行医疗系统人机融合数字孪生机理模型构建、基于数字孪生的院内导诊、手术实时三维影像导航和基于数字孪生的医疗资源优化管理等关键技术研究[46]。

The medical DTS can obtain data information based on digital medical records, disease registry and wearable sensors to construct different DTs, such as patients’ digital virtual status and hospital virtual environment. The it can realize personalized medical care, medical treatment and surgery programs verification and optimization of medical resource management, etc. The research objects of the medical DTS include patients, doctors, and medical resources. The data of the system comes from emergency cards, medical equipment, and patient cases. However, there are still issues when using the system, for example, inaccurate description of the mechanism of patients and medical equipment and the limitation that the medical and surgical plans rely on the experience of doctors. Therefore, it is necessary to conduct technical research on the construction of a DT mechanism model of human-machine fusion of medical systems, in-hospital guidance based on DT, real-time 3D image navigation for surgery, and optimal management of medical resources based on DT [46].

医疗数字孪生系统的研究和应用目前处于起步阶段，具有代表性的是初创公司 Unlearn.ai 通过收集参与者的身体数据，创建医疗数字孪生模型来作为对照组使用，这样可以让尽量多的参与者加入实验组，提升试验效率。法国达索（Dassault Systèmes）使用磁共振成像（Magnetic Resonance Imaging，MRI）和心电图（Electrocardiography，ECG）测量结果开发了一种数字孪生模型，可以模拟人心脏的结构和某些生理功能，将难以看到的解剖结构可视化，以开发更安全有效的心脏治疗设备及器械。OnScale 公司与 LEXMA Technology 公司共同开发了“数字双肺”模型，帮助临床医生预测新冠肺炎患者的通气需求[47]。

The research and application of the medical DTS are currently in their infancy. A typical example is the Unlearn.AI company, which collects participants’ physical data and creates a medical DT model to act as a control group, to allow as many participants as possible to join the experimental group to improve the efficiency of the experiment. In addition, Dassault Systemes of France has developed a DT model via Magnetic Resonance Imaging (MRI) and Electrocardiography (ECG) measurements. It can simulate the structure and some physiological functions of the human heart and visualize the anatomical structure that is difficult to observe and to develop safer and more effective cardiac treatment equipment and instruments. Moreover, OnScale and LEXMA Technology have jointly developed a “digital lungs” model to help clinicians predict the ventilation needs of patients with new coronary pneumonia [47].

（5）工业数字孪生系统（iDTS）

与其他领域相比，DT 技术在制造业的研究最早，目前技术应用相对成熟，但是理论研

究和技术应用集中在数字孪生体的表达、基于数字孪生的设计制造一体化、基于数字孪生的产品故障诊断和运行维护，缺少面向产品生命周期不同阶段的数字孪生系统的内涵、架构设计和运行模式的研究。

Compared with the above fields, the research of DT technology in the manufacturing industry is the in the leading position. Nevertheless, the theoretical research and technical application of iDTS made some achievements in the expression of DT, i.e. design and manufacturing integration based on DT, product fault diagnosis and operation, and DT-driven maintenance. There is a lack of research on the connotation, architecture design, and operation mode of iDTS for different stages of the industrial product life cycle.

iDTS 的研究对象是工业产品、制造装备、物料、人员和能源等，其数据主要来源于设备、传感器、摄像头等采集的多模态数据。iDTS 的定义和特点见 4.1 节，它是一个以人为中心、“人-机-环境”交互融合的系统。目前，在 iDTS 的研究中，存在着数字孪生体成熟度划分模糊、不同数字孪生体融合困难、系统运行模式多样等问题。因此，需要进行数字孪生体建模与评价技、复杂工业系统多物理场仿真融合和数字孪生体生命周期管理等关键技术研究性[48]。

As illustrated in Table 1, the study objects of iDTS are mainly industrial products, manufacturing equipment, materials, personnel, and energy, etc. The data mainly includes multi-modal data collected by equipment, sensors, cameras, and etc (See section 4.1 for the definition and characteristics of iDTS). The iDTS is a human-centered, named as “human-machine-environment” interactive system. Fundamental issues in the research of iDTS include the fuzzy division of maturity of DTs, difficulty in a fusion of different DTs, and the analysis of diverse system operation modes. Thus, it is necessary to research DT modeling and evaluation technology, complex industrial system multi-physics simulation fusion, and DT life cycle management [48].

4 iDTS 的定义和功能结构 Definition and functional structure of iDTS

4.1 iDTS 的定义和特点 Definition and characteristics of iDTS

iDTS 是建立在数字孪生体、数字孪生技术和数字孪生系统基础上，其中，一个物理对象的数字孪生体是该物理对象的数字化表达。数字孪生技术是构建一个数字孪生体过程中涉及的方法与技术手段，用于仿真和刻画该物理对象在真实环境中的属性、行为、规则等技术。数字孪生系统是数字孪生技术在城市、建筑、汽车、航空航天、电力等不同行业的应用，它是一个由物理对象与数字孪生体结合，并可进行连续过程优化的功能系统[5]。

iDTS is built based on Digital Twin (DT), Digital Twin Technology (DTT), and Digital Twin System (DTS). These concepts are different but interrelated. A DT, as described in Section 1, is the virtual representation, which serves as the real-time digital counterpart of a physical object. Compared with DT, the DTT refers to technical approaches for modeling DTs, which can simulate and reflect the attributes, behaviors, and rules of the physical object. In terms of DTS, it stands for the application of DTT in different areas such as cities, construction, automobiles, aerospace, electric power, and etc. Moreover, a DTS is a functional system that combines physical objects with DTs for continuous optimization [5]. Therefore, iDTS is a special type of DTS, which is defined in the following.

iDTS 定义：iDTS 是面向工业产品的需求分析、方案设计、生产制造和运行维护等全生命周期，运用数字孪生技术建立全要素、全流程、全业务的数字孪生体，通过物理对象与数字孪生体的双向映射与实时交互，实现工业产品的优化设计、产线规划仿真、制造过程优化

和服务运行调控等功能的软硬件一体化系统。iDTS 除了具备精准映射、虚实交互、智能反馈和优化迭代等主要特点外，还具有以人为中心、“人-机-环境”相互融合、系统保高保真度和孪生模型复杂等典型特点。

Definition of iDTS: An iDTS is a software-hardware integrated system constructed by using DDT to establish DTs with all elements, entire processes, and full services, oriented to mirror the industrial product’s lifecycle from the demand analysis, scheme design, manufacturing, operation, and maintenance to recycling, to achieve the product optimization design, production line planning simulation, manufacturing process optimization and service operation control and other functions through the bidirectional mapping and the real-time interaction between physical objects and the corresponding DTs. An iDTS have certain characteristics that distinguish it from other DTSs. In addition to the general DTS’s four features of accurate mapping, virtual-real interaction, intelligent feedback, and optimization iteration, an iDTS has four more typical characteristics: human-centered operation, “human-machine-environment” mutual integration, high-fidelity requirement, and complex fusion of twin models.

（1）以人为中心

(1) Man-centered operation

随着个性化的生物识别、全方位情感感知、可穿戴动作捕捉、光学视觉动作捕捉、VR/AR/MR 等技术将在工业数字孪生系统中大量应用，其不再是一个以自动化程序和程序化工艺为主的系统，而是一个以人的行为为主的系统。工业产品的需求分析、方案设计、生产制造和运行维护等全生命周期活动虽然是由软件和机器完成的，但软件和机器的运行需要基于人的决策，并满足人的需求。所以，工业数字孪生系统的正常运行需要充分考虑人的工作状态、人的熟练程度，甚至人的情感等因素[49]。

With advanced technologies such as personalized biometrics, omni-directional emotion perception, and vision-based motion capture, VR/AR/MR are widely applied in iDTS. The system will be primarily driven by human behaviors instead of automated programs and programmatic processes. Although significant factors for successful completion of engineering tasks of industrial products throughout the entire product life cycle are software and machines, they should be controlled by human decisions, operated to meet human needs, and restricted by a different culture. As a result, the working status, proficiency, and even emotions of every operator contribute to the normal and efficient running of the iDTS[49].

（2）“人-机-环境”相互融合

(2) “Man-machine-environment” mutual integration

iDTS 是由人、机器和环境协调运行的复杂系统。在工业数字孪生系统中，人是工程命令发出者，机器负责执行由人发出的命令，环境保证了人和机器的安全、有效、稳定的交互和协作。其中，人指的是参与工程任务的设计师、工艺师、工人、系统工程师、管理者等人员；机器泛指完成工业产品的设计和制造任务计算机和各类型设备；环境指的是人机协作完成工程任务的工作环境。

As defined in Section 4.1, iDTS is a complex software-hardware integrated system coordinated by human, machine, and environment. In the iDTS, ‘human’ refers to the subject (designers, workers, system engineers, managers, users, and etc.) who issues engineering decisions and proposes demands in the workplace. In terms of ‘machine’, it represents general objects (tools, machines, and computers) that can complete the design and manufacturing tasks according to the decisions issued by ‘human’. As for ‘environment’, it describes the specific working conditions under which ‘human’ and ‘machine’ interact, such as temperature, noise, vibration, lighting, chemicals, and hazardous gases, and etc. The working environment creates a wider or narrower set of factors that guarantee safety, high efficiency, and stable interaction and collaboration among ‘human’ and ‘machines’.

（3）系统高保真度要求

(3) High-fidelity requirement

根据工业应用的需要，工业数字孪生系统需要满足高保真度要求。iDTS 中的孪生数据、孪生模型和孪生环境与物理对象在外观、尺寸、材料、性能、行为等要求完全一致，应充分考虑所构建模型的非线性和线性、时变和时不变特性。如生产线中的关键设备，或者设备中的关键零部件都有高保真度要求，只有达到了高保真度要求，iDTS 才能够准确反映复杂物理对象的真实运行状态。

According to the requirement of industrial applications, an iDTS needs to satisfy the high fidelity requirement. The twin data, twin model, or twin environment in iDTS should be in its closest resemblance to the final physical object in terms of appearance, size, material, performance, and behavior under the consideration of the non-linear and linear, time-varying and time-invariant characteristics. For example, the influential equipment in the production line or crucial parts of the equipment has high-fidelity requirements. iDTS can accurately reflect the sophisticated operating status of complex physical objects, only when the high-fidelity requirement is satisfied.

（4）Complex fusion of twin models

机械、电子、控制和软件等不同学科人员协同构建 iDTS，不同学科背景的人员所建立的孪生模型在类型、结构和功能等方面各不相同，增加了孪生模型的建立和使用的复杂性。典型的孪生模型包括三维结构模型、流程模型、多物理场模型和不同专业的机理模型等，iDTS 能够对这些复杂孪生模型进行关联、融合、驱动运行与评估。

Typical twin models in an iDTS include 3D structural models, process models, multi-physics models, and mechanism models of different domains. These models established by engineers from different disciplines (machinery, electronics, control, and software) vary largely in the type, structure, and function, which increases the complexity when engineers integrate them. Hence an iDTS should enable users to collaboratively associate, merge, drive and evaluate different twin models.

根据以上的分析，已有学者建立了 iDTS，例如数字孪生车间[50]和基于数字孪生的产品服务系统[51]。其中，数字孪生车间[50]由物理车间、虚拟车间、车间服务系统和车间孪生数据组成。数字孪生车间是在新一代信息技术和制造技术驱动下，通过物理车间与虚拟车间的双向真实映射与实时交互，实现物理车间、虚拟车间、车间服务系统的全要素、全流程、全业务数据的集成和融合，在车间孪生数据的驱动下，实现车间生产要素管理、生产活动计划、生产过程控制等在物理车间、虚拟车间、车间服务系统间的迭代运行，从而在满足特定目标和约束的前提下，达到车间生产和管控最优的一种车间运行新模式。与之相对应的，基于数字孪生的产品服务系统[51]也是一个典型的 iDTS，通过不同物理产品和/或服务组合的智能分析决策、快速个性化产品服务配置和服务过程体验，有效支持复杂产品与服务生命周期的智能决策、快速供给、智能服务、价值与环境分析等。

Based on the above analysis, systems represented by scholars already have the characteristics of an iDTS, such as the digital twin workshop (DTW) [50] and DT-based product service system (PSS) [51]. The DTW is a new paradigm for future workshops composed of physical workshops, virtual workshops, workshop service systems, and workshop twin data. Through the bidirectional mapping and the real-time interaction between the physical workshop and the virtual workshop, the DTW aims to promote the iterative operation of workshop production management, production activity planning, production process control, and etc., to achieve optimal production and control under the specific requirements and constraints [50]. DT-based PSS is also a typical iDTS. Rapid personalized configuration, periodical optimal decisions, and rapid supply, etc. can be obtained via aggregating real-time data from physical warehouse PSS and then mapping it to the cyber model [51].

4.2 iDTS 的系统功能结构 Functional structure of iDTS

iDTS 的功能结构如图 4 所示，包括物理层、感知层、孪生层、应用层和控制层。这五个层次并不是独立存在的，iDTS 的结构层次之间通过功能接口实现信息交互，例如物理层通过数据感知接口与感知层进行数据交互，感知层通过数据/模型传输接口和协议将多源异构实时数据传输到孪生层，孪生层再通过应用服务接口为应用层提供设计、制造、运维等服务。

The functional structure of an iDTS includes the physical layer, perception layer, twin layer, application layer, and control layer, which interact with data and information through certain logical interfaces, as illustrated in Figure 4. For example, the physical layer exchanges data with the perception layer through the data perception interface. The multi-source, heterogeneous and real-time data is transmitted to the twin layer via data/model transmission interfaces and protocols. The design, manufacturing, operation, and maintenance services from the twin layer are provided to the application layer by the application service interface.

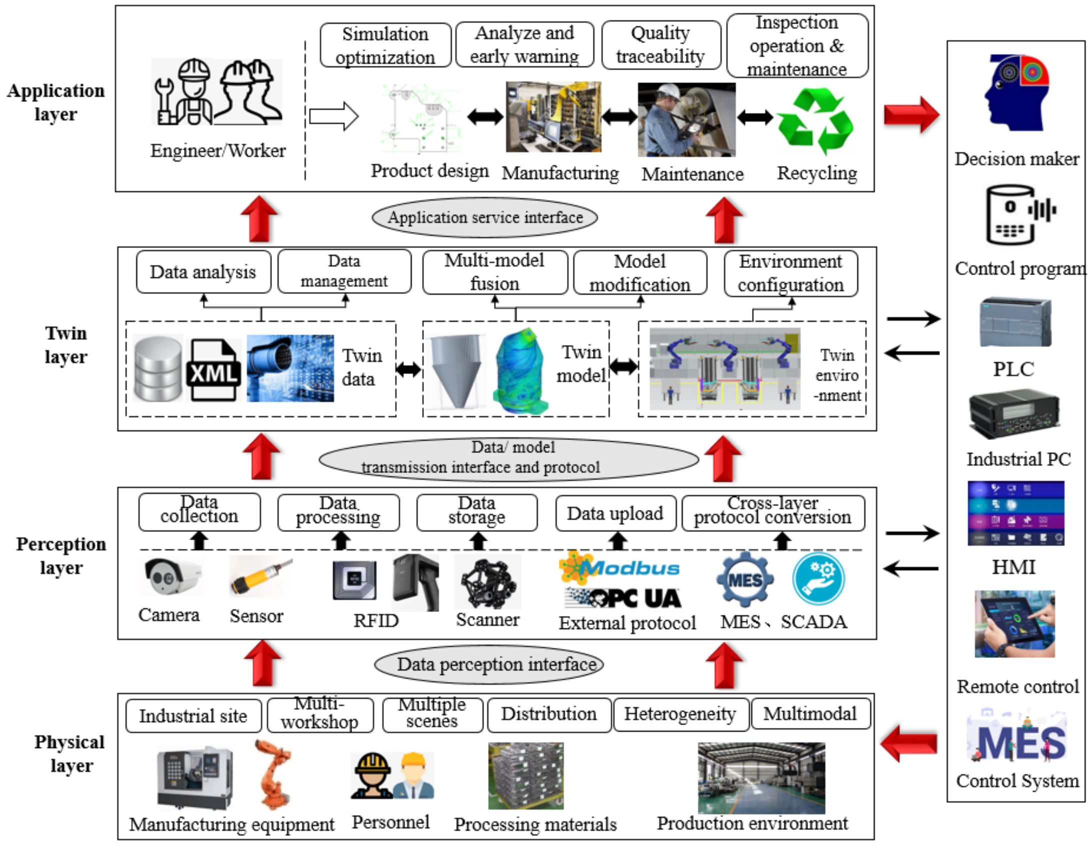

Figure 4. Functional structure of iDTS

（1）物理层：包括工业现场参与生产的物理对象，包括人员、制造装备、加工物料和生产环境等。其中，人员指的是参与生产制造的所有人员，处于物理层的主导地位，例如一线生产工人和管理人员；制造装备指的是执行特定生产任务的装备，例如进行车削加工的数控机床、进行焊接的焊接器械臂、搬运工件的 AVG 小车（Automated Guided Vehicle）等；加工物料是用于制造过程的原材料、半成品和成品等；生产环境指的是完成生产作业的场地

及其设备布局、物料摆放、库存状态和安全环境等环境因素。不同的物理对象分布在工业现场的多个车间，完成多场景任务，产生异构的、多模态的数据。

(1) Physical layer: It includes all physical objects involved in production at the industrial site, such as personnel, manufacturing equipment, processing materials, and production environment. According to the characteristic of the “man-machine-environment” mutual integration, the personnel is in a dominant position. Manufacturing equipment performs specific production tasks, such as CNC machine tools for turning, robots for welding, and Automated Guided Vehicle (AVG) for carrying workpieces, etc. Processing materials, such as raw materials, semi-finished products, and finished products, are processed by manufacturing equipment. Production environment refers to the industrial site where the production operation is completed, including equipment layout, inventory status, and safe environment, and other environmental factors. On top of that, various physical objects are distributed in multiple workshops in the industrial site, completing multi-scene tasks and generating heterogeneous and multi-modal data.

（2）感知层：用于采集和传输来自物理层的多源异构实时数据，突破环境智能感知、生产全要素按需互联、高可靠端到端数据传输。感知层可以根据需求通过不同的方式进行数据感知，例如使用摄像头采集视频数据，使用传感器采集制造装备的运行状态数据，采用射频识别技术（Radio Frequency Identification，RFID）获取生产线运转状态数据，通过扫描仪得到的产品几何数据，基于 OPC-UA、MODBUS TCP 等外部访问协议采集控制数据，以及与企业已有的系统，例如数据采集与监视控制系统（ Supervisory Control And Data Acquisition，SCADA）和制造执行系统（Manufacturing Execution System，MES）集成获取生产数据。由于这些数据的来源不同、结构不同，感知层需要具备数据的加工、存储、上传和协议转换等功能，需要建立一致的感知接口和通讯协议实现对这些多源异构实时数据的统一封装，另外需要协调各感知器的任务，实现分布式的信息汇总，并保证数据的容错性。

(2) Perception layer: By collecting, processing and transmitting multi-source, heterogeneous, and real-time data from the physical layer, the perception layer is equipped with the ability of environmental intelligent perception, on-demand interconnection of all production elements, and high-reliability end-to-end data transmission. There are various approaches to perceive different data according to actual needs, such as a) collecting video data via cameras, b) getting operating status data of manufacturing equipment through sensors, c) acquiring production line operating data using radio frequency identification (RFID), d) obtaining product geometry data through scanners, e) collecting control data based on external access protocols like the OPC-UA and MODBUS TCP, as well as f) obtaining production data by integrating with existing systems like the Supervisory Control and Data Acquisition (SCADA) system and the Manufacturing Execution System (MES). Due to the different sources and various structures of the data, the perception layer needs to have functions of data processing, storage, uploading, and protocol conversion. A consistent perception interface and communication protocol need to be established to achieve unified encapsulation of these data. In addition, it is necessary for the layer to coordinate the tasks of each perceptron to achieve distributed information aggregation and acceptable fault tolerance.

（3）孪生层：与物理层中生产制造全要素全流程对应的虚拟对象，包括孪生数据、孪生模型和孪生环境。其中，孪生数据来自感知层，可以保证孪生模型和孪生环境的高保真性，进行加工过程的动态评估优化；孪生模型包括三维结构模型、流程模型、多物理场模型、仿真模型和机理模型等，这些模型不仅要在几何结构上与物理实体保持一致，而且要能够模拟物理实体的时空状态、行为和功能[52]；孪生环境是对生产环境的虚拟映射，逼真的三维环境能够提高使用者的沉浸感。另外，孪生层需要具备数据中台和业务中台的作用，能够进行数

据管理、模型修正、模型融合和环境配置等。

(3) Twin layer: It includes twin data, twin model, and twin environment, which are virtual objects corresponding to the whole elements and processes of production and manufacturing in the physical layer. Specifically, the twin data coming from the perception layer can ensure the high fidelity of the twin model and twin environment, and guarantee dynamic evaluation and optimization of the industrial process. Correspondingly, twin models include 3D structural models, process models, multi-physics models, simulation models, and mechanism models, etc. The geometric structure of twin models is not only consistent with the physical object, but also can mirror the temporal and spatial state, behavior, and function of the physical object [52]. The twin environment is a virtual mapping of the actual production environment, and the realistic 3D environment can improve the user's immersion feel. Moreover, the twin layer plays a pivotal role as a data center or a business center, thus it can complete data management, model modification, model fusion, and environment configuration.

（4）应用层：基于孪生层为产品设计、加工制造、运行维护和报废回收等全生命周期提供应用服务，包括仿真优化、分析预警和质量追溯等。例如，在产品设计阶段，通过多精度、多尺度特征的孪生模型仿真分析进行复杂产品的跨层协同与协议设计，并通过孪生层与物理层的精准映射和共同进化找到理想设计和真实设计条件之间的误差，帮助快速验证产品原型设计；在加工制造阶段，通过孪生数据对工艺过程进行分析优化，实现多场景的加工过程动态评估，以及动态扰动下的分布式资源优化调度；在产品运维阶段，提供基于孪生模型的故障检测、寿命预测和运行状态监测等应用服务；在报废回收阶段，提供报废指导和产品生命周期归档等应用服务。

(4) Application layer: Based on the twin layer, the application layer provides application services for the product design, manufacturing, operation and maintenance, and recycling, including simulation optimization, analysis and warning, and quality traceability, etc. For example, in the product design stage, cross-layer collaboration and protocol design of complex products is carried out by simulation analysis of twin models with multi-precision and multi-scale features, and deviation between the ideal design and real design can be distinguished via the precise mapping and co-evolution of the twin layer and the physical layer. Finally, the twin layer helps designers effectively verify the product prototype design. In the manufacturing stage, the twin data is used to optimize the process, to realize the dynamic evaluation of the multi-scenario processing, and the optimal scheduling of distributed resources under dynamic disturbances. In the product operation and maintenance stage, the layer can provide application services such as fault detection, life prediction, and operating status monitoring based on the twin model. In the recycling stage, services like scrap guidance and product life cycle archiving and other applications are furnished.

（5）控制层：通过控制命令对物理层中的物理对象进行在线、实时的智能调控，实现以虚控实。控制层主要由决策者、控制程序、控制设备、控制方式和控制系统组成，其中决策者根据应用需求发出控制指令，通过远程或本地的方式将控制指令传达给 MES、DCS 等控制系统，最终通过 PLC、工控机等控制单元执行控制命令，完成现场过程控制。另外，控制命令的执行必须以保证工业安全为前提，例如远程操控安全、人机协作控制安全、环境不确定性安全、网络安全和安全态势感知与检测预警等[49]。

(5) Control layer: The control layer is an abstraction layer that realizes virtual control of physical objects in the physical layer by online, real-time intelligent control. The control layer is mainly composed of decision-makers, control programs, control equipment, control methods, and control systems. The decision-makers issue control instructions according to application requirements and transmit the control instructions to MES, DCS, and other control systems remotely or locally, and finally pass PLC, industrial computer and other control units execute control commands to complete on-site process control. On top of it, the execution of control commands must be premised on ensuring industrial safety, which is related to remote control security, man-machine cooperation control security, environmental uncertainty security, network security, and security situation awareness, detection and early warning, etc. [49]

4.3 iDTS 的成熟度模型 Maturity model of iDTS

根据孪生模型是否与物理模型互联与控制，可将 iDTS 分为两类：以仿真为主的 iDTS 和以控制为主的 iDTS。

According to whether the twin model is interconnected and controlled with the physical model, iDTS can be mainly categorized into two subclasses, as the simulation-oriented iDTS and the control-oriented iDTS.

（1）以仿真为主的 iDTS：通过建立物理系统的孪生模型，实现孪生环境与物理对象在外观、尺寸、材料、性能、行为等的精准映射，能准确仿真运行系统的动态特性。这类系统一般以仿真为主，并不与物理系统互联并形成闭环系统，常用于产品设计仿真、生产线设计仿真、虚拟装配仿真、虚拟样机调试、操作训练仿真等工业场景中。

(1) Simulation-oriented iDTS: Through the establishment of twin models corresponding to the physical system, the iDTS can realize the precise mapping between the twin environment and physical objects in appearance, size, material, performance, behavior, etc., and can accurately simulate the dynamic characteristics of the running system. This type of system is generally based on simulation rather than being interconnected with the physical system, nor will it form a closed-loop system. In practice, it is usually applied in industrial scenarios such as product design simulation, production line design simulation, virtual assembly simulation, virtual prototype debugging, and operation training simulation.

（2）以控制为主的 iDTS：通过数字化建模建立系统的数字孪生模型，基于专用软件或工具完成孪生模型与物理系统实时交互，实现数字孪生系统与物理系统的实时同步、数据反馈与迭代优化。以控制为主的 iDTS 一般用于生产线运行监测与控制、装备运行状态监测与控制、关键零部件或者系统的性能预测等工业场景中。

(2) Control oriented iDTS: In order to achieve real-time synchronization, data feedback, and iterative optimization between the iDTS and the physical system, it is important for the iDTS to establish twin models of the system based on digital modeling and to realize real-time interactions between the twin model and the physical system via dedicated software or tools. In practice, this type of system can be used in industrial scenarios like production line operation monitoring and control, equipment operation status monitoring and control, performance prediction of key components or systems, etc. generally use control-based iDTS.

iDTS 会随着产品或系统的生命周期进展而不断的丰富和进化。以仿真为主的 iDTS 在 DT 的概念正式产生之前就已经存在，随着先进技术和工具的应用而不断得到推广。与之相比，以控制为主的 iDTS 是 DT 概念提出后开始快速成为研究的热点方向。在不同的应用阶段和应用场景，不同类型 iDTS 的作用和特点并不相同，它们会产生不同的价值。所以，根据实际的工业应用，本文提出了 iDTS 发展的成熟度模型，分为仿真阶段、孪生阶段、“人-机”交互阶段和“人-机-环境”融合阶段（如图 5 所示）。以仿真为主的 iDTS 和以控制为主的 iDTS 出现在不同的成熟度阶段。

As the life cycle of a product or system progresses, iDTS will continue to evolve and be enriched as well. Before the concept of DT is formally produced, the simulation-oriented iDTS already exists. With the application of advanced technology and tools, it is continuously promoted. In contrast, after the concept of DT is proposed, control-oriented iDTS quickly becomes a hot research direction. Different types of iDTS have specific functions and characteristics in certain application stages and industrial scenarios, with values in application. Therefore, to address real industrial needs, this paper proposes a maturity model for the development of iDTS, which is divided into a simulation phase, a twin phase, a “human-machine” interaction phase, and a “human-machine-environment” integration phase (as exhibited in Figure 5). It is observed from Figure 5 that both of the simulation-oriented iDTS and the control-oriented iDTS appear at different maturity stages.

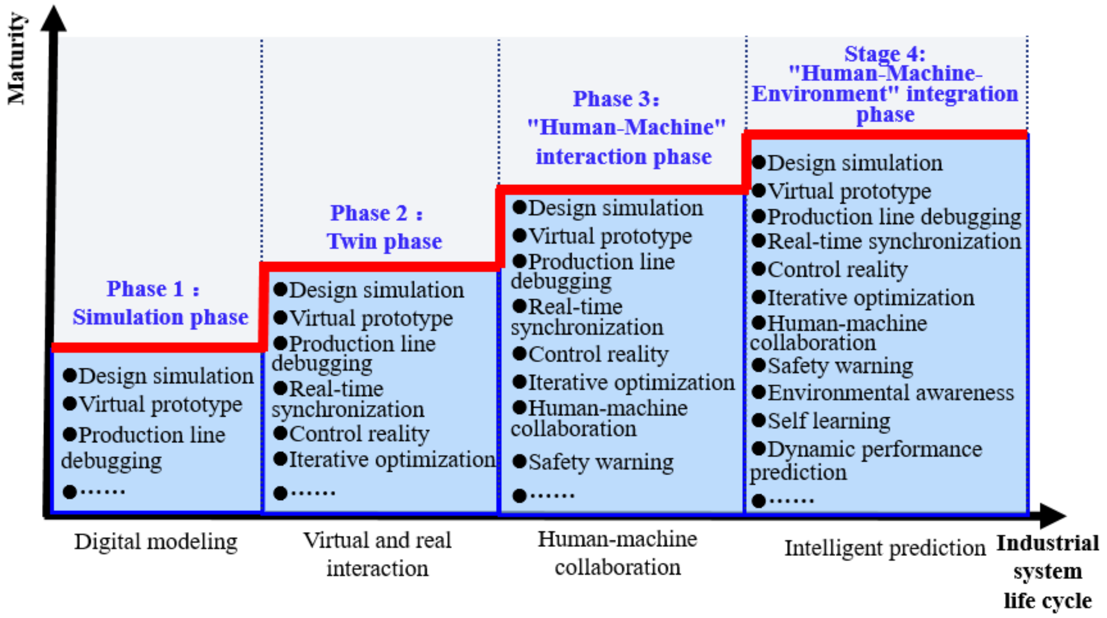

图 5 iDTS 成熟度模型

（1）**仿真阶段**：该阶段是以仿真为主的 iDTS 使用阶段。该阶段主要建立物理对象的虚拟仿真模型，iDTS 只存在于虚拟空间，相当于传统的数字样机或者虚拟产线。数字孪生体主要用于产品的优化设计、生产线规划和虚拟调试等，iDTS 支持概念设计和初步设计中的决策，能够发现或者改善工程活动中的技术风险。

(1) Simulation phase: This phase is mainly oriented by the simulation-driven iDTS. At this phase, the virtual simulation model of the physical object is established. Since the iDTS only exists in a virtual space, its function is equivalent to a traditional digital prototype or virtual production line. DTs are mainly used for product optimization design, production line planning, and virtual commissioning, etc. The decision-making part of conceptual design and preliminary design is completed by iDTS, which can recognize or improve technical risks in engineering activities.

（2）**孪生阶段**：该阶段在以仿真为主的 iDTS 应用基础上，iDTS 能够实现虚拟对象与物理对象之间的虚实交互。iDTS 能够通过感知层从物理对象实时接收数据更新，实现数字孪生系统与物理系统的实时同步，并通过控制层实现数据反馈与迭代优化。具备以控制为主的 iDTS 的功能特征。

(2) Twin phase: Based on the simulation-driven iDTS, in this phase, the iDTS can realize the interaction between virtual objects and physical objects. Through the perception layer, the iDTS can receive data from physical objects in real-time, and realize real-time synchronization between the digital twin system and the physical system. Moreover, the iDTS can realize iterative optimization via the control layer. Thus, the system in this phase has the functional characteristics of the control-driven iDTS.

（3）“人-机”交互阶段：在以仿真为主的 iDTS 和以控制为主的 iDTS 应用基础上，除了包含孪生阶段的功能外，在产品或系统运行时，能支持人机交互。例如，VR/AR/MR 等技术得到融合应用，iDTS 能够通过物理规则和机理模型进行智能计算与分析，实现人与系统协同运行与安全预警[49]。

(3) “Man-machine” interaction phase: According to the application of the simulation-driven iDTS and the control-driven iDTS, this stage not only includes the functions of the twin phase but also supports man-machine interaction while the product or system is running. For example, with the application of technologies like VR/AR/MR, iDTS can perform intelligent calculation and analysis through physical rules and mechanism models, and realize the collaborative operation and safety warning of humans and systems [49].

（4）“人-机-环境”融合阶段：在以仿真为主的 iDTS 和以控制为主的 iDTS 应用基础上，具备人机交互、环境感知、智能预测等功能，形成一个人、机和环境协调运行的复杂系统。iDTS 能够根据历史和实时数据与模型，综合应用智能感知、模型仿真、决策优化等人工智能技术，具备无人监管的自学习能力，实现智能动态性能和安全预测，同时也具有反馈控制能力。

(4) “Man-machine-environment” integration phase: Based on the application of the simulation-driven iDTS and the control-driven iDTS, this stage can provide functions like human-computer interaction, environment perception, and intelligent prediction, and finally form a complex system that coordinates the operation of human, machine, and environment. In addition, iDTS can comprehensively apply artificial intelligence technologies such as intelligent perception, model simulation, and decision-making optimization through historical and real-time data and models. Particularly, the system has feedback control and unsupervised self-learning capabilities to achieve intelligent dynamic performance and safety prediction.

5 iDTS 的运行模式与架构 Running mode and architecture of iDTS

5.1 不同 iDTS 运行模式分析 Analysis of different iDTS running modes

通过分析总结，iDTS 的运行模式主要包括四种：①本地化配置的 iDTS 运行模式、②基于“云-端”的 iDTS 运行模式、③基于“云-边-端”的 iDTS 运行模式、④基于分布式计算的 iDTS 运行模式。其中，本地化配置的 iDTS 是一种局域网部署数字孪生系统的运行模式；基于“云-端”的 iDTS 是一种以云计算为中心的 iDTS 运行模式；基于“云-边-端”的 iDTS 是以云平台为中心、云边端协同计算、存储与业务协同的运行模式，是未来数字孪生系统部署运行的主流模式；基于分布式计算的 iDTS 是在统一的分布式物联网操作系统支持下的一种运行模式。

There are four kinds of iDTS running modes: (1) the localized configuration mode, (2) the “cloud-end” mode, (3) the “cloud-edge-end” mode, and (4) the distributed computing mode. Among them, the localized configuration mode deploys and configures the iDTS in a local area network (LAN). As for the “cloud-end” mode, it is a cloud computing-centered iDTS running mode. In terms of the “cloud-edge-end” mode, it is a running mode with a cloud platform as the center and relies on the cloud edge-end collaborative computing, storage, and business collaboration. On top of that, the “cloud-edge-end” mode is the mainstream mode of deployment and operation of the iDTS in the future. For the last one, the distributed computing mode is supported by a unified distributed IoT operating system.

不同类型的 iDTS 运行特点不同，使用的工业场景也差异较大。通过分析，表 2 给出了不同 iDTS 运行模式在计算效率、存储方式、部署与运行成本和适用场景等方面的不同。为 iDTS 系统实施提供指导。

The four kinds of iDTS running modes have typical running characteristics and different industrial scenarios. Table 2 shows the differences in the computing efficiency, storage methods, deployment and operation costs, and applicable scenarios of them, which guides iDTS system implementation.

Table 2. Characteristic analysis of different iDTS running modes

序号	**名称**	**计算效率**	**存储方式**	**部署与运行成本**	**适用场景**
1	本地化配置的 iDTS 运行模式	局域网配置、计算速度快	本地化存储	局域网部署，运行成本高	适用于安全性高、实时性高、运行参数多、调控频繁的复杂工业产品。
2	基于“云-端”的 iDTS 运行模式	云平台上集中式计算，计算效率受云平台算力与网络传输速度影响较大	云平台集中式存储	租赁云平台的服务，可低成本快速使用	适用于计算实时性不高、运行参数较少的轻量化终端工业产品。
3	基于“云-边-端”的 iDTS 运行模式	云、边协同计算，效率高	云、边分工存储	租赁云平台的服务，需要投入资金加强边缘层能力建设	适用于实时性要求较高、运行参数调控较为频繁的工业产品或智能车间。
4	基于分布式计算的 iDTS 运行模式	算力资源具有分散性	分布式存储	通过部署统一的分布式物联网操作系统，可快速、低成本使用	适用于计算效率高、运行可靠性高的工业产品，但是需加强安全防护能力。

Type	**Computing efficiency**	**Storage mode**	**Deployment and Running cost**	**Applicable scenarios**
Localized configuration mode	LAN configuration and fast computing speed.	Local storage	LAN deployment, high running cost.	Complex industrial products with high safety, high real-time performance, large running parameters and frequent regulation.
“Cloud-end” mode	Centralized computing on cloud platform, the computing efficiency is greatly affected by the computing power of the cloud platform and network transmission speed.	Cloud platform centralized storage	The service of the leasing cloud platform can be used quickly at low cost.	Lightweight terminal industrial products with low real-time calculation and few running parameters.
“Cloud-edge-end” mode	Cloud and edge collaborative computing, high efficiency.	Cloud and edge storage	Leasing cloud platform services require investment to strengthen the capacity-building of the edge layer.	Industrial products or intelligent workshops with high real-time requirements and frequent regulation of operating parameters.
Distributed computing mode	Computing resources are decentralized.	Distributed storage	By deploying a unified distributed Internet of things running system, it can be used quickly and at low cost	Industrial products with high calculation efficiency and high running reliability, but the safety protection ability needs to be strengthened.

5.2 本地化配置的 iDTS 运行模式 Localized configuration mode

本地化的 iDTS 通常依托于厂区范围内的各种局域网和算力资源进行部署运行，数字孪生系统的物理对象、测量感知、设备控制、通信网络、数字孪生体、用户域均处于同一地理空间。

The localized configuration mode iDTS usually relies on various LANs and computing resources within the factory area for deployment and operation. In the mode, physical objects, measurement perception, equipment control, communication network, DTs, and user domain of iDTS are all in the same geographical space.

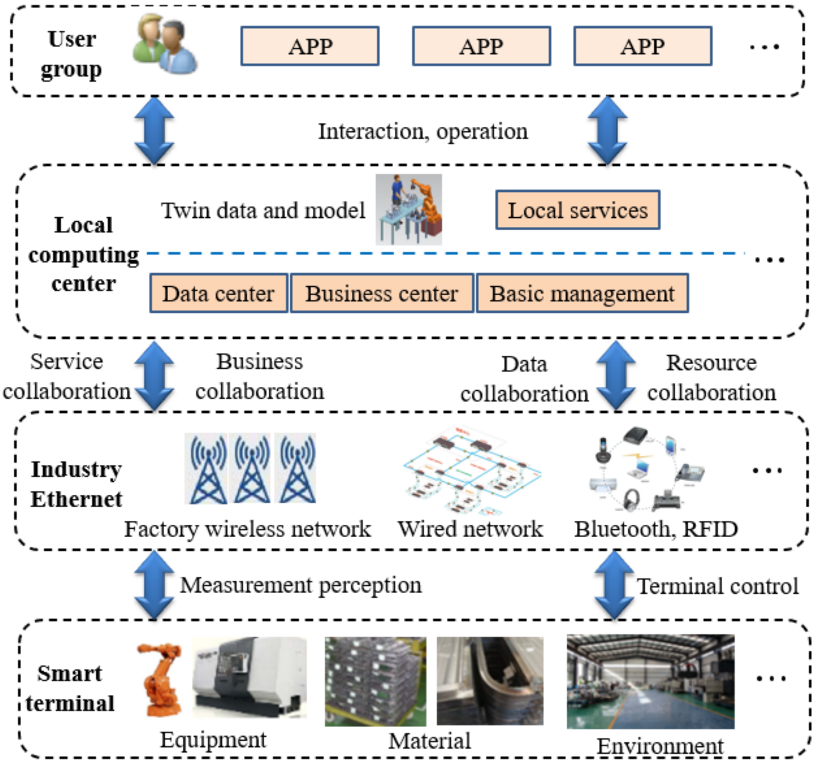

Figure 6. Running architecture of the localized configuration mode

如图 6 所示为一种 iDTS 本地化运行模式。iDTS 的通信网络为厂域范围内的工业以太网，厂域网根据需要接入网络的接入点分布情况可选择环形网络、总线型网络和星型网络。其中，环形和总线型网络沿着接入点拉设网络干线，星型网络从中心向各接入点辐射状布线。iDTS 的人员、设备、物料等物理对象和数字孪生体，通过各自的通信接口连接至厂域网。iDTS 本地化运行模式，需在本地具备一定的运算能力。平行于物理对象的孪生体运行于算力平台之上。另外，本地运行的物理对象和本地运行的孪生体基于厂域网进行信息交互，数据从物理对象到孪生体，为数字孪生体提供数据驱动；数字孪生体的仿真运算结果和用户的决策指令在作用于物理对象，实现信息的闭环，随着信息的交互实现系统的优化运行。

Figure 6 reveals the architecture of the iDTS running mode under a localized configuration. The communication network of iDTS is industrial Ethernet within the factory area. The specific type of the Wide Area Network (WAN) can be a ring network, a bus network, or a star network according to the distribution of access points that need to get access into the network. Among them, the ring network and bus network pull the network trunk along with the access point. The star network routes radially from the center to each access point. Physical objects and DTs of iDTS, such as personnel, equipment, and materials, are connected to WAN via certain communication interfaces. In addition, the localized configuration mode requires certain local computing power. The twin parallel to the physical object runs on the computing platform. Moreover, the local running physical objects and the local running twins exchange information based on WAN, and the data from the physical objects drives DTs. The simulation results of DTs and the user's decision instructions can feedback to the physical objects to realize the closed-loop of information and achieve the optimized running of the system through the information interaction.

本地部署运行模式适用于工厂间连接需求较少，系统运行对算力资源要求不高无需借助于远程算力的情况。本地部署运行模式具有以下优点：

（1）低成本运行：无需接入高速光纤专线，节约了互联网接入成本。

（2）低延时通信：本地网络可以设置宽裕的带宽资源，为各种需要接入网络的生产要素提供宽带和低延时通信。

（3）高安全性：本地化部署运行的iDTS，内部数据流动局限于厂域范围内，对工厂数据的保密和信息安全工作提供了便利。

但是本地化的运行模式需要在本地配备足够的算力资源以支撑大数据和模型仿真的需求，本地部署运行的服务器和超级计算机会产生一定的电力成本。

The localized configuration mode is suitable for the iDTS that requires seldom connection between factories and need weak remote computing power when the system is running. This kind of mode has the following advantages.

(1) Low cost: No necessary to access dedicated high-speed fiber-optic lines when the iDTS is running, so it saves the cost of Internet access.

(2) Low latency: The local network can set up generous bandwidth resources to provide broadband and low latency communication for various production factors that need access to the network.

(3) High security: With iDTS deployed and running locally, the internal data flow is limited to the factory domain, which facilitates the confidentiality of factory data and information security work.

However, the localized configuration mode needs to be equipped with sufficient computing resources locally to support the requirement of big data and intensive model simulation. As a result, the local deployment of running servers and supercomputers will generate certain power costs.

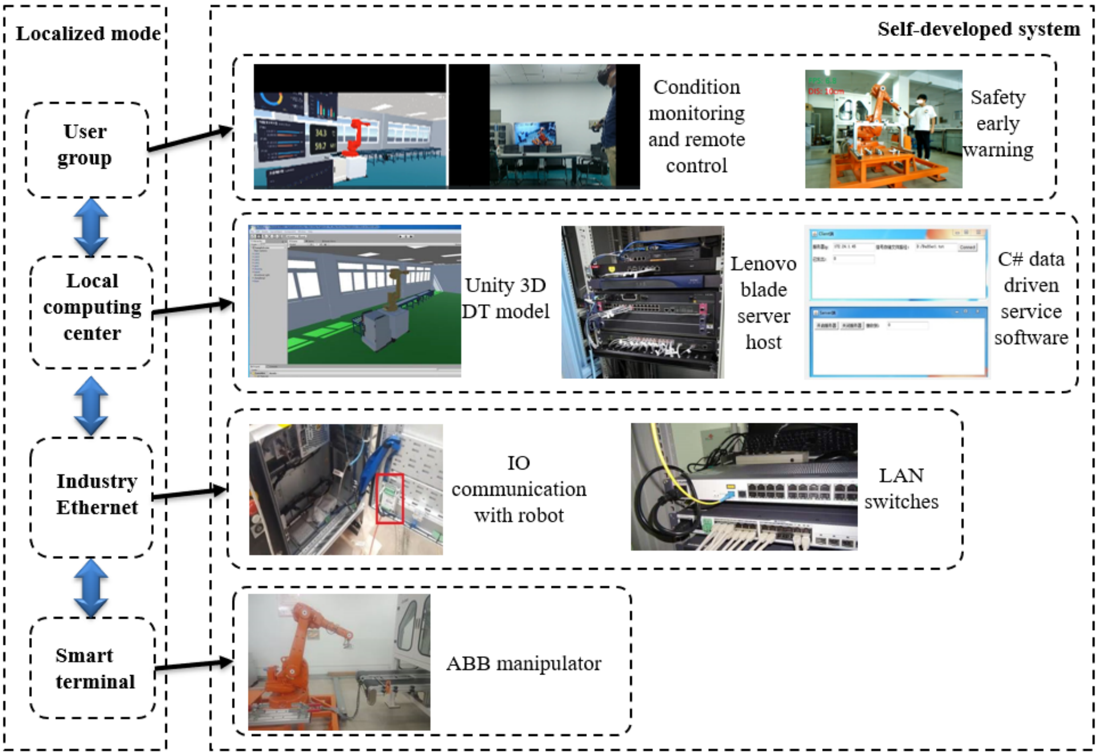

Figure 7. Example of iDTS operation mode with localized configuration

如图 7 所示为郑州轻工业大学所开发的一套本地化运行模式的 iDTS。在该系统中，以 ABB 工业机器人为对象，使用 Unity 3D 建立与之对应的数字孪生模型。首先，通过 ABB 机器人控制系统的 IO 信号板实现对机器人的感知测量和设备控制。然后，使用 C#自助开发数据驱动服务软件，并通过局域网交换机将感知到的数据传输至本地的联想刀片式服务主机。最后，在本地化的运算平台上运行 Unity 3D 中的虚拟机器人，为用户提供远程操控服务。

Figure 7 represents an iDTS of a set of localized running modes developed by Zhengzhou University of Light Industry. It takes the ABB industrial robot as the object and uses Unity 3D to establish the corresponding DT model. Firstly, the sensing measurement and equipment control of the robot is realized through the IO signal board of the ABB robot control system. Then, we use C# to develop the data-driven service interfaces and transmit the sensed data to the local Lenovo blade service host through LAN switches. Finally, the virtual robot in Unity 3D runs on the localized computing platform, which provides a remote control service for users.

5.3 基于“云-端”的 iDTS 运行模式 “Cloud-end” model

基于“云-端”的 iDTS 运行架构是以云计算为中心的 iDTS 运行模式，如图 8 所示，系统由智能设备、网络传输、云计算和用户等层次构成，用户服务、业务逻辑、模型、数据均在云平台上运行，智能设备没有较大的智能算力与存储支持。云计算平台上基础管理平台、数据中台、业务中台和业务前台服务构成，实时处理不同智能设备对应的孪生数据与模型，不同用户群通过 APP 登录并实时监测设备运行状态，根据需要发送控制指令。基于“云-端”的 iDTS 运行模式是一种成本低、高扩展和高可靠的模式，适用于计算实时性不高、长周期场景。智能终端设备一般为轻量化的工业产品，状态监测与控制的运行参数数量较少。如 GE 公司的工业互联网平台 Predix，是一个支持“云-端”的 iDTS 运行模式的系统，在该平台上成功实现了发动机的远程监控与诊断，具有在线监视、预测维护和优化运营的功能[53]。滴滴打车系统是涵盖出租车、专车、快车、顺风车、代驾及大巴等多项业务在内的一站式出行平

台，预约用车、智能分配、实时查询车辆位置、服务需求交流、在线支付、订单评价等多种服务，是一种典型的基于“云-端”的 iDTS 运行模式[54]。

The “cloud-end” mode iDTS runs mainly on cloud computing. As shown in Figure 8, the running architecture of the mode is composed of intelligent devices, network transmission, cloud computing, and users, with user services, business logic, models, and data all running on the cloud platform. It is necessary for intelligent devices to have great computing power and storage support. The cloud computing platform includes the basic management platform, data center, business center, and business forefront service, which can process twin data and models corresponding to different intelligent devices in real-time. Different user groups logging in through certain APP can monitor the running status of devices in real-time, and sending control instructions as needed. The iDTS running mode based on "cloud-end" is a low-cost, highly scalable, and highly reliable mode, which is suitable for scenarios with low real-time computing and a long period. The intelligent terminal equipment is generally lightweight industrial products. The number of operating parameters for condition monitoring and control is small. For example, Predix, an industrial internet platform of GE Company, is a system supporting the “cloud-end” running mode, which has successfully realized the remote monitoring and diagnosis of engines and has the functions of online monitoring, predictive maintenance and optimized operation [53]. In addition, Didi Taxi system is a one-stop travel platform covering many businesses such as taxis, special cars, express, hitch, designated driver and buses, and etc. It has a variety of services such as car reservation, intelligent allocation, real-time vehicle location query, service demand exchange, online payment, order evaluation. It is a typical iDTS running based on the “cloud-end” mode [54].

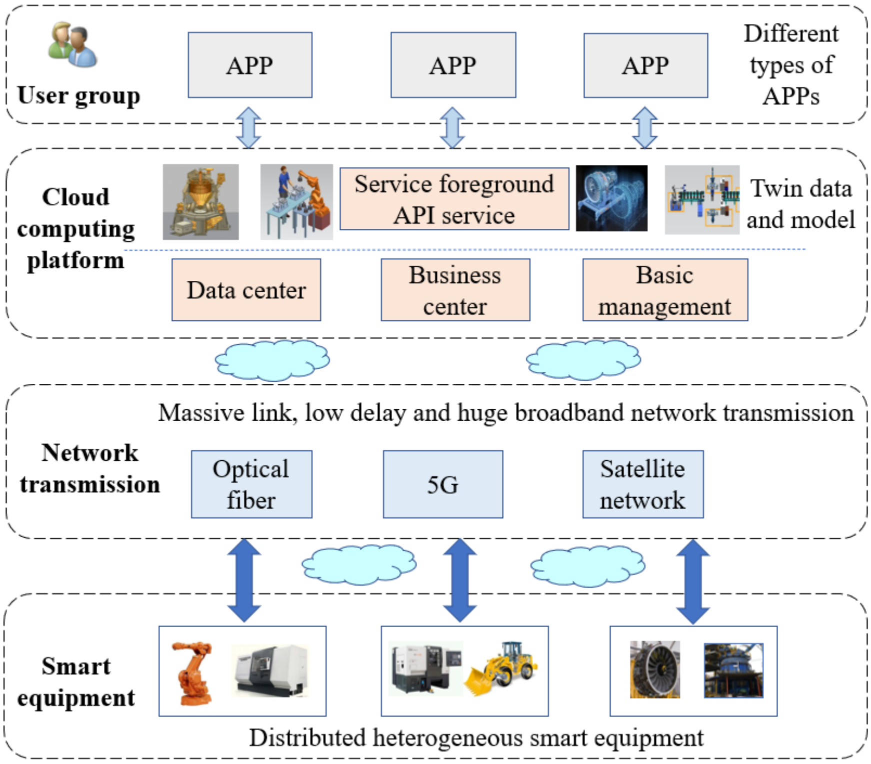

Figure 8. iDTS running architecture based on the “cloud-end” mode

基于“云-端”的 iDTS 系统特点如下：

（1）集中式管理：云端具有高性能计算与存储能力，实现数字孪生系统的业务、模型与数据的集中管理，具有系统分析、计算、控制、存储等服务功能，在处理或存储方面，可

以将资源整合在一起，避免重复计算，重复存储。

（2）节省成本：云计算集中运行，可以集中更新组件，不间断操作。云计算不需要购买多余服务器及其扩容备件，也不用重复安装服务器系统环境，重复更新和修复。

（3）异构资源运维：在底层，需要面对各类众多的基础软硬件资源，利用云计算可实现异构环境下的资源协调与优化，支持资源动态扩展。可以有效兼容各种不同种类的硬件，可以同时运行多个不同类型的业务。

The characteristics of the “cloud-end” running mode are as follows.

(1) Centralized management: The cloud has high-performance computing and storage capabilities to realize centralized management of the business, models, and data of the iDTS, with system analysis, computing, control, storage, and other service functions. In terms of processing or storage, the resources can be integrated to avoid duplicate computing and storage.

(2) Cost saving: Cloud computing runs without interruption, as well as updates components centrally. Moreover, cloud computing does not require the purchase of redundant servers and their expansion spare parts, nor does it require repeated installation of server system environments, repeated updates, and repairs.

(3) Heterogeneous resource operation and maintenance: At the bottom, it is necessary to face all kinds of numerous basic hardware and software resources. Using cloud computing can realize resource coordination and optimization in a heterogeneous environment and support dynamic resource expansion. It is effectively compatible with various kinds of hardware and several different types of business at the same time.

5.4 基于“云-边-端”的 iDTS 运行模式 “Cloud-edge-end mode

基于“云-边-端”的 iDTS 运行模式是一种边缘云计算模式，是基于云计算技术的核心和边缘计算的能力，构筑在边缘基础设施之上的柔性云计算平台，形成“云-边-端”协同。该运行架构是在基于“云-端”的 iDTS 运行架构基础上增加了边缘计算能力，边缘位置具有计算、网络、存储、安全等能力。基于“云-边-端”的 iDTS 运行模式是一种低延时、高可靠和更安全，适用于计算实时性、短周期场景；它通过将网络转发、存储、计算，智能化数据分析等工作放在边缘处理，降低响应时延、减轻云端压力、降低带宽成本，并供全网调度、算力分发等云服务，如图 9 所示。例如，西门子将 MindSphere 是一个基于云的开放式物联网操作系统，是一个基于“云-边-端”协同的开放式架构，使用 MindSphere 就可以创建物理机器及其相应数字化双胞胎之间的实时反馈环路。这样就可以监控能源利用率、运营状态和性能之类运营数据。运营数据还可以通过能源优化、预测性维护、性能调整等方式支持产品生产，从而改进设计的未来迭代。杭州城市大脑项目是一个基于阿里云云计算平台的“云-边-端”架构的数字孪生系统，阿里云边缘计算更包含四层技术栈：边缘硬件和芯片、边缘计算平台、边缘计算操作系统、边缘中件间和面向边缘的应用与服务；城市大脑包括警务、交通、文旅、健康等 11 大系统和 48 个应用场景，日均数据可达 8000 万条以上。

The “cloud-edge-end” mode is a kind of edge cloud computing mode. It is a flexible cloud computing platform based on the core of cloud computing technology and the capability of edge computing, and forms “cloud-edge-end” collaboration. The running architecture adds edge computing capability on the basis of the “cloud-end” running architecture illustrated in Figure 8. The edge position has computing, network, storage, security, and other capabilities. Compared with the “cloud-end” running mode, the “cloud-edge-end” mode is a low-latency, high-reliability, and safer one, which is suitable for real-time computing and short-cycle scenarios. Moreover, it puts network forwarding, storage, calculation, intelligent data analysis, and other work on edge processing, which can reduce response delay, cloud pressure, and bandwidth cost, and provide cloud services such as scheduling and computing power distribution for the whole network, as shown in Figure 9. For example, Siemens regards MindSphere as an open IoT operating system based on the cloud. It is an open architecture based on “cloud-edge-end” collaboration. In addition, MindSphere can create a real-time feedback loop between physical machines and their corresponding digital twins. In this way, operational data such as energy utilization, operational status, and performance can be monitored. Operational data can also support product production through energy optimization, predictive maintenance, performance adjustment, etc., so as to improve the future iteration of the design. Similarly, the Hangzhou City Brain Project in China is an iDTS running on the “cloud-edge-end” architecture of Alibaba Cloud Computing Platform. Alibaba Cloud edge computing includes four layers of the technology stack, which are edge hardware and chips, edge computing platform, edge computing operating system, edge middleware, and edge-oriented applications and services. Another example is the urban brain, and it includes 11 systems and 48 application scenarios, such as police affairs, transportation, cultural travel, and health, with an average daily data of over 80 million.

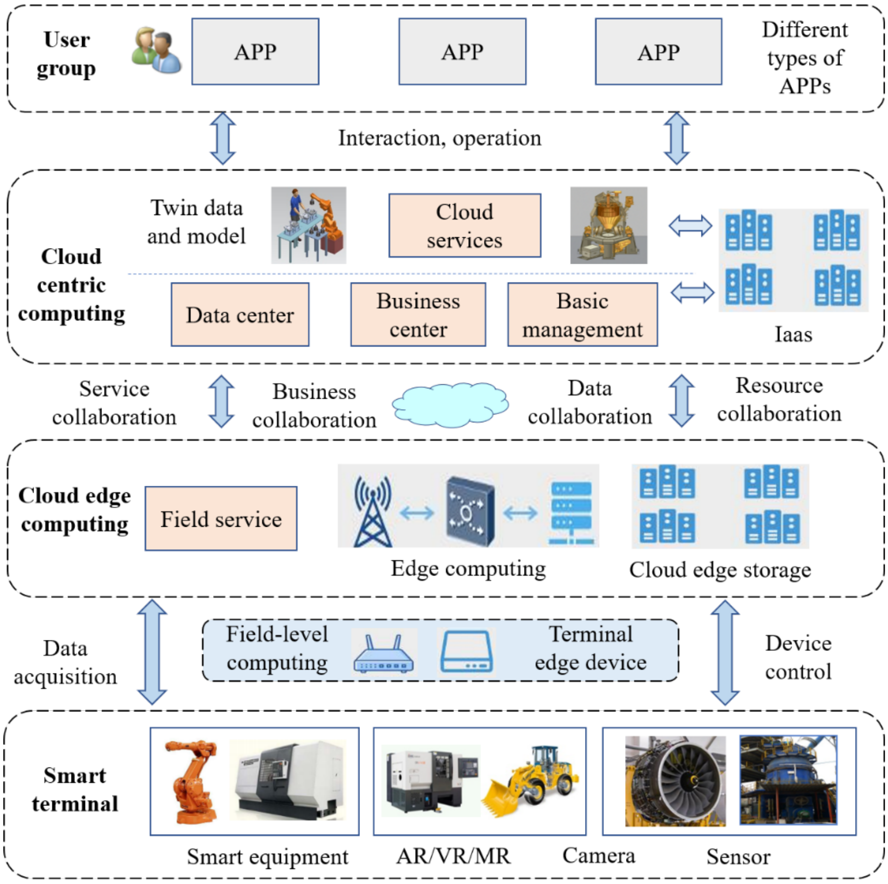

Figure 9. iDTS running architecture based on “cloud-edge-end” mode

基于“云-边-端”的 iDTS 系统特点如下：

（1）边缘计算：是在移动网络边缘提供 IT 服务环境和计算能力，强调靠近移动用户，以减少网络操作和服务交付的时延，提高用户体验。

（2）“云-边”协同：中心云、边缘计算以及 IoT 进行连接和计算力的协同，发挥云中心规模化、边缘计算本地化与低成本、IoT 终端感知等各方面的优势。充分利用云、边、端

全路径的智能异构资源进行多媒体的实时处理，让数据信息最大化，同时基于算法仓、服务仓灵活部署，有效实现计算、存储资源的全拉通。以 AI 场景为例，把推理放到边缘进行，然后从边缘收集数据在中心进行训练，训练好的模型又下发到边缘。另外，云上的能力也需要形成联动，比如把边缘的有用数据收集上来，在云上做呈现和再加工。除了云边协同，还有边边协同与端边协同。

（3）资源调度：边缘计算场景下资源很分散，负载随着时空不同而差异很大，如何根据时空差异对资源做合理有效的调节，使资源使用达到最佳效果也是一件很有意义的事情。合理的资源调度可以让系统变得更高效、稳定、低成本。

The characteristics of the “cloud-edge-end” running mode are as follows.

(1) Edge computing: It provides an IT service environment and computing capacity at the edge of the mobile network, and emphasizes proximity to mobile users. Thus, it can reduce the delay of network operation and service delivery, and enhance users’ experience.

(2) “Cloud-edge” collaboration: It can collaborate with the central cloud, edge computing, and IoT computing power, thus giving full play to the advantages of cloud center scale, localization and low cost of edge computing, and IoT terminal awareness. Moreover, it can make full use of the intelligent heterogeneous resources in the whole path of cloud, edge, and end to process multimedia in real-time, to maximize data information. At the same time, based on the flexible deployment of algorithm warehouse and service warehouse, it can effectively achieve the full pull-through of computing and storage resources. Taking the AI scene as an example, the reasoning is carried out at the edge, then data is collected from the edge for training in the center, and the trained model is distributed to the edge. In addition, the capabilities in the cloud need to be linked. For example, useful data is collected at the edge, and then in turn is presented and reprocessed on the cloud. In addition to cloud edge collaboration, there are edge collaboration and end-edge collaboration as well.

(3) Resource scheduling: In the edge computing scenario, resources are scattered, and loads vary greatly with time and space. It is significant to adjust resources reasonably and effectively according to the difference of time and space, to make the best use of resources. Thus, reasonable resource scheduling can make the system more efficient, stable, and low-cost.

5.5 分布式计算驱动的 iDTS 运行模式 Distributed computing mode

iDTS 的分布式运行模式中，物理空间中的人、设备、物料、工作场地具有分散性；数字空间中的算力资源也具有分散性。这种运行模式适用于生产各要素分散，企业规模大厂区数量多，又需要统筹调度管理分散于各处的资源实现各处资源互联互通，或者需要调用云端服务器或算力资源实现复杂模型仿真运算的情况。分布式 iDTS 从实现方式上有多种技术方案，一种方案是在应用层实现分布式，该种模式中系统的拆分和整合都发生在应用层，由相应的通信软件等功能软件实现整个系统的分散部署；另一种方案是在操作系统层实现分布式，iDTS 的应用开发部署于一个操作系统之上，无需考虑分布式的具体实现细节，由操作系统负责各处分散资源的统一调度。从整体来看，运行在各种硬件载体之上的分布式的操作系统构成了一个大的虚拟的操作系统，iDTS 的各项功能都运行于该虚拟系统之上，从而实现系统逻辑上的一体化和具体运行中的分布式。这种实现方案就需要基于一种分布式的操作系统来部署工业数字孪生系统。

In the distributed computing running mode of iDTS, people, equipment, materials, and workplaces in physical space are dispersed, and computational resources in digital space are distributed as well. This kind of running mode is suitable for cases where the production elements are scattered, the enterprise has a large number of plants. The resources scattered in various places need to be coordinated and managed to achieve the interconnection in various places. The cloud servers or computing resources need to be called to achieve complex model simulation operations. Distributed computing iDTS has various technical solutions in terms of implementation. One solution is to implement the distributed iDTS at the application layer. In this mode, the splitting and integration of the system occur at the application layer. The corresponding communication software and other functional software realize the decentralized deployment of the whole system. Another solution is to implement distributed iDTS at the operating system layer. Thus, the iDTS application development is deployed on an operating system without considering the specific details of distributed implementation. The operating system is responsible for the unified scheduling of decentralized resources in various places. As a whole, the distributed operating system running on various hardware carriers constitutes a large virtual operating system on which all functions of iDTS run, thus realizing the logical integration of the system and the distribution of the specific operation. Moreover, this implementation requires a distributed operating system to deploy the iDTS.

如图10所示为基于分布式操作系统的iDTS运行模式。整个系统以广域网为数据传输纽带将各个分散系统连接起来。分布式iDTS具有分散的物理空间，物理空间分布在不同的地域，可以无限拓展。物理空间中各种物理对象需要建立在统一的操作系统平台之上。对物理对象的感知测量和控制功能由操作系统支持。运行iDTS各种软件的运算平台同样分布式部署，由统一的分布式操作系统管理运行并与网络中的其他分布资源保持通信。运算平台可以无限拓展，各运算平台由分布式操作系统整合为一个逻辑统一的虚拟运算平台。在分布式iDTS运行模式中，用户域同样也是分散的，在统一操作系统平台基础上实现分散部署和逻辑统一。

As shown in Figure 10, the whole system uses WAN as a data transmission link to connect various decentralized systems. The distributed iDTS has a decentralized physical space, which is distributed in different geographical areas and can be expanded infinitely. Various physical objects in the physical space need to be built on top of a unified operating system platform. The sensing measurement and control functions of the physical objects are supported by the operating system. The computing platforms running the various iDTS software are also distributed, and managed by a unified distributed operating system, and communicate with other distributed resources in the network. In addition, the computing platforms can be expanded indefinitely. Each computing platform is integrated by the distributed operating system into a logically unified virtual computing platform. In the distributed iDTS running mode, user domains are also decentralized and need to be deployed and logically unified based on a unified operating system platform.

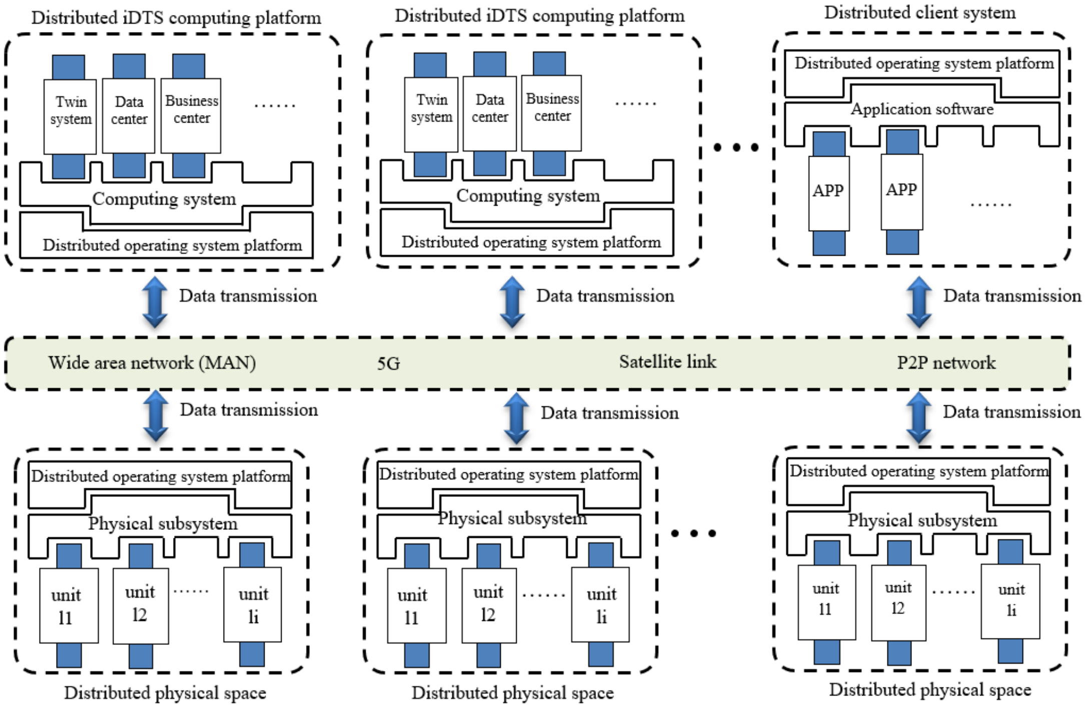

Figure 10. iDTS running architecture based on distributed computing

分布式 iDTS 的特点如下。

（1）信息物理高度分布式：物理实体和数字模型的底层操作系统均采用统一的操作系统平台，所有设备形成一个“超级虚拟设备”，物理功能、资源算力、模型、数据和应用无需绑定，根据任务不同它们将被分布式地弹性部署和调用。

（2）信息物理高度协同：基于 5G、卫星链路、P2P 网络，整个系统不再是树状的垂直金字塔结构，而是扁平结构，在信息与物理之间通过高速的网络实现连接，推动信息物理高速协同和数据快速交互。

（3）信息物理高度共享：实现基于硬件互助的制造资源能力动态可扩展，并实现功能、算力、数据、模型、应用在信息物理空间的高度共享。

（4）信息物理高度模块化：基于数字孪生系统具有高度分布式、高度协同和高度共享的特性，今后新一代基于数字孪生的设备、单元和系统都应该是高度模块化，它们之间可以通过“搭积木”的方式实现集成、互助和共享。

（5）信息物理高度智能化：基于底层操作系统分布式任务调度，使得数字孪生系统具有强大分布式计算能力和远程启动、调用和迁移能力，从而使原来不具备强大的功能、算力和算法的小型硬件设备也具有大型智能设备的能力。

The features of the distributed computing running are as follows.

(1) Information physics is highly distributed: The underlying operating systems of physical entities and digital models all adopt a unified operating system platform, and all devices can form a “super virtual device”. Furthermore, physical functions, resource computing power, models, data, and applications do not need to be bound, and they will be distributed and deployed flexibly according to different tasks.

(2) Information physics is highly coordinated: Based on 5G, satellite links, and P2P networks, the whole system is no longer a tree-like vertical pyramid structure, but a flat structure that enables connections between information and physics through high-speed networks to promote high-speed information-physical collaboration and rapid data interaction.

(3) Physical sharing of information: It can realize the dynamic expansion of manufacturing resources based on hardware mutual assistance, and can also achieve the high sharing of functions, computing power, data, models, and applications in the information physical space.

(4) Information physics is highly modular: Based on the highly distributed, collaborative, and shared characteristics of the iDTS, the future generation of DT-based devices, units, and systems should be highly modular, and they can be integrated, mutually supportive and shared through the "building blocks" approach.

(5) Information physics is highly intelligent: Base on that distributed task schedule of the underlying operating system, the iDTS has powerful distributed computing capability and remote start-up, call, and migration capability, and thus it enables the small hardware devices without powerful functions, computing power and algorithms to have the capability of large intelligent devices.

例如，基于 HarmonyOS （HMS）系统可以实现如图 10 所示的分布式工业数字孪生系统运行模式。HMS 是一个分布式物联网操作系统，HMS 采用的分布式软总线、分布式设备虚拟化、分布式数据管理和分布式任务调度技术，可实现多设备间的能力互助和资源共享。所有安装 HMS 设备都采用统一的框架和组件技术，使得用户程序的开发应用不依赖设备形态，支持程序一次开发、多端部署和弹性部署[55]。此外，HMS 采用基于微内核架构设计保证了终端设备的可信安全，同时采用确定时延引擎和高性能 IPC 技术（Inter-Process Communication）实现了实现系统快速流畅。此类型的支持分布式功能的操作系统平台可以完美支持分布式 iDTS 运行模式。

For example, the HarmonyOS (HMS) based system can realize a distributed iDTS running mode as represented in Figure 10. HMS is a distributed IoT operating system. The distributed soft bus, distributed device virtualization, distributed data management, and distributed task scheduling technologies used by HMS can realize mutual assistance and resource sharing among multiple devices in terms of capabilities. All installed HMS devices use a unified framework and component technology, which makes the development and application of user programs independent of device form and supports program development at once, multi-terminal deployment, and flexible deployment [55]. In addition, HMS uses a microkernel-based architecture design to ensure the trusted security of end devices, while the use of a deterministic latency engine and high-performance IPC technology (Inter-Process Communication) enables the realization of a fast and smooth system. Therefore, this type of operating system platform supporting distributed functions can perfectly support distributed the iDTS running mode.

6 总结 Conclusion

DT 的理论研究和技术应用已经从最初的制造业扩展到农业、城市、建筑、电力和医疗等众多领域。与其他领域相比，DT 技术在制造业的研究最早，目前技术应用相对成熟，但是其理论研究和技术应用集中在数字孪生体的表达、基于数字孪生的设计制造一体化、基于数字孪生的产品故障诊断和运行维护，涉及工业产品的数字孪生系统的特点、系统组成、逻辑架构和系统运行模式的研究较少。本文针对这一问题，提出了 iDTS 的概念，建立了 iDTS 的组成架构模型、逻辑功能模型、成熟度模型，并分析了针对不同工业场景下的 iDTS 典型运行模式。

根据 DT 技术在不同领域的研究和应用情况，论文首先给出了通用数字孪生系统的组成结构。在此基础上，论文通过对比不同数字孪生系统，总结 iDTS 的特点，并给出了 iDTS 的定义。iDTS 除了具备精准映射、虚实交互、智能反馈和优化迭代这四个数字孪生系统的通

用特点之外，还具有以人为中心、“人-机-环境”相互融合、系统保高保真度和孪生模型复杂等特点。iDTS 通过由物理层、感知层、孪生层、应用层和控制层组成的功能结构满足这些特点。另外，随着产品或系统的生命周期进展，iDTS 不断丰富，形成具有特定成熟度的模型。最后，针对具体的工业应用场景，论文分析了 4 种 iDTS 的运行模式，并通过典型案例验证所提出 iDTS 的可行性。

在未来的研究中，我们的研究重点是解决 iDTS 运行的关键技术，包括数字孪生体建模与评价技术、多物理场仿真融合技术、数字孪生体生命周期管理技术和 iDTS 安全管控技术等。

The theoretical research and technical application of DT have been expanded from the initial manufacturing industry to many fields such as agriculture, cities, construction, electricity, and medicine. Comparing with other fields, DT technology was first applied in the manufacturing industry, with mature application at present. However, its theoretical research and technical application focus on (1) the expression of digital twins, (2) the integration of design and manufacturing based on digital twins, and (3) the fault diagnosis and operation maintenance of products based on digital twins. Few research addresses the characteristics, system composition, logic architecture, and system operation mode of digital twin systems involving industrial products. To tackle this problem, this paper proposes the concept of iDTS, establishes the composition architecture model, logic function model, and maturity model of iDTS, and analyzes the typical operation modes of iDTS for different industrial scenarios.

According to the research and application of DT technology in different fields, the paper firstly presents the composition structure of a generic DTS. Then the paper summarizes the characteristics of iDTS and defines iDTS by comparing different digital twin systems. The iDTS not only has four common features of digital twin systems, namely accurate mapping, virtual-real interaction, intelligent feedback, and optimized iteration, but also has the characteristics of human-centered, human-machine-environment mutual integration, system fidelity, and a complex twin model. The iDTS meets these characteristics through the functional structure composed of physical layer, perception layer, twin layer, application layer, and control layer. In addition, with the life cycle of products or systems progressing, iDTS will be constantly enriched ro generate a model with a specific maturity. Lastly, for specific industrial application scenarios, the paper analyzes four iDTS operation models and verifies the feasibility of the proposed iDTS by typical cases.

In the future, our research will focus on solving key technologies for iDTS operation, including digital twin modeling and evaluation technology, multi-physics field simulation fusion technology, digital twin lifecycle management technology, iDTS security control technology and etc.

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