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Internet of Digital Twin: Framework, Applications and Enabling Technologies

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***Abstract*—Intelligent physical systems, such as smart vehicles and robotic arms, are increasingly integrated into both industrial and everyday applications. However, the systems typically face hardware limitations that constrain their computational capacities. Digital twin systems offer a solution by creating real-time digital replicas of physical systems that enhance computational efficiency, overcoming physical limitations. Moreover, multiple digital twins that hold complementary knowledge can conveniently collaborate to share information and computational resources, further improving the performance of physical systems by forming an Internet of Digital Twin (IoDT). This paper presents a comprehensive investigation of the digital twin network, tracing the evolution of digital twins and providing a classification of the key technologies, functional frameworks, and application domains of IoDT. This paper delves into the IoDT communication framework by studying the fundamental communication modes of IoDT, exploring its integration with advanced technologies such as edge computing, blockchain, 5G/6G networks, and machine learning to facilitate data transmission, interaction, and omni-directional sensing. By offering a broad perspective, the paper aims to deepen stakeholders' understanding of current research and potential future developments, encouraging further exploration of IoDT technologies and their evolution.**

***Index Terms*—Internet of Digital Twin, Wireless Communication, Edge/Cloud Computing, Machine Learning, 5G and Beyond, Blockchain, Security.**

I. Introduction

Over the past few decades, technological advancements—ranging from the *Internet* and *cloud computing* to *artificial intelligence (AI)*—have fundamentally transformed the way we interact with the world, unlocking unprecedented opportunities for innovation and efficiency.

The digital twin (DT) concept seamlessly integrates these technologies by creating a real-time mapping from physical entities (PEs) to their digital counterparts, which accordingly can effectively utilize the resources of both the physical and digital worlds. As in Fig. 1, the digital counterpart, referred to as the digital representative (DR), can offload the data processing and computational demands of PEs to edge or cloud servers. Using computational power and extensive data resources, the digital twin can simulate, predict, and provide high-performance feedback, thereby enhancing the efficiency of physical operations. Supported by advanced AI capabilities, scalable cloud resources, and real-time synchronization with its physical counterpart, the digital twin serves as a collaborative peer, assisting physical systems in real-world tasks and driving the co-evolution of both virtual and physical entities through continuous data exchange and analysis.

Digital twins explore heterogeneous resources to effectively mitigate the hardware limitations of their physical counterparts. In spite of numerous advantages, the design of digital twins faces two fundamental challenges:

- *Data Synchronization with a Twin*: Real-time data synchronization between PE and DR is essential. Since PEs are often mobile, wireless communications are required to maintain synchronization. Note that the data being synchronized are typically multi-modal sensory data from PE, resulting in large volumes of data. The continuous synchronization of such high data volumes not only places considerable strain on wireless networks, but can also be expensive and hard to achieve to DT.
- *Data Collaboration among Twins*: DRs hold vast and constantly updated datasets from their corresponding PEs.

TABLE I
Summary of Abbreviations

Abbreviation	Definition
DT	Digital Twin
IoDT	Internet of Digital Twin
PE	Physical Entity
DR	Digital Representative
AI	Artificial Intelligence
AVN	Autonomous Vehicular Network
SAGIN	Space-Air-Ground Integrated Network
DITEN	Digital Twin Edge Network
VANET	Vehicular Ad Hoc Networks
UAV	Unmanned Aerial Vehicle
IoV	Internet of Vehicle
uRLLC	ultra Reliable Low Latency Communication
mMTC	massive Machine Type Communication
O-RAN	Open Radio Access Network
RIS	Reconfigurable Intelligent Surface
NDN	Named Data Networking
IoT	Internet of Thing
IIoT	Industrial Internet of Thing

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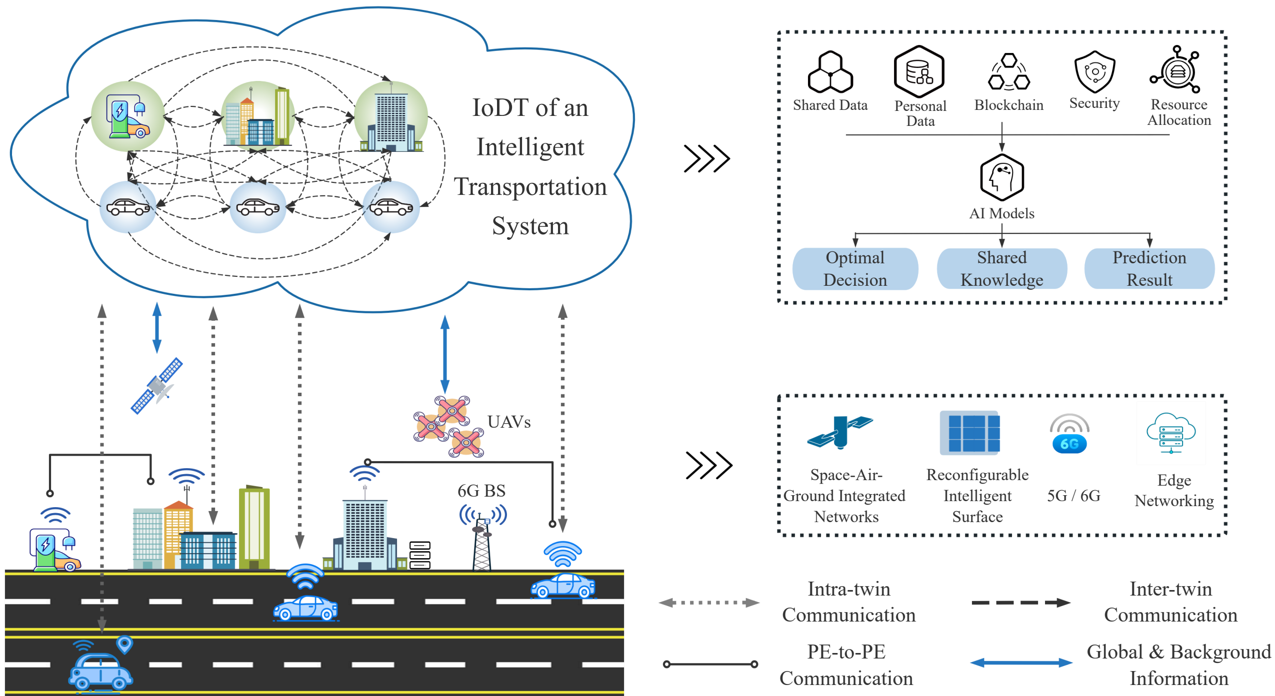

Fig. 1. An IoDT scenario in the context of intelligent transportation system.

However, the data that is most pertinent to target tasks of each DR is usually sparse. In the meantime, due to the limited storage space and computational capability of individual devices, the data retrieved from a single PE may not be sufficient to obtain a global view for complex task execution. To make efficient use of the valuable data assets, an Internet of Digital Twin (IoDT) that constructs a collaborative network among multiple twins is necessitated. As systems scale up, how to efficiently locate and retrieve necessary data within IoDT systems emerges as another key challenge, requiring a distributed data-sharing strategy without reliance on any central node.

In this paper, we focus on DT systems that utilize wireless communication as the primary synchronization approach and provide an in-depth review on IoDT communication systems. The IoDT include multiple DTs collaboratively accomplish real-world tasks, playing a vital role in building next-generation autonomous and intelligent communities through different communication frameworks, as shown in Fig. 1. To address aforementioned design challenges of IoDTs, we introduce two fundamental communication modes of DT: intra-twin communication and inter-twin communication. Intra-twin communication represents the communication between DR and the corresponding PE, while inter-twin communication manages the communication between different DRs, complementing the DT ecosystem with enhanced performance through collaboratively shared global knowledge. The main contributions of our work are summarized as follows.

- From the perspective of interconnected networks, we investigate the distinct characteristics of DT and further depict the communication purposes, process, and evaluation criteria of IoDT systems based on a functional-oriented taxonomy, *i.e.,* intra-twin and inter-twin communication.
- We elaborate on the roles, functions, and significant aspects to be addressed for intra-twin and inter-twin communication, respectively. The application scenarios are also presented in detail.
- We categorize the types of DT communication frameworks for existing works. The evolution of enabling technologies in IoDTs, as well as the improvement and deployment possibilities, are further discussed to help reduce the implementation gap between theoretical research and practical deployment.
- Focusing on real-life implementations, we examine the open issues of the entire IoDT systems from three aspects (*i.e.,* data communication, data security, and integrated IoDT system), and discuss the possible solutions, respectively.

The rest of the paper is organized as follows. Section II delineates the literature review protocol that we adhere to in this work, followed by an in-depth summary of existing survey papers related to DT communication. The motivation gained on this basis is also elaborated in this section. Section III presents the basic concept of IoDT in the literature and identifies the structure and evaluation criteria of an IoDT system. Section IV and Section V discuss definitions, goals, challenges, and enabling techniques of intra-twin and inter-twin communication, respectively. In Sections VI and VII, we discuss learned lessons as well as open research issues, respectively. Section VIII summarizes the paper with conclusions. The basic structure and relationship of the main sections are illustrated in Fig.2, and the summary of relevant abbreviations

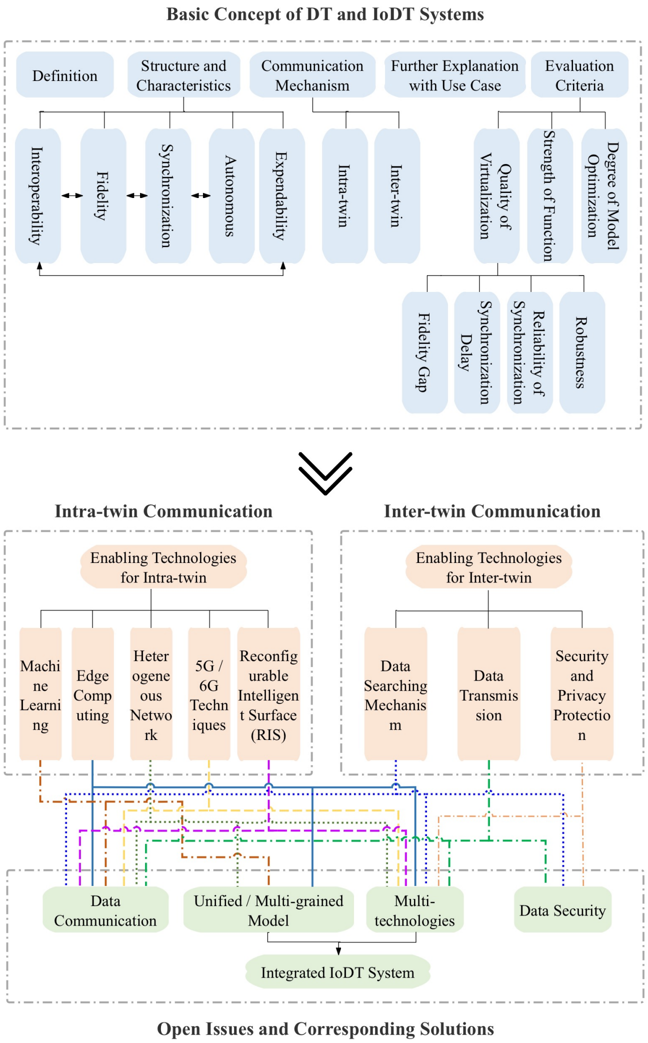

Fig. 2. The Structure of the survey. Describing the characteristics of IoDT and the correlation between different communication frameworks and state-of-the-art technologies.

in this survey is listed in Table I.

II. Literature Review Protocol and Related Survey Articles

The relevant surveys in the field have observed the flourishing evolution of DT-related theories and technologies across diverse domains and perspectives. In this work, we comprehend over 200 publications in the past few years, from 2018 to 2024, to incorporate the latest advances in this rapidly evolving realm. All reviewed works are meticulously selected from esteemed databases, including IEEE Xplore, ACM, Web of Science, and Scopus. For related survey papers, we specifically chose the keyword "digital twin" to isolate a focused examination from similar topics and provide us with a seminal landscape of DTs and futuristic IoDTs. This is followed by a series of more extensive and comprehensive searches for the discussion of enabling technologies, containing keywords pivotal to the intersection of DT and manufacturing, healthcare, heterogeneous networks, edge computing, 5G/6G, *etc.*, depending on the specific DT-related tasks we discussed. By leveraging the functional-oriented taxonomy, our work aims to propose a comprehensive spectrum of recent research while providing a nuanced synthesis of state-of-the-art technologies with the idea of IoDT, constructing a comprehensive and holistic ideological framework for stakeholders to further realize the large-scale implementation of IoDT in real-world scenarios.

A. *Review of DT-related Surveys*

Considering the integral role of DTs in complex environments, existing survey efforts can be broadly categorized into three folds: Foundational Concepts and Groundworks of DTs, DT Integration with Other Technologies, and DT-related Security & Privacy. In this subsection, we meticulously assembled a selection of key surveys in these categories, a systematic discussion is demystified below.

1) Foundational Concepts and Groundworks of DTs: To lay the groundwork for a holistic architecture concerning the advancement of DT theory and technologies, several works endeavour to provide general and comprehensive perspectives for DT-related concepts.

- *Core Definitions and Architectural Perspectives.* Barricelli *et al.* [1] provide a nuanced yet comprehensive perspective to synthesize concepts related to DT, including the evolution of DT definitions, main characteristics, and real-world applications. Minerva *et al.* [2], Li *et al.* [3], and Yin *et al.* [4] further extend the exploration by discussing DT architectures from diverse domains (*e.g.*, industry, aerospace, and manufacturing), although most of them lack focus on detailed investigation due to divergent focus.
- *Data Communication in DT Systems.* To exhibit a strong concern for issues related to data communication, [5]–[9] emphasize the interdependence between DTs and networks as well as the pivotal role of efficient data communication from different perspectives. How to faithfully represent the overarching status and information of a target entity is thoroughly examined. However, the synchronization challenges faced in the systems for maintaining coherence are overlooked by such endeavours.
- *Applications and Use Cases*. Towards futuristic applications and practical use cases, [10] provide an in-depth view of state-of-the-art enabling technologies and possible challenges, especially for industry. Chen *et al.* [11] emphasizes the complexities of human DTs in healthcare. Several enabling technologies facilitate pervasive sensing, electronic health records, on-body communication, beyond-body communication, data storage, *etc.*, are elaborated to provide a theoretical foundation for not only healthcare but also the diverse research directions involved in DT-related communication.

2) DT Integration with Other Technologies: The works that we categorized as "DT Integration with Other Technologies" investigate the endeavours of DTs in aiding other technological domains, such as industrial automation, 5G and beyond, *etc.*

- *Synergy with Wireless Systems.* In [12], Khan *et al.* accurately elucidate the critical role of wireless systems in

TABLE II
COMPARISON OF DT-RELATED SURVEY ARTICLES

No.	Evaluation Criteria	Key Features Identification	Applications and Expectations Around Related Fields of Information or Communication Technologies	DTs toward Other Technologies / Other Technologies toward DTs	Detailed Analysis of Enabling Technologies & Architectures	Inter-twin and Intra-twin Privacy and Security	Inter-twin and Intra-twin Communication
Barricelli *et al.* [1]	✗	✓	✗	✗/✓	✗	✗	✗
Wu *et al.* [5]	✓	✗	✓	✗/✓	✓	✗	✓✗
Wen *et al.* [6]	✓	✓	✗	✗/✓	✗	✗	✗
Jeddoub *et al.* [7]	✗	✗	✓	✗/✓	✗	✗	✗
Correia *et al.* [8]	✗	✗	✓	✗/✓	✓	✗	✗
Chen *et al.* [11]	✓	✓	✓	✗/✓	✓	✗	✗
Khan *et al.* [12]	✗	✗	✓	✓/✓	✗	✓✗	✓✗
Alcaraz *et al.* [13]	✓	✗	✓	✗/✓	✗	✓	✗
Ramu *et al.* [14]	✗	✗	✓	✗/✓	✗	✗	✓✗
Kuruvatti *et al.* [15]	✓	✗	✓	✓/✗	✗	✗	✗
Lin *et al.* [16]	✓	✗	✓	✓/✗	✗	✗	✗
Wang *et al.* [17]	✗	✓	✓	✓/✓	✓	✓	✗
Ours	**✓**	**✓**	**✓**	**✓/✓**	**✓**	**✓**	**✓**

the context of futuristic integrated systems, highlighting the synergistic development and integration of DT with wireless systems.

- *Practical Perspectives in 5G and Beyond.* [15] summarises the latest progress by delineating a variety of potential use cases regarding the deployment of DT in 5G and beyond, as well as in related wireless networks, to fully investigate the intrinsic advantages of DT in assisting others. Lin *et al.* [16] further offer a delicate explanation of the data-related workflows covered in the same context, ranging from data acquisition and target data types to data storage, providing valuable insights into standardizing system construction guidelines.

Such survey articles provide a coherent and thorough template for stakeholders to dialectically examine the inherent nature and advantages of DTs in assisting the all-around improvement of other emerging technologies for testing, market assessment, AI model training, prediction, *etc.*

3) DT-related Security & Privacy: Another topic of survey papers regarding DT communication lies in the security & privacy problems.

- *Security Challenges across DT-based Systems.* Alcaraz *et al.* [13] extensively examine security threats across various layers within DT networks. The survey highlights the multi-scale and multi-dimensional challenges encountered within DT systems but lack a detailed analysis of enabling technologies and system architecture. [17] provide a taxonomy of attacks targeting data retrieval and storage. The subsequent privacy and trust issues among multiple DTs are also discussed to meet the rigorous reliability requirements, which are identified as the high-fidelity and high-synchronization nature we summarized in our work.
- *Privacy Protection in DT-based Systems.* Other than [17], Ramu *et al.* [14] examined federated learning as a solution for enhancing privacy in DTs. Nonetheless, the persistence of concerns surrounding data quality, integrity, and the establishment of effective data-sharing mechanisms among diverse DT systems during their interactions remains a notable and ongoing challenge.

A comparison of our work with survey articles that are highly relevant to the topic of DT-based communications is summarized in Table II.

B. Motivation and Research Scope

It is revealed by numerous works [3], [6]–[8], [11], [12] that the communication problems encountered by IoDT systems extend beyond mere data transmission or network construction, especially under wireless environments. It encompasses all-around challenges to fulfill a well-functioning IoDT collaboration, ranging from data collection, storage, high-quality data retrieval, latency, and transmission gaps, to security and privacy concerns. As a result, there is an urgent need for a comprehensive communication framework to equip stakeholders with a thorough understanding of the challenges that large-scale IoDT systems may encounter during the system design.

However, prior works in this domain mainly consider DTs as a simulation approach where a single DT is often used to simulate the reaction of its PE and provide feedback accordingly. The potential of exploring mutually iterative evolution between DTs and communication performance has not been fully considered. Another concern arises from the fact that wireless communication has emerged as the preferred foundation for DT-based data transmission. They often assume that communication techniques with high-quality real-time performance, such as 5G/6G inherently satisfy the DT requirements in terms of synchronization, fidelity, *etc.*, while this may not always hold as fluctuations in physical conditions, data volume, transmission distance, *etc*. Of more importance, most current works tend to consider the DT as a fully-fledged individual system for model construction and functional analyses. Nonetheless, they disregard the fact that DT systems under large-scale scenarios are more like a combined ecosystem of multiple smaller DTs (i.e., IoDT system), which requires precise and heterogeneous modeling and data interaction for effective and efficient communication among the overarching system.

In this context, our work is devoted to providing a fine-grained analysis regarding the communication and cooperation process among the entire IoDT life-cycle, establishing a sophisticated internal data interaction framework for large-scale IoDT systems while thoroughly dissecting the enabling technologies and their synergy with DT-related works for mutual evolution, thus narrowing the gap between theory and actual deployment of futuristic IoDT systems in the context of wireless environment.

III. Concept, Evolution, and Criteria

As shown above, DT has gone through decades of development. Limited by hardware and software availability, it has only caught public attention in recent years and has opened up a new avenue for the evolution of enterprises. The IT research and consulting company Gartner's introduction in "Top 10 Strategic Technology Trends for 2019" [18] brings DT to a new level of stakeholder concern. In this section, we introduce in detail the development histories, standard definitions, classification standards, and evaluation criteria of DT, aiming to help readers form the basic theoretical framework of DT.

A. Definition

The concept of "twin" can be dated back to Apollo 13 Mission [19] from NASA in the 60s. They point out in a mission report that "at least two identical spacecraft will be built to reflect the condition of the spacecraft during the mission". More concretely, NASA constructs two identical real-life spacecraft during each mission execution, one of which is sent into space and the other one is left at the Houston and Kennedy Space Center to assist engineers in understanding the status of the spacecraft during the mission and to help resolve emergencies that arise in space. This is the first mention of "twin" concept. A groundbreaking concept of

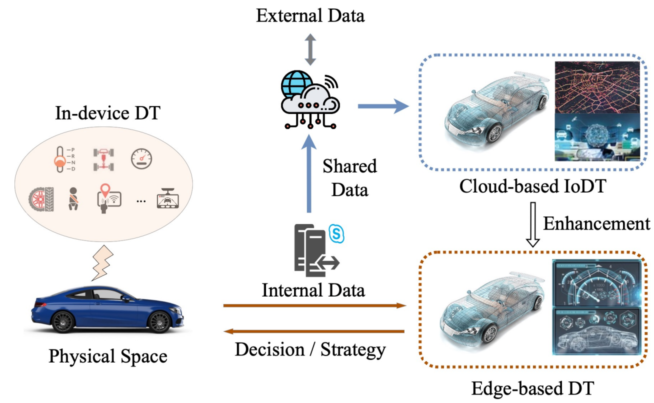

Fig. 3. The concept model of DT. The data collected by the physical devices and sensors in the real space are taken as raw data and transmitted to the virtual space for DT construction. The DT-based system can be hosted in distinct places as needed.

a virtual, digital counterpart for physical products was then introduced by Dr. Michael Grieves [20], propelled by the relentless progression of technologies. At this period, although the term "Digital Twin" had not yet been formally introduced, the standard structure of DT had basically taken shape by Dr. Grieves. He notes that there are three main parts of DT: a) physical products in Real Space, b) virtual products in Virtual Space, and c) the connections of data and information that tie the virtual and real products together [20]. As shown in Fig.3, we depict diverse deployment possibilities for DT-based systems, which are further explored in Section VI-B.

In 2010, the term "Digital Twin" was formally introduced, setting a key milestone for DT to officially step into the technology arena. After further modifications and refinements, in 2012, NASA highlighted the definition of DT is "an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, *etc.*, to mirror the life of its corresponding flying twin" [21]. In subsequent research, the applications of DT are gradually expanded and are no longer limited to aerospace. In the description of cyber-physical models for future manufacturing in 2013, Lee *et al.* define DT as "a coupled model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data-driven analytical algorithms as well as other available physical knowledge" [22]. In recent years, researchers have begun to focus on combining the use of DT with the concept of product life cycle, pointing out that DT is "a real mapping of all components in the product life cycle using physical data, virtual data and interaction data between them" [23]. The definitions of DT that evolved over the last decade are shown in the Table III.

B. Structure and Characteristics of DT

Three main components are considered in a DT system: a physical entity, a digital representative, and a connection between these two entities, in which the connection between is bidirectional and represented by the data that flows from the physical to the DR, and the information that is generated

TABLE III
SUMMARY OF DIGITAL TWIN DEFINITION IN DIFFERENT SCENARIOS

No.	Year	Definition	Case Scenario
Glaessgen *et al.* [21]	2012	A Digital Twin is an **integrated multiphysics, multiscale, probabilistic simulation** of an as-built vehicle or system that uses the best available physical models,sensor updates, fleet history, *et al.*, **to mirror the life** of its corresponding flying twin"	Military vehicles or systems
Tuegel *et al.* [24]	2012	A **cradle-to-grave model** of an aircraft structure's ability **to meet mission requirements**, including submodels of the electronics, the flight controls, the propulsion system, and other subsystems.	Aircraft design and maintain
Gockel *et al.* [25]	2012	Ultra-realistic, cradle-to-grave computer model of an aircraft structure that is used **to assess the aircraft's ability** to meet mission requirements.	Aircraft assessment through virtual flight
Lee *et al.* [22]	2013	Coupled model of the real machine that **operates in the cloud platform** and **simulates the health condition** with integrated knowledge from both data-driven analytical algorithms, as well as other available physical knowledge	Predictive manufacturing
Reifsnider *et al.* [26]	2013	**Ultra-high fidelity physical models** of the materials and structures that control the life of a vehicle.	Fleet management
Majumdar *et al.* [27]	2013	**Structural model** which will include quantitative data of material level characteristics with high sensitivity.	Prognosis for structural composite materials
Bielefeldt *et al.* [28]	2015	**Ultra-realistic multi-physical computational models** associated with each unique aircraft and combined with known flight histories.	Fatigue cracks detection of aircraft
Bazilevs *et al.* [29]	2015	**High-fidelity structural model** that incorporates fatigue damage and presents a fairly complete **digital counterpart** of the actual structural system of interest.	Fatigue-damage prediction
Schluse *et al.* [30]	2016	Virtual substitutes of real-world objects consisting of **virtual representatives and communication capabilities** making up smart objects acting as intelligent nodes inside the Internet of Things and services.	Experimentable Digital Twins
Canedo *et al.* [31]	2016	Digital representative of a real-world object with **focus on the object itself**.	Industrial IoT management
Gabor *et al.* [32]	2016	The simulation the physical object itself to **predict future states** of the system.	Predictable cyber-physical system
Schroeder *et al.* [33]	2016	Virtual representative of a real product in the context of **Cyber-Physical Systems**.	Model attributes related to manufacturing and product service
Kraft *et al.* [34]	2016	An integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by Digital Thread that uses the best available models, sensors information, and input data to **mirror and predict activities/ performance** over the life of its corresponding physical twin.	DT analytical framework of air vehicles
Bajaj *et al.* [35]	2016	A unified system model that can coordinate architecture, mechanical, electrical, software, verification, and other discipline-specific models across the system lifecycle, **federating models in multiple vendor tools and configuration-controlled repositories**.	Seamless model-based communication between systems engineering
Söderberg *et al.* [36]	2017	Using a digital copy of the physical system to perform **real-time optimization**	Real-time geometry assurance for simulations of products and production processes
Bacchiega *et al.* [37]	2017	A digital twin is a **real time digital replica** of a physical device	Embedded DT for device diagnostics
Bolton *et al.* [38]	2018	A dynamic virtual representative of a physical object or system across its lifecycle, using real-time data **to enable understanding, learning, and reasoning**	Digital customer experience framework
Tao *et al.* [23]	2019	Digital twin is a **real mapping of all components** in the product life cycle using physical data, virtual data, and interaction data between them	Product design
Wu *et al.* [5]	2021	DT is **the accurate digital replica** of a real-world object across multiple granularity levels, and this real-world object could be a **device, machine, a robot or an industrial process or a complex physical system**.	Digital Twin Networks
Gao *et al.* [39]	2022	Digital Twin is a **virtual replica** of a physical product by using artificial intelligence and machine learning techniques and big data analytic.	Virtual representation
Yarali *et al.* [40]	2022	Digital Twin technology involves **creating virtual simulation models** of technical and physical assets that are untouched but maintained and changed by the information within a physical object.	Intelligent connectivity

from the DR to the physical environments [41]. According to the description from the frontier research [11], [17], [42], we summarize the key features of DT systems from the perspective of data interaction, which are presented as follows:

1) Interoperability: Interoperability refers to the ability of different computer systems, networks, operating systems, and applications to cooperate and share information. The physical object and digital space in a DT system can be mapped bilaterally so as to interact dynamically and connect in real time. This is why DTs have the ability to map physical entities with a variety of digital models and further transform, merge, or create "representatives" between multiple digital models. For example, in the vehicular use case, a DR is created in the cloud based on the collective information and AI functions of a physical vehicle. By collecting information from the cloud, the DT can attain new information and synchronize with its physical vehicle with the upgrade information. As a result, the overall knowledge system of the DT is expanded, which directly leads to the improvement of the intelligent functions of the physical vehicle. More details are explained in Section III-E as a concrete example.

2) Fidelity: The term "fidelity" of a DT refers to the proximity and accuracy of data descriptions between the virtual and the physical entities. It reflects the degree of how close the virtual entity represents the real-world information, including not only in geometric structure, but also in state, phase, tense, *etc*. In the meanwhile, the requirements for the degree of simulation accuracy vary in different application scenarios. This character can be adjusted and optimized by selecting or designing different information models based on different usages of DTs.

3) Synchronization: The term "synchronization" refers to the real-time precise alignment of information and knowledge between the virtual and the physical entities. The DTs are required to minimize the deviation within the system and ensure a simultaneous update during the entire DT life cycle, including the raw data transmitted from PE to DR, as well as the calculated decisions returned. For example, a DR hosted in the virtual environment may collect information from cyberspace and evolve with more accurate AI models; its PE as an operating unit in practice would retrieve information and change its states in the real-world environment. During this process, the DR and its PE need to synchronize to have the same knowledge and maintain each other's fidelity.

4) Autonomous: Although only a virtual version of its physical entity, the DR can make decisions on behave of its physical entity and synchronize the decision with its physical entity. For example, DRs in the cloud can decide whether they need to communicate and share information with other DRs without notifying their physical entities. The autonomous functions of DRs, however need to acquire permissions from their physical entities at the first beginning when the DT system is activated.

5) Expandability: DT technology is required to have the ability to integrate, add, and replace digital models, as well as to extend model content under multiscale, multiphysics, and multilevel based on the feedback from the interoperated physical entity, *i.e.,* performance results or system instructions from the latest round of experiments. This is not only a functional requirement based on standard definition, but also a basic management function that a DT-based integrated system should have in order to realize the bidirectional evolution of the performance of both virtual and physical entities.

C. IoDT Communication

At present, DT surpasses conventional goals, promising benefits across an expansive spectrum of scenarios and tasks coupled with rapidly moving technologies and further amplifying the performance of physical devices underpinned by information technologies. This new target of DT perfectly complements the goals of the Multi-agent system and the Internet of Things in terms of low-latency and high-efficiency data communication and interaction for large-scale intelligent communities, this is where the IoDT communication system comes into play.

Specifically, a complete DT system that consists of a PE, the corresponding DR, and the connection link guarantees the data interaction between a single physical device and its own digital mapping. When multiple DT systems collaborate with each other and trying to optimize the overall system performance through data communication and interaction, the IoDT is formed. As a matter of fact, the IoDT can be seen as an integration of multiple DT systems, which tries to optimize the DTs' own knowledge structure through the sharing of external data, thus achieving better performance than a single DT to fuel the capabilities of the overall system in terms of decision-making, diagnostic, and analysis, *etc.* In other words, when numerous DT systems are involved in the task, each PE-DR pair in the system should be able to obtain better performance than the original system through data communication and knowledge sharing in an IoDT.

According to different communication objects and purposes, the communication of IoDT can be broadly divided into two categories: inter-twin communication and intra-twin communication.

The intra-twin communication refers to the information interaction between physical entities and their own DRs. Noted, each pair of the physical and virtual entities maintains a unique encrypted link to ensure that the content of the intra-twin communication cannot be obtained by other DT systems. That is, the intra-twin communications maintain for the synchronization nature of DT; the link has to be private and completely protected to share the information and knowledge (or AI models) within the twin.

The inter-twin communication refers to the information interaction between DRs in a DT-based integrated system (or cloud), which can simultaneously deploy numerous physical and virtual entity pairs. The inter-twin communications are mainly used to share data between different DRs. To perform inter-twin communications, the DRs do not need to notify their physical entity according to the autonomous feature. However, the shared information must fully comply with the privacy protection policy established in advance by the physical entity to ensure privacy and security.

By combining intra-twin and inter-twin communications, IoDT is becoming a comprehensive intelligent system that fully integrates AI, cloud computing, blockchain, and other emerging techniques, which can significantly reshape a lightweight, secure, efficient paradigm for both communication and product performance optimization. With intra-twin communications, the digital representative can learn real-world information about its physical entities in real-time. Using inter-twin communications, the DR can acquire global information. With the overall information and using rich cloud resources to process the information, the DR can overcome the limitations of its physical entity in terms of computing resources and data volume, therefore helping improve the AI performance of its physical entity. With the digital representative being a comprehensive virtual body and continuously grow and improve with its physical entity, the collaborations of digital representative and physical entity enables significant potential for AI and autonomous systems.

D. Evaluation Criteria

Although there are no clear criteria for evaluating the DT communication systems, based on the functional goals, characteristics and architectures of the DT system, we can evaluate DT communications according to the following aspects:

1) Quality of Virtualization: With the innate features of DT, we evaluate the performance of DT communication from the following four aspects:

a) Fidelity Gap: In the process of conducting a DR, as the first principle of implementing a DT system, it is necessary to ensure that the virtual entity can accurately describe every detail of its physical entity. In some extreme scenarios, such as network congestion and data conflict, there might be disconnections during the intra-twin communication, hence the synchronization between the physical entity and its DR can be interrupted, resulting in the loss of fidelity and causing the mismatch in the physical and virtual entity pair. The large fidelity gap may result in poor computing performance of the DT due to a lack of real-time local information and feedback updated by the physical entity.

b) Synchronization Delay: The primary function of DT is to be able to reflect the most realistic state of the physical entity in the virtual entity in a timely manner and to make a decision or propose an optimization strategy accordingly. Therefore, whether the state of the virtual entity can be highly synchronized with the observable physical entity is also an essential criterion for evaluation.

c) Reliability of Synchronization: Reliability refers to the ability to fulfill a predefined requirement or return a specific result under given time and conditions. High reliability of synchronization can be used to ensure the most accurate decisions and strategies from the virtual entity. This performance indicator vividly demonstrates the enhancing effect of DTs in the digital production of enterprises.

d) Robustness: Robustness refers to the degree to which a system or component can function properly under invalid inputs or stresses. As a primary performance indicator of a digital program, robustness also has a high reference value for the performance evaluation of DT systems in practical applications.

2) Strength of Function: Regarding the functional effect evaluation of the whole DT system, the strength of analytical ability and interoperability are the key indicators that a DT system needs to consider. The analysis ability refers to the ability to describe, evaluate, or predict a physical entity through models, data, and algorithms; interoperability refers to the ability to exchange information, synchronize information or collaborate business between two or more interconnected DRs. After completing the specified tasks (*e.g.*, plan route or give the optimal solution), the system will comprehensively consider the performance of the above two functions based on the feedback of the physical entity and give a score for their completion as the basis for evaluating the performance of the DT system.

3) Degree of Model Optimization: A complete DT system contains several execution processes, such as data processing, modeling, and simulation processes, involving different engineering and statistical models. It should be evaluated based on corresponding indicators according to the needs of different tasks. For example, in the classification task model, indicators such as accuracy, F1-score, the Receiver Operating Characteristic, and Area under the Curve *etc.* can be used to evaluate the classification accuracy and stability. The performance of each model and the degree of their optimization should also be regarded as important indicators when evaluating the performance of a DT system.

E. Example: IoDT in Vehicular Networks

To better present the idea of how IoDT works and how multiple entities collaborate with each other, we showcase a practical example of IoDT in vehicular networks as follows.

Fig. 1 shows the scenario of applying IoDT for intelligent transportation systems. A DR can be created and maintained in the server (*e.g.*, cloud) for each autonomous vehicle within the system. The intra-twin communication ensures a continuous bidirectional connection between DR and the corresponding physical vehicle, holding vehicular information such as location, speed, vehicular status, *etc*. Multiple DRs hosted on the same server may choose to communicate through inter-twin communication, sharing global data and knowledge for a bird's view of the overarching physical environment. During this process, the system is required to meet the quality of virtualization criteria to guarantee all the information is precise and up to date. Specifically, setting an upper/lower bound on *synchronization latency* and *reliability* of DR-retrieved data lays the foundation for the effective analysis of real-time traffic and vehicular status. A separate *fidelity* indicator further ensures that the synchronized data is not only updated in real time, but also accurately reflects the realistic conditions of the environment.

By driving on the road, an autonomous vehicle must continuously process the collected sensing data for self-driving and trip planning. With the limited processing capability on the physical end, the autonomous vehicle can offload partial computation jobs to the DR and let DR help with its cloud resource as well as the global knowledge attained from other DRs. The quality of tasks executed, which also reflects the quality of the IoDT system, is judged by two criteria, namely, *degree of model optimization* and *strength of function*. Since each DR within the system holds diverse objectives (*e.g.*, target recognition, parking management, fault prediction, *etc.*), the *degree of model optimization* should be determined separately for each AI algorithm according to personalized task requirements. After obtaining all the results from simulation and AI algorithms, the final strategy regarding complex tasks of different vehicles (*e.g.*, path planning, or driving strategy) can be returned to the PEs. The *strength of function* is then regarded as a consolidated evaluation of the overarching system and conducted periodically based on the feedback from PE ends, elaborating how well the analysis from the DR has served its purpose.

IV. Intra-twin Communication

In pursuit of the overarching goal to enhance the communication performance of both single DT pairs and the entire

IoDT systems, intra-twin, and inter-twin communication direct their attention to distinct communication tasks with different emphases. Particularly, intra-twin communication focuses on the data communication and interaction between PE and its corresponding DR. It is concerned with communication performance and the utilization of the retrieved data in a single DT pair. Inter-twin communication, on the other hand, is specifically responsible for data transmission and knowledge sharing between different DRs, which means that the primary focus is to address issues related to security, integrity, reliability, as well as transmission efficiency. Intuitively, varied communication tasks necessitate diverse goals and challenges. In the following two sections, we elaborate on intra-twin and inter-twin communication and their enabling technologies with a detailed discussion of the different goals and application scenarios. As a further extension to the practical implementation of the integrated IoDT system, the open issues and possible solutions of the overarching system regarding an in-depth combination of intra-twin and inter-twin communication are discussed in Section VII.

A. Overview

In general, the first priority of intra-twin communication is to ensure well-performing data exchange and coordinate the work between PE and DR that endows DT systems with high intelligence and automation. In response to this core mission, we further recognize two major goals for intra-twin communication as follows.

- ***Data/State Synchronization.*** Data/state synchronization of intra-twin communication refers to the process of comparing data and state information within the intra-twin communication (*i.e.*, between PE and its own DR) and updating all the discrepancies to ensure the data and state information are in the same condition in both entities. Unlike the traditional requirements for synchronization, intra-twin communication requires the data/state synchronization to be automated and updated in a real-time manner to simultaneously ensure the fidelity and synchronization nature of DT. This goal plays a vital role in maintaining the ecology within single DT systems, laying the foundation for real-time collaboration and highly reliable decision-making in the system.
- ***PE-DR Joint Computing.*** Internal joint computing between PE and DR largely ensures the effective resource utilization of both physical and digital entities and fulfills the real-time requirement of the DT system. Specifically, the PE end may contain basic computing resources for simple tasks while holding first-hand data of physical devices. The DR obtains all the knowledge from the corresponding PE and other DRs, but with richer computational resources for more complex tasks with the help of edge or cloud servers. Suppose all the tasks are offloaded to DR for execution (*i.e.*, the DR is heavily utilized while the PE remains idle), the system may be overloaded and unable to handle the large-scale computation as required, resulting in unsatisfactory system performance or even a system crash. Therefore, how to find a trade-off for collaboration computing among intra-twin communication to balance the competing factors and ensure the efficiency and accuracy of the system is of most importance.

Compared to inter-twin communication, intra-twin communication is envisioned as the basic foundation of the overall DT-based system that bridges the gap between PEs and DRs. The role in constructing a highly synchronized and distributed communication structure paves its way into a new paradigm for future intelligent societies, ranging from smart cities [43], [44], digital hospitals [45], to Autonomous Vehicular Networks(AVNs) [46]–[48] and Space-Air-Ground Integrated Networks (SAGINs) [49], [50]. However, due to deficiencies in resource scheduling, device mobility, and communication mechanism, *etc.*, it is still far from a satisfactory performance from a global perspective. In the remainder of Section IV, we detail the application scenarios, state-of-the-art works, and enabling technologies related to intra-twin communication, shedding light on the bi-directional evolution between individual DTs and communication performance.

B. Enabling Technology: Machine Learning

Due to the adaptive and self-updating learning capabilities, machine learning has become a powerful assistance in both intra-twin and inter-twin communication, especially in some large-scale intelligent communities consisting of pervasive algorithm optimization, up-to-date decision-making, as well as intelligent detection and identification tasks, such as smart cities, autonomous driving, and medical treatment, *etc.* In this part, we summarize several important technologies of machine learning in DT and their typical applications, the details are shown in Table IV.

1) Federated Learning: Benefiting from the unique distributed collaborative sharing model, FL endows the digital twin with the ability to collaborate on a shared model while securing sensitive data and enabling distributed training. With the advent of AI and cloud computing, it is a new trend to apply federated learning to DT to help physical entities obtain global knowledge.

Sun *et al.* [51] propose an asynchronous federated learning architecture, which classifies nodes with different computing capabilities and assigns a corresponding manager to each group. Every group uses different aggregation frequencies to train independently, and then the trust-weighted aggregation strategy is used to aggregate the parameters on the local node and perform on the next iteration to obtain an optimal result. Considering the dynamic environment of the overarching system, this aggregation strategy leverages the reputation of diverse nodes to dynamically modify the aggregation frequency. As a result, this approach serves as a demonstrative method to mitigate discrepancies between DR and PE during the process of virtual replica construction, consequently enhancing the convergence rate and learning efficiency of the overall system. To narrow the gap between physical devices and digital entities and optimize the network for high-quality scenarios, [52] details an integrating digital twin edge network (DITEN) based federated learning scheme, which uses a federated learning framework authorized by blockchain to improve the security and efficiency of the model, so as to provide private data protection and reasonable allocation of resources. In addition, the team further explores how similar technologies can further improve the performance of data transmissions in wireless networks such as 5G and 6G to achieve edge intelligence in [53] and [54]. To meet the demand for simultaneous processing of multiple task requester faced in heterogeneous vehicular networks, Hui *et al.* [55] present a two-way selection scheme to jointly consider data amount, price, and training experience to match the best base station for each task requester. In such works, DT is particularly designed to construct a virtual replica of the system, thus contributing to the system's ability to simulate and, in this particular example, to complete the gaming process of the two-way selection problem in a digital environment. In a subsequent study [46], the authors further optimize the model and propose a marginal utility-based vehicle selection mechanism to implement the on-demand matching. The simulation results show that the matching mechanism can obtain better performance in both system accuracy, performance-cost ratio, and task completion rate.

Considering the air-ground network, Sun *et al.* [56] envision DT's ability to react to the time-varying status of the PEs, detailing how to apply DT to the air-ground network to build a distributed SAGIN. It mainly studies static and dynamic incentives in federated learning to capture the real-time status of physical devices and help make decisions, which is useful to encourage high-performance devices and reduce the impact of malicious devices. The designed DT model dynamically captures the real-time characteristics of all the participants, thus, in turn, boosting the data accuracy of the FL-based training task using DT. A similar scenario can be found in [57], where a DT-based time-sensitive network is used to provide bounded low latency services for satellite networks. In this novel framework, DT is introduced to virtually predict latency and verify the routing strategy via a real-time simulation of the dynamically changing network. In [58], a Lyapunov-based framework is presented to jointly consider computation offloading, communication improvement, and resource scheduling problems among heterogeneous agents. The integrated satellite network is utilized to ensure low-latency data transmission and sufficient computation resources for real-time DT construction. However, although a blockchain-aided federated aggregation policy has been proposed to address the distrust problem among DTs, the limitation of blockchain in transaction speed may not be able to satisfy DTs' demand for frequent data synchronization. Moreover, the problem of data tampering caused by the selfish attributes of the devices themselves is unable to be effectively eliminated. Utilizing deep federated reinforcement learning for privacy protection, Gong *et al.* [59] investigate a blockchain-based computation offloading algorithm for satellite-ground DT networks to enhance mutual trust among DTs, providing outperformed resource allocation and task scheduling scheme. However, the core idea of such approaches necessitates continuous storage and verification of on-chain DT data to prevent tampering, significantly increasing the system's computational and communication overhead, which conflicts with the real-time requirements of DTs.

2) Deep Reinforcement Learning: Compared with federated learning, deep reinforcement learning is more adapted to dynamic environments, and can make intelligent decisions through real-time status feedback of the environment. As early as DT was proposed, how to apply deep learning and related technologies to DT aroused great discussions and achieved promising results [66].

With the development of deep reinforcement learning and the increasing problem complexity, many researchers have begun to study the application of deep reinforcement learning in DT and blend them perfectly. While a DT strives to represent its physical counterparts as accurately as possible, slight model or data errors remain. To reduce this error, Cronrath *et al.* [67] propose an algorithm to compensate for those residual errors through reinforcement learning and data feedback from the manufacturing system. During the learning process, DT acts as a teacher and security policy to ensure minimum performance. Tian *et al.* [68] also propose a new framework for model parameter inference based on reinforcement learning, reconstructing the inference problem into a tracking problem to learn a strategy to force the response based on the physical model to follow the observation results. The team also proposes an Actor-Critic algorithm based on constraint Lyapunov to reliably and accurately deduce physics-based model parameters in real-time under noisy real-world conditions. Although the simulation in this work is elaborated based on turbofan engines and not particularly on DT systems, the intrinsic solution exhibits a bright future in reducing the information gap by resolving the calibrations in physics-based models such as large-scale DT. In addition, in a recent attempt to bridge the gap between virtual and physical systems, Xia *et al.* [69] utilize DT as a digital transformation tool to train a deep reinforcement learning agent for intelligent manufacturing plants. The Siemens Tecnomatix Process Simulate is employed for constructing a virtual environment of the DT system. As this process unfolds, the data communication among the overarching system occurs via two distinct methodologies, fostering data fusion and rejuvenation between PE and DR. The initial method involves a sequential process wherein newly acquired data in DR undergoes an upfront check before transmission to the PE. Conversely, the alternate approach relies on a semantic communication framework driven by machine learning, thus facilitating real-time decision-making capabilities across the entire system. Another new attempt emerges in the combination of DT with reinforcement learning-based semantic communication. Tao *et al.* [63] define a novel data dissemination architecture for a 6G vehicular network based on an energy-efficient semantic communication mechanism. Under this architecture, DT is utilized in parallel with a physical network for semantic data dissemination, thus reducing the data transmission burden with lower cost in terms of model update. In pursuit of continuous data synchronization, Liu *et al.* [64] present a vision-based semantic communication framework for a metaverse scenario, where the semantic pose data is utilized to substantially diminish the amount of original image data to the skeleton coordinates. Such efforts optimize the extensive synchronization between PE and DR within dynamic environments, such as video data transmission. Nevertheless,

TABLE IV
THE APPLICATION OF LEARNING-BASED METHOD IN IODT

No.	Year	Scenario	Category	Technologies	Contributions	Limitations
Xu *et al.* [60]	2019	Manufacturing	intra-twin inter-twin	Transfer learning	A two-stage double fault diagnosis method to enhance the transparency, flexibility, and efficiency of traditional diagnosis.	The virtual entity is only used to simulate practical scenarios for cost reduction purposes.
Liu *et al.* [61]	2019	Healthcare	intra-twin	Cloud computing	Using DT to bridge the PE, DR, and massive computing resources from the cloud.	As an earlier attempt, in this article, DT is only used as a simulation approach for medical purposes.
Lu *et al.* [54]	2021	IIoT	intra-twin	Federated learning; DITEN	Propose an asynchronous federated learning architecture to eliminate the straggler effect between PE and DR, as well as improve communication performance.	The selected dataset is based on image recognition applications. Lack of construction of dynamic scenarios.
Sun *et al.* [51]	2021	IIoT	intra-twin	Federated learning	A trust-based aggregation method is proposed to alleviate the information gap between PE and DR. Realize better performance to adapt to the heterogeneity of IIoT.	It fails to consider the security issues during data transmission. In addition, it does not consider the model's effect in practical scenarios with limited resources.
Pang *et al.* [62]	2021	Healthcare	intra-twin	Federated learning	A new urban collaborative DT framework based on federated learning is proposed to quickly obtain historical infection data and effectively predict future trends without neglecting data security.	For the prediction problem, the model considers a relatively limited number of influencing factors, which may cause bias in the results.
Lu *et al.* [53]	2021	IIoT	intra-twin inter-twin	Federated learning; Blockchain	Apply federated learning and DT to the wireless network to build a DT wireless network and improve reliability and security for data transmission in 6G scenario.	This method does not consider the information gap between PE and DR.
Hui *et al.* [55]	2022	Heterogeneous vehicular network	inter-twin	Multi-task federated learning; Game theory	A two-way selection to find the optimal strategies for each task requester in a multi-task scenario.	It does not consider the transmission latency and security issues during data communication between DT and BS.
Sun *et al.* [56]	2022	Manufacturing	intra-twin	Federated learning; SAGIN	A DT-based air-ground network is proposed to receive dynamic user data for federated learning models. A dynamic incentive mechanism is designed to find the most suitable client each time.	The article assumes that DT can provide real-time data to the network, ignoring the possible data gap between PE and DR.
Hui *et al.* [46]	2023	Heterogeneous vehicular network	inter-twin	Multi-task federated learning; Game theory	An on-demand selection mechanism for better performance in terms of system accuracy, performance-cost ratio, and task completion rate.	It fails to discuss the performance of the proposed structure in high-density scenarios, which is a practical issue for vehicular networks.
Lu *et al.* [57]	2023	Satellite time-sensitive networks	inter-twin	Deep convolution generative adversarial network	A DT-based satellite time-sensitive network is proposed for deterministic communication. In this paper, DT is leveraged to simulate the virtual model and provide prediction results in terms of scheduling performance.	The authors only consider homogeneous satellite time-sensitive networks where all the nodes work with similar processing capacity and scheduling strategy.
Tao *et al.* [63]	2023	Autonomous driving service	inter-twin	DRL; Semantic communication	In this paper, a semantic-based architecture is proposed to reduce data communication burden in high-dynamic scenarios, where DT system is deployed in parallel with the physical system to alleviate part of physical transmission.	The work seems mainly consider 6G homogeneous networks in a limited area. A more complex environment with heterogeneous devices and networks should be explored with a dynamic dissemination strategy.
Liu *et al.* [64]	2023	Metaverse	inter-twin	DRL; Semantic communication	The authors propose a vision-based semantic communication framework for a metaverse scenario, where the semantic pose data is utilized to substantially diminish the information gap to ensure high-level synchronization between PE and DR.	The meticulous frame-by-frame capturing of body key points poses a significant challenge in ensuring the synchronization efficacy of the system, particularly in scenarios with vast volumes of video data.
Tang *et al.* [65]	2024	UAV	intra-twin	DRL; Semantic communication	The authors propose a tiny DNN-based semantic communication framework, in which the UAVs are utilized as semantic encoders and decoders to accelerate real-time data synchronization.	The trajectories of UAVs are predetermined, nevertheless this assumption may lead to data loss in highly dynamic vehicular networks.

the meticulous frame-by-frame capture of body key points poses a significant challenge in ensuring the synchronization efficacy of the system, particularly in scenarios with vast volumes of video data.

In terms of daily management and application, DT and AI can become a powerful combination to bring convenience to ordinary people and enterprises. Cui *et al.* [70] showcase a digital dual-function automated optical transceiver employing deep reinforced learning and DT, where the monitored data and the received orders are transmitted through a software-defined network controller. In [71], Cicirelli *et al.* detail a novel method of using cognitive technology to manage buildings. They use deep reinforcement learning to learn from physical and simulated environments so as to optimize people's comfort and energy consumption. The applications of AI-based DT technologies greatly improve the daily life experience of ordinary people and are the best representative of DT in practical applications.

3) Transfer Learning: The intrinsic ability to transferring established problem-solving models to meet diverse needs and promptly disseminate these models for resolving associated issues underscores the efficacy of transfer learning when integrated within the IoDT system. Under such context, the IoDT system possesses the capability to interchange learning models among multiple DRs, thereby empowering the learning processes of the system. Benjamin Maschler *et al.* argue that transfer learning is the promoter of the development of DT [72], which can be simulated in the twin body to train a better learning model in advance, and use transfer learning to transfer the trained model to the entity, saving the training time in real space and improving the AI performance. Xu *et al.* use the transfer learning combined with DT to carry out fault diagnosis [60], proposes a two-stage double fault diagnosis method to enhance the transparency, flexibility, and efficiency of traditional diagnosis. With the help of DT, the simulation operation in virtual space can find out the fault in advance and obtains the diagnosis model. Then, transfer learning can be used to transfer the knowledge learned from the simulation from the virtual space to the physical space. Fig. 4 depicts the differences in the utilization of diverse machine learning approaches in the context of IoDT.

In consolidating the aforementioned research endeavors, machine learning-based techniques commonly harness DT as a distributed computing architecture, often deployed in cloud or edge environments. These methodologies, in most cases, assume that the DT already had the ability to achieve fundamental communication effectiveness. Subsequently, after conducting operations such as data validation or narrowing the communication gap among the IoDT system, the primary objective of these endeavors is to maximize the deployed DT system's potential for refining the training process and aiding machine learning models in more precisely accomplishing tasks encompassing prediction, learning, allocation, among others. These collective tasks are denoted as DTs toward Other Technologies tasks.

C. Enabling Technology: Edge Computing

In this subsection, we delve into edge computing as a primary avenue for deploying DT, exploring its critical role and the reciprocal relationship wherein DT advances contribute to the evolution and enrichment of edge computing in practical applications.

In general, IoDT-based edge computing tends to outperform in reducing latency and optimizing resource utilization, which has spawned a new field of research, namely DITEN [73]. As a complement to cloud computing, which often fails to deliver prompt services to users due to the long distance from the endpoint, an edge server functions as a light-weight, nimble local cloud in DT-based systems. It hosts the DR community within an entire IoDT framework, offloading computing tasks from individual PEs. The security and efficiency of data-centric operations are also bolstered during such proximal deployment [58], [74], [75].

In DITEN (*i.e.*, the edge network that forms an IoDT environment for multiple DT systems), edge computing is applied in the database layer, which is located between the infrastructure layer (consisting of the physical entities) and the model layer (consisting of numerous models) to receive, pre-process data from physical devices and transmit them to the model layer. In other words, edge computing ensures that the DT system possesses the capability to store, update, analyze, and communicate throughout the whole life-cycle [76]. The twin in the real-world (*i.e.*, physical entity) collects data through sensors and synchronizes them to the virtual twin (*i.e.*, DR). As a following step, large-scale data fusion, cleaning, pre-processing as well as data processing tasks are all conducted in the edge servers, the transmission delay during the edge-based offloading is considerably low compared to traditional cloud computing since the proximity between edge servers and physical products experiences a significant reduction. As shown in Fig. 5, the DRs are first generated in edge and then uploaded to the cloud for backup, migration, or data analysis. At present, edge computing has achieved good results in many applications of DT. Some typical applications of DITEN are described in detail as follows.

1) Task Offloading and Scheduling: Current mobile edge computing offloading methods ignore the user's mobility and the unpredictability of the mobile edge computing surroundings. In [77], the authors advocate employing a deep reinforcement learning algorithm to construct a virtual environment tailored for vehicular networks. This environment functions as a global controller, monitoring vehicle dynamics and the fluctuating state of edge servers while primarily focusing on generating an optimal offloading decision, including selecting the ideal edge server, segmenting tasks, and establishing task execution sequences. This approach enables a dynamic strategy that fosters effective collaboration, strategically considering the locations of individual vehicles in geographic terms. Similarly, Liu *et al.* [78] propose a DT-assisted task offloading paradigm. In this approach, DITEN is used to collect data from the real world and monitor the operation of the entire network to assist mobile users in selecting the appropriate edge servers. Dedicated to further reducing the gap between

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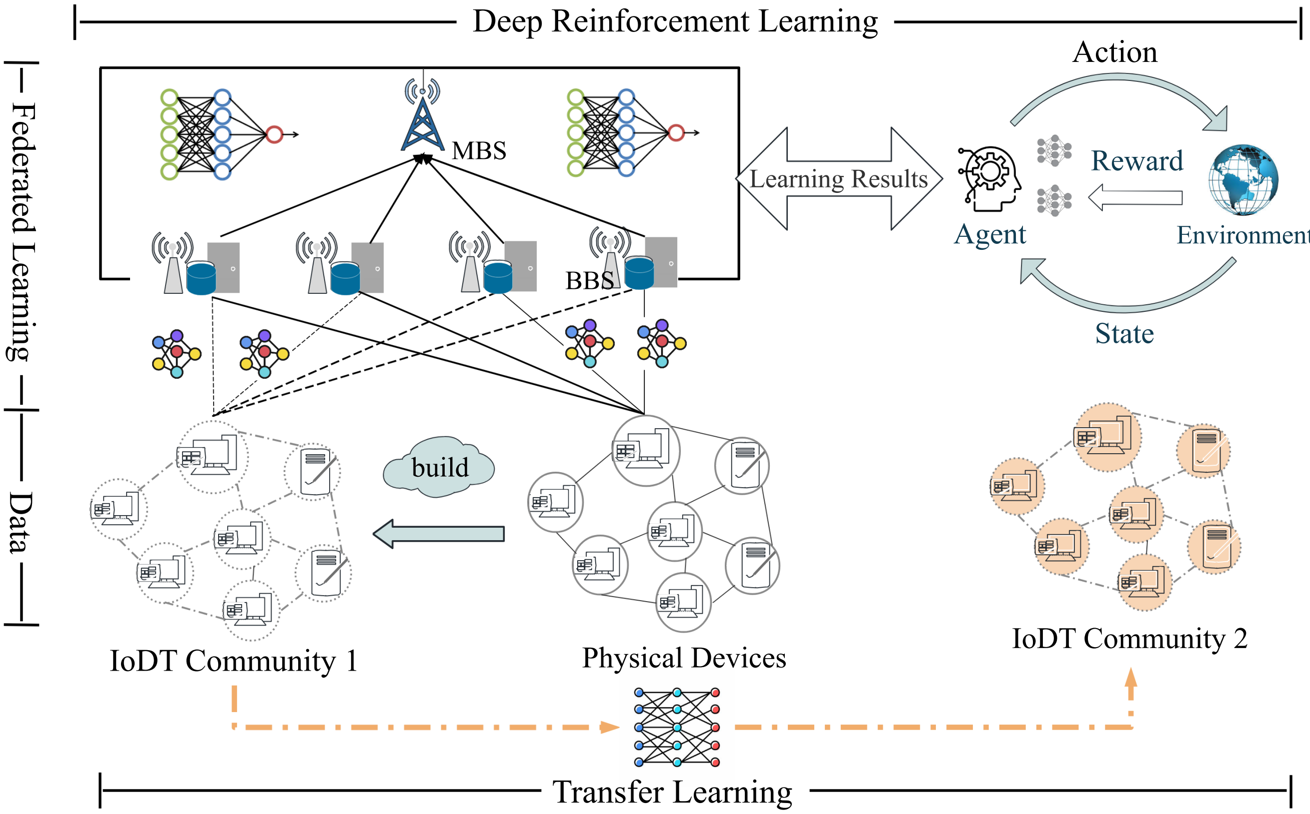

Fig. 4. The utilization of diverse machine learning approaches in the context of IoDT. Federated learning can be used for both physical devices (*i.e.,* IoT devices) and digital replicas (*i.e.,* DTs) to improve the security and efficiency. Deep reinforcement learning is utilized to optimize the results obtained from federated learning. Transfer learning can benefit the migration among multiple IoDTs, thus providing lightweight, low-latency, and high-accuracy computation results for various systems.

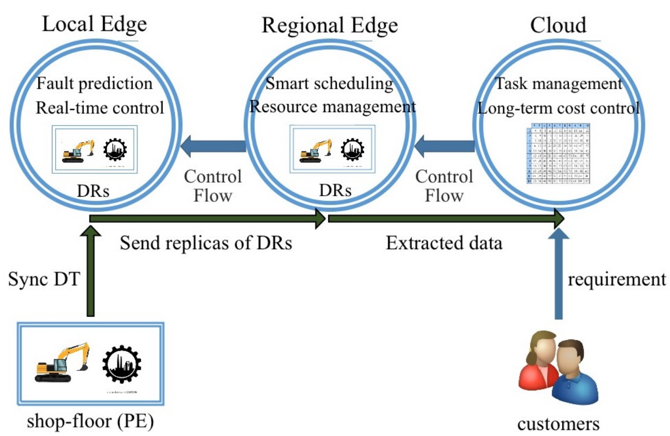

Fig. 5. Applications with different locations of IoDT. The DRs can be first generated on the PE side or edge as needed and then uploaded to the cloud for backup, migration, or data analysis.

physical networks and digital systems, [79] proposes a joint optimization approach to find a balance between sensing time, successful sensing rate, as well as efficient communication. As a result, the authors further ensure the freshness of the data by simultaneously considering the latency effects of sensing, transmission, and processing operations on the system. All the simulation results show that DT-based offloading and scheduling tasks can usually realize better performance with higher service reliability and lower cost. Notably, such applications of DT are also prevalent in Internet of Vehicles (IoV) scenarios [80]–[83].

2) Fault Prediction and Efficiency Optimization: With the development of a Cyber-Physical System, DTs are frequently anticipated to function as precise virtual representations mirroring real products or systems. By monitoring the performance reflection of physical entities, DR can be used to help the real operator predict and analyze the state in many situations. Take the smart grid as an example, the grid's information, such as voltage, electric current, and frequency, is measured and then synchronized to DR to predict the fault. Various control operations' effects are predicted and evaluated in the DR end, and the best operation and strategy are returned to the real grid as the final choice. To obtain early warning measurements, Tzanis *et al.* [84] introduce a novel cyber-physical system architecture wherein the cyber system operates within a low-latency IIoT network with all the computational tasks offloaded to the edge, while concurrently, DT is used to offer a near real-time representation of the physical system of the smart grid. This integrated system functions to detect warning severity, identify the network area of interest, and execute real-time predictions for incoming failures. Lin *et*

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al. [85] present an incentive-based congestion control method that comprehensively considers the relationship between delay, incentives, and individuals to obtain an optimal congestion control decision, thereby improving the stability and real-time performance of DT to ensure a more efficient DT communication environment.

3) Clock Synchronization: Accurate clock synchronization is one of the key factors for efficient distributed interaction among integrated IoDT systems. Collaborations between distributed devices could only be supported with the accurate clock. On the other hand, if there is no consistent clock between industrial infrastructure, the packets with unaligned time indexes can be out-of-order, which may directly lead to the false analysis of key data and out-of-date decisions. To accommodate the non-deterministic delay and heterogeneity of communication standards, Jia *et al.* [86] propose a way of improving on clock oscillator by constructing a DT model of the clocks at remote locations. It sends the series of continuous time stamps generated by the clock device to the corresponding edge node, and then the time stamps are modeled to reflect the clock oscillator. After the edge node completes the modeling of all clock devices, it will send a copy of the model to the corresponding devices to verify the correctness of the model coefficients. The final accurate model can be obtained after several iterations and is sent to the cloud for backup. As communication resource consumption decreases, a significant enhancement of on-the-clock accuracy is accomplished. We summarize the state-of-the-art endeavors of DITEN in Table V.

Apart from the key applications outlined above, the integration of DT-based systems and edge computing further spawns the capabilities of complex systems in joint optimization, which is critical in domains with hierarchical devices such as IIoT, smart manufacturing, metaverse, *etc*. More importantly, by adopting this perfect combo, combined with multiple up-to-date technologies (*e.g.*, machine learning, heterogeneous network, 5G/6G, *etc.*), the integrated IoDT systems enable dynamic allocation and coordination of communication and computing resources from both physical, edge and cloud ends, for diverse applications [87]–[89], as depicted in Fig. 6. We further discuss such joint communication and computing problems in Section VI-A, after scrutinizing all enabling technologies for both intra-twin and inter-twin communication.

D. Enabling Technology: Heterogeneous Network

The heterogeneous networks (HetNets) refer to a complex network composed of different types of smaller network components (*i.e.*, computers, systems, or network devices deployed by different network providers). These smaller networks are mostly under different protocols with various network topologies, data transmission performance, and hardware support, such as wireless fidelity network, wireless sensor network, AVNs, and mobile communication network [94]. Due to the sharing and collaboration property of IoDT, most of the users (*i.e.*, single PEs) and their data originate from diverse devices equipped with varying hardware resources. In addition, the entire IoDT system may consist of multiple sub-DT network

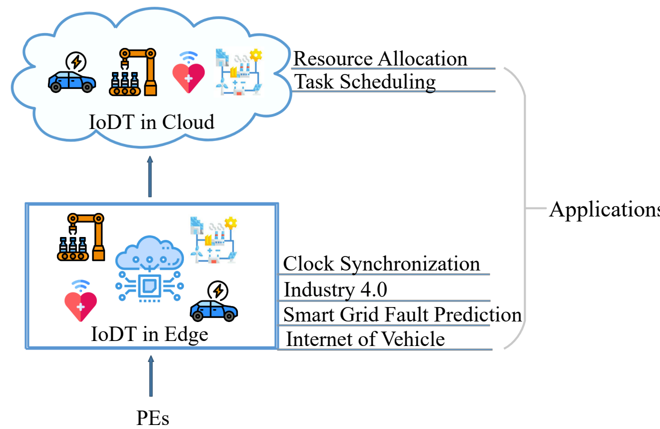

Fig. 6. IoDT shop-floor and corresponding application scenarios based on edge computing, fog computing, and cloud computing.

communities, leading to a potential collision between distinct network topologies and protocols. To this end, how to use the existing heterogeneous communication systems to interconnect among multiple networks has been of great interest to researchers [95]–[98]. Noted, such efforts is usually investigated in conjunction with machine learning and edge computing technologies mentioned in Section IV-B and IV-C.

From a macro perspective, the HetNets in IoDT can be roughly divided into two categories: single-path networks and multi-path networks. Single-path networks refer to networks containing only one transmission path, the primary purpose is to provide fundamental data transmission and communication services for IoDT. This kind of network can ensure stable data transmission between devices. As a result, the low latency feature can meet the requirements for real-time transmission in intra-twin communication to maintain the fidelity and synchronization nature of a single DT. However, when facing multi-user and multi-task scenarios, especially in some high-mobility or high-density scenarios, the communication failure of the only available path may force the entire communication link to be interrupted, resulting in data loss or even system breakdown. In contrast, with the support of reliable path selection and resource scheduling algorithms, multi-path networks can maintain concurrent transmission for multiple tasks simultaneously, ensuring robust transmission in multi-user and multi-base station scenarios, and finally facilitating the intelligent and automated collaboration of the IoDT system. The main works of IoDT-based HetNets are described as follows.

1) Resource Scheduling: Resource scheduling in a heterogeneous network refers to the process of optimizing the allocation of network resources (*e.g.*, bandwidth, storage of devices, virtual machines on a cloud, *etc.*) and scheduling the usage of these resources to ensure real-time data sharing and collaboration while improving resource reuse rate based on varying capabilities and requirements of heterogeneous devices.

Motivated by the performance of HetNets in terms of reducing mutual interference, optimizing system capacity, as well as reducing package loss and latency, a myriad of research

TABLE V
THE APPLICATIONS OF EDGE COMPUTING IN IODT.

No.	Year	Scenario	Category	Technologies	Contributions	Limitations
Zhang *et al.* [90]	2019	Industry 4.0	intra-twin inter-twin	Edge computing; IoT	This paper introduces a data and knowledge-driven framework for DTMC to maximize the intelligent performance of manufacturing systems.	How to solve resource limitations in large-scale manufacturing scenarios and how to locate the most meaningful information among massive data needed to be concerned.
Sun *et al.* [91]	2020	DITEN	intra-twin	DRL; Edge computing; 6G	To solve the dynamic offloading problem across the edge servers and minimize the long-term latency.	System performance under high-density and low-density scenarios should be discussed for mobile edge networks.
Campolo *et al.* [92]	2020	MaaS Smart transportation	inter-twin	Edge computing; IoT	A DT system is designed to retrieve data from mobile devices to provide customized transportation information for users.	The scalability and information gap of DT systems when retrieving mobility data needed to be considered.
Tzanis *et al.* [84]	2020	Fault prediction	intra-twin	DRL; Edge computing; IoT	In this paper, the grid DT is used for data-driven close-loop fault identification.	The data security and authentication problems are not taken into account in this article.
Jia *et al.* [86]	2020	Clock synchronization	intra-twin	Edge computing; 5G; IoT	Aiming at realizing stringent clock synchronization, a DT-based model is designed to predict the state of the dynamic clock and reduce resource consumption.	The performance and differences between a DT-based three-stage model and a two-stage model without DT should be discussed.
Lu *et al.* [52]	2021	IoT	intra-twin	Federated learning; DITEN; Blockchain	A DITEN-based framework is presented to narrow the gap between PE and DR. Protect communication security and data privacy by leveraging lightweight blockchain.	The simulations are conducted based on image-based datasets and do not consider dynamic scenarios.
Liu *et al.* [78]	2022	DITEN	intra-twin	Edge collaboration; Blockchain; Double Deep-Q-Learning	DITEN is utilized to collect data and monitor the network to assist mobile users in selecting the most suitable edge servers and offloading tasks.	For a model that uses DT as a tool for collecting real-time data from PE, a comparison experiment regarding data consistency of the system with and without DT should also be provided.
Xu *et al.* [80]	2022	IoV	intra-twin	DRL; Edge computing	To provide high-quality service for overloaded edge servers, this paper proposes a service offloading method based on deep reinforcement learning.	Lack of experiments on the impacts of DT on system performance.
Lin *et al.* [85]	2023	Congestion control	intra-twin	Edge computing; Smart contract	In this paper, an incentive-based congestion control method is proposed to comprehensively consider the relationship between delay, incentives, and individuals. As a result, the performance of stability and real-time capability of DT communication is enhanced.	It fails to take into account the mutual interference among devices in ultra-dense scenarios.
Li *et al.* [93]	2023	Mobile edge computing	intra-twin	Age of Information; Approximation and online algorithms	The authors consider a dynamic DT placement strategy to reduce the communication gap between PE and DR, thus improving user service satisfaction in mobile environment.	Whether the communication of heterogeneous data and networks could cause further data latency and reduce user satisfaction should be further discussed.
Kurma *et al.* [75]	2024	Mobile edge computing	intra-twin	RIS; DRL	The authors delve into the additive role of RIS for mobile edge computing systems and propose a joint optimization algorithm based on deep deterministic policy gradient. The proposal achieves lower end-to-end transmission delay by adjusting RIS phase, bandwidth allocation, processing rates, *etc.*	Although the authors consider the discrepancy between the true and estimated values of DT systems, it is seen as inherent during performance estimation process and is not further optimized.

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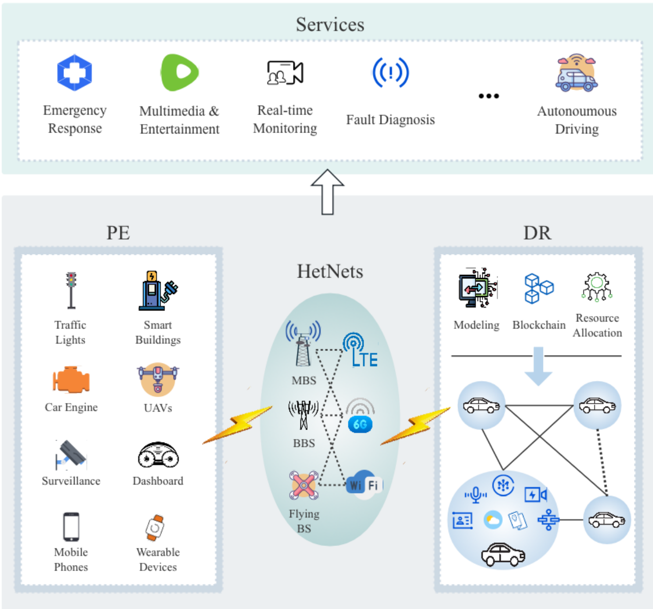

Fig. 7. Architecture description of heterogeneous network-based IoDT. With the on-demand and collaborative scheme, users can obtain target contents collaboratively between heterogeneous devices on a regional basis with the highest resource utility and lowest transmission delay.

has been developed in recent years. To automate the management of large-scale industrial scenarios, Bellavista *et al.* [99] propose an application-driven approach for the deployment of DT-based applications. Specifically, the authors introduce a middleware called Application-driven digital twin networking, which tries to reduce the management complexity by combining semantically enriched simple digital twins distributed on edge users and centralized composed digital twins for flexible orchestration. By adopting an SDN based cross-layer approach, [99] is able to simplify the data communication and interaction between heterogeneous devices and dynamically allocate the network resources in a dynamic manner, so as to fully explore available resources for multiple competing applications.

In vehicular networks, how to ensure the robustness of network transmission in a highly dynamic environment and how to choose the appropriate heterogeneous network for different devices in the vehicle (*e.g.*, LiDAR, ultrasonic sensors, cameras, *etc.*) are also challenging to achieve. Focusing on the DT-based IoV, Zheng *et al.* [100] present an actor-critic learning scheme to address the challenge of optimizing the connection between the vehicle and its own DR. By dividing vehicles into learner and expert categories, the knowledge can be shared among entire IoV system through the selected network. To efficiently distribute content to respond to a wide variety of user requirements with limited resources, Hui *et al.* [101] propose an on-demand content delivery approach in a DT-based heterogeneous vehicular network. By jointly considering multiple content parameters, such as the popularity and relevance of different contents, users can obtain target contents collaboratively on a regional basis. A double auction game based architecture is formulated for the transaction price between groups and roadside units. With the on-demand and collaborative scheme, the system can provide an optimized data-sharing approach with the highest resource utility and hit ratio while ensuring the lowest transmission delay. To elaborate further, a general functional structure of an IoDT system with HetNets in the context of vehicular networks is summarized as Fig. 7.

E. Enabling Technology: 5G/6G Techniques

Wireless communication technologies such as 5G and 6G techniques usually do not appear alone in the design process of IoDT systems but are used as core bases and auxiliary technologies to provide reliable communication guarantees for data transmission using edge computing, machine learning, and other technologies.

Within the integrated IoDT system, data-related tasks encompass various stages such as data collection, cleaning and fusion, storage, mining, and transmission. Specifically focusing on data transmission tasks, different DT systems impose distinct requirements for the quality of transmission. Some systems necessitate abundant sensors for system construction, while others prioritize transmitting data with high reliability and low delay, *etc.* Therefore, wireless communication technologies such as 5G and 6G are commonly employed in such scenarios to help other technologies efficiently complete data transmission and data analysis tasks to meet the IoDT system's requirements for synchronization, fidelity, and interoperability, *etc.* The emerging applications of DT and next-generation wireless communication technologies are demonstrated as follows:

1) Scenarios of uRLLC: Intrigued by the allure of "high reliability and low latency" characteristics of 5G communications, [102] applies the DT system in intelligent workshops. This intelligent workshop DT system is divided into five layers: physical layer, network layer, data layer, model layer, and application layer, respectively. The network layer is used to upload the equipment status information to the equipment database (data layer) through wireless network communication technology (network layer). The transmitted information includes but is not limited to product information, job scheduling, on-time delivery, production method, energy saving, and cost, *etc.* In order to form good control of the production process in the workshop and optimize the performance of the DT system, most of the transmitted data have a higher requirement for real-time acquisition of information, the uRLLC of 5G thereby can meet these requirements.

In the medical field, most of the data processing processes have the requirements of high reliability and low delay. Remote robot surgery is a hot topic in medicine, and DT technology can be well applied in this scene to help reduce the risk of human error through VR and robots. Compared with traditional operations in which doctors directly conduct operations with a scalpel, remote robots can imitate surgery smoothly through the doctor's remote action instructions. During the remote surgery, the data transmission must be real-time to ensure that the patient's life will not be threatened. In this process, uRLLC effectively ensures that the data

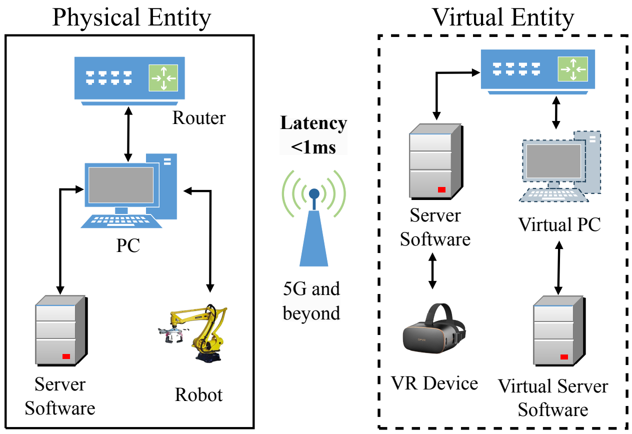

Fig. 8. The remote robot surgery under 5G uRLLC environment. The uRLLC is used to ensure that the data and feedback information received by DT technology during simulated surgery are always synchronized with the real surgical scene.

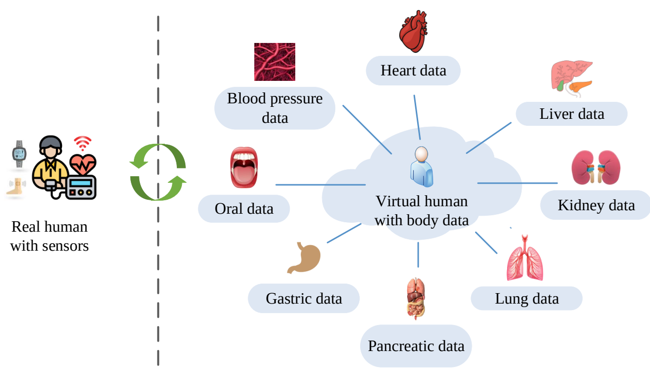

Fig. 9. Simulation of human organs in 5G mMTC environment. In IoT-based applications (*e.g.,* DT-based healthcare), mMTC can provide unlimited possibilities for large-scale deployment of physical devices and alleviate network overload during massive data communication between PEs and DRs.

and feedback information received by DT technology during simulated surgery is always synchronized with the real surgical scene, as shown in Fig. 8.

2) Scenarios of mMTC: With the help of advanced sensors, AI, and communication technology, medical and health departments can replicate various organs in the virtual world, which can be termed as healthcare DT [103]. Healthcare DT can detect the human body in a real-time manner, during this process, the virtual bodies of each organ need to transmit analyzed data (*e.t.*, body condition assessment, organ function diagnosis, *etc.*) to the corresponding physical monitoring equipment to assess the health level of real organs. In which a large number of sensors are needed, as shown in Fig. 9. Compared with traditional data communication, mMTC scenarios are mainly oriented to the IoT businesses, which can effectively solve the problem of network access overload, provide unlimited possibilities for large-scale deployment of physical devices in the context of IoT, well meet the transmission requirements of massive sensor data in the medical and healthcare field, and ensure the diversified communication requirements in the DT system [104].

3) DT Empowered Open Radio Access Networks: The synergy between DT and open radio access networks (O-RAN) unquestionably unlocks a novel avenue for complex systems in terms of flexibility, interoperability, synchronization, *etc.* While research exploring DT's application in O-RANs remains nascent, the present work only offers a rough silhouette and the specific combination scheme and performance await validation, it still signals a promising trajectory for futuristic 6G wireless services.

Focusing on strategic deployment of intelligent, resilient, automatic, and open 6G radio access networks, Masaracchia *et al.* [105] envision a synergistic fusion of DT with O-RAN. Perfectly suited to the O-RAN's emphasis on openness, interoperability, and intelligence, Masaracchia *et al.* advocate leveraging DT's strengths in constructing virtual replicas to assist the next-generation networks in extracting fine-grained channel features, optimizing channel models within intricate network architectures, forecasting and managing network states, and conducting fault detection, among other functionalities. [106] presents an O-RAN-based DT framework to explore the cooperation possibilities among multiple vehicular DT pairs. This new attempt shines a spotlight on the solid challenge posed by frequent transfer of DRs in dynamic environments, changing the conventional one-to-one synchronization within PE-DR pairs to many-to-many synchronization without frequent offloading, which actually consolidate the IoDT communication concept. Relevant studies focusing on data security issues in similar O-RAN-based dynamic scenarios can also be found in [107] and [108]. Targeting improved internet quality in rural areas, Ndikumana *et al.* [109] investigate O-RAN-based 5G fixed wireless access with closed-loops, where DT is utilized to provide real-time replications for both wireless environments and edge cloud systems. The objectives of the closed-loops are two folds, one is to allocate sliced radio resources for the overarching system, another one is to conduct resource allocation within single slice. Supported by AI technologies such as reinforcement learning and federated learning, O-RAN-based systems for communication optimization purposes offer more possibilities to improve responsiveness and quality of service in multi-DT environments. However, at the current stage, the deep integration and practical deployment of IoDT systems and O-RAN under complex systems need to be further explored. Synchronization delays in dynamic environments and higher security vulnerabilities exposed under open architectures also warrant further discussion.

F. Enabling Technology: Reconfigurable Intelligent Surface

From a physical point of view, wireless signals continue to propagate in all directions and gradually attenuate as the transmission distance increases as they are sent toward a designated location. Intuitively, some reflective planes, such as windows and mirrors, or even better, rough reflective planes, such as walls and object surfaces, can enhance the strength of the signal received at the target location through reflection or scattering of the signal. However, since the direction of the reflected or refracted signal by these surfaces is not controllable, a large portion of them will still be redirected to the unintended

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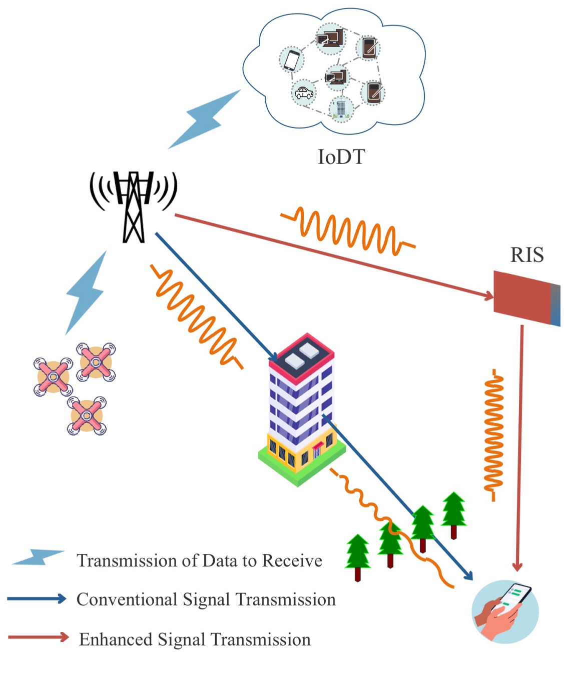

Fig. 10. Application scenario of RIS. By intelligently adjusting the reflection path, phase, and amplitude, RIS is able to improve the quality and reliability of transmitted data significantly.

location [110]. At this juncture, the Reconfigurable Intelligent Surface (RIS) takes center stage, significantly enhancing DT-based communication quality atop the foundation laid by 5G/6G technology.

RIS is regarded as one of the most promising technologies for future wireless communication other than 6G, which utilizes controllable reflective surfaces to automatically manipulate the propagation of transmitted signals and enhance data transmission performance. Inspired by the physical mirror, RIS consists of a two-dimensional surface with multiple discrete elements, where the signal can be regulated and controlled in a real-time manner by adjusting the phase and amplitude of the reflective elements [111]. As illustrated in Fig. 10, compared with traditional wireless communication, where signal attenuation and packet loss are caused by passing through obstacles and long-distance transmission, RIS can further enhance the original signal by intelligently adjusting the reflection path, phase, and amplitude, *etc.*, thus improving the quality and reliability of data transmission. While the research on integrating RIS with DT is still in its infancy, the rest part of this subsection aims to delve into the state-of-the-art advancements in RIS, uncovering potential applications of RIS across different phases of data communication and collaboration of IoDT.

1) Intelligent Configuration: Intelligent configuration refers to a technology that uses AI algorithms and other 5G / 6G candidate technologies (such as terahertz communications) to learn corresponding parameters such as load conditions, transmission reliability, robustness, *etc.*, to ultimately achieve a real-time, automatic configuration scheme that allows the RIS to provide optimal wireless communication performance for the receivers. [112] proposes a deep learning-based method to learn the interaction and relationship between RIS elements and the receiver. By modeling a virtual environment to map both the real and virtual parts of the RIS, [112] excels in predicting RIS performance and can provide optimal RIS configuration solutions for subsequent receivers. Committed to better performance for cell-free systems for next-generation wireless networks, Cui *et al.* [113] present a DT-based learning framework by virtually learning the characteristics of both the access point and user association, as well as the power control and RIS beamforming, the new user-centric cell-free system can effectively reduce the solution space and maximize the sum-rate in the physical environment.

2) Advanced Wireless Communication: In addition to research on improving the intelligence and robustness of RIS configurations, taking advantage of the impressive performance of RIS in establishing line-of-sight connections to enhance wireless communication performance, numerous studies have been conducted in recent years to explore the complementary role of RIS in different communication scenarios to enable the advanced wireless communication networks. To obtain better performance for massive multiple-input multiple-output systems, Zhi *et al.* [114] leverage genetic algorithm to maximize the sum data rate of the system with the help of RIS. Targeting the terahertz (THz) wireless systems, [115] presents a path loss model to optimize the phase shifting scheme of RIS. By considering numerous variables such as RIS size, RIS-user distances, the radiation pattern, and the reflection coefficient, *etc.*, the new RIS-assisted THz system can dramatically benefit the design of advanced wireless systems. In lightweight and flexible environments, such as the UAV-enabled communication environment, RIS can also help enhance the propagation and quality of communication [116]. Leveraging UAV's advantages in terms of high flexibility and the ability to build line-of-sight connection, [117] proposes a new method that uses the UAV to carry the RIS to reflect signals, thus fueling data communication in multi-input single-output scenarios. As an in-depth study, to eliminate the limitation of onboard energy in an integrated UAV-RIS system, Peng *et al.* introduce a deep reinforcement learning-based scheme to jointly consider the information transport and energy harvest problem, thus ensuring the Quality-of-Service under a highly dynamic environment [118]. The wireless communication works that can facilitate the integrated deployment of IoDT are summarized in Table VI.

G. Key Application Scenarios and Use Cases

In this subsection, we discuss the ground-breaking attempts related to intra-twin communication in key application scenarios, including industry and manufacturing, mobile device systems, smart scenarios *etc.*

As mentioned before, industry and manufacturing are the best pioneers in driving the application and development of IoDTs in various fields since they are considered typical industry-driven technologies. By performing simulations in the DR of each PE and feeding back the prediction results among the DT community, IoDTs can make the production more

TABLE VI
PROMISING WIRELESS COMMUNICATION WORKS FOR FUTURE IODT.

No.	Year	DT Location	Scenario	Technologies	Objectives
Bellavista *et al.* [99]	2021	edge	IIoT	Edge computing; Software-defined networking	Simplify the data communication and interaction between heterogeneous devices and dynamically allocate network resources.
Sheen *et al.* [112]	2021	N/A	RIS	Convolution neural network (CNN)	Optimize RIS configuration
Zhi *et al.* [114]	2021	N/A	RIS-aided massive multiple-input multiple-output system	The genetic algorithm	Maximize the sum data rate of RIS-aided massive multiple-input multiple-output systems; conduct the phase shift problems of RIS in the system.
Liu *et al.* [119]	2021	N/A	MIMO network	Interference-to-noise-ratio (INR) based analytical scheme	To analyze the interference that is caused by non-serving RIS in MIMO network.
Boulogeorgos *et al.* [115]	2021	N/A	Terahertz (THz) wireless system	Electromagnetic theory	Optimize the phase shifting of RIS.
Wu *et al.* [117]	2021	N/A	Aerial-reconfigurable intelligent surface (ARIS); multi-input single-output	UAV-enabled communication system	To generate data by using UAV carry RIS for wireless network.
Zheng *et al.* [100]	2022	cloud	IoV	Markov Decision Process; Transfer learning	Optimize the heterogeneous network selection scheme; transfer knowledge among systems
Anjana *et al.* [120]	2022	N/A	RIS assisted communication; next-generation networks	Intelligent discrete phase shifter	To enhance the signal-to-noise ratio of the system by adjusting the phase shift of RIS.
Chapala *et al.* [121]	2022	N/A	Multi-RIS empowered multi-hop transmission	Double generalized fading channels	To obtain better insight regarding the performance of RIS-based multi-hop transmission system.
Feng *et al.* [122]	2022	N/A	Indoor mmWave	Intelligent reflecting surface; Decode-forward relay	Compare the performance of intelligent reflecting surface (IRS) with traditional decode-forward relay to better eliminate the indoor path loss of the millimeter wave band (mmWave) and improve the data rate.
Hui *et al.* [101]	2023	cloud	IoV	Game theory	On-demand content delivery with high utility, high hit ratio, and low transmission delay.
Cui *et al.* [113]	2023	edge	RIS-assisted uplink, user-centric cell-free (UCCF) system	Position-adaptive binary particle swarm optimization; Twin-delayed deep deterministic policy gradient	Maximize the sum-rate and reduce solution space.
Nguyen *et al.* [123]	2023	N/A	SAGIN	Hybrid free-space optics/radio-frequency communications	To diverse the free-space optics link by reflecting the signal from the high-altitude platform with the help of additional UAV.
Peng *et al.* [118]	2023	N/A	Integrating unmanned aerial vehicles with RIS	DRL	To simultaneously transport information and harvest on-board energy for UAV.

reliable and predictable, which has become the latest trend for research to realize the intelligentization of control and assembly in real-world [124], [125]. This kind of application places high demands on the real-time, synchronization, and fidelity of data communication between PE and DR. Meanwhile, more than one component or accessory may be involved in some complex DT models, leading to heterogeneous data and data migration challenges between different virtual accessories. The same concern could also occur in [126], where Siemens introduces a new gas turbine for energy production, and a new AnyLogic-based DT system is performed to model the sophisticated simulation for further data analytics on the fleet operations of Siemens gas turbines.

From the perspective of mobile device systems, [127] introduces an advanced driver assistance system based on Vehicle-to-Cloud communications to guarantee the performance of DT in fidelity and synchronization nature. The author examines the DT-based autonomous driving system from the aspects of communication delay and packet loss and demonstrates the benefits of the proposed system, offering an alternative solution for reducing the communication delay within a DT system. In [128], He *et al.* examine a novel multi-spectrum propagation approach for enhanced data transmission performance. From a practical standpoint, the authors investigate various frequency bands under realistic environments (including microwave, laser, and visible light) and further elaborate an optimized DT construction of radio propagation, opening new possibilities for DT-based dynamic systems with low complexity and high accuracy.

Apart from enabling real-time monitoring and predictive maintenance akin to industry and manufacturing scenarios [129], smart scenarios (*e.g.*, smart healthcare, smart agriculture, smart home, *etc.*) demonstrate a higher dimensional emphasis on real-time data synchronization and fine-grained analysis due to the diversity and dynamics of the participants [130]. Pang *et al.* apply federated learning to COVID-19 and propose a new urban collaborative DT framework based on federated learning [62]. Harnessing the learning process from shared models, the framework neatly mitigates the problem of insufficient historical data upon building a DT system, permitting quick access to historical infection data of new viruses and effective management of private data across entities. Thus ensuring multi-city collaboration and intelligence under limited data. Targeting smart park construction with low-carbon requirements, Su *et al.* [131] develop a federated learning-based DT framework. The proposal considers a multi-tier deployment approach for model training, pursuing a perfect balance to simultaneously obtain the desired accuracy and DT synchronization performance in constructing the smart park simulator. In [132], the authors delve into the development of DT-based smart farming, dedicated to water-saving irrigation management. The data collected from sensors and actuators is utilized to feed the simulator for monitoring and in-advance evaluation regarding the performance of specific irrigation strategies. In this work, the data acquired from various sources are unified and processed by the FIWARE-based IoT platform, generating a coherent DT system for the subsequent simulation. Additionally, under specific circumstances such as those scenarios with service requisitions (*e.g.*, metaverse, IoVs), DT-based systems may be constructed in a way that places a higher demand on the users' experiences. Given that such systems are generally more intricate, involving collaboration and cooperation between multiple DTs, we will further explore relevant use cases in Section V-E.

Thus far, we have provided a snapshot of potential use cases related to intra-twin communication along with corresponding solutions. It's crucial to emphasize that intra-twin and inter-twin communications are inherently interdependent, constituting integral facets of a well-integrated IoDT system. Consequently, attempting to entirely segregate research of intra-twin and inter-twin is practically unfeasible, given their complementary nature within the system. Some other practical applications of the combination of both intra-twin and inter-twin communication will be discussed in Section V-E.

V. Inter-twin Communication

Assuming that intra-twin communication is considered the foundation and ultimate landing point of the entire IoDT system, then inter-twin communication, a goal-oriented communication architecture, is the benchmark indicator that determines the upper limit of system performance. In this section, we detail the goals of inter-twin communication and further delve into the enabling technologies and existing works.

A. Overview

In a larger sense, the ultimate goal that inter-twin communication seeks to achieve is to find an efficient data communication and knowledge-sharing method for the integrated system that enables them to infinitely converge to an optimal solution of a common goal while satisfying the individual needs of each device. This really leads us to the two goals that are illustrated as follows.

- ***Data Sharing.*** Data sharing refers to allowing multiple devices to share and exchange data to achieve better performance for the entire system. It plays a vital role in enabling users within the IoDT system to collaborate and cooperate in an efficient and effective way [133]. By sharing data with each other, the DRs can obtain a better understanding of the system from a global perspective (*e.g.*, the global environment of the system, available resources, tasks, and goals of other DRs, *etc.*), which can benefit the performance and task offloading of individual DT pair. In addition, for some knowledge or skills (*e.g.*, models based on reinforcement learning or transfer learning) already mastered by other DRs, the target DR can directly inherit them through inter-twin communication as needed, thus reducing the computational load and improving the accuracy and flexibility of a single device. Noted, several factors can influence the effectiveness of data sharing in inter-twin communication, for example, the communication mechanisms used by different DRs, the quality and amount of the shared data, the level of trust and collaboration among DRs, and the degree of heterogeneity of different devices in terms of tasks and hardware capabilities.
- ***Distributed Computing.*** As an essential component of large-scale intelligent systems such as IoDT and multi-agent systems (MASs), distributed computing enables the users to collaborate in a distributed manner and simultaneously conduct a huge number of complex tasks that cannot be completed by a single intelligent device, leading to better overall performance in terms of efficiency, scalability, and task processing capability. In particular, distributed computing provides a way to divide a complex task into multiple smaller and simpler subtasks and distribute the tasks from the target DR to other DRs among IoDT through inter-twin communication. Benefiting from this parallel processing mechanism, the workload on the individual device can be greatly reduced. In the meantime, with the help of other DRs within the system, the capability of a single DR is no longer limited by the hardware capacity of its own PE, which greatly improves the performance of each DT pair in IoDT systems such as the processing speed, efficiency, accuracy, and robustness.

In conclusion, as two main goals of inter-twin communication, data sharing and distributed computing enable IoDT systems for higher reliability, accuracy, intelligence, and automation. However, the heterogeneity of different devices in terms of hardware, software, system mechanism design, security, *etc.* inevitably hinders the coordination and knowledge migration in a wide range of areas. The enabling technologies that facilitate all-round improvement of both IoDT systems and communication performance are delineated in the following subsections.

B. Enabling Technology: Searching Mechanism

The searching mechanism in inter-twin communication refers to the process of retrieving information or data from other DRs based on specific criteria or queries. In contrast to traditional search tasks, different DRs in the same IoDT system may hold diverse data for the same topic. That is, DRs may specialize in different areas due to various goals and tasks, leading to discrepancies in the accuracy and reliability of the data they can provide for different topics. Therefore, how to search and select the most reliable data for the target DR among many collaborators to empower the complex tasks of a single device, while ensuring the privacy and security of both the sender and receiver when dealing with sensitive information is a major research task in inter-twin communication.

In general, a typical search process in inter-twin communication can be divided into five steps: data query, data searching, source selection, task allocation, and data transmission. Among them, data searching is responsible for collecting all available data sources in the target area. Source selection focuses on selecting one or more optimal data providers based on their professionalism, reliability, reputation degree, data quality, *etc.* Task allocation is responsible for generating the optimal data transmission strategy for multiple data providers, including transmission order, target data to be transmitted, and channel and resource allocated to each provider.

Targeting on the searching steps mentioned above, searching techniques in inter-twin communication can be further divided into two categories: centralized algorithm and distributed algorithm. The centralized searching algorithms can make macro control for global information and provide faster and more comprehensive search to the target DRs. However, due to the extensive search scope, the accuracy and matching degree of the results may present a more complex situation with the assistance of widely used information retrieval approaches such as greedy search, fuzzy search, and semantic search, which enhances the difficulty of subsequent source selection tasks. Meanwhile, in the process of building next-generation large-scale intelligent communities, the complexity of search will gradually increase with the increase of the number of users in the system. On the other hand, distributed searching algorithms have a better ability to handle complex and variable data requests and establish an efficient and robust search mechanism for the system, the peer-to-peer search structure also ensures that each DR's preferences and transmission history are taken into account when selecting new data provider or collaborator. However, the parallel execution of multiple requests and transmission tasks may lead to resource shortages and link conflicts, resulting in relatively slow responses. The up-to-date works related to the search mechanism are discussed as follows.

As a typical data distribution and dissemination technique that empowers the centralized searching algorithms, publish/subscribe is more beneficial in many-to-many communication scenarios, *i.e.*, data from multiple publishers trying to be transmitted to multiple subscribers [134]. Focus on the information search and retrieval, to address the problem that the current carpooling service often uses a threshold-based approach to filter subscription information for drivers and cannot determine the optimal detour threshold, [135] proposes top-k subscription queries scheme to continuously search and return the best k results, so as to realize a better performance for driver-rider matching in practice. In subsequent research, Wu *et al.* [136] introduce a mobile crowdsensing system to enumerate the available parking space in the target area. Through a proper incentive mechanism, all mobile users in the target area can detect and publish information about the parking space, which will be disseminated to urban drivers on-demand through the publish/subscribe communication mode, thus realizing real-time information sharing on a global scale. A similar publish/subscribe-based information retrieval technique is also used in [137] for topic subscribe to facilitate the construction of AVNs.

To achieve fast matching in a publish/subscribe system, Ding *et al.* [138] design “MO-Tree” as a new data structure. By indexing data in a concise way with limited height, the proposed method is able to effectively enhance the matching speed and reduce the maintenance cost for subscriptions. Targeting on the shortcomings of distributed hash tables (DHTs) in querying non-exact content, Zaarour *et al.* [139] present a new semantic-based system called “OpenPubSub”, by changing the exact-match query to approximate query, [139] is able to point out the semantically similar content, and cluster the user nodes based on interests. To overcome the limited query capability and computational resources in the spatial-keyword skyline query, Deng *et al.* [140] propose a distributed framework for query processing and an optimized skyline computing scheme to suit the geo-textual streaming data. In conjunction with the proposed communication optimization method, [140] has proven to be effective in ensuring high query performance in spatial-keyword publish/subscribe systems while reducing update and communication costs.

Taking advantage of the named data networking (NDN) in terms of efficient and stable data distribution and search capabilities, Wang *et al.* [141] propose an NDN-based MANET to enhance the success rate of data acquisition while reducing the cost of data retrieval. Targeting the Internet of Vehicles scenario, Chen *et al.* [142] propose a novel Vehicular Named Data Network based data caching scheme, by analyzing the spatial-temporal characteristics of transmitted data. The proposed method can divide the data into different categories and effectively reduce the data acquisition delay.

As a direct and efficient method for data broadcasting, flooding has the ability to quickly and directly disseminate the messages to all nodes but is prone to message overlap, resulting in significant resource consumption. To mitigate the interest flooding on a wireless NDN, [143] presents a multi criteria-based forwarding strategy to effectively detect the flooding so as to obtain better forwarding efficiency for the overall system. A similar theory is also used in [144] for multimedia data retrieval to eliminate packet flooding and

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improve the overall efficiency of the system. The related works are summarized in Table VII.

C. Enabling Technology: Data Transmission

In addition to the same considerations as intra-twin communication about how to leverage heterogeneous networks to ensure accurate and timely data transfer, it is also necessary for inter-twin communication to consider the willingness and preference of users when transferring, as well as the flexibility, scalability, and automation of large-scale intelligent communities that IoDT forms.

1) Inter-data Transmission: In IIoT scenarios, in order to achieve automatic information interaction between different users and ensure the interoperability between DRs, Amoretti *et al.* [148] present a Message Queuing Telemetry Transport based communication framework. By facilitating the dynamic interaction between multiple users, the system is able to ensure better control over different data flows, thus ensuring the overall security and scalability of the system. For efficient content dissemination, Jahanian *et al.* [149] propose a name-based publish/subscribe framework to handle topic-based and recipient-based data dissemination. The load-splitting mechanism effectively eliminates the traffic concentration and maintains seamless information delivery and satisfied load-sharing.

Targeting on video data, George *et al.* [150] introduce a low latency and high accuracy method for video transmission in a multi-camera based application. For transmission efficiency in highly mobile scenarios such as Vehicular Ad Hoc Networks (VANETs), a vehicular named data network-based method is proposed in [151], by predicting the future location of the access point of vehicles, [151] is able to forward the returned packets with higher communication Quality-of-Service. Similarly, Hou *et al.* [152] also present a data forwarding scheme targeting on vehicle tracking to tackle the problem of path-breaking during data transmission in vehicular networks.

2) Incentive Mechanism: Considering the privacy and security issues of both sender and receiver in large-scale IoDT networks, as well as the possibility of the existence of dishonest nodes, the design of incentive mechanisms in IoDT networks is another significant component to ensure the accuracy and reliability of the data transmitted through inter-twin communication.

In order to provide selected data to other vehicles in a future intelligent transport system to ensure sufficient security and privacy for each node, Yeh *et al.* [153] propose a privacy-preserving and sustainable data query scheme for 5G-based VANET. With the help of a token-based incentive mechanism, the users are encouraged to share the traffic data with the community to realize auditable transmission and sharing records. In [154], Chen *et al.* design a novel reputation and payment-based incentive mechanism to increase users' willingness to honestly participate in data sharing in federated learning. An evolutionary game theory model is introduced to dynamically adjust the benefits for different conditions to enhance the adhesion of user engagement. To address the need for large-scale data sharing and collaboration in IoT scenarios, Zhang *et al.* [155] propose a data quality-based incentive mechanism, where users can be rewarded differently depending on the quality and size of the dataset, thus inspiring positive data sharing mechanism. To address attacks during intelligent collaboration on cloud-hosted platforms, Purohit *et al.* [156] present an incentive-based cooperation. By obtaining threat data and selecting trustworthy peers, the users can detect and finally mitigate cyber attacks. We summarize several important applications in Table VIII.

D. Enabling Technology: Security and Privacy Protection

As a comprehensive technology to realize massive, real-time data communication among multiple entities, the DT wireless communication system has higher requirements for data reliability and security. Specifically, for intra-twin communication, the DT system needs to generate a private link between the physical entity and its corresponding DR during the data synchronization process to ensure that data will not be intercepted by a third party. Meanwhile, in the inter-twin data sharing process, since each DR holds all the information of its physical entity, privacy protection is another key issue that the DT system needs to consider. In this part, we discuss the threats and challenges that DTs face during the communication from both the internal and external perspectives and further demonstrate the key technologies that can tackle the problems.

1) Security Challenges of DT Communication: The possible security risks faced by DTs are shown in Fig. 11. On the one hand, as a virtual replica of a physical entity, a DT will obtain all internal views of its physical system. Once the adversary breaches and accesses DT, it could be able to analyze and detect the vulnerable spots of the system, and acquire all private and sensitive information, or even bypass all related security mechanisms. Therefore, access control to the DT system is essential. On the other hand, a major advantage of DT lies in its real-time and dynamic simulations of the physical entity. Therefore, a DT has a high requirements on data synchronization and rapid AI model exchange. If the adversary launches a Distributed Denial of Service attack or data poisoning against the intra-twin communications, which delays the communication between the real world and the virtual world or exchanges false information, it will directly affect the accuracy of its twin and its subsequent prediction and evaluation functions. More concretely, the security protection can be discussed from the following aspects:

a) Data Synchronization: A fundamental purpose of DTs is to accurately reflect the internal state of the physical system to the corresponding DR. If there is a difference in behavior between the physical twin and the virtual twin, it is very likely that the system will be misjudged and leading to severe consequences. Therefore, achieving synchronization between DTs is the priority of security problems. Specifically, state replication and behavior synchronization are two major steps to achieve DTs. Replicating states is a prerequisite for implementing a multitude of security and safety-enhancing on the basis of DTs [160]. The mainstream state replicating will use a state observer [161], because it is not a simple modeling and simulation of the physical entity, but an attempt to provide specific input for DR so that it can run the functions of its

TABLE VII
PROMISING SEARCHING MECHANISMS FOR IODT.

No.	Year	DT Location	Scenario	Technologies	Objectives
Li *et al.* [135]	2021	N/A	Carpooling service	Query processing; Publish/Subscribe	By matching the top-k query, find the most suitable passengers for each driver to improve the application performance of carpooling service in practice
Ding *et al.* [138]	2021	N/A	Pub/Sub Systems	Publish/Subscribe	Effectively enhance the matching speed and reduce the maintenance cost for large-scale spatiotemporal-aware publish/subscribe systems.
Blazy *et al.* [145]	2021	N/A	IoT	Secure publish/subscribe; Attribute-based cryptography	Ensure the security and privacy of users in a topic-based publish/subscribe system.
Wu *et al.* [136]	2022	N/A	Smart city Smart parking	Mobile crowdsensing; Publish/Subscribe	Information sharing in a timely manner
Zaarour *et al.* [139]	2022	N/A	Information search and retrieval	Publish/Subscribe	Enhance event matching performance and reduce the messaging overhead.
Cintuglu *et al.* [146]	2022	N/A	Power system	Publish/Subscribe	Real-Time asynchronous information processing.
Deng *et al.* [140]	2022	N/A	Query Processing	Spatial-keyword publish/subscribe	Maintaining query performance; reducing storage costs, update costs, and communication cost.
Wang *et al.* [141]	2022	N/A	MANET	NDN; MANET	Enhance the success rate of data acquisition while reducing the cost of data retrieval.
Araújo *et al.* [143]	2022	N/A	UAVs	NDN; Interest flooding attack	To detect and mitigate interest flooding and obtain better packet forwarding efficiency for the overall system.
Chen *et al.* [142]	2022	N/A	IoVs	NDN; Spatial-temporal characteristics	To divide the message into three categories based on application requirements and reduce data acquisition delay.
Arsalan *et al.* [144]	2023	N/A	Wireless Multimedia Sensor Network	NDN	To improve the overall efficiency for both individual nodes and the entire network, and enhance the data store and retrieve performance.
Hamad *et al.* [147]	2023	cloud	Mobile IoT	End-to-end (E2E) security; Message queue telemetry transport	Provide secret sharing and trust delegation for end-to-end message publish/subscribe.
Liu *et al.* [137]	2023	edge	AVN	Publish/Subscribe; Lyapunov Optimization	Joint optimization for both resource allocation and conflict avoidance inter-vehicular communication.

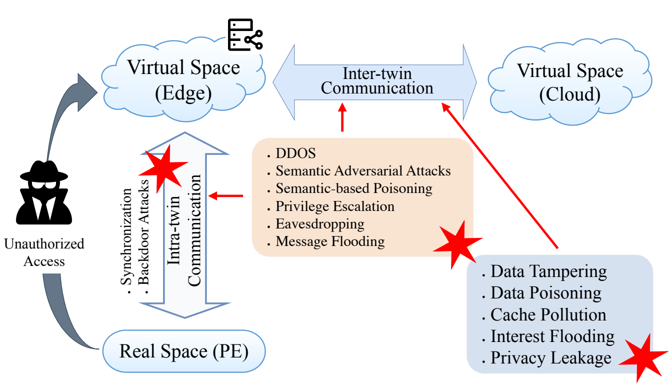

Fig. 11. The risks faced by IoDT. Intra-twin and inter-twin communication are exposed to distinct risks based on the differentiated communication frameworks. Among them, the risks common to both are elucidated in the orange rectangular box, while the risks occurring during inter-twin communication are enumerated around the arrow and in the blue rectangular box, respectively.

physical entity on the virtual side. Based on this, Akbarian *et al.* propose in [162] to establish a "Proportional, Integral, Derivative controller" in the digital domain, so that it can use the received a real system output signal as a reference signal, and finally calculated a virtual signal with a smaller error from the real signal in the digital control to achieve relatively accurate and fast state transition. In addition, clock cycles can also be introduced to realize the synchronization process between the real device and the digital representative. [163] proposes a synchronization model in which the physical entity and DR process their inputs independently as a priority, then synchronizes the state at this very moment in the next time slot based on the input received during the previous synchronization.

b) Data Protection: Another key to protecting the security of DTs lies in their data sharing. Up to now, the paradigm of DT is still in the early stages. Most people have not considered data-sharing security too much. Currently, DTs are primarily used in industry and enterprises, which need to run through the entire lifecycle of assets. Different parties may

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TABLE VIII
PROMISING DATA TRANSMISSION WORKS FOR INTER-TWIN COMMUNICATION.

No.	Year	DT Location	Scenario	Technologies	Objectives
Amoretti *et al.* [148]	2021	N/A	IIoT	Message Queuing Telemetry Transport; Data authentication	Maintaining a higher degree of scalability and security of the system.
Jahanian *et al.* [149]	2021	N/A	Information dissemination in disaster management; IoT; distributed file systems, *etc.*	Information-centric networking; Publish/Subscribe	Provide real-time information dissemination and efficient load-sharing.
George *et al.* [150]	2021	edge	IoT	Edge computing; Machine vision; Adaptive computing	Realize satisfied latency and accuracy performances in an IoT-based multi-camera application by adjusting the quality of transmitted video frame.
Hou *et al.* [151]	2021	edge	VANETs	Vehicular Named Data Network; Kalman filtering	To reduce the packet delay and loss ratio in the mobile communication environment.
Hou *et al.* [152]	2021	N/A	VANETs	VANETs; NDN	To tackle the problem of path-breaking during data transmission in vehicular networks.
Wang *et al.* [157]	2022	edge	IoT	NDN; IoT	To solve the resource limitation problem while reducing the data delivery delays and transmission costs.
Yeh *et al.* [153]	2022	N/A	Vehicular Network	VANET; Blockchain	To provide secure vehicular communication service and to realize auditable data transmission records.
Chen *et al.* [154]	2022	N/A	Federated Learning	Dynamic incentive model; Evolutionary game theory	To increase users' willingness to honestly participate in data sharing in federated learning.
Zhang *et al.* [155]	2022	N/A	IoT	Stackelberg game; Smart contract	Improve the overall social welfare and data sharing in IoT scenarios.
Purohit *et al.* [156]	2022	N/A	Financial technology industry	Consortium Blockchain; Cyber defense	To detect and mitigate attacks in could-hosted applications.
Yu *et al.* [158]	2023	cloud	Metaverse 6G	DRL	To design an asynchronous uplink-downlink approach to tackle dimensional discrepancy problem during data transmission, thus obtaining reliable and low-latency DT system.
Yang *et al.* [159]	2024	multi-ends	Metaverse	Alternating algorithm	To investigate the optimal solution for balancing the accuracy of DT and performance cost when transmitting large amounts of data under delay minimization requirements.

intervene at different stages. Therefore, it is crucial to protect data security when multiple parties participate but do not trust each other. For now, the DT security research mainly focuses on the security of communication between physical twins and digital twins and the research on data protection and traceability when different participants in the industrial lifecycle access the DTs. [164] adopts the method named Distributed Ledger Technology and proposes a security design scheme without a trusted third party. The proposal uses the immutability of the original data in the ledger to support data integrity and uses blockchain-based access control scheme to support the issue of confidentiality. As a result, it can meet the R1-R5 data sharing guidelines for safe operation requirements, which are multi-party sharing, support for various data formats, low-latency data sharing, data integrity, confidentiality protection, and support writing.

c) Data Traceability: Data traceability refers to a technology that ensure the data is traceable throughout the whole life cycle. It is considerably important in the DT communication system since it allows you to trace back to the original source, validate the accuracy of the data, as well as guarantee the life cycle events such as data reading, data writing, and authorization [165]. Dominik *et al.* [166] adopt blockchain to achieve data traceability from model-based engineering to after-sales services, describing how to integrate DT and blockchain in the automotive industry to improve the reliability of the supply chain. For the same purpose, Mandolla *et al.* [167] describe the connection at the supply chain level and proposes a DT solution for aircraft component manufacturing by using blockchain. They propose that blockchain can be used to establish a secure and interconnected manufacturing infrastructure to ensure traceability, compliance, authenticity, and component quality control. Nielsen *et al.* [168] demonstrate a conceptual integration between a DT and an Ethereum-based blockchain through the ERC721 token [169], in which DT is applied to ensure that physical asset can be represented by

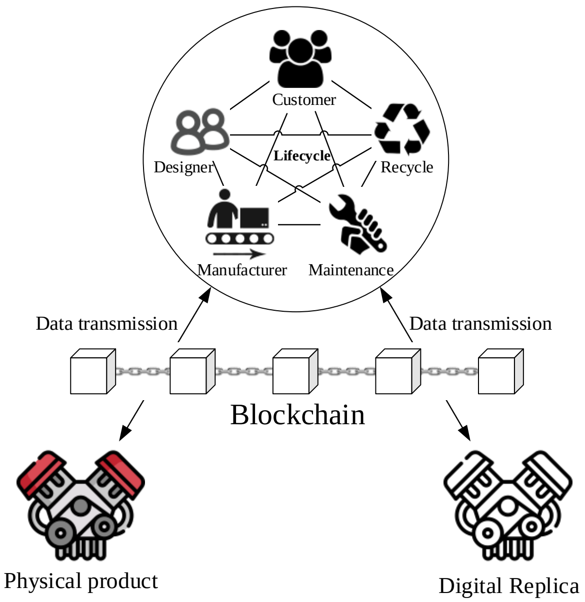

Fig. 12. The structure of blockchain-based data management framework. The blockchain is utilized to build data records for PEs and corresponding DRs to effectively verify data authenticity during the product manufacturing process.

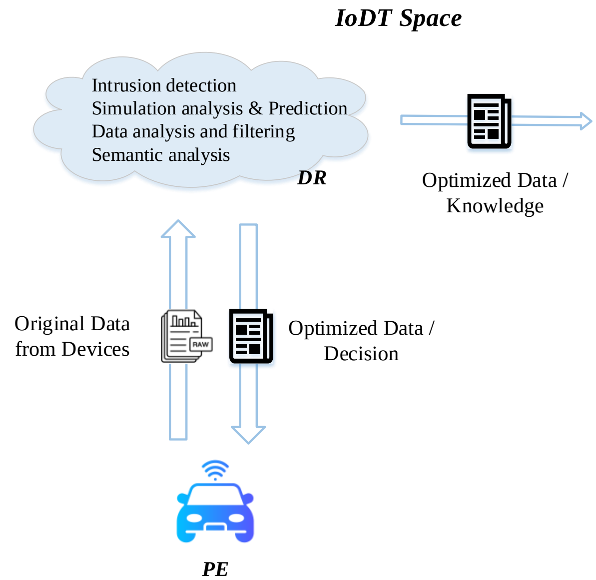

Fig. 13. The security functions of IoDT. The original data collected from PE is transferred to the cloud (*i.e.,* DT space); the corresponding models deployed in DT space can help analyze and digest the raw data, complete a series of tasks (*e.g.* simulation and prediction) in DT space while protecting data security and privacy of PE, and finally return the core knowledge (*i.e.,* decisions and strategies) as optimized data to PE or share them to other DRs in IoDT space.

a unique token without being tampered with. From a macro management perspective, Zhang *et al.* [170] combine IIoT and blockchain to propose a new manufacturing blockchain-IoT architecture named MBCoT, which defines a data- and knowledge-driven DT manufacturing unit and configure a traceable manufacturing system. Huang *et al.* propose a data management method based on blockchain [171], as shown in Fig. 12. This method builds a P2P network that uses the transactions to record all the behaviors of DT between participants. As a result, the authenticity of data can be verified by tracing the history.

2) DT-based Security Applications: In addition to using blockchain and other technologies to enhance the data security level within the DT system in the wireless communication process, a well-designed DT system can also, in turn, protect the physical system. On the one hand, DT technology can be used as a digital carrier of the physical world to provide stakeholders with an environment consistent with reality, and perform security detection and simulating attacks without affecting the actual work process; on the other hand, the digital space can be used as a barrier to block malicious input that attempts to enter the system. At the same time, building a security checkpoint in the digital world can also reduce the cost impact of adding a security layer to the physical device [172], the possible function of DT in Cyber-Physical System can be summarized briefly as Fig. 13.

a) Security Architecture: Designing a security architecture based on DTs is a prerequisite for applying it to improve security performance. To provide a macro perspective for DT-based security in wireless scenarios, Wang *et al.* [173] propose a four-step framework to generalize a proactive analytic for the wide range of attacks. Matthias *et al.* [174] propose a framework for generating DTs based on existing Cyber-Physical System standards and using Extensible Markup Language. Taking safety and security rules as part of the framework, Matthias suggests that security modules such as monitoring, security analysis, and intrusion detection can be added to this framework to protect the system and develop advanced security technologies that require more computing resources. As a related detection method, [175] introduces a new intrusion detection method that uses the Kalman filter to detect attacks and classify the attack types. In the meantime, the deployed intrusion detection system in DT ensures that the achieved remote security testing will not negatively affect the real-time system.

b) Simulation Analysis and Prediction: Another major advantage of DTs is that they can save asset status data for later analysis, optimization, and prediction. For example, by monitoring the real-time state, outliers and changes that could be caused by malicious activities can be detected. By analyzing the relationship between variables over time, possible safety/safety rule violations can be detected [176]. However, if a system is very active, it may limit the framework's ability to check past behaviors. Therefore, a way to store the historical state is proposed, so that the state information or other data of the twins can be switched back and forth by calling the stored input data to conduct comparative analysis and improve the awareness of network situations. Duc *et al*, based on the known security framework [174], present the use of DTs to realize visualization and playback of DT recording states to reproduce specific events and improve network awareness of complex events. In some software manufacturing scenarios, by introducing the concept of Cyber Digital Twin [177], the firmware is transferred to the digital world. Through continuous monitoring of Cyber DT, the potential problems can be solved before the release of firmware in the pre-production phase.

c) Privacy Protection: Besides the above functions, DTs can also be used as a booster for privacy protection. For instance, in the scene of the IoVs, smart cars may expose private data when communicating with connected entertainment and service applications, and each party should have different access rights to data. Therefore, when the DT is introduced, the transmitted data will not be sent directly to the communicating parties but will enter the virtual space first, where the company can build a privacy protection regulation and standard system, such as "General Data Protection Regulation" and "Network Information Services" directives and European-level electronic alarm systems [178]. After the data arrives at the twin, it first conducts a privacy assessment, obfuscates, and replaces sensitive messages to protect personal data, and then sends it to the service party to ensure that privacy is not leaked. At the system architecture level, Kanak *et al.* [179] propose a distributed collaborative DT environment model based on blockchain. This model includes public or private institutions in a DT system and provides the undeniability, security, and privacy protection of blockchain transactions to ensure data integrity and accountability. A review of the representative studies regarding security and privacy protection in DT systems is summarized in Table IX.

E. Key Application Scenarios and Use Cases

In contrast to intra-twin communication, which aims to address specific modeling and task processing challenges, inter-twin communication primarily focuses on a macroscopic perspective, exploring secure and effective ways to foster collaboration and mutual benefits among multiple entities.

Smart City is a concept proposed to solve the worldwide overloaded problems of cities in recent years. It is a perfect practice of IoDT due to the interaction and collaboration of hierarchical and heterogeneous data [187], [188]. Specifically, the smart city is supported by countless information and communication technologies to achieve real-time data communication and generate highly reliable intensive calculations and intelligent strategies. By combining the Internet of Things (IoT), AI, cloud/edge computing, big data, and a series of other emerging technologies to sense, analyze, and integrate key data from the core systems of urban operation, DT-based smart city is able to achieve a high fusion of informatization and urbanization, make intelligent responses to various demands including public security and urban services, and finally promote sustainable development for cities. In this sense, apart from intra-twin communication tasks delineated in Section IV-G, it is imperative to consider how inter-twin communication can be deployed to obtain external data for local tasks while ensuring the privacy of each entity. With the implementation of projects such as "Smart Shanghai" [189] from China and "Smart Nation" [190] from Singapore, smart cities have long become the primary trend of future urban development. The IoDT of the physical city supports policymakers and area developers in making complex decisions about city management. A DR of each sub-entity of the city optimizes the processing of data collection, data analysis, and visualization methods in a virtual smart city and, therefore, lays the foundation for a large-scale application of a smart city.

In line with the advancement seen in smart cities, the widespread use of mobile devices and the evolved computational performance of edge devices have propelled large-scale mobile device communities, such as UAVs, Intelligent Transport Systems, AVNs, and SAGINs into the spotlight as key players in the evolution of futuristic IoDTs. To be more specific, large-scale mobile device systems integrate a variety of different mobile devices (each of the devices may be seen as a PE of a separate DT system) and, therefore, have a broader and heterogeneous database that facilitates more efficient and intelligent decision-making with a big picture of the overarching system. Take AVNs as an example, the introduction of DT technology makes greater progress in environment perception, data processing, and transmission, and promotes the further automation of the overall AVNs. During this process, intra-twin communication takes all the responsibility for conducting computing and results feedback, yet the inter-twin is essential to assist in the realization of the intra-twin's tasks by helping the system capture macroscopic information. Some practical application examples in terms of inter-twin communication are listed as follows.

In [191], fog computing is introduced to construct DT-based autonomous vehicles, allowing a DT-based simulation system to process data-intensive applications near the edge so as to reduce the delay during data transmission. As a powerful adjunct for advanced IoV system, a novel framework is proposed in [192] for edge-computing-enhanced Internet of Vehicles, which uses edge computing-based SAGIN to compensate for the lack of vehicle communication in remote areas, thereby minimizing task completion time and resource consumption. Considering the impact of different weather and atmospheric conditions on SAGIN performance, Nguyen *et al.* [123] propose a UAV-assisted method to ensure high-speed and stable communication of free-space optics link by leveraging additional UAV to reflect the signals from the high-altitude platform. As a new attempt for SAGIN-based IoT, RIS is considered in [193] as a flexible approach to control the signal transmission path. By proposing a sparse Bayesian super-resolution estimation approach, [193] can find a trade-off between transmission accuracy and computational complexity, thus obtaining a spectral-efficient solution with lower cost for SAGIN-based IoT under a 6G environment.

For industry and manufacturing scenarios involving all-around collaboration, Ren *et al.* [194] propose a complex aircraft assembly framework utilizing multiple DTs deployed on edge servers. The DTs are considered heterogeneous simulators among the system and coordinated to optimize resource management throughout the life cycle, enabling minimized energy consumption while ensuring the quality of service (QoS) requirements of the entire system. Committed to establishing a green metaverse with energy efficiency and sustainability, [195] introduces a green metaverse system for the maritime industry, undertaking maritime-related navigation,

TABLE IX
SECURITY AND PRIVACY PROTECTION IN IODT COMMUNICATION SYSTEM

No.	Year	Scenario	Category	Technologies	Objectives
Eckhart *et al.* [160]	2018	Cyber-Physical System	intra-twin	State observers; State machine replication; Intrusion detection	Propose a novel state replication approach that first identifies stimuli based on the system's specification; Demonstrate that attacks against CPSs can be successfully detected by leveraging the proposed state replication approach.
Damjanovic-Behrendt [178]	2018	Smart car	intra-twin	Machining learning; Clouding computing	Design methods for the DT-based privacy enhancement demonstrator that are based on behavioral analytics informed.
Dietz *et al.* [164]	2019	Enterprise asset management	intra-twin	Distributed ledger	Propose a framework for secure DT data sharing based on Distributed Ledger Technology. Examine the applicability of distributed ledgers to secure Digital Twin data sharing.
Mandolla *et al.* [167]	2019	Manufacturing	intra-twin	Blockchain	The author proposed to use blockchain to establish a secure and interconnected manufacturing infrastructure to ensure traceability, compliance, authenticity, and component quality control.
Gehrmann *et al.* [163]	2019	Industrial automation and control system	intra-twin	State replication; Synchronization	Discuss how a digital twin replication model and corresponding security architecture can be used to allow data sharing and control of security-critical processes.
Zhang *et al.* [170]	2020	Manufacturing	intra-twin	Blockchain	This paper combined IIoT and blockchain to propose a new manufacturing blockchain-IoT architecture named MBCoT.
Akbarian *et al.* [162]	2020	Smart factory ICS	intra-twin	State observers; Kalman filter; Proportional, integral, derivative controller	Point out that synchronization between the digital and physical parts is crucial; Propose three different architectures for digital twins.
Eckhart *et al.* [174]	2020	Cyber-Physical System	intra-twin	State replication	Propose a framework that provides a security-aware environment for DTs; Introduce security relevant use cases for digital twins in CPSs and show how security and safety rules can be monitored.
Akbarian *et al.* [175]	2020	ICS	intra-twin	Kalman filter; Swarm optimization algorithm	Developed and evaluated an intrusion detection mechanism for the DT, which can both detect attacks and also classify the type of attack.
Huang *et al.* [171]	2020	Product lifecycle management	intra-twin	Blockchain	This method builds a peer-to-peer network to connect each participant in the product life cycle and solves the data management problem.
Nielsen *et al.* [168]	2020	Manufacturing	intra-twin	Blockchain	The author proposed a conceptual integration between a DT and an Ethereum-based blockchain through the ERC721 token.
Tuegel *et al.* [180]	2021	Product lifecycle management	intra-twin	Blockchain	The author proposes a distributed sharing model and overcomes many challenges related to decentralized data sharing.
Silva *et al.* [177]	2021	Smart manufacturing	intra-twin	Objects simulation	Introduce a new method based on DT to analyze and continuously monitor a firmware to find threats and security vulnerabilities.
Liao *et al.* [181]	2022	Intelligent Transport System; Smart city	inter-twin	Consensus mechanism; Double-auction	This paper presents a blockchain-enabled DT as a Service (DTaas) architecture to ensure a secure and reliable matching between the service level of DT and dynamic intelligent transport system.
Zhang *et al.* [182]	2022	Smart home	inter-twin	Data-centric network	Provide secure device-to-device wireless communication for user-controlled smart home.
Li *et al.* [183]	2022	Autonomous DT system	inter-twin	Blockchain; Provable data possession	To conduct time state verification and integrity checking problem in autonomous DT systems through anonymous and trusted time state information.
Feng *et al.* [184]	2022	VANET; Intelligent transport system	inter-twin	Blockchain	To simulate the real traffic situation in a DT-based intelligent transport system system with blockchain-based data transmission scheme to ensure low average delay and message leakage rate.
Kumar *et al.* [185]	2023	IIoT	inter-twin	Deep learning; Smart contract	By using smart contract-based data transmission scheme, the method can ensure the integrity and security of the data transmitted to the DT model.
Hamad *et al.* [147]	2023	Mobile IoT	inter-twin	End-to-end (E2E) security; Message queue telemetry transport	Provide secret sharing and trust delegation for end-to-end message publish/subscribe.
Gautam *et al.* [186]	2024	VANET	inter-twin intra-twin	Blockchain	Present a blockchain-based data authentication method for VANET, ensuring data compactness and verifiability in both inter-twin and intra-twin communication.

traffic management, sea rescue, underwater pipeline maintenance *etc.* Although industry and manufacturing scenarios primarily utilize DT for simulation and prediction purposes, the necessity to examine data correlations between different devices remains understated. Nevertheless, enhancing system performance through interactions between independent and unrelated data is expected to be a key focus of future research.

In conclusion, despite the in-depth communication and cooperation among multiple DTs open up thrilling opportunities for the evolution of DT systems, which is evident from many survey papers, the exploration and implementation of IoDT in practical research is still in its infancy. Most existing research still struggles to concurrently address studies pertaining to both intra-twin and inter-twin communication. The differences between these two in terms of target problems, the type of data, and potential solutions remain significant challenges in developing IoDT, shedding light on the focal directions for future exploration.

VI. Learned Lessons for Improving IoDT Performance

The integrated utilization of state-of-the-art technologies in IoDT has witnessed the evolution of large-scale intelligent systems in both academia and industry. In this section, we incorporate the aforementioned technical details and distil key insights aiming at enhancing the overall performance of IoDT systems.

A. Joint Communication and Computation Design

Envisioned as an integrated and intelligent communication framework, the communication paradigm and consequent computational design practically permeate all phases in the design of IoDT systems. In light of existing works, the key lessons learned from the perspective of joint communication and computation can be summarized as follows.

1) Joint Optimization Design: In general, the joint optimization design refers to the strategic design that simultaneously coordinates communication and computation resources. As the core component of joint communication and computation design, the key principle here is to fully consider the dependency between communication and computation throughout the entire life-cycle of IoDT systems. In a nutshell, IoDTs are expected to enable ubiquitous data interactions and seamless communication while addressing inter-device resource management issues such as scheduling, resource control, data offloading, *etc.* to guarantee fidelity, synchronization, interoperability, and expandability.

In [88], The authors utilize DT as a digital representation of the real MEC servers for flexible resource allocation tasks in IIoT scenarios. With near-instant monitoring and prediction of the computation state of the MEC server, the new combination of DT and MEC can effectively improve computation performance while reducing resource consumption and operational costs. Nonetheless, although the authors detail a special twinning pipeline for real-time mapping between PEs and DRs, they only consider computation capability as data model for constructing DT systems, while the data required for real-world deployments are much more complex, especially in IIoT scenarios. Aiming at complex aircraft assembly tasks, Ren *et al.* [194] argue that DT is a powerful tool for efficiently allocating limited resources and coordinating large amounts of heterogeneous devices in the assembly process. However, for complex scenarios such as the aircraft final assembly line, whether the computational power of edge servers is sufficient to handle large-scale computational tasks in real applications requires further verification.

Taking advantage of DTs, UAVs, and RIS, Wu *et al.* [83] construct a novel power consumption minimization problem to conduct vehicular communication under highly dynamic environments. Specifically, RIS helps to reconfigure the network environment, UAVs help with poor channel conditions, and DTs predict large-scale changes in dynamics. However, although both online and offline policies are proposed to reduce computation complexity from diverse aspects, the limited battery energy may still be an obstacle in complex and real-time application scenarios. In addition, the placement of RIS and UAVs greatly affects the performance of the system, which may pose additional challenges to the generalization capabilities of the system. In [159], the authors also formulate a joint optimization problem to simultaneously conduct multiple sub-problems such as device scheduling, data offloading, power control, *etc.*, taking into account the energy budget and low-latency requirement of DT in wireless networks. This work investigates the optimal solution for balancing the accuracy of DT and performance cost when transmitting large amounts of data. However, a common problem arises from the fact that such approaches tend to make simplifying assumptions in terms of the wireless channel model, user behavior, network environment, *etc.*, potentially restricting the applicability of the model to cover complex and diversified conditions.

2) Deviation Minimization: The primary advantage of implementing IoDT systems lies in their ability to enable near-realistic simulations and predictions through real-time modeling. Additionally, they facilitate multi-device collaboration by integrating data through inter-twin communication, supporting enhanced performance optimization and decision-making processes. However, achieving the desired performance of IoDT systems requires maintaining a high degree of consistency within the entire system. This introduces another critical challenge, that is, to minimize the deviation or delay between the DRs and corresponding PEs.

Considering uRLLC-based IIoT scenarios, Huynh *et al.* [196] propose an iterative optimization algorithm to jointly enhance the communication and computation performance of the system, with an overarching goal of minimizing DT latency. Similarly, in [197], the authors investigate a fairness-aware optimization problem for DT-based edge computing networks to minimize the total communication latency of the system, taking into account both the offloading latency and DT-caused latency. In [198], the DT framework is also utilized to model and mimic the edge servers for optimized computation offloading schemes, with a fully consideration of both local and edge processing latency, as well as transmission latency. Nevertheless, since varying ways of defining the deviation between DTs and real values may cause a direct

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influence on the latency performance and DT accuracy, how to define this deviation and how to obtain relevant variables need to be further discussed in relevant studies. Leveraging the benefits of lightweight and mobile computing for disaster scenarios, [199] digs into the advantages of DT in terms of low latency and real-time prediction to optimize computation offloading strategies in dynamic environments for disaster scenarios. Compared to the conventional deviation measure approach that assumes it can be obtained in advance, the authors well capture the mapping deviations from certain relations data, yet this deviation may not accurately reflect the dynamics of the deviation by learning only from the historical data, resulting in an inaccurate estimation of the real-world status. To mitigate the negative impact of lacking timeliness data, and to improve the consistency between PEs and DRs, Liao *et al.* [200] argue that the age of information can be an efficient metric to measure data quality in DT-based resource management tasks, thus enhancing the prediction effectiveness of the system. However, although the proposed method shows better performance in joint consideration of signal processing, communication, and computing, whether the minimized age of information leads to insufficient data resources and affects DT consistency needs to be further investigated.

Dedicated to metaverse applications, [201] proposes a MEC-based uRLLC DT architecture to meet the extreme time-sensitive requirements by jointly considering multiple communication, computation, and storage variables, *e.g.*, offloading portions, bandwidth allocation, edge caching, *etc*. In follow-up work, the same team takes DT as a fundamental part of metaverse applications, highlighting ultra-reliability and low latency as two main requirements of DT communication [202]. The paper envisions a novel architecture where the DT services are separately deployed on edge and cloud servers according to the degree of delay sensitivity. However, they assume that the virtual entities can fully represent the physical entities by using uRLLC without targeted consideration of data loss or asynchronous during the mapping process. Yu *et al.* [158] focus on the dimensional discrepancy of the mapping process from 2D real-world images to 3D DTs, designing a novel asynchronous uplink-downlink approach for reliable and low-latency DT-based metaverse. However, the asymmetry degree of data size between uplink and downlink may vary depending on the data type, increasing the computational complexity and the possibility of re-transmission.

3) Multi-tier Computing: To address the two above-mentioned problems, researchers embark on the consideration of separately deploying DRs to distinct servers following the tolerance level of system performance such as latency, accuracy reliability, *etc.*, incorporating multi-tier computing for achieving on-demand resource allocation and scheduling schemes.

With the purpose of real-time monitoring and deployment in smart park scenarios, [131] introduces a federated learning-based DT framework that strives to find the perfect balance between DT deviation and accuracy. This framework is further utilized to represent the real-time status of the vehicles to obtain optimized access scheduling and resource allocation schemes. Although the process of training models separately on the device side and edge side may not be able to accommodate the stringent fidelity and synchronization requirements of DT in highly dynamic and dense scenarios. Gong *et al.* [203] introduce a DT and network slicing-based network virtualization framework for resource allocation in Internet of Vehicles (IoV) scenarios, dedicated to minimizing response times to meet latency-sensitive requirements. The authors pioneered a refined two-level structure for DT, where level-one is responsible for creating DT models of individual participants, while level-two oversees aggregating level-one's models and generating service-oriented slice DTs. However, the proposed method only considers one-lane and unidirectional road conditions to increase the service time for inter-vehicle collaboration.

To tackle the communication reliability and efficiency problems, Liao *et al.* [204] introduce a collaborative cloud-edge-device equipment management framework, where the DT is utilized to collaboratively establish the digital environment for model training, prediction, resource allocation *etc.* The authors raise a loss function and communication cost minimization problem to simultaneously eliminate electromagnetic interference and redundant resource consumption during DT construction. In contrast to conventional DT-based systems, the proposed framework fully exploits the multidimensional computation resources of both cloud and edge servers, albeit complex model aggregation and multi-layered data transmission could exacerbate the data deviation between DT and the physical devices. Holding similar objectives, in [205], DTs are employed to simulate the real state of futuristic edge computing networks, including both the user layer and edge layer information. The configuration, setting, and state information of all the user and edge layer devices are replicated to the DT system in a real-time manner for optimized resource management strategy, guaranteeing ultra-reliable and low latency communications. However, the authors take the deviation of CPU frequency to denote the gap between DT and the true value, with the assumption that such data can be obtained in advance, potentially preventing DT from rigorous simulation of physical network environments. This challenge can also be observed in [206].

B. Deployment of IoDT Systems

The increased availability of computing resources, combined with recent advancements in communication technologies, has greatly supported the flexibility and scalability of IoDT systems deployments on an unprecedented scale. In this section, we elaborate on the possibilities of IoDT deployment in different environments and compare their characteristics and scope of application.

1) On the Cloud: Cloud-based deployment has inevitably become one of the primary deployment approaches with high expectations for its powerful computing and storage capabilities [15], [17], [100], [101], [147]. By centralizing the storage and management of massive data and computing resources, DRs deployed on the cloud can access shared assets from other PEs with greater efficiency to achieve sophisticated simulation and analysis. In [61], Liu *et al.* introduce a cloud environment for a DT healthcare system, guaranteeing a scalable framework to alleviate the burdensome computing and analysis of medical information. Similar setting can also be found in other studies [46], [47], [55], where idle resources are motivated to be shared among DTs with minimal communication cost through cloud servers. In addition, DRs deployed on a cloud server enable inter-twin communication with more efficiency, further strengthening the inter-device collaboration across the overarching system [62], [130]. For example, [62] utilizes a federated learning-based central server, which can be provided by the cloud, to manage local updates for multiple DTs in a collaborative city environment. This framework enables a global view by learning knowledge from multiple ends, improving single DT performance without disclosing private information.

For network selection, cloud-based deployment often necessitates the integration of multiple transmission approaches tailored to the needs of PEs [102]. In smart city or industry scenarios, where large-scale remote data is needed for complex data interaction, wired networks like optical fibre are more suitable for providing high-speed and reliable long-distance data transmission. In [70], Cui *et al.* argue that DTs can, in turn, be beneficial to a dynamic configuration of programmable optical transceivers. Such a proposal not only provides a new perspective for optimized throughput and reduced blocking probability but also proves the existence of bi-directional bonus effects between DTs and communication networks. For data transmission among localized PEs with dynamic requirements (*e.g.*, vehicles or UAVs), wireless networks may ensure desired transmission performance with high reliability and low latency [127]. Additionally, diverse communication protocols may be considered for different scenarios [132], [163], [183]. Take [132] as an example, a DT-based IoT platform is formulated for a smart irrigation system. The physical devices (*i.e.*, soil probe) transmit the collected data to the corresponding DRs through a gateway, where short-range communication protocols such as JSON are mainly considered. For the simulation of the irrigation system, OPC UA protocol is utilized to maintain real-time monitoring and control.

In summary, cloud-based deployment is particularly well-suited for large-scale applications across extensive areas. It does not suffer from the geographical constraints of PEs while enabling more complex and flexible computational and analytical tasks. The variety of network options available in cloud-based deployment offers substantial support for IoDT deployments involving large volumes of data and remote mobile devices. However, transmitting data from PEs to remote cloud servers may incur higher communication latency, which can be exacerbated in highly dynamic environments due to frequent network transitions [158]. Sophisticated resource allocation and deviation minimization strategies [65], as well as network vulnerability detection [177] and data integrity verification [183] are desperately needed as a complement for enhancing the overall performance of IoDT in cloud-based deployments.

2) On the Edge: Edge-based IoDT deployment has arisen as a new paradigm in response to the development and popularization of mobile devices [57], [59], [63], [75], [106]. Taking DITEN as an example, the edge servers are deployed as a supporter of physical entities, significantly boosting the storage and computational capabilities of light-weight physical assets to pre-process and forward data for further analysis [76], [78]. In contrast to cloud-based deployment, IoDT systems deployed on edge servers are more suitable for highly dynamic applications within a limited area [63], [106]. In particular, data interaction and task offloading on edge devices close to the data source reduce the transmission delay caused by intra-twin communication and effectively eliminate the deviation between DRs and the corresponding PEs [79], [86]–[88]. In addition, to further realize a high-level synchronization in dynamic scenarios, semantic extraction can also be considered as an efficient complementary technique to capture key knowledge while reducing the volume of transmitted data [63], [64].

In terms of network selection, edge-based IoDT systems display a higher reliance on wireless communication for seamless interaction as higher mobility and real-time requirements are imposed [53], [54], [91], [198]. For instance, in air-to-ground [199] and metaverse services [201], mobile edge computing coupled with uRLLC emerged as the most widely used architecture, ensuring high accuracy and low latency data transmission while enhancing the data processing capability through the cooperative sensing of multiple edge nodes. In [194], the physical aircraft assembly site interacts with its own DT through an industrial wireless network, *e.g.*, a nonorthogonal multiple access (NOMA)-based wireless network. NOMA dynamically adjusts the allocation according to user demand and is particularly suitable for scenarios such as the Internet of Things (IoT), which needs to support massive device connectivity. 6G is selected in [200] for data communication among heterogeneous devices, coupled with sophisticated resource management strategy to guarantee satisfied age of information in a long period, enhancing synchronization performance of DT systems.

In conclusion, edge-based deployment demonstrates greater advantages in handling high mobility scenarios with real-time requirements such as IoVs [80], [192] and UAVs [199], providing timeliness data interaction and processing capabilities to ensure the synchronization and fidelity of the system. However, such deployment poses additional challenges for IoDT systems. Specifically, due to the limited computing and storage capacity of edge servers, the system is required to conduct resource scheduling [198], [205] and data migration/offloading [58], [59], [88] problems of DRs while PEs travel among edge nodes. In addition, communication interruption or packet loss due to frequent changes on edge nodes can be a new element that affects the reliability of the systems.

3) In the Device: For scenarios that have particular needs for security and privacy concerns, deploying a single DR directly on the device side provides more possibilities for personalized IoDTs. [128] constructs a multi-spectrum communication system to share the sensing data across multiple vehicles collaboratively. The system, considering scattering models for diverse frequency bands, is deployed on each vehicle for accurate DT construction in vehicular scenarios. In such a scenario, PEs may implement seamless data interaction with the DRs through serial peripheral interface or shared memory and maintain a private path with DRs through TLS/SSL or end-to-end encryption.

Such a deployment measure significantly reduces the latency problem, ensuring a higher degree of both consistency and secure link between PEs and DRs. However, DRs hosted in the device may not be able to carry out complex analysis and simulation tasks due to the limited computational resources. Moreover, without communication channels with other DRs, device-based deployment entails additional resources to maintain a brand new inter-twin communication environment, which makes it unsuitable for scenarios requiring continuous data interaction with other DRs. In most cases, in-device DTs often appear as a complementary deployment approach to edge and cloud-based deployment, which we call a hybrid deployment across multiple ends. The details of such deployments are further discussed in Section VI-B4.

4) Across Multiple Ends: An indisputable fact that can be recognized from the deployment approaches is that no single deployment approach can perfectly solve the heterogeneous deployment problem induced by diverse requirements during intra-twin and inter-twin communication of IoDTs. A novel perspective of solution arises from an extensive combination of all the advantages of the three deployment means, leveraging multi-tier computing for deploying DRs on diverse ends [89], [202].

Reviewing existing works in relevant areas, [86] proposes an edge-cloud collaborative framework for DT deployment. The raw data from each node device is collected and processed on intelligent edge devices to eliminate transmission latency. The cloud server is then utilized to calibrate local clocks and further conduct complex computation and data management, guaranteeing the long-term performance of the overarching system. Such efforts can also be found in [178], [181]. Su *et al.* [131] present a three-layer model for a DT-based smart park. The local model of individual entities is first trained on each physical device; the edge server is then utilized to perform heavy computational tasks with the transmitted parameters from local models, gaining global knowledge for an optimized resource management strategy. [159], [170], [185], [195] and [203] provide a packaged device-edge-cloud service architecture for intelligent manufacturing and industry systems. In such a framework, local devices gather and transmit real-time data to edge servers for pre-processing and data analysis in a delay-efficient way. Meanwhile, cloud servers handle high-level services that require significant computational and storage resources but can tolerate higher latency.

Wireless communication is dominant in the network selection of such hybrid deployment scenarios, although flexible and heterogeneous usages can be observed. 5G and beyond are often adopted for SAGINs, IoVs, and UAVs, in which dynamic devices may frequently be involved [203]. Due to the diversification of devices, [129] depicts a DT-based healthcare monitoring architecture where two separate ecosystems are constructed. For wireless devices within the system, 802.11 AP and wireless network card are utilized as the transmitter and receiver, respectively, for status monitoring and fall detection. The wearable devices, on the other hand, are responsible for collecting and displaying the ECG signal for atrial fibrillation detection. Noted, data authentication problem should also be considered since open communication channels may raise security and privacy concerns in such heterogeneous networks [186].

In conclusion, the innovative design of combining multiple deployment approaches complements sophisticated IoDT scenarios, offering promoting solutions while compensating for the shortcomings of aforementioned deployment approaches in terms of efficiency, stability, reliability, *etc.* It is particularly suited to complex scenarios that involve heterogeneous entities such as metaverse, smart cities, and large-scale vehicular networks [43]. However, a case-by-case network selection strategy is essential to meet the diverse transmission requirements of individual devices.

VII. Open Issues and Possible Solutions

The efficient and proper fusion with more technologies, as well as the need for system performance improvement in all aspects stimulates the considerations of open issues faced by futuristic IoDTs. In this section, we summarize the open issues based on the reviewed works and further discuss the potential solutions from a broad sense, a brief summary is depicted in Fig. 14.

A. Data Communication

To realize the full potential of IoDT, greater revolutions in data storage, data accuracy, data consistency, and stability of data transmission are required in both intra-twin and inter-twin communication with diverse emphasis [76]. The most noteworthy areas of concern are highlighted as follows.

1) Intra-twin Communication: In general, the more sophisticated and intelligent an IoDT system is, the greater the data challenges it will face. Spotlighting internal communications that need to be highly consistent, intra-twin communication focuses on solving data transmission and synchronization problems in different scenarios between PE and DR within a single DT pair.

- ***How to support the synchronization requirement of DT pair?*** In an IoDT-based system, a DR is often considered as a broker between its PE and other DRs. With the constant and dynamic connection link, DR contains all the knowledge and knows the history and future demands of the PE, which makes it a key element to be able to communicate and collaborate with other users (*i.e.*, DRs) directly on behalf of its own PE. This is a promising structure to simultaneously ensure the privacy of all users and the efficiency of the system's performance. In such a context, improving the transmission performance of the system to meet the synchronization nature of the DT pair is a key issue in guaranteeing the performance of IoDT. From the perspective of hardware and networking design, a heterogeneous network architecture would be an ideal solution to ensure real-time and fidelity of data transmission in intra-twin communication under different requirements and resource constraints. To be more specific, aiming to provide a higher data transmission

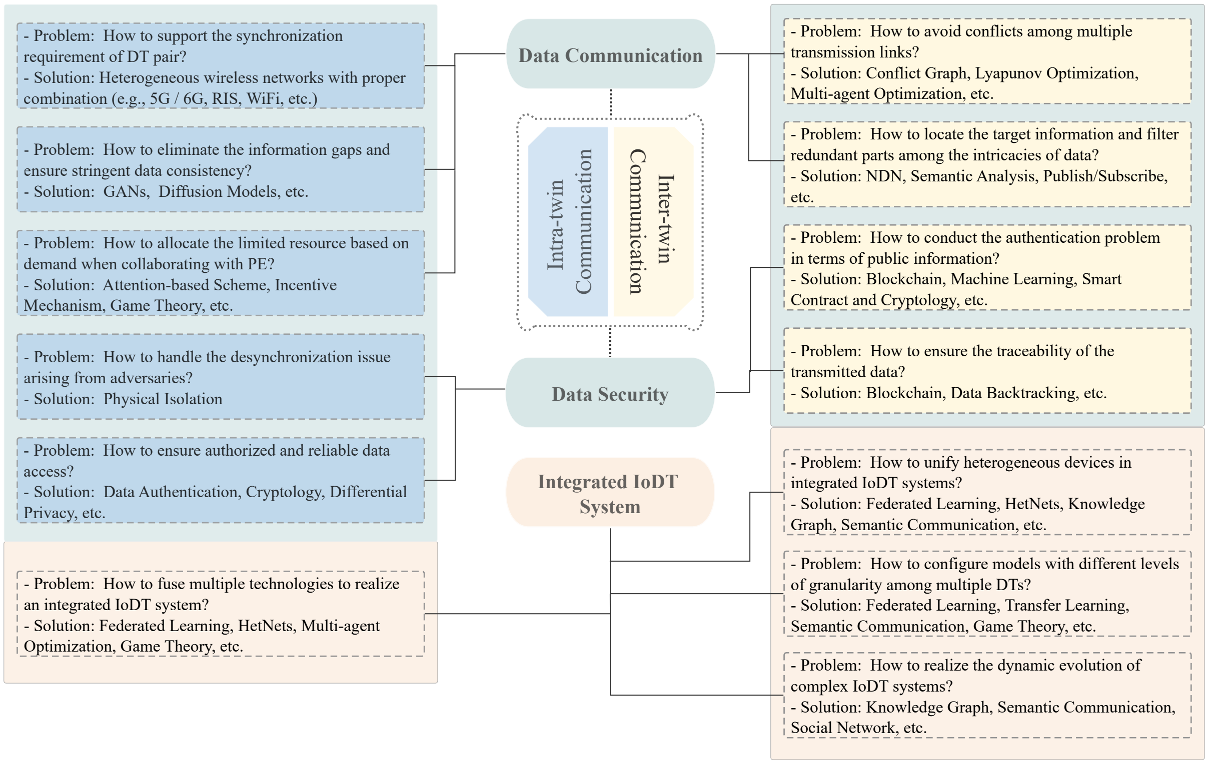

Fig. 14. Open issues and possible solutions.

rate with lower latency, 5G/6G is endowed with great expectations in large-scale futuristic applications with mobile devices (*e.g.*, autonomous vehicular networks, smart cities, remote surgeries, *etc.*) [102], [207]. Targeting DT usage under limited area and shorter-range coverage, Wi-Fi and Bluetooth would be better choices that offer more targeted, point-to-point data transfer, facilitating small-scale data transmission between near-end deployed DR and its PE [208]. Satellite and RIS, on the other hand, are better aligned with the needs of long-distance and complex scenarios such as SAGIN, UAV, and aviation communication, where the primary goal is to avoid data transmission being limited by base stations or other infrastructure facilities and to reduce the interference from other transmission links, rather than latency [117], [123]. Each communication technique has its own strengths and weaknesses, but a proper and comprehensive combination strategy is urgently needed to ensure that each heterogeneous device in a complex IoDT system is assigned to the most appropriate data transmission link, thereby improving the overall communication efficiency and reducing the data gap between PEs and DRs.

- ***How to eliminate the information gaps and ensure stringent data consistency?*** Despite the support of ubiquitous wireless access technologies, it is still quite challenging to guarantee stringent data consistency between PE and DR in dynamic IoDT systems. However, with the long-lasting connectivity nature of intra-twin communication links, it is achievable for DR to utilize learning-based methodologies and predict the transmitted data to eliminate the information gap between the true value of PE and the obtained value of DR and further compensate for the lack of wireless technologies.
In light of this intuition, generative artificial intelligence has received a great deal of attention in recent years due to its high-quality generative capabilities. It has been proven to hold immeasurable promise in supporting sensing and communication tasks within wireless environments [209]. For example, since DR has most of the real-time data held by PE and always holds PE's historical data, the data generated by generative models such as generative adversarial networks have the potential to highly match the actual data, thus better meeting the stringent data consistency requirements of IoDT. The variational auto-encoders, on the other hand, can benefit data transmission and processing in complex scenarios, which is also considered a promising technology to reduce the transmission gap between PE and DR.
Another promising solution for this problem would be diffusion models [210]. Excelling at learning the underlying features and filling in incomplete parts of data, diffusion models are proven to obtain even better results than conventional generative adversarial networks [211] and are well-suited for eliminating data deviation and ensuring stringent data consistency. By filling in incomplete information with generated plausible data. Although little research has been developed on generative models for improving DT performance, interested stakeholders

are encouraged to further investigate the IoDT-based new communication paradigm for next-generation intelligent communities.

- ***How to allocate the limited resource based on demand when collaborating with PE?*** As a digital technology with continuous interaction between PE and DR, the DR can be deployed in multiple locations as needed. In addition, with dynamic application scenarios dominating communication-based research, how to optimize the use of limited resources in highly mobile, lightweight applications is another issue. Attentional resource allocation mechanisms can be an ideal solution for such problems [212]. In general, attention mechanism refers to a cognitive-based technique inspired by the human cognitive attention function, it aims to improve the performance of deep learning models by focusing on the main targets by setting different weights for various parameters. In intra-twin communication, especially for cases with mobile devices, the attention-based scheme would be very useful to allocate limited resources to the primary data transfer tasks. For example, targeting the Metaverse scenario, Du *et al.* [213] leverage attention mechanism to optimize network resources allocation strategy to pay more attention to virtual objects, which can help improve the quality of experience in the next generation uRLLC. In the near future, the optimized performance of intra-twin communication under limited resources, especially in mobile scenarios, deserves further study.

2) Inter-twin Communication: Unlike intra-twin communication, inter-twin communication is responsible for data transmission between multiple DRs. This ultimate goal makes the bandwidth and performance of a single communication link no longer the primary concern of inter-twin communication. Instead, how to precisely locate the available information and achieve accurate transmission among the massively available data contributed by different DRs becomes the primary issue.

- ***How to avoid conflicts among multiple transmission links?*** Focusing on the virtual layer communication of an IoDT system (*i.e.*, the inter-twin communication), the simultaneous stability of multiple efficient and reliable communication links between different DRs is the primary condition to ensure the smooth operation of the overall system. The inter-twin communication bridges the raw data from one DR to another and can receive analyzed knowledge from other DRs to further expand the local knowledge. However, the difference here between intra-twin and inter-twin communication environments is obvious. Data sharing and transmission between different DRs in the same region often need to be performed simultaneously, which leads to conflicts and interferences between adjacent links, resulting in data distortion and packet loss, *etc.* As a result, how to keep as many links as possible at the same time while maximizing resource utilization to empower the cooperation and collaboration of the IoDT system forms the first research question for inter-twin communication. Inspired by traditional resource allocation algorithms, the resource allocation and conflict avoidance of the communication links can be jointly considered to enable a multicast tree under the bandwidth-constrained environment. [137] introduce a joint optimization algorithm to simultaneously allocate limited resources and reduce conflicts among transmission links in vehicular networks, which enables a long-term stable structure for information communication between multiple entities.
- ***How to locate the target information and filter redundant parts among the intricacies of data?*** With the massive data and knowledge constantly updated within inter-twin communication regions (*e.g.*, cloud), the future intelligent system will be required to receive and process a large amount of real-time data. Hence, how to combine existing searching mechanisms to quickly locate target data in a complex information environment while filtering out duplicate or redundant data in different DRs is another challenge for us. The semantic-based method may be the main solution for such a problem. Unlike the original contextual analysis tasks for natural language analysis, the use of semantic-based technologies has been extended to all aspects of structured or unstructured data analysis in recent years, ranging from video, image to sensor data and knowledge graphs [214], [215]. For example, by analyzing the relevant attributes of the target data (*e.g.*, contextual relationships, semantic relationships, attributes, features, *etc.*), semantic analysis can extract core knowledge, meaningful insights, or high-level semantic features according to different types of data, thus facilitating the searching mechanisms to locate target data and filter redundant information [216], [217].

B. Data Security

With the advancement of intelligent agent systems and the digital transformation of enterprises, IoDT has become the best choice to help enterprises successfully achieve an intelligence revolution. However, since the data connection in large-scale IoDT systems is based on network transmission, with the emergence of massive data and deep integration with the Internet, IoDT systems are bound to face severe network and data security challenges. Noted, in this section, we only focus on the security issues that have been paid less attention. For attacks during data communication in IoDT (*e.g.*, data tampering, poisoning, eavesdropping, *etc.*), there is already a large body of literature proposing different solutions, as detailed in Section V-D, which will not be repeated in this section.

1) Intra-twin Communication: With the purpose of imitating the real state of PE in an all-around way based on real-time data sharing and knowledge synchronization, DR holds all the knowledge and history of its PE, which makes it vulnerable and a target for intruders. As a result, the primary objective of intra-twin communication is to solve privacy protection and attack defense problems during data transmission to guarantee a secure communication path for DT pair [133].

- ***How to handle the desynchronization issue arising from adversaries?*** Different from solving the data synchronization problem in communication challenges, the

desynchronization issue refers to a kind of attack behavior launched by external intruders into the DT systems during intra-twin communication [17]. For example, the adversaries can interfere with the synchronization verification process between the DR and PE and further modify the data, thus tricking the DT pair, making both the DR and PE believe that the data has been synchronized in real-time when, in fact, it is not. In [163], the authors provide a secure framework that only allows information to interact with a dedicated GateWay through a specific secure channel, enabling a much easier and secure single relation between PE and DR. For future research, in addition to considering desynchronization attacks on the DR side, people should also consider how to use proper means such as physical isolation to tackle desynchronization attacks against hardware devices on the PE side.
- ***How to ensure authorized and reliable data access?*** Unauthorized and unreliable data access is a type of attack that both intra-twin and inter-twin communication may experience with minor differences. In intra-twin communication, the system tries to maintain all the data interaction between DR and its own PE in a secure manner due to the pervasive privacy information. Therefore, although a continuous and automatic data sharing and transmission link is maintained between the DR and PE, the DR is required to obtain authentication and permission from the PE to activate the link before the first transmission to ensure the correspondence between the DR and PE, as well as form a reliable transmission link. To tackle this problem, Xu *et al.* [218] develop a mutual authentication protocol for intra-twin communication governed by a central authority, allowing a shared secret key to be generated between the successfully paired DR and PE to enable private communication. This paper also proposes a corresponding authentication protocol for inter-twin communication, which will be further discussed in Section VII-B2.

2) Inter-twin Communication: The inter-twin communication is usually used to share public information or data between different DRs in an IoDT. Due to the data interaction of multiple subsystems of IoDT, other than the communication performance, the credit authentication, integrity, and traceability of data have also become important issues in the communication of inter-twin.

- ***How to conduct the authentication problem in terms of public information?*** Although the state synchronization and data authentication in the intra-twin communication can ensure that the data uploaded by the PE is accurate and reliable, due to the selfish nature of the users, the data may still be modified by the owner during the process of inter-twin communication, which may cause significant errors in the data analysis process in the overall system. In addition, the data tampering and distortion caused by third-party attacks during inter-twin communication cannot be ignored. For example, in a DT-based autonomous vehicular network, inaccurate road condition data can lead to a false perception of nearby road conditions, thus further causing biased computational results in path planning, which significantly affects the efficiency of the autonomous vehicle. This problem is solvable by integrating multiple technologies such as blockchain, machine learning, and cryptology *etc*. In Xu's proposal [218], the inter-twin authentication can be realized by a three-stage methodology. Specifically, after passing the central authority's authentication, DR will generate a unique signature coupled with the data to be transmitted together for broadcast in the cloud. To further verify the data integrity, this set of data can only be successfully received after passing the receiver's verification of validity. Another promising solution for this issue is to present a credit score-based smart contract mechanism. In such a mechanism, every user in the system will have a credit score in their smart contract to prove the reliability to other DRs, and each shared or licensed data operation will get the corresponding score. In addition, in order to weigh the interests of different users in the process of sharing data, game theory can be used to further restrict users during inter-twin communication, thereby optimizing the smart contract.
- ***How to ensure the traceability of the transmitted data?*** Trusted traceability provides more possibilities for data verification during inter-twin communication, further ensuring high-quality communication performance for the overall IoDT system. Blockchain is the most widely used technology in this field due to the capability of providing a clear record of data trajectory. Currently, a considerable number of researchers are dedicated to using the traceability of blockchain to verify the data reliability and integrity of DT systems or to build a complete lifecycle of the system [165], [167], [186], but very few have attempted to use this feature to proactively address the attack problem in inter-twin communication from a macro perspective. In future attempts, stakeholders should try to leverage the traceability nature of blockchain to build backtracking data to assist AI models in generating prediction models to avoid being attacked by intruders in advance.

C. Integrated IoDT Systems

In contrast to the conventional notion of DTs as predominantly serving as precise simulators for low-mobility or high-cost physical devices, IoDT systems, as intelligent clusters of multiple DTs, have been observed to have considerable potential to evolve into the new communication framework for forthcoming generations of large-scale intelligent communities. At present, advanced technological developments enable us to have better solutions for a wide range of single-objective problems, ranging from target detection and result prediction to data protection and fault diagnosis. However, as an integrated system that poses higher performance requirements in all aspects, IoDTs possess distinct characteristics in comparison to similar technologies such as multi-agent systems and Avatars.

To elucidate further, diverging from multi-agent systems, which emphasizes collaboration among multiple entities through data communication and interaction, IoDTs markedly focused on comprehending and optimizing both individual entities and the overall system by leveraging real-time simulated data reflecting the intricate characteristics of physical systems. Conversely, as opposed to Avatars concentrating on the digital representation of single physical entities, IoDTs impose higher precision requirements for constructing a comprehensive and integrated digital replica of authentic physical systems. Therefore, despite the apparent alignment in constructing an integrated IoDT system with similar technologies, it poses notable challenges greater than ever before to better integrate various technologies, so that the effect of technologies overlay in IoDT systems is greater than the simple stacking of existing techniques.

- ***How to unify heterogeneous devices in integrated IoDT systems?*** As a powerful and comprehensive ecosystem, IoDTs are implemented by a myriad of devices with diverse environments. These heterogeneities of devices and networks in large and complex systems lead to a notable gap in current mobility management techniques, particularly in their capacity to effectively handle heterogeneous data. Such limitations compromise the ability to meet the seamless communication and collaborative demands intrinsic to IoDT systems. The combination of DTs and enabling technologies illustrated in Section IV and Section V is anticipated to provide a unified platform for cross-system coordination and optimization, overcoming the limitations of conventional techniques in high-density and high-mobility environments. However, in the current stage, DT-based research is still limited to simple scenarios with restricted devices, which is far from satisfactory in achieving in-depth interaction among entire systems. For future research, there is an urgent need for novel management strategies with higher accuracy and reliability to address seamless data transmission and sharing across heterogeneous devices in different environments.
- ***How to configure models with different levels of granularity among multiple DTs?*** To further extend the preceding issue, during the process of system operation, IoDTs often encounter the necessity to concurrently analyze models and corresponding data across various levels of granularity, spanning from macroscopic to microscopic, to obtain a holistic perception of the overall system. For example, a large-scale intelligent transportation system is typically required to fulfill a combination of tasks such as traffic management, environment sensing, pedestrian analysis, and vehicle monitoring, *etc*. Among these tasks, traffic management inevitably encompasses the analysis and prediction of not only macro data ranging from overall traffic flow to road congestion but also micro and detailed information such as traffic signals, on-site data of an accident (*e.g.*, the real-time data of vehicle damage and personal vitals), *etc.*, which are essential for optimizing system performance in terms of route planning, traffic diversion, and management, as well as emergency response. Such data processing and modeling under diverse granularity can significantly upgrade the accuracy of IoDT systems, yet no work has been attempted to thoroughly tackle relevant issues under the existing technological environment. To further evolve the implementation of IoDT systems, it is urgently needed to deeply investigate the functional objectives of IoDTs across all scenarios, decompose the system structure, and further refine the functionalities through delamination, fusion, and nesting of various granularities of models. Integrating unified models with such endeavors is anticipated to substantially mitigate system complexity and ensure fidelity, while improving the synchronization nature throughout the overall system.
- ***How to fuse multiple technologies to realize an integrated IoDT system?*** As a matter of fact, the fusion of multi-technologies is an issue that is worth exploring in various research areas. There are numerous paradigms for technology fusion during the development of IoDT systems. For example, incorporate next-generation wireless networks into edge computing to enhance the real-time requirements of data transmission [84], to reflect the prediction results of faults promptly. Combining big data and machine learning technologies with edge computing [92] is another example. By building an IoDT system for traveller's data, it can recommend the optimal travel plan for users and predict future travel desires. However, most applications are still limited to the integration of only 2-3 related technologies. For the purpose of achieving larger scale and generic model designs, researchers need to consider how to eliminate the technological gaps to accommodate the requirements of standard models in terms of data sharing and interaction methods.
- ***How to realize the dynamic evolution of complex IoDT systems?*** In contrast to conventional techniques that focus on analyzing real-time data to monitor the current state and movement patterns of entities, one of the main advantages of IoDTs is that they incorporate a wealth of historical data and environmental context, coupled with insights into both short-term and long-term goals of entities. These attributes equip IoDTs with the capability to construct real-time mappings and evolutions of physical entities. However, as the system scales up, how to consistently ensure synchronous mapping for DT pairs and continuous optimization of related strategies throughout the system's life-cycle emerges as another challenge in maintaining system performance. Therefore, future research should explore strategies that utilize knowledge graphs and social networks, aiming to offer proactive modeling and data optimization for IoDT systems. Such efforts intend to propel the dynamic evolution of systems while guaranteeing their efficacy in intricate environments.

VIII. Conclusion

Existing survey articles mainly focus on a single DT pair and consider it a simulation approach, in which the DT is only a digital replica of its physical entity and is responsible for simulating in the virtual environment for prediction and efficiency purposes. In this paper, we argue that DTs together can form an integrated collaborative network named IoDT system, facilitating interconnected DTs with more intelligence and automation.

Delving into the fundamental communication modes of IoDT systems, this paper first introduces a functional-oriented taxonomy throughout the entire life-cycle of IoDTs, namely, intra-twin communication and inter-twin communication, respectively. Furthermore, a detailed classification and introduction of enabling technologies as well as applications regarding the two communication modes are delineated. Finally, the improvement and deployment possibilities based on state-of-the-art technologies are also investigated, shedding light on the large-scale implementation of IoDT communities.

In conclusion, IoDTs offer a promising framework to complement the next-generation intelligent societies, especially those consisting of ubiquitous mobile devices. By combining different technologies, it can provide seamless connection and collaboration through shared knowledge among entities in a real-time manner. Despite that, the study of IoDTs is still in its infancy, by further classifying the communication mode and data transmission path, this paper provides a more macroscopic way for researchers to understand the functions and mechanisms of IoDTs from the perspective of data communication, thus contributing to the evolution of next-generation intelligent societies.

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