Chapter 1
Introduction

Abstract This chapter first gives an overview of digital twin, including the development timeline and possible application areas. The features of digital twin are summarized in detail. Then, the concepts, fundamentals, and visions of digital twin are presented.

1.1 Overview of Digital Twin

In recent years, digital twin has emerged as one of the most promising enabling technologies for sixth-generation (6G) mobile networks. Both academic and industry have shown increasing interest in unlocking the potential applications of digital twin in a range of areas, including smart cities, intelligent transportation, healthcare, energy, and Industrial Internet of Things (IIoT).

The overall development timeline of digital twin is shown in Fig. 1.1. The term *digital twin* was first introduced in 2002 by Michael Grieves in a presentation about product life cycle management. Thereafter, Framling et al. [1] proposed an agent-based architecture that maintains a corresponding virtual counterpart or agent for each product item with a faithful view of the product status and information [2]. These works advanced the initial exploration of digital twins from a conceptual point of view. Before 2010, NASA put the digital twin concept into practical application by developing two identical space vehicles for the Apollo project that could simulate and reflect the flight status in training. Since then, the idea of digital twins has been explored in areas such as aircraft maintenance and air force product management [3]. In 2017, Grieves gave the formal definition of digital twin in a digital twin white paper [4]. This white paper presented the basic digital twin model, which consists of physical objects, virtual objects, and a data link between physical space and virtual space. Recently, digital twin has been widely investigated in the areas of the IIoT and manufacturing for applications such as predictive diagnosis, production planning, and performance optimization [5]. Gartner listed digital twin as one of the top 10 strategic technologies in 2017, predicting that millions of things would have digital

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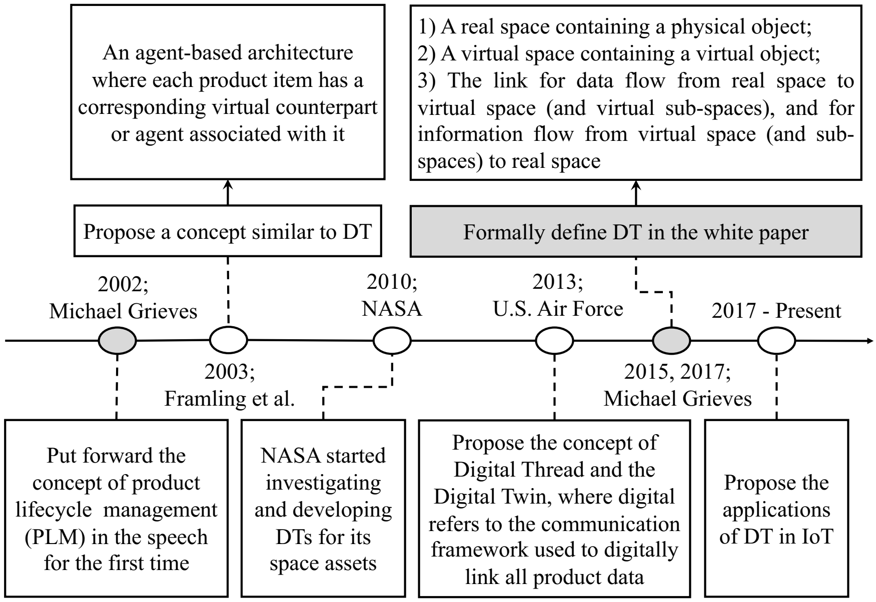

Fig. 1.1 The development timeline of digital twin

twin representations within three to five years. Gartner also listed digital twin as one of the top 10 strategic technologies in the next two years [6, 7], which shows industry's great confidence in digital twin technology. Gartner's top 10 strategic technologies for 2018 are shown in Fig. 1.2, with digital twin listed at the peak of inflated expectations.

More recently, digital twin has attracted a great deal of attention and has been widely explored in aviation, healthcare, smart cities, intelligent transportation, urban intelligence, and future wireless communications. The digital twin fulfils the role of collecting the real-time and historical running status of physical objects and making corresponding predictions and optimized decisions to improve the running performance of physical systems. In the field of aviation, digital twin has been used for aircraft maintenance, structuring, and risk prediction. For example, the authors in [8] proposed leveraging digital twin to model aircraft wings in the detection of fatigue cracks. In healthcare, with the assistance of wearable sensors and Internet of Things (IoT) devices, digital twin can be used to collect detailed physiological status and medication data about patients, which can help to monitor their medical condition and provide them with advanced medical care. In intelligent transportation systems, digital twins can help manage traffic, plan driving paths, and maintain transportation facilities. Real-time traffic conditions and the status of transportation facilities can be mirrored and analysed by digital twins in these transportation systems. Moreover, although the application of digital twins to scenarios of wireless communications is still in its infancy, several works can already be found that introduce digital twin to wireless networks to improve overall performance. For example, in [9], the authors

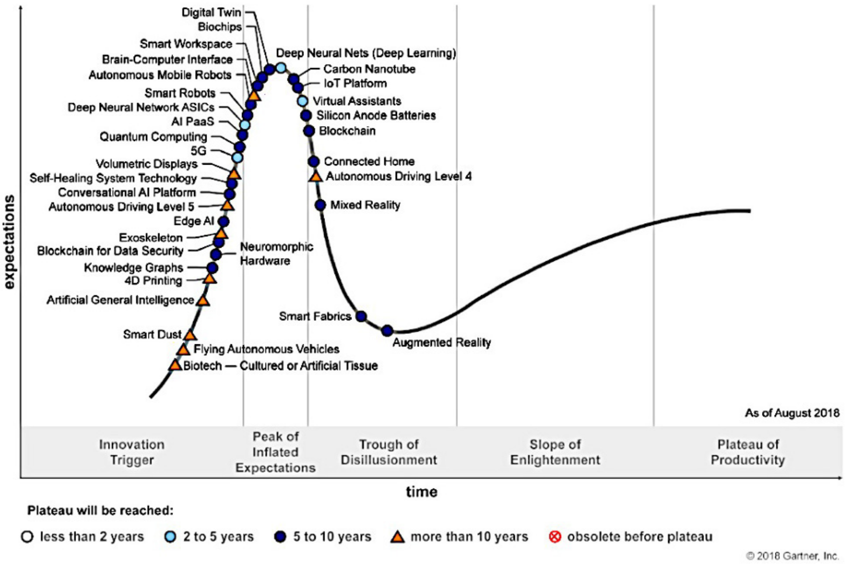

Fig. 1.2 The hype cycle of emerging technologies and digital twin [6]

proposed a new architecture, that is, digital twin edge networks, by integrating digital twins with blockchain to provide secure and accurate edge computing in multi-access edge computing systems.

1.2 Digital Twin Concepts, Features, and Visions

Recent studies have provided a series of definitions for digital twin. In our work, we categorize the definitions into three types: virtual mirror model–based definitions, computerized model–based definitions, and integrated system–based definitions. In the virtual mirror model–based definitions, a digital twin is defined as the virtual representation of a physical product, process, or system [10]. However, in this definition, the interaction between physical objects and digital space is neglected. The status change of physical objects can hardly be reflected by the digital model after its creation. In the computerized model–based definitions [11], digital twins are treated as computerized models, which can be simulation processes or a series of software. The performance of physical objects can be improved through prediction, real-time control, and optimization. In the integrated system–based definitions, digital twins are regarded as an integration of physical objects, virtual twins, and related data [12]. The real-time interaction between physical objects and virtual twins is emphasized in this definition. The virtual twin collects the update information from physical objects and makes corresponding predictions of their future state.

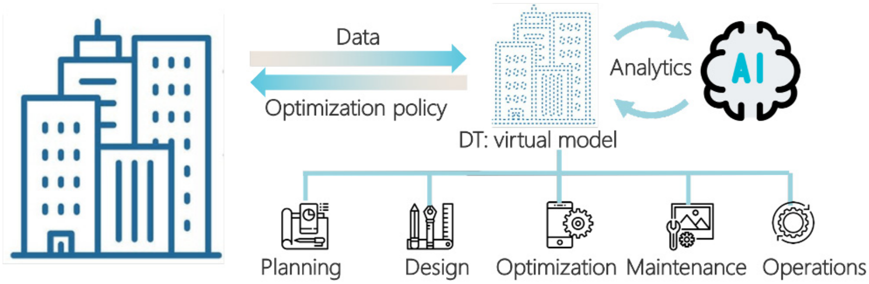

Fig. 1.3 Illustration of the digital twin model

Based on the above analysis, we can give a comprehensive definition of digital twin. Digital twins are accurate digital replicas of real-world objects across multiple granularity levels, and the real-world objects can be devices, machines, robots, industrial processes, or complex physical systems. As shown in Fig. 1.3, the digital twin in virtual space is composed of a virtual model, corresponding running data, and analytical tools. The interaction between real-world objects and digital space is bidirectional: on one side, physical systems transmit real-time data to the virtual space for building digital twin models; on the other, digital twins analyse the collected data, update digital twin models, and provide physical objects with optimization policies to improve their operation performance.

A complete digital twin model consists of three components: the data, the model, and software, as shown in Fig. 1.4.

- *Data, the foundation:* Because the establishment of digital twins relies heavily on historical and real-time running data, data are the foundation of the entire digital twin model. The physical systems contain data, the running principle of the entities, and the controller that can adjust the running of the physical systems.
- *The model, the core component:* The models (both theory models and data-driven models) are the core component of digital twins. The theory models are constructed based on the principles from the physical systems. The data-driven models are trained by collecting the large amounts of historical and real-time running data from the physical systems. A variety of techniques, including artificial intelligence (AI) and data processing, can be used to train the data-driven model. Learning models from data is an iterative process, where the models are trained and updated constantly, as a self-learning process.
- *Software, the essential carrier:* Software is the carrier of digital twins and provides the interface between physical systems and digital space. The digital twin models, composed of algorithms, code, and software, are implemented through developing corresponding software. The functions of representation, diagnosis, prediction, and decision are deployed in a software-defined way that provides the physical controller with optimized command to improve the running performance of the physical systems.

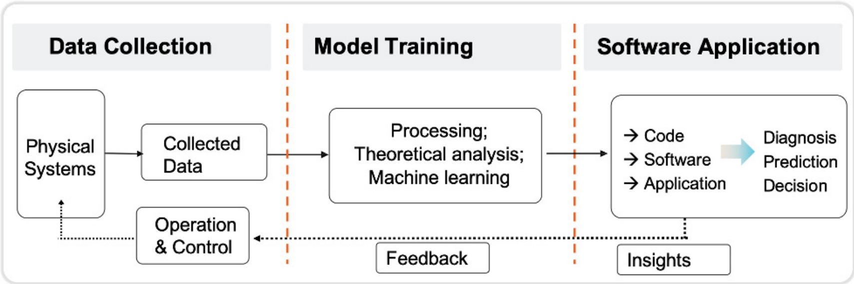

Fig. 1.4 Digital twin: data–model–software

The digital twin provides precise mapping from the physical world to digital space, with real-time interactions. Digital twin mitigates the huge gap between physical space and digital space through continuous synchronization and updates. The features of digital twins can be summarized as follows.

- *Precise mapping*: Digital twin establishes the mapping between physical objects and digital space. The historical data and current running status of physical objects are synchronized to the digital space for further processing and analysis. Based on the transmitted data, digital twins can completely reflect the status of physical objects and establish full mapping between the physical space and digital space. The mapping should completely reflect the full state of physical objects, with low mapping error.
- *Real time*: Different from conventional simulation and modelling technologies, digital twins keep synchronizing with physical objects in real time. The collected data are computed on the digital twin side to extract the corresponding status and build the model of physical objects. Communication is also executed continuously to update the digital twin models. Thus, real-time edge computing should be implemented to ensure the timeliness of digital twins.
- *Distributed*: The physical objects of digital twins can be sensors, IoT devices, and physical systems. In digital twin–assisted wireless networks, multiple physical entities are distributed across the network. The digital twins of these entities are also distributed among different edge servers. In such cases, distributed AI techniques are required to model digital twins from distributed physical objects.
- *Intelligent*: In addition to reflecting the running status of physical objects through real-time data, digital twins also incorporate running models of physical objects. Intelligent techniques, especially AI algorithms, can be used to build digital twin models by processing and analysing the large amounts of running data. With the help of the constructed models, digital twins can provide physical systems with optimization, decisions, and predictions. For example, in intelligent transportation, the digital twin of road traffic can help drivers decide on the optimal

path by analysing real-time traffic conditions and predicting traffic conditions in the near future.

- *Bidirectional*: The interactions between digital twins and physical objects are bidirectional: physical objects transmit and update their running data to digital twins, and digital twins provide physical objects with optimization decisions. The real-time feedback from digital twins to physical objects is one of the unique characteristics of digital twin technology.

Digital twins can provide physical systems with the following benefits through optimization, prediction, and automation processes.

- *Higher performance:* Digital twin can improve system performance through making optimal decisions and executing operations to adjust and control the running of physical systems. In addition, the planning and design of physical systems, such as industrial equipment and healthcare products, can be implemented by using a digital twin to simulate the real-world running performance. Thus, the performance of physical systems can be improved by using digital twins to collect their real-time data and instruct their further operation.
- *Closer monitoring:* Digital twins should copy the complete status of physical objects. To achieve this, physical objects continuously update their running data at a digital twin server. Digital twin servers can closely monitor physical objects in a proactive way that could not be achieved by human operators or conventional monitoring instruments. Digital twins integrate historical data, real-time data, and predicted data to track past states, monitor the current status of physical objects, and predict future conditions for making optimization decisions.
- *Lower maintenance costs:* By collecting the real-time states of physical objects and systems, digital twins can provide optimal maintenance strategies for executing real-time operations. Conventional scheduled maintenance is usually determined in the design phase of physical objects, which leads to high costs and low maintenance efficiency. Digital twins can perform predictive maintenance based on the real-time status of physical objects, which considerably reduces maintenance costs.
- *Increased reliability:* Digital twins can be used to provide virtual tests or simulations of the running of physical objects or systems. The timely digital twin–assisted assessment can improve the quality of physical objects and enhance the reliability of real-world systems.
- *Lower physical system failure risks:* Certain operations can cause physical system failure, resulting in high loss and damage. Digital twins can provide more realistic and accurate simulations for various operations. The simulated environment provided by digital twins is identical to real-world conditions. Thus, the operations of real-world objects and systems can be precisely explored, simulated, and tested to avoid detrimental impacts on physical systems.

With the aforementioned benefits, digital twins can be applied in a variety of scenarios to enhance physical system performance.

- *Smart manufacturing:* Traditional manufacturing faces the problems of limited production efficiency and long product life cycles. Although historical data and simulation have been applied, non–real-time interactions are involved, as well as the low utility of real-time data. The connection between physical objects and virtual space is the key challenge for smart manufacturing in the era of Industry 4.0. Digital twins can integrate physical systems with digital space by analysing huge amounts of historical and real-time data throughout a product life cycle. The results from digital space can provide instructions to the products and processes of physical space. In this way, operation instructions can be optimized, and the quality and efficiency of the manufacturing process can be improved.

- *Aviation:* Aviation was the first area to apply digital twins to practical scenarios. Digital twin has improved data processing and problem diagnosis in aircraft maintenance, risk prediction, construction, and self-maintenance. The full life cycle status of aircraft can be monitored and evaluated by digital twins through real-time data analysis. Real-time operations, such as for flight routes and predictive maintenance, can be determined and optimized with the help of digital twins. However, some challenges remain to be addressed in this area. Because aircraft need precise control and instructions to ensure flight safety, digital twins should be modeled with high accuracy. However, unreliable communications between physical aircraft and digital twin servers can decrease robustness and increase the error rate of digital twin models, which is one of the critical challenges for digital twin–assisted aviation.
- *Intelligent transportation:* Conventional transportation systems have faced serious problems such as traffic jams and accidents. With the assistance of electronic sensors, data analysis, and intelligent control, digital twins can help to improve traffic management and optimize transportation planning efficiency. Traffic accidents can be effectively predicted and avoided through the real-time monitoring and analysis of digital twins. In addition, digital twins can make optimal maintenance decisions for transportation facilities, based on simulations and evaluations of their usage. However, digital twins also face several challenges in this area. The dynamic and time-varying traffic environment poses critical challenges for establishing accurate transportation digital twin models. In addition, the large amounts of data that contain the running states and information of smart vehicles must be transmitted to digital twin servers. Unreliable communication conditions and high transmission latency increase the difficulty of building perfect digital twins.
- *Healthcare:* With the help of IoT devices, it is possible to establish a digital twin for the human body by using IoT sensors and intelligent monitoring equipment to detect a patient's health condition. The physiological status, medication input information, emotional state, and lifestyle of a patient can be collected and analysed in real time by a digital twin. The full range of medical care can be provided by closely monitoring the patient's status and predicting their future health condition. In addition, digital twins can be used in short-term scenarios, such as in remote surgery. For example, experts can obtain real-time feedback by performing operations on the patient's digital twin and identifying potential emergencies that could occur during real-world surgery. Moreover, digital twins can play an important role in the monitoring, management, and maintenance of

medical devices. However, given the sensitive nature of patient information, the privacy and security of this data must be treated seriously. Emerging technologies such as privacy computing and blockchain have the potential to improve the protection level of sensitive data.

- *6G Networks:* 6G is predicted to realize the visions of global coverage, enhanced efficiency, fully connected intelligence, and enhanced security. With such visions, tremendous amounts of data must be processed at the edge of the network to provide ultra-low–latency services. In addition, security and privacy issues in data processing need to be addressed. The emergence of digital twins opens up new possibilities to address these challenges for 6G networks. Digital twin technology could be used in various ways to improve the performance of 6G networks. For example, in 6G terahertz communication, digital twin can be used to model, predict, and control signal propagation to maximize the signal-to-noise ratio. In addition, the real-time mirror of physical systems can help to mitigate unreliable and long-distance communications between end users and servers in 6G networks. Digital twins can bridge the huge gap between physical systems and digital space in 6G networks, which can enhance the robustness of wireless connectivity and the intelligence of connected devices. Moreover, network facilities, such as mobile cell towers, can be monitored, planned, and maintained by using digital twins to simulate and evaluate their real-time status.

1.3 Book Organization

This book aims to provide a comprehensive view of digital twin, including fundamentals, visions, and applications. As an emerging technology, digital twin will play an important role in various fields, including manufacturing, transportation, and future networks. However, the high requirements of digital twin, such as ultra-low latency, huge amounts of data transmission, and distributed processing, pose new challenges to the implementation and application of this technology.

To help us confront these challenges, this work provides a comprehensive theory of digital twin and discusses enabling technologies and applications of this paradigm. We first present the fundamental principles of digital twin, including concepts, architectures, features, and visions. Next, we provide digital twin modeling methods and digital twin networks. We also discuss a number of enabling technologies for digital twin, including AI, edge computing, and blockchain. Moreover, we discuss research opportunities for digital twin in the emerging scenarios such as 6G, unmanned aerial vehicles, and Internet of Vehicles. This book is organized as follows. Section 2 presents digital twin models and digital twin networks. Section 3 discusses the use of AI in digital twin, including deep reinforcement learning and federated learning. Section 4 describes the integration of digital twin with edge computing and presents in detail the new architecture of digital twin edge networks. The application of edge intelligence for digital twin is also introduced. Incorporating blockchain into digital twin is discussed in Section 5. Section 6 details the application of digital twin in 6G networks. Finally, Sections 7 and 8 describe the application of digital twin to unmanned aerial vehicles and Internet of Vehicles.