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A Novel Cloud-Based Framework for the Elderly Healthcare Services Using Digital Twin

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ABSTRACT With the development of technologies, such as big data, cloud computing, and the Internet of Things (IoT), digital twin is being applied in industry as a precision simulation technology from concept to practice. Further, simulation plays a very important role in the healthcare field, especially in research on medical pathway planning, medical resource allocation, medical activity prediction, etc. By combining digital twin and healthcare, there will be a new and efficient way to provide more accurate and fast services for elderly healthcare. However, how to achieve personal health management throughout the entire lifecycle of elderly patients, and how to converge the medical physical world and the virtual world to realize real smart healthcare, are still two key challenges in the era of precision medicine. In this paper, a framework of the cloud healthcare system is proposed based on digital twin healthcare (CloudDTH). This is a novel, generalized, and extensible framework in the cloud environment for monitoring, diagnosing and predicting aspects of the health of individuals using, for example, wearable medical devices, toward the goal of personal health management, especially for the elderly. CloudDTH aims to achieve interaction and convergence between medical physical and virtual spaces. Accordingly, a novel concept of digital twin healthcare (DTH) is proposed and discussed, and a DTH model is implemented. Next, a reference framework of CloudDTH based on DTH is constructed, and its key enabling technologies are explored. Finally, the feasibility of some application scenarios and a case study for real-time supervision are demonstrated.

INDEX TERMS Digital twin, elderly healthcare, personal health management, cloud computing, precision medicine, interaction, convergence.

I. INTRODUCTION

According to the latest statistics from the United Nations Department of Economic and Social Affairs, the elderly population is forecasted to be 2.1 billion in 2050, with the aging population in the developing regions growing faster than in the developed regions [1]. In the aging society of the future, it is projected that nearly 50% of medical resources will be used for the elderly healthcare, which poses a major challenge for the allocation of limited medical resources [1]. Currently, the health threats of the elderly mainly focus on chronic diseases [2] such as hypertension, stroke, diabetes, cancer and respiratory diseases.

Generally, chronic diseases have characteristics of high incidence, long duration, variety, and are more difficult to cure, especially when accompanied by complications. In addition, compared to younger persons, the elderly have weaker bodies, more significant memory loss, and fall more

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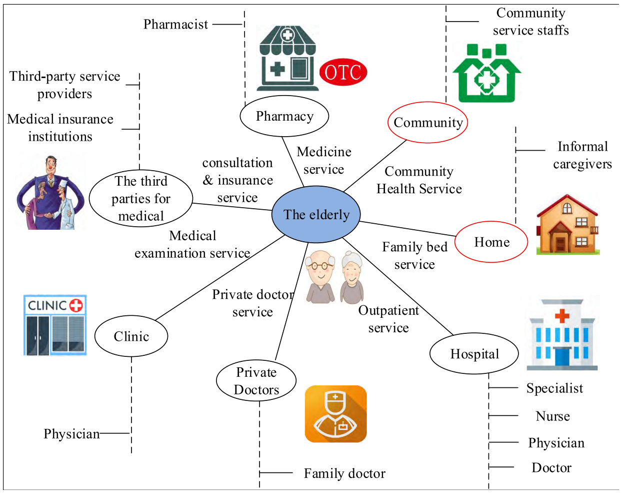

FIGURE 1. Elderly healthcare services demands.

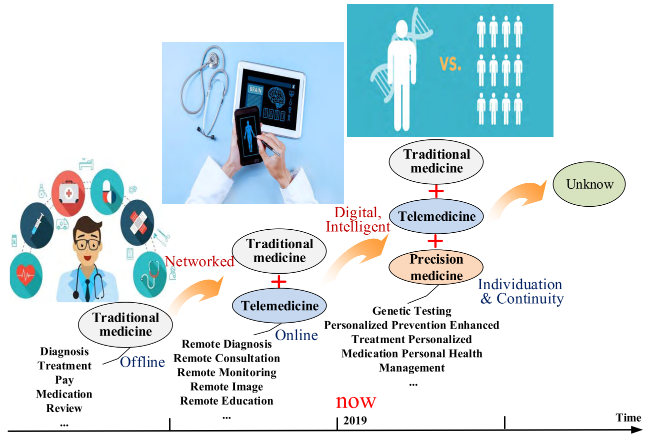

FIGURE 2. The evolution process of medical service.

easily, so they need to be taken care of most of the time. Therefore, as shown in Fig. 1, the elderly have higher demands on a multitude of medical services, especially on community and family healthcare services.

Meanwhile, many elderly persons do not know which types of diseases they have because of reasons such as low visiting rate to medical centers or clinics and low diagnosis accuracy. Hence, they do not have enough knowledge or information about preventing or addressing the medical needs of their chronic diseases. Therefore, they are eager to get regular health consultation and guidance most of time. In addition, the uneven distribution of medical resources results in the ''three long and one short'' situation - long registration time, long waiting time, long payment time and short time of treatment. Consequently, they cannot get opportune consultation or complete treatment by the traditional medical service, and there are still lacking of effective solutions for real-time monitoring, crisis warning, and medical guidance for elderly patients in the entire lifecycle of their personal health management.

For the elderly, the demands for convenient and accurate medical services are increasing rapidly. Along with the computer application technologies, medical technologies are evolving in networking, digitization and intelligence, as shown in Fig. 2. At the same time, based on cloud computing, Internet of Things (IoT), big data, and mobile internet, medical models are evolving from the current medicine mode focused on evidence-based medicine to the precision medicine mode focused on person-specific targeted drugs. In precision medicine, an important goal is to target the disease before it occurs, using, for example, genetics, genomics and smart healthcare monitoring systems. If the disease is unavoidable, then it will be treated in an individual or personalized manner, rather than treatment for the average person as was done in the past. In addition, precision medicine using smart healthcare in a data driven service mode requires a variety of data such as patient data, medical data, service data, and their fusion data. The net result of these evolutions is that the new medical service mode is shifting to an individual and continuous healthcare service mode, and more intelligent medical systems and platforms are being built to realize personalized data-driven smart healthcare.

Currently, most researches and commercial applications mainly focus on the following aspects of intelligent medical systems.

(1) Platforms: Adopting hierarchical distributed architecture to make information sharing and management easily available through ''centralized'' platforms, and to do implementation of rapid and flexible deployment through ''distributed'' platforms.

(2) Business model: Changes in the medical business model brought by cloud computing, such as cloud medical services and cloud health imaging services, which reduce overall construction costs and increase utilization rate of resources.

(3) Standards: Using a combination of international standards, national standards and local characteristics to achieve personalized innovation.

(4) Interoperability in Health IoT: Using IoT and mobile internet in health IoT to achieve interoperability of the medical devices, and to improve the monitoring and alerting capabilities of wearable devices [3]–[6].

Despite advances in intelligent medical services, the following four problems persist.

(1) There are no routine real-time interactions between medical institutions and patients.
(2) True fusion of medical physical systems with information systems is not yet implemented.
(3) The accuracy of crisis warning service for elderly patients is not high enough, and there is no intelligent supervision, including intelligent monitoring, feedback, and management.
(4) Existing systems or platforms do not provide continuous personal health management services throughout the entire lifecycle of the elderly.

To address these issues, the key is to solve the problem of interaction and convergence between physical space and virtual space in medical field. One effective way is to use the concept of digital twin. Therefore, a new concept for the elderly healthcare in the cloud based on the digital twin is proposed. Then, the conceptual model of digital twin healthcare (DTH) and a DTH model are constructed in order to implement the services such as real-time monitoring for the elderly. In order to facilitate computation and effective management, a reference framework of the cloud health system based on digital twin healthcare (CloudDTH) is constructed. Finally, how the DTH model enables the individualized healthcare is discussed through a case study.

The rest of this paper is organized as follows. A brief review of related work is presented in Section 2. In Section 3, the concept and an implementation method for DTH are described. In Section 4, the framework of CloudDTH and its key enabling technologies are introduced. Then a case study about digital twin-driven health monitoring for the elderly care is described in Section 5. The conclusions and some ideas for future work are given in Section 6.

II. RELATED WORK

A. CLOUD HEALTHCARE

Cloud computing technology is very suitable for the medical service because of its characteristics of on-demand service, high scalability and virtualization. At present, many publications [7], [11]–[18] have reported on the combination of cloud computing and healthcare, and some papers call this "e-health cloud(s)" [44]. In this paper, it is called "cloud healthcare". Strictly speaking, cloud healthcare belongs to electronic health technology (e-health), but cloud healthcare differs from normal e-health in that it offers new possibilities such as ubiquitous access to medical data, and opportunities for new business models. Also it can alleviate the burdensome task of healthcare information and infrastructure management for health organizations, and minimizes deployment and maintenance costs.

In academic research, a cloud-based medical information service center to provide higher-performance services for primary healthcare institutions was presented in [11]. In [12], a cloud-based medical platform environment was constructed and an intelligent management system was developed, laying the foundation for the redistribution and optimization of medical resources. The design of a cloud-based personal health record (PHR) system health solution that leverages virtualization technology to allow patients to establish lifelong PHR records and share them with stakeholders was reported in [13]. Next, CHISTAR, a cloud-based, interoperable electronic health record (EHR) system that enables semantic interoperability and data consolidation was proposed [14]. In [15], a new cloud platform architecture for pervasive medical services was proposed. This platform processed semi-structured and unstructured heterogeneous physiological data to solve the problem of high concurrency requests with good results. Also, a novel cloud-based pervasive medical system architecture to improve home care for lonely elderly was reported in [16]. A new framework based on cloud and a state-of-the-art architecture that collects data in real time using wireless biosensors for monitoring the health status of patients with chronic diseases was presented in [17]. The privacy of health data is very important. So privacy preserving approaches and the security of health information in a cloud environment were reviewed in [18].

In the practical or commercial area, a personal health management service system named "HealthVault" was developed by Microsoft [19]. Seoul National University Hospital used a cloud-based virtual desktop infrastructure (VDI) to build a hospital-wide private cloud [20]. "Huawei eHealth" published the "Smart Health Cloud Solution" to establish a medical information exchange platform covering multiple medical systems, and pioneered the provision of medical clouds and regional health cloud services in China [21]. In addition, commercial cloud service providers such as Ali Health [22] and Baidu Medical Cloud [24] provide solution services for medical service scenarios such as telemedicine cloud, graded diagnosis and treatment cloud, medical image cloud and cloud medicine.

As described in the two paragraphs above, various cloud medical platforms or systems on information integration, security, medical business models etc., were designed and implemented by both academic researchers and commercial enterprises. However, there are very few cloud healthcare platforms or systems supporting the monitoring and real-time feedback for the elderly to manage their long-term lifecycle healthcare. To address this need, a novel cloud-based framework for the elderly healthcare services using the digital twin is proposed.

B. DIGITAL TWIN

The concept of digital twin (DT) was proposed in 2003 [10], [25]. To date, many researchers have interpreted and studied digital twins [10], [26]–[28]. At present, one commonly used definition from NASA [28] is, "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, etc., to mirror the life of its corresponding flying twin." A digital twin consists of three parts: physical objects, virtual objects, and connected data.

From the description of the digital twin, it has the following characteristics [29]:

(1) *Real-time reflection:* Various types of physical object data should be integrated, and it can keep real-time mapping of physical objects.
(2) *Interaction and convergence:* It exists in and co-evolves with the full lifecycle of physical objects.
(3) *Evolution and iteration:* It can not only describe physical objects, but also optimize physical objects based on the iterative virtual model.

Currently, the digital twin is mainly used in product design and service management, manufacturing, product life prediction, and real-time monitoring of equipment in industry. Also, to our knowledge, there are no research papers or technical reports describing the digital twin concept combined with medical technologies. From the successful applications of DT in the industrial field, it is believed that the DT can also play a major role in the medical field. For example, for medical staff, it can assist researchers do experiments and testing of medicines in virtual patients to reduce risks and costs. Also, based on the digital twin model, medical experts or doctors do not need to see patients in person. They can determine the symptoms and prescribe treatment plans based on various real-time dynamic data from DT models, and optimize treatment options through model iteration on a virtual platform. For medical devices organizations, they can do the real-time monitoring, structural life prediction, and devices management of the medical devices. For patients, the DT can do real-time monitoring of their physiological states through DT models, and feed back their information data to patients or their informal caregivers in real time.

C. SIMULATION IN HEALTHCARE

In the medical field, there are very complex interactions among people, medical institutions and business or insurance organizations. In addition, because of the dynamic and uncertain properties of current healthcare systems that can be regarded as a system of systems (SoS) [30], [31], it is very difficult for us to research the behavior, patterns and laws of healthcare systems with real scenarios. Therefore, modeling and simulation provides a good way to deal with healthcare systems. Specifically, simulations in healthcare such as medical surgery training simulation, and medical auxiliary equipment design simulation, can improve the flexibility of medical research, reduce medical risks and save costs.

At present, research in healthcare simulation mainly focus on healthcare education using virtual reality simulation, healthcare mechanical simulation, resource allocation optimization and business process simulation, and clinical trial simulation, etc. [32]–[37]. However, there are rarely simulation platforms or system for healthcare that focus on research of behavioral laws, service models and intelligent decision-making of the entire healthcare system to support the rapid construction of realistic healthcare simulation scenarios. With cloud computing and lightweight architecture of micro-service technologies [38], simulations can be quickly performed about issues such as regional cooperation, grading diagnosis and treatment (healthcare pathway), resource allocation, business model, cloud healthcare network evolution, and disease prediction in the cloud environment. Such simulations can allow us to achieve improved quality and efficiency of healthcare services in a cloud healthcare system based on DTH. The architecture to achieve this will be discussed later in Section IV.

III. CONCEPT AND IMPLEMENTATION OF DTH

A. CONCEPT OF DTH

With the development of IoT, and CPS technologies, it is easier to perform accurate simulations with multi-science, multi-physics and multi-scale models using data of physical models, sensor data and their operation history. Taking healthcare treatment as an example, the parameter data from healthcare devices can be fed back to the digital models in real time through sensors, thus making it fast to complete the simulation verification and dynamic adjustment. Bringing digital twin into the healthcare field will allow for real-time monitoring of health, as well as prediction of the medical equipment failures. Drawing on Grieves' description of digital twin [10], Digital Twin Healthcare (DTH) is presented next.

DTH is a new medical simulation approach for a medical activity or a medical system to provide fast, accurate and efficient medical services using DT technology with multi-science, multi-physics and multi-scale models. DTH mainly consists of three parts: physical object, virtual object and healthcare data. The physical object may be a medical device or a wearable device for the elderly, a patient, an external factor such as social behavior, weather or government policy influencing their health, or a system consisting of several or all of these unit objects. The virtual object is the medical device model, wearable device model, digital person model, external factor model, and the digital system model, respectively. The healthcare data includes detection data from medical devices or external systems, real-time monitoring data from wearable devices, simulation data from digital models, historical data and medical records from medical institutions, and service data from service platforms or systems that connect the physical and virtual spaces.

The operation mechanism of DTH consists of four main stages. First, accurate digital twin models should be established corresponding to the physical entity objects (unit level object or system level object) by means of advanced modeling techniques or tools such as SysML, Modelica, SolidWorks, 3DMAX and AutoCAD. Second, data connection should be done through health IoT and mobile internet technologies in order to maintain the interaction between physical and virtual objects in real time. Third, simulation is validated by quick execution and calibration to ensure that the model is correct. Fourth, according to the needs and actual conditions, model evolution should be carried out continuously to optimize and iterate the DT models. Then, data from DT models are fed back to the physical objects and the service systems to provide better solutions for elderly healthcare services.

The DTH can play two distinct application roles in healthcare: hospital management and design, and patient healthcare. Using the DTH, different possible solutions can be tested in virtual environments before scheduling and implementing actual changes such as beds' planning, schedules of staff, surgical simulation and virtual drug experiments. For example, a digital twin of a human body can allow doctors to

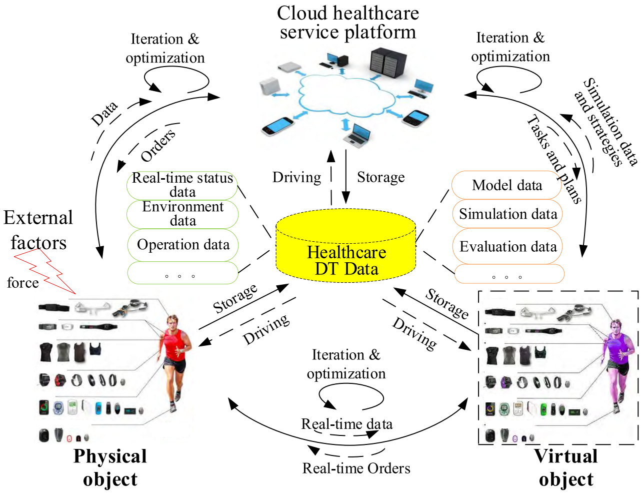

FIGURE 3. Reference model of DTH system.

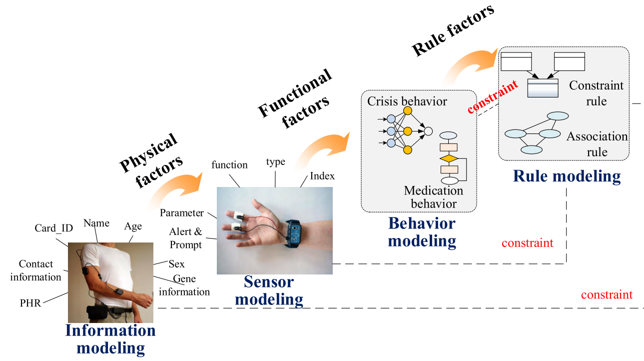

FIGURE 4. DTH modeling process.

discover ailments before they are apparent, experiment with treatments and prepare better for surgeries. Without a DTH, hospital staffs can only rely on their domain knowledge and basic analysis to plan new facilities and new drug treatments, and wait to see their effects. With a DTH, problems can be predicted before they actually occur in patients so as to reduce risks and save costs.

B. IMPLEMENTATION OF DTH

If the physical object is a system that can monitor the elderly in real time and give them important messages, how does this system work based on DTH? Fig. 3 shows the main system components of DTH, composed of the physical object, digital object, cloud healthcare service platform, healthcare DT data, and external factors. The DTH data and external factors are the main driving forces of the system. External factors such as weather or social policy will affect the health and decisions of patients, which in turn affect the digital simulation, and impacts the decision-making from the cloud healthcare service platform, and it is the external driving force. Physical object's data, digital object's data, service data, external factors data, and their fusion data are internal driving forces of the system. The DTH database manages and analyzes real-time status data, environmental data, behavioral data and other data from physical object, and model data, simulation data, evaluation data and other data from digital object, as well as service data, connection data and interaction data from the cloud healthcare service platform.

1) PHYSICAL OBJECT

The physical object mainly consists of physical people and devices such as medical instruments, medical auxiliary equipment and wearable sensors connected to real persons. These units are also able to realize interconnection and interaction among themselves. The dynamic and static multi-source data of physical humans can be collected through a variety of new medical detection and scanning instruments and wearable devices. Data from these unit components from physical people are conveyed to a virtual space in real time, and the physical people then receive orders from the virtual space in real time. However, data from different equipment may be transmitted with different communication protocols and interfaces, which makes it very difficult to access data. Therefore, a uniform interface and protocol should be implemented for facile data integration and data transmission to the virtual space. Then, orders from the virtual space are transmitted to the data interface for protocol conversion to different communication modes of medical equipment and to physical people. The orders are performed to provide messages to physical people and to control the medical equipment.

2) VIRTUAL OBJECT

The modeling process of the virtual object model is illustrated in Fig. 4. The purpose of this modeling process is to monitor the patient's physiological condition in real time with wearable devices, and to give a medication reminder or crisis warning to users. First, the patient's information model is built to describe their age, sex, and their genetic and PHR information. Second, physical properties (physiological information) are given to the sensor to construct the sensor model, which includes parameters type index, alert and prompt. Then, the behavioral models are built to describe the elderly person's actions such as medication behaviors (take more or less pills for a specific disease) and crisis behaviors (falling or stop breathing). Finally, rules of associations, constraints and deductions are modeled to describe the domain knowledge and make the above three kinds of models be capable of evaluating, reasoning and predicting.

The DTH model can be formulated as:

$$\text{DTH\_P\_Des} = < \text{P\_Attr}, \text{Phy\_data}, \text{EF}, \text{Sym}, \text{Sol} > \quad (1)$$

P_Attr contains the following information - name, gender, age and PHR historical information. These data are used as basic information for personal health management. Phy_data mainly includes blood pressure, ECG (electrocardiogram), body temperature and other medical data from medical sensors. EF represents an external factor such as the weather, natural disasters or government decisions that may cause sudden diseases or medical problems of the elderly. Sym means patient's symptoms diagnosed by DTH model, and Sol represents an optimized solution for the patient's symptoms given by DTH model. In addition, to ensure the correctness and accuracy of the models, verification, validation and accreditation (VV&A) should be strictly performed [45] in the lifecycle of modeling and simulation. Finally, model evolution is executed in parallel, and models run synchronously with physical entities through calibration strategies. The evolved models will support more accurate estimation, optimization and prediction for the operation processes.

3) CLOUD HEALTHCARE SERVICE PLATFORM

Demands from physical people include real-time monitoring, crisis warning, disease diagnosis, medication reminder, medical treatment plan pathways and management, which require a quick optimal solution in real time according to the patient's physiological state, the environment and other relevant data to achieve early warning or disease prevention. Meanwhile, demands from virtual people require tests, data mining and plans etc., to support the model evolution and its optimization. These demands or tasks can be decomposed into sub-tasks which only focus on a specific problem such as algorithm selection, model selection, and model selection in the cloud healthcare service platform. Then, according to these sub-tasks, the service platform selects suitable sub-services from the candidate services, and integrates them into a complete service for physical people or virtual people. These services run under the service monitoring mode, and if they worked as expected, are composed to complete the task. The services are transmitted to virtual people models first for verification and then to physical people for execution. Patients can manually select which services they want through their mobile phones or wearable devices. The cloud healthcare service platform can either be developed in a private cloud environment or in a public cloud environment.

4) HEALTHCARE DIGITAL TWIN DATA

Digital twin healthcare data (DTH data) consists of physical objects data, virtual objects data, service data and their fusion data. There are three main data processing tasks work to be performed (Fig. 5). First, data from the physical people and virtual people are collected and transmitted through adapters or data interfaces to the middleware or data base. Physical people data includes data related to disease treatment such as medical examination results, medical images and reports and medical records after diagnosis in medical institutions; data related to health that are acquired by users outside of the hospital with smart healthcare devices such as heart rate, blood pressure, body fat or blood glucose; and data from a third party including medical insurance data and medical consultation data. Virtual people data include data related to digital twin models such as model data, simulation data, and

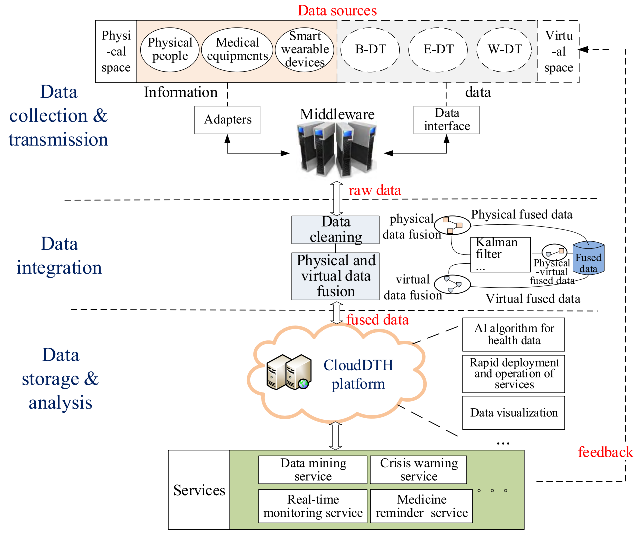

FIGURE 5. The operation of data process.

evaluation data of human body digital twin (B-DT), medical equipment digital twin (E-DT), and wearable devices digital twin (W-DT) models. Second, physical data and virtual data should be integrated through data cleaning and data fusion algorithms (e.g. neural network, Kalman filter, etc.) to ensure data integrity and consistency. Third, fused data are stored in the data center of the cloud medical service platform with a unified data structure. Then, predictions and diagnoses are given in the form of healthcare services such as data mining service, real-time monitoring service and medication reminder service with the help of these stored data and AI algorithms [43]. Finally, the data generated during the service are fed back to the physical and virtual spaces to give important information and to optimize the DTH models.

IV. CloudDTH ARCHITECTURE

A. CONCEPTUAL MODEL OF CloudDTH

With the computing and management capabilities of cloud computing, DTH is combined with cloud architecture to ensure that it can quickly provide high quality services to users. Therefore, a cloud healthcare system framework based on DTH (CloudDTH) is proposed. CloudDTH provides a new healthcare service mode that achieves the goals of decentralized resources sharing and coordination, rational distribution of healthcare services, and large-scale benefits to healthcare institution and patients using the flow activity of healthcare resources, healthcare capabilities and resources. Drawing on the conceptual model used for Cloud Manufacturing [7]–[9], a conceptual model of CloudDTH is presented in Fig. 6. CloudDTH realizes the maximization of the interests of both parties, and enables the rational utilization of resources.

CloudDTH has three main roles: resource provider, platform operator, and users.

1) ***Resource provider*** includes the patients providing patient resource (P-Resource), the medical institutions such as hospitals, organizations, and the third parties for

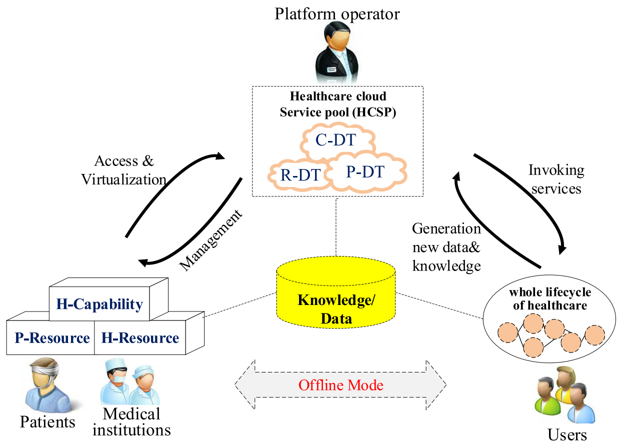

FIGURE 6. Conceptual model of CloudDTH.

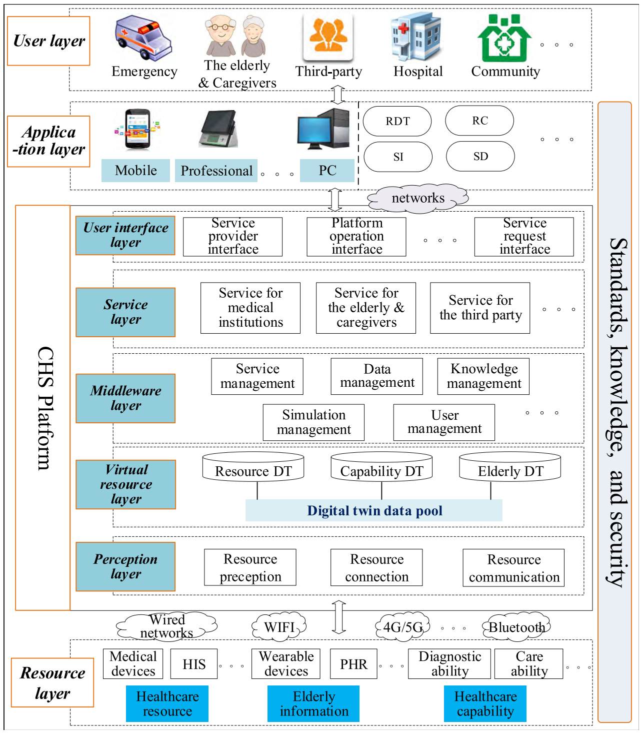

FIGURE 7. The reference framework of CloudDTH.

medical information etc., providing healthcare resource (H-Resource), and healthcare capability (H-Capability). For medical institutions, the resources and capabilities of healthcare institutions such as hospitals, clinics, community health centers and third-party healthcare agencies can be provided to a cloud healthcare platform in form of services using intelligent perception and virtualization access. For patients, personal health record (PHR) and wearable devices of elderly patients can also be provided to the platform in the form of services. At the same time, their DTH models such as capability DT (C-DT) models, patient DT (P-DT) models and resources DT (R-DT) models should also be uploaded to the CloudDTH system by the model developers or model providers among the medical institutions in form of services.

2) The ***platform operator*** responsible for the management and operation of healthcare cloud services.

3) The ***users*** mainly include medical staff, researchers, elderly patients and their informal caregivers.

The service platform is used to dynamically and flexibly provide healthcare institutions with services such as infrastructure construction, regional cooperation, resources sharing and fault prediction. It can also be used to provide researchers, elderly patients and their informal caregivers with services such as a medical pathway plan, surgical simulation, remote diagnosis and treatment, real-time monitoring, health consultation and crisis warning throughout the lifecycle of healthcare management. These services aggregate and form a healthcare cloud service pool (HCSP). New data and knowledge will be generated and fed back to the platform after the services are used.

CloudDTH provides two service modes: offline and online. The online mode generally refers to services such as remote consultation, expert interaction and health consultation which are obtained over the Internet. The offline mode is usually combined with online mode to obtain physical services face to face.

In the CloudDTH platform, knowledge, derived from data, is a key in its operation. Knowledge not only provides support for virtualized access and service encapsulation, but also provides support for cloud-based healthcare service management. And data is also a core driver of digital twins since tacit knowledge can be mined from existing data. This knowledge is used to help healthcare science experimentation and behavioral decision making, thereby providing more precise information and services to physicians and patients.

B. REFERENCE FRAMEWORK OF CloudDTH

In this paper, we present the reference framework of the CloudDTH system, which is supported by cloud computing, health IoT, digital twin and big data. The whole system includes eight layers that are shown in Fig 7. The functions of each layer will be briefly introduced below.

1) RESOURCE LAYER

In this layer, various resources involved in health and public health service activities, including healthcare resources, healthcare capability and the elderly information are provided.

1) Healthcare resource includes two parts based on hardware and software. Healthcare hardware resources mainly refer to professional healthcare equipment such as computed tomography (CT), magnetic resonance imaging (MRI) and physiotherapy auxiliary equipment. Healthcare software resources mainly refer to professional software matched with professional healthcare equipment, as well as health information system (HIS); clinical information system (CIS); electronic health record system (EHR).

2) Healthcare capabilities are formed with diagnostic ability, collaboration ability, rehabilitation care ability, expert knowledge and other intellectual resources (e.g. clinical trials, professional healthcare data and advanced healthcare equipment).

3) The elderly information includes: PHR and wearable devices such as smart bracelets, smart step counters or smart sphygmomanometers, and other smart systems for daily care of the elderly.

2) PERCEPTION LAYER

In this layer, healthcare resources (HR) such as doctors and patients, healthcare devices, and medicines are identified. Then, the data of HR should be collected, classified, and integrated to provide support for CloudDTH, so resources can be intelligently identified and managed. This includes three steps: perception of HR, connection of HR, and the communication of HR.

Perception of HR: Uses radio frequency identification (RFID) tags, two-dimensional code, sensors and other smart sensing technologies to identify objects and their locations.

Connection of HR: Enables resources access to CloudDTH system using 4G/5G networks, satellite networks, cable networks and the Internet, etc., then collects and analyzes the status information of HR.

Communication of HR: Realizes the communication between people, machines and systems utilizing communication technologies such as M2M (Machine to Machine) or M2C (Machine to Cloud).

3) VIRTUAL RESOURCE LAYER

Here, virtualization technologies (e.g. resource virtualization, application virtualization, platform virtualization) are used to upload all kinds of scattered HR into the CloudDTH platform. Different kinds of virtual resources are gathered to form a virtual resource pool, and the virtual resources are encapsulated as cloud healthcare services. This layer mainly includes the process of virtualization and servitization to realize the uniform description, virtualization of the heterogeneous healthcare resources and healthcare capabilities. The virtualization process provides a standard interface to receive inputs and provide outputs for healthcare hardware, software and applications, and healthcare capabilities, etc.

Meanwhile, the virtual resource layer also gathers fully digitized DTH models corresponding to their physical objects, and forms a pool of virtual models of Capability DT (C-DT), Patient DT (P-DT) and Resources DT (R-DT). These models must be verified and validated through verification, validation and accreditation (VV&A) before they are uploaded to the pool, to ensure that they are correct and accurate. Then, this virtual resource layer transforms them into available services. Physical and virtual devices interact by the data in DT data pool to enable full-element, full-service, full-process data integration and convergence of physical devices, virtual models and cloud healthcare systems.

4) MIDDLEWARE LAYER

This layer includes the middleware of service management, data management, knowledge management, simulation management, user management, etc. The service management middleware is mainly responsible for publishing, searching, combining, executing, monitoring and evaluating the QoS (quality-of-services) of the cloud healthcare services. The data management middleware is mainly responsible for the storage, analysis, and transmission of medical data. The knowledge management middleware is mainly responsible for the storage, representation, tacit knowledge mining, search and analysis, etc. The simulation management middleware is mainly responsible for the deployment, execution, verification and optimization of the healthcare simulation tasks. The user management middleware provides the functions of user basic information management, user PHR information management and user genetic information management, etc.

5) SERVICE LAYER

The service layer provides users with functional support when they use the cloud healthcare system services, which mainly includes: service for medical institutions, service for the elderly and their caregivers, and service for third parties. Service for medical institutions enables the institutions to get the elderly information, send health advice to the patients, and do simulations for resource allocation. Services for the elderly and their caregivers including family members, enables them to get the services of real-time monitoring, crisis warning and medical guidance, etc. Service for third parties enables the insurance company, the third healthcare service platform or the government, to get the billing information, and guarantee the safety of healthcare services fee payment, quick payment, and other related functions.

6) USER INTERFACE LAYER

This layer includes the service request interface, service providing interface and platform operation interface. These interfaces provide interactive support for service provision, service request and platform operation. The service request interface provides functions or updates for healthcare institution and patient requests. The service provider interface also provides the required service port to the healthcare institution or patient platform operation, enabling the human-machine interaction interface for remote operation or remote diagnosis and treatment.

7) APPLICATION AND USER LAYERS

The application and user layers provide specific healthcare services, support efficient coordination of multi tasks, and allow users to interact with CloudDTH platforms by using different terminals, e.g. mobile phone, personal computer (PC), and medical professional terminals. The application services include: remote diagnosis and treatment (RDT), health consultation (HC), regional cooperation (RC), sharing and interconnection (SI), simulation and decision-making (SD), real-time monitoring and crisis warning. The users include the elderly and their caregivers, health service community, emergency centers, hospitals, clinics, third-party healthcare institutions, banks and government departments.

8) SECURITY SYSTEM

The security system is responsible for ensuring security in all layers in the CloudTH system. This includes system and platform security, network security, healthcare data security, the user's personal privacy and information security [23], application security and security management. Security is vital to prevent malicious attacks from third parties, theft and tampering of the information and data. The security system ensures that the entire smart healthcare system has the ability of disaster recovery backup, emergency response, monitoring and management and other security functions.

9) STANDARD SYSTEM AND SPECIFICATION

In addition to the eight layers described above, the standard and system specification module are also needed. This includes: electronic healthcare records and health records of information exchange standards (e.g. HL7 and IHE), healthcare information sharing standards, health standards system, and standardized management of the system. This is to guarantee the standardization of healthcare data collection, data sharing and exchange, and the application service management.

C. KEY ENABLING TECHNOLOGIES FOR CloudDTH

The key enabling technologies involved in the construction of CloudDTH platform can be classified to the following six parts described below in Fig. 8.

1) HEALTHCARE RESOURCE ACCESS

Related technologies include health IoT [3], heterogeneous healthcare resource protocol analysis and data acquisition, and multimodal data fusion and packaging. In particular, health IoT technologies include the intelligent identification technology such as RFID, two-dimensional code identification; wearable device technology; and network transmission technology such as M2M and WiFi.

2) HEALTHCARE DATA MANAGEMENT AND ANALYSIS

For this, various technologies are needed for healthcare data acquisition, multi-granular data planning and cleaning, heterogeneous data fusion, structured healthcare data storage, healthcare data transmission, healthcare big data, healthcare data mining and intelligence analysis. All data need to be identified and tagged.

3) HEALTHCARE DATA SECURITY

Here, the technologies are used for personal privacy and information security (e.g. access control, anonymous generalization, etc.), storage security (storage networking technology, storage backup technology, etc.), payment security (dynamic passwords, digital certificates, etc.), and blockchain (consensus mechanism, encryption algorithms, etc.).

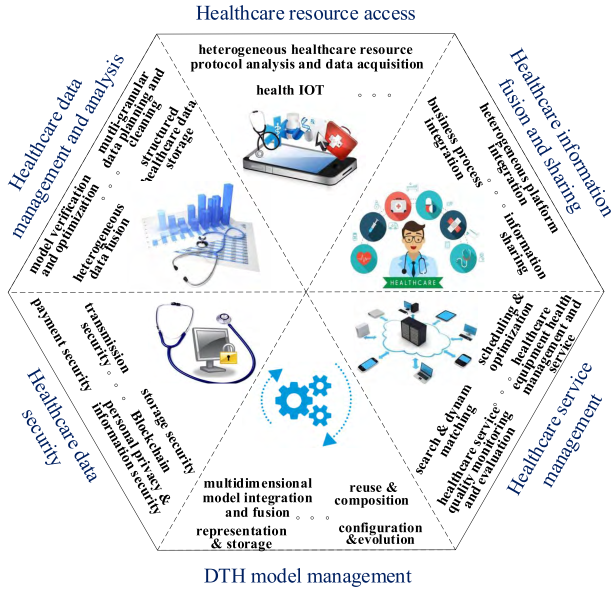

FIGURE 8. Key enabling technologies for CloudDTH.

4) DTH MODEL MANAGEMENT

Related technologies for DTH digital twin models include multidimensional model integration and fusion, model reuse and composition, model representation and storage, model configuration, and model verification and optimization.

5) HEALTHCARE SERVICE MANAGEMENT

Technologies for healthcare service such as for healthcare equipment health management and service, healthcare service quality monitoring and evaluation, service search and dynamic matching, and scheduling and optimization need to be addressed.

6) HEALTHCARE INFORMATION FUSION AND SHARING

Here, information sharing technology, heterogeneous platform integration technology to support HL7, IHE and other multi-protocol specifications and integration specifications; business process integration technology for process reconstruction and management; and information sharing technology including cross-domain healthcare collaboration and information integration should be explored.

D. HEALTH MANAGEMENT IN LIFECYCLE OF THE ELDERLY IN CloudDTH

As shown in Fig. 9, the medical life cycle process of elderly patients generally consists of four parts: monitoring, diagnosis, treatment, and evaluation. In the CloudDTH service platform, a health management file of each individual person is created for long-term continuous management over

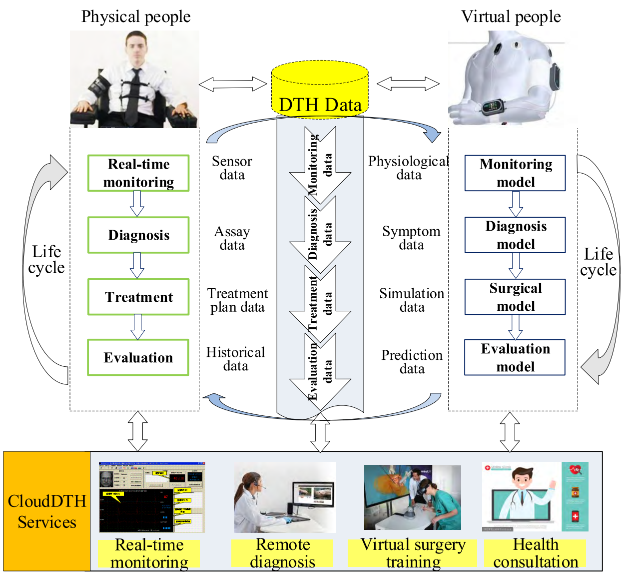

FIGURE 9. Personal health management in the lifecycle of the elderly.

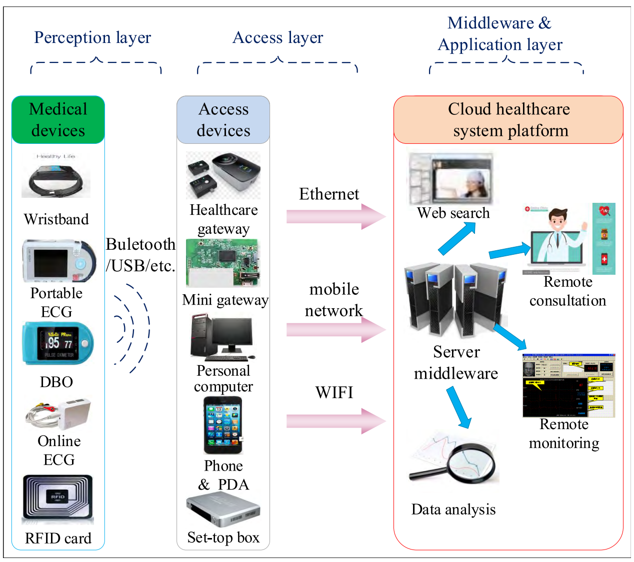

FIGURE 10. Device access architecture.

their entire life. This file data is derived from the DTH data including monitoring data, diagnosis data, treatment data and evaluation data. The platform provides services such as real-time monitoring, remote diagnosis, virtual surgery training and health consultation throughout the entire lifecycle of elderly patients for their personal health management.

One example of the stage of real-time monitoring of physiological states is the real time detection if an elderly person has fallen. After analysis of the monitoring model [42], if there is any abnormal data, the model will feedback orders to multiple devices for multi-attribute, higher frequency monitoring. The diagnosis stage is mainly for laboratory testing and medical examination. The diagnosis model will infer, with high probability, any disease of the elderly patient based on symptom data, the patient's PHR and their genomic data. Then, a message is given to doctors to assist them in making the final diagnosis. The treatment stage mainly consists of medication treatment, lifestyle recommendations or surgery. The surgical model provides virtual surgical verification and training, and optimizes the treatment plan and targeted medication or lifestyle recommendations according to the individual patient's condition. The evaluation stage includes health assessments of post-treatment and regular health consultations. Based on the individual's historical and physiological data, the assessment model gives predictions such as the status of rehabilitation and the corresponding probability of what disease they may have.

E. DEVICE ACCESS AND DATA TRANSMISSION IN CloudDTH

When getting the real-time data, CloudDTH platform can be simply divided into three layers - perception layer, access layer, and middleware & application layer, as shown in Fig. 10. The perception layer includes various sensors or devices for measuring human body data, such as ECG (electrocardiogram), blood pressure meter and DBO (dissolved blood oxygen). Our platform has implemented the access to the sensors for ECG, blood pressure, body temperature and pulse. These devices are connected to some adapters such as healthcare gateway, phone or personal digital assistant (PDA) through a short-distance transmission protocol such as Bluetooth or USB. Then, the access layer transmits the sensor data to the cloud server. With the development of IoT, many methods and protocols are used for device access [39]–[41]. They include 6LoWPAN, ZigBee, WiFi, 4G and wired network.

The middleware & application layer provides users with various application services such as user management, data management, data analysis, remote monitoring and remote consultation. In our implementation, the ECG sensor is directly connected to the WiFi module. The transmission control protocol (TCP) is used to transmit the data to a cloud server, as shown in Fig.11. A physical person is connected to the ECG device and they can see their heart rate status information in real time on the website of the cloud server. Accessing different types of sensors using ZigBee, Bluetooth or other protocols to the cloud will be studied in future.

In our work, a simple cloud medical platform called "*Big Data-based Precision Medicine Cloud Platform*" was built. This platform can realize online display of human physiological health data, thereby providing the foundation of data management, data analysis and other functions. Through continuous testing of the user's physiological parameters, and further detection and assessment of risk factors for disease occurrence, the platform applies scientific health management to achieve targeted interventions before the diseases gets worse, and to make accurate predictions, accurate detections and precise treatments.

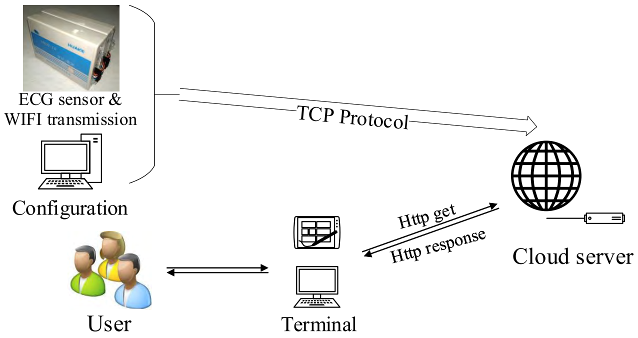

FIGURE 11. Device access implementation schematic.

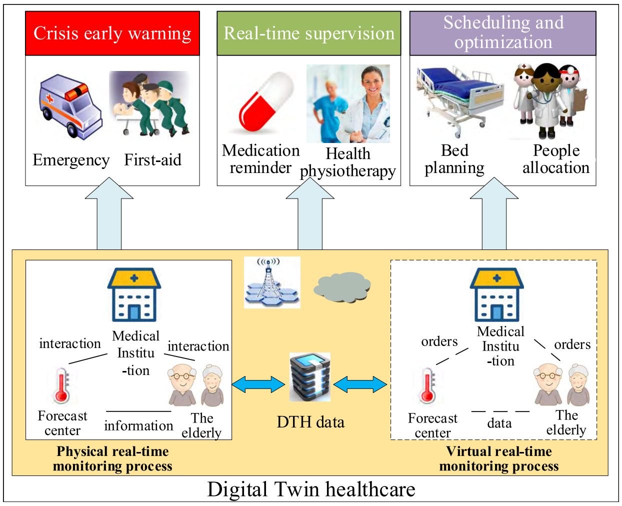

FIGURE 12. Scenario of CloudDTH applications.

V. CASE STUDY

A. SCENARIO OF CloudDTH APPLICATIONS

In this subsection, a possible future healthcare mode will be discussed. As shown in Fig. 12, in this application scenario, DTH includes external factors (e.g. weather), elderly patients (including their wearable monitoring equipment), healthcare institutions (healthcare resources and healthcare capability), corresponding mirror virtual model and DTH data. The DTH data includes real-time weather data (e.g. wind speed and temperature) from weather forecasts, real-time physiological data of elderly patients (e.g. blood pressure, blood oxygen, body temperature) from their wearable smart devices, digital healthcare records from healthcare institutions, and virtual data from digital models. After data fusion, these data will be uploaded onto the cloud healthcare service center. Below, we discuss the specific services of crisis early warning, real-time supervision and resources scheduling.

First, as a crisis early warning service, external environmental factors such as the temperature change, road surface status and wind speed; healthcare records data; and physical sensor data of elderly patients will be transferred to the virtual supervision process module. With the help of modeling methods based on the CloudDTH simulation service, a DTH simulation scenario will be constructed. After that, fast simulation can be done according to a virtual model, and the simulation results will be sent to the healthcare institution, elderly patients and their caregivers. Furthermore, dangerous events such as falling can be predicted through iteration of the virtual DTH model using machine learning algorithms, and these dangerous events signals will be input into the crisis early warning system. As a result, the corresponding healthcare institution, patient and caregiver will be informed so as to quickly schedule healthcare resources or take any required emergency measures. After confirmation of a crisis, the patient's location will be accurately determined to facilitate the emergency measure treatment.

Second, the real-time supervision system receives real-time data such as blood pressure and blood oxygen level values. The virtual model will be repeatedly simulated and evaluated. After iterative optimization, the virtual healthcare model will recommend dosage and frequency of medication according to the EMR system and the PHR data of elderly patients, and will remind the caregiver to monitor the elderly person's health status.

Third, the resource scheduling and optimization service will predict which diseases are in high-incidence in each season according to the physical conditions of elderly patients and weather factors. For planning purposes, healthcare equipment and healthcare personnel will be pre-arranged in order to accommodate the peak demands of elderly patients. The cloud healthcare simulation service can help the DTH mechanism to quickly construct simulation scenarios in order to improve the quality and operational efficiency of healthcare services.

B. CASE STUDY

To confirm the feasibility of real-time supervision service for the elderly based on CloudDTH, an online ECG device (Huake HKW-10) is accessed to cloudDTH platform. First, the server address in a local PC computer is configured, then it accessed the network through the WIFI module that comes with the ECG device. Then, it transmits the real-time data to the cloud medical platform server through the TCP protocol. Second, the data should be pre-processed and visualized in CloudDTH platform, and transmitted to a DTH model for analysis and predication. After data processing, the module of medication reminder will give suggestions to the patient through a display device if there are any abnormal phenomena about them. In our experiment, two volunteers participated in the experiment for simulating normal and abnormal heart rates. The experimental process and results are shown in Fig. 13. The CloudDTH platform server receives the real-time monitoring requirement. Then, after data processing and data analysis according the patient ID, PHR records, and their gene type, the DTH model gave a simulation result that one person had symptoms of arrhythmia, and the medication reminder service is activated. This service gives medication tips such as "you should take anti-arrhythmia drugs to balance your heart rate" to that patient

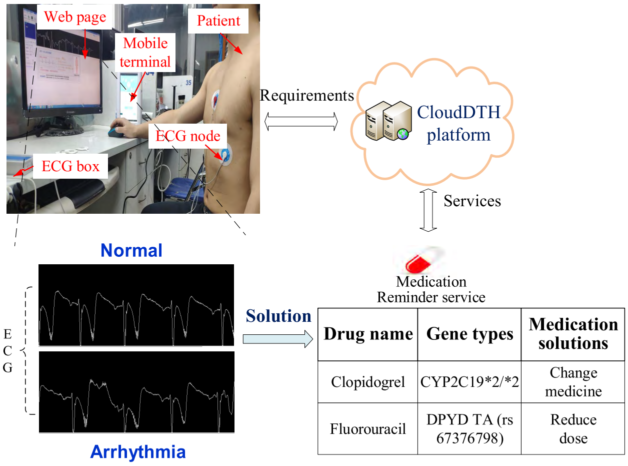

FIGURE 13. The process of real-time supervision.

and their caregivers with a smart terminal, the dosage of medicines is based on their personal physical and genetic condition. For example, one volunteer's gene type belongs to DPYD TA (rs 67376798), so that person was reminded to reduce the dose of the drug named Fluorouracil. Also they had a gene type named CYP2C19*2/*2, which affects the drug named Clopidogrel, so the service suggested that they do not take this medicine. This function reflects that the individualized medication can be achieved in this platform based on DTH.

In addition, to confirm the feasibility of scheduling and optimization service for the elderly, the interaction of emergency patients and routine patients with hospital wards in the emergency situation was also simulated using the system dynamics modeling method with the help of scheduling and optimization service in the CloudDTH platform. Due to external factors such as high temperature, many elderly people need emergency services, and what capacity a hospital can afford needs to be studied through simulation services based on DTH model with the real-time dynamic data. As shown in Fig. 14 (a), this system dynamic model demonstrates the interaction between emergency patients and patients planning to be hospitalized for bed conditions. The reception capacity of the bed is a default parameter, which is related to the size of the hospital. This experiment set the number of beds to 100 and 200, and the horizontal axis represents units of time and the vertical axis represents quantity. The simulated results are shown in Fig. 14 (b). The red line represents the number of emergency patients, represented by the variable PatientsInED, the orange line represents the number of hospitalized patients planned, expressed by the variable emergencyAdmitRate, the purple line represents the number of beds that can be scheduled, represented by the variable ScheduleElectiveAdimssions. When affected by external factors such as high temperatures, the number of elderly emergency patient increases, and the demand for hospital beds increases. At this time, high requirements for the scale and treatment capacity of hospitals and communities are needed. Through

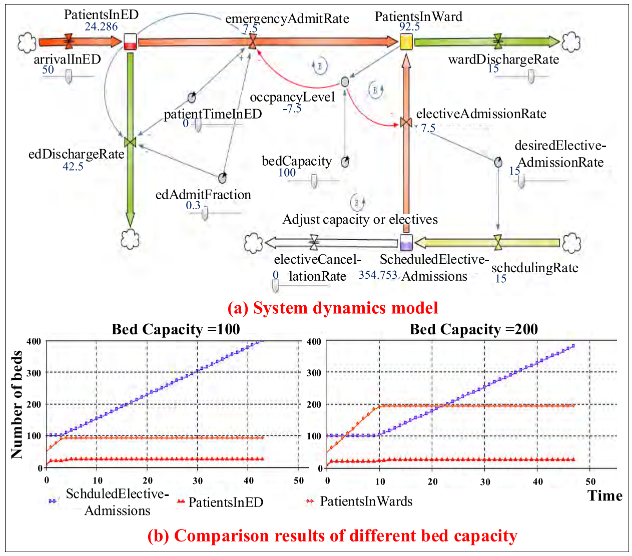

FIGURE 14. System dynamic model and simulation results. (a) System dynamics model. (b) Comparison results of different bed capacity.

this experiment, the number of beds and reception capacity can be adjusted using the simulation module in the platform in order to optimize medical resource allocation for the decision makers. This will help the leaders of the medical field in improving hospital management and design.

VI. CONCLUSION AND FUTURE WORK

At present, technologies such as cloud computing, Internet of Things and mobile Internet are widely used in the healthcare field. However, most research focused on platform concentration and data monitoring, and there are very few publications on real-time supervision or crisis warning for the elderly. The digital twin provides an effective way to solve the bottleneck of information-physical interaction and convergence. When applied to healthcare, the digital twin can provide strong support in cloud healthcare services for the elderly.

The main contributions of this paper are the following. The digital twin healthcare (DTH) was proposed in order to solve the problem of real-time supervision and accuracy of crisis warning for the elderly in healthcare services. Next, the reference framework of CloudDTH was given and a DTH model was constructed. Then, a case study of digital twin healthcare was given to demonstrate its feasibility.

The preliminary results in this paper provided the framework and application methods of digital twin healthcare in the cloud. Our future work will concentrate on the following aspects of our proposed cloud-based framework for digital twin healthcare services - data integration and fusion; quickly building and managing the DTH models; model accuracy verification and model evaluation; collaboration and interaction between machines and between services; and accessing different medical devices and sensors using different protocols to the CloudDTH platform.

REFERENCES

[1] U. N. (2017). *World Population Ageing 2017*. [Online]. Available: http://www.un.org/en/development/desa/population/theme/ageing/WPA2017.shtml

[2] World Health Organization, *Preventing Chronic Diseases: A Vital Investment*, vol. 126, no. 2. Geneva, Switzerland: World Health Organization, 2008, p. 95.

[3] Y. Ma, Y. Wang, J. Yang, Y. Miao, and W. Li, "Big health application system based on health Internet of Things and big data," *IEEE Access*, vol. 5, pp. 7885–7897, 2017.

[4] S. Majumder, T. Mondal, and M. J. Deen, "Wearable sensors for remote health monitoring," *Sensors*, vol. 17, no. 1, p. 130, Jan. 2017.

[5] E. Nemati, M. J. Deen, and T. Mondal, "A wireless wearable ECG sensor for long-term applications," *IEEE Commun. Mag.*, vol. 50, no. 1, pp. 36–43, Jan. 2012.

[6] B. Jin*et al.*, "Walking-age analyzer for healthcare applications," *IEEE J. Biomed. Health Inform.*, vol. 18, no. 3, pp. 1034–1042, May 2014.

[7] B. Li *et al.*, "Cloud manufacturing: A new service-oriented networked manufacturing model," *Comput. Integr. Manuf. Syst.*, vol. 16, no. 1, pp. 1–7, 2010.

[8] L. Zhang *et al.*, "Cloud manufacturing: A new manufacturing paradigm," *Enterprise Inf. Syst.*, vol. 8, no. 2, pp. 167–187, 2014.

[9] L. Ren *et al.*, "Cloud manufacturing: From concept to practice," *Enterprise Inf. Syst.*, vol. 9, no. 2, pp. 186–209, Mar. 2015.

[10] M. Grieves, "Digital twin: Manufacturing excellence through virtual factory replication," White Paper, Jan. 2015, pp. 1–7.

[11] Q. Yao, X. Han, X.-K. Ma, Y.-F. Xue, Y.-J. Chen, and J.-S. Li, "Cloud-based hospital information system as a service for grassroots healthcare institutions," *J. Healthcare Syst.*, vol. 38, no. 9, p. 104, Sep. 2014.

[12] L. Guo, F. Chen, L. Chen, and X. Tang, "The building of cloud computing environment for e-health," in *Proc. IEEE Int. Conf. E-Health Netw., Digit. Ecosyst. Technol.*, Apr. 2010, pp. 89–92.

[13] P. Van Gorp and M. Comuzzi, "Lifelong personal health data and application software via virtual machines in the cloud," *IEEE J. Biomed. Health Informat.*, vol. 18, no. 1, pp. 36–45, Jan. 2014.

[14] A. Bahga and V. K. Madisetti, "A cloud-based approach for interoperable electronic health records (EHRs)," *IEEE J. Biomed. Health Informat.*, vol. 17, no. 5, pp. 894–906, Sep. 2013.

[15] C. He, X. Fan, and Y. Li, "Toward ubiquitous healthcare services with a novel efficient cloud platform," *IEEE Trans. Biomed. Eng.*, vol. 60, no. 1, pp. 230–234, Jan. 2013.

[16] Y.-Y. Ou, P.-Y. Shih, Y.-H. Chin, T.-W. Kuan, J.-F. Wang, and S.-H. Shih, "Framework of ubiquitous healthcare system based on cloud computing for elderly living," in *Proc. IEEE Signal Inf. Process. Assoc. Summit Conf.*, Kaohsiung, Taiwan, Oct./Nov. 2014, pp. 1–4.

[17] A. Benharref and M. A. Serhani, "Novel cloud and SOA-based framework for e-health monitoring using wireless biosensors," *IEEE J. Biomed. Health Informat.*, vol. 18, no. 1, pp. 46–55, Jan. 2014.

[18] A. Abbas and S. U. Khan, "A review on the state-of-the-art privacy-preserving approaches in the e-health clouds," *IEEE J. Biomed. Health Informat.*, vol. 18, no. 4, pp. 1431–1441, Apr. 2014.

[19] A. Sunyaev, D. Chornyi, C. Mauro, and H. Krcmar, "Evaluation framework for personal health records: Microsoft HealthVault vs. Google Health," in *Proc. Hawaii Int. Conf. Syst. Sci.*, Honolulu, HI, USA, 2010, pp. 1–10.

[20] S. Yoo *et al.*, "Implementation issues of virtual desktop infrastructure and its case study for a physician's Round at Seoul National University Bundang hospital," *Healthcare Inform. Res.*, vol. 18, no. 4, pp. 259–565, Dec. 2012.

[21] (Oct. 30, 2018). *Huawei iLab Releases a White Paper to Help Move Medical Images to the Cloud*. [Online]. Available: https://www.huawei.com/en/press-events/news/2018/10/huawei-ilab-whitepaper-medical-images-cloud

[22] (May 4, 2015). *Ali Health: A Revolution for China's Healthcare Industry*. [Online]. Available: https://thediplomat.com/2015/05/ali-health-a-revolution-for-chinas-healthcare-industry/

[23] C.-C. Lee, P.-S. Chung, and M.-S. Hwang, "A survey on attribute-based encryption schemes of access control in cloud environments," *Int. J. Netw. Secur.*, vol. 15, no. 4, pp. 231–240, Jul. 2013.

[24] (Jul. 26, 2014.). *Baidu's Health Cloud Aims to be the App Store for Distance Health Management*. [Online]. Available: https://www.forbes.com/sites/ericxlmu/2014/07/25/baidus-health-cloud-aims-to-be-an-app-store-for-distance-health-management/#765ab4d153dd

[25] M. Grieves and J. Vickers, "Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems," in *Transdisciplinary Perspectives on Complex Systems*. Berlin, Germany: Springer, 2017, pp. 85–113.

[26] J. D. Hochhalter *et al.*, "Coupling damage-sensing particles to the digital twin concept," NASA Langley Res. Center, Hampton, VA, USA, Tech. Rep. NASA/TM-2014-218257, L-20401, and NF1676L-18764, Apr. 2014.

[27] K. Reifsnider and P. Majumdar, "Multiphysics stimulated simulation digital twin methods for fleet management," in *Proc. 54th AIAA/ASME/ASCE/AHS/ASC Struct., Struct. Dyn., Mater. Conf.*, Boston, MA, USA, 2013, pp. 1–11.

[28] E. Glaessgen and D. Stargel, "The digital twin paradigm for future NASA and U.S. air force vehicles," in *Proc. 53rd AIAA/ASME/ASCE/AHS/ASC Struct., Struct. Dyn. Mater. Conf., 20th AIAA/ASME/AHS Adapt. Struct. Conf., 14th AIAA*, Honolulu, HI, USA, 2012, pp. 1–14.

[29] S. Boschert and R. Rosen, "Digital twin—The simulation aspect," in *Mechatronic Futures*. Berlin, Germany: Springer, 2016.

[30] A. Gorod, B. Sauser, and J. Boardman, "System-of-systems engineering management: A review of modern history and a path forward," *IEEE Syst. J.*, vol. 2, no. 4, pp. 484–499, Dec. 2008.

[31] D. DeLaurentis and R. K. Callaway, "A system-of-systems perspective for public policy decisions," *Rev. Policy Res.*, vol. 21, no. 6, pp. 829–837, Nov. 2004.

[32] V. Augusto and X. Xie, "A modeling and simulation framework for health care systems," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 44, no. 1, pp. 30–46, Jan. 2014.

[33] B. P. Zeigler, "The role of modeling and simulation in coordination of health care," in *Proc. IEEE Int. Conf. Simulation Modeling Methodol., Technol. Appl. (SIMULTECH)*, Vienna, Austria, Aug. 2015, pp. IS-5–IS-16.

[34] S. Mende, J. Queiroz, and P. Leitão, "Data driven multi-agent m-health system to characterize the daily activities of elderly people," in *Proc. IEEE Inf. Syst. Technol.*, Lisbon, Portugal, Jun. 2017, pp. 1–6.

[35] M. A. Ahmed and T. M. Alkhamis, "Simulation optimization for an emergency department healthcare unit in Kuwait," *Eur. J. Oper. Res.*, vol. 198, no. 3, pp. 936–942, Nov. 2009.

[36] I. Mohamed, I. El-Henawy, and R. Zean El-Din, "An early discharge approach for managing hospital capacity," *Int. J. Model., Simul., Sci. Comput.*, vol. 8, no. 1, Sep. 2017, Art. no. 1750006.

[37] K. Lee *et al.*, "Modeling and optimizing the public-health infrastructure for emergency response," *Interfaces*, vol. 39, no. 5, pp. 476–490, Oct. 2009.

[38] C. Pautasso, O. Zimmermann, M. Amundsen, J. Lewis, and N. Josuttis, "Microservices in practice, part 1: Reality check and service design," *IEEE Softw.*, vol. 34, no. 1, pp. 91–98, Jan./Feb. 2017.

[39] F. Tao, Y. Zuo, L. Da Xu, and L. Zhang, "IoT-based intelligent perception and access of manufacturing resource toward cloud manufacturing," *IEEE Trans. Ind. Informat.*, vol. 10, no. 2, pp. 1547–1557, May 2014.

[40] S. Majumder *et al.*, "Smart homes for elderly healthcare-recent advances and research challenges," *Sensors*, vol. 17, no. 11, p. 2496, Oct. 2017.

[41] M. J. Deen, "Information and communications technologies for elderly ubiquitous healthcare in a smart home," *Pers. Ubiquitous Comput.*, vol. 19, nos. 3–4, pp. 573–599, 2015.

[42] M. F. Masouleh, M. A. A. Kazemi, M. Alborzi, and A. T. Eshlaghy, "Identification of electrocardiogram signals using Internet of Things based on combinatory classification," *Int. J. Model., Simul., Sci. Comput.*, vol. 8, no. 3, Mar. 2017, Art. no. 1750035.

[43] X. You, C. Zhang, X. Tan, S. Jin, and H. Wu, "AI for 5G: Research directions and paradigms," *Sci. China Inf. Sci.*, vol. 62, no. 2, pp. 021301-1-021301-13, Oct. 2018.

[44] E. AbuKhousa, N. Mohamed, and J. Al-Jaroodi, "e-Health cloud: Opportunities and challenges," *Future Internet*, vol. 4, no. 3, pp. 621–645, 2012.

[45] R. G. Sargent, "Verification and validation of simulation models," in *Proc. IEEE Winter Simul. Conf.*, Baltimore, MD, USA, Dec. 2010, pp. 166–183.

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