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An ISO/IEEE 11073 Standardized Digital Twin Framework for Health and Well-Being in Smart Cities

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ABSTRACT The use of the digital twin has been quickly adopted in industry in recent years and continues to gain momentum. The recent redefinition of the digital twin from the digital replica of a physical asset to the replica of a living or nonliving entity has increased its potential. The digital twin not only disrupts industrial processes, but also expands the domain of health and well-being towards fostering smart healthcare services in smart cities. In this paper, we propose an ISO/IEEE 11073 standardized digital twin framework architecture for health and well-being. This framework encompasses the process of data collection from personal health devices, the analysis of this data, and conveying the feedback to the user in a loop cycle. The framework proposes a solution to include not only X73 compliant devices, but also noncompliant health devices, by interfacing them with an X73 wrapper module as we explain in this paper. Besides, we propose a configurable X73 mobile application, designed to work with any X73 compliant device. We designed and implemented the proposed framework, and the X73 mobile app, and conducted an experiment as a proof of concept of the digital twin in the domain of health and well-being in smart cities. The experiment shows promising results and the potential of benefiting from the proposed framework, by gaining insights on the health and well-being of individuals, and providing feedback to the individual and caregiver.

INDEX TERMS Digital twin, health, well-being, physical activity, standards, ISO/IEEE 11073, X73, wearables, data collection, data analysis, artificial intelligence, user interaction, user feedback.

I. INTRODUCTION

The digital twin concept was proposed in 2002 [1] and referred to the digital replica of a physical object. Although the digital twin has a high benefit to industry, its main uses are industrial processes. A new vision of the digital twin was introduced in [2] to re-define it as a digital replication of a living or nonliving physical entity. By bridging the physical and virtual worlds, data are transmitted seamlessly, which enables the virtual entity to exist simultaneously with the physical entity. A digital twin facilitates the means to monitor, understand, and optimize the functions of the physical entity and provides continuous feedback to improve the quality of life and well-being. A digital twin is hence the convergence

of several technologies, such as data analytics and artificial intelligence, haptics and the Internet of Things, data visualization techniques, cybersecurity and communication networks.

The digital twin, as defined in [2], has multiple characteristics. Other than a unique identifier, the digital twin uses sensors and actuators, which enables it to continuously collect data and renders it an accurate replica of the real twin at any given time, as well as conveys feedback to the real twin. These sensors and actuators can have the form of wearables and personal health devices, which use has exploded in recent years. The wearables market continues to expand, and the high amount of data collected by wearables contains valuable health and well-being information [3] that is mostly unused. With the concept of the digital twin and the structured storage in the cloud of all information that pertains

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to the physical twin, these data will be collected over time and provide very valuable insight on the state of health and well-being of individuals in smart cities, as smart healthcare is among the critical smart city applications [4]. The digital twin technology presents potential solutions to some smart healthcare issues in smart cities, discussed in [5], where the authors discuss the importance of personalized healthcare, efficient data analytics, and interoperability of health data. Indeed, in our approach, the data is collected following the X73 standard, facilitating interoperability. It is then subjected to data analytics as we will discuss later in this paper, and the feedback provided is personalized as it emanates from data collected individually for each citizen.

II. RELATED WORK

A. DIGITAL TWIN FOR HEALTH AND WELL-BEING SYSTEMS

The digital twin started as a concept related to industry and product manufacturing. As reported in a survey of 599 companies conducted by Gartner in August 2018, 62% of companies that use the internet of things are either in the process of integrating the digital twin technology or have it in their plan, and 13% of companies (total of 75%) declared that they are already utilizing digital twins [6]. One of the benefits of this technology is that a certain product has a digital replica that can be manipulated as close as possible to how the physical product would be manipulated but at a substantially reduced cost. One of the survey findings [6] is that the digital twin is applied to a variety of business objectives.

Another survey on digital twins in industry [7] qualifies this technology as one of the most promising technology for smart manufacturing. Research addresses different aspects in the domain of the digital twin. The work in [8] addresses the inefficiencies of cost and production in the industrial technology. The findings suggest the use of a digital twin that represents a synchronized replica of manufacturing components and processes and focuses on gathering tracking data from the past and present and utilizing it for future decision-making. The research in [9] describes a digital twin architecture reference model for cyber physical systems, where every physical thing is connected to a cyber thing via sensors. Other research addresses 3D printing [10] and explains how the digital replica of a 3D printing machine can reduce the cost of printing by lessening the number of trial and errors, which can make the process more time-effective.

The interest in digital twins is increasing in both industry and academia [7]. Limited interest in this concept has been observed in the domain of health and well-being. A search in Scopus, including the title, abstract, and keywords for (“digital twin” AND (wellbeing OR well-being)) returns only 1 research paper [2] that discusses the potential of the digital twin concept for human beings and redefines the digital twin as a replica of any living or nonliving entity. This redefinition introduces the benefits of the digital twin concept to human beings. Furthermore, the domain of health, sport,

and well-being is one of the domains where this concept can make a positive impact.

A search in Scopus, including title, abstract, and keywords for (“digital twin” AND (health OR healthcare)) returns 45 documents. The same query, including title and abstract, in Pub Med returns 0 documents. A search in Pub Med for “digital twin” returns only 4 documents. Many of these publications such as [11]–[13] and [14], discuss the prognostics and health management of components or machines in the industrial process rather than human health.,

However, some of these publications are also related to human healthcare. Some publications are not concerned with the digital twin of a human being; rather, they propose the digital twin of an emergency unit, for example, the system proposed in [15]; the twin of a hospital, such as the work proposed in [16]; or the twin of chain management of healthcare assisting devices, such as the work proposed in [17]. Other research discusses the digital twin in healthcare from an ethical perspective [18] and raises points, such as the potential societal benefits, and the potential inequality due to the notion that the technology may not be accessible for all. Few works related to the health domain propose digital twins for human beings, such as [19] and [20]. Research in [19] proposes a digital twin for the human head to detect carotid stenosis severity, while the work in [20] focuses on a framework to monitor elderly patients and help with possible disease diagnosis or emergency measures that they might need using the digital twin. Both of these systems are implemented for medical use, and literature on a digital twin system to promote individuals’ well-being and sport is lacking.

In this paper, we use the digital twin in its more recent and much broader definition, which considers the digital twin as a replica of any living or nonliving entity [2]. We use sensors for the digital twin as humans use their five senses. These sensors are used by the digital twin to learn as much information as available about the real twin and his or her context. These collected data are then stored in cloud storage, which serves as the “memory” of the digital twin. Data processing by means of artificial intelligence algorithms and data analytics is the mapping for the digital twin of human intelligence. This process enables decision-making and feedback transmission to the real twin. Feedback can take the form of actuation, such as haptic actuation or notifications or manipulation of a home environment to improve the health and well-being of the real twin.

B. ISO/IEEE 11073 STANDARDS-BASED HEALTH SYSTEMS

The explosion of wearable technology and availability of personal health devices to the general public have high potential to make healthcare much more efficient in the near future. This development creates the need for interoperability, which enables more efficient health services and a reduction in the technological complexity. The ISO/IEEE 11073 standards can fulfil this need.

1) ISO/IEEE 11073 STANDARDS

The ISO/IEEE 11073 standards, which are also referred to as X73 standards, are the result of a collaboration between the International Organization for Standardization (ISO) and IEEE. These standards were established when the need for a standard in this domain has never been higher.

The ISO/IEEE 11073 Personal Health Device standards emerged in 2008 to facilitate communication between personal health devices and managers, such as computer systems and smartphones, etc. They are aimed at facilitating health data exchange while providing plug-and-play real-time interoperability. The minimum requirement for personal health devices and managers to be X73 compliant, is to adhere to the X73 communication model. As such, the X73 standards ensure that a health device and a manager that are both compliant, are able to complete the data transfer successfully. The X73 standards do not address security or related challenges such as users' privacy. Some research works propose solutions to these issues given their high importance [21].

X73 standards provide a standardization solution for personal health systems employed by both the research community and the industry. Research using X73 standardized systems is increasing. For example, some research suggests health-related systems to serve persons at their homes using the X73 standard, such as the system in [22], which presents a personal connected health system. Some other systems are mobile and have been designed to remotely monitor people's health parameters, such as [23], which provides fall detection.

2) X73 STANDARDS PERSONAL HEALTH DEVICES

A variety of X73 compliant devices has been included in research. An X73 pulse oximeter was utilized in a mobile Android based system for well-being [24]. A blood pressure monitor was employed in an in-home system [25] to monitor some elderly people who are vulnerable to diseases. Other related research uses X73 devices such as the weighing scale [26], the blood glucose meter [27], the body temperature sensor [28], the ECG [29], the thermometer [30], and the shoe insole [31].

3) X73 STANDARDS USE IN MEDICAL SYSTEMS

Some of the systems proposed in the literature apply X73 personal devices to design medical systems. An example is proposed in [24], where a system was designed to provide patients with medical-care content delivered to their mobile phones. This content varies depending on the patient's profile and their current medical condition. Some research suggests the use of the X73 standard in cardiovascular diseases. An example of these systems is proposed in [32], which investigates issues related to the mobile monitoring of cardiovascular activity and reports its malfunction while preserving the mobility of the patients. Another research that focuses on the mobility of the patients and uses an X73 standardized ECG device is explored in [33]. This work is based on an Android system to enable patients to monitor

their heart condition without having to be at a hospital. An electrocardiogram simulator is utilized as a source of ECG data to test the system and show that it can display the ECG signal in real time.

The research in [34] proposes a system for the detection of acute myocardial infarction diseases to enable the necessary early intervention for patients. The device proposed in this research is a wearable device that is not covered by the X73 standard, so, a specification for this device type that follows the X73 standard has been proposed in this research. The authors suggest the use of the data collected by this device and transmitted to the server for the diagnosis and medical treatment of acute myocardial infarction disease.

The potential of the use of X73 compliant devices have also been investigated for medical conditions other than cardiovascular diseases. For example, a system that is X73 compliant was proposed in [28] using a body temperature sensor for use by patients who require hypothermic therapy. The authors of this research suggest the use of their system as part of the local first aid to monitor a patient's temperatures until the patient reaches the hospital emergency room, where caregivers will have access to registered data. The authors also suggested the use of their system in sports, such as American football, where players sometimes have lower body temperatures caused by their uniforms. The primary focus in these described systems is patients with a specific medical condition that needs to be monitored by doctors. However, the main objective of the work in this paper is to design a system that can help subjects achieve and maintain a healthy condition, while also being available for use by medical doctors as needed.

4) X73 STANDARD ADOPTION IN SYSTEMS FOR WELL-BEING

In addition to systems that target patients with medical diagnoses to facilitate monitoring and treatment by doctors and caregivers, there are also systems in literature designed to monitor subjects to improve their well-being. In [35], the authors perform activity monitoring of users, which is performed remotely by means of commands sent by a monitoring server. An activity monitor is placed on users' wrists and can be controlled by the server as needed. Although this paper only presents use of the system by medical staff, it is not specific for any health condition and we did not find anything in the paper that restricts it from being applied to improve an individual's well-being and healthy individuals.

The research in [36] explores the potential of the X73 standard by emulating an X73 manager who communicates with some X73 agents. The study discusses challenges, such as moving from fixed systems to mobile systems, with the evolution of the X73 standard from the point of care for hospital use to personal health devices for particular use by any individual. The research in [36] concludes that this evolution from point of care to personal health devices has caused an optimization of the end-to-end platform with the advantages of ubiquitous and plug-and-play solutions. The authors of [37] discuss the

potential of sharing health data collected from devices that follow the X73 standard format among different managers in different locations. The research in [38] proposes a middleware for mobile health services for collecting health data from personal devices and sending it to a log data node. The authors perform tests on the proposed middleware using a pulse oximeter that communicates with an Android platform.

These described systems are reasonable steps toward the use of technological advances to provide individuals with better options for personal health systems. These systems ensure the standard adoption but focus on the use of one health device and target the collection of health data and its transmission to a server. However, in this work, we aim to provide individuals and caregivers with a framework that is end-to-end, including the health data collection and transfer but also its analysis and the derivation of vital information to provide the user with feedback. We aim to facilitate the use of any personal health device, while preserving the interoperability whenever a device specification that follows the X73 standard exists. The adoption of X73 standards in personal health devices and fitness devices is an important part of the work in this paper. This adoption guarantees the interoperability of collected data about individuals' health, sport, and well-being, and hence, ensures the usefulness of these data for caregivers by eliminating hundreds of proprietary data formats that caregivers would have to address if they want to utilize the personal health data available on the cloud.

III. DIGITAL TWIN SYSTEM REQUIREMENTS ANALYSIS

Based on research conducted in [2], [39] and our analysis, we derive the requirements that a digital twin system needs to fulfil to provide value to the real twin.

First, the real twin has to be continuously monitored to ensure that his or her collected data were accurate. The majority of self-reported data are inaccurate. If we consider the common example of physical activity, we discover that people are not usually aware of how long they remain sitting during the day and how little they move physically. However, with a high number of people recently starting to wear all kinds of health monitoring devices, it is time for the data from these devices to be leveraged for their benefit. The explosion of wearables came at the right time to facilitate the emergence of the digital twin.

While data from wearables are available in high volumes, a substantial amount of data are lost because the usability of the data are governed and limited by proprietary data formats from an increasing number of manufacturers, which shows the necessity of standardization to enable interoperability [2]. Thus, data can be transmitted to a coach to help follow up with accurate time spent exercising in addition to the reported time.

Visualization of data is important in the digital twin system, given the high amount of data collected. The greater is the amount of data collected over time, the harder it is to observe any patterns from numbers. However, translating these

numbers into well-suited graphs will enable caregivers to observe patterns that would otherwise remain undetected. This step provides a source of virtual feedback to follow-up on the real twin's well-being and/or sports goals.

The digital twin also conveys physical feedback to the real twin via actuators and hence continuously reminds the individual of their exercise time and their motivation.

To provide the right feedback while a person is being monitored, collected data has to be analyzed, which enables personalized actuations for physical activity recommendations and reminders to be developed and provided at the right time. The need for data analytics and/or artificial intelligence is distinct.

Often, reminders received from devices such as smartphones with some installed fitness apps for example, are disregarded by users. This is because they are usually triggered rather arbitrarily, at a preferred user reminder time. They don't take into account the person's health parameters that personal health devices can record over time. However, the use of health devices to collect data, combined with data analytics to analyze this data, has the potential to deliver a much more personalized solution.

To transfer this collected data securely to the cloud, cyber-security and privacy are necessary for the digital twin system. Although these research areas are beyond the scope of this paper, we took into account related aspects in our system due to their importance. Notably, all of our data transmissions are carried out using a secure connection. Furthermore, all sensitive data that are stored in our database are encrypted.

Hence, the previously described requirements can be summarized in the four following points:

1. Data collection using sensory devices
2. Standardization of data communication
3. Data analytics to detect patterns
4. Providing real twin and caregivers with feedback using hard and soft actuation.

In our previous work, we proposed the ecosystem shown in Figure 1, which depicts a high-level view of different digital twin modules and the relationship between them. These modules include the data sources, AI-inference engine, and multimodal interactions between the real twin and their digital twin. The ecosystem also shows the necessity of utilizing a highly efficient network and the importance of considering security and privacy in all aspects of the digital twin. We employ this ecosystem as a basis for the architecture proposed in this paper, as discussed in the next section.

IV. CLOUD DIGITAL TWIN SYSTEM BASED ON X73 STANDARD

In this section, we discuss the architecture, uses and benefits of the proposed X73 standard-based digital twin system. Our objective is to design and build a system that helps improve the state of health and well-being of individuals via digitization, processing and analysis of health data and the increasing computing power of today's machines.

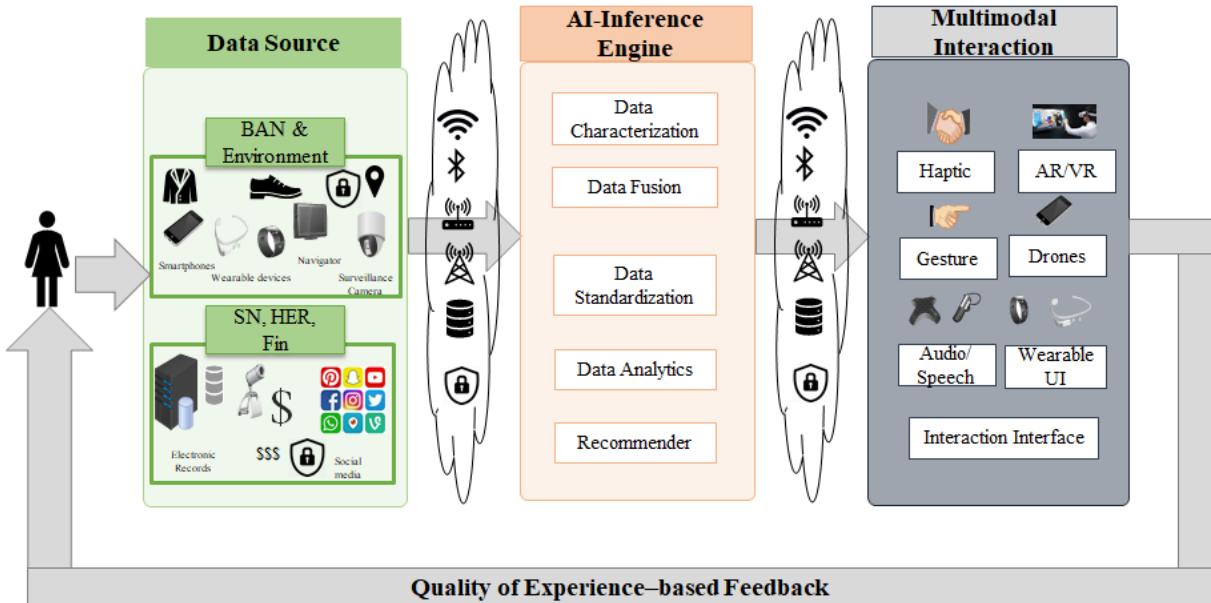


FIGURE 1. Ecosystem of the Digital Twin for Health and Well-being (adapted from [39]).

A. DIGITAL TWIN DATA SENSING

1) HEALTH AND WELL-BEING DATA COLLECTION

As discussed in the previous section, a requirement of our system is that the input is derived from health data collection using sensors. Researchers have determined that self-reported data are not accurate [40], [41]. Manual input of data in a system through a user interface is tedious. Instead, automatic data collection makes the task much easier and more accurate and is facilitated by the explosion of wearables and all kinds of personal health devices.

Given the explosion of wearable use in the past few years, the adoption of a standard to ensure interoperability becomes critical. Without standards, the data collected by personal devices and the ability to contain users' vital signs are unfortunately wasted. The emergence of the ISO/IEEE 11073 (X73) Personal Health Device Standards is timely and addresses the pressing need for interoperability.

In our architecture shown in Figure 2, we use a variety of personal health device types and divide them into two categories to achieve the second requirement, which is the standardization of the data communication between the devices and the server. In the first category, health devices are X73 compliant and capable of communicating directly with our X73 communication module. The second category contains the noncompliant devices, as explained later in this section.

2) DIGITAL TWIN STANDARDIZATION

The goal is to provide a system that can be used by caregivers in the health and well-being domain or coaches in the sports domain to provide personalized services to athletes. The system eliminates concern about a device's proprietary

communication protocol or data format. Users who will benefit from this service will use personal health devices that are X73 compliant. A greater problem faced by health and well-being service providers who aim to track their subjects to tailor their services to the subjects' needs is the interoperability. Adopting our suggested X73 communication system module would solve this problem.

Note that only a small number of health devices currently on the market follows the standard; most wearables remain noncompliant partly due to the recent emergence of the X73 standard. A survey that we conducted of X73 compliant personal health systems [21] shows the interest in this standard by the research community. While health devices standardization is slowly influencing personal health data collection, a solution that can be promptly applied and includes the existing devices is needed. For this reason, our proposed digital twin framework includes both standardized devices and non-standardized devices.

3) PERSONAL HEALTH DEVICES CATEGORIES

The X73 standard supports a number of personal health device types. For each of these device types, ISO/IEEE defines a standard document called device specialization. Each device specialization document contains, among other information, a set of specifications on the communication protocol requirements to comply with the X73 standard. Based on the compliance of devices with the existing X73 device specializations, we divide the personal health devices into two categories, as shown in the digital twin data sensing component in Figure 2:

X73 standard compliant personal health devices: these devices are X73 compliant health devices that communicate

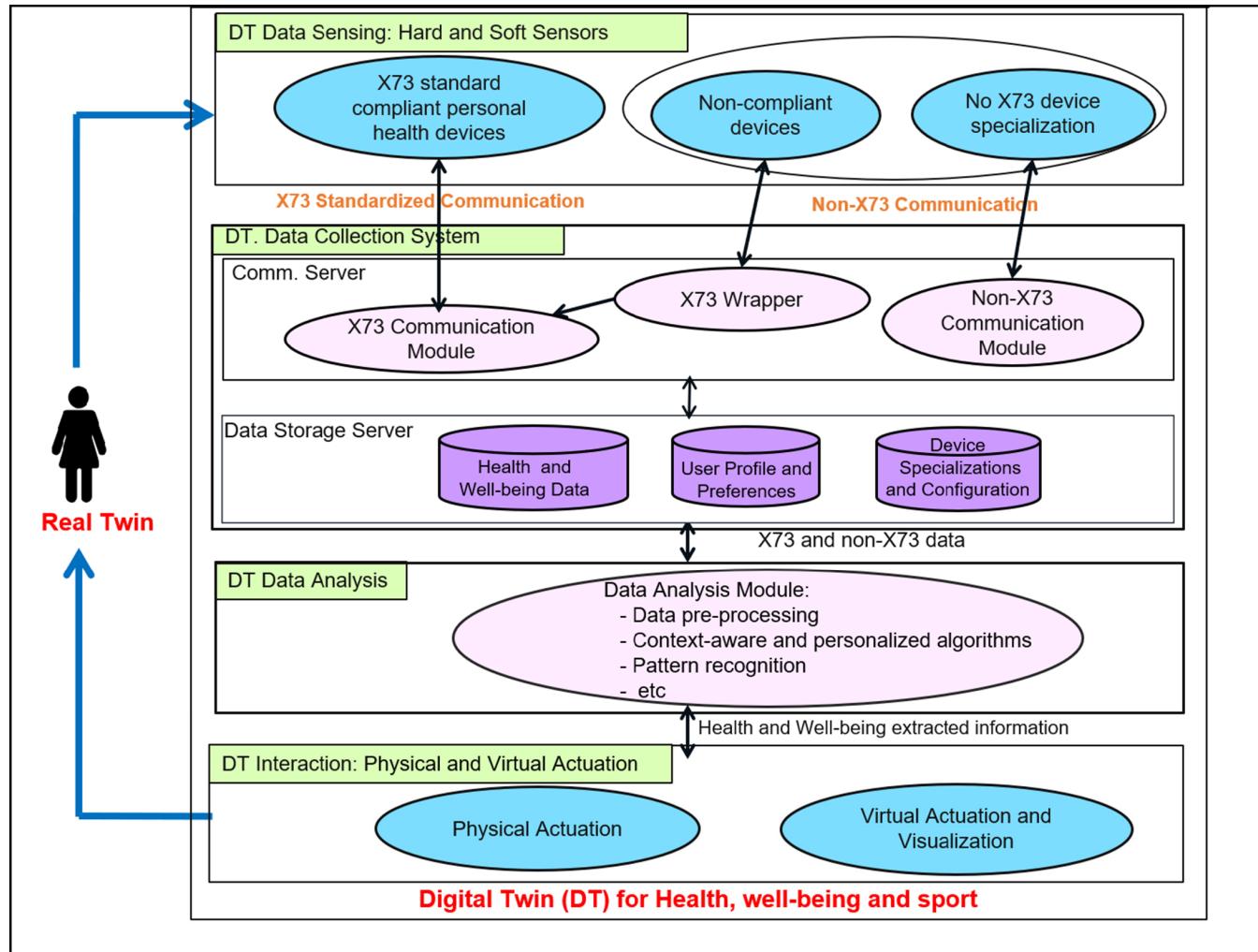


FIGURE 2. Proposed X73-based Digital Twin (DT) System Architecture.

with the X73 communication module. This server module follows the standard and utilizes device specifications designed by the ISO/IEEE workgroup and stored in our server's database. For each device type, these specifications state the information to be exchanged in each of the X73 communication stages.

Non-X73 personal health devices: this second category includes all other devices that are not standardized. These devices follow some proprietary manufacturer specifications. For this category, we have two sub-categories.

- Noncompliant devices: this first sub-category contains the device types that have a specialization defined in the standard; however, this specialization was not followed by the manufacturer. For this sub-category, we have designed in our system architecture a module that we refer to as X73 wrapper. This module serves as a gateway between the server and non-standardized devices and is explained later in this paper.
- No X73 device specialization: this second sub-category includes existing health devices that are available on

the market but are not standardized and do not have a defined standard specialization. This category has to be taken into account in the digital twin framework to incorporate all device types, while a transition toward the standard adoption slowly ensues.

4) X73 MOBILE APP

We designed and developed a generic mobile application that communicates with compliant devices in order to collect health data, and send it to the X73 communication model of our system. This means that the mobile device hosting this app is part of the X73 devices category in Figure 2, in the first sub-category which is the X73-compliant personal health devices. In the X73 standard, an agent is a node that gathers and transfers health data to an X73 manager. And a manager is a node that receives health data from agents. So the personal health device implementing this standard can connect to the X73 communication module with Wi-Fi, and transfer the collected data as an X73 agent. However, most personal health devices use Bluetooth connectivity, and will

usually not connect directly with the X73 communication module. So designing a mobile app that is X73 compliant is important, as it will serve as a data collection point, and save the health data gathered by the personal device. This mobile app serves as an X73 manager in its communication with a compliant device agent. Later, the X73 mobile app will send this data to the server. For this, the mobile app will connect as an X73 agent in its communication with the X73 communication module which is the manager. This means that the mobile app implements both the X73 agent and X73 manager protocols.

The powerful part about this mobile app is that it can be configured for use with any compliant device by simply changing its local database to contain the X73 configuration that pertains to this specific device. With the mobile app configurable design, the user may adopt a single X73 device or multiple X73 devices, as the app can work with one device or more devices as per the user's preference.

This mobile app collects data from the X73 personal health device and stores them locally. The app uploads the data to the server at the user's request (menu option) or at a set time every day that is chosen by the user. When the app sends data to the server, we store the data from the last 7 days locally for offline user access, and the data that have been sent to the server are flagged to avoid duplicate transmission. To enable more data to be kept on a smartphone as configured by the user, we have set the default value to 7 days due to the limited mobile phone storage, and the remaining data are deleted once transmission is successful.

B. DIGITAL TWIN DATA COLLECTION

As shown in Figure 2, the digital twin data collection system is composed of two modules, which serve for the communication and the data storage. The communication server is itself composed of three modules as shown in Figure 2 and explained in the following sub-sections.

1) X73 COMMUNICATION MODULE

This module is designed and built based on the X73 standard. Following the X73 communication protocol, our communication module acts as a manager. The manager receives requests from personal health devices that are referred to as agents. First, the X73 manager receives an association request, which it parses to extract the type of device. This device type enables our manager to access the database to respond to the association response that corresponds to the device. The manager also checks the agent identifier and indicates within the association response whether it recognizes the identifier and has information about this specific agent configuration in the database. If the manager does not recognize the identifier, the agent has to send its full configuration, which contains the device configuration information. The manager stores the configuration in the database and then sends the accepted configuration response.

The next step in the X73 communication protocol is the operating procedure, during which the health data

transfer occurs. This procedure contains two stages. In the first stage, which follows the configuration stage, the agent waits for the manager to send a request to obtain the medical device system (MDS) attributes. The agent responds with a list of its attributes depending on the device. The second stage of the operating procedure is the data transfer. During this stage, the agent transmits its data measurements to the manager, which stores the transmitted data on the cloud. When the data transfer is complete, the agent and the manager exchange a disassociation request and response and close the current connection. The sequence of the communication messages exchange is illustrated in the diagram in Figure 3. The figure shows the X73 agent as the personal health device, which is one possible case scenario. In our framework, the communication module can accept communication from a personal health device, but also from the X73 mobile app as an agent, as explained in the previous section. Additionally, the communication module can accept connections from the X73 wrapper as we detail in the following subsection.

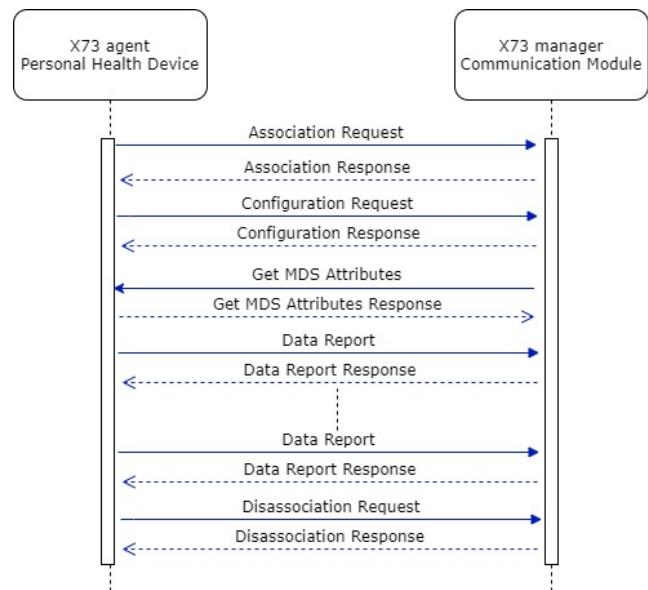


FIGURE 3. X73 Communication Sequence Diagram.

2) X73 WRAPPER MODULE

The wrapper module acts as an intermediary module between noncompliant personal health devices and the standardized communication module. The module is depicted in Figure 4. The main role of the module is the data format conversion from proprietary format to X73 standardized format, which means that this module accommodates noncompliant devices by obtaining personal health data from them following the proprietary data format. The module subsequently communicates as an X73 agent with the X73 communication module and transfers the collected data to the digital twin cloud database.

It is worth mentioning that we designed the X73 wrapper as a standalone module that can live on a separate server

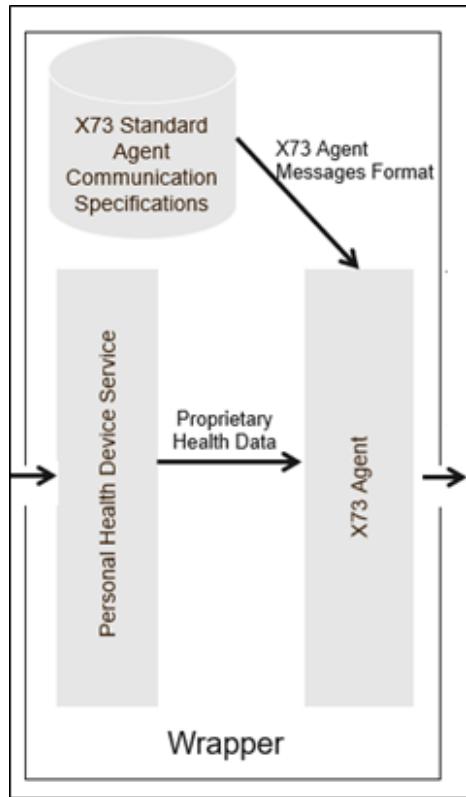


FIGURE 4. X73 Wrapper module.

as needed and transfer the data to the X73 system. This design can be especially useful in the case of a caregiver who would only host the standardized system and not worry about any proprietary devices communication, which is very understandable. The wrapper module would then be hosted and maintained by a third party that offers this service and enables inclusion of data from as many devices as possible to benefit the individuals using these devices.

The wrapper module can transfer data from a proprietary device if a device specialization is defined for this type of device. The ISO/IEEE personal health device standard currently includes 15 devices that have an active device specialization. However, many other devices do not have a defined specialization, even though they are extensively applied in the market. Some research papers propose device specializations for some devices, such as the smart phone camera, Wii Balance Board and shoe insole, and the list of standardized devices is expanding.

3) CONFIGURABILITY OF THE X73 DIGITAL TWIN SYSTEM

We designed the X73 communication module to be configurable. To achieve this goal, first, we designed the system to follow the main standard document of the X73 personal health devices 11073-20601, on which all device specializations are based. Second, we made the specifications, extracted from each device specialization, configurable in our system database. The communication module reads these

specifications from our database and excludes any device-specific configuration from the code. Subsequently, we included all specifications from available specializations into our server database, as shown in Figure 5. With this design, any X73 compliant device is able to communicate with our system, as it is required to follow one of these device specializations. Thus, the device can transmit data in a plug and play manner without any human intervention.

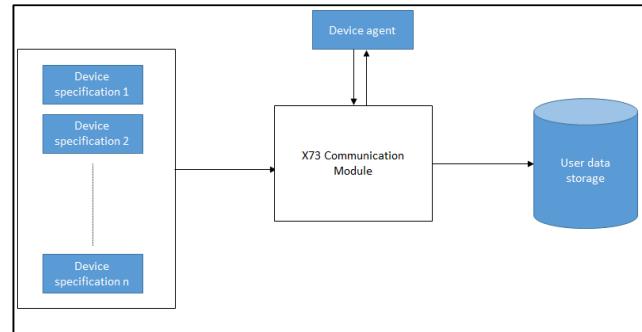


FIGURE 5. Configurable X73 Communication module.

We did not identify this configurability in any other X73 system because the systems that we surveyed [21] were designed for specific device types, and any additional device types would necessitate changes in the design/code or the addition of extra modules to handle them. The configurability is important because any new device type standardized by the ISO/IEEE working group can be smoothly incorporated into our system without further implementation. The new device specifications will be added to the database, and personal health devices that follow this specification will be recognized seamlessly by our system.

This configurability is even more important due to the continuous improvement and changes introduced by the ISO/IEEE working group to the device specializations because the standards are fairly recent. In our case, the changes can be introduced to the database, and we do not need to constantly change in the code, which is convenient for caregivers who choose to utilize our system.

C. DATA ANALYTICS

The objective of the digital twin is to understand the real twin's health and well-being, which can be achieved via data collection, data storage and data analysis and taking into account the history and current state of well-being to detect patterns. This process can be achieved using algorithms, artificial intelligence, and taking into account the external context of the real twin as much as possible. Performing the data analytics on the cloud allows running artificial intelligence algorithms on large amounts of data from a high number of users and stored over longer periods of time. This facilitates the means to extract patterns from data history of many users. Feedback is then provided to each user individually, based on their specific case. However, part of the data analytics can also be performed on the edge such as on the user's

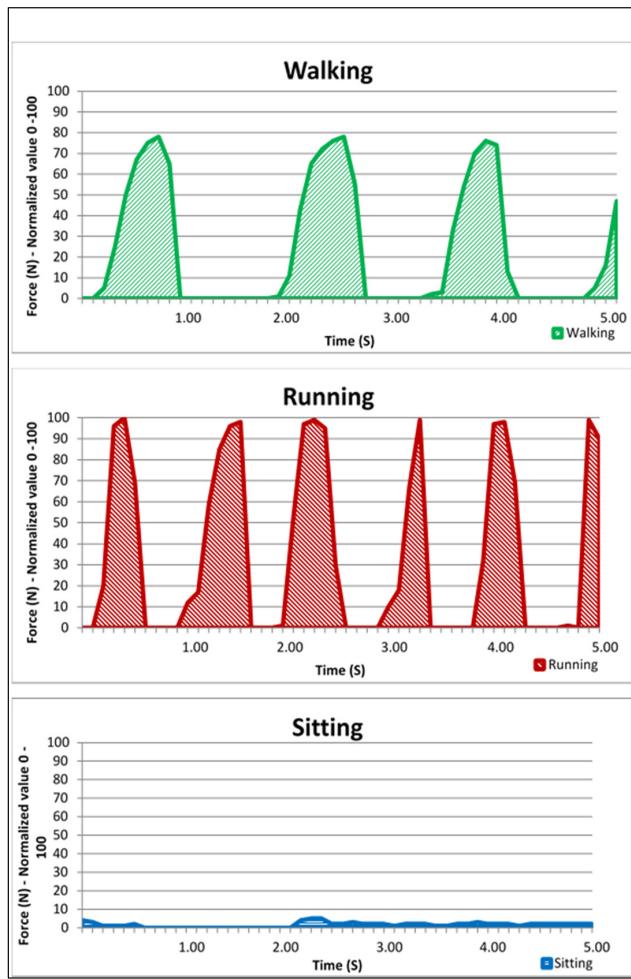


FIGURE 6. Charts showing plantar pressure force patterns for (a) walking, (b) running, and (c) sitting.

smartphone, given the increasing power of today's devices. This has the advantage to allow for fast and continuous user feedback. Depending on the personalized objectives of the real twin and the real twin context, the role of the digital twin is to provide context-aware feedback and recommendations by real and virtual actuators. The range of possibilities that can be achieved using this concept is extensive and the potential for improving individuals' well-being is high. This finding is validated by the explosion of wearables and the vast variety of health parameters that they can track and make available for data analysis, the increasing processing power of today's machines, and the advances in artificial intelligence. Thus, what can be achieved by the digital twin system is very diverse and open to the creativity of researchers and caregivers. As a proof of concept in this paper, we conduct a case study in which we collect data on real twins using two health devices and analyze the data using machine learning to show how the digital twin system can help improve the state of well-being of the real twin. We detail this study in the following sections.

D. DIGITAL TWIN INTERACTION: PHYSICAL AND VIRTUAL ACTUATION

1) PROVIDING USER FEEDBACK THROUGH ACTUATORS

Physical and virtual actuation are employed in our suggested framework to provide feedback to the real twin, based on a digital twin examination to collect data over time. The goal is to make the real twin aware of his or her state of well-being, positively influence his or her behavior and motivate him to take action to improve his or her well-being. Different motivational methods, such as leveraging people's inclination for social good, can be utilized to motivate them to engage in physical exercise while donating green energy to the poor.

With advances in technology, an extensive variety of physical actuators exist and have the potential to make a positive impact in the real twin's life if used creatively. For example, haptic feedback can assist in sports training, as suggested in [42], and improve physical and mental well-being. Another example is virtual feedback such as persuasive notifications, which can improve social well-being as shown in [43].

2) DATA VISUALIZATION

Data visualization is part of the virtual feedback that is conveyed to the real twin and/or to caregivers but not necessarily in real time. Data visualization is important because it enables caregivers to analyze the data and facilitate the detection of patterns that can go unnoticed in the data. Examples are graphs that show how the real twin has progressed over time, for example, in terms of physical exercise. Another example is heat map visualization, which shows the foot pressure that enables a health care provider or a sports physiologist to observe possible imbalances in an athlete's posture.

V. CASE STUDY AND RESULTS

A. METHODOLOGY

The proposed digital twin architecture can be employed in an extensive range of cases in health and well-being. In this section, we focus on one case scenario that we hope will serve as an example of an end-to-end multimodal interaction with the real twin from data collection and data analysis to personalized feedback, followed by continued data collection. We conducted a user study that we describe here.

In this proof of concept, we use the digital twin system to assist the real twin in getting physically active. This case study involves the system requirements that were derived in section III. The first requirement is data collection via sensors. We used a personal health device to track the real twin's physical activity. Tracking and recognition of physical activity is important and can have a variety of other applications in health and well-being, such as rehabilitation, elderly care, and ambient assisted living. We opted to use the smart insole as a personal health device, for which a detailed description is provided in [44]. Various useful information can be gathered via the smart insole, which renders it a promising wearable device that is employed in the domain of health and well-being. Its full potential has not been explored.

In this case study, we propose using this device for physical exercise motivation and encouragement, which we perform in two steps. First, via activity recognition, which enables the digital twin to be aware of whether the real twin is performing a physical activity, such as walking or running, or just sitting for long periods of time. This recognition will provide the digital twin with the necessary context information to track the real twin. Second, the digital twin encourages the real twin when they are walking and running and provides them with reminders of their goal when they are not moving enough.

To fulfil the second requirement, namely the standardization of data communication, we used an X73 standard compliant smart insole, as detailed in [31], to facilitate the use of the collected data by caregivers and coaches in future applications. We employed the smart insole to collect physical activity-related data and send it to the X73 mobile app, which transfers it to our server. Once we collected the data, the next step in the digital twin system was to analyze these data and extract useful information from them, as per the third requirement, to provide the real twin with constructive feedback. This step was performed via the data analysis module, which is the intelligent part of the digital twin.

B. USER STUDY

Ten (10) participants participated in this study: 5 males and 5 females, whose ages ranged between 25 and 60. They wore the smart insoles and followed the instructions for walking, followed by running and then sitting on a chair while moving their legs as they would usually do. We collected the data using the mobile app via a Bluetooth connection and labelled the data according to each of the three activities that were performed. Before each physical activity, we chose the corresponding activity type on the mobile phone prior to starting data collection to ensure proper labelling of the data. Pre-processing of the constructed dataset involved removing noise generated at the beginning and end of an activity, for example, when the participant is about to start walking, and at the end of the activity, such as the deceleration at the end of running, for example. We segmented the data into samples of 4.5 seconds to ensure that every sample contained at least 2 steps in the case of walking. We maintained the same sample duration for running (which contains more steps in this case) and sitting. After collecting and pre-processing the pressure data, we split it into training data and test data.

First, we split our data into 80% training data and 20% testing data, where each of the participants' data were included in both the training set and the testing set. For each participant, the model would be trained on part of their data. In a second phase, we split the data so that all participants' data, except for two participants, are fully included in the training set, while data from two of the participants are used only for testing without having been employed for training. Instead of the traditional random split, which can cause an unbalanced distribution of data instances, we opted for cross-validation, to make full use of the collected participants' data. The testing data were utilized to evaluate the performance of our model.

Our hypothesis is that the first case will have better results given that the model has been trained for part of the data of all users. However, this hypothesis also implies that the system would need to be trained for each new user that adopts this system. The graphs in VI show the plots of the pressure patterns in each of the three activities.

The next step was to use deep learning to classify the different activities. We built a convolutional neural network (CNN) model and trained it on the training dataset. We used TensorFlow to run the model on the mobile phone with the objective of providing the real twin with mobile tracking and feedback. We trained our CNN model on the server before running it on the mobile phone once it was optimized. The optimization of the CNN model was obtained by performing many experiments with different model structures. The best results were obtained using three convolution layers, two pooling layers, two dropout layers and three output neurons (Softmax). The best accuracy is 96.85% for the first case, when part of every participant's data was employed in the model training. In the second case, the accuracy is 90.57% when the model was tested using a new participant's data, which supports our hypothesis.

When we ran the test on the mobile phone, the confidence level obtained in the first case, where every participant's data were used in the training, was 95%. For the second case, where we tested the model on a totally new participant's data, the confidence level on the mobile phone was 88%. Running the CNN model on the mobile phone is important because it allows feedback to be displayed to the users, such as positive encouragement when the mobile app detects walking, a stronger encouragement in the case of running, and a persuasion message for physical activity when the activity matches sitting. Communicating feedback to users satisfies the fourth requirement for the digital twin system, which is providing real twin and/or caregivers with feedback using hard and soft actuation. The system subsequently continues data collection for longer-term data analysis and feedback. The goal of this system is long-term data collection, combined with the use of multiple personal health devices, to provide more comprehensive insight on the well-being of individuals and more beneficial feedback.

VI. CONCLUSION

We have presented a digital twin framework for health and well-being that enables the integration of personal health devices and the collection of as much data as possible on the real twin to serve his or her quality of life. As a proof of the potential of our framework, we have also presented an application of the digital twin system for physical well-being to give the reader a sense of how the digital twin can improve the health and well-being of the real twin by data collection, storage, analysis, and user feedback. We have explained the design and implementation of each aspect of the system and conducted experiments and their results. Such system provides individual and caregivers with insights on health and well-being. And when this system is used at a

smart city level, it can reflect the health and well-being of the citizens, and inform proper action in the smart city, improving its smart healthcare services. The impact of this action is again evaluated through continuous health data collection, analysis and feedback. In the future, we plan to conduct a study of the positive influence of this system on the real twin in the long term, which requires a longer-term experiment and a larger-scale study, towards an effective deployment of the digital twin technology to facilitate the smart healthcare services in smart cities.

REFERENCES

- [1] M. Grieves and J. Vickers, "Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems," in *Transdisciplinary Perspectives on Complex Systems*. Cham, Switzerland: Springer, 2017, pp. 85–113.
- [2] A. El Saddik, "Digital twins: The convergence of multimedia technologies," *IEEE Multimedia Mag.*, vol. 25, no. 2, pp. 87–92, Apr. 2018.
- [3] H. F. Badawi and A. El Saddik, "Biofeedback in healthcare: State of the art and meta review," in *Connected Health Smart Cities*. Cham, Switzerland: Springer, 2020, pp. 113–142.
- [4] M. Lytras and A. Visvizi, "Who uses smart city services and what to make of it: Toward interdisciplinary smart cities research," *Sustainability*, vol. 10, no. 6, p. 1998, Jun. 2018.
- [5] M. D. Lytras, P. Papadopoulou, and A. Sarirete, "Smart healthcare: Emerging technologies, best practices, and sustainable policies," in *Innovation in Health Informatics*, M. Lytras and A. Sarirete, Eds. Amsterdam, The Netherlands: Elsevier, 2020, pp. 3–38.
- [6] (2019). *Gartner Survey Reveals Digital Twins Are Entering Mainstream Use*. Gartner. Accessed: Mar. 20, 2019. [Online]. Available: <https://www.gartner.com/en/newsroom/press-releases/2019-02-20-gartner-survey-reveals-digital-twins-are-entering-mai>
- [7] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital twin in industry: State-of-the-art," *IEEE Trans. Ind. Informat.*, vol. 15, no. 4, pp. 2405–2415, Apr. 2019.
- [8] K. T. Park, Y. W. Nam, H. S. Lee, S. J. Im, S. D. Noh, J. Y. Son, and H. Kim, "Design and implementation of a digital twin application for a connected micro smart factory," *Int. J. Comput. Integr. Manuf.*, vol. 32, no. 6, pp. 596–614, Jun. 2019.
- [9] K. M. Alam and A. El Saddik, "C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems," *IEEE Access*, vol. 5, pp. 2050–2062, 2017.
- [10] T. Mukherjee and T. DebRoy, "A digital twin for rapid qualification of 3D printed metallic components," *Appl. Mater. Today*, vol. 14, pp. 59–65, Mar. 2019.
- [11] C. Li, S. Mahadevan, Y. Ling, S. Choze, and L. Wang, "Dynamic Bayesian network for aircraft wing health monitoring digital twin," *AIAA J.*, vol. 55, no. 3, pp. 930–941, Mar. 2017.
- [12] U. T. Tygesen, M. S. Jepsen, J. Vestermark, N. Dollerup, and A. Pedersen, "The true digital twin concept for fatigue re-assessment of marine structures," in *Proc. 37th Int. Conf. Ocean, Offshore Arctic Eng.*, vol. 1, 2018, Art. no. V001T01A021.
- [13] K. Sivalingam, M. Sepulveda, M. Spring, and P. Davies, "A review and methodology development for remaining useful life prediction of offshore fixed and floating wind turbine power converter with digital twin technology perspective," in *Proc. 2nd Int. Conf. Green Energy Appl. (ICGEA)*, Mar. 2018, pp. 197–204.
- [14] D. N. Mavris, M. G. Balchanos, O. J. Pinon-Fischer, and W. J. Sung, "Towards a digital thread-enabled framework for the analysis and design of intelligent systems," in *Proc. AIAA Inf. Systems-AIAA Infotech. Aerosp.*, Jan. 2018, p. 1367.
- [15] V. Augusto, M. Murgier, and A. Viallon, "A modelling and simulation framework for intelligent control Of emergency units in the case of major crisis," in *Proc. Winter Simul. Conf. (WSC)*, Dec. 2018, pp. 2495–2506.
- [16] A. Karakra, F. Fontanili, E. Lamine, J. Lamothe, and A. Taweeel, "Pervasive computing integrated discrete event simulation for a hospital digital twin," in *Proc. IEEE/ACS 15th Int. Conf. Comput. Syst. Appl. (AICCSA)*, Oct. 2018, pp. 1–6.
- [17] G. Landolfi, S. Menato, M. Sorlini, A. Valdata, D. Rovere, R. Fornasiero, and D. Pedrazzoli, "Intelligent value chain management framework for customized assistive healthcare devices," *Procedia CIRP*, vol. 67, pp. 583–588, Jan. 2018.
- [18] K. Bruynseels, F. Santoni De Sio, and J. van den Hoven, "Digital twins in health care: Ethical implications of an emerging engineering paradigm," *Frontiers Genet.*, vol. 9, p. 31, Feb. 2018.
- [19] N. K. Chakshu, J. Carson, I. Sazonov, and P. Nithiarasu, "A semi-active human digital twin model for detecting severity of carotid stenoses from head vibration—A coupled computational mechanics and computer vision method," *Int. J. Numer. Biomed. Eng.*, vol. 35, no. 5, p. e3180, May 2019.
- [20] Y. Liu, L. Zhang, Y. Yang, L. Zhou, L. Ren, F. Wang, R. Liu, Z. Pang, and M. J. Deen, "A novel cloud-based framework for the elderly healthcare services using digital twin," *IEEE Access*, vol. 7, pp. 49088–49101, 2019.
- [21] H. F. Badawi, F. Laamarti, and A. El Saddik, "ISO/IEEE 11073 personal health device (X73-PHD) standards compliant systems: A systematic literature review," *IEEE Access*, vol. 7, pp. 3062–3073, 2019.
- [22] D. F. S. Santos, H. O. Almeida, and A. Perkusich, "A personal connected health system for the Internet of Things based on the constrained application protocol," *Comput. Electr. Eng.*, vol. 44, pp. 122–136, May 2015.
- [23] A. Talaminos, D. Narango, G. Bararov, L. M. Roa, and J. Reina-Tosina, "Design and implementation of a standardised framework for the management of a wireless body network in a mobile health environment," *Healthcare Technol. Lett.*, vol. 4, no. 3, pp. 88–92, Jun. 2017.
- [24] Z. Ji, I. Ganchev, M. O'Droma, X. Zhang, and X. Zhang, "A cloud-based X73 ubiquitous mobile healthcare system: Design and implementation," *Sci. World J.*, vol. 2014, pp. 1–14, Mar. 2014.
- [25] J.-H. Lim, C. Park, and S.-J. Park, "Home healthcare settop-box for senior chronic care using ISO/IEEE 11073 PHD standard," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol.*, Aug. 2010, pp. 216–219.
- [26] X. Chen, X. Bao, Z. Fang, and S. Xia, "Design and development of a ubiquitous healthcare monitoring system based on Android platform and ISO/IEEE 11073 standards," in *Proc. IEEE Int. Conf. Inf. Autom. (ICIA)*, Aug. 2016, pp. 1165–1168.
- [27] J.-C. Nam, W.-K. Seo, J.-S. Bae, and Y.-Z. Cho, "Design and development of a u-Health system based on the ISO/IEEE 11073 PHD standards," in *Proc. 17th Asia Pacific Conf. Commun.*, Oct. 2011, pp. 789–793.
- [28] M. Frohner, P. Urbauer, M. Bauer, F. Gerbovics, A. Mense, and S. Sauermann, "Design and realisation of a framework for device end communication according to the IEEE 11073-20601 standard," in *Proc. Tagungsband der eHealth*, Vienna, Austria, 2009, pp. 135–139. [Online]. Available: <http://citeseerkx.ist.psu.edu/viewdoc/download?doi=10.1.1.214.4391&rep=rep1&type=pdf>
- [29] J. Yao and S. Warren, "Applying the ISO/IEEE 11073 standards to wearable home health monitoring systems," *J. Clin. Monitor. Comput.*, vol. 19, no. 6, pp. 427–436, Dec. 2005.
- [30] S. Carot-Nemesio and J. A. Santos, "OpenHealth-The OpenHealth FLOSS implementation of the ISO/IEEE 11073-20601 standard," in *Proc. 3rd Int. Conf. Health Informat.*, 2010, pp. 505–511.
- [31] H. Badawi, F. Laamarti, F. Arafsha, and A. El Saddik, "Standardizing a shoe insole based on ISO/IEEE 11073 personal health device (X73-PHD) standards," in *Proc. ICITS*, 2019, pp. 764–778.
- [32] D. S. Gangwar, "Biomedical sensor network for cardiovascular fitness and activity monitoring," in *Proc. IEEE Point-of-Care Healthcare Technol. (PHT)*, Jan. 2013, pp. 279–282.
- [33] Z. Q. Xiong, H. H. Fan, W. Z. Wang, G. S. Xie, and B. Y. Hwang, "Design and development of a 3-lead ECG system based on the ISO/IEEE 11073-10406 standards," in *Health Information Science (Lecture Notes in Computer Science)*, vol. 8423, Y. Zhang, G. Yao, J. He, L. Wang, N. R. Smalheiser, and X. Yin, Eds. Cham, Switzerland: Springer, 2014.
- [34] J. Jung, J. Lee, J. Lee, and Y. T. Kim, "Development of service network for wearable type acutel myocardial infarction diagnosis system," in *Proc. IEEE SENSORS*, Nov. 2013, pp. 1–4.
- [35] K. Park and S. Lim, "A multipurpose smart activity monitoring system for personalized health services," *Inf. Sci.*, vol. 314, pp. 240–254, Sep. 2015.
- [36] I. Martinez, J. Escayola, I. F. de Bobadilla, M. Martinez-Espronceda, L. Serrano, J. Trigo, S. Led, and J. Garcia, "Optimization proposal of a standard-based patient monitoring platform for ubiquitous environments," in *Proc. 30th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug. 2008, pp. 1813–1816.
- [37] D. F. S. Santos, A. Perkusich, and H. O. Almeida, "Standard-based and distributed health information sharing for mHealth IoT systems," in *Proc. IEEE 16th Int. Conf. e-Health Netw., Appl. Services (Healthcom)*, Oct. 2014, pp. 94–98.

- [38] Z. Ji, X. Zhang, I. Ganchev, and M. O'Droma, "A personalized middleware for ubiquitous mHealth services," in *Proc. IEEE 14th Int. Conf. e-Health Netw., Appl. Services (Healthcom)*, Oct. 2012, pp. 474–476.
- [39] A. El Saddik, H. Badawi, R. A. M. Velazquez, F. Laamarti, R. G. Diaz, N. Bagaria, and J. S. Arteaga-Falconi, "Dtwins: A digital twins ecosystem for health and well-being," in *Proc. IEEE COMSOC MMTC Commun. Frontiers*, 2019, pp. 39–43.
- [40] A. Adams, S. Soumerai, J. Lomas, and D. Ross-Degnan, "Evidence of self-report bias in assessing adherence to guidelines," *Int. J. Qual. Health Care*, vol. 11, no. 3, pp. 187–192, Jun. 1999.
- [41] M. de Reuver and H. Bouwman, "Dealing with self-report bias in mobile Internet acceptance and usage studies," *Inf. Manage.*, vol. 52, no. 3, pp. 287–294, Apr. 2015.
- [42] F. Laamarti, F. Arafsha, B. Hafidh, and A. El Saddik, "Automated athlete haptic training system for soccer sprinting," in *Proc. IEEE Conf. Multimedia Inf. Process. Retr. (MIPR)*, Mar. 2019, pp. 303–309.
- [43] F. Laamarti and A. El Saddik, "Multimedia for social good: Green energy donation for healthier societies," *IEEE Access*, vol. 6, pp. 43252–43261, 2018.
- [44] F. Arafsha, C. Hanna, A. Aboualmagd, S. Fraser, and A. El Saddik, "Instrumented wireless SmartInsole system for mobile gait analysis: A validation pilot study with tekscan strideway," *J. Sensor Actuator Netw.*, vol. 7, no. 3, p. 36, Aug. 2018.



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