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Towards Digital Twin in the Context of Power Wheelchairs Provision and Support

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Abstract. Recent advances in digital technologies have been triggered by Industry 4.0, deeply focused on connectivity, real-time data and digitization, with Digital Twin (DT) at the forefront of this. A DT is a virtual counterpart seamlessly linked to a physical entity, both sharing the same properties, characteristics and behavior, using data and information. Applications of DT include real-time monitoring, design/planning, optimization, maintenance, prediction, remote access, etc. This paper gives an overview of the Digital Twin concept and seeks to synthesize the technologies frequently used to enable it. It is also proposed the creation and use of a Digital Twin of a Power Wheelchair to promote the health and wellness of wheelchair users and facilitate services by healthcare professionals in the provision and support of wheelchairs.

Keywords: Digital Twin, Monitoring, Power Wheelchair, Remote Control.

1 Introduction

The World Health Organization estimates that about 15% of the world's population has a disability [1]. In Portugal, it corresponds to almost 1 million people with the highest prevalence related to mobility [2]. For these people, operating a wheelchair can be a way to be able to live with freedom and independence. To accommodate those who are unable to use a Manual Wheelchair, one can opt for a Power Wheelchair (PWC), which generally offers a wider range of features to meet different needs and user capabilities. The main obstacles are that the industry is currently limited to high-income markets, and those with lower economic resources end up relying on charity services, which in most scenarios only provide low-quality or used products, unsuitable for the user in the context, with lack of repair and follow-up mechanisms. In addition, in many low- and middle-income countries, access to trained healthcare professionals (HCPs) is limited, but they are essential for the proper provision and support of PWCs [3]. Even now, with the COVID-19 pandemic situation, the scenario got worse, with a significant impact on budgets that concern access to PWCs; and by restricting in-person clinic or home visits. Given this, the idea of performing some parts of the provision of wheelchairs remotely, via telehealth and videoconferencing, has been encouraged [4]. Nowadays, the concept of Digital Twin [5] is emerging applied to different areas as a promising approach to gather

insightful data shared between the physical and virtual worlds, and facilitate the means to design, monitor, analyze, optimize, predict, control, etc. physical entities [6]. In this way, the following research questions aroused: “How to use Digital Twin in the context of Power Wheelchairs provision and support?” and “To what extent does the Digital Twin represent a real Power Wheelchair?”. In view of this, the objective of this paper is to propose the creation and use of a Digital Twin of a PWC to promote the health and wellness of people who use wheelchairs, as well as to facilitate and improve the comprehensive delivery of remote services by HCPs.

2 Relation and Contribution to Digitalization and Virtualization

The use of Digital Twin (DT) in the current days had its boom around 2016, a few years after the proposal of Industry 4.0 in 2013 [7]. Since then, the concept has expanded to different areas, in which new DT applications have emerged to support digitalization as a way of innovation, detecting problems, anticipating challenges and increasing efficiency [8]. Digital Twin allows the virtualization of anything in the real world to be represented in the virtual world, with physical and virtual entities connected sharing the same properties, characteristics and behavior by means of data and information; changes that occur at the physical entity (PE) or at the virtual entity (VE) lead directly to changes in the other. Some of the DT advantages are [9]: (1) it considers large amounts of data derived from different sources, providing a reliable way to model VE and mirror the PE for the duration of its lifecycle; (2) VE synchronizes with the counterpart, which allows DT to monitor and analyze PE in real-time, supporting design, maintenance, control, etc.; (3) it can help optimize the PE, using simulations and predictions, assessing the impact of different scenarios, that can be verified and validated before they occur; (4) it is able of performing diagnostics and intelligent control over the PE, with VE sending instruction when necessary; (5) it allows remote access for human interaction with the PE; just to mention the most relevant advantages. Indeed, due to its advantages, DT can be used in different contexts. This paper proposes the use of DT to promote digitalization and virtualization in the Power Wheelchair sector, in the context of provision and support.

3 Digital Twin Overview

Three common elements to represent a Digital Twin are [10]: a real space, corresponding to the physical world where PEs exist; a virtual space, where VE mirrors PE; and a bidirectional connection for data synchronization between spaces. In [11], a particular proposal highlights the presence of PE and VE interacting with services (Ss) and data (DD) using connections (CN) that link elements. In short, DT supports the representation of PE through VE if: (1) it guarantees the entanglement of entities; (2) PE values are timely mapped to VE; and (3) VE reproduces the relevant PE attributes in the context. These are the properties of entanglement, reflection and representativeness. Optional properties (e.g. replication, composability, memorization or augmentation) [12] will depend on the application and DT type. A DT can be

classified according to its position in the lifecycle [13]: Digital Twin Prototype (DTP) or Digital Twin Instance (DTI); or based on individual values [14]: Supervisory Digital Twin (SDT), Interactive Digital Twin (IDT) or Predictive Digital Twin (PDT); etc. In the first case, DTP is the DT of a physical prototype to be used early in the lifecycle to support tests that are difficult to perform during traditional prototyping. In the realization of PE, DTP becomes a DTI, corresponding to the DT already defined; it lasts beyond PE life. In the second group, SDT monitors PE and collects data to support the perception of PE attributes and their relationship to its performance. IDT leads to a more reliable PE by diagnosing and controlling processes. PDT can help drive PE by simulating or predicting the impact of planned or potential scenarios.

Mapping a PE in the digital world starts with cognition of the physical world and data acquisition: measurement technologies capture PE characteristics; sensory technologies and Internet of Things (IoT) technologies collect PE data in real-time; other data is collected through application programming interfaces or web crawlers; etc. [15]. Thus, different data can be used to build and maintain VE, for it to operate faithfully and control PE via power technologies, drive systems, control technologies, among others. To support the data flow and connectivity of all DT elements, transmission technologies are used together with appropriate network architectures, communication and security protocols, middleware platforms, etc. [16]. In addition, all data are made available for further processing, analysis and visualization using storage technologies [15] and ontologies for knowledge representation and management [16]. Data processing helps to eliminate redundant and inconsistent data using data cleaning and transformation technologies [17], to later extract useful information using statistical methods, artificial intelligence (AI) methods [15] and Big Data technologies, such as cloud, fog and edge computing [18]. Data fusion is also suggested to help filter and correlate the processed data [15], which can then be used in functions provided by the DT (e.g. prediction, optimization and validation), encapsulated in services to facilitate their use [17]. Services are based on: virtualization, verification, validation, and simulation technologies [16]; platform-related technologies used to manage resource services, knowledge services, or application services; and application interface technologies to enable user interaction with the services. Even so, mirroring a PE is a long process where it is also up to the VE to reproduce its characteristics, properties and behaviors through different models. Section 5 builds on the aforementioned aspects, focusing on how to enable VE.

4 Digital Twin for Power Wheelchairs Provision and Support

The provision of wheelchairs is a process for users to obtain and maintain their wheelchairs. Since the outbreak of COVID-19, the option to remotely carry out some parts of wheelchair provision is being valued; users can stay at home, reducing the risk of exposure and helping professionals determine day-to-day challenges; and it may be possible for users who do not live near a clinic to have access to HCPs. Still, telehealth do not cover important phases of wheelchair provision, such as when additional modifications and adjustments are required, or HCPs are asked to provide maintenance and repair of technical issues. To deal with this, the use of Digital Twin

is proposed in the context of Power Wheelchairs provision and support. Fig. 1 presents each step of the provision process, where a DT of a PWC can support the digitalization and virtualization of the product preparation, fitting, training, and follow-up, maintenance and repair steps; 3 groups of participants are also highlighted.

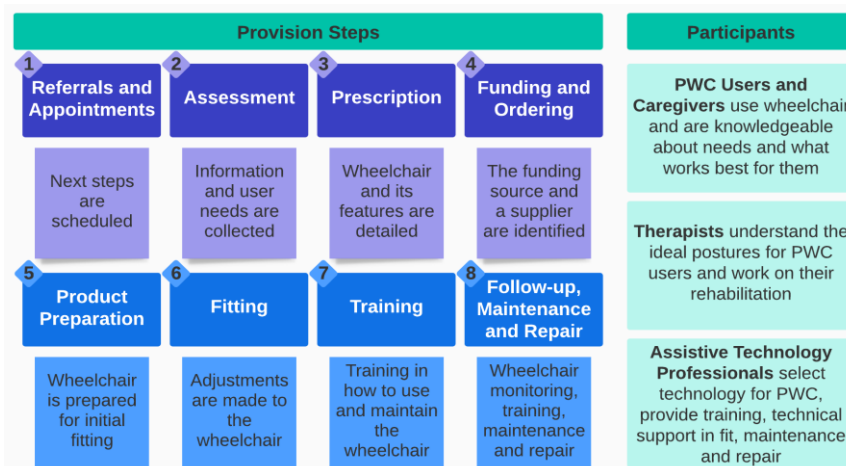


Fig. 1. Steps and participants in the wheelchair provision process.

First, a DT of a PWC can be used during product preparation and fitting to help understand the functioning of the wheelchair and improve the planning and testing of various scenarios for its use. Concretely, assistive technology professionals (ATPs) can use DT to justify, design, and validate new or existing features and parts of the PWC; and simulate PWC's health conditions, to determine and eliminate the cause of problems and undesired situations. ATPs can also use DT to predict the performance of PWC, including the occurrence of unforeseen scenarios. Its predictive capability can also be used during training to anticipate future risks, with PWC users being advised on how to avoid accidents based on PWCs usage data and the computation of patterns of usage and misuse situations. The DT can also guide PWC users with personalized training services, based on the users' health data, therapists' assessments, etc. In the last step, the DT can acquire real-time operational data from PWC and increase user engagement by showing PWC users and caregivers what is happening inside their PWCs, and giving insight on possible consequences of their use. It can also help therapists monitor users' rehabilitation activities, tracing usage patterns and reporting which PWC configurations and functionalities are used. This can influence the planning of the rehabilitation process, and help PWC users to follow it. Also during follow-up, maintenance and repair, a DT of a PWC can trigger alerts to help diagnose problems, as well as identify actions to improve PWC performance. In case of a wheelchair repair, DT facilitates PWC analysis and remote intervention with real-time control over the PWC. Here are some ways to use a DT of a PWC, as a possible answer to the question "How to use Digital Twin in the context of Power Wheelchairs provision and support?".

5 Digital Twin of a Power Wheelchair

In Fig. 2 a conceptual model for a Digital Twin of a Power Wheelchair is shown; the model is based on [11] and has been extended to consider the user element and its interactions. While DT abstracts the complexity of a PWC, offering specific services, users continue to interact with the PWC and contribute with different knowledge.

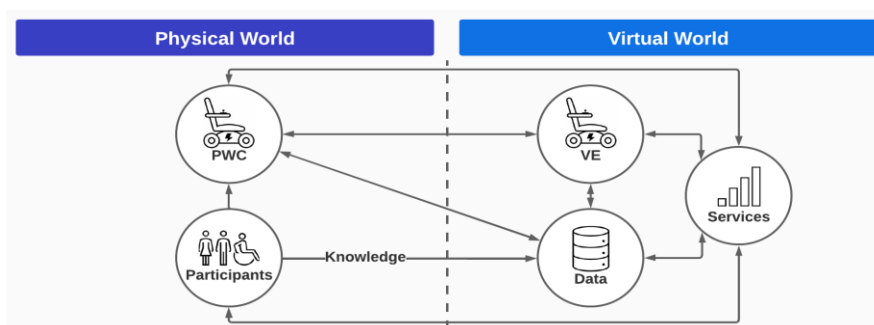


Fig. 2. Proposed conceptual model for a Power Wheelchair DT.

To implement the model, PDT is the type of DT considered; as well as a DTI to adapt PWCs that come with predefined functionalities, or a DTP to add them to those that don't [6]. Properties that characterize the proposed model are: augmentation and servitization for the PWC to be modified, updated and improved by VE augmentation as new services are offered; persistency so if the PWC malfunctions, VE continues reporting to services, and restores it to a known acceptable state; and composability for when a VE represents only a subpart of a PWC, and an aggregation of VEs represents the PWC itself [12]. In fact, the PWC can be seen as an aggregation of the parts that make it up (e.g. joystick module, power module or seating module) and each one can have its VE; the VE in Fig. 2 corresponds to a series of sub-models integrated to mimic specific parts of PWC. To deal with this modularity, the proposal considers a Model-Driven Development (MDD) approach that supports all stages of systems development using models as the primary artifact [19].

MDD ensures a high level of specification abstraction while attaining the level of detail required for a DT; it has the ability to [20]: (1) enable hardware and software design; (2) eliminate errors early in development; (3) facilitate testing with automated verification and validation techniques; and (4) support automatic code generation for target platforms. Besides, MDD supports various modeling formalisms, enabling the use of technologies and tools that are essential for VE. The VE has to represent the PWC (or part of it) in a way that users can analyze and manage it through the services, based on the data; so, the DT model in Fig. 2 represents a real PWC through VE, considering three types of models: geometric, behavioral and rule model.

The geometric model will represent the global solid appearance of the PWC based on data structures of topological and geometric information, used to feed software for three-dimensional modeling, computer-aided design, or virtual reality. The behavioral model will describe the PWC's behaviors according to its state model, dynamic model and kinematic model. The state model will be specified using the Petri net formalism,

suitable for the development of complex and concurrent systems. A new class of non-autonomous high-level Petri nets will be created based on IOPT nets [21], colored Petri nets [22], and DS-Pnets [23], which have the potential to reduce the complexity of data modeling and data processing; also, the use of Petri nets will provide evidence on the representation of requirements for the VE state models through their verification and validation, using automation tools supported by MDD. Regarding to the dynamic model and kinematic model, they will be described through mathematical equations; initially, it will be considered a unicycle model to deal with the motion of the PWC. Additionally, the rule model will provide VE means to describe patterns and make predictions. This will be based on rule-based learning algorithms under the unsupervised branch of machine learning [24]. The rule model will allow associate PWC users actions with virtual model of PWC. In this way, it is believed that a DT can represent a real Power Wheelchair and may answer the question “To what extent does the Digital Twin represent a real Power Wheelchair?”.

6 Related Work and Discussion

Many users find it difficult to use a wheelchair, even for daily activities. They need to have continue access to HCPs for proper provision, training and follow-up; and that’s sometimes limited. Additionally, many users suffer injuries from tips or falls near stairs, ramps or curb [25]; other injuries occur in the scenario of wheelchair breakdown. So, although a PWC is designed to promote the well-being of many users, it often ends up being abandoned, or it does not bring any benefit. In this sense, innovations and proposals for wheelchair revolve around technological advances; examples are: alternative control devices, assessment and prescribing tools, simulators and training applications, or mobility aids. Some examples of recent technology include: LUCI, which is a smart technology accessory that is mounted on a PWC to allow the user to navigate with greater safety and independence [26]; blind spot sensor systems used to easily provide obstacle detection and avoidance [27]; and a fleet management system to provide access to valuable data and analysis of customers’ wheelchairs and improve diagnostic [28]. None of these proposals use Digital Twin which can offer multiple benefits: (1) promote the well-being and safety of PWC users; (2) increase their engagement; (3) support PWCs adaptation and repair, increasing their safety and reliability, while reducing maintenance costs; and (4) offer new mechanisms for HCPs to remotely assist more people.

7 Conclusions and Future Work

This paper presents a proposal for the creation of a Digital Twin of a Power Wheelchair, enabling new services for wheelchairs users, as well as their HCPs. So far, there is no evidence of its application in this sector. Several ways of using DT in the context of provision and support of PWCs were pointed out. The proposal of a conceptual model identifies the Model-Driven Development approach to combine different sub-models and allow specification, verification, simulation and implementation of the virtual entity in the DT. In particular, a new extended Petri net

formalism will aim to model VE state model. As future work, it is intended to analyze different descriptions of VE dynamic and kinematic models while associating them to a geometric model; in parallel, the new formalism of Petri net will begin to be defined; and it is intended to call participation of users, therapists, and ATPs to assess their opinions, comments and recommendations on the values of the proposed DT.

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