A Cyber-Physical Social System Approach for User-Centric Power Wheelchairs

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Abstract

Conventional power wheelchair models often prioritize basic navigation and comfort at the expense of user-centric solutions. This overlooks the opportunity for solutions that can address specific challenges and promote user empowerment towards a sustainable society. This article explores a cyber-physical social system (CPSS) approach for power wheelchairs; a CPSS that brings together different stakeholders to promote better understanding, customization, and assistance of wheelchairs. The aim is to enhance user experience and safety while contributing to sustainability in the sector. To achieve this, this approach comprehends the use of digital twin (DT) technology employing Petri net models. DT allows for the creation of a virtual replica of a power wheelchair (or part), enabling iterative design through real-time simulations and remote control. Petri nets specify the DT within the CPSS, facilitating formal analysis and automated implementation.

Keywords

Cyber-physical system, Digital twins, Petri nets, Real-time information, Remote monitoring and control

1. Introduction

A wheelchair is most effective when designed to meet the user's needs. This may involve exploring alternative control devices [1], sensor technologies [2], and training in simulated environments [3]. Clinicians can also make use of assessment tools to prescribe wheelchairs [4] or educate users about their operation [5]. This user-centric attitude aligns with the rise of Industry 5.0 (I5.0) [6], wherein cutting-edge technologies can transform the power wheelchair sector. I5.0 goes beyond the limits of cyber-physical systems and acknowledges the interaction between humans, technology, and the environment, encouraging for exploration within cyber-physical social systems (CPSSs). However, the design of CPSSs is a complex task due to the heterogeneity of hardware, software, communication networks, and human interactions; and this makes it challenging to ensure that all of these components work seamlessly together and do not pose safety risks. Therefore, the proposed cyber-physical social approach encompasses the use of digital twins modeled with Petri nets (PNs).

Petri nets are a graphical modeling formalism for describing system behavior [7]. They benefit from rigorous mathematical analysis techniques to identify faults early on and verify whether systems meet the desired requirements. This aspect is also advantageous for creating digital twins, which deeply rely on behavioral modeling to ensure virtual entities accurately mirror their physical counterparts [8]. The benefit of creating and manipulating virtual copies lies in the ease of anticipating challenges, detecting problems, and increasing efficiency of the systems. Ultimately, this will lead to various possible end-user services within the proposed cyber-physical social approach. This means that the digital twin is not intended for the resulting CPSS. Instead, its main application is to design new parts to augment wheelchairs and support their use and maintenance, thus promoting user well-being and environmental integrity. Three dimensions are explored as follows: the cyber dimension involves the use of Input-Output Place-Transition Petri nets [9] and associated tools [10] for deploying digital twins; the physical dimension includes tangible components of power wheelchairs, assistive devices, microcontrollers, sensors, and interfaces; and the social dimension focus on addressing and meeting

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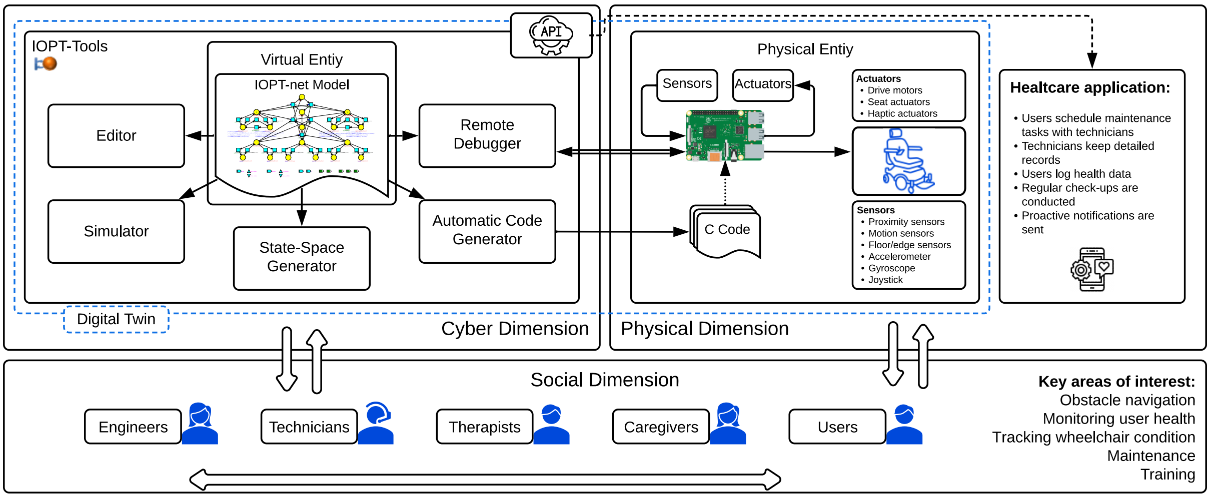

Figure 1: A framework for a cyber-physical social approach to power wheelchairs.

the diverse needs of users and stakeholders. Section 2 presents the proposed cyber-physical social approach; Section 3 provides some discussion around the proposal and work in progress; and Section 4 presents concluding thoughts and future work.

2. A Cyber-Physical Social Approach to Power Wheelchairs

Each dimension in a cyber-physical social approach contributes to a user-centric solution. Notable, in this approach, stakeholders placed in the social dimension can rely on the cyber dimension for services that can enhance their experience in the physical dimension. The proposal overview is in Fig. 1, with detailed explanations in the following subsections, beginning with the assessment of essential system requirements within the social dimension.

2.1. The Social Dimension: Stakeholder Interactions and Requirements

The social dimension of the CPSS in Fig. 1 includes users and caregivers using power wheelchairs, therapists involved in rehabilitation, technicians responsible for selecting technology for power wheelchairs and providing training and technical support, and engineers who can design innovative solutions within that framework. The focus is precisely on collaboration among them (in social dimension) to optimize users' capabilities through seamless operation of wheelchairs and related services, ultimately promoting sustainability in the context. This involves selecting features and functionalities to enhance user safety, comfort, and handling, while reducing maintenance and repair expenses. To reach this goal and as part of a user-centric strategy, an online questionnaire was used to gather insights from those with personal or professional experience with power wheelchairs [11].

A total of 139 participants were informed about the study through a list of non-governmental organizations for people with disabilities and companies specializing in wheelchairs. For users, the survey delved into their disabilities, current power wheelchair details, control devices, past experiences, and desired features. It also explored their maintenance history, preferences for remote services, and their thoughts on integrating health monitoring. For others involved, the survey focused on their preferred features, the services they wished users had access to, and how support for wheelchair users could be improved. To end, the survey offered an opportunity for general feedback. The findings underscored several key areas of interest for participants; highlighted here are obstacle navigation, monitoring user health, tracking wheelchair condition and maintenance, and training.

Power wheelchairs pose practical challenges due to their bulkiness, obstructive seating, and lack of visibility aids, making navigation difficult in tight spaces. Respondents suggested incorporating mirrors, cameras, and/or sensors. Additionally, therapists and caregivers are concerned about users' prolonged sitting and pressure points on cushions leading to ulcers. Regarding users' health, they may also face respiratory issues, digestive problems, sleep disorders, and so forth. Therefore, respondents expressed interest in obtaining posture duration, comprehensive health data, and medication intake details. Technicians are also worried about users' misconception that wheelchairs do not need maintenance, leading to problems being addressed only after they arise. However, for users, maintenance also drives a demand for regular, fast, and affordable services. A systematic approach is required, with both preventive and corrective measures. Finally, there is a growing concern about the lack of user training, highlighting the need for improved education on power wheelchair usage. These insights lay the groundwork for the proposed CPSS, wherein the digital twin application (in cyber-physical dimensions) can address these issues by improve wheelchair design, operation, and maintenance. Also, by integrating users' health factors, it can significantly enhance the overall user experience and quality of life.

2.2. The Cyber Dimension: Petri Nets and Digital Twins

In the cyber dimension, Input-Output Place-Transition Petri nets (IOPT-nets) model digital twins. IOPT-nets are a class of non-autonomous Petri nets in which behavioral models can be conditioned through input and output signals or events. This makes them useful for specifying the interaction between systems and the external world, also suitable for creating a digital twin. In a digital twin, there is an automatic and two-way data flow from a physical entity (PE) - such as a wheelchair or its components - to the virtual twin (VE). The entities are dynamically updated and adjusted based on data, with changes in one leading to corresponding changes in the other. Thus, the creation of a digital twin relies on precise physical-digital mapping and the data flow between the entities that make it up. While other models can be considered, behavioral modeling stands out because it can explicitly specify how a PE behaves, interacts, and reacts to external stimuli. Moreover, it is ideal to simultaneously design both PE and VE with the same characteristics, properties, functions, and models.

For this reason, this approach proposes using IOPT-nets to model the behavior of both the PE and VE in DT. In particular, using the same IOPT-net model can ensure that PE and VE evolve and align as intended, maintaining the consistency of the DT over its lifecycle. On the PE side, the model can effectively satisfy numerous functional and safety requirements. The net can model the behavior of the power wheelchair and its augmentations with sensors, actuators, user input devices, and other features that may need to be added. On the VE side, the same model can be used to monitor and control the PE after deployment. The design of the model and implementation of PE are facilitated by the IOPT-Tools framework [10]. IOPT-Tools is an online framework meant for developing controllers specified with IOPT-nets. The provided tools include a graphical IOPT-net model editor, a simulator [12], a state-space generator [13], an automatic code generator [14], and a remote debugger [15]. The editor is used for model specification; the simulator and state-space generator verify and validate the desired requirements for PE/VE; and the automatic code generator converts the IOPT-net model into software code for microcontrollers or hardware descriptions for FPGAs. Afterward, the VE and its connection to PE are placed using the IOPT-tools remote debugger (refer to Fig. 2).

The PE-VE connection within the DT primarily serves to enable the VE to oversee and potentially influence the PE. For the VE, the aim is not only to observe and predict PE actions, but also to exert control over the physical dimension as needed. This enhances the VE's ability for remote intervention, such as adjusting the speed of drive motors based on sensor-detected obstacles. This underscores the importance of interacting with PE related elements in the physical dimension, specifically sensors and actuators. Sensors provide input signals to the PE, conveying instructions to the model or monitoring real-world conditions; actuators translate the model's output signals into actions in the environment. The IOPT-nets enable this particular feature through their inputs and outputs, with each signal potentially being mapped to a GPIO for deployment purposes. During implementation, the code generator maps IOPT-net signals to platform pins, enabling interaction for the PE. This way, the PE, e.g. a wheelchair, can gather sensor data, receive input from joysticks, buttons, or switches; or issue commands to actuators, and manage displays/LEDs for user communication.

When the VE aims to control the PE, it does so by modifying inputs and outputs, overriding real

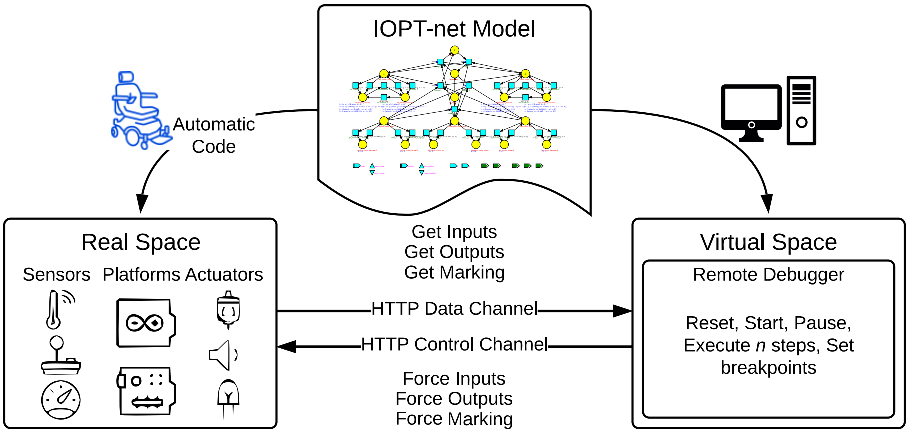

Figure 2: An IOPT-net model used to specify a PE and a VE within a digital twin, and their connectivity across cyber-physical dimensions.

values on GPIO pins; and the PE evolves towards the desired behavior. This points out the need for seamless data exchange between PE and VE that bridges cyber-physical dimensions. In this sense, the IOPT-tools remote debugger facilitates the connection between the VE and PE. This feature proves particularly beneficial when models are running on devices that are not easily accessible, extending remote operation capabilities to the DT. For instance, this is advantageous for customers residing in remote areas with limited access to service providers and healthcare professionals – who can start offering remote assistance. The code generated for the PE incorporates an HTTP server definition intended to establish a connection with the remote debugger, where the VE is running (refer to Fig. 2). This enables the VE to promptly receive notifications regarding any alterations in the PE's state, and to transmit commands. By monitoring PE changes, the VE visually mirrors its state in the IOPT-net model. The remote debugger also includes tracing for step-by-step execution, breakpoint setting, and remote PE state control via VE. Finally, the remote debugger incorporates a history recording feature, saving the evolution of the net. This recorded history can be replayed later through the simulator, facilitating a thorough analysis of PE conditions.

2.3. The Physical Dimension: Power Wheelchairs, Sensors, and Interfaces

Within the physical dimension power wheelchairs are the core. Customizing and ensuring their regulatory compliance is costly and difficult to address. Therefore, the use of a digital twin with low-cost add-on devices presents a good alternative to high-end equipment. Namely, wheelchairs equipped with obstacle and proximity sensors can address concerns around navigation and maneuverability. These sensors, along with motion sensors and floor/edge detectors, create a comprehensive awareness system. They help users navigate by detecting objects in their path, including blind spots, tracking their movement, and identifying changes in terrain. Through features like audible alerts and vibration feedback, these sensors can educate, train, and ultimately empower users, particularly those with visual impairments, to move safely and confidently in their environment.

While here the main focus of the digital twin is on developing new features for a power wheelchair, its application has the potential to extend and integrate into various applications via APIs, thereby enhancing the overall end-user experience. Addressing some of user's concerns may simply involve a solution similar to healthcare apps, which offer real-time tracking, proactive notifications, and user engagement. These apps give users the ability to establish plans, set goals, and schedule reminders. Improving healthcare for wheelchair users may involve using an application for logging health records and setting timely alerts, granting users autonomy over when and with whom to share their health information, enabling a personalized and flexible approach to disclosure. This type of application encourages user engagement for customization based on individual needs and preferences; and can be used to help power wheelchair users monitor details of medication intake, stay hydrated, manage (rehabilitation) activities and sitting positions, and ensure adequate rest, all through personalized notifications. An accelerometer and a gyroscope can track users' sitting positions, providing insights into the time spent in a specific posture; and coupled with personalized plans, users can heighten awareness of their sitting habits, reducing the risk of skin injuries and promoting better posture. Ultimately, such a tool can provide insights into users' habits and help those who face challenges in maintaining a consistent routine.

This user-centric strategy can also facilitate users' adherence to wheelchair maintenance practices assisted by someone capable of checking tire pressure, tightening screws, cleaning, etc. An application for users' adherence to wheelchair maintenance practices can be a way to raise awareness about self-regular checks and help identify issues early on, preventing unexpected breakdowns; users can also be alerted through timely notifications to schedule necessary maintenance tasks with technicians. But if on the one hand, there is a need to educate users about the maintenance of their wheelchairs, on the other hand, technicians need a way to keep detailed records of the support and maintenance procedures they carry out. This includes documenting the repair and modification history, reporting the procedures performed, along with dates, requested parts, quotations, and other relevant information readily available to track the wheelchair's condition over time. Ultimately, supporting preventive maintenance practices through this strategy can result in long-term cost savings.

3. Discussion and Overview of Work in Progress

Around 16% of people worldwide face a higher risk of discrimination, poverty, and abuse due to disabilities [16]. Assistive technologies can greatly improve their independence and overall well-being, while reducing the need for healthcare. Yet, 90% of these individuals lack access to these essential products [17], hindering their participation in society equitably. Although many challenges faced are not tech-related (e.g. wheelchair accessibility barriers), investing in technological advances helps to meet users' diverse needs so they can seize their rights and opportunities. In this way, it is possible to tap into varied talents and contributions, leading to increased stability, balance, and sustainability for everyone. On the other hand, it is important to involve people with disabilities in decision-making processes to ensure that assistance is built into solutions from the design phase, rather than being an afterthought. The WHO's GATE initiative aims to improve access to high-quality affordable assistive products through a person-centred approach [18]. It collaborates with multiple stakeholders, including users, to strengthen policies, ensure reliable supply chains, and improve services and workforce capacity.

In light of this, advocating for a cyber-physical social approach is paramount. The first steps of the approach described above have already been taken. In addition to conducting a stakeholder inquiry survey, an IOPT-net model was designed to deploy a digital twin for a power wheelchair. IOPT-nets and IOPT-Tools have proven successful in achieving this goal. The model specifies the behavior required for the wheelchair to move and adjust seating positions as needed, serving as basis for further development. The model showed in Fig. 3 is accessible under the name "CPSS4Sus2024.pnml" within the IOPT-Tools environment [19] (user: models, pass: models). Part A outlines the inputs and outputs necessary for cognition/control in the DT; submodels B and C control the wheelchair's drive motors, enabling actions of stopping, moving forward, and backward; submodels D, E, and F similarly adjust the positions of the backrest, seat, and footrest for user comfort; and submodel G manages the operational mode of the wheelchair, ensuring the joystick functions differently based on the selected mode (driving or seating), which prevents unintended seat adjustments during driving. The IOPT-Tools simulator verified the behavior of the model ensuring it functioned as expected and confirmed it was deadlock-free. Following this, it was generated C code for the model; and this code ran on a Raspberry Pi, which communicated with a remote debugger. This allowed to remotely monitor and control the state of the physical wheelchair prototype. The future work using this CPSS approach will involve incorporating user feedback and preferences into this model, making the wheelchair meeting the presented requirements.

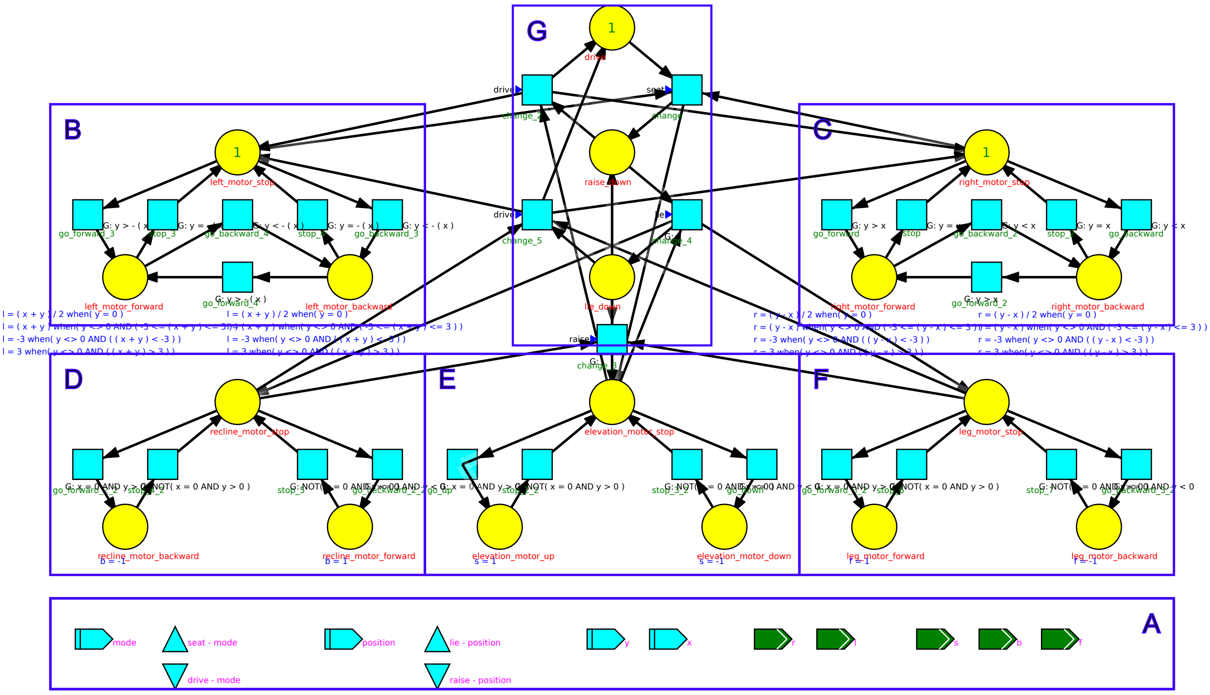

Figure 3: *CPSS4Sus2024.pnml*: IOPT-net model of a digital twin for a power wheelchair.

4. Conclusion and Future Work

Power wheelchairs have the potential to significantly increase the independence of people with mobility impairments in their daily lives. However, many market offerings fail to fully meet user needs. Just like other industries, the power wheelchairs sector must also adopt new technologies and user-centric strategies to empower users and contribute to a more inclusive and sustainable society. The framework presented here offers a significant advancement in the design and implementation of user-centric power wheelchairs through a cyber-physical social approach. This approach not only can address the limitations of conventional models but also sets a precedent for inclusive design and collaboration among stakeholders. Through the integration of social aspects, technology, and the environment, power wheelchairs can be enhanced to better meet diverse user needs while ensuring safety and reliability.

The use of IOPT-net-based digital twin serves as a cornerstone in this proposal. Digital replicas of power wheelchair, or specific components, enable iterative design, real-time simulations, and remote control, thus facilitating the development of innovative and personalized solutions in the sector. Furthermore, IOPT-Tools proved to be instrumental in modeling and validating the behavior of both physical and virtual entities within the cyber dimension; as well as in deploying a prototype at the physical dimension. Looking ahead, the approach future application, using a real Invacare Fox wheelchair [20], will provide valuable insights into its practical benefits and applications for mobility solutions.

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