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Development of a Teleoperated Knee Rehabilitation System Base on the Industry 4.0 Model

Desarrollo de un sistema de rehabilitación de rodilla teleoperado basado en el modelo Industria 4.0

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Abstract

Health Care Institutions in Colombia are geographically distributed irregularly. The entities that provide specialized services, such as physical rehabilitation, are concentrated in the main cities. Although the coverage of the Colombian health system has increased in recent years. Barriers to access to health services, such as geographic vulnerability and the cost of transportation to rehabilitation centers, continue to be a problem that is felt in the country. This project presents a control system for teleoperation via the internet of a technological aid for physical rehabilitation of the knee based on the industry 4.0 model. For this, a design methodology is proposed that integrates several resources and tools from various areas, including mechanical, electronic, and information technology, such as SysML, distributed control, databases, and rehabilitation devices, among others. As a result, a functional prototype of the system is achieved that allows us to technically evaluate an infrastructure that allows patients to perform their procedures without moving long distances from their place of residence. In addition, the implementation of the Industry 4.0 model allows us to have an integral vision of the system, facilitating later scalability of the project such as the implementation of a predictive maintenance program.

Keywords: Industry 4.0 applications, Remote-Controlled Knee Therapy, Smart Healthcare Technology

Resumen

Las Instituciones de Atención de Salud en Colombia se encuentran distribuidas geográficamente de manera irregular. Las entidades que brindan servicios especializados, como rehabilitación física, se concentran en las principales ciudades. Aunque la cobertura del sistema de salud colombiano ha aumentado en los últimos años. Las barreras al acceso a los servicios de salud, como la vulnerabilidad geográfica y el costo del transporte a los centros de rehabilitación, siguen siendo un problema que se hace sentir en el país. Este proyecto presenta un sistema de control para teleoperación vía internet de una ayuda tecnológica para la rehabilitación física de la rodilla basado en el modelo de industria 4.0. Para esto se propone una metodología de diseño que integra varios recursos y herramientas de diversas áreas, incluyendo mecánica, electrónica y tecnologías de la información, como SysML, control distribuido, bases de datos y dispositivos de rehabilitación, entre otros. Como resultado se logra un prototipo funcional del sistema que permite evaluar técnicamente una infraestructura que permita a los pacientes realizar sus procedimientos sin desplazarse grandes distancias de su lugar de residencia. Además, la implementación del modelo Industria 4.0 nos permite tener una visión integral del sistema, facilitando la posterior escalabilidad del proyecto como la implementación de un programa de mantenimiento predictivo.

Palabras clave: Aplicaciones de la Industria 4.0, Terapia de rodilla por control remoto, Tecnología sanitaria inteligente

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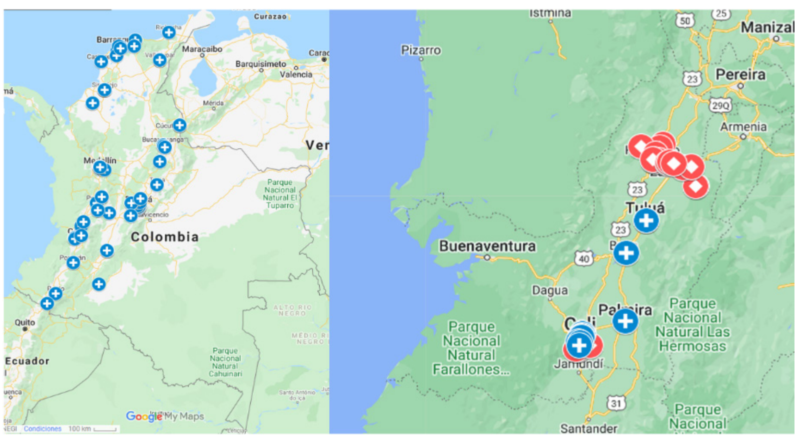
Introduction

In Colombia, Health Care Provider Institutions (IPS for its initials in Spanish) are classified into four levels according to the type of complexity of the service (1). According to the Special Registry of Health Service Providers database (2), level II and III centers offering specialized services, such as physical rehabilitation, are geographically distributed in the main cities, as shown in Figure 1a. At the departmental level, similarly, this type of institution is centralized in the main municipalities, such as Cali and Palmira. See Figure 1b. While those of level I, mainly oriented to promotion and prevention activities, are in rural areas, small municipalities, and peripheries of the cities.

This problem is compounded by the fact that the resources associated with these specialized services are limited, both in terms of health personnel and technology. For example, in 2018, an average of 2.2 physicians per 1000 inhabitants was recorded (3), of which only 26.5% are specialists (4).

According to statistics from the 2005 General Census and the 2018 National Population and Housing Census, the number of people with difficulties in performing daily activities increased by 19.4% (5). Of these difficulties, 27.3% correspond to disabilities that affect daily activities of moving the body, walking, or going up and down stairs. In addition, this population is distributed in low socioeconomic levels 1 and 2 (5).



(a) (b)

Figure 1 (a) Distribution of level III IPS in Colombia (b) Distribution of level III and II IPS in the department of Valle del Cauca.

Based on the above, and although the percentage of health system coverage has increased to 99.6% in 2022 (6), complete and equitable access to health services for the Colombian population is still not guaranteed. In other words, the health system continues to present a barrier to access to specialized services for part of the population based on socioeconomic status and geographic location. An example of this fact is the difficulty of the care of a knee injury in inhabitants of rural areas of Colombia, or who are in the Amazon and eastern plains regions. They must travel to a specialized physical rehabilitation center to receive care (7). Consequently, people with physical disabilities

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located in rural areas find it difficult to access rehabilitation procedures and therapies, affecting the well-being of both the affected person and his or her family (8). This critical scenario is exacerbated by the fact that these conditions often require several sessions for proper recovery, which implies an additional economic burden for patients and a recurrent demand for resources for the health center.

One of the solutions to integrate coverage with ease of access to health care services is telemedicine. Although over time, technological offers, and studies on the application of telemedicine have increased (9), they focus on topics such as palliative care, internal medicine, pediatrics, psychology, postoperative care, and ophthalmology, among others. For example, in Colombia, in 2020 during the COVID-19 health emergency, there was an increase in the number of healthcare providers offering telemedicine services. The five telemedicine-enabled services are internal medicine, psychology, nutrition and dietetics, dermatology, and cardiovascular diagnosis (10).

In the case of physical telerehabilitation, programs, and studies have focused on therapy sessions via videoconferencing where the physician instructs the patient on the exercises to be performed, or with computer programs with pre-recorded videos, avatars, or mobile applications. These programs show the exercises to be followed by the patient and which the patient must then record for follow-up (11, 12, 13, 14). In the context of teleoperated physical rehabilitation, the studies found are mostly performed on the upper extremity (15, 16, 17, 18) and a few on the lower extremity (19, 20). However, these solutions did not integrate the Industry 4.0 model into their proposal.

For the background search of industry 4.0 in physical rehabilitation, the keywords "industry 4.0" and "industria 4.0" were used on the Web of Science and EBSCO Discovery Service databases. The publishers with the largest number of related publications are Elsevier, IEEE, Spring, and Wiley. Subsequently, the search was refined in the databases of the aforementioned publishers and in Scholar Google with the keywords: "industry 4.0 telerehabilitation teleoperation", "industry 4.0 physical therapy teleoperation" "industria 4.0 rehabilitación física teleoperada" "industria 4.0 telerehabilitación física" indicating the originality of this proposal, since no studies implementing this methodology were found. In this context, this work is presented as a contribution in the area of physical rehabilitation in the framework of the fourth industrial revolution. The implementation of this model presents the advantage of holding a digital representation of the system, which allows for having an integral vision with greater control and feedback of the system.

This degree project proposes to develop a control system for teleoperation via the internet of a technological aid for physical rehabilitation of the knee. Thus, allowing patients to perform their procedures without having to travel long distances from their place of residence. Additionally, the integration of the Industry 4.0 model in this solution makes it a contribution to the transition of the healthcare sector towards digital transformation.

The following objectives were established for the development of the architecture: identify the requirements for an Industry 4.0 architecture applied to the physical

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rehabilitation sector, using SysML modeling techniques; propose the architecture of the control system for the technological aid considering an Industry 4.0 approach; validate the proposed architecture through a functional prototype defined as a pilot case. These objectives were the guides for organizing the production of the architecture.

Conceptual framework

Passive knee therapy

For the rehabilitation of knee injuries for those patients who do not have the qualities to perform it actively, passive therapy is used. This is supported by technological aids for the early recovery of the patient who cannot try to perform the movement voluntarily (21), such as Continuous Passive Motion therapy (CPM).

CPM is considered a suitable procedure for clinical cases such as partial or total knee arthroplasty (knee replacement), cruciate ligament damage, arthrolysis (removal of tissue adhered to the joint), and tibial plateau fracture, among others.

In Figure 2, the physical asset of the continuous passive motion rehabilitation unit is depicted. This device presents a functional topology inspired by a 4-bar mechanism, where motion is generated through the activation of a power screw. A detailed description of the mechanical component and its application can be found in Balanta Tovar (22). Additionally, specifics regarding its electronic composition and strategies employed in the control system are discussed in Camacho Sánchez (23).

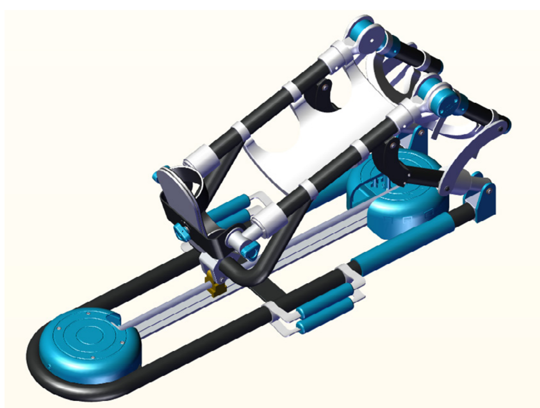

Figure 2 Industry 4.0 asset of the Teleoperated Knee Rehabilitation System.

The following discusses the generation of the digital model of the passive motion unit in accordance with the guidelines presented in the Industry 4.0 model. These guidelines are aimed at reducing barriers to access medical care in physical rehabilitation using teleoperation techniques.

Industry 4.0

By integrating advances in information and telecommunication technologies with robotics, simulation, and other areas, an industrial model called Industry 4.0 has been defined. This concept defines an intelligent network of machines and processes for

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the industry with the help of information and communication technology. This new smart manufacturing model is standardized by the Plattform Industrie 4.0, a platform supported by the German government (24). And since the fourth industrial revolution, it is promoted worldwide, such as in Latin America (25, 26).

The model enables system flexibility, as the digitally represented modular type structure allows a holistic view of the system with increased control and feedback of the components. The implementation of value-based services with sustainability is the central objective of this model (27). The generated infrastructure offers a better use of the resources involved in increasing product value by collecting data, such as considering the complete product life cycle and receiving feedback from the end user. This data can then be used to offer new services to the user such as predictive and corrective maintenance (28).

To help researchers and companies understand and implement the I4.0 model, the Reference Architectural Model Industry 4.0 (RAMI 4.0) was established as a reference model that provides a framework for the different aspects of I4.0 and how they work together (29, 30). The RAMI 4.0 architecture consists of three-dimensional coordinate systems (Figure 3) that are based on a modular concept. This allows us to upgrade or reconfigure systems easily and without significant disruptions.

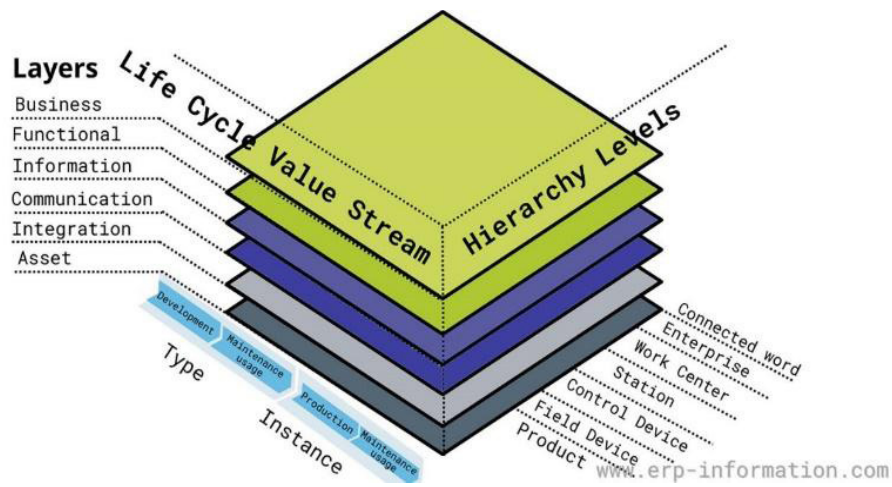

Figure 3 Reference Architectural Model of the Industry 4.0. Original: www.erp-information.com

OMG SysML®)

The OMG Systems Modeling Language™ (OMG SysML®) is a domain-specific modeling language for engineering systems applications, to specify, analyze, design, and verify complex systems that may include hardware, software, information, processes, personnel, and facilities. Primarily, this language provides graphical representations with semantic foundations for modeling system requirements, behavior, structure, and parametric; to be later integrated with other analytical engineering models (31).

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The basic unit of a structure in SysML is the block, and it is used to represent hardware, software, and personnel, among other system elements. This modeling language is structured under four pillars, structure, behavior, requirements, and parametric (32). Figure 4 shows the four pillars and the diagrams that conform to them.

The blocks highlighted in green were the diagrams implemented to model the knee teleoperation system, which are presented later in Figures 7, 8, 9 and 10. These consist of the activity diagram, which specifies the transformation of inputs and outputs, as well as those responsible for these activities. The sequence diagram, which models the control flow. The use case diagram, which describes the basic functions in terms of the use or objectives of the system by the actors. The requirements diagram, which establishes the system's hierarchy and specifications. And the internal block diagram, which describes the internal structure of a block in terms of its properties and connectors (33).

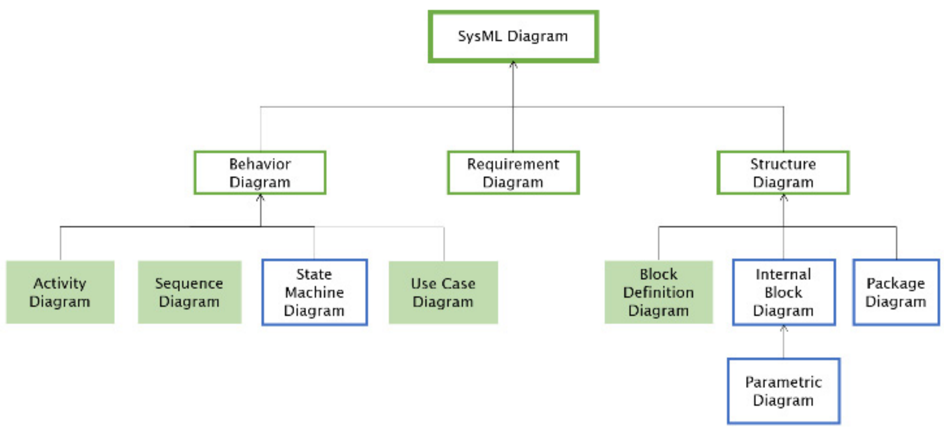

Figure 4 OMG SysML® diagram types

Requirements

The requirements diagram, shown in Figure 5, shows a consolidation of the requirements for the telerehabilitation control system. These are classified into three main contexts, technical control, therapy session control, and connection and diagnosis, which correspond to functional aspects related to technology, medical application, and communication with the device, respectively.

An approach to the requirements is presented in Figure 6. Where each requirement has: a name, an identification number, and a description. The figure shows the functional requirement therapy session parameters, which display the current angle, speed, time, and duration of the session on the therapy session screen.

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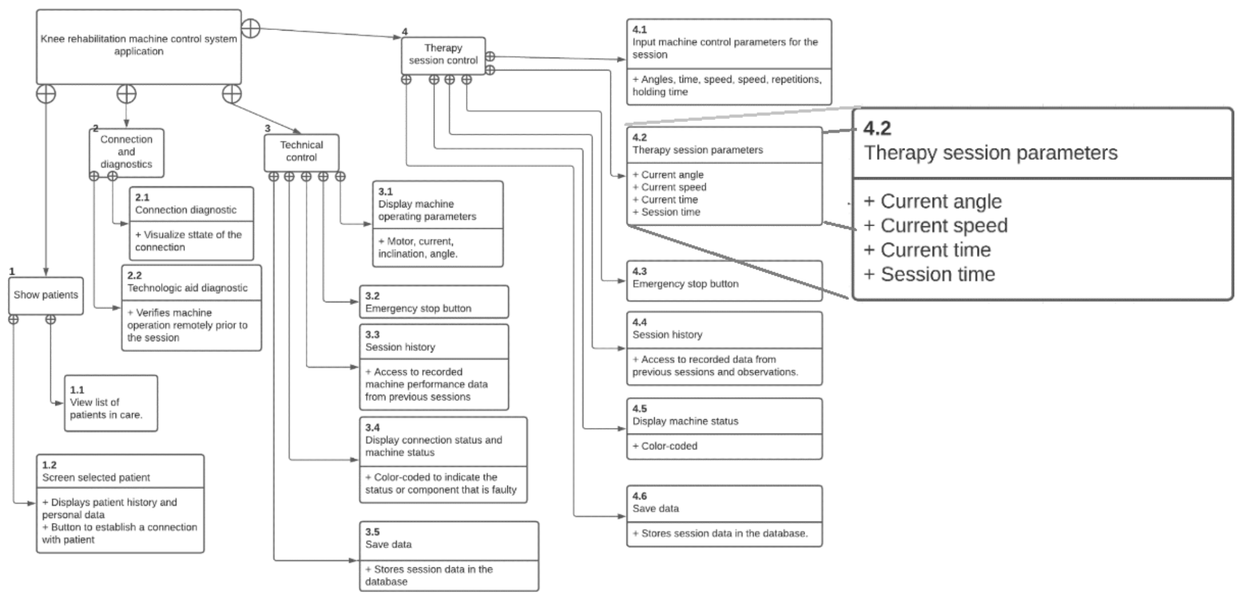

Figure 6 Requirement diagram of the Teleoperated Knee Rehabilitation System.

Design

Figure 7 shows the proposed architecture for the teleoperation of the technological aid for the knee. The system is composed of three main blocks: the knee rehabilitation machine, the OPC UA server, and the web application for its control. Where the communication protocol of the OPC UA server allows the data obtained by the sensors in the technological aid to be available for other machines or OPC UA clients to use. Thus, transforming the knee rehabilitation machine into an I4.0 Component.

The use case diagram for the telerehabilitation system of the knee machine is presented in Figure 8. The environment includes the rehabilitation machine, its virtual representation located in the OPC UA server, implementing the information model considering the recommendations of Industry 4.0, and the web application. On the other hand, the actors that interact with the system are the Physician in charge of directing the therapy session and the Technician, to follow up on the operation of the machine.

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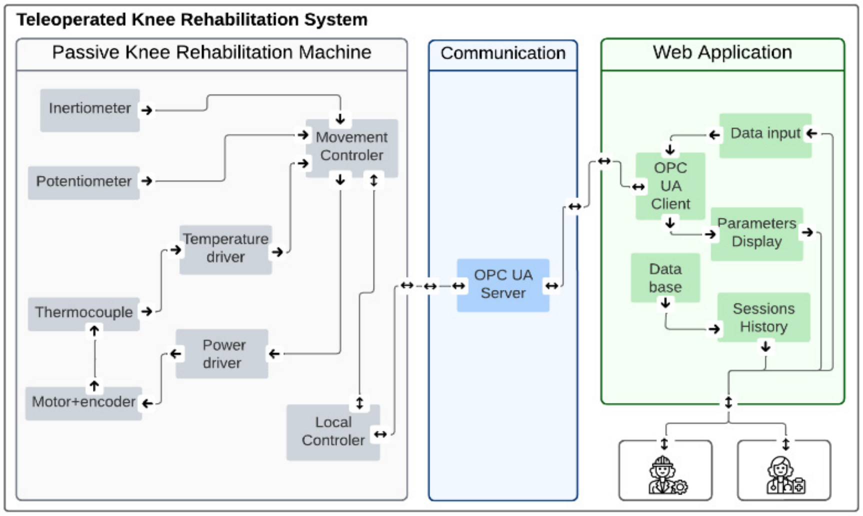

Figure 7 Teleoperated Knee Rehabilitation System architecture.

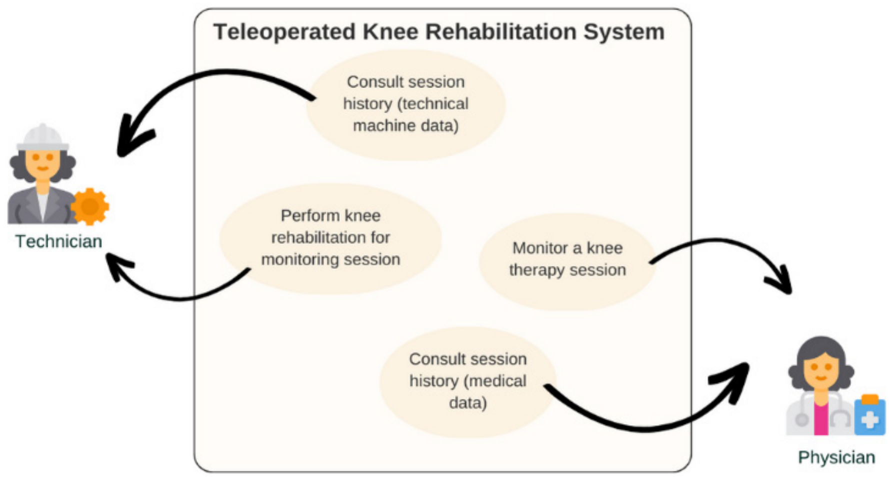

Figure 8 Teleoperated Knee Rehabilitation System Use Cases.

Based on the system's use case diagram, activity diagrams were created for each of the cases. Figure 9 represents the activities to be performed for the fulfillment of the use case of Perform knee therapy session, in which the physician participates as an actor. The TeleRehab I4 system connects the client with the service and the knee rehabilitation machine. The scenario starts with the identification of the actor, depending on the role, Physician or Technician, the interface presents different screens; in the case of the Physician, it shows the patients and by selecting one it allows the creation of a new session and gives access to the history of previous sessions of each patient. In the case of the Technician, it shows the monitoring sessions previously performed and allows the creation of a new session. In the session created, the parameters for the therapy or monitoring to be performed are entered and sent to the server, which communicates them to the machine to start the therapy.

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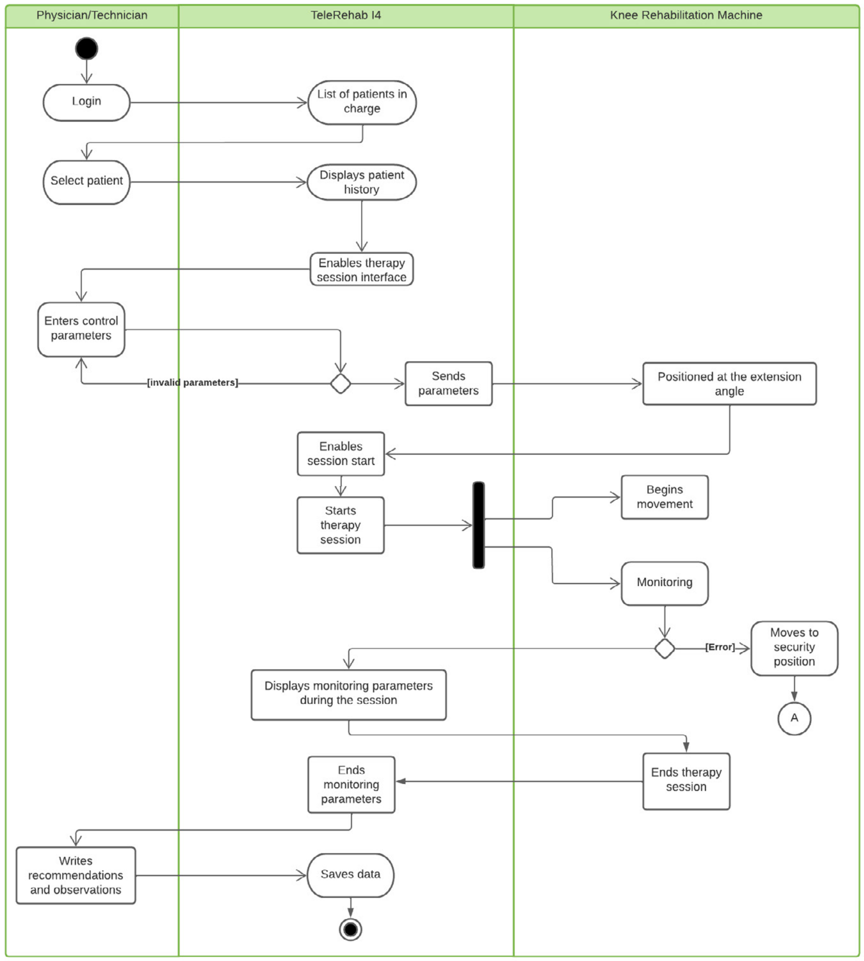

Figure 9 Teleoperated Knee Rehabilitation System activities diagram.

The interaction between these elements is shown in Figure 10 using a sequence diagram. This diagram describes the communication of three main processes between the components of the control system. The first is the communication between the OPC-UA server and the controller; the second is the sending of the parameters entered from the TeleReha-I4 web application to the database and the technological help. Finally, the values received from the sensors installed in the machine are sent to the web application for display.

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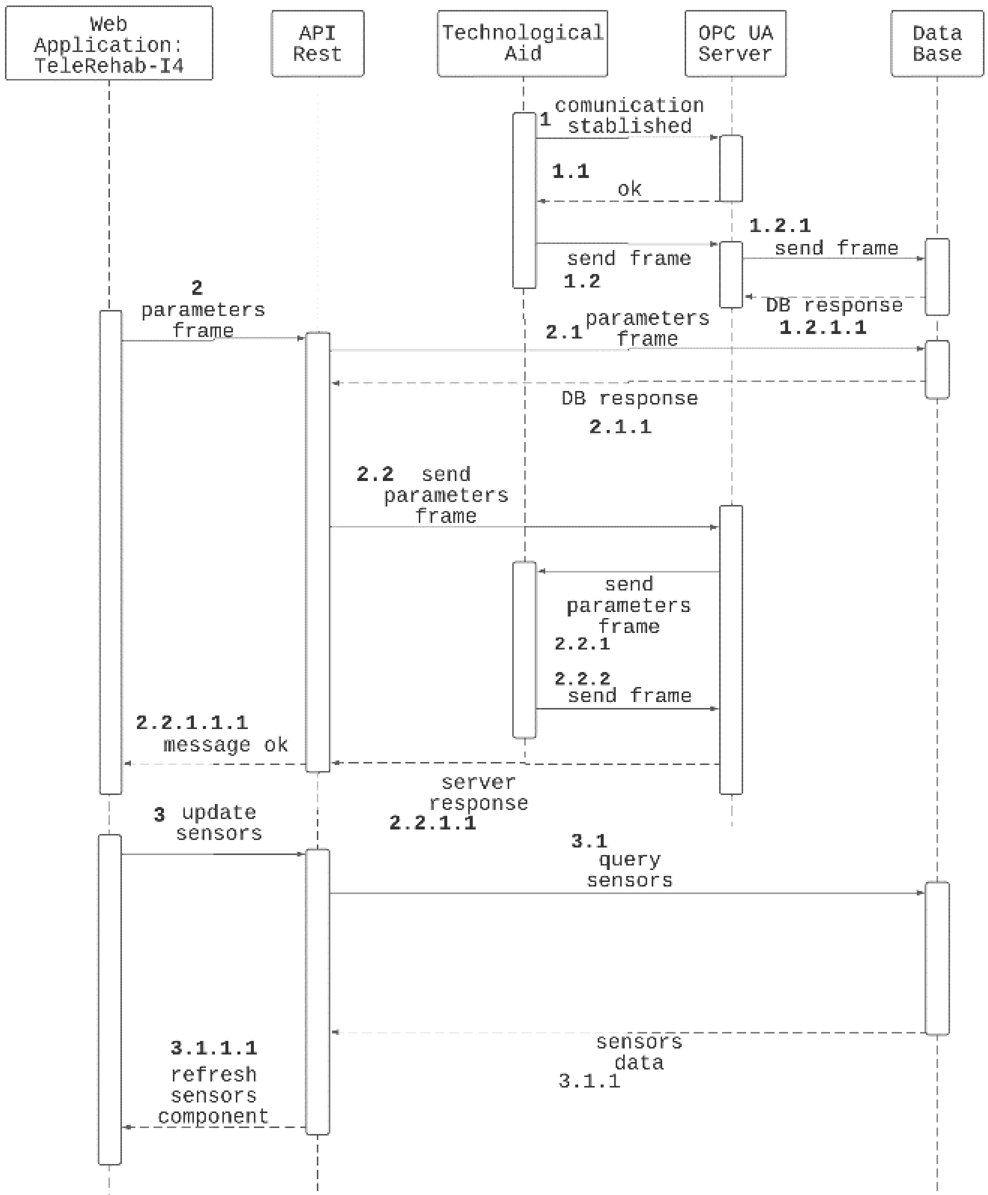

Figure 10 Teleoperated Knee Rehabilitation System Sequence Diagram.

The virtual representation of the server in the distributed system of telerehabilitation is achieved by employing an Address Space and is shown in Figure 11. This contains nodes, with their corresponding variables and methods, that characterize the server and are used to communicate with the other components.

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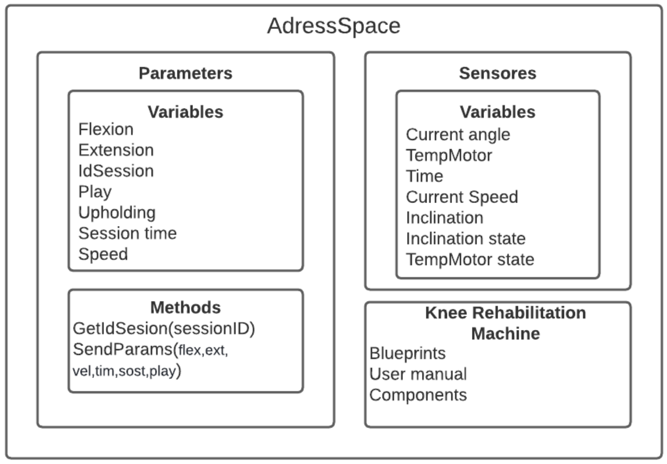

Figure 11 Virtual representation of the Teleoperated Knee Rehabilitation System.

The total implementation of the information system is presented in Figure 12 showing the components used to build the functional prototype (34). The information system TeleRehab I4, is then, consists of three components, i) the client, a web application that allows the user to transmit the desired information for remote control of the machine; ii) an integration layer that allows the communication between the client and the server through a set of resources and a database for data storage and query; iii) the server, is an element that offers the services of technological aid for its remote control.

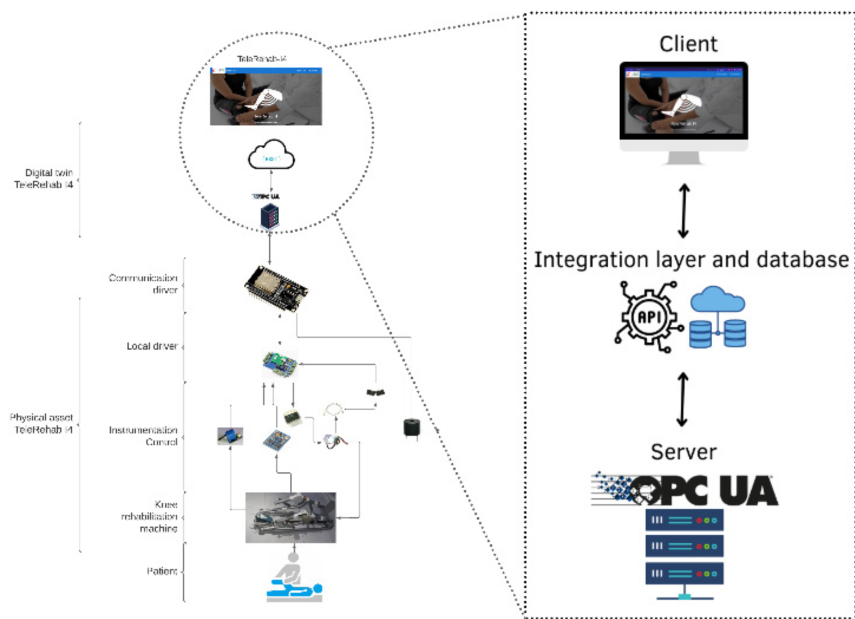

Figure 12 Functional prototype architecture of the Teleoperated Knee Rehabilitation System.

Figure 13 presents a decomposition into the layers of the RAMI 4.0 model of the technological aid as an I4.0 Component. Where the administration shell consists of the

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business, function, and information layers, that is, the database where the information input through the web application TeleRehab I4 is stored and the manifest from the OPC UA. It shows, as well, that for communicating the information obtained through the sensors, OPC UA is used.

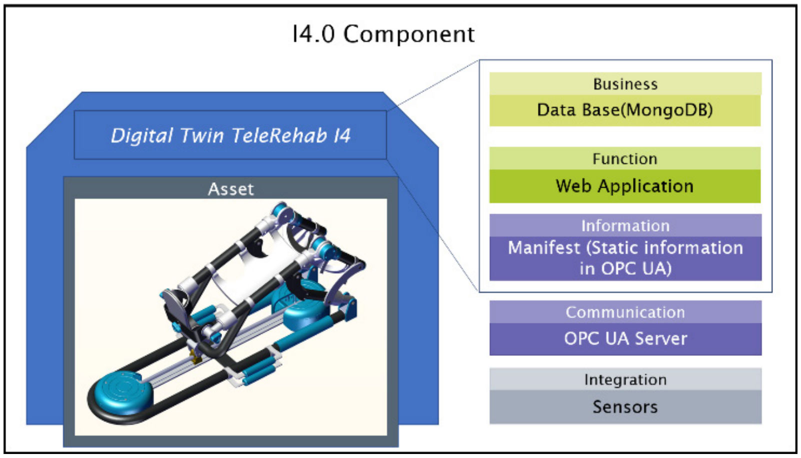

Figure 13 Component I4.0 of the Teleoperated Knee Rehabilitation System.

Validation

Validation serves to verify that the built prototype follows the proposed models. For this case, the validation scenarios are presented in Table 1. The five scenarios follow the sequence presented in Figure 10 Teleoperated Knee Rehabilitation System Sequence Diagram.

Table 1 Validation scenarios

Test	Scenery	Description	Verification item
1	First, start-up.	The machine is installed at the test site and connected to the internet network.	The server prints its availability and connection port by console.
2	Communication between the server and the controller	The server sends and receives data with the controller.	A response message from the controller to the server is displayed.
3	Creation of a therapy session in the web application.	The server puts the web application on the local network to perform sessions.	When a new session is created, the browser console displays the session id generated by saving it to the database.
4	Sending session parameters	The database is updated with the session parameters and sent to the machine.	When the form is submitted, a pop-up window confirms the data submission, and the updated frame with the values is printed on the console.
5	Therapy session starts	The controller continuously sends the status of the components.	The relevant values of the frame that is printed on the console are displayed in the web application.

To exemplify compliance with the table of scenarios, the last one is presented, Therapy session starts. Figures 14 and 15 show the web application where the values are displayed,

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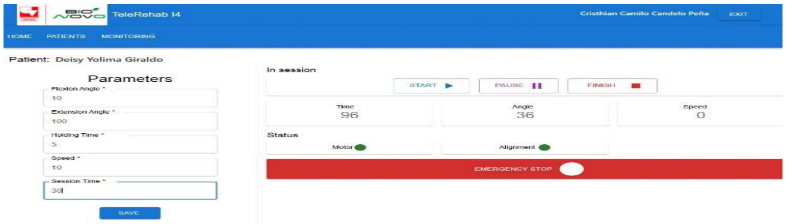
and the document created in the database corresponds to the session started. To be able to execute the last scenario, all the previous ones had to be valid, so the global operation of the architecture was verified.



(a)

(b)

Figure 14 Therapy session starts (a) Web application (b) Document in MongoDB database.

Figure 15 Therapy session test and communication flow. (35)

Discussion

Analyzing the results in three contexts: connectivity, functionality and management of the rehabilitation section, the following observations stand out: In relation to

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connectivity, the functional prototype evidenced positive aspects that favor the usability of the device, such as the indication of availability and connection port by the server. However, the tests showed that the user interface needs to be improved to facilitate the configuration of the IP address by the end user. Additionally, although the wireless connection mode favored the user experience, wired connectivity is recommended to minimize the dependency on the location of the router, server, and controller. In relation to functionality, the proposed standardized architecture evidenced acceptable performance, the lactation times, <0.1s, allowed acceptable logging and message exchange between the rehabilitation unit, server. However, the need for system saturation testing is evident. Regarding the section management, the proofs of concept evidenced an acceptable performance of the system in terms of the implementation of a loosely coupled architecture, such as the use of a non-relational database. In this sense, the scalability of the system is favored, facilitating the integration of future components, for example, modules for information analysis or diagnosis of rehabilitation devices.

Conclusions

This work contributes to the development of teleoperated technological aids for the physical rehabilitation of the knee, a feature that favors access to this specialized health service. For this purpose, a distributed infrastructure that integrates advances in information technology, such as industry 4.0, is presented, which favors the exchange of messages between a health professional and knee rehabilitation units using the Internet as a communication channel. For the specification of the system, a model-based approach, such as SysML, was adopted. This modeling tool with a high graphical representation favored the multidisciplinary work of this application. Additionally, the modular modeling of the architecture and a structuring of the information system according to the Industry 4.0 model were validated in three contexts, connectivity, functionality, and management using a functional prototype. The establishing of a standardized model, such as the RAMI 4.0 model, facilitated its implementation and allows for system scalability. The results achieved show favorable aspects of the integration of the Industry 4.0 model to the development of teleoperated technical.

Using the industry 4.0 models, a functional prototype was developed, which enabled for validating of the proposed architecture and obtaining improvement ideas for future projects.

This project is a contribution to the area of physical rehabilitation in the framework of the fourth industrial revolution and as a basis to be implemented in other technological aids in this field or others with similar functionalities.

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