DIGITAL TWIN: AN OPTION FOR THE INTEGRATED DESIGN OF UPPER LIMB ROBOTIC EXOSKELETONS FOR REHABILITATION TASKS

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ABSTRACT

The development of the Digital Twin of an exoskeleton for upper limb rehabilitation task for hemiplegic patients, and its Virtual Commissioning prior to its manufacture is presented in this work. In these context biomechanical and clinical design criteria are integrated into Digital Twin concept. The power actuators, the development of 4 freedoms degree's mechanisms for shoulder and elbow flexion/extension, external and internal rotation and abduction of the upper limb, and prone/supination of wrist, the control system and user interface as well as its integration with the mechanical system is carried out. The mechatronic concept design is done using NX MCD software. Automation takes place in the TIA Portal software. A PLC which can be virtually simulated with the use of PLCSIM Advanced software and a Human-Machine Interface (HMI) for the control of the exoskeleton are included in the hardware configuration. The Real Commissioning of the designed prototype has been successful and its operation has been validated in pilot tests carried out at the Santiago de Cuba Surgical Clinical Hospital in hemiplegic patients with painful shoulder syndrome.

Keywords: exoskeleton, digital Twin, NX MCD, rehabilitation tasks.

INTRODUCTION

According to health systems database, cerebrovascular accidents (CVA) are the third leading cause of death in the world, with an estimated annual rate of about 15 million patients, of which five million remain with a permanent disability [1, 2]. These patients, as part of their neurological treatment, receive long hours of physiotherapy training for the affected limbs, to recovered their joint range of motion and muscle strength as well as possible. However, the levels of recovery with traditional physiotherapeutic work are very reserved, with sequelae remaining in 50 ÷ 70% of surviving cases, a third of these are unable to fend for themselves and approximately 75% lose their ability to return to work [3, 4, 5].

Exoskeletons for rehabilitation purposes development is the topic of many medical researches. Its applications include a wide spectrum ranging from the rehabilitation task of patients to replacement of vital functions, such as walking in people with permanent disable conditions. As rigid external structures exoskeletons incorporate actuators that allow controlled and precise movements, even allowing self-assisted rehabilitation, giving the possibility of controlling the equipment from the patient's electrical muscular activity (EMG) or electroencephalographic (EEG) [6-8].

The evolution of assisted design tools has improvement significant advances in the design of exoskeleton prototypes [8], allowing to obtain prototypes in 3D through Computer Aided Design (CAD) programs, manufacture them on machine tools by Computerized Numerical Control (CNC) with the use of Computer Aided Manufacturing (CAM) and perform simulations and analysis using Computer Aided Engineering (CAE). All these tools are today perfectly identified within the concept of Product Lifecycle Management (PLM).

With the rise of Industry 4.0, a term coined in Germany at the Hannover 2011 conclave [9], the focus shifted towards manufacturing and smart products through an environment generated where the physical world - real and the virtual world come together in a system called Cyber Physical- System (CPS), which is possible through what has been called the Internet of Things (IoT) [10].

One of the main protagonists of Industry 4.0 are the Digital Twins (DT), a phrase first coined by John Vickers, NASA's chief technology officer and later used by the engineer and computer scientist Michael Grieves in 2003 [11, 12]. According to [13], a Digital Twin is a virtual replica of a living or non-living physical entity. It is the virtual model of a product, process or service so that it serves to detect errors early in the design phase, test potential changes and reduce the time and costs used in the development of a real prototype.

The main goal of this work is to develop the Digital Twin of the exoskeleton for the rehabilitation purposes of the upper limb in hemiplegic patients. A methodology is applied in order to integrate design features, as well as biomechanical and clinical criteria, guaranteeing the design of the mechatronic concept, its automation and simulation in a virtual way with an HMI interface for the control of the exoskeleton.

MATERIALS AND METHODS

For the development of the mechatronic exoskeleton, the technologies provided by Siemens Digital Industries were used. Figure-1 shows the engineering flowchart used to achieve this.

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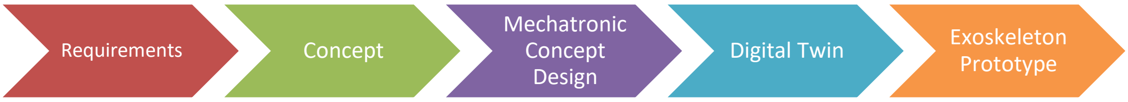

Figure-1. Digital Twin flowchart for the development of an upper limb exoskeleton. Source: Authors.

For the exoskeleton design, requirements related to ergonomic, biomechanical and clinical variables were taken into account, beyond the conceived criteria of mechanical resistance and requirements of structural materials that work in clinical environments [14,15].

The authors' experience in the design, manufacture and operation of equipment of this nature was taken into account, and especially those related to the therapeutic routines used in the clinical practice of rehabilitation of the upper limb and its kinematic and kinetic parameters (including those that depend on the degree of spasticity of the limb) and considering the ranges of physiological displacements for each degree of freedom of the joints and body segments involved. The movement routines selected for the study (4 degrees of freedom with 5 therapeutic movements) were: flexion/ extension of shoulder and elbow, external and internal rotation and abduction of the upper limb, and prone/supination of wrist [8,16].

The calculations were performed for patients with anthropometric characteristics 168 ± 12 cm of height, and 75.7 ± 15.4 kg of weight [16].

From the torques determined for the different movements [15], the required power of the electric motors was determined and the actuator system is complemented with the use of electric stepper motors, gearboxes and sliding adjustment plates. The rotation speed of each joint was estimated in the range of 20÷25 °/s from the consensus of the designers and physiotherapists.

Exoskeleton Digital Twin

For the development of the exoskeleton Digital Twin, as seen in Figure-2, the 3D modeling part is performed first in the NX software and then the mechatronic concept. Subsequently, the automation of the product is carried out using the TIA Portal (Totally Integrated Automation) software and finally the behavior of the virtual model is simulated with the help of the PLCSIM Advanced software.

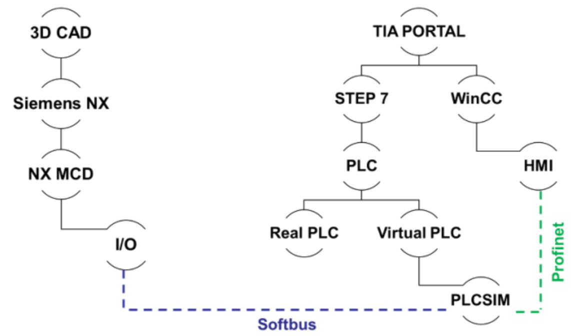

Figure-2. Schematic representation of Digital Twin concept. Source: Authors.

Three-Dimension Model of Rehabilitation Exoskeleton

Rehabilitation exoskeleton 3D modelling was designed in Siemens NX v1888 software. The dimensions of the pieces are preliminarily established to ensure the kinematic operating conditions, guarantee the anthropometry of the mechanisms that guarantee ergonomic and safe conditions for the patients. Figure-3 shows the CAD model of the exoskeleton.

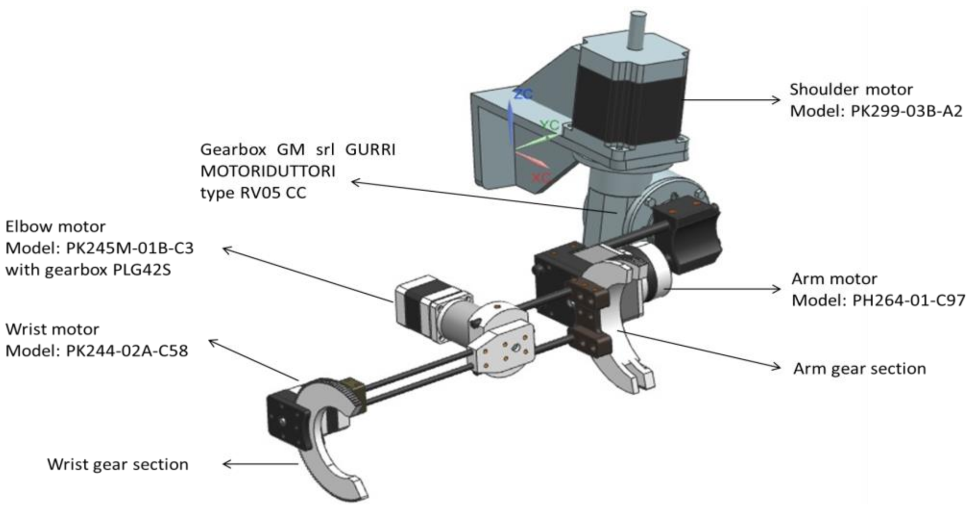

Figure-3. The 4 DoF upper limb exoskeleton. CAD model. Source: Authors.

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CAE Simulation

Using the Finite Elements Method (FEM), the geometric models obtained from the established kinematic and kinetic parameters, the mathematical modeling of the elements to be evaluated is carried out in order to evaluate the structure and design problems in the most critical working conditions.

Mechatronic Concept Design

The Siemens NX MCD (Mechatronics Concept Designer) package was used for Digital Twin design. This software enables 3D modeling and simulation of concepts with multi-body physics and automation related behavior. It accelerates the development of products that involve mechanical, electrical and software design disciplines, allowing them to work in parallel, focused on a design concept that includes mechanical components, sensors, actuators and motion [17].

For the simulation, the software lets inserting elements such as rigid bodies, of which their center of mass, mass and inertia are automatically calculated or entered manually, taking into account the material properties, joints and restrictions that restrict the degrees of freedom of rigid bodies or link them with others are also established. In addition, it considers to simulate existing gear mechanisms and control the position and speed value of the driving elements. Finally, using the signal adapter, output signals of NX MCD are exported, which serve as inputs for the control program [18].

Totally Integrated Automation (TIA PORTAL)

TIA Portal is an automation platform from Siemens which links the advantages of automation and digitization in a single tool. This makes production faster, more flexible, more efficient and improves results. Version 15.1 of the TIA Portal [19] software has been used for the automation of the exoskeleton Digital Twin.

Hardware Configuration

The hardware configuration [20, 21, 22, 23] includes a PLC for the control of the Digital Twin for virtual simulation (with the use of the PLCSIM Advanced software) and a Human-Machine Interface (HMI) to interact between them. The characteristics of the PLC model and the HMI used are shown in Table-1.

Table-1. Hardware configuration of the exoskeleton Digital Twin.

Devices	Model	Reference	Version
PLC	CPU 1511-1 PN	6ES7 511-1AK01-0AB0	2.6
Signals input card	DI 32x24VDC HF	6ES7 521-1BL00-0AB0	2.1
Signals output card	DQ 32x24VDC/0.5A ST	6ES7 522-1BL00-0AB0	2.0
Motor control modules	TM PTO 4	6ES7 553-1AA00-0AB0	1.0
Power supply	PM 190W 120/230VAC	6EP1333-4BA00	
HMI	TP900 Comfort	6AV2 124-0JC01-0AX0	

PLC Programming

For the development of the PLC code, the STEP 7 [24] tool was used, which permits the programming of all SIMATIC controllers. The automation programming was carried out in the Structured Control Language (SCL) and in the ladder diagram (KOP)

HMI Programming

The SIMATIC WinCC [25] software was used to program the HMI screen, which is a Siemens Supervisory Control and Data Acquisition (SCADA) system and Human-Machine Interface. The SIMATIC WinCC Runtime Advanced program was used for the simulation of the screen.

Virtual PLC Simulation and Protocol Communication

S7 - PLCSIM Advanced V2.0 [26] has been chosen to simulate the PLC in a virtual way in order to verify the virtual model performance. A local communication was stablished through the Softbus protocol (Figure-4), ensuring that no data can be lost or broken. The instance of PLCSIM Advanced is on the same PC or virtualization platform (VMware) as STEP 7

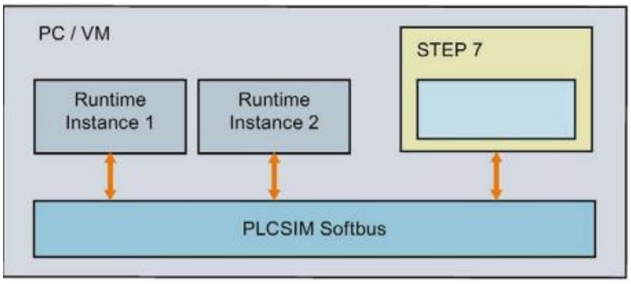

Figure-4. Local communication through the Softbus protocol. Source: Siemens [26].

Validation

Once the prototype was designed and manufactured, an experimental study was conducted in 16 patients with painful shoulder post- ischemic stroke. At

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different stages of its evolution, the robotic therapy effectiveness applied with anti-gravitational movements was evaluated. Clinical trial was developed at the Physical Medicine and Rehabilitation Department of the Surgical Clinical Hospital "Dr. Juan Bruno Zayas Alfonso" in Santiago de Cuba, Cuba. Among other variables: the presence of humeral scapular subluxation (HSS), pain, spasticity, mobility, tone and muscle strength, and the satisfaction degree were recorded. Results with 95% reliability were compared between admission and third months of treatment. The report of this study can be found in [8].

RESULTS

Mechanical Design of the Exoskeleton Prototype

Considering the anthropometric parameters of the patients and as a result of the analysis carried out, the torques calculated for each therapeutic movement are presented in Table-2.

Table-2. Joint torque calculated for each DOF.

Patient weight (kg)	Shoulder Flexo-extension (N·m)	Elbow Flexo-extension (N·m)	Forearm Prone/supination (N·m)	Arm Rotation (N·m)
50	13.9	2.75	0.49	9.45
100	27.8	5.5	0.965	20.8

The design procedure was outlined in [15, 16, 27] and once the CAD models were generated, all the elements of the structure were controlled with the application of the Finite Elements Method to assurance ergonomics and properly safety functionality. Table-3 shows the mechanical properties of the materials in the different elements considered in the structure. It should be noted that those materials that are part of the structure and that are not stainless steels received thermochemical treatment to avoid corrosion.

Table-3. Mechanical properties of materials.

Material	Elastic Module (MPa)	Poisson coefficient	Density (kg/m^3)	Elastic Limit (MPa)
AISI 304	$1.9x10^5$	0.29	7.92	206
AISI 1020	$2x10^5$	0.29	7.9	330
SAE 4140	$2x10^5$	0.28	7.8	436

The mechanical resistance control of each element from the different mechanism of the exoskeleton was carried out using the Simcenter Nastran solver. Figures 5 and 6 show the stress distribution of the rotation mechanism gear pair and those obtained in the frame for a therapeutic routine that includes flexion of the arm and elbow and external rotation as the most critical conditions.

The dimensions of the gear pairs were selected (Dp1 = 33 mm, Dp2 = 198 mm for the rotation mechanism) and of the pronosupination mechanism (Dp2 = 120 mm, Dp1 = 15 mm), related to those required to adjust these dimensions to arm and wrist respectively of a person weighing 50-100 kg and according to AGMA standards [28, 29]. The modules of the gears pairs) were selected according to the operating conditions (low powers and revolutions according to the aforementioned standards 1 and 1.5 mm respectively. For their safety, simplicity of manufacture, low speeds and light loads it was decided to manufacture them with straight teeth. As material for the wheels, AISI 304 steel was selected.

Because for certain combinations of tooth numbers, interference may occur between the tip of the pinion tooth with the root of the gear tooth, which is intolerable, to avoid the appearance of interference the teeth of the gears were finally elaborated through the generation process, which guarantees that the interference is eliminated automatically because the cutting tool removes the interfering part of the flank [30, 31].

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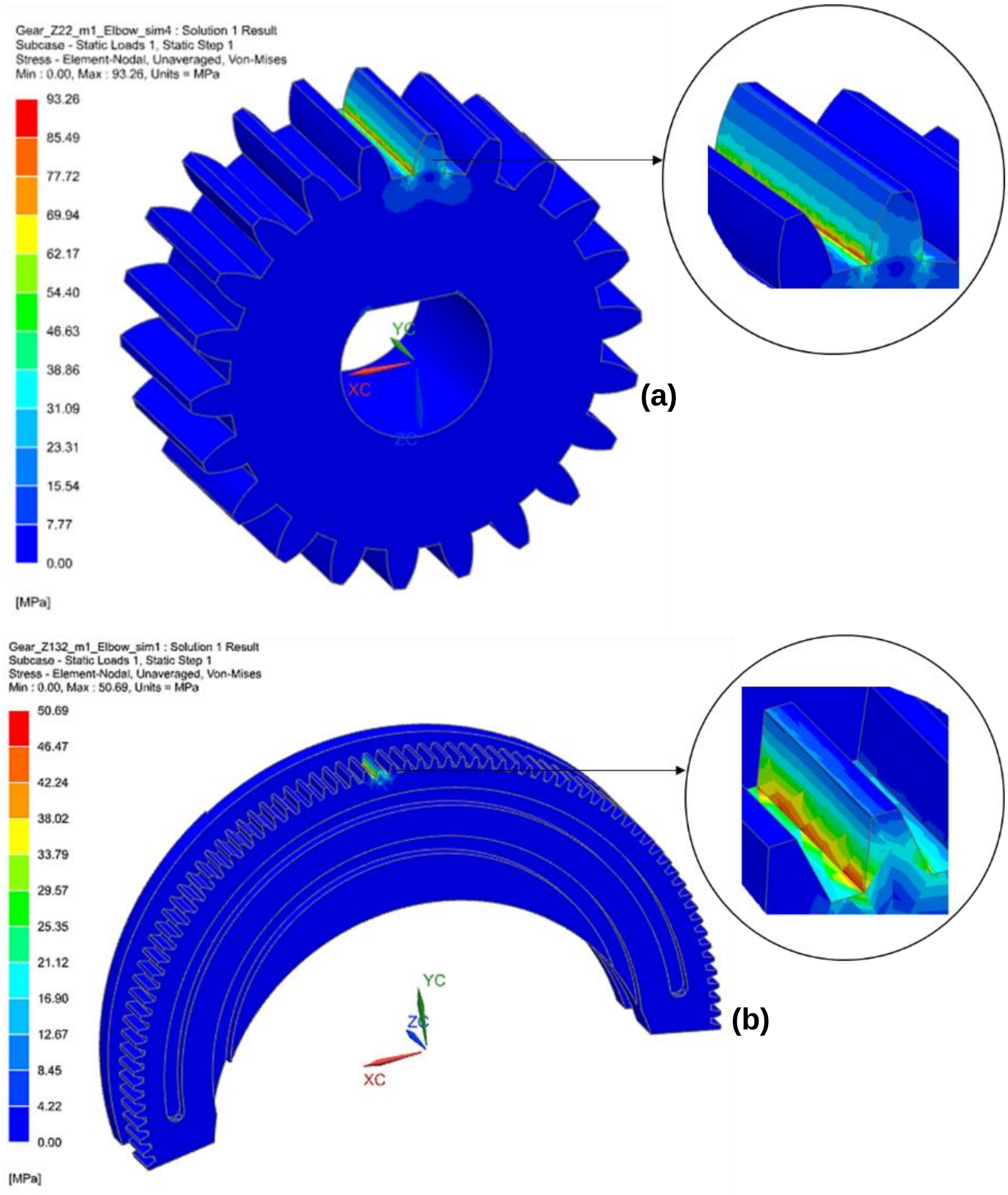

Figure-5. (a) Maximum stresses on the pinion from the rotation mechanism (93.26 MPa), 155 750 nodes and 99 785 elements. (b) Stress analysis toothed sector, max = 50.69 MPa, 94 086 nodes and 59 088 elements.

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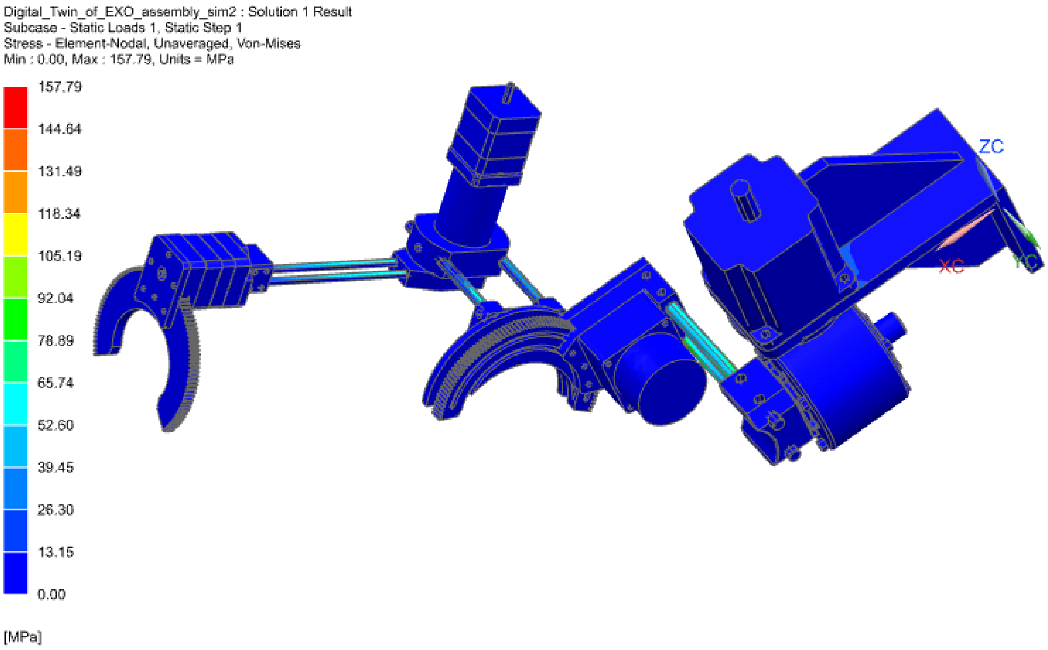

Figure-6. Stress distribution in the framework for the most critical condition in the rehabilitation program, max = 157.79 MPa, 583 890 nodes and 363 276 elements.

Siemens NX MCD

For the development of the mechatronic concept, it is necessary to add basic physics, in which rigid bodies are inserted as shown in Figure-7. To get the virtual model to move just like the real model would, joints and constraints were added, such as fixed and hinge joints, see (Figure-8).

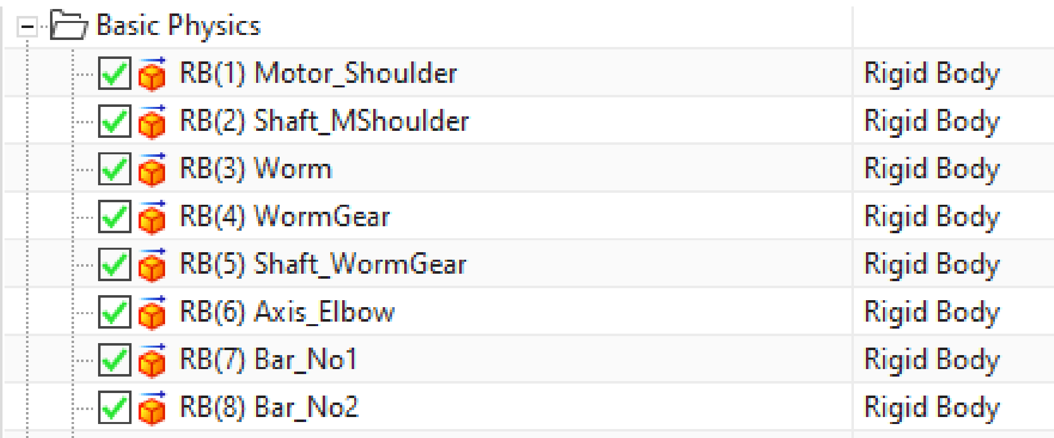

Figure-7. Exoskeleton basic physics. Source: Siemens NX MCD.

Figure-8. Joints and constraints of virtual model. Source: Siemens NX MCD.

The coupling between the different rigid bodies is carried out through gears (Figure-9) to achieve that the input and output transmission ratio is fulfilled.

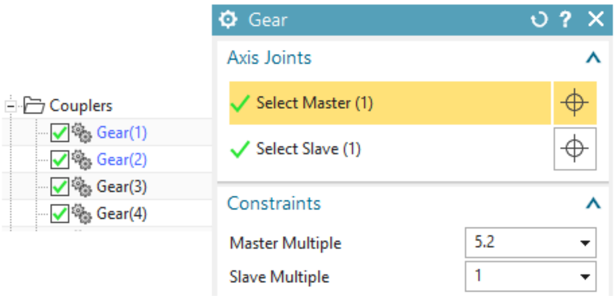

Figure-9. Model coupling through gears. Source: Siemens NX MCD.

The movement of each motor has been controlled by position controls (Figure-10) to which the target values in (°) and speed in (°/ s) are giving through the NX MCD input signals.

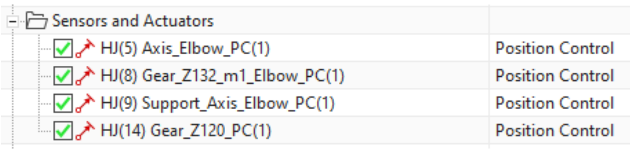

Figure-10. Actuators for twin movement. Source: Siemens NX MCD.

The signal adapter (Figure-11) allows the link between the position control parameters with the input signals and the necessary formulas to achieve a conversion of the value that comes out of the PLC and the one that arrives in the virtual model for its correct functionality.

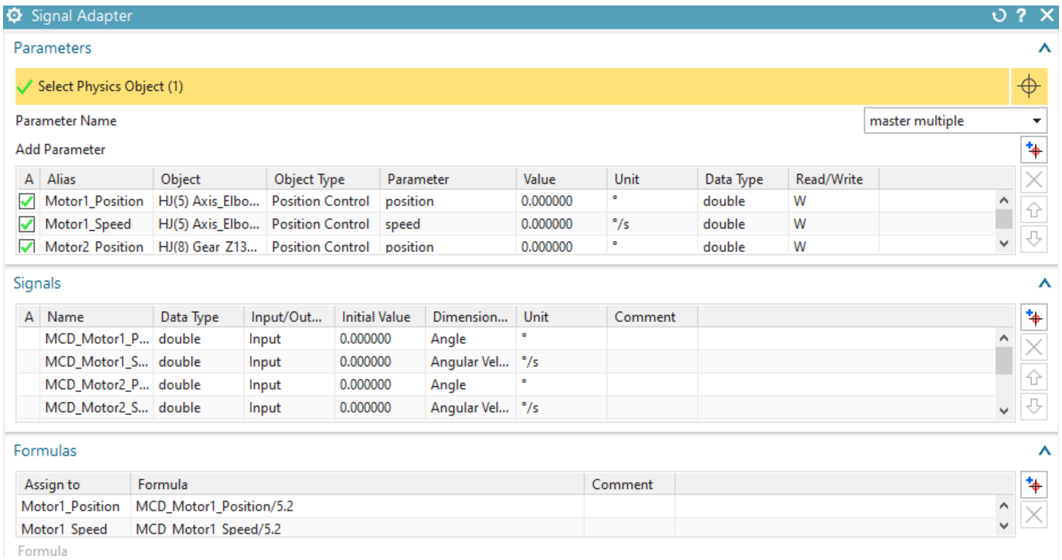

Figure-11. Signals Adapter. Source: Siemens NX MCD.

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The mapping between the input signals of the NX MCD with the output signals of the PLC that are carried out through the PLCSIM Advanced software (Figure-12).

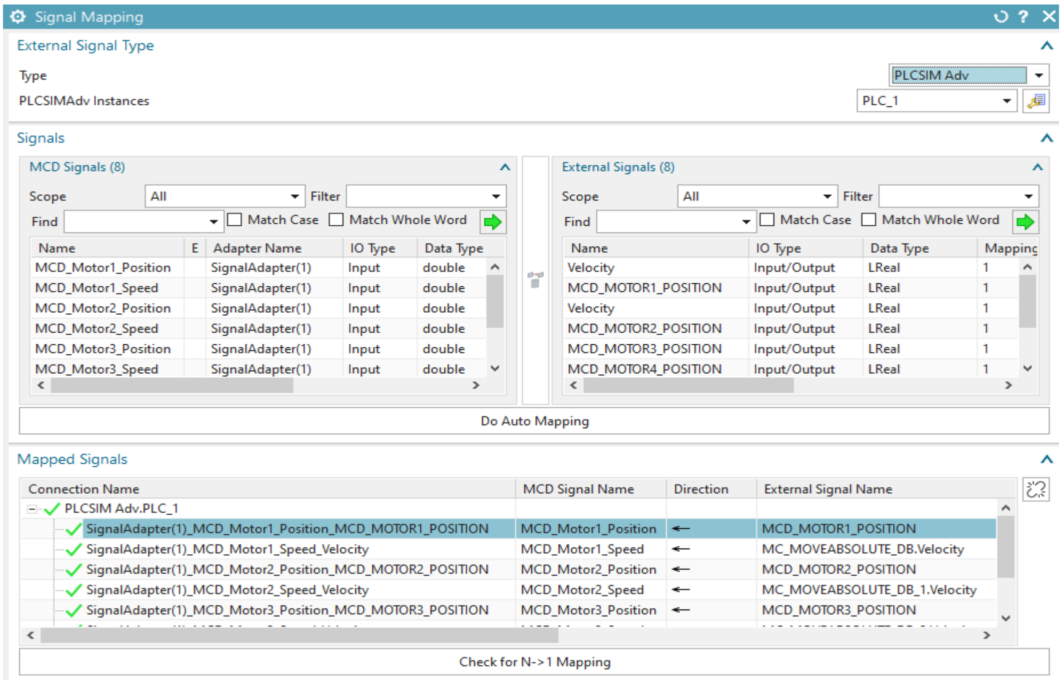

Figure-12. Signal Mapping of mechatronic concept. Source: Siemens NX MCD.

S7 - 1511 PLC Programming

Flowchart

Figure-13 shows a part of the STEP 7 flowchart for PLC control. It can be seen the organization block (OB1) cyclical main program that are executing constantly while the PLC is running. In it, all the functions (FC) are loaded both for the control of the HMI drives and to load the routines (10 in total) that in turn activate the function blocks to move each motor of the twin according to the one it has been selected. Function blocks store their intermediate variables in data blocks (DB) [32].

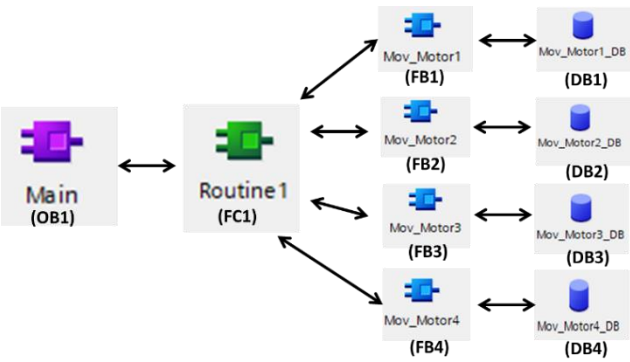

Figure-13. PLC encoding with STEP 7. Source: TIA Portal V15.1.

Technological object

The selected technology object [33] was the positioning axis ("TO_Positioning Axis"). It was configured. by means of the real dynamics and mechanics parameters of the motors, and the data is saved in a technological data block.

From the user program with the Motion Control instructions [34] and through "Motor1_Run", a movement request is launched with absolute coordinates to the target position defined by the variable "Position" and set speed (Figure-14). When system is "Busy", set to TRUE, and positioning commands are sent to the axis, which with the help of pulse generators PTO (Pulse Train Output), from telegram 3, establish the connection with the driver controllers M542 [35]. These drivers are power controller (voltage and current) and convert the pulses sent by the card into motor steps, as well as setting the direction of rotation (Figure-15). As soon as the target position is reached, the system reports this via "Motor1_MoveON".

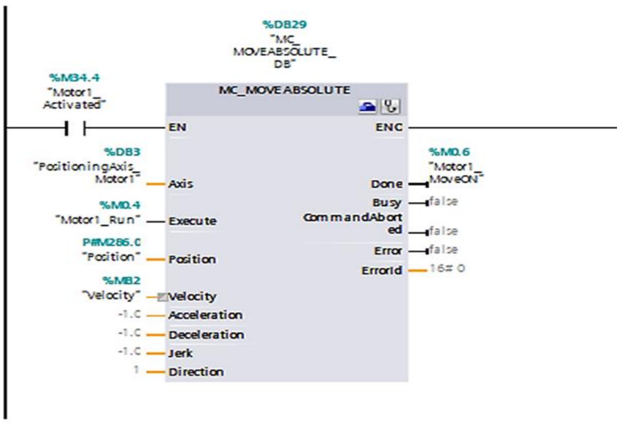

Figure-14. Motion request with absolute coordinates. Source: TIA Portal V15.1.

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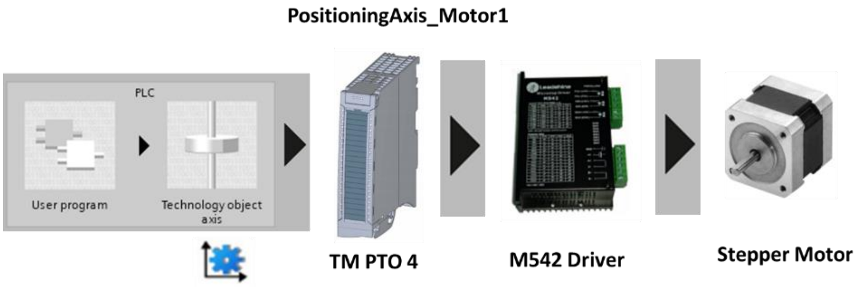

Figure-15. Scheme for stepper motor control. Source: Authors.

S7-1500 Motion Control allows us to configure an axis as a virtual axis. One virtual axis has Motion Control, but unlike real axes it does not have connection to any driver or encoder. Signals are only processed in the controller and never control a real driver.

HMI (TP900 Comfort)

The HMI project for the control of the rehabilitation exoskeleton includes 3 screens. The main screen as shown in Figure-16. When it is turned on, offers the facilities to use and create new routines, store ("Save") the new ones, to modify the amount of "Repetitions" and the "Speed" at which the movements are executed and buttons "Pause" and "Stop" to be used in emergency stops.

The designed interface presents the following characteristics and benefits: possibility to move the joints independently through selecting the joint, the direction and the degrees to be moved, the repetitions progressive count of those that are executed and remain to be executed, control of the duration time of each of the routines, buttons for "Play / Pause", "Stop", "Exit", "Open", "Save", "Load", "Help", and the use of LEDs for the status and switch on indicators of the engines.

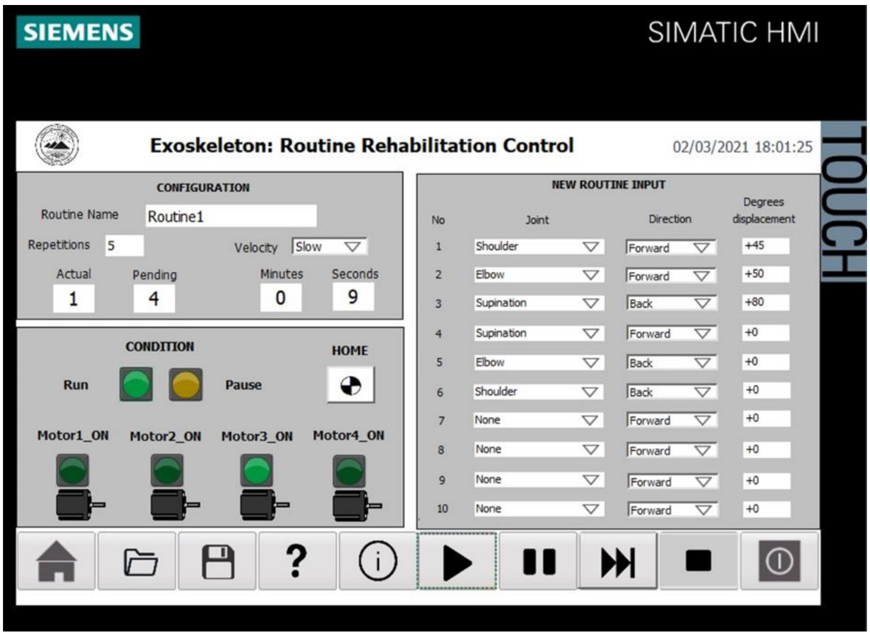

Figure-16. Main screen for controlling the Digital Twin. Source: SIMATIC WinCC Runtime Advanced.

The proposed design of the safety system considered several alternatives from different perspectives: from the software it is possible to permanently stop any execution in progress at any time, it also to avoid an input of angular displacements beyond those physiological for each one of the joints.

The second screen is the so-called "Recipes" in which the operator can select a group of routines already programmed to execute or create new routines and save them, as well as being able to open and execute them again, it has a button to return to the main screen. The third and last screen includes the "Help", to learn how to work with the equipment, it also has a button to return to the main screen.

S7 - PLCSIM Advanced

Once the PLCSIM software is open, the user loads the project (PLC_1 for example) and create the PLC. Then it is necessary to load into PLCSIM the PLC project made in TIA Portal, which should be compiled and

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without errors. Finally, it can be seen the PLC activated and able to "Execute" with all its variables and program blocks running (Figure-17).

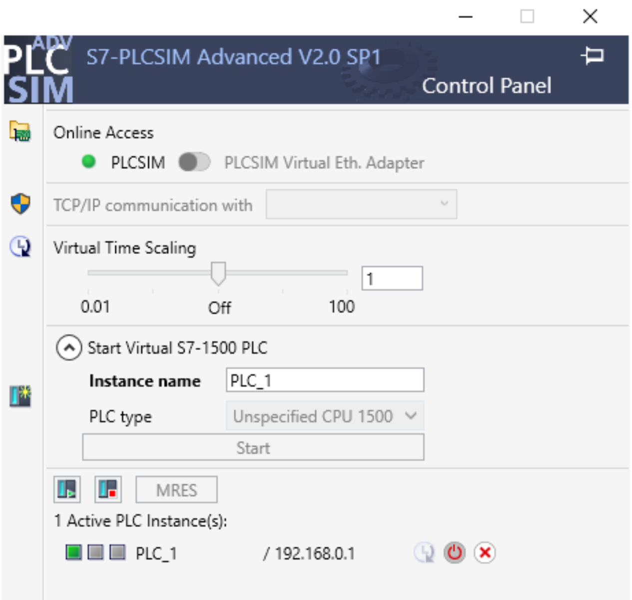

Figure-17. Virtual PLC simulation. Source: S7-1500 PLCSIM Advanced.

Communication between S7-1500 and HMI device (TP900)

Communication between the PLC and the HMI device is carried out through the PROFINET interface (PN/IE) (Figure-18) through IP protocol of both device [36].

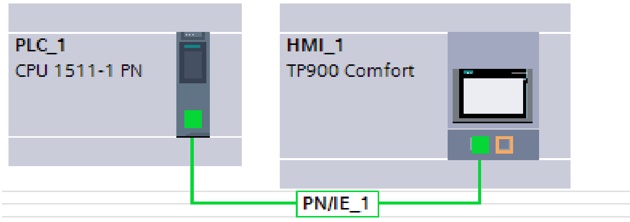

Figure-18. Communication between the PLC and the HMI device. Source: TIA Portal V15.1.

Virtual Commissioning

The Virtual Commissioning [37] of the rehabilitation exoskeleton using the NX MCD software is shown in Figure-19. Case (a) corresponds to the validation of the Digital Twin and case (b) corresponds to the actual implementation of the product and its operation in the rehabilitation of patients.

Based on the 3D data that maps the physical and kinematic properties of the prototype, the mechatronic model was made. This model was linked to virtual and real controller. In a virtual environment the HMI screen sends routines movements orders through the PLCSIM Advanced software to the virtual PLC controller.

In a real validation HMI sends the orders to S7-1500 PLC and with the Motion Control instructions and the PTO pulse generators, controls the drivers that move the exoskeleton actuators.

The developed robotic platform was included in an experimental study conducted in patients with painful shoulder post- ischemic stroke. The performance of precise routines and gradually controlled movements, lead to the decrease of these abnormal muscle tones, spasticity, the disappearance of pain and the greater recovery of joint movement with the use of this robotic therapy [8].

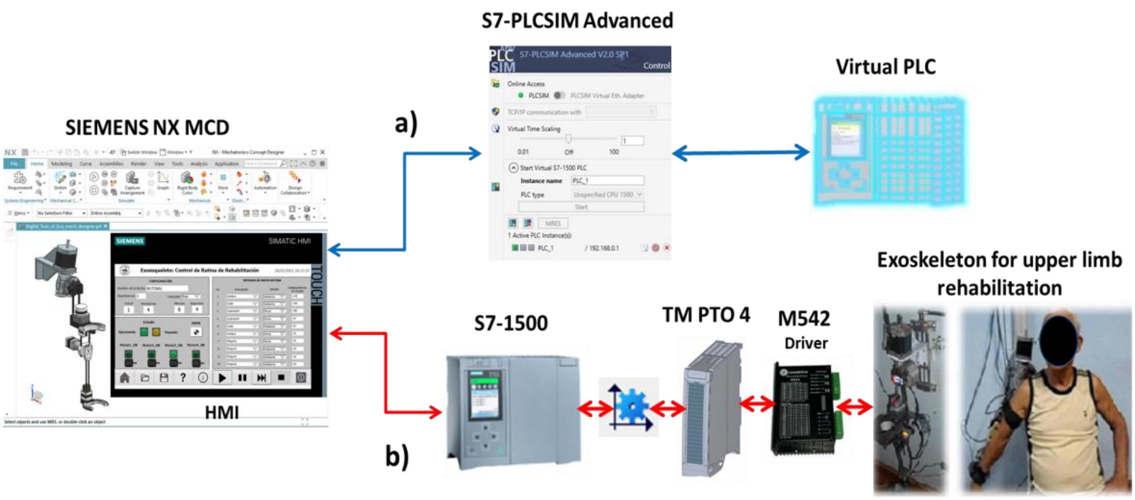

Figure-19. Virtual Commissioning of the rehabilitation exoskeleton using the NX MCD software. Source: Authors.

CONCLUSIONS

The present work proposes, based on the author's experience, an integrative methodology using Digital Twin advantages for the development and evaluation in a clinical setting of a mechatronic exoskeleton for the rehabilitation of the upper limb of the hemiplegic patient. The use of Siemens Digital Industries technologies made it possible to design the mechatronic concept and its automation, integrating biomechanical aspects that determine design and control parameters with clinical analysis protocols for the evaluation of the functionality of the rehabilitation equipment. With the implementation of the Digital Twin of the exoskeleton and its Virtual Commissioning, it has been possible to reduce the design time until the manufacture of the prototype, detect errors in the design phase, and verify that its operation is safe and correct for the patient. In addition, it offers the possibility of making modifications to the model and quickly checking its effectiveness.

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