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Teaching Mechatronics Design: A Theoretical-Practical Approach

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Abstract

The teaching of design for engineers in mechatronics is presented as the appropriate space for the integration of knowledge related to mechanics, electronics, control and programming, in search of the development of products that meet the needs of an increasingly demanding market in terms of technological-economic requirements. This work presents a methodology focused on product development, emphasizing the importance of prototype construction, to measure possible differences between the development of a conceptual design and the actual performance of a product, presenting the results obtained in the design and construction of an exoskeleton prototype.

Keywords: Methodology of mechatronic design, modeling and simulation, product development, exoskeletons.

INTRODUCTION

Since the term Mechatronics was coined by engineer KO Kikuchi in the late 1960s [9], this discipline that involves the integration of knowledge in mechanics, electronics and control [41], [7], [39], has evolved rapidly, with product development as an interesting opportunity to demonstrate the need for technology integration [28] [6].

With the recognition of the importance of engineering in Mechatronics, the need arises to train professionals in this area of knowledge and begins the development of curricula at the undergraduate and postgraduate levels worldwide [7], [45], [18], [43], evaluating the educational model to be implemented, the relevance and impact of the program in the environment.

The project-based teaching model is a strategy used in Europe, Asia and North America [7], [45], [44], [36], addressing the need to educate engineers with a capacity for teamwork and ability to integrate technologies. This document presents an educational approach for the teaching of mechatronics design focused on last-year students of the undergraduate curriculum, project-based and product development oriented.

The present work indicates in section 2, the motivation to use a methodology of teaching based on projects. Section 3 establishes the competences to be developed in future engineers, using a theoretical-practical approach. Section 4 details the methodology used and section 5 presents an example of product development based on this one. Section 6 evaluates the results obtained using the proposed methodology and section 7 concludes the work.

MOTIVATION TO USE A PROJECT-BASED APPROACH TO TEACHIN

The speed with which technology is developed in the various fields of knowledge makes the professional in any area of study to be obliged to constantly update, motivating teachers to reflect on the methodology used to encourage the active participation of students in the teaching-learning process [39], [43], [45], [24], [18], proposing strategies that include the use of audiovisual media, tools derived from information technologies (ICT) [11], [30], laboratory practices and even use of the mobile phone as an element of support to the teaching work [41], [44]. However, the use of these tools facilitates learning, but does not necessarily motivate it, then the following questions arise:

- Is the knowledge acquired sufficient to address and solve an engineering problem in the real sector?
- How are the acquired knowledge related in separately developed subjects?
- How important is the experience when applying the theoretical knowledge to solve a practical problem of engineering?

In order to solve these questions, it should be taken into account that the rapid development of information technologies, sensors, electronics, new materials and elements of action has allowed the development of devices and mechatronics systems, with the integration of knowledge of mechanical engineering, electronics, control and information systems, as shown in Figure 1 [29].

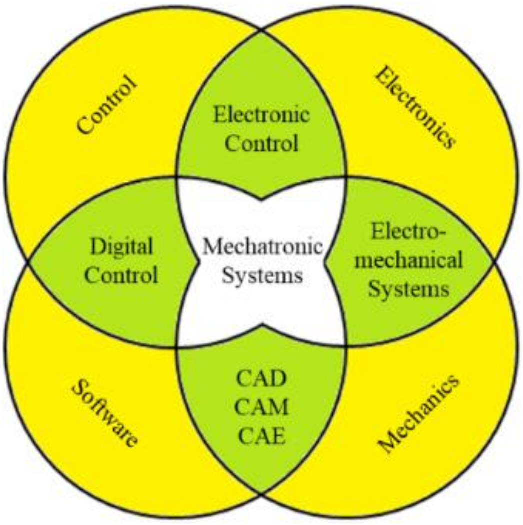


Figure 1. Knowledge areas involved in a Mechatronic system.

The need to involve so many engineering domains implies a high complexity in the development of this type of products, which have as requirements the reduction of time, development and production costs, and therefore, the following approach is made in order to ensure the correct development of engineering skills:

1.- There is a need to introduce students to the implementation of real projects that allow them to measure their competences in solving unstructured problems associated with engineering needs.
2.- It is necessary to involve the practical development that allows the student to apply theoretical concepts to propose solutions, which can be evaluated once they materialize through a prototype.
3.- It is important that future engineers explore the practical aspects related to the construction and thus to dimension the aspects to be solved in the solution of a real engineering problem.

Given the need to relate theory to practice, the development of a course in which the design process is involved, supported by concepts such as concurrent engineering [37], design for manufacturing [20], design for assembly [2], robust design and parametric design [1]. The trend in high technology products points to the optimum development of intelligent products [32], [34], and in the near future the need to include optimization courses that allow to address developments through concurrent design. However, this topic is currently addressed only in advanced post-graduate courses.

COMPETENCES TO BE DEVELOPED

The use of knowledge to solve problems and/or needs has been the work of engineers, but practical experience allows to determine the close relationship between knowledge and know-how [45], reason why it is necessary to establish what skills must be taken when someone is part of a mechatronic development. These skills are described below:

- Communication: effective oral and written communication allows the engineer to interact appropriately with his clients and work team.
- Teamwork: the ability to interact efficiently with a work team facilitates the implementation of concurrent engineering [37], in which it is sought that the expertise of each of the participants is used to reduce errors from the conception of an idea to the placing on the market of a product.
- Ability to conceptualize: the understanding of problems that must be clearly conceptualized and then elaborate the mechanical, electronic and control models, will lead to the proposal of solutions, that are adapted to the needs of the user and are technically and economically viable.
- Criteria for decision making: Design support technologies, such as computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM) and rapid prototyping, serve to streamline the development process, but so far they do not substitute for the analysis capability and the criteria that the engineer should have when approaching solutions to engineering requirements is required.
- Recognition of technological resources of easy and economic access for the reduction of development times and costs.
- Ability to plan, execute and monitor project development.

METHODOLOGY OF DESIGN AND CONSTRUCTION PROCESS

For the development of an engineering project there are different methodological proposals. This paper is based on what was proposed by [45] and [12] and is illustrated in Figure 2, having as a clear purpose the development of a prototype evaluable from the perspective of the end user and competitive with products of similar characteristics that are in the market. Teamwork allows effective introduction of concepts of concurrent engineering, which is why groups are integrated in which it is intended to have five members, with clear skills in: mechanics, electronics, control and programming, simulation and project management.

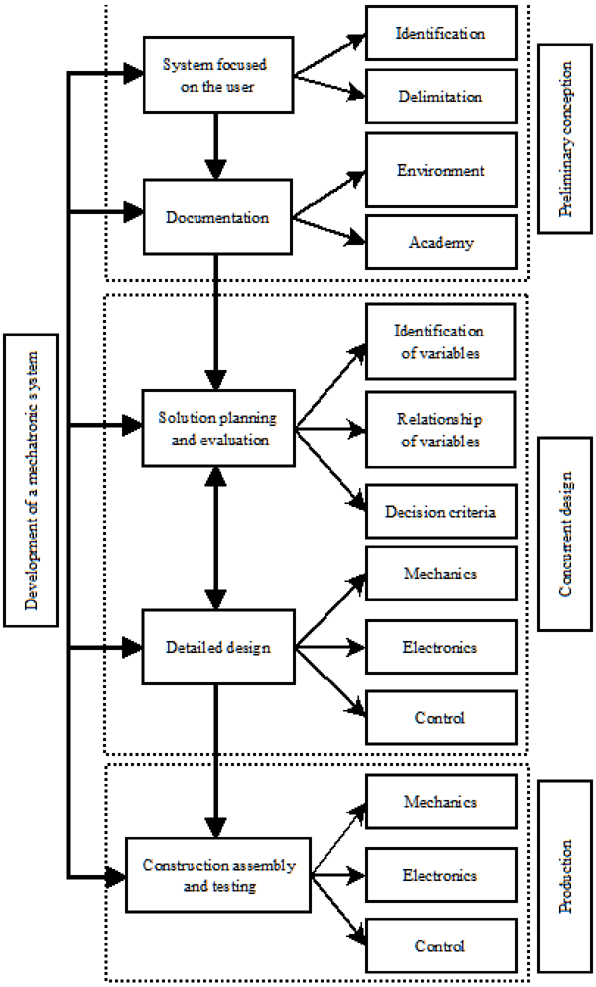


Figure 2. Design Methodology

Product focused on the user

In order to avoid any possible differences between what the end user expects of a product (identification of needs and / or requirements) and the technical specifications of the product (delimitation of the scope of the project), the working groups are oriented in the elaboration of the house of quality [2] (matrix associated to the methodology: quality function deployment, QFD), methodology that allows to evaluate the final prototypes based on the approach proposed in this matrix.

With the systematic exploration of the products available in the market (Benchmarking) that can give solution to the requirements of the client [25] and the identification of the bibliographic resources that will be of support, the planning of the project is made, specifying times, processes, tasks, resources and responsible, taking advantage of the strengths of each member of the group.

Documentary review

The use of the Internet has facilitated the rapid collection of preliminary information for the project approach, but at this stage the engineer must understand the difference between primary sources of information (derived from search engines in the network) and knowledge derived from databases, patents and specialized technical literature. In this part of the design process, the future engineer must learn to use extensively/intensively the technical/scientific information from reliable sources of information such as international standardization entities: ANSI, DIN, ISO, SAE, ASME, ICONTEC, API, etc. Databases such as IEEE, SCIENCE DIRECT, E-BRARY, are some of the sources of normal use information to document the development of a project.

Approach and evaluation of solution alternatives

The identification of the variables that must be taken into account as part of the development is done through the elaboration of conceptual maps and the solution proposals (at least three) are related to the functional decomposition. For the choice of the alternative to be developed, a selection matrix is elaborated that is directly related to the approaches left in the QFD.

Detailed design

The mathematical modeling should be used for the choice of actuators, selection of materials and definition of geometries of the different components of the prototype. Tools to simulate the behavior of the mechanisms allow to evaluate the kinetic behavior of the proposed mechanical systems, to then select geometries and materials that meet resistance and rigidity requirements, which are detailed with CAD tools and validated using CAE programs [23]. With the selection of the actuators, it is started the electrical/electronic design, control and interface, tasks that are also supported by specialized programs [6], [15], [21], [33], [3].

Construction, assembly and testing

The detailed design should be thought taking into account manufacturing design and assembly design, including the use of computer-aided manufacturing (CAM) technologies, with ongoing evaluation of manufacturing and assembly costs. At this stage, students resort to strategies such as laser cutting, water, plasma, rapid prototyping, conventional and numerical control machining. For cost rationalization, designers now understand the importance of using standardized parts, materials, specifications and appropriate manufacturing methods.

In rare cases the designs that have been developed and simulated previously work according to the initially stated, this happens to a great extent due to problems in the specifications and execution of the manufacture. Documenting performance tests introduces students to concepts related to quality, reliability, and assurance [2], [22].

Documentation

Written communication is of great importance when it is necessary to document a project, with a view to giving traceability to the developments and to build a knowledge base that allows to advance more quickly when addressing new developments. For this reason, during the development of the course, special attention is paid to the documentation of each one of the projects, obtaining in the end a writing, with which it is possible to quickly and effectively reconstruct each of the developed prototypes.

CASE STUDY:

Design and Construction of an Exoskeleton for Upper Limb Rehabilitation: An Example of Implementation of the Design Methodology

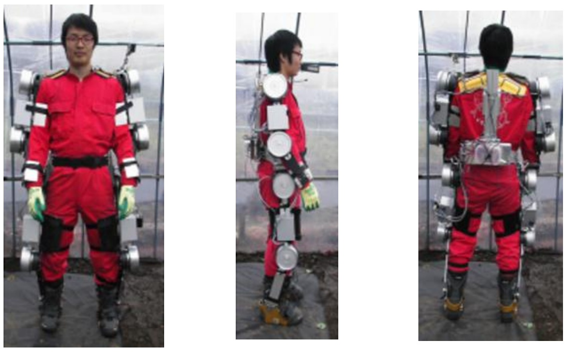
The development of devices for physical rehabilitation is a field in which have been made systems that synergistically integrate mechanical and electronic components and controls with increasingly friendly human-machine interfaces, so they can be cataloged as mechatronic systems. These devices in most current research are categorized as robotic devices, because of their high degree of integration with advanced control technologies, the possibility of reproducing the movement of one or several joints of the human body and the possibility of performing routines usually performed by a physical therapist [26]. For these reasons, it was decided to develop an exoskeleton type device for upper limb rehabilitation.

Product focused on the customer

Strokes affect a significant number of adults, decreasing their motor capacity in upper and lower limbs [27], [46], which motivates the development of systems that aid in the rehabilitation process [13], [16], [19]. To set the design requirements, it is elaborated a matrix called the quality house (as part of the QFD methodology). The results indicate that for the customer the two most important aspects are cost and portability. The geometric design and the movement control are the most relevant parameters from the point of view of design.

Documentary review

An exoskeleton is an electro-mechanical structure that copies the shape and functioning of the upper and lower limbs of the body by attaching itself to the functioning of the musculoskeletal system of the human being (See Figure 3) [42]. These systems can be used to increase muscle capacity, assist in rehabilitation processes of joints or muscles, and in some cases to reduce motor problems caused by neurological problems [16], [19], [40]. In the field of rehabilitation of problems such as hemiplegia or neuromuscular problems derived from cerebrovascular accidents, the works developed by [38], [8], serve as a starting point for the development of the exoskeleton presented as an example of application in this document. For the implementation of the active therapy in [4], a detailed review of the control systems is presented from the first developments of this type of devices that were made in the 1960s by the US military until recent work.



a) Front view b) Side view c) Rear view

Figure 3. Exoskeleton designed for help in agriculture.

The use of interfaces that include simulated environments to mentally and physically stimulate patients with mobility problems are evidenced in developments such as [5], work in which a training station for upper limb is developed, integrating the use of computers, projectors and screens (Figure 4), to stimulate sensorially the user of the therapy.

a) Patient & System b) Mirror display c) ARMin

Figure 4. Station development for rehabilitation and sensorial stimulation.

Approach to solution alternatives

Based on the elaboration of conceptual maps, such as that shown in Figure 5, and brainstorming, the working groups initiate the elaboration of solution proposals that are initially discussed based on manually elaborated sketches, as illustrated in the Figure 5.

As an instrument of evaluation of the different approaches made during the conceptual design phase, the decision matrix is used. With this strategy the aspects raised in the how of the QFD matrix are taken and are evaluated taking into account the proposed goal values for each of these.

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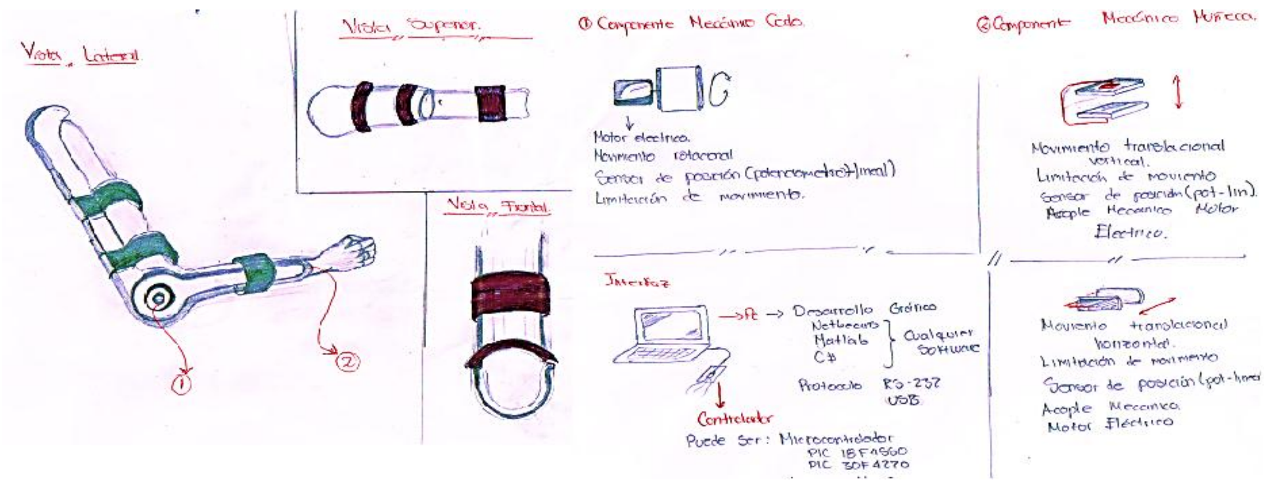

Figure 5. Initial sketches for discussion

Detailed design

Once a design proposal has been selected, the mathematical models associated with the proposed design scheme are developed. In the present work a revision of the anthropometry and biomechanics was done to delimit the complexity of the exoskeleton to detail, achieving in this way to associate a geometric and mathematical model to the design (Figure 6).

The mathematical model is made to obtain the required torques in the actuators, in this case it was based on the energy method proposed by Euler-Lagrange.

$$\frac{\partial}{\partial t}\left(\frac{\partial L(q,\dot{q})}{\partial \dot{q}}\right) - \left(\frac{\partial L(q,\dot{q})}{\partial q}\right) = \tau \qquad (1)$$

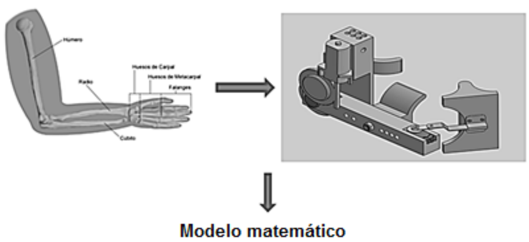

Figure 6. Physical and mathematical modeling of the system.

Where $q(t) = (q_1(t) \cdots q_n(t))^T$ and $\dot{q}(t) = (\dot{q}_1(t) \cdots \dot{q}_n(t))^T$ the position and the angular velocity respectively, $\tau = [\tau_1 \cdots \tau_n]$ is the vector of torques applied to the arm. $L(q, \dot{q})$ denotes the Lagrangian of the system, defined by the difference of kinetic energy $K(q(t), \dot{q}(t))$ and the potential energy of a rigid structure of n degrees of freedom, $U\big(q(t)\big)$.

$$L\big(q(t), \dot{q}(t)\big) = K\big(q(t), \dot{q}(t)\big) - U\big(q(t)\big) \qquad (2)$$

For this case of two degrees of freedom, the kinetic and potential energy of the links are determined by:

$$K(q, \dot{q}) = K_1(q, \dot{q}) + K_2(q, \dot{q}) \qquad (3)$$

$$U(q) = U(q) + U_2(q) \qquad (4)$$

So

$$K(q, \dot{q}) = K_1(q, \dot{q}) + K_2(q, \dot{q}) \qquad (5)$$

$$K(q, \dot{q}) = \left[\frac{1}{2} m_1 v_1{}^2 + \frac{1}{2} I_1 q_1{}^2\right] + \left[\frac{1}{2} m_2 v_2{}^2 + \frac{1}{2} I_2 (\dot{q}_1 + \dot{q}_2)^2\right] \qquad (6)$$

Where m_1 and m_2 denote the masses of the links, I_1 and I_2 represent the moments of inertia of links 1 and 2 respectively, v_1 and v_2 are the velocity of the center of mass of the links.

In developing the model, it was found the expression that allows to calculate the torques according to the masses, lengths and angular positions, Eq. (7) and (8).

$$\tau_1 = \left[m_1 l_1{}^2 + m_2 l_1{}^2 + m_2 l_2{}^2 + 2 m_2 l_2 \cos(q_2)\right]\ddot{q}_1 + \left[m_2 l_2{}^2 + m_2 l_1 \cos(q_2)\right]\ddot{q}_2 \qquad (7)$$

$$\tau_2 = \left[m_2 l_2{}^2 + m_2 l_2 \cos(q_2)\right]\ddot{q}_1 + \left[m_2 l_2{}^2\right]\ddot{q}_2 - m_2 l_2 \sin(q_2)\, \dot{q}_1 \dot{q}_2 + I_2[\ddot{q}_1 + \ddot{q}_2] - [m_2 l_2] sin(q_1)[q_1{}^2 + \dot{q}_1 \dot{q}_2] + m_2 l_2 g sin(q_2 + q_1) \qquad (8)$$

With the mathematical model it is proceeded to calculate the torques of the actuators, completing the dimensioning of the mechanical part. At this stage of design, the concepts of concurrent design, parametric design, design for manufacturing and design for assembly are involved [37], [35], [14], [31].

After the mechanical dimensioning, the structure is validated by the finite element method (Figure 7), emphasizing the analysis of stresses and deformations, seeking to guarantee that the structural component will withstand the loads to which it will be subjected (resistance design), and will not have deformations that can affect the operation (stiffness design).

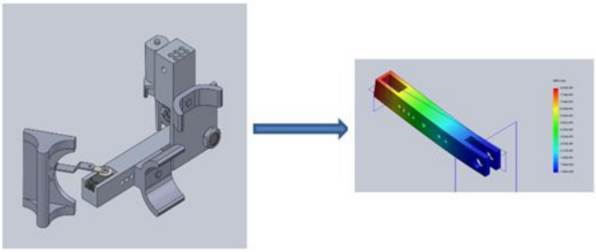

Figure 7. Detailed mechanical assembly and finite element validation.

Once the mechanical component is defined, the electrical / electronic design is performed and simulated (see Figure 8 and Figure 9).

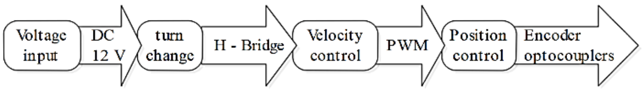

Figure 8. Elements for electric/electronic drive

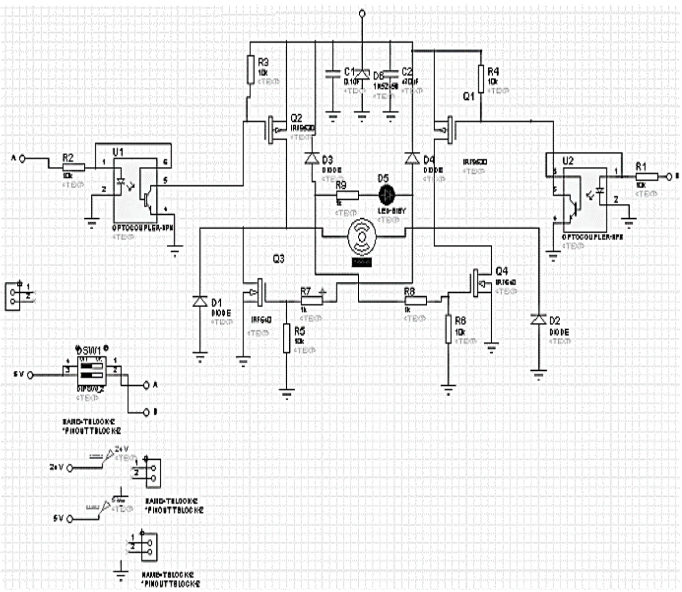

Figure 9. Power circuit for driving the actuators.

Based on the physical modeling of the system, the characteristics required in the actuators in terms of speed and torque are estimated, aspects that are validated for each of the joints selected based on simulation (see Figure 10).

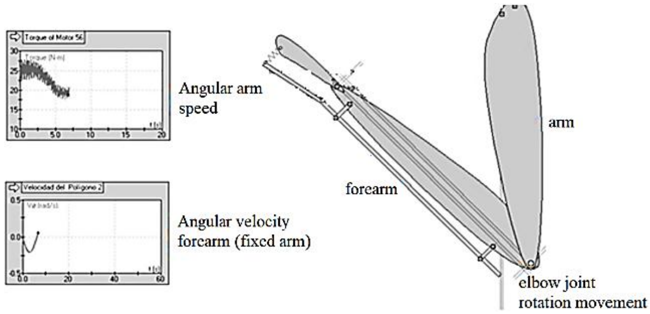

Figure 10. Obtaining torque and velocity curves based on simulation.

For the development of the human-machine interface, the aspects raised in product development are taken into account depending on the user, which includes the following requirements:

- Simple to use: preferably with graphic adjustment modes and configuration and use helps.
- Security options: must include physical emergency stops and per control panel.
- Flexibility: possibility to adjust values of movement, speed and work routines.

Figure 11 shows the flowchart developed for the development of an interface, which provides for a quick familiarization by the end user who may be either a private individual or a health professional, Figure 12.

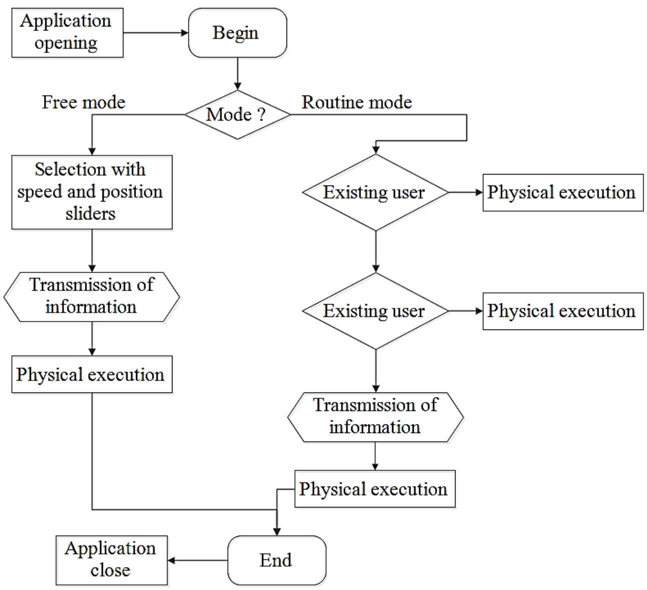

Figure 11. Block diagram for the implementation of the interface.

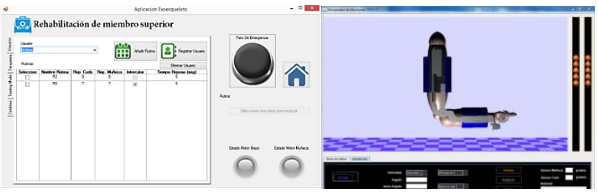

Figure 12. Two examples of human-machine interface..

Construction of the prototype

The construction process allows the working groups to understand the importance of correct drawing, applying proposed concepts in the parametric design [10], [47] and robust design [17], [48], seeking to reduce the modifications and adjustments of last moment. At this stage the working groups make use of conventional technology, as well as modern manufacturing techniques such as rapid prototyping and CNC (Figure 13).

The use of tools for simulation and execution of manufacturing processes (CAM) are used for the manufacture of components using the machining center, lathe and CNC thread cutting machine. It is also usual to make designs for processes such as laser, plasma or water cutting, which offer good precision, low cost and short execution times.

Figure 13. Manufacture process.

RESULTS

The creative process and the possibility of achieving different solutions to a problem is not affected by the follow-up of the proposed methodology, which can be evidenced in the three prototypes illustrated in Figures 14 and 15.

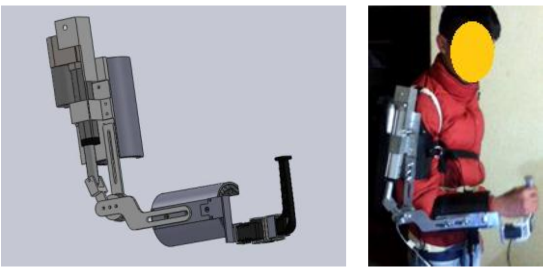

Figure 14. Modeling and prototype of exoskeleton for rehabilitation of elbow and wrist.

The operation of the exoskeleton shown in Figure 14 was adequate, since it allowed the programmed movement of the elbow and wrist joints, with the option of setting limits on the angular position of each of these. The use of sliders allows to adapt the mechanism to arms of different size. The linear actuator used facilitates position control, but adds weight to the device, which limits its use for extended periods of time. The materials selected for construction comply with sanitary regulations related to the application.

Figure 16 shows a functional alternative that also uses a linear actuator for the movement of the elbow joint and a rotation for the wrist. The structural component was lighter than previously proposed, but still has a significant weight in the ratio to the type of linear actuator used. The materials also conform to the applicable standards.

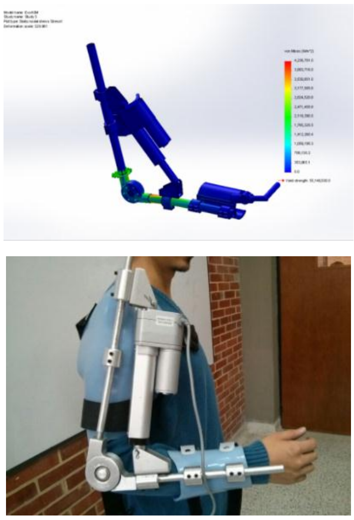

Figure 15. Modeling and prototype of exoskeleton for elbow rehabilitation.

The use of rotary actuators for the movement of the joints was also an option, in which the use of polymeric materials for the structural component can also be used, making the device lighter than those presented in Fig. 14 and Fig. 15. The material has more difficult to achieve adequate precision in the assemblies; however, the joints work in an acceptable manner for the application.

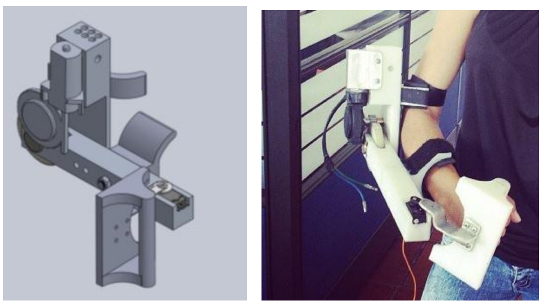

Figure 16. Alternative modeling and prototype of exoskeleton for elbow rehabilitation.

CONCLUSIONS

The engineer in mechatronics with its ability to integrate modern technologies, can carry out a product development process from its conceptual design to the construction and evaluation of prototypes, supported by modern tools for modeling, analysis and manufacturing. The transition from design to construction and commissioning of a product requires expertise in manufacturing processes and design for assembly, because, despite the great advance in the tools of analysis and modeling, the real world is full of large quantities of noise factors (precision of construction and assembly, surface finishes, acquisition and signal processing, etc.) that can hardly be determined and taken into account before moving on to the manufacturing and assembly process.

The analysis of human-machine controls and interfaces (HMI), developed by the students, makes it possible to verify that the technology currently available in actuators, sensors and controllers makes their integration into mechatronic systems easier, transferring the greatest difficulty to the development of the mechanical component.

The ability to work in a group is a current requirement at a professional level and the development of mechatronics projects allows developing competencies in this regard, which is reflected in the monitoring of the distribution of responsibilities that is done in the beginning of the project and allows a first approximation to the methodologies associated with quality assurance, through plan, do, check and act (PDCA).

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