Design and construction of robotic device for rehabilitation

Master in Optomechatronic

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Acknowledgements

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Chapter 1

Introduction

Due to the necessity of people to receive an adequate medical service, delicate and precise processes, and the lack of doctors and specialists, some alternatives has been proposed to solve this issue (in the case of this paper, a prototype of exoskeleton for rehabilitation is offered). One of them is the introduction of robots to medical field, with the purpose of help them to do their daily activities easily. The exoskeletons are part of such devices, the aim of this work is to propose a prototype of an exoskeleton for upper limb rehabilitation.

In recent years, interest on exoskeletons has increased, it has paid attention specially to ones that offer a better rehabilitation therapy and also that provide suitable health care to people that need assistance, not only in hospitals, also in their own houses [2].

Figure 1.1: An example of the use of robots on medical field [1]

1.1 Contribution

This work describes the process of mechanical and electronic design, in this work a solution to the problem of implementation of control to an exoskeleton prototype with the aim to be used on rehabilitation of people with some physical disability. Also, the work includes the mathematical development of the project, which link the mathematical model of exoskeleton and a robust control for it. The complete system is composed for the robotic device and the human interaction.

The stability of control equation is proved with the use of Lyapunov theory, the mathematical model of the device is given by nonlinear dynamic equations. From the theoretic point of view, in this work it is attacked the problem of torque estimation due to the robot-human interaction. That interaction (perturbation) is unknown and hard to measure with a conventional sensor. For such estimation we propose a sliding-mode-based observer, once this variable is estimated, it can be compensated by an output feedback controller proposed by the authors.

In the next section we talk about causes of disability to give the reader a better context and to get familiar with terms that will be handled throughout this work.

1.2   Introduction

Nearly 70 percent of patients with SCIs (Spinal Cord Injuries) have reported reduced quality of life, significant levels of pain, and a reduction in long-term satisfaction level [3]. Also strokes are the second largest cause of disability worldwide after dementia [5].
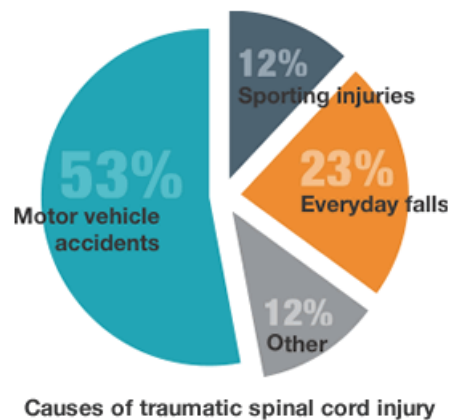
Figure 1.2: Principal causes of spinal cord injuries. [4]

It is caused by an interruption of blood flow to the brain. It results in brain cell damage and could be fatal. A stroke typically manifests itself with the sudden onset of local neurological deficits, such as partial loss of movement, sensory deficit, or difficulties with speech. Stroke are classified by their cause in two main types: ischemic and hemorrhagic (see fig.1.3).

- In the ischemic stroke, which occurs in approximately $85-90$ percent of strokes, a

blood vessel becomes occluded and the blood supply to part of the brain is totally or partially blocked.

- The hemorrhagic stroke, or intracranial hemorrhage, occurs in about $10 - 15$ percent of strokes, when a blood vessel in the brain bursts, spilling blood into the spaces surrounding the brain cells. Hemorrhagic strokes generally carry a greater risk of death and permanent disability than ischemic strokes [6].
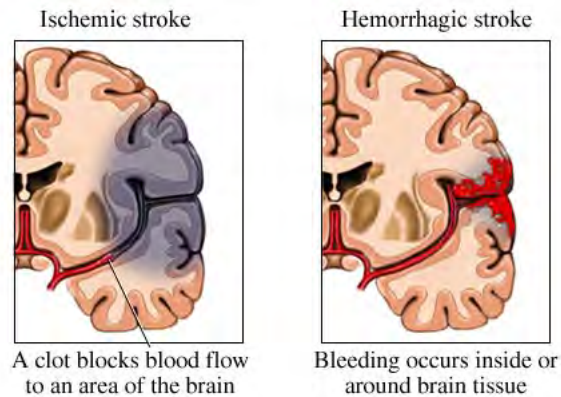
Figure 1.3: Both types of stroke and how they are produced [7].

The neurological impairment after stroke frequently leads to hemiparesis or partial paralysis of one side of the body that affects the patients ability to perform Activities of Daily Life (ADL) such as walking and eating. Physical therapy, involving rehabilitation, helps improve the lost functions as movement of arms or legs.

Specific parameters must be made sequentially to an effective exercise program during the therapy. These to ensure that patients can be able to back to normal activities. Each of these parameters must be restored to at least pre-injury levels time.

In their proper order these parameters are [8]:

- Flexibility and range of motion

- Strength and muscle endurance

- Proprioception, coordination and agility.

Each one of above points has as objective recover motor plasticity of the patient and therefore improve motor recovery (in this case as is mentioned on [9], range of motion of elbow is approximately 0° to 110°) and minimize functional deficits. Rehabilitation process depend on limb that need it. Rehabilitation is the main treatment to these disabilities, a process which allows the stroke patient to relearn the best possible use of their limbs and recover independence [10].

It is necessary to define planes that cross the body to make easiest the comprehension of limbs movements, these are:

- The sagittal plane: is the dominant plane of motion during human locomotion. Joint motion in this plane is simply referred to as flexion (positive direction).

- The coronal plane: Motion of the hip; in this plane it is referred to as abduction (away from the center of the body) and adduction. Further, motion of the ankle is referred to as eversion (away from the center of the body) and inversion.

The remaining Degrees of Freedom (DOF) of the hip and ankle are simply referred to as *rotation* (see fig.1.4) [11].
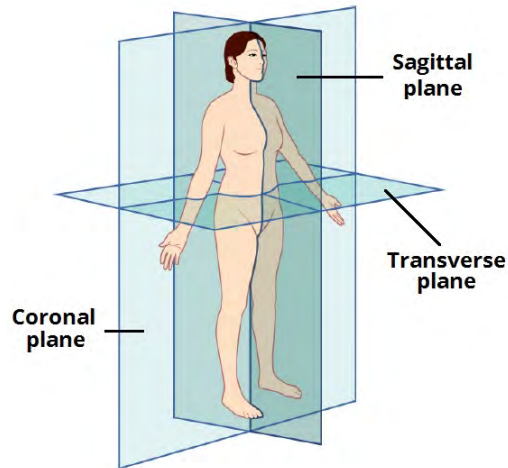
Figure 1.4: Planes of human body [12].

Other causes as overhead work as in assembly line is a risk factor of musculoskeletal injury as show [13]. Also as is mentioned in [14] a lot of tasks that require to maintain a static posture on arm, while the person exerts force in hand of the same arm is another cause of injuries. Despite of evolution of technology a lot of processes still require the presence of a human operator to perform certain tasks due to decision making and cognitive reasoning [15]. In case of industry application, the use of exoskeletons is relatively new and advances made in these devices and their application are few, the advances made in laboratory tests are greater [16]. Also workers will prefer not to use the devices if the loads are within their capacity of resistance, if the device hinders their movements or if these require a long apprehension, it has also been said that the devices are very expensive [17]. In industries such as naval or aerospace they use exoskeletons to reduce the risk of injury to the upper limbs, however it is not mentioned if these exoskeletons transfer these risks to other areas of the body [18]. Ergonomic

off-body materials handling devices, such as: hoists, lifts, and body slings are being used to reduce workers mechanical exposure to these acute and cumulative Risk Factors (RFs), while still maintaining a lean production strategy. However, these devices possess limitations including: large spinal forces due to the inertia of the device and load when moved dynamically. Using such devices can be time and space consuming. It is very important to consider the biomechanical load in the joints that were not taken into account when performing the mechanical design.

This paper provides a possible solution to the factors not considered in the mechanical design of exoskeletons, a robust control that has a disturbance observer that serves as an estimator of human-machine interaction and thanks to which we can compensate for this interaction .

The following chapter describes the state of the art of a variety of exoskeletons for rehabilitation and also the techniques used to generate movement in these devices. Control strategies and actuators that are implemented in them are also mentioned. Likewise, the subject of state observers is briefly addressed and how they have been incorporated into various devices, mainly to estimate disturbances.

Chapter 2

State of the art

An exoskeleton is a wearable powered device, typically endowed with an anthropomorphic shape. They are usually designed to track user's motion, and interact with the user through position, velocity or even force among human and exoskeleton. One of the areas in which exoskeletons are popular is in the physiotherapy, because it result in a good option comparing to manual therapy, this is due exoskeletons have a major duration and potential comparing to fatigue of therapist [19]. Exoskeleton designs can be classified in terms of their assisted capabilities as either passive or active devices as mentioned below and that will be widely explained on following subsections.

- *Passive exoskeletons* are systems that focus on gravity compensation, spring or even elastic members to store and release energy during movements, for instance please refer to fig.2.1. The main purpose of passive exoskeletons is providing

support to the user. These can not supply more energy to the environment than the provided from the user.

Figure 2.1: Example of passive exoskeleton based on springs [20].

- *Active exoskeletons* are devices that count with motors, PMAs (*antagonist pneumatic muscles*, these devices are constructed as two-layered cylinder, this design has an inner rubber liner, an outer containment layer and endcaps that seal the open ends of the muscle [21], valves or similar actuators that augment human force or assist their motion) and others. Their purpose is to reduce user's fatigue

and physical stress.

As an important fact, actual hybrid exoskeletons are no commercially available and they are not expected to be cheap. [22].

2.1 Passive exoskeletons

Some examples of passive-based exoskeleton include [3]

- *Passive gravity support.* In many instances they provide partial support to the users by providing strength by means of a mechanical path that direct forces to the ground.

- *Load-carrying assist.* A special case of gravity support device. An example of this kind is the BLEEX system (see fig. 2.2) developed at UC Berkeley [23], in which the exoskeleton partially or totally supports a load carried by the user, for example a heavy backpack.

- *Force-offsetting assist.* As a complement to load carrying capabilities, the system is developed by James Walsh. It uses passive devices like springs to store energy released during negative-work phases of the gait cycle. It releases energy during the positive-work phases to assist the process of walking motion [24].

- *Resonance-based assist.* This exoskeleton modifies the limb dynamics to make

it functioning closer to its resonant frequency, thus helping the user to perform effectively their own muscles.

Figure 2.2: BLEEX exoskeleton [25].

2.2 Active exoskeletons

Active exoskeletons use different kind of actuators, such as PAM, see fig.2.3 for an example of this device. Also, active exoskeletons use several kind of sensors, one of them is the electromyography sensor aka EMG [9]. in the case of control system some active exoskeletons are based on position and force control [26] but usually the force

provided by the user is not measured. This is due to the difficulty in estimating such a force and the lack of efficient force sensors.
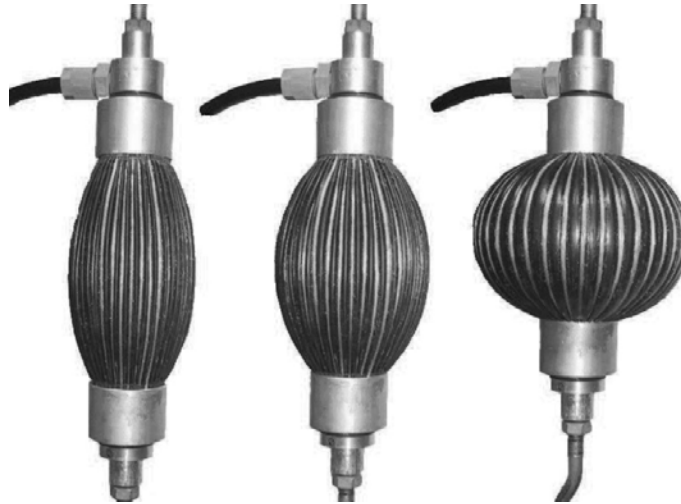
Figure 2.3: PAM system example [27].

2.3 Exoskeleton control

Exoskeletons are used normally for two basic purposes: force augmentation and user movement control. For instance, the exoskeleton HEXAR (depicted at fig.2.4) is used to augment the user upper limb force [28]. The interaction between exoskeleton and operator demands several algorithms, especially of control and estimation [9]. Exoskeleton like the *light exoskeleton* (L-EXO) shown at fig.2.5 implements a tracking control based on sliding mode technique [29]. In [30] an exoskeleton for upper limb with 7 degrees of freedom (DOF) and a weight of 72.4kg is presented. It has a controller responsible to track torque commands.
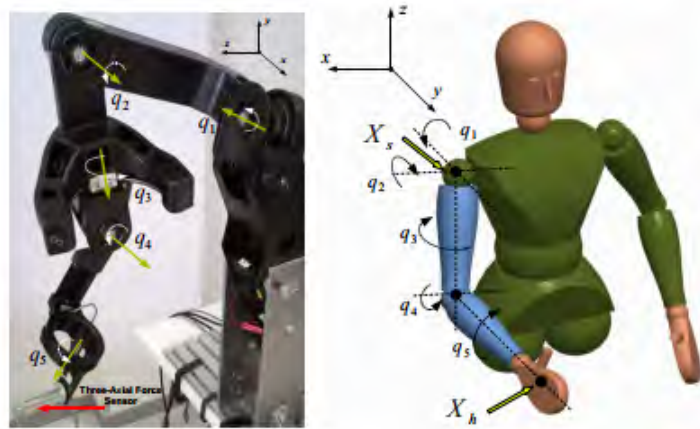
Figure 2.4: Hexar system [28]

Figure 2.5: L-exo and human body movements.

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There are several works of exoskeleton control and estimation presented in the literature. Researchers have been incorporating more DOF into exoskeletons, to get variety of upper limb movements. Current upper limb exoskeletons focus on movements of the shoulder, elbow and/or wrist complex. Several researchers have developed exoskeletons which include movements of the 2 DOF sternoclavicular joint at the shoulder complex. For example the tree showed on fig.2.6 [31].

Figure 2.6: Examples of exoskeletons with various DOF, the first one is CADEN-7 [32], second RUPERT IV [33] and the last ARMin III [34]

Also most of the current rehabilitation devices are useful just on some stages of rehabilitation, especially in cases where no force is received from the patient. For cases where small forces from patient are presented, exoskeletons with force feedback from the patient is needed. As the vast majority of these exoskeletons do not estimate the force exerted by the patient, there is no feedback for the human-robot interaction. Patient interaction is important since this patient is responsible for giving feedback force to the device [35, 36]. Also as it is mentioned on [5] the majority of current hybrid exoskeletons are focused on functional movement rather than on patient monitoring.

Most exoskeletons are not available to be portables due actuators that drive functionality of these requires to be powerful and it implicates to be weighted and big, also these kind of exoskeleton are available to be used on rehabilitation only if the patient count with a bit of force (due to weight), it means that are not optimal to patient that can not apply any quantity of force. [37]. Hence it is required an exoskeleton capable to move the limb of the patient when he or she can not apply any strength. Also, it is desired that the exoskeleton applies a defined movement to the patient in order to act as a muscle re-trainer.

As far as measurements are concerned, some methods to measure angular position on exoskeletons of upper limb are:

- Collocate marks on joint and take images of that with CCD cameras and after use an algorithm to process that and analyze angular parameters

- Using magnetic sensor with 3 axis coupling to joint, it computes 3D orientation and compare it to earth magnetic axes.

- using Inertial sensor like accelerometers or gyroscopes.

- Using a rotational potentiometer to measure angular position due it haves a linear dependence to electrical resistance and it provides an angular absolute position.

as is mentioned on [38].

2.4 Observers

Human robot interaction is a very difficult an important factor to considerate on system as exoskeletons due as it is working with 2 systems (human arm and exoskeleton) and the interaction between these produces vibrations. So, to measure that, exist various methods:

- Use an artificial impedance to decouple haptic control and model of the virtual environment.

- model the system and adaptive adjust the controller parameters using sensors related to the human movement in order to avoid the vibrations.

- considered as a variable forcetorque perturbations in complex 3D workspace. [29]

- create an observer to estimate vibrations caused by this interaction.

[39] In other cases as on developed system on [40] is necessary to obtain a detailed model of exoskeleton and upper limb to reduce that vibrations produced by interaction but it result very difficult, however in the same paper is showed the analysis of feedback linearization that does not requires detail of biological model, but it does not show a good performance.

Although dynamics of exoskeleton is known, dynamics of human limb generally is unknown and it change between every single persons. In consequence use of exoskeleton

and interaction with human user vary and depends of capacity of adaptation of control designed [2]. A control strategy that can be helpful are observers.

Observers are an important part of control systems cause these are a tool that provide information about parameters that, for difficulty, lack of instruments or non adequate sensors, is not possible to estimate value. In consequence some states of the system are unknown. These observer are subsystems that emulates original system and their behavior is related to these. These are designed using information of output of system and estates that is possible measure. Whit this information is possible say that observer can be use to estimate human-robot interaction.

2.5   Aim of work

As described in the previous sections, exoskeletons have difficulties to be implemented due, in part, to the human-robot coupling problem, because it generates unwanted vibrations and there is no mathematical model to describe it, besides being a device that, in this case, will be aimed at medical use, it should be very careful and controlled in relation to the movements made by the device to ensure the safety of the user. The objective of this work is design and create a prototype (based on its mathematical model). It has a control system that can follow a certain trajectory (a tracking control) based on parameters such as the position and speed of the device as well as an estimator of the human-robot disturbance as it has been investigated in [9, 29, 41, 42] and [28] (a

disturbance observer) that will serve to the same control. For the development of the observer the method of sliding modes was used to generate a compensation, which is integrated into the control equation to make it robust.

Chapter 3

System description and problem statement

To an adequate rehabilitation exoskeleton design, it is necessary to consider a mathematical model that represents the human-robot interaction due to the coupling of two systems (human and robotic) [26, 28, 42]. However, in the vast majority of works, only the modeling of the robot itself is considered, lacking of any function that models the aforementioned interaction [41].

3.1   State of the art of exoskeleton modeling systems

Various devices has been development and these have different ways to act and be modeled. Here are exposed some modeled systems of exoskeletons that exist on literature,

for example the device developed by Jožef Stefan Institute [9]. It was modeled based on model of force of muscle:

$$F_m = (f_0 f_1 f_v \alpha + F_p) \cos(\phi)$$

where f_0 represent the optimal muscle force; f_1 is the active force-length relationship; f_v is the force-velocity relationship; ϕ is the muscle tendon penation angle; and α is the activation level.

Other devices presented at [41], [29], [42], [40] and [28] (among others) use models based on robot equation due to the number of DOF that they have. The base model equation of such exoskeleton is as follows

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = u \tag{3.1}$$

where every variable correspond to one parameter of the device, q denotes position; $\dot{q}$ is the velocity; $\ddot{q}$ is the acceleration; $M(q)$ inertial matrix; $C(q, \dot{q})$ is the centrifugal and Coriolis matrix; and $G(q)$ is the gravity torque. This modeling is the most popular one, however in general it lacks of any term that relates the human-robot interaction.

As human-robot interaction represents a challenge since it causes vibrations [30], various methods has been applied as an alternative such as artificial impedance or using the energy transferred in the system with concepts such as time domain passivity.

However, both have problems, cause the first one reduces the performance and the other one has problems with the computational burden [39]. Now like a better alternative for that, a term of disturbance (δ) that represents that interaction was proposed.

3.2 Mathematical model

It was necessary to obtain a simple mathematical representation of system that will be easy to control but also describe system on a optimal way. This means represent principal parameters on a generalization but without a big loss of information. The mathematical model of exoskeleton was developed based on Lagrangian approach and the obtained model is similar to an actuated pendulum [43] (the joint of elbow) plus an unknown term that models the human-robot interaction, (a representation on free body diagram for the exoskeleton is shown at Fig. 3.1. It exposes the relationship between fixed frame and actuator frame and how coordinate system changes between each frame).

Lagrangian equation is given as:

$$L = K - \upsilon \tag{3.2}$$

where L is the Lagrangian, K kinetic energy and υ is the potential energy. By using
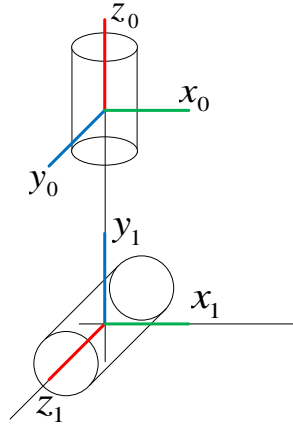
Figure 3.1: System diagram, that show relation between fixed frame and first frame (the one of actuator) based on Denavit-Hartenberg convention.

the Lagrangian approach and using (3.2) is obtained:

$$\xi_i = \frac{d}{dt}\frac{\partial L}{\partial \dot{\lambda}_i} - \frac{\partial L}{\partial \lambda_i} \tag{3.3}$$

The equations of K is:

$$K = \frac{1}{2}\dot{\theta}^2 l \tag{3.4}$$

where $\dot{\theta}$ and l represents angular velocity and length of system respectively. Also the equations of υ is:

$$\upsilon = lmg(1 - \cos{(\theta)}) \tag{3.5}$$

Where m is the mass and g is the gravity of the piece respectively and θ is the angular

position of joint. Then replacing equations (3.4) and (3.5) in (3.2):

$$L = \frac{1}{2}\dot{\theta}^2 l - lmg(1 - \cos(\theta))$$

and using the new Lagrange equation on equation (3.3):

$$\frac{\partial L}{\partial \dot{\theta}} = \dot{\theta}l \rightarrow \frac{d}{dt}\frac{\partial L}{\partial \dot{\theta}} = \ddot{\theta}l \quad \text{and} \quad \frac{\partial L}{\partial \theta} = -lmg\sin(\theta)$$

in this case $\ddot{\theta}$ is angular acceleration of joint. Considering that ξ is given by torque and friction ($\xi = T - F\dot{\theta}$) [43] and also a perturbation δ, originated by human-robot interaction:

$$\ddot{\theta}l + lmg\sin(\theta) = T - F\dot{\theta} + \delta$$

finally we get (in state space)

$$\Sigma = \begin{cases} \dot{\theta}_1 = \theta_2 \\ \\ \dot{\theta}_2 = \dfrac{T - F\theta_2 - lmg\sin(\theta_1) + \delta}{l} \end{cases}$$

that represents control term of the system. Mathematical model defined in this section represents the physic behavior of system, based on cinematic and kinematic energy. It is a starting point to continue with analysis. Then is necessary to delimit problem or problems to solve based on this model.

3.3 Problem statement

Considering the previously modeled system it is possible to see that, before all, due to the human-robot interaction it is produced a term (δ, that was defined previously and will be consider it time dependent and derivable) that can not be measured but it affects the system's behavior, so it is necessary to find a way to estimate that value (introduce an observer) of that term. In that way we will have an approximation of the value [39] with the sake of avoid a strange behavior of system. The problem is twofold: first, from a simple robot model it is necessary to introduce a function that models the interaction between the machine and human. For that aim we design a sliding-mode-based observer for the estimation of such unknown function. Second, once this function is known, a controller is designed with the aim of compensating the robot-machine interaction. This is possible defining it as follows:

Problem 1. *Designing a system (observer) ($\hat{\delta}$) that is able to estimate an approximation of value of the term δ i.e. converges to it in a finite time with a little error.*

In consideration of the necessity of strength feedback is necessary to apply a control system based on it and, because of the trajectories already set, we can focus on velocity of the device doing that the strength reference modifies the velocity. This because EMG signal is directly related with muscle length and velocity of contraction of it and also EMG signal has a direct relation to muscle force [44], so is possible to say that velocity of movement modifies force applied on muscle of patient. In this way is

available estimate it and, indirectly, control muscle force of patient in an non-invasive way. As a consequence, an adaption of the system to reach the required force level could be achieved. So it requires a velocity control for all the system that cushion the effect of δ, this due to force of the patient will be controlled through velocity of actuator and it is needed that this velocity will be guided by a reference in such a way that it will be safe for the patient.

Problem 2. *Using the previous designed perturbation observer, design a velocity control for mathematical model described on system Σ, such that it can be able to follow a velocity reference given by a time variant function, i.e. a tracking control.*

The objective of this work is to find a precise solution to both problems, using nonlinear control methods.

Chapter 4

Main result

4.1   Introduction

Taking into account the previous information of the theoretical framework, the problem statement and the objective that is expected to be achieved in this work, it is possible now to begin developing the solution, which starts from the mathematical model of the device and is based on its position and velocity. It is also introduced the observer of disturbances, which had been previously mentioned, as a way to complement the control. In this section the theorems of observer and control are presented, developed and tested using the Lyapunov technique.

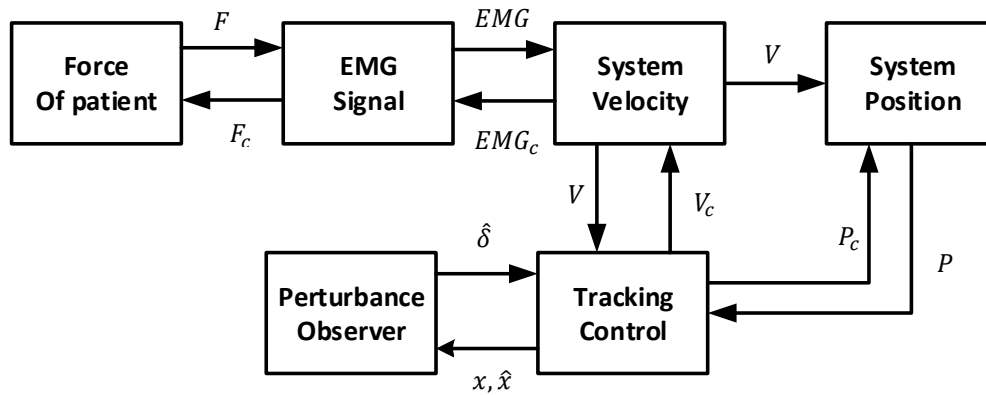A control diagram of this control system is shown at Fig.4.1.

Figure 4.1: Here is presented a simple diagram of control system where c means "correction" as an indication of change, as is possible see observer is a primordial step to control the entire system because it provides all the first correction and the other changes in consequence of that.

For simplicity parameters are adjusted as follow:

$$l = 1$$

$$F = a$$

$$mg = b$$

and

$$T = u$$

It is necessary show some examples of observers, beginning for one used on linear systems, the Luenberger observer. Below is a system to which an observer will be

designed:

$$x = Ax + Bu$$

$$y = Cx$$

estimated system is

$$\hat{x} = A\hat{x} + Bu + L(y - C\hat{x}$$

where L is a matrix called Luenberger gain and $\hat{x}$ is estimated state. Then is necessary

obtain an estimation error.

$$\tilde{x} = x - \hat{x}$$

Then error dynamics is given as

$$
\begin{aligned}
\dot{\tilde{x}} &= Ax + Bu - A\hat{x} - Bu - L(y - C\hat{x} \\
&= A(x - \hat{x}) - L(y - C\hat{x}) \\
&= A(\tilde{x}) - L(y - C\hat{x}) \\
&= A(\tilde{x}) - CL(x - \hat{x} \\
&= [A - CL]\tilde{x}
\end{aligned}
$$

which results in an exponentially stable error system, an then $\hat{x} \rightarrow x$.

Some observers are exponential as the one presented on [45], that also is used on an

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exoskeleton. Other observers (of disturbance and used for spacecraft formation flying) is as the one that can appreciate on [46] and the one of [47]. The observer mentioned on [48] is used to estimate mechanical values that will be used on a control to track the wind turbine maximum power point. Observer development on [49] is used to estimate the angular velocity of a rigid body from vector measurements. It should be noted that the aforementioned observers are non-linear.

4.2 Main Result

As is mentioned on [40] better results of control for upper limb are obtained using sliding mode. In this section we present our main result: an observer for an unknown disturbance. Such disturbance represents the force interaction between human and machine. The observer is based on the sliding mode approach. Once the observer is designed, the estimated state is used for feedback in a controller, as a result a feedback controller is obtained. Let's begin with a simple scalar system which shows our methodology.

Example 3. *Scalar system. Let the system*

$$\dot{x} = -ax + \delta(t)$$

$$y = x$$

where x is the system state; y is the available output; and $\delta(t)$ is an unknown distur-

bance. Define the disturbance estimation error and estimation state error as follows

$$\tilde{\delta} \;=\; \hat{\delta} - \delta \tag{4.1}$$

$$\tilde{x} \;=\; \hat{x} - x \tag{4.2}$$

Consider the following estimator

$$\dot{\hat{x}} \;=\; -a_1\hat{x} + \hat{\delta} - \theta(\hat{x} - x) \tag{4.3}$$

$$\dot{\hat{\delta}} \;=\; -k_1 \operatorname{sign}(\hat{x} - x) - k_2\hat{\delta}. \tag{4.4}$$

where $\theta \in \mathbb{R}^+$. Then the error dynamics of (4.1) together with (4.3) is given as

$$\dot{\tilde{x}} \;=\; -(a_1 + \theta)\tilde{x} + \tilde{\delta}$$

$$\dot{\tilde{\delta}} \;=\; -k_1 \operatorname{sign}(\tilde{x}) - k_2\tilde{\delta} - k_2\delta - \dot{\delta}$$

Proof.

$$V = a_1|x_1| + b|x_2| + \frac{1}{2}\delta^2$$

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deriving, we have:

$$\dot{V} = a\,\text{sign}\,(x_1)\dot{x}_1 + b\,\text{sign}\,(x_2)\dot{x}_2 + \tilde{\delta}\dot{\tilde{\delta}}$$

$$= a\,\text{sign}\,(x_1)x_2 + b\,\text{sign}\,(x_2)(u_1 - ax_2 + x' - af_2(t) + \tilde{\delta} - \dot{f_2}(t)) +$$

$$\tilde{\delta}\dot{\tilde{\delta}}$$

$$= a_1\,\text{sign}\,(x_1)x_2 + b\,\text{sign}\,(x_2)(u_1 - ax_2 + x' - af_2(t) + \tilde{\delta} - \dot{f_2}(t)) +$$

$$\tilde{\delta}(-k_1\,\text{sign}\,(e) - k_2\,\text{sign}\,(\hat{\delta}) - f(t))$$

So making the control

$$u_1 = a_1 x_2 - x' + af_2(t) - (\dot{f_2}(t) + Kx_2)l$$

$$\dot{V} = -kb|x_2| + \text{sign}\,(x_1)(a_1 x_2 - k_1\tilde{\delta}) + \text{sign}\,(x_2)(b\tilde{\delta}) -$$

$$k_2 \text{sign}\,(\hat{\delta})\tilde{\delta} f(t)\tilde{\delta}$$

$$\leq -kb|x_2| + \text{sign}\,(x_1)(a_1 x_2 - k_1\tilde{\delta}) + \text{sign}\,(x_2)(b\tilde{\delta}) -$$

$$k_2(\text{sign}\,(\tilde{\delta}) + \text{sign}\,(f(t)) + 1)\tilde{\delta} - f(t)\tilde{\delta}$$

$$\leq -kb|x_2| + \text{sign}\,(x_1)(a_1 x_2 - k_1\tilde{\delta}) + \text{sign}\,(x_2)(b\tilde{\delta}) -$$

$$k_2|\tilde{\delta}| - k_2\tilde{\delta}\,\text{sign}\,(f(t)) - k_2\tilde{\delta} - f(t)\tilde{\delta}$$

$$\leq -kb|x_2| + (a_1 x_2 - k_1\tilde{\delta}) + b\tilde{\delta} - k_2|\tilde{\delta}| + k_2|\tilde{\delta}| -$$

$$k_2\tilde{\delta} - f(t)\tilde{\delta}$$

consider:

$$|f(t)| < D$$

$$k_2 = D$$

have:

$$\dot{V} \leq -kb|x_2| + (a_1 x_2 - k_1\tilde{\delta}) + \frac{b\tilde{\delta}}{l} - k_2\tilde{\delta} + D\tilde{\delta}$$

$$\leq -kb|x_2| + (a_1 x_2 - k_1\tilde{\delta}) + b\tilde{\delta}$$

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also consider:

$$k > b > 0$$

$$k_1 = b$$

finally:

$$\dot{V} \leq -kb|x_2| + a_1 x_2$$

so now we define the next statement:

$$b > a_1$$

this helps the observer to be negative definite. □

The main results is stated in the following theorems.

Theorem 4. *To estimate perturbations of the system described by Σ it can be designed an observer based on sliding modes and error between output and observer of it. The next equation is a control for the observer to estimate human-robot interaction.*

$$u = ax_2 - x' + af_2(t) - (f_3(t) + Kx_2)$$

$$\dot{\tilde{\delta}} = \dot{\hat{\delta}} - f(t)$$

where

$$\dot{\hat{\delta}} = -k_1 \operatorname{sign}(x_1) + k_2 \operatorname{sign}(\hat{\delta})$$

$$\tilde{\delta} = \hat{\delta} - \delta$$

Proof. assumption:

- control u is global Lipschitz respect to vector of states $\vec{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

- there is a set of controls $\mathbf{u} \in L^\infty(\mathbb{R}^+, \mathbb{R}^2)$, such that any trajectory $x(t)$ associated with any $u \in \mathbf{u}$ is bounded.

Equations of model need to be modified to be able to follow references of velocity and movements i.e. a tracking control system. So system must be reconditioned as follows:

$$\Sigma = \begin{cases} \dot{x}_1 = x_2 \\ \\ \dot{x}_2 = u - ax_2 + x' - af_2(t) + \tilde{\delta} - f_3(t) \end{cases}$$

where

$$x_2 = \dot{\theta}_1 - \dot{\theta}_{1d}$$

$$x' = -b\sin(x_1)\cos(f_1(t)) - b\sin(f_1(t))\cos(x_1)$$

And $f_3(t)$ is an assumption of perturbation is bounded by a function as is mentioned

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on [50]. Due to is needed to know velocity of device and estimation of position to determine perturbation $(\hat{x}_1 - x_1)$, it is necessary to include an observant system, based on [51]. So the system Σ is modified:

$$\Sigma = \begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 \\ \\ \dot{\hat{x}}_2 = u - a\hat{x}_2 + \hat{x}' - af_2(t) + \hat{\delta}(t) - S_\alpha^{-1}C'[\hat{x}_1 - x_1] \end{cases}$$

That is the original system with a corrective term where:

$$\hat{x}' = -b\sin(\hat{x}_1)\cos(f_1(t)) - b\sin(f_1(t))\cos(\hat{x}_1)$$

where $C = [1, 0]$, S_α is solution of:

$$\alpha S_\alpha + A^T S_\alpha + S_\alpha A - C^T C = 0 \qquad (4.5)$$

where:

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$$

and the solution of (4.5) is given by:

$$s_\alpha(i, j) = \frac{(-1)^{i+j} C_{i+j-2}^{j-1}}{\alpha^{i+j-1}}$$

for $1 \leq i$ and $j \leq 2$ where:

$$C_p^q = \frac{p!}{(p-q)!q!}$$

is an exponential observer for Σ such that converges in a finite time. $\square$

Theorem 5. *The next equations describe a velocity control for the system Σ, where U is a control entrance that makes the system globally asymptotically stable.*

$$u = F x_2 - x' + F f_2(t) - \tilde{\delta} - (f_3(t) + k(x_2))l \tag{4.6}$$

and

$$\dot{\hat{\delta}} = -k_1 \operatorname{sign}(x_1) - k_2 \operatorname{sign}(\hat{\delta}) \tag{4.7}$$

where:

$$f_2(t) = \dot{f_1}(t)$$

where $f_1(t)$ is the reference of desired velocity that vary on time and is continuously differentiable

Proof. Is necessary to propose a Lyapunov candidate function such that, according to the stability theorems of non autonomous systems, $W_1(x)$ and $W_2(x)$ should be K or K_∞ ($\forall t \geq 0$ and $\forall x \in R^n$, where $W_1(x)$ and $W_2(x)$ are continuous definite functions on R^n [50]) and according to La Salle generalization [50], W_3 should be a positive definite

and radially unbounded function.

$$W_1(x) \le V(t) \le W_2(x) \tag{4.8}$$

$$\dot{V}(t, x) = \frac{\partial V}{\partial t} + \frac{\partial V}{\partial x} f(x, t) \le -W_3(x) \tag{4.9}$$

Taking these on consideration it can be propose a Lyapunov function:

$$V = a_1 |x_1| + b_1 |x_2| + \frac{1}{2} \tilde{\delta}^2 \tag{4.10}$$

The derivative of this is computed as:

$$
\begin{aligned}
\dot{V} &= a_1 \operatorname{sign}(x_1) \dot{x}_1 + b_1 \operatorname{sign}(x_2) \dot{x}_2 + \tilde{\delta} \dot{\tilde{\delta}} \\[2mm]
&= a_1 \operatorname{sign}(x_1) x_2 + b_1 \operatorname{sign}(x_2)(u - ax_2 + x' - af_2(t) \\[2mm]
&\quad + \tilde{\delta} - \dot{f_2}(t)) + \tilde{\delta} \dot{\tilde{\delta}} \\[2mm]
&= a_1 \operatorname{sign}(x_1) x_2 + b_1 \operatorname{sign}(x_2)(u - ax_2 + x' - af_2(t) \\[2mm]
&\quad + \tilde{\delta} - \dot{f_2}(t)) + \tilde{\delta}(-k_1 \operatorname{sign}(e) + k_2 \operatorname{sign}(\hat{\delta}) - f(t))
\end{aligned}
$$

So making the control

$$u = ax_2 - x' + af_2(t) + \dot{f_2}(t) - kx_2$$

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We have:

$$\dot{V} = -kb_1|x_2| + a_1 \operatorname{sign}(x_1)x_2 + \tilde{\delta}(-k_1 \operatorname{sign}(e) + k_2 \operatorname{sign}(\hat{\delta}) + f(t))$$

As we can see state x_1 is bounded by the $\operatorname{sign}()$ function so taking in to account that:

$$\operatorname{sign}(a + b) \leq \operatorname{sign}(a) + \operatorname{sign}(b) + 1$$

we have:

$$\dot{V} \leq -kb_1|x_2| + a_1 \operatorname{sign}(x_1)x_2 + \tilde{\delta}(-k_1 \operatorname{sign}(e) +$$

$$k_2 \operatorname{sign}(\tilde{\delta}) + k_2 \operatorname{sign}(\delta) + k_2 + f(t))$$

$$\leq -kb_1|x_2| + a_1|x_2| + k_1\left|\tilde{\delta}\right| + k_2\left|\tilde{\delta}\right| + k_2\left|\tilde{\delta}\right| + k_2\left|\tilde{\delta}\right| +$$

$$f(t)\left|\tilde{\delta}\right|$$

considering:

$$|f(t)| < D$$

$$|k_2| > D$$

have:

$$\dot{V} \leq -kb_1|x_2| + a_1|x_2| + (k_1 + 3k_2)|\tilde{\delta}| + D|\tilde{\delta}| \tag{4.11}$$

also consider:

$$k > b_1 > a_1$$

$$|k_2| > |k_1|$$

$$k_2 < 0$$

And considering $f(t)$ like a function that is bounded above and below it's possible to say that (4.11) is a defined negative function:

$$\dot{V} \leq -k|x_2| + k_2|\tilde{\delta}|$$

Also is easy to see that a positive definite function exists and satisfies inequality (4.9). This function is given by:

$$W_3(x) = a_1 x_1^2 + b_1 x_2^2 + \tilde{\delta}^2$$

that is a globally radially unbounded function, and also exist functions that satisfy inequality (4.8):

$$W_1(x) = |x|_1 + |x|_2 + \frac{1}{4}\tilde{\delta}^2$$

and

$$W_2(x) = 2a_1 x_1^2 + 2b_1 x_2^2 + \tilde{\delta}^2$$

and in both cases are K_∞ functions so we can say that our function (4.10) is bounded above and below and fulfill inequalities (4.8) and (4.9) therefore (by LaSalle generalization) it is globally asymptotically stable. $\qquad\square$

And finally, next equation serves to prove finite convergence time of perturbation observer, based on equation $\dot{V} = -Ka$.

$$t = \frac{-v_0^{(1-a)}}{K(a-1)} \tag{4.12}$$

where K and a are constants and $0 < a < 1$. So first, solving equation:

$$\dot{V} = -KV^a$$

$$\frac{dv}{V^a} = -kdt$$

$$\int_{V_0}^{V} \frac{1}{V^a} \cdot dV = \int_{0}^{t} K \cdot dt$$

$$\frac{V^{(1-a)}}{1-a} - \frac{V_0^{(1-a)}}{1-a} = -Kt$$

$$\frac{V^{(1-a)}}{1-a} = -Kt + \frac{V_0^{(1-a)}}{1-a}$$

$$V^{(1-a)} = Kt(a-1) + V_0^{(1-a)}$$

$$V = \sqrt[1-a]{Kt(a-1) + V_0^{(1-a)}}$$

taking last equation we can use it to find convergence time like follow:

$$0 = \sqrt[1-a]{Kt(a-1) + V_0^{(1-a)}}$$

$$0 = Kt(a-1) + V_0^{(1-a)}$$

$$\frac{-V_0^{(1-a)}}{K(a-1)} = t \tag{4.13}$$

As it can be seen on equation (4.13), convergence time is defined by the initial condition V_0, constants K and a value. It proves that observer converges on finite time.

Chapter 5

Numerical and experimental results

Simulations of control system and behavior and respective results are show below with a little explanation of graphs an a brief description of parameters and values taking in to account to every one. Simulations of closed-loop system with the control and observer were conducted using Matlab Simulink, this helped to visualize behavior and effectiveness of control system. Normalized values for model parameters were considered; a signal $\theta_d = \sin(t)$ was chosen to follow; $\alpha = 2000$ and a constant $D = 3$ (that represent the bounded of $|\delta|$) as parameters to work it and show effectiveness, that parameter was selected randomly, the function $\sin(t)$ emulates a repetitive movement on sagittal plane, it is a constant flexion and extension of muscle of arm, as it would be done in therapy, to return the plasticity to this (see fig.5.1).

The graphics of the convergence of the observer of system and controller are depicted

Figure 5.1: description of movements of arm to therapy rehabilitation [52]

at 5.2 (where is show how observer of states converges to original states), 5.3 and 5.4 (in every picture is possible appreciate the functionality of tracking control that converges to the function to follow ($\sin(t)$)) and results of perturbation estimation on 5.5 (that shows the difference (error) between δ signal and $\hat{\delta}$). In every results it can be appreciate that system converges in finite time (on question of seconds) so the system is available to work.

In the case of observant, it was try to determine human-robot interaction (vibrations caused by these) and it was represented by a generated random signal and on simulation was defined by pseudo code show on algorithm 1 that provides a non periodic behavior.

Finally, discussion of these results and conclusions are presented on final chapter were analyze that and criticize it.
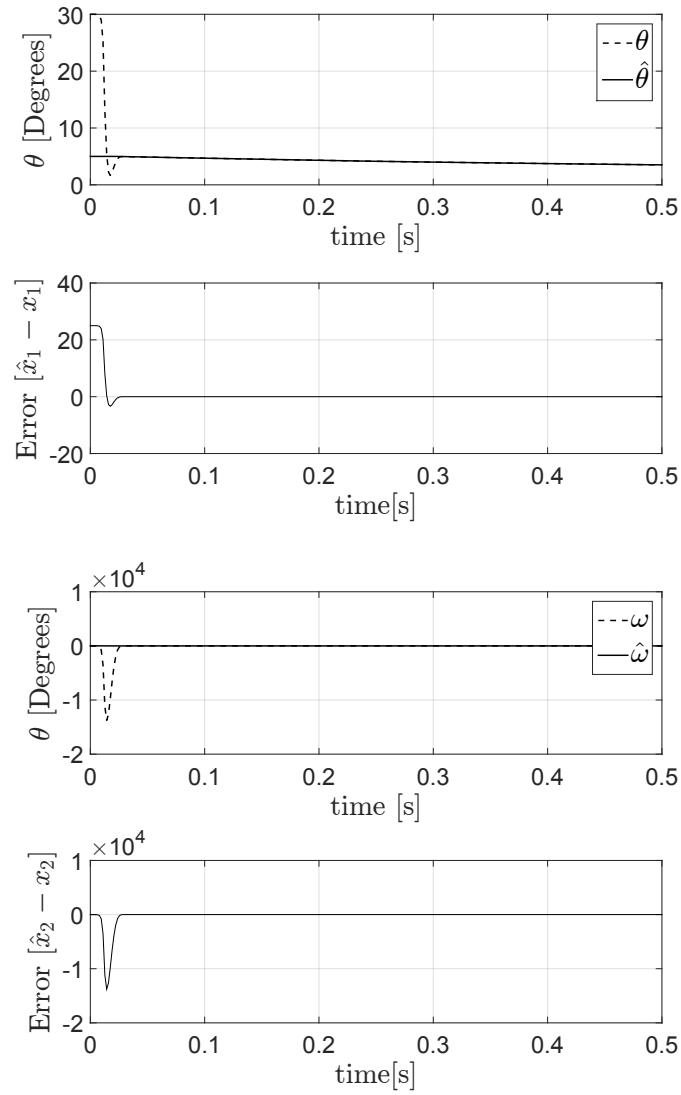
Figure 5.2: Here is possible see the behavior of observer $\hat{x}_1$ (graph 1) and $\hat{x}_2$ (graph 3) that represent states $\hat{\theta}$ and $\hat{\omega}$ respectively and its errors.
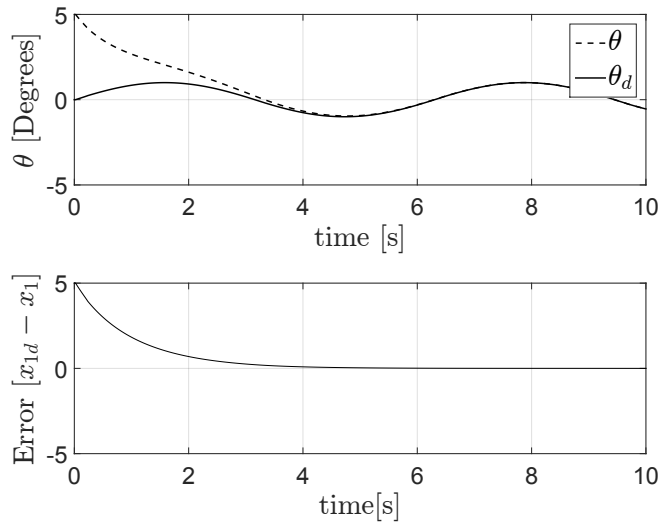
Figure 5.3: Above on first graph is possible appreciate the behavior of states x_1 that represent position of system and how is that it converges to x_1d that represent the function to follow, and the second one shows error between both and how it converges to zero.
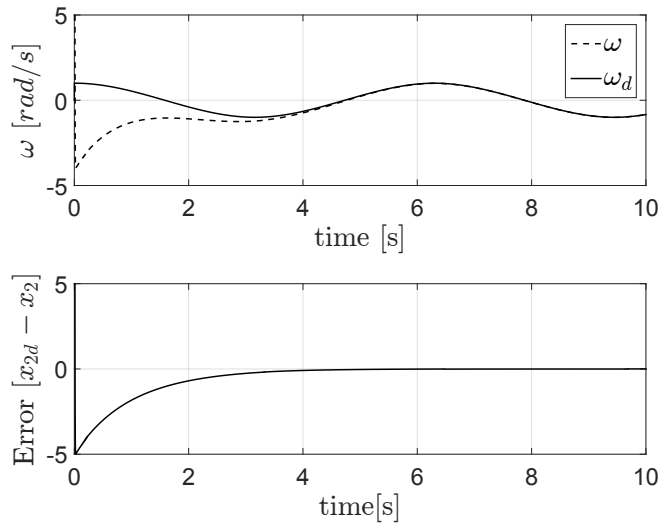

Figure 5.4: First graph shows second state x_2 behavior and the function to follow x_2d and also, on second, the error between both, with a window of 10 seconds (this time is just to be able to appreciate the convergence on finite time of system)
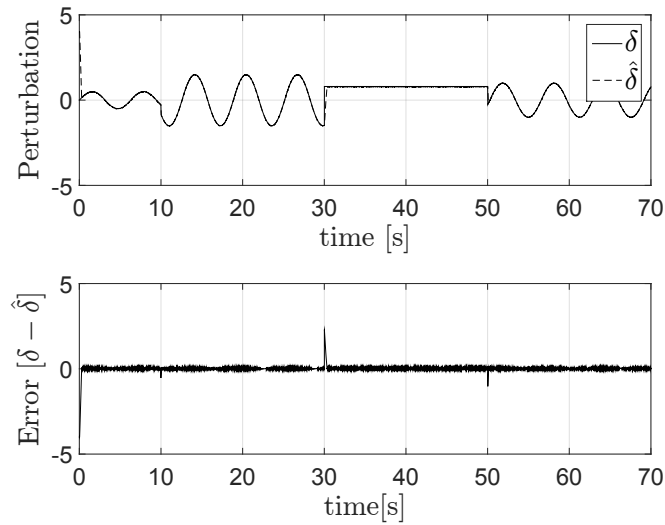
Figure 5.5: On first graph is easy to see that observer $\hat{\delta}$ (dashed line), using a sliding mode, converges quickly to original state δ and, second graph, shows the error between observer and original state. (the time windows of 70 seconds is just to show that error keep going be little on a big time.)

Algorithm 1 Perturbation algorithm
___

   if $t < 10$ **then**
      $\delta \leftarrow 0.5 \sin{(t)}$
   else if $10 \leq t$ and $t < 30$ **then**
      $\delta \leftarrow 1.5 \sin{(t)}$
   else if $30 \leq t$ and $t < 50$ **then**
      $\delta \leftarrow 0.8$
   else
      $\delta \leftarrow \sin{(t)}$
   end if
___

Chapter 6

Experimental platform and experiments

Here it is described the mechanical system, how it was designed, parameters and adaptations that was taking into account, materials, shape and size. The way to control electronic components and interaction with mechanical model is also described.

As is possible to see on literature, there is an existent necessity to obtain a device that collect different characteristics as portability, functionality and effectiveness, in consequence it tried to design a device that count with all of that. It is necessary remark that it is a first design and due this it had a lot of modifications. This device will be used just for tests, but not yet to rehabilitation therapy.

6.1　Mechanical design

To design the mechanical system, simplicity, lightweight and portability were considered. Then it was designed in the easily way that was considered with just 1 actuated DOF and coupled to right arm. Considering this, first system approach was proposed as a diagram of frames based on Denavit-Hartenberg convention taking into account just the frame of shoulder(as fixed frame) and elbow. It was decided to focus in elbow
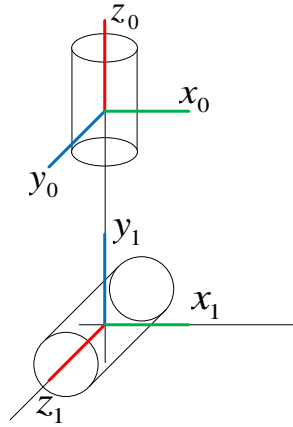

Figure 6.1: System diagram, that show relation between fixed frame and first frame (the one of actuator) based on Denavit-Hartenberg convention.

but provide movement to shoulder, to make the device more comfortable, consequently the device count with 3 DOF (two on shoulder and one in the elbow), two bars be guided by upper arm and forearm and a pair of pulleys that provides movement to the bar attached to forearm and in consequence to elbow.

The representation of first ideas was designed on a CAD file using SOLIDWORKS software for that purpose. All measurements corresponding to a male of around 24

years, also it was taken on count a previous existent designs of an exoskeleton of upper limb as the one described on [38].
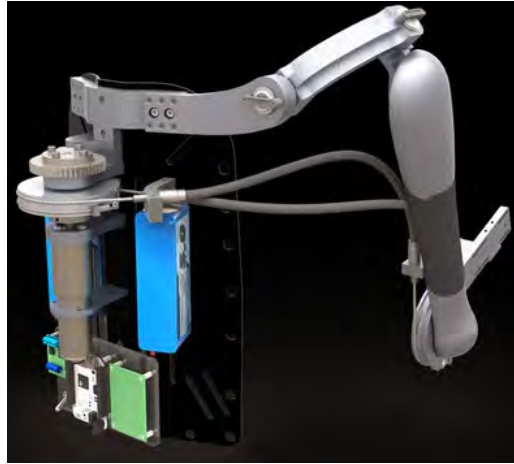

Figure 6.2: Design of titan Arm [53]

Figure 6.3: Mechanical design of exoskeleton for elbow

The back of system consists on a plate of aluminum that will be burden by patient as a backpack as we can see on Fig. 6.5, also this plate will contain the electronic system and a pair of pulleys. This plate is just a rectangle adapted to size of the back of the patient.
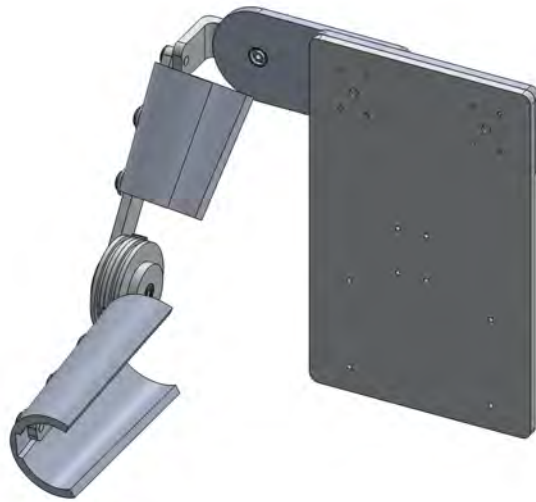
Figure 6.4: Isometric view of CAD of the exoskeleton.

Figure 6.5: Backpack structure

The shoulder joint counts with 2 DOF, with a L shaped structure and 2 holes to put bearings and give movement to shoulder of patient, also this piece acts as union between back and arm parts.

Figure 6.6: L shaped piece of shoulder

Arm piece was designed to be similar to a bar but with a circle structure on final of piece (fig 6.7). It count with 4 holes; 1 to attached to shoulder piece, 2 to attached to PLA piece that will hold arm and the other one, located on circle part, to be attached to the pulleys.

Figure 6.7: arm piece

Pulleys are a very important part of the system. due to it, along with DC motor, they provide movement to elbow joint. 2 pair of pulleys were created; one to be placed

on back, directly to motor axis, and the second one to be placed on elbow joint. All pulleys have canals along of its circumference, of 5 mm of width, and have a little cut L shaped with dimensions of 26x26 mm. An image of these pieces is shown in Fig. 6.8.
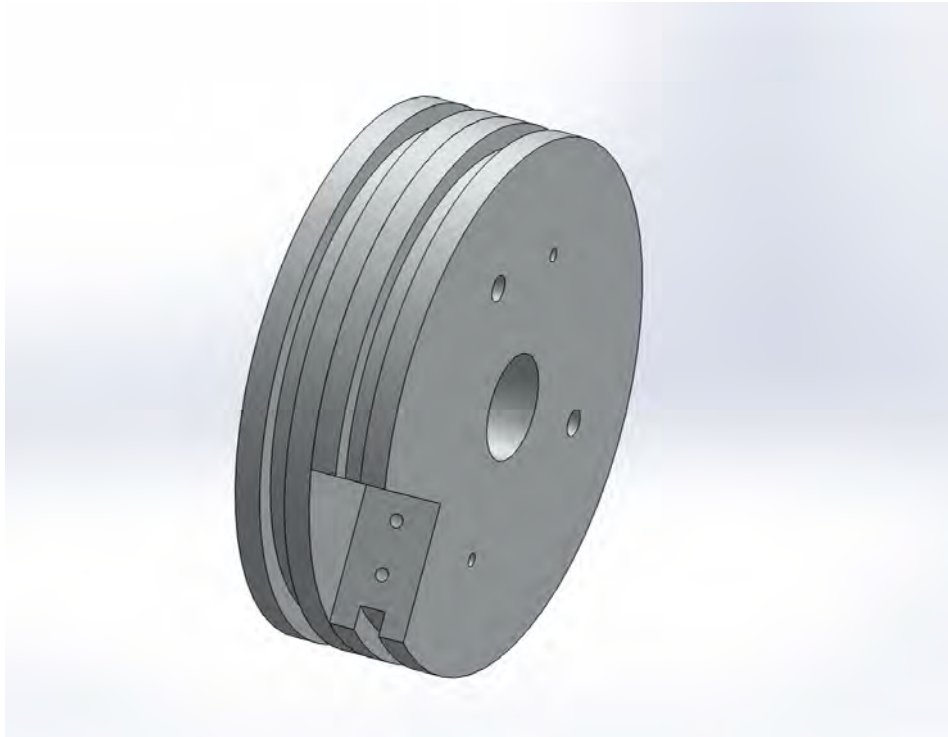

Figure 6.8: Pulleys view

On canals of pulleys there will be placed 2 iron cables (one each to just one pulley of every pair) to generate tension and, in consequence, move pulleys and elbow. As we can appreciate in Fig. 6.8, the DOF will move around an axis. One of them will move it from 90 to 180 degrees and the other one form 90 to 0 degrees.

PLA pieces were designed to be adapted to human arm and printed on 3D printer (Fig. 6.9). This pieces will hold the arm of patient with help of straps. Forearm piece

is very similar to the arm piece. It has the same shape and number of holes. The hole
of the circular part is attached to elbow and the other 3 to piece of forearm.

Figure 6.9: PLA piece for forearm

6.2 Electronic system

The electronic system will be placed on back (into a box) to reduce the load supported
by patient and for proximity to the DC motor. The electronic system is simple (in this
first prototype). It just contains a microcontroller, an encoder, an H bridge, a motor
and a battery as power source. Sensors signals (encoder and EMG signal) will be read
by the microprocessor and processed by it. It will be placed in the box aforementioned
and this and the other components will be powered by the battery. The encoder will
not be placed directly on elbow joint, as the DC motor will be mounted on back and,
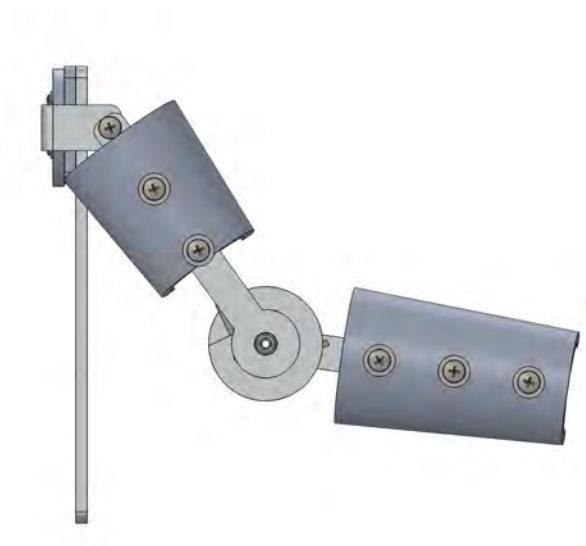
Figure 6.10: pulleys on elbow place

how system is guided by pulleys and it has a relation 1:1 encoder will be mounted on axis of motor.

EMG signal needs to be taken directly of muscle to ensure a correctly measurement of force. To solve that and avoid taking the signal directly this will be read by the microcontroller using a pad extension that has 3 electrodes and thanks to it, it is not necessary to place the sensor directly on muscle.

Battery will be located in the box. This battery needs to have a capacity to give minimally 4A and 12V to ensure a correct functioning of the motor. Also an H bridge is needed to help the motor to be driven by the microcontroller. The H bridge simulation and the PCB design was done using Proteus software. It counts with 2 canals and ensures a capacity to support 4.5 A per canal. A view of the PCB model is shown on
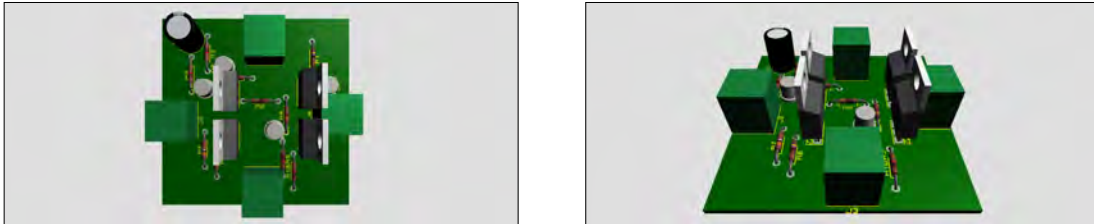
Fig.6.11

Figure 6.11: 3d views of PCB of H bridge

The motor is the principal mechanical/electronic device of the project because it provides movement to elbow, under tests it consume 12V and 2A to move a load of approximately 2kg. It will be hold by two pieces of PLA attached to the back.

A diagram of the complete system functioning is shown in Fig. 6.12. This diagram shows how electronic and mechanical parts interact and the action of every part of the system. The microcontroller will perform the control equation previously mentioned.
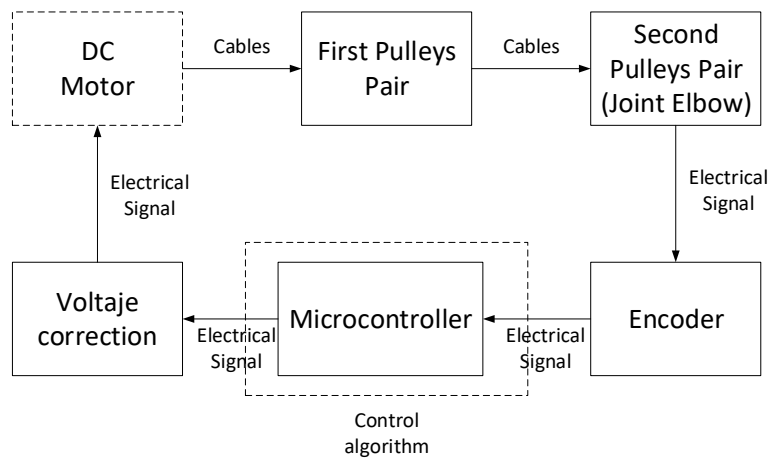
Figure 6.12: Diagram of complete system

6.3 Experiments

The final prototype of the exoskeleton is shown at Figures 6.13 and 6.14. Exoskeleton was directed tested by applying a sequence of movements using an arduino. Measures were made with a simple rotative encoder to delimit movements.
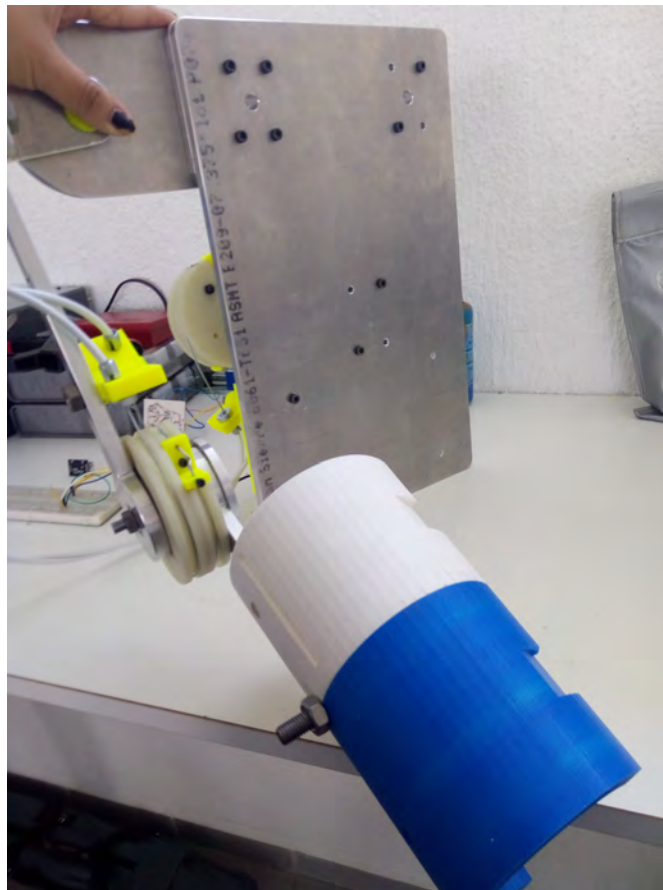

Figure 6.13: Isometric view of mechanical prototype with the pulleys, cables and PLA piece
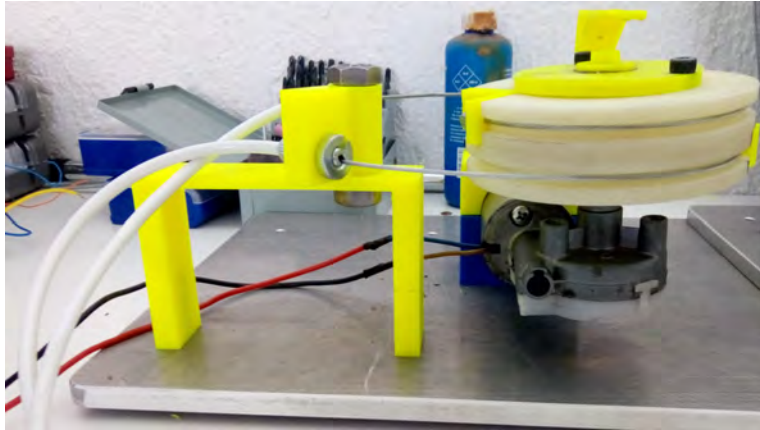
Figure 6.14: View of pulley system of back where motor is placed, it counts with an structure to fixed it and avoid it rotates due tension of cables

6.4 EMG

When the muscle generate force an electrical signal is generated that is associated to this, this signal can be measured using electrodes and is called EMG (electromyography). The EMG is the method of sensing and recording the electrical activity of a muscle, including information about the physiological processes that occur during muscle contraction [44]. Muscle force refers to the ability of muscle to generate tension and this depends of the length of muscle and the angular position of this directly related to that length [44]. Some factors that intervene on force generation are showed on fig 6.15.

As is mentioned on [54], in patients with spasticity after a stroke exist a decoupled on relation between EMG signal and muscle force. Also relation between EMG signal and muscle force (during voluntary contraction) is not clear at all. Some authors have

concluded that exist a proportional relation for isometric and isotonic contraction with a constant velocity but others said that this relation is non linear. In most cases non linear relation increases with increasing force or muscle contraction [44]. Even so EMG
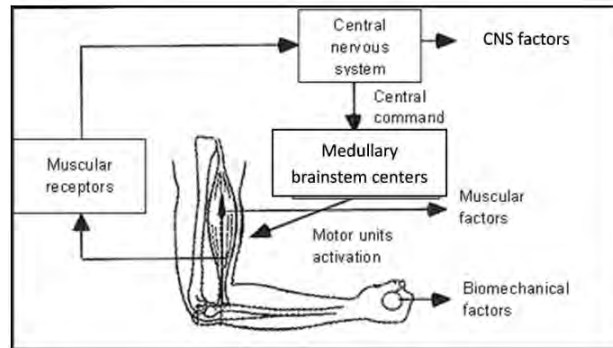

Figure 6.15: Diagram that shows different factor associated to muscle force generation. [44]

signal is good reference to estimate human robot interaction. This signal will be use to estimate stage of rehabilitation that patient needs and his progress. EMG signal is used in several hybrid exoskeletons and it showed that is the best method to obtain information of patient but, at same time, the most complex [5]. Some devices that use that sensor are Orthojacket, FES/Robot Hand, RUPERT (mentioned on [5]), Robot Suit HAL-5, CADEN-7 (see [38]) and various other.

Exist a function that describes the relation between distance of motor unit and recording electrodes. That function is:

$$V = \frac{V_0}{r/r_0{}^D}$$

where D and V_0 are constant and r_0 some reference distance from the electrical center of the motor unit, where $V = V_0$. [55]

6.5   Experiments

To observe behavior of EMG sensor it was taken some proves registering maxim voltage in every case. The used device was the Myoware muscle sensor (see fig.6.16) that count with 2 electrodes united to board and a third (reference electrode) outside of it. To have a better handle of electrodes a plug extention board was used with the muscle sensor.

Process was the next.

- Prepare the skin of voluntaries: The skin was shaved.

- Clean the area: Using alcohol the skin was cleaned of dust or every possible dirt trail.

- Electrodes placement: The two electrodes of signal was placed as is show on the image 6.17 (over forearm muscle) and reference electrode on back of forearm.

- Measure: It was taken with help of digital oscilloscope connecting the output of signal of sensor.

Skin preparation to place the EMG sensor vary from paper to paper, some mentioned that shave the skin before collocate the sensor, after that clean the skin with alcohol,
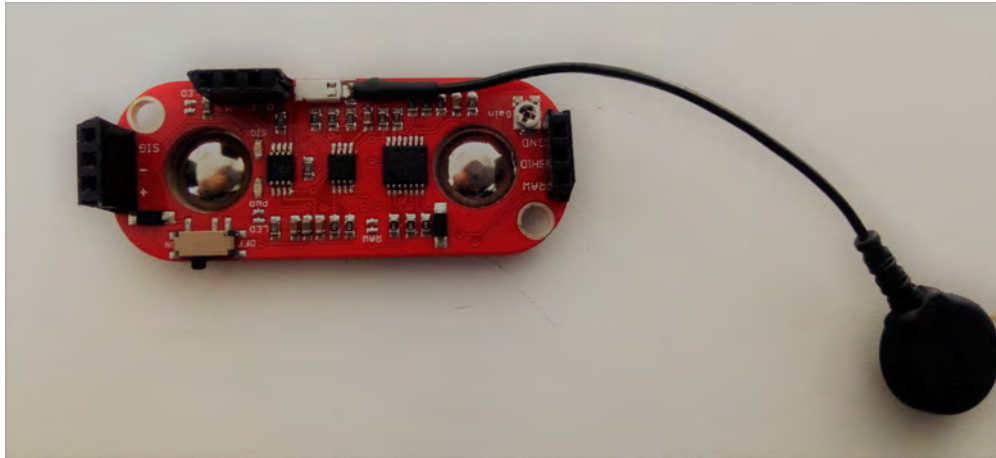
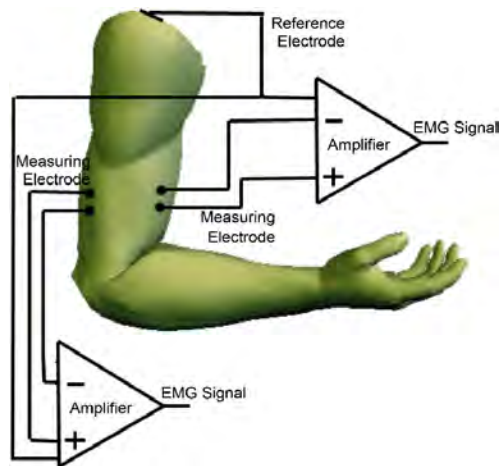Figure 6.16: Top view of Myoware muscle sensor

Figure 6.17: A little diagram of configuration of EMG sensor basic function [56]

ethanol, cleaning gel or another clean products. All authors accepted a maximum impedance skin of $10K\Omega$. In majority of works they does not said if they use gel.

Person	Weight (Kg)	Height (m)	BMI ($\frac{Kg}{m^2}$)	Voltage (v)
1	44	1.64	16.36	4.23
2	67	1.71	22.91	4.22
3	82	1.69	28.71	4.10
4	50	1.68	17.72	4.22
5	57	1.68	20.20	4.21

Table 6.1: Table of parameters taking on count and response of EMG sensor

On table 6.1 it shows interaction of EMG sensor with 5 persons of different weight and height but the result is more interesting taking on count the BMI (Body Mass Index) and is easy to see that for a person with low BMI, the sensor signal rise to a higher voltage. Accord to literature this is because they have less muscular mass and is more easy to EMG signal go through muscles and skin and reach surface of the skin [44].

Another measure was taken to graph response of EMG signal. It was taken with arduino but this time at same time graphicated on Matlab (see fig.6.18). For this the voluntaries (a man and a woman) was asked to contracted and relax the arm 3 times during 30 seconds.

On figures 6.19 and 6.20 is possible appreciate that the measures vary because each one have different BMI, the woman has 18.7 BMI and the man has 22.91 of BMI, in every graph the peaks was situates on the moment when the elbow had 90 degrees during movement.
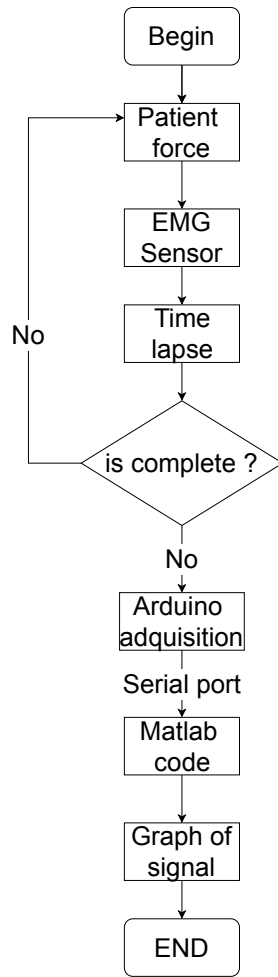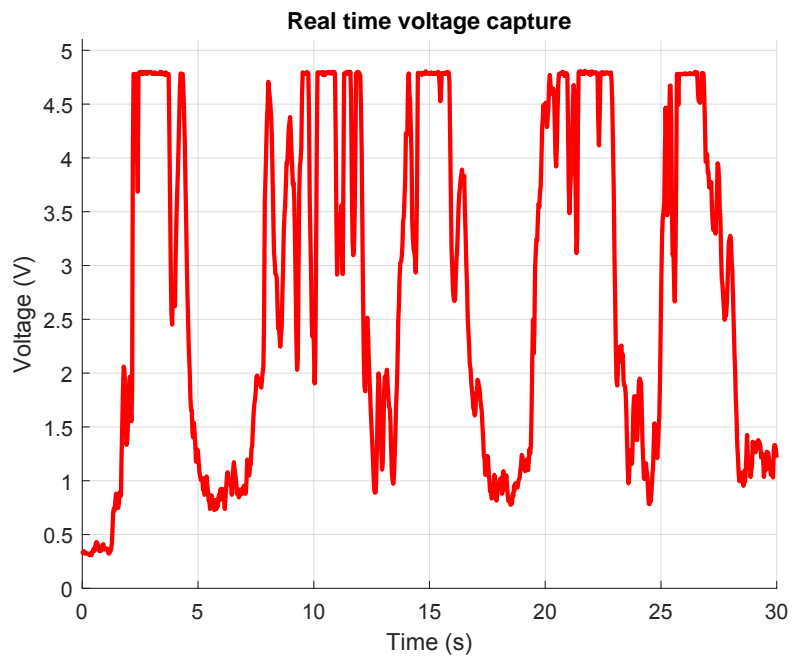
Figure 6.18: Process to graph signal

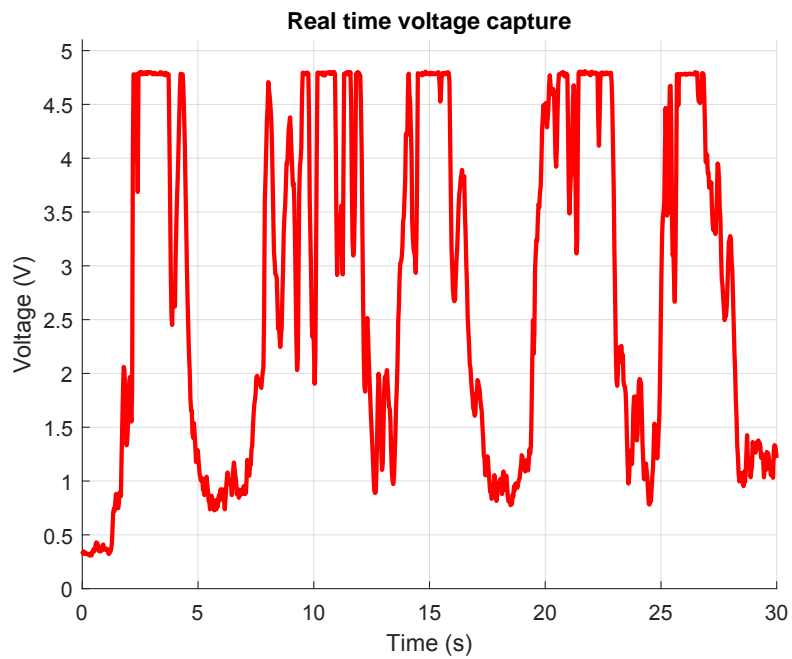Figure 6.19: Measures of force of a woman around 22 years old

Figure 6.20: EMG measures of a man of 24 years old

Chapter 7

Conclusions and Future Works

Referring to results exposed on section 5, and analyzing it we can say that control system is effective because it makes that states (x_1 and x_2) converges to their respective reference of position and velocity, this means that is able to make the system follow the reference that we introduce to the system, and error (e) converges to zero. On case of observer($\hat{x}$) we can see that it converges very quickly, it shows typical scattering of sliding mode but it is acceptable because it is very tiny and this control helps to cushion perturbation. However tracking control is slow yet, cause need some seconds (4 seconds) to converges to reference. This is an acceptable time but it can be better. So is necessary find a better control equation or a better control method to upgrade system to some that can be faster than now.

Talking about mechanical design, it works like a test prototype however is afar to

be implemented as a medical device because it need some improvements. The system is so weight yet so is necessary change material, adapt the back to have a better shape to adapt to human back, arm restraints should be designed to have better coupling to human arm. Then it will be necessary development a new prototype with a optimal design and a light material.

On section 5 we can appreciate that mechanical model have an aggressive behavior so is necessary found a better interaction between physical devices (electronics and mechanical) due movements are acceptable for people that have not a disable but for patients it could be dangerous, hurt them and in consequence increase they time of therapy.

7.1 Future Work

For the future works we want to use the information and experience acquired in this project in a new version of this device with a better control, a faster convergence time, and implying the signal of EMG sensor as well as to get better system design, to make it more easy to use (lightweight and portability) and after this design a new exoskeleton, this time for a lower limb with more DOF's.

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