



Universidad Autónoma de San Luis Potosí
Facultad de Ingeniería
Centro de Investigación y Estudios de Posgrado

**Modeling, design, and development of a rotational joint with
variable stiffness**

T H E S I S

This thesis is submitted for the *degree* of:
Maestría en Ingeniería Mecánica

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September 2020





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Modelado, diseño y desarrollo de una articulación rotacional con rigidez variable

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UASLP
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En atención a su solicitud de Temario, presentada por los **Dres. Alejandro González de Alba y Jesús Hiram Lugo Calles**, Asesor y Co-asesor de la Tesis que desarrollará Usted, con el objeto de obtener el Grado de **Maestro en Ingeniería Mecánica con Orientación Terminal en Mecatrónica y Sistemas Mecánicos**, me es grato comunicarle que en la Sesión del H. Consejo Técnico Consultivo celebrada el día 16 de julio del presente, fue aprobado el Temario propuesto:

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Introducción

1. Dispositivos deformables para rehabilitación de la muñeca.
2. Diseño mecánico y construcción de un dispositivo de rehabilitación con un actuador neumático con rigidez variable.
3. Modelo dinámico y control del dispositivo.
4. Validación experimental del dispositivo y del controlador.

Conclusiones

Referencias

Apéndices

"MODOS ET CUNCTARUM RERUM MENSURAS AUDEBO"

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"1945-2020: 75 años de formación de profesionales en la Facultad de Ingeniería"

Abstract

At some point in the future there may be few physical therapists for the number of patients who will need treatment. To address the problem, a device has been created that could rehabilitate the wrist movements like flexion/extension and abduction/adduction, in addition to being able to fit either the left or right wrist.

The design and development of a single Degree of Freedom (DOF) rehabilitation device driven by a pneumatic Variable Stiffness Actuator (pVSA) are described, intended to rehabilitate, and assist with wrist movements. The proposed device is designed to be stationary, placing the patient's forearm on the device, where he/she grabs a handle.

A kinematic analysis of the mechanism and a dynamic modeling of the pneumatic cylinder are provided along with a suitable control law. A compilation of orthosis design requirements is presented, which can be used as a guide. The pneumatic system allows the control of both the output position and stiffness of the system by pressure control.

Resumen

En algún momento del futuro puede haber pocos fisioterapeutas para el número de pacientes que necesitarán tratamiento. Para abordar el problema, se ha creado un dispositivo que podría rehabilitar los movimientos de la muñeca como la flexión/extensión y la abducción/aducción, además de ser capaz de adecuarse tanto a la muñeca izquierda como a la derecha.

Se describen el diseño y desarrollo de un dispositivo de rehabilitación de un Grado de Libertad (GDL) impulsado por un actuador neumático con rigidez variable (pVSA), destinado a rehabilitar y ayudar con los movimientos de la muñeca. El dispositivo propuesto está diseñado para ser estacionario, colocando el antebrazo del paciente en el dispositivo, donde se agarra a una empuñadura.

Se proporciona un análisis cinemático del mecanismo y un modelado dinámico del cilindro neumático junto con una ley de control adecuada. Una recopilación de los requisitos de diseño de la órtesis se presenta, que puede ser utilizada como guía. El sistema neumático permite controlar tanto la posición de salida como la rigidez del sistema mediante el control de la presión.

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Introduction

If upper limbs are impaired by neurological or musculoskeletal accidents, the subject's mobility and independence will be affected and he or she will have a limited life, dependent on the help of someone to perform the Activities of Daily Living (ADL). Working and performing independently is a part of everyday life, as are the six basic habits of ADL eating, toileting, getting dressed, bathing, continence, and transferring which can be performed by the mobility of the lower and upper limbs. One of the joints that plays an essential role in the daily life of the human being is the wrist. It is also one of the most susceptible to injuries, either by the high use of this one or by falls. In order to perform some ADL, the recovery of the subject's wrist is desired. This can only be achieved after following a rehabilitation treatment prescribed in accordance with his/her needs.

The current way of doing rehabilitation on the wrist is expensive as there are many more patients (by 2014 there were 2.3 and 1.9 million individuals with a disability and an upper limb limitation respectively in Mexico [1]) than physiotherapists (by 2016 there were 3000 in Mexico [2]) and another factor is that the overall expectations of robotic devices in rehabilitation to cope with a global aging population forecast and shortage of clinical professionals.

In the near future a way to handle that situation is to better automate rehabilitation, but not in the current way, with rigid actuators, as they are too rigid and unnatural for the patient, so it is better to use something between automation and human exercises. The opportunity is given by using the safest interaction of robots with humans. That is why the use of soft robotics, specifically using an actuator that has the characteristic of behaving like human muscles, this way is the use of a Variable Stiffness Actuator (VSA).

As the name says, this type of actuator implies the actuator varies its stiffness, and is composed of rigid actuators (two or more), elastic elements, compliant mechanisms, and mechanical guides among other components, which make the actuator mechanically complicated. Usually, the more components a device has, the more it tends to fail, and regularly requires more maintenance. The most common VSA include two motors one for the displacement and the second one to deform the elastic element or elements, thus achieving a variable stiffness.

A pneumatic cylinder is used as the VSA in this project as it does not need any extra components. The cylinder works by means of clean air, which is a compressible fluid. This would happen, for example, when the cylinder is subjected to an external force. That is, the pneumatic cylinder is not a rigid actuator at all, making it the ideal actuator for the project. Stiffness in a pneumatic cylinder is given by the sum of the pressures inside its chambers.

In 2019, a collaboration between UASLP- CIEP and the University of Genoa was established to develop a device of one Degree of Freedom (DOF) for rehabilitation of the human elbow, but due to limitations of the pVSA it was decided to make the device for the human wrist.

Thesis Contributions

Objectives

At the beginning of the project, the aim was to develop a rehabilitation device with variable impedance to be used for elbow rehabilitation, operated by a hydraulic cylinder like the one presented by Lugo Calles [3]. But as there was no hydraulic pump in the faculty of engineering, therefore a pneumatic actuator was chosen. Fortunately, the engineering faculty had a pneumatic cylinder with the necessary characteristics for the project. Due to the fact that a hydraulic cylinder was replaced by a pneumatic one, it was thought more convenient to focus the rehabilitation device on the wrist, to avoid stressing the pneumatic cylinder when using it on the elbow.

The main objective of the research presented in this project is to design, model

and develop a single-joint robotic dynamic orthosis with a variable-stiffness pneumatic actuator to achieve motion suitable for use in wrist rehabilitation exercises.

Specific Objectives

- Design of a human-machine interface suitable for rehabilitation of the human wrist movements
- Model the mechanism
- Prototype construction
- Control the stiffness
- Human testing

Scope

This study consists of making a dynamic stationary orthosis with variable stiffness for the human wrist. Is dynamic because it has movement (by the device or by the patient), and it is stationary because it is used in a specific place (e.g. a clinic). The stiffness provided by the actuator is in a range which is safe for the patient and the device, even if there are preconfigurations with the main exercises (isometric, isotonic, isokinetic) for the rehabilitation of the wrist.

In Plewa et al. [4] a total of 28 Canadian subjects, men and women between the ages of 25, were tested for wrist strength, from which data is taken on the maximum torque a subject can exert with his or her wrist. While for anthropometry, mexican women and men aged 6, 20 and 40 were considered [5] for the design of the forearm support, handle and base.

Contributions

Understanding what the thesis is about, the contributions are listed below:

- Design, modelling and construction of a dynamic stationary orthosis for the wrist.

- Pneumatic variable stiffness actuator consolidation.
- Stiffness and position control of a pneumatic actuator.
- This thesis works as a guide to replicate the orthosis or create another similar.
- Conference paper of COMROB 2020.

Thesis Outline

This thesis is structured as follows: compliant orthoses and bio-mechanics described in chapter 1, the design process of the rehabilitation device, control of stiffness and the prototyping are described in detail in chapters 2 and 3 respectively; the performance of the device, as well as the discussion are presented in chapter 4; finally the Conclusions are presented and Future work for the project.

Chapter 1

Compliant devices for wrist rehabilitation

1.1 Compliant actuators

Muscles have several mechanical properties that differ from conventional actuators. Muscle contraction consists of the relative motion between two types of muscle fibers composed of either myosin or actin proteins [6]. The closest thing to these properties is the behavior of the springs, because they contract and extend, and modify their stiffness, similarly the muscle.

A conventional (rigid) actuator used in robotics, is composed of a motor and a transmission connected to an output where the power is acquired. When energized, it maintains its position or movement by exerting a force. The movements of the human joints are given as a result of an antagonistic arrangement of muscles. By setting up springs antagonistically, an artificial joint can be created, of which, if it only has one actuator to manipulate the position, the actuator is known as a Series Elastic Actuator (SEA), this because it has a fixed stiffness, making the actuator behave elastically. Adding one more actuator attached in a mechanism to stretch, compress, twist or bend the springs results in a Variable Stiffness Actuator (VSA), resulting in a safer and more natural actuator for human-machine interaction, if it is properly controlled. Some simplified examples of these actuators are shown in Fig. 1-1.

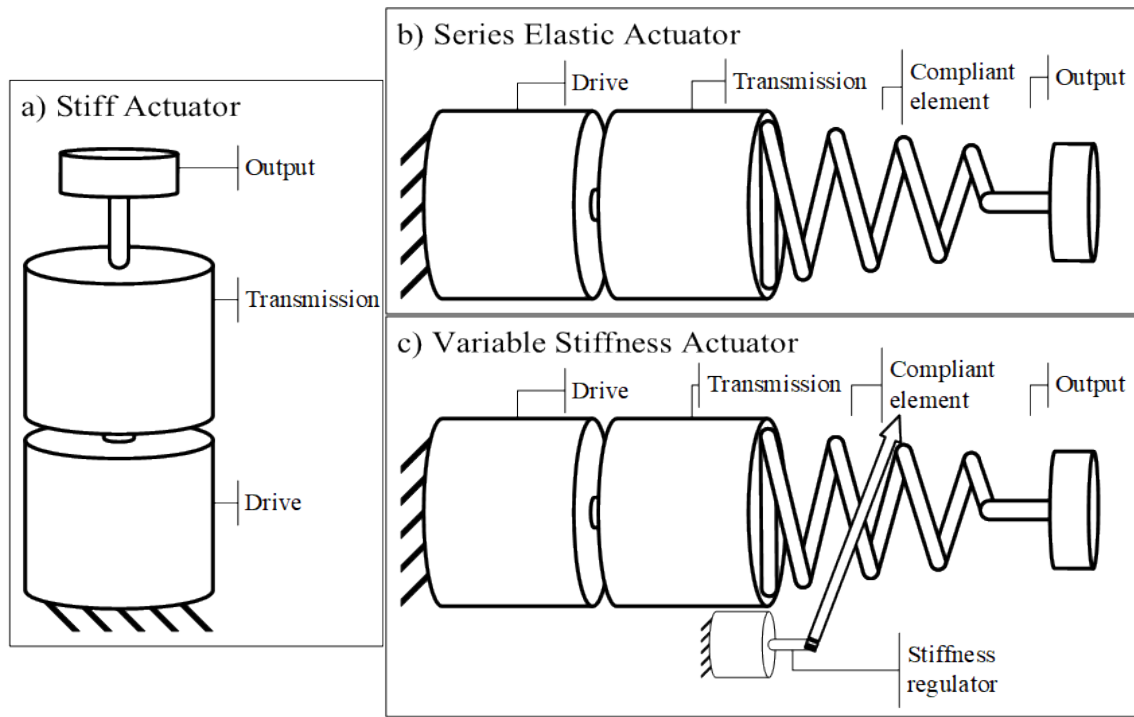


Figure 1-1: Actuator types: a) with a motor and a transmission gives a conventional actuator, b) when an elastic or compliant element is added a SEA is obtained, c) if an actuator or mechanism that manipulates the compliant element, it becomes a VSA.

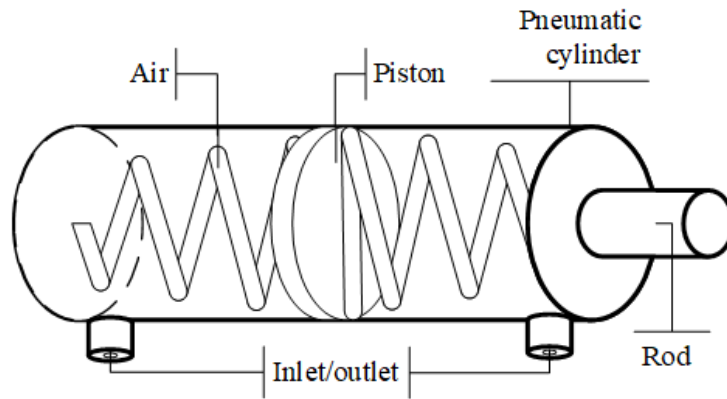


Figure 1-2: Description of a pVSA. Air acting like two springs in a pneumatic cylinder, inlet/output acts as a drive to regulate the stiffness of that spring.

There are different configurations for springs and motors (or other actuators) to make a compliant actuator each with its own classification. Since each configuration allows the variation of the actuator's stiffness, position, elasticity or impedance, it is possible to have variable stiffness in a rigid actuator, through active control, mimicking the stiffness or impedance behavior from a spring. The problem of this

is that the controller be saturated, i.e. it has limited bandwidth [7]. Saturation is given by the high frequency it has to sense in order to respond as quickly as a spring.

The bandwidth is a measurement of the speed with a reaction to the change of the input instruction [8], determined by the response time of the controller using the information from the sensors. The configuration of this project is a Parallel-type Dual Actuator (PDA), see Fig. 1-2. The air in a pneumatic cylinder behaves like two springs, one each side of the piston. For these actuators, a variation on the cylinder's stiffness can be achieved by regulating the pressure on each chamber.

The technology of the compliant actuators is not only useful for orthoses, but also for human-machine interaction, which in the future will be found in many robots, which could be of industrial application, or like the bipedal robot shown in Fig. 1-3, was built with rapid prototyping, in addition it varies its impedance and stiffness mechanically.

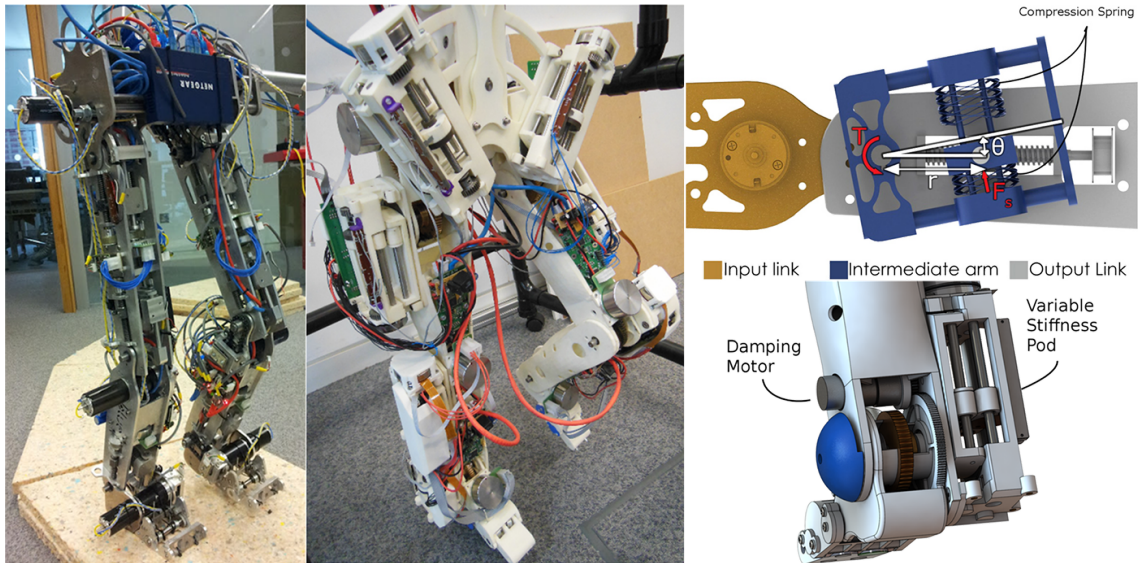


Figure 1-3: BLUE and miniBLUE built using metal and FDM plastic respectively, robotic legs for mechanical variation of joint dynamics [9].

1.2 Orthotics

An orthosis is a rehabilitation or treatment device that stabilizes a joint to correct a deformity or fracture. They are used on a daily basis to provide support, prevent deformity, maintain or restore affected joint function.

1.2.1 Orthoses classification

The orthoses are classified into two groups: static and dynamic. The static group is to immobilize and restrict movement, getting inflammation, scar, pain and stress reductions, and preventing deformities by maintaining joint alignment providing proper healing. While the dynamic group is to mobilize by assisting the weakness of the muscle and stretch soft tissue contractures to improve the function of range of motion and strength with exercises [10].

The standard nomenclature of an orthosis is given by an acronym of words for the joints that the orthosis covers [11]. The orthosis developed in this work has been named WHO-DS following this convention. Fig. 1-4 illustrates this. It has been called WHO-DS as it covers from the wrist to the hand, the joint is movable, but the limb is fixed.

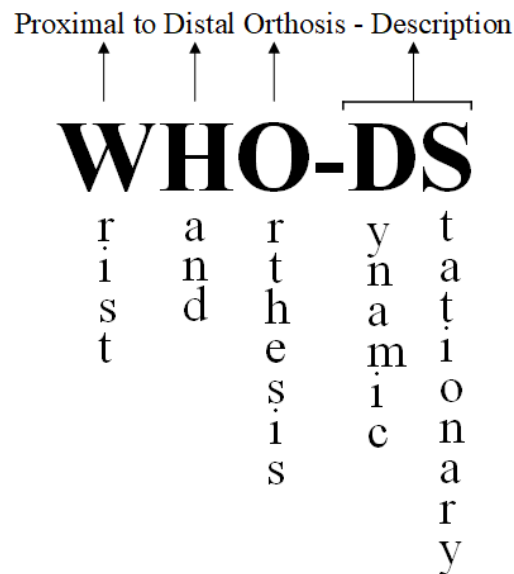


Figure 1-4: Orthosis nomenclature according to the ISO/DIS 8549-3.

1.2.2 Existing orthoses wrist joints

There are many orthoses driven by rigid actuators, some examples of these devices are shown in the Fig. 1-5. At the time of writing, no wrist orthosis with compliant actuators have been found. The conceptual orthosis with variable stiffness found in [12] is the closest thing to the work of this thesis. It simulates the dynamic

behavior of a single joint with a DOF and varying the stiffness torsionally with an arrangement of a motor and a pneumatic cylinder, the developers infer that their system (shown in Fig. 1-7) can be used to decrease tremor.

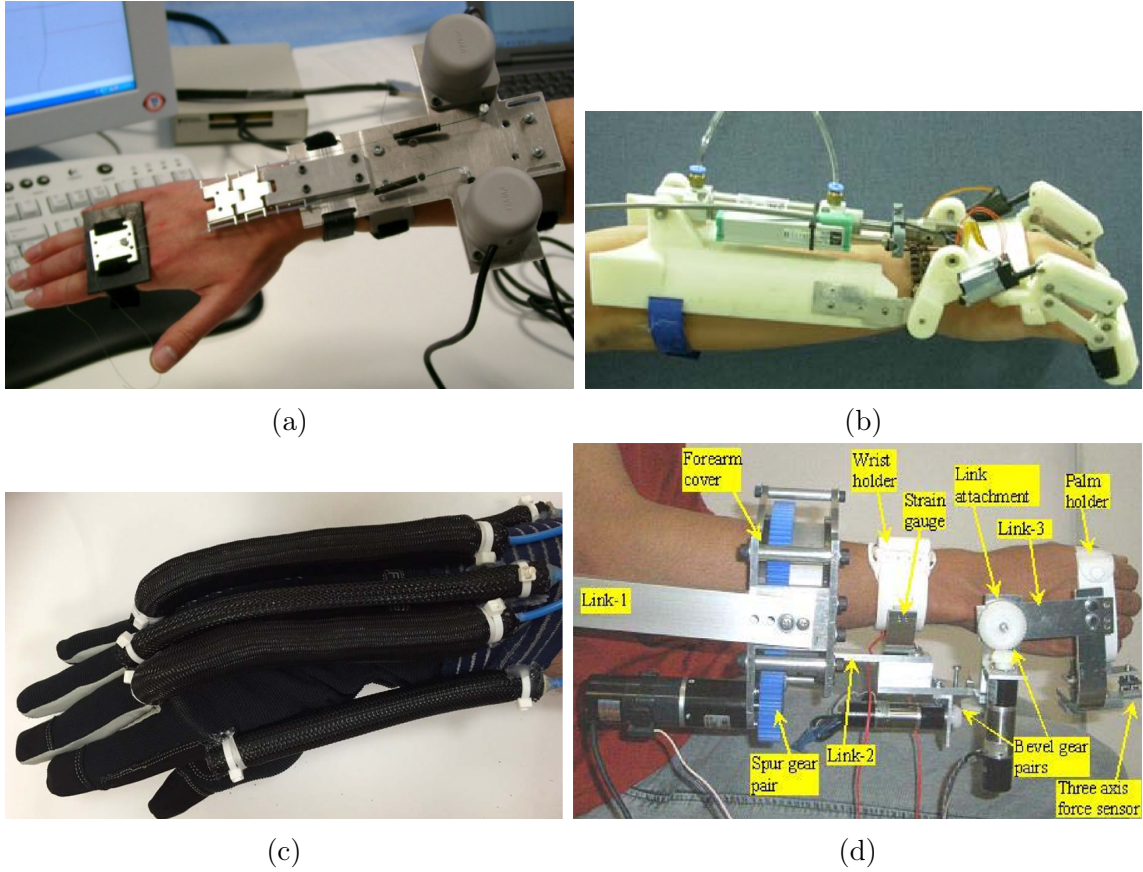


Figure 1-5: Current research wrist orthoses: a) Prototype of a Wrist exoskeleton [13], based on cable actuation. b) Exoskeleton for wrist rehabilitation [14], based on pneumatic actuation. c) Wearable splint for wrist joint rehabilitation [15], based on PAM actuation. d) Exoskeleton robot for the forearm pronation/supination, wrist flexion/extension and abduction/adduction motions [16].

Regarding lower limbs, there exist prototypes and conceptual designs of mobile and stationary dynamic orthosis, some of which can be seen in Fig. 1-6. From their sources it can be concluded that they are functional and safe for rehabilitation in humans, in addition to having a reduction in energy consumption compared to orthoses that have rigid actuators.

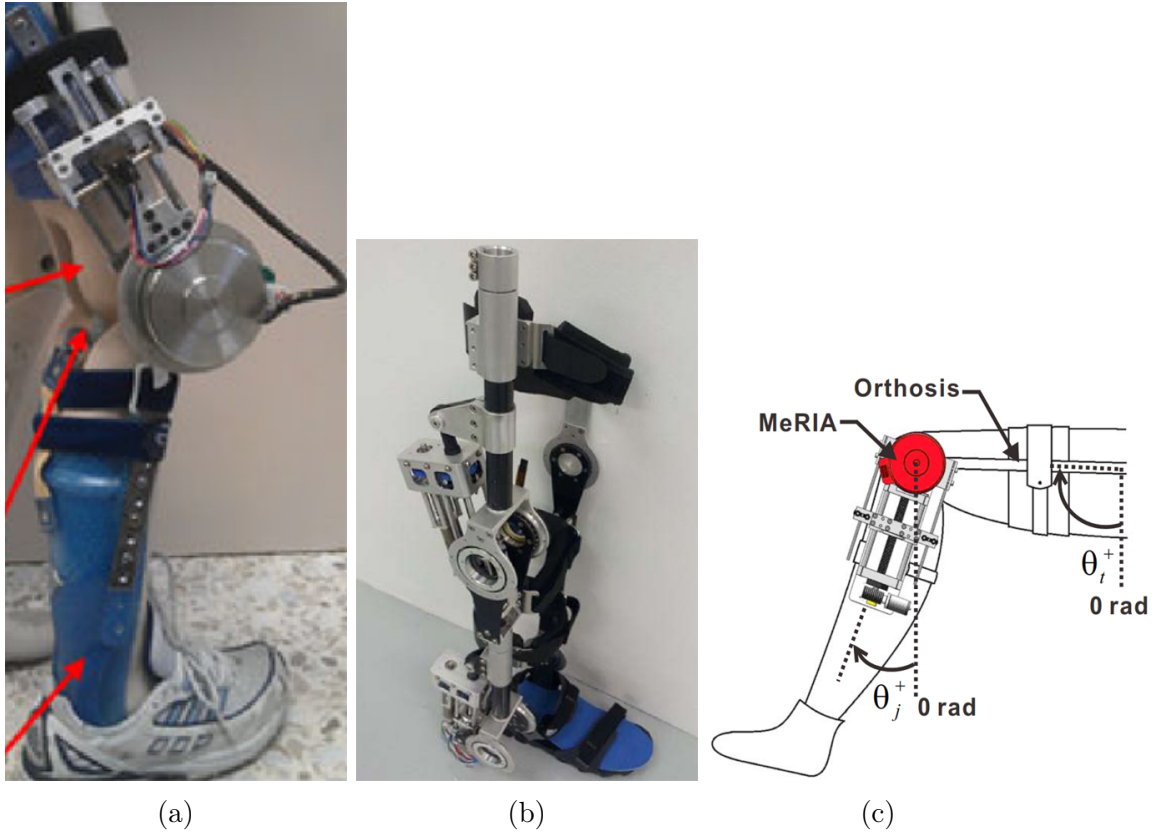


Figure 1-6: Compliant orthoses: a) This prototype [17] reduces the amount energy demanded form the user and is capable to account for external disturbance. b) Compliant knee ankle robot [18]. c) Stationary leg-orthosis impedance-controlled VSA [19].

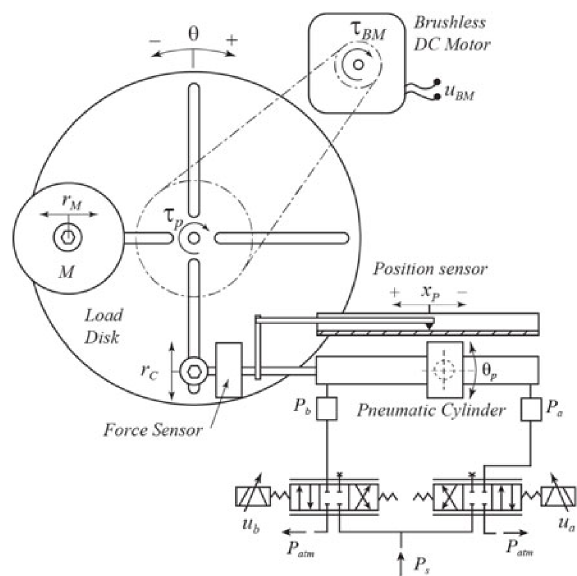


Figure 1-7: Schematic representation of force-stiffness pneumatic for decrease tremor [12].

1.3 Bio-mechanics of the human wrist

The mechanical factors of the musculoskeletal system of the wrist have an important role in providing support and mobility in the joint.

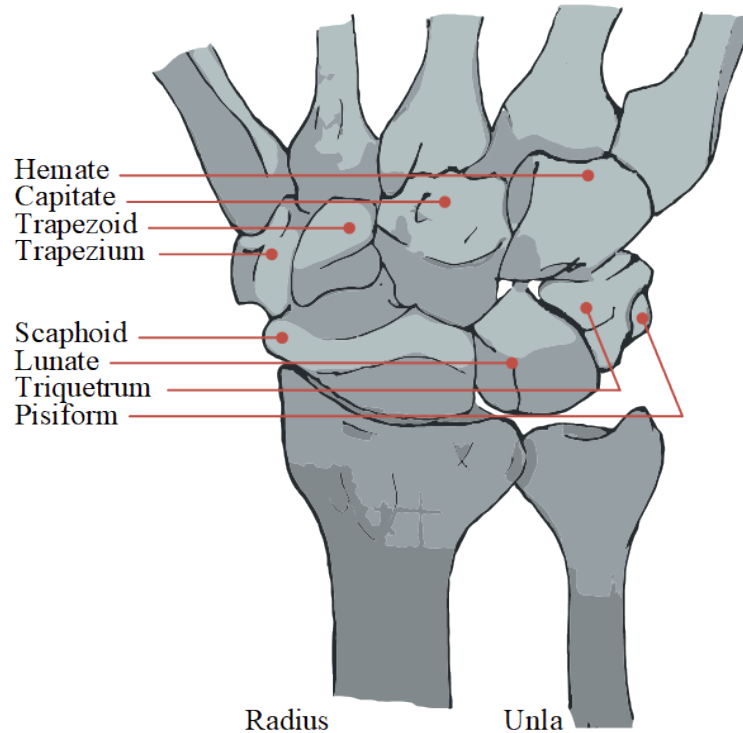


Figure 1-8: Anatomy of the wrist.

The wrist is an articulated mechanism consisting of two joints in the same functional assembly. It is composed of eight bones and the surrounding soft-tissue structure, connects the forearm to the hand [20]. The eight bones are divided into two rows, as shown in Fig. 1-8. The proximal row of the carpi is composed of the scaphoid, lunate, triquetrum and pisiform bones, while the distal row is composed of the hemate, capitate, trapezoid and trapezium bones.

The wrist can be considered a revolute or hinge joint, given that the radius and the ulna have an arc-shaped surface, which rotates around a pin-shaped pivot made up by the proximal carpal bones.

1.3.1 Wrist joint motion

The shape of the carpal bones, along with the wrist ligaments, contributes in a unique way to the movement of the joint. It is composed of three different movements that can occur at the same time. They can be described as sliding, rolling, and twisting [21] shown in Fig. 1-10. Usually modeled as a revolute joint, when only flexion/extension movements are considered, and the same goes for abduction/adduction. Taking the movements of a plane, for example, in flexion/extension (frontal plane) a movement similar to that of opening and closing a door whose joint is a hinge (revolute). Although, in reality the human wrist is composed of combined movements, this simplification is made, because of the little effect that the movements of both planes have. The movement given by the different shapes of the carpal bones results in the movements of the wrist, if the eight bones are taken as one entity, the four movements flexion/extension on the frontal plane and adduction/abduction on the sagittal plane occur.

Flexion is when the anterior face of the hand moves toward the anterior face of the forearm, while for extension the palm moves toward the posterior face of the forearm shown in Fig. 1-9. When the ulnar edge (side of the little finger) moves toward the elbow it is adduction and when the radial edge moves toward the inner part of the elbow it is called abduction [20].

However, each of these movements is composed of a combination of the oblique axis, i.e. the flexion is composed of itself and some of the adduction. This is due to an offset in the rotation axes of $5mm$ [16] between the orthogonal plane of each one, making the movements performed around an instantaneous axis, which changes as the wrist moves. Given the small offset, this fact is often ignored and for practical purposes the axis is taken as fixed. This axis is determined by the perpendicular bisectors of the displaced points and those of the previous position as shown in Fig. 1-10. The active flexion/extension range is 170° and for the passive range 195° , distributed at 85° , 85° and 100° , 95° respectively. For the abduction/adduction it is 60° being 15° and 45° respectively. However, in everyday use of the wrist, the ranges are reduced.

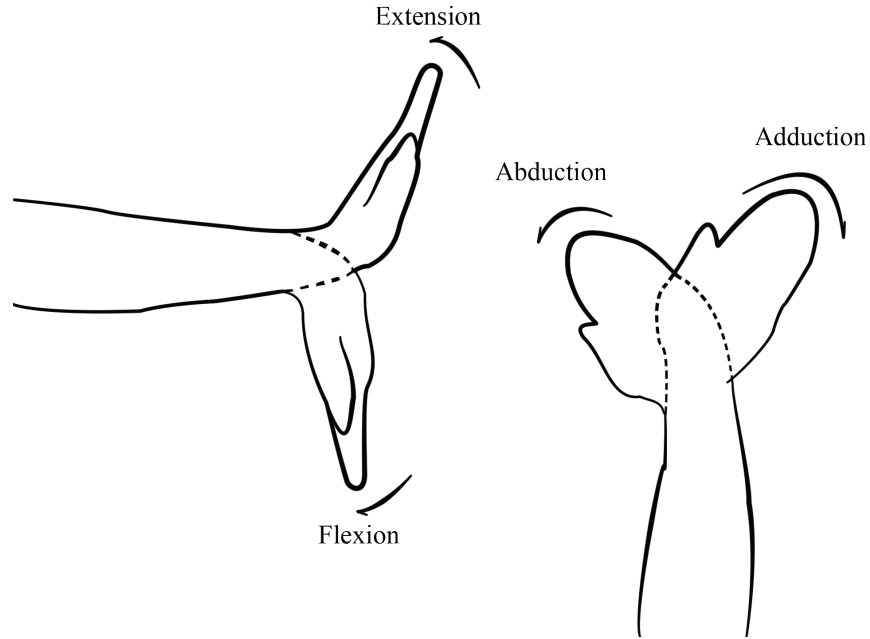


Figure 1-9: Movements of the wrist.

The torque of the wrist joint was studied by Plewa et al. [4], in a neutral position, i.e. without pronation/supination or adduction/abduction, in 14 Canadian men and 14 women about the ages of 25 years. For the development of components that will move along with the human endoskeleton, it is necessary to know the shape and internal behavior of the human limbs and joints. As well as the characteristics of the actuators in charge of moving those limbs.

1.4 Chapter conclusion

This chapter presented the biomechanics of the human wrist, which is necessary to know in order to develop any device oriented to it. An orthosis with compliant actuators directed to lower limbs was presented and it was explained what these actuators are.

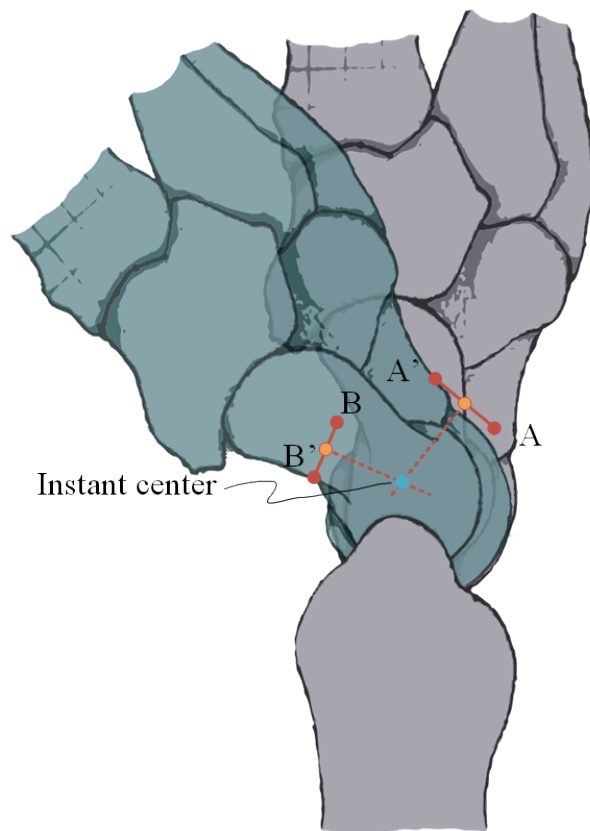


Figure 1-10: Point A' is the result of the movement of point A on the wrist, in the same way for B and B'. By bisecting both segments perpendicularly, it is possible to find the instantaneous center of rotation of the wrist.

Chapter 2

Mechanical design and construction of a rehabilitation device with a variable stiffness pneumatic actuator

To develop a dynamic orthosis it is necessary to combine different areas of study, such as biomechanics, physiology, mechanical design and in the case of this thesis, knowledge of deformable actuators, among others.

2.1 Design considerations

Using creativity, it is possible to create a functional design, based on the requirements of a conventional orthosis, as mentioned below.

Orthoses generally consist of pressure systems, which are responsible for stabilizing the affected joint [10]. They operate like a lever arm [22], applying pressure at three points, creating the reciprocal patterns seen in Fig. 2-1. By increasing the lever arm between points 1 and 2, the force that stabilizes the joint is reduced, resulting in increased comfort and stable hand movement at pressure point 3.

Wide components distribute the pressure on the soft tissue and increase comfort, avoiding large stresses on the skin [10]. Preventing restriction of blood and lymph flow, which causes ulcers and skin damage. However, in hot climates they should not be so wide to avoid affecting patients with edema and dermatitis; these are the

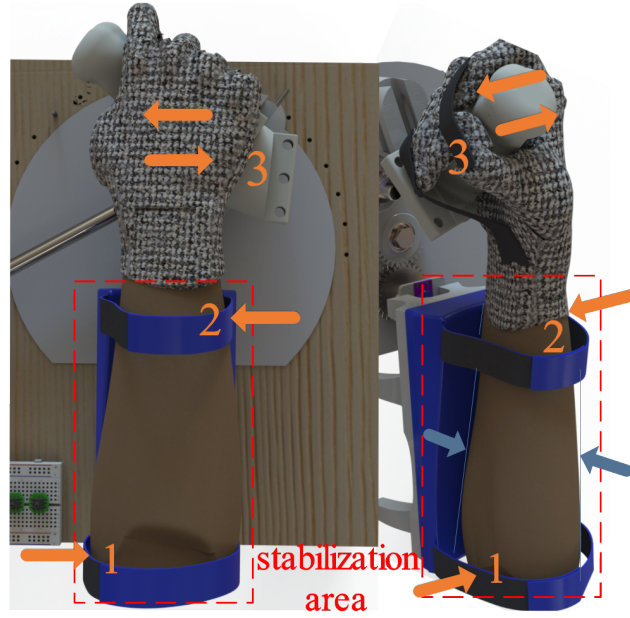


Figure 2-1: Three point pressure system in flexion/extension and abduction/adduction movements on the device.

reasons for taking a midpoint in the width of the strips and support of the forearm as shown in Fig. 2-1.

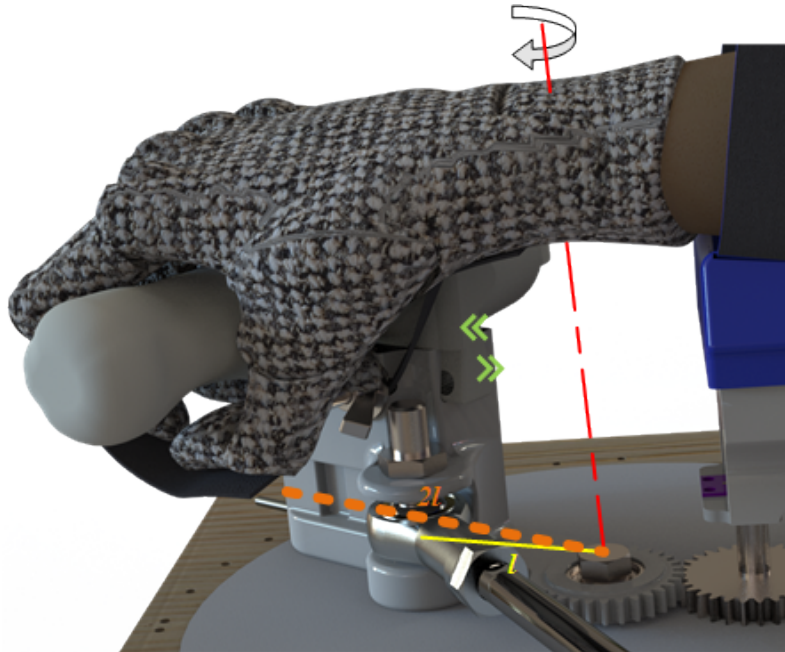


Figure 2-2: Torque reduction by dividing the length of the lever in half. The red line is the alignment between the endoskeleton and exoskeleton. Green arrows are the movement to adjust the device to the limb size.

Care should be taken with the length of force application to avoid large torques

that could damage the wrist [22]. Therefore, force applied to the rocker arm (orange dotted line) is placed at the middle of its length (yellow line), rather than at the end of its length as shown in Fig. 2-2.

The patient's joint (endoskeleton) must match with that of the device (exoskeleton) [13]. Aligning one with the other, is achieved by moving the handle back or forth as shown in Fig. 2-2 to adjust the length of the device to the wrist.

To avoid laceration and cuts to the patient's skin, the topology of the elements of the rehabilitation device should avoid sharp edges and rough surfaces. Taking advantage of the fact that the concentration of stresses is lower by avoiding sharp edges in the design of the elements, all edges near and in contact with the patient's upper limb were rounded.

To eliminate limb slippage of the device components, a design according to key skin creases was used on the handle and forearm support that can be seen in Fig. 2-3. Which also ensure that the device does not impede the desired movement of the joint.

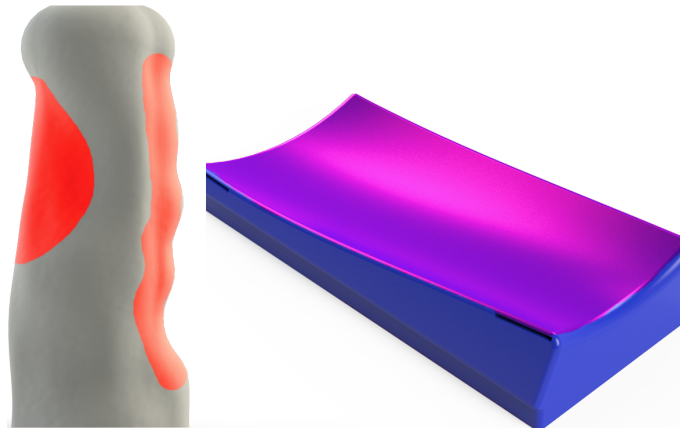


Figure 2-3: Creases of the handle and forearm support shaded.

All of these consideration influence the patient's comfort level, and must be present in a rehabilitation device, so the patient can perform his exercises continuously during several hours without inconvenience. The device's visual aspect also plays an important role psychologically, because the first impression must show a clear use, and not forgetting that the use of such device may cause patient's aversion [23]. In this project the visual aspect was taken into account without leaving

aside the functionality which is the most important thing, taking care that the physiotherapist can quickly and easily teach it's use to his/her patient.

In order to create a device capable of generating forces in the range of that feasible by the human wrist, it were used the results given by Plewa et al. in their 2016 wrist strength study [4]. The maximum torque recorded in the study is $4Nm$, from which the force is obtained through Equation 2.1 of torque τ .

$$\tau = Fl \sin(\beta) \quad (2.1)$$

where F would be the maximum wrist force performed in the WHO-DS, l is the length of the rocker arm which is equal to $50mm$ and β is the angle between the air cylinder and the rocker arm as can be seen in Fig. 3-5. The maximum force of $419N$ performed by the mechanism of the WHO-DS, is with a torque of $4Nm$ and β of 159° . Knowing the force, the necessary characteristics of the actuator (shown in Table 1) can be obtained to be able to move the wrist without problems through a mechanism. This maximum force is given by the pressures inside the chambers of the cylinder, where in the chamber A with the largest volume gives a pressure of $1MPa$, while in B it is $0.85MPa$, which are obtained in section 3.1.1 with the following equation:

$$P_{ch} = \frac{F}{A_{ch}} \quad (2.2)$$

where P_{ch} is the pressure of one chamber or the other according to the input data, F is the force of the rod and A_{ch} is the area of the chamber. However, the air compressor used has a limit of $0.8MPa$, so it will work with pressures lower than that, but not lower than $0.15MPa$ due to the pneumatic equipment specifications. This and other safety requirements in dynamic orthoses such as those seen in subsection 2.3.1 should be taken into account to avoid accidents.

The stiffness control of the WHO-DS ensures that the patient will suffer stresses below those which would cause the breakdown of soft tissues, muscles or even bones that interact in the movement of the wrist given by the rehabilitation device. That is, the forces felt by the patient are considered safe [4].

Auxiliary force and motion control based on patient needs, require the actuator to be able to control position and stiffness (which is on itself position dependent), as well as being backdrivable by the patient [13, 18]. A VSA is therefore a suitable choice to achieve the requirements, as safety and control were considered when choosing a compliant actuator, specifically for interaction with the human.

This device has a limited bandwidth (due to the characteristics of the solenoid valves) of 15 Hz as mentioned in subsection 4.2.1 and according to Yu et al. [18] is a sufficient bandwidth for rehabilitation devices.

The material commonly used in orthoses are thermoplastics, because they have strength-to-weight ratios comparable to steels, and can be machined or molded [10]. Therefore, Polylactic Acid (PLA) and Thermoplastic Polyurethane (TPU) are the ideal materials for the construction of the WHO-DS prototype.

2.1.1 Materials and manufacture

The use of thermoplastics such as PLA and TPU for some of the prototype's components is suitable, because they meet the requirement for ideal orthosis materials. Although PLA is not ideal for a rehabilitation product, due to its fragility, and sensitivity to humidity and temperatures above $60^{\circ}C$ which are able to deform it. However, it is suitable for prototype development because it is easy to manufacture, strong enough for test purposes, and biodegradable [24, 25, 26]. While TPU is appropriate for products and prototypes, because it has good strength, flexibility and is easy to manufacture.

The orthosis components must be fitted to the patient's hand and forearm, not in a personalized way (which would be better), but the best next thing was made. This device as it is a prototype has been designed for an average user, which data is based on the anthropometry of a population, in this case the average Mexican male/female (as required). For WHO-DS, significant measurements were taken, such as the length and width of the palm of the hand, for men and women of 6, 20 and 40 years of age [5]. To have three sizes of handle and to be able to slide it to adjust to the size of the patient's wrist as seen in Fig. 2-2. The measurements taken for the three ages were the average of those ages, so that the rehabilitation

device can be adapted to a large percentage of the population. The DIN 33-402-2 standard measurements were also taken into account while designing the grip diameter. Therefore, the ideal manufacturing process for these parts is the Fused Deposition Modeling (FDM) (as it is a prototype), which allows to have parts that otherwise would not be achieved [27], given its topology that is difficult and expensive to machine by conventional methods. In addition to meeting the requirement of ideal materials for orthoses, such as thermoplastics.

For the base that supports all the components, plywood was used because of its low cost, and as it is easy to machine and has the necessary resistance for the prototype. A base was built of four pieces of plywood that was not strong enough, so the base was changed for a single piece of plywood base with a thickness of 18mm and was hand machined.

Table 2.1: Bill of materials.

Nº	Component	Model	Quantity
1	Solenoid valve 3/2	SMG SY523-5L0Z-01	1
2	Solenoid valve 3/2	SMG SY513-5L0Z-01	1
3	Solenoid valve 5/3	SMG SY5320-5LZ-01	1
4	Double acting pneumatic cylinder	SMG CDG1BN25-100Z	1
5	Bolt	SMG CG-T025	2
6	Pivot bracket	SMG CG-025-24A	1
7	Piston rod ball joint	Camozzi KJ10D	1
8	Pressure sensor module	XGZP6847	2
9	Flow control fitting	SMC AS2201FG-01-04-J	2
10	Throttle valve	Camozzi 8512 4-1_8	2
11	Filter regulator	SMC AW20-01E-B	1
12	Single action relief valve	SMC VHS20-01B	1
13	Power supply unit	Generic 24V-10A	1
14	Microcontroller	Arduino Mega 2560	1
15	Microcontroller	Arduino UNO	2
16	Angle sensor	Potentiometer Hw-526	1
17	Sliding surface	PTFE-V	1/32x12x24"

The off-the-shelf components used in the WHO-DS prototype are listed in Table 2.1, where quantities and models are specified. All materials and components were bolted to the base and to each other. This makes it possible to disassemble and replace damaged or malfunctioning parts. They attached to each other compo-

nents are the sliding pad and a small one for the base of the handle, with these it is possible to create a movement without friction.

2.1.2 Sensing and actuation

Two pressure sensing modules and one position sensing module were used in the prototype. Their model numbers are given in Table 2.1. Two pressure sensors are required, one to measure the pressure in chamber A and one for chamber B, as a pressure control in each chamber is necessary to control the stiffness of the pneumatic actuator. The characteristics of the pressure sensor module are suitable for the rehabilitation prototype, as its pressure measuring range goes from 0 to $1000kPa$ and with a temperature compensation from 0 to $85^{\circ}C$. According to the manufacturer (CFCSensor), it is presumed to have a deviation of $\pm 1\%$ over the entire scale, and is ideal for medical applications, such as therapeutic equipment, oxygenation equipment, monitoring, breathing machines, among others. However, to achieve such accuracy, a moving average filter had to be implemented each time the rehabilitation device was initialized; the filter should consider a 256 samples window to obtain a good filtering.

The ideal position sensor for the device is an absolute rotary encoder with a resolution equal to or greater than 512 Pulses Per Revolution (PPR). The use of an incremental encoder is not recommended, because an initialization sequence is necessary to reset the index, which can be dangerous to the user as well as time consuming. However, due to the limitation of funds, a potentiometer was used to measure the angle. This was deemed sufficient for a prototype. The potentiometer used has a resistance of $10k\Omega$, $\pm 2\%$ linearity, an effective rotational range of 333.3° and a vibration tolerance of 10%.

A pneumatic cylinder naturally has a behavior of variation of stiffness, by the pressure exerted inside the chambers, the displacement due to the internal pressure that compresses the air, which is a compressible fluid. Although it is necessary to control the internal pressure of the chambers, to have one stiffness or another. The stroke of the double acting cylinder is $100mm$, with a piston diameter of $25mm$ and an operating pressure from 0.05 to $1MPa$.

2.2 Design of elements

2.2.1 Design iterations

To start with the design, the mechanisms were sketched and then modeled in 3D to detect undesired collisions and give a clear idea of the parts along with the space they require once built. Different designs were conceptualized, starting with simple ideas as shown in Fig. 2-4.

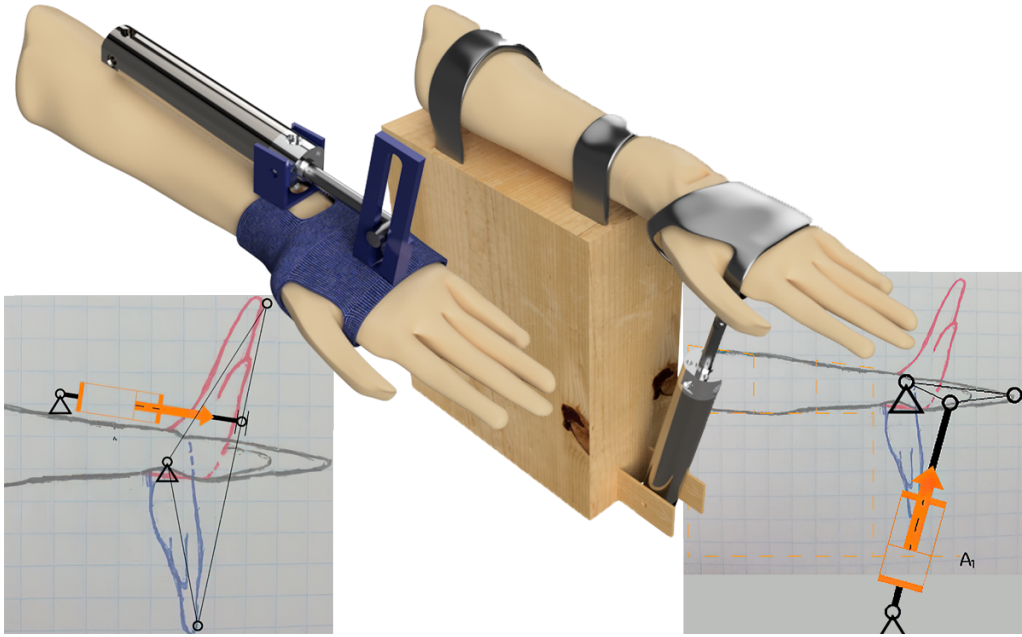


Figure 2-4: First conceptual designs of the orthosis.

Some of the conceptual designs were designed to be mobile rehabilitation devices as shown in Fig. 2-5 each accompanied by its kinematic diagram. However, the idea was soon discarded, given that a pneumatic cylinder that needs to maintain the pressure of the chamber according to the required stiffness, needs a continuous flow of air pressure, which can only be achieved with a reservoir.

Therefore, the design was focused on developing a stationary orthosis. Fig. 2-6 shows the conceptual designs according to the objective. Fig. 2-6a shows a non-fixed axis of rotation, which is intended for the deviation of the wrist axis when the wrist moves. But it was discarded when it was found that the wrist axis of rotation can be considered fixed [16]. The Fig. 2-6b shows a brace capable of supporting any size of wrist, but was discarded because it was considered dangerous to apply the

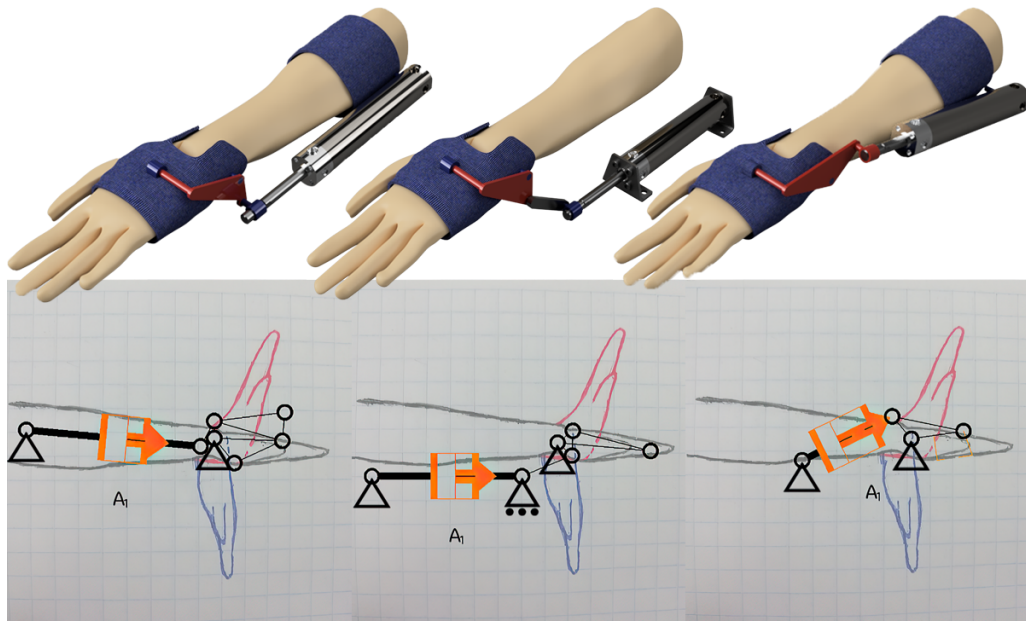


Figure 2-5: Conceptual designs focused on a mobile orthosis.

force directly to the wrist, and unfortunately at that time not all the advantages of this design were noticed. Such as the direct application of the actuator force on the wrist (with a safety system that avoids damaging it), and as a personal point of view when moving only the wrist it feels exercised better.

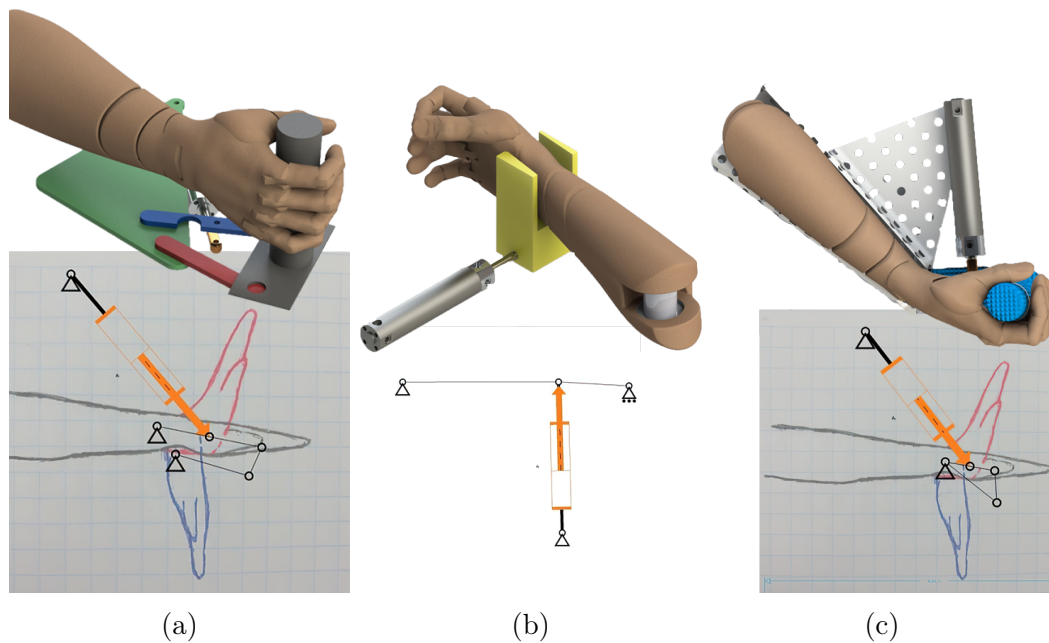


Figure 2-6: Conceptual designs focused on a stationary orthosis, being the best according to the requirements.

Finally, Fig. 2-6c was considered the most suitable for the project, however, the idea of using a slot like the one in Fig. 2-6b the design considered again, but this time for the hand, the conceptual design is shown in Fig. 2-7.

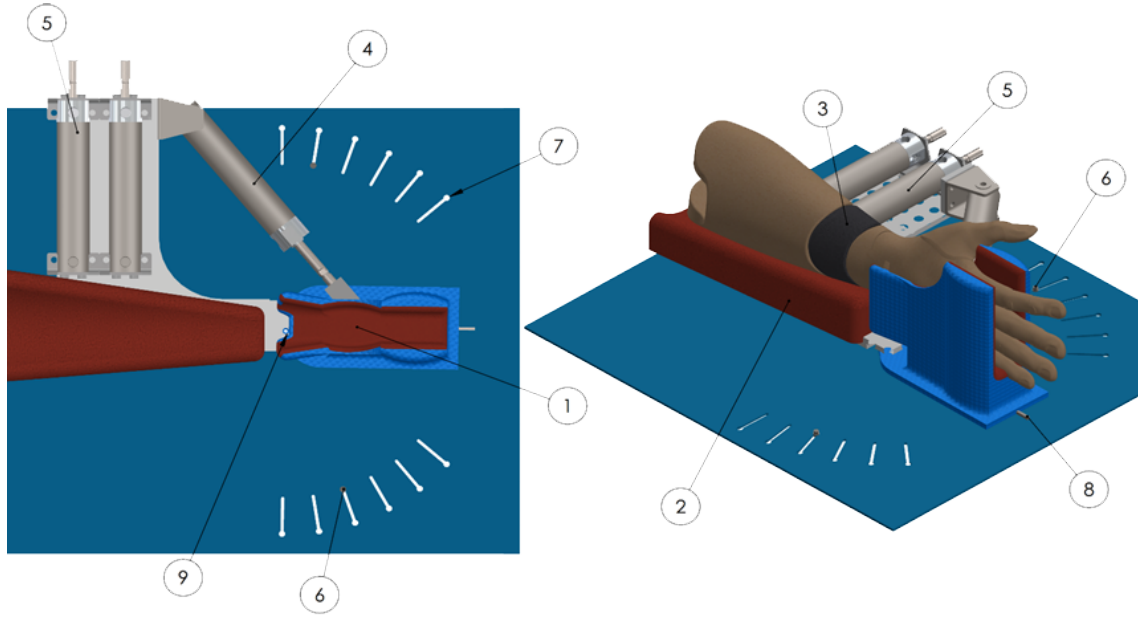


Figure 2-7: Preliminary conceptual design. 1: hand slot, 2: forearm rest, 3: fastening strap, 4: pneumatic actuator, 5: accumulators, 6: pins, 7: slots, 8: stop pin and 9: rotational joint.

This solution was considered ideal until it was found in the study by Cooper [22] that the lack of strength or grip of the hand in a position of power, is an obstacle to the recovery of the flexion/extension movements. Therefore, the idea of in Fig. 2-6 was taken up again and improved as shown in Fig. 2-8.

Once the design in Fig. 2-8 was built, manufacturing and design errors were detected in the base that caused a weakness that could destroy the prototype. Therefore, the base, which was made up of four pieces joined by glue and tongue-and-groove joints, was replaced by a single-piece base shown in Fig. 2-9. As it is a smaller piece, the components were relocated so that the components not required by the patient were out of its reach.

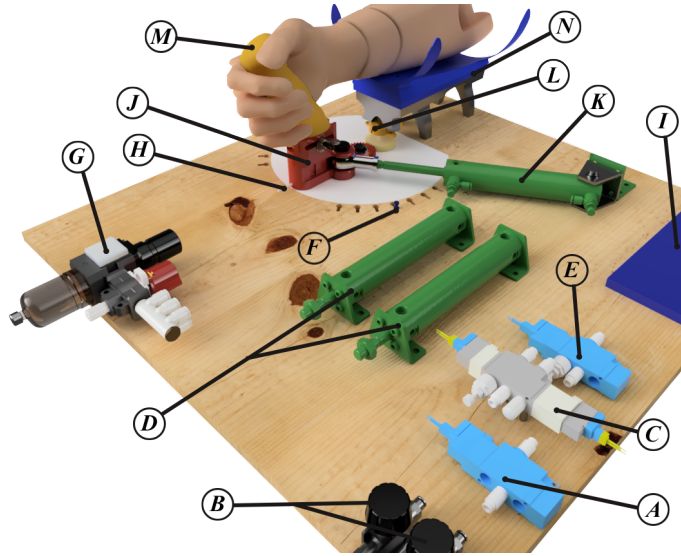


Figure 2-8: Design layout of first prototype. A: valve 2, B: throttle valves, C: valve 3, D: accumulators, E: valve 1, F: safety limit, G: maintenance unit, H: safety pin, I: electronics, J: handle base, K: pVSA, L: encoder joined to idle gear, M: handle, and N: forearm support and base.

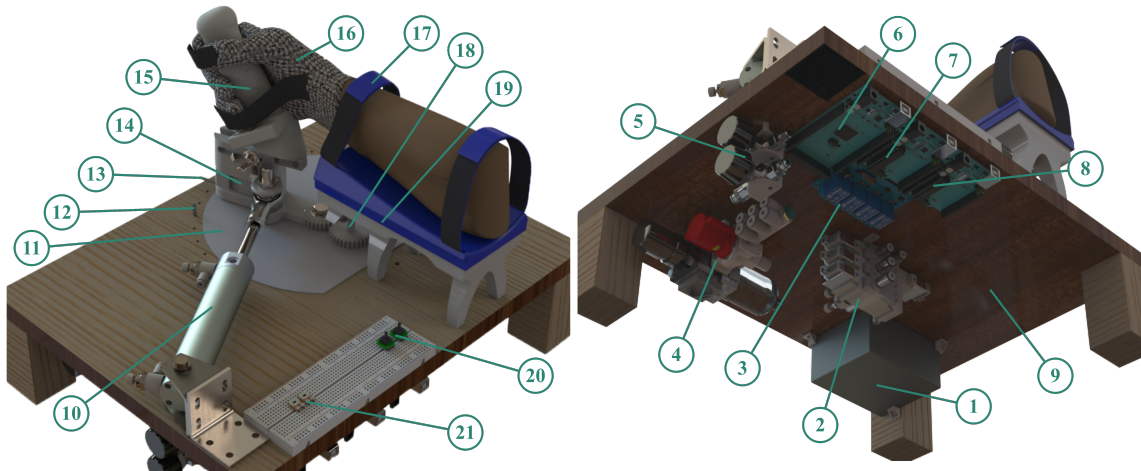


Figure 2-9: Dynamic stationary orthosis for the wrist. 1: power supply, 2: solenoid valves, 3: relay module, 4: maintenance unit, 5: flow control valves, 6: Arduino MEGA (as master), 7: Arduino UNO (slave for chamber A), 8: Arduino UNO (slave for chamber B), 9: base support, 10: pneumatic cylinder pVSA, 11: sliding surface, 12: safety limit pin, 13: safety pin, 14: handle base, 15: handle, 16: grasping glove, 17: velcro straps to hold the forearm, 18: potentiometer joined to idle gear, 19: forearm support, 20: pressure sensors, and 21: potentiometers

2.2.2 Finite element analysis of PLA parts

In every mechanical design it's essential to analyze the resistance of the components, to ensure that they will be able to support the loads to which they will be subjected. To find out if the parts that are stressed by the patient and the pVSA during the rehabilitation process are resistant to yield. A finite element analysis of the 3D printed parts was performed with Autodesk's Fusion 360[®], which allows mesh configuration and convergence analysis of it. The model and element type used by the software is

$$F = kx \quad (2.3)$$

an elastic k body extends or compresses x in proportion to the force F acting on it; and parabolic tetrahedron with curved edges [28] respectively. It is assumed that the material is linear, the loads are static and applied slowly and stably. The printing layers (porosity), type of infill (gyroid) and density (above 60%) are not considered.

The methodology followed to make the finite element analysis of each piece built with rapid prototyping, to know if it is safe at least in simulation is shown below:

1. Set-up for each piece

- Material

As mentioned above, the parts to be analyzed are made of PLA whose mechanical properties [29] are shown in Table 2.2. However, some studies were done on the sub-assemblies considering metal parts such as screws, nuts and washers, using the mechanical properties that are given by default on the software.

- Constrains

Constraints are shown in each of the resulting figures of the solutions of the Finite Element Analysis (FEA). For the cases of the forearm support, the legs were fixed with a screw option since in the prototype is the way they are fixed. For the cases of the handle assembly, the screw was fixed in which the device rotates.

Table 2.2: Mechanical properties of materials [29] used for FEA.

Mechanical property	Bulk PLA	Default steel
Density	1.24E-06 kg / mm ³	7.85E-06 kg / mm ³
Young's Modulus	3500 MPa	210 GPa
Poisson's Ratio	0.36	0.3
Yield Strength	70 MPa	207 MPa

- Loads

In each figure of the results, the configuration and magnitude of the forces are mentioned. All loads are distributed over a representative area of the contacts between the parts, as well as the patient's limb.

- Contacts for the assembly

When assembling the parts, it was constrained according to the type of joint to make use of the automatic contact tool. To check the correct definition of these, one DOF analysis was used. The correct definition of the contacts, allows to treat the assembly as a part, in which it can be placed the required loads and constraints.

2. Discretization

A seven-step adaptive mesh refining was used, 30% of the elements were refined, i.e. in areas of concentrated stress. In some cases, the seven-step mesh refinement was not performed because the results for the Von Mises stress baseline accuracy converged earlier (in the forearm support was performed slower than the handle assembly, which means a higher computational effort), with a 5% convergence tolerance. This convergence analysis is shown next to the figures for each result.

3. Solution

The base for the forearm was constrained from the struts with screws, two different loads cases were considered, one where the movement of the wrist

goes beyond the limit. In Fig. 2-10 it is observed that the piece does not yield, however, the convergence is not satisfactory, but the safety factor is 15. The second load case is for when the wrist lifts the handle (Fig. 2-11), it is observed that the piece does not yield, and the convergence is not far from the target, as well as the last one the safety factor is 15.

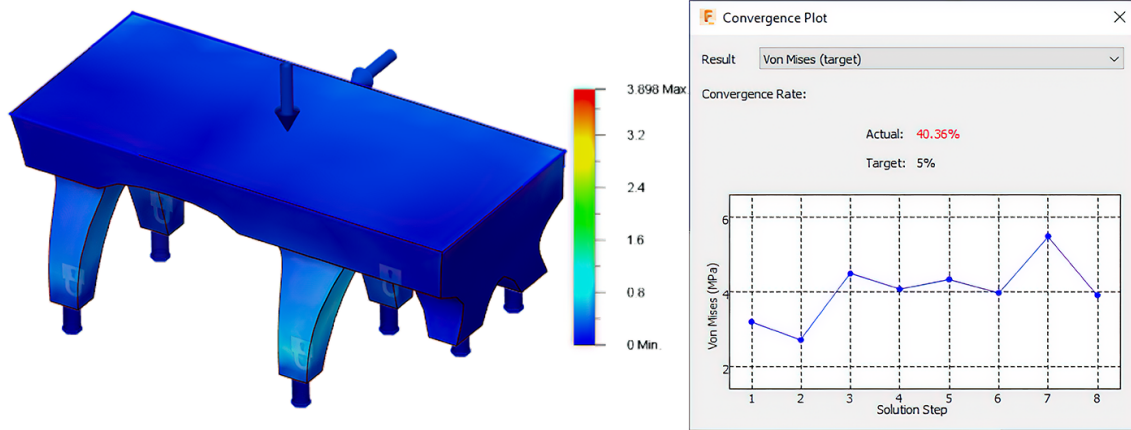


Figure 2-10: FEA of forearm support load case 1, with a maximum stress of $3.898MPa$.

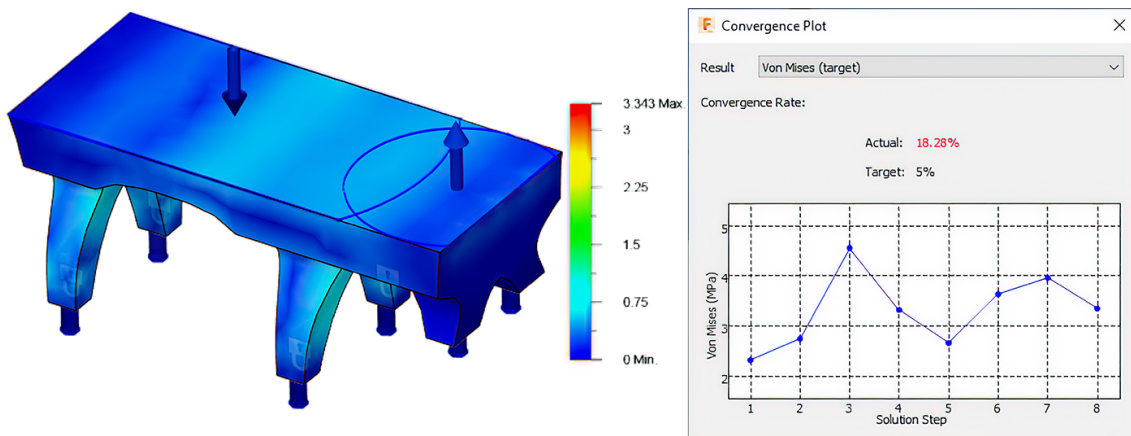


Figure 2-11: FEA of forearm support load case 2, with a maximum stress of $3.343MPa$.

For the handle assembly it was constrained from the threaded insert for wood which is attached to a bolt that keeps the bearing fixed to a hole for it at the base of the handle which has a slot where the handle is housed and fixed with a bolt. For this analysis three load cases were made, the first one (Fig. 2-12) has a load of $90N$ from the pVSA and another from the patient's wrist of the same

magnitude, simulating an active rehabilitation exercise with a small increase in the maximum force developed by the wrist (calculation based on Equation 2.1). The analysis resulted in a satisfactory convergence, in addition to the non yield of the piece and a safety factor of 4.

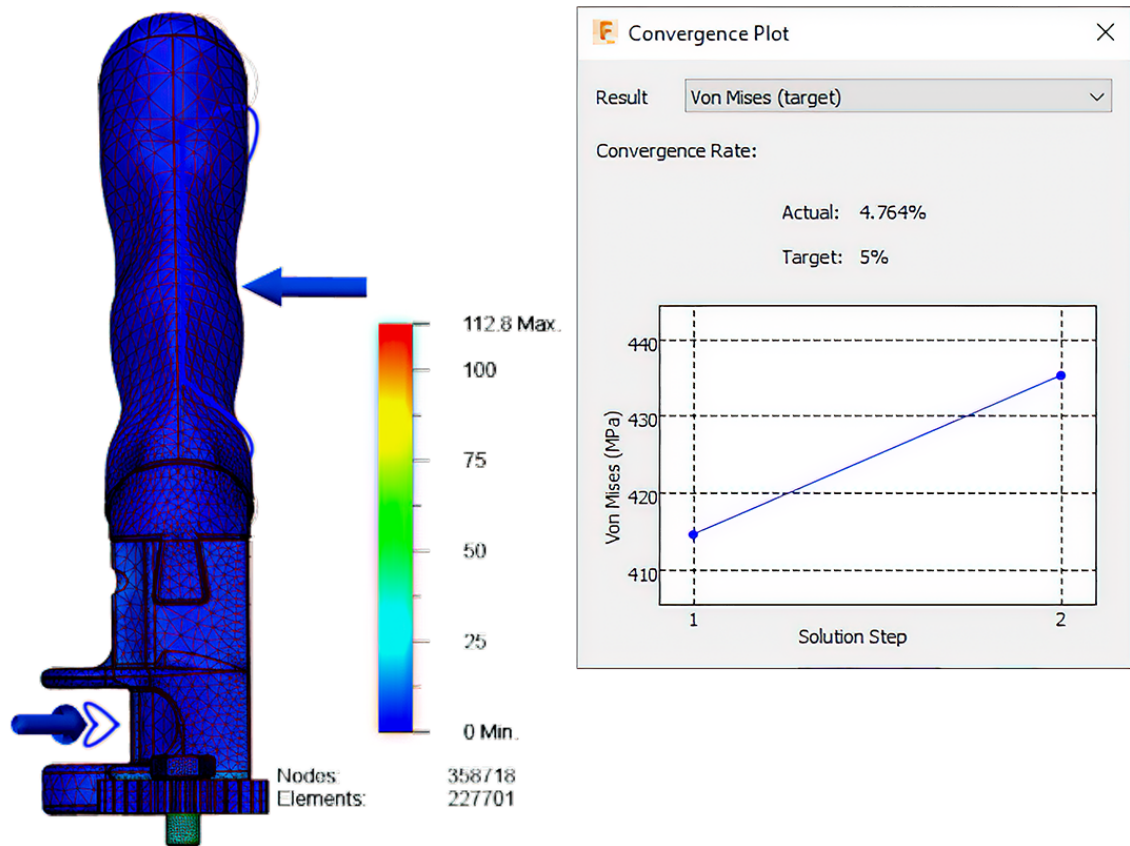


Figure 2-12: FEA of handle assembly load case 1, with a maximum stress of 112.8MPa .

The second case has the same forces only that the wrist is 45° upwards (Fig. 2-13), simulating a movement that one wants to avoid, but that the patient can do without thinking. The analysis of this second load case resulted in a satisfactory convergence, with a safety factor of 3, in this way the piece did not yield. In the third case the wrist force is changed to the opposite side of the handle and a reaction force is put on the safety pin (Fig. 2-14), simulating the situation where the mechanism is at the safety limit. In this case the result is a satisfactory convergence and a safety factor of 2.139, which indicates that it could fail. However, the failure would not affect the patient, given that only

the hole where the safety pin is housed would be broken.

4. Post-processing

Torres et al. [29] observed in destructive tests that for FDM PLA with a 0.2mm layer at 90° from the vertical, PLA's Young's modulus decreased by 20% with respect to the bulk. Therefore, the results obtained from the FEA would need to be adjusted, but the most recommendable thing is to make destructive tests to specimens in order to obtain the mechanical properties for the FEA. Although the safety factor allows some confidence in the results, since print orientation, infill density and infill pattern were not considered. However, with the safety factor obtained on the pieces, it can be interpreted as if those considerations had been taken into account.

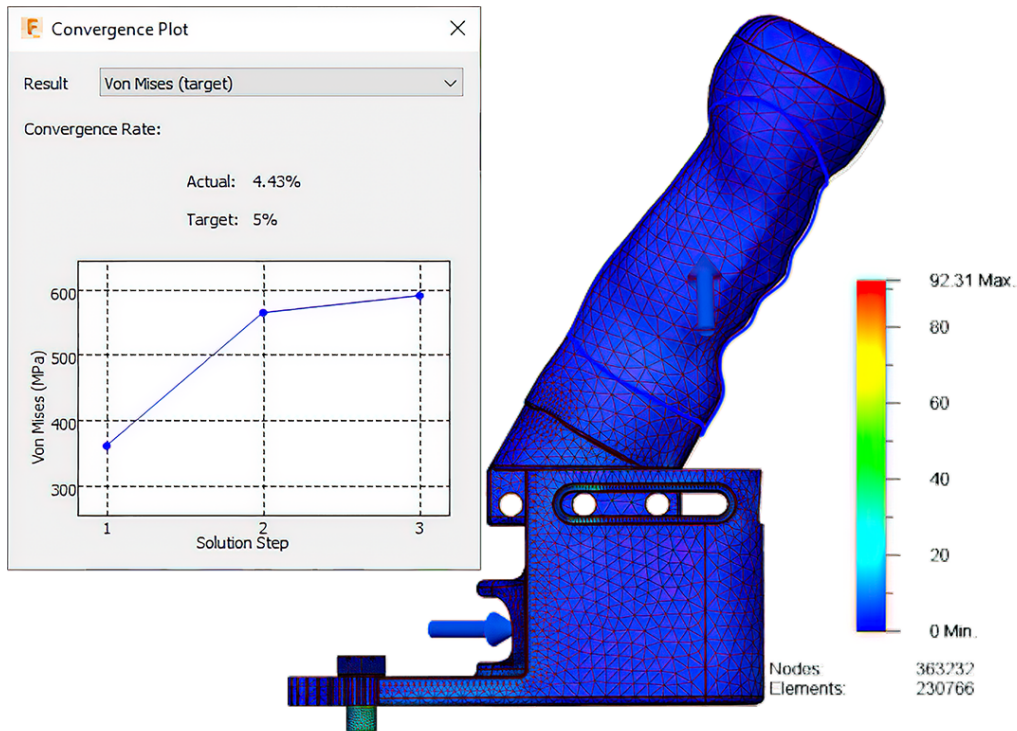


Figure 2-13: FEA of handle assembly load case 2, with a maximum stress of 92.31MPa .

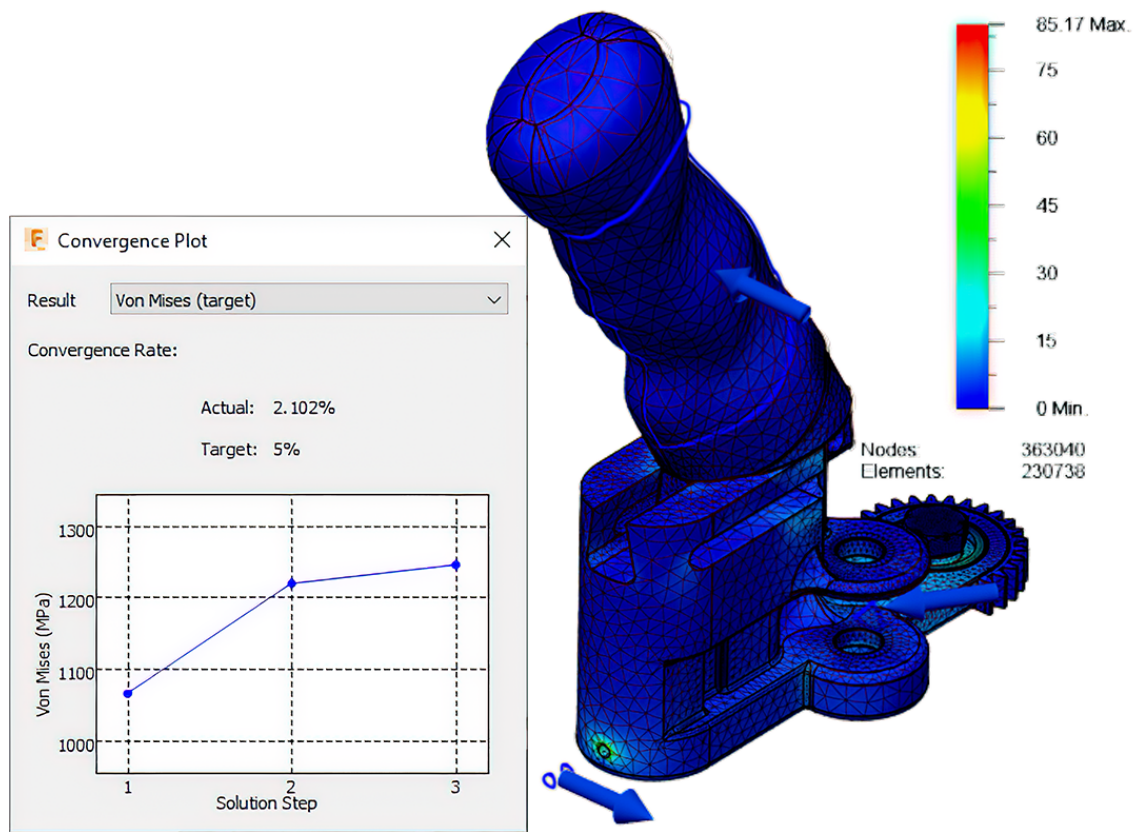


Figure 2-14: FEA of handle assembly load case 3, with a maximum stress of 85.17MPa .

2.3 General description of the systems involved in the orthosis

The components of the following systems were chosen for having the right characteristics for the project, and their availability at the Faculty of Engineering. The following is a general description of the systems that integrate the rehabilitation device.

2.3.1 Safety system of the rehabilitation device

By having an actuator with variable stiffness it is possible to provide the stiffness control that required for safe interaction with humans. As the stiffness is position-dependent, it (the position) is also controlled and allows movements within a safe

range for the patient. However, in the event of any failure, there are mechanical limits that prevent exceeding the pre-set range of motion for the patient.

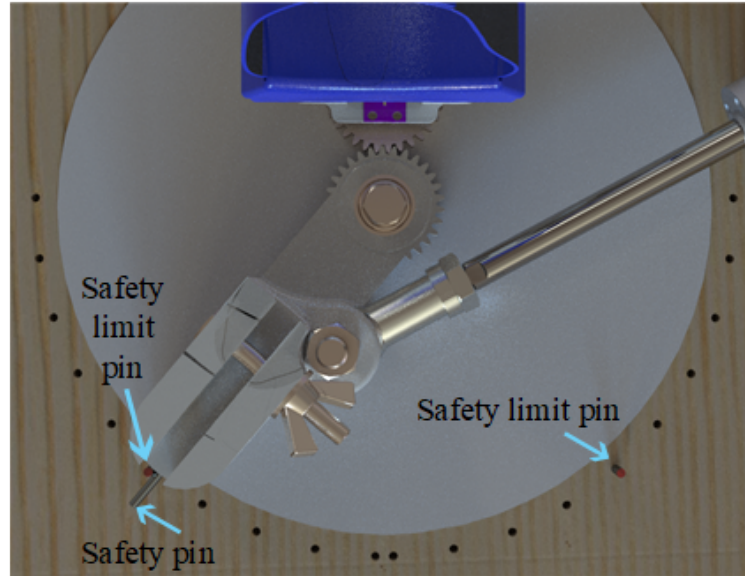


Figure 2-15: Mechanical safety limits.

As can be seen in Fig. 2-15, there is a pin placed in the base of the handle, which allows it to collide and thus stop the device. The pins are placed in one of the dedicated holes spaced by 10° over the entire range of movement of the device which has a maximum range of 180° according to kinematic analysis of the mechanism. To set the oscillating range of movement of the handle, the limit of the right and left sides must be written in the Arduino's IDE. Mechanically, it is only necessary to remove the pins and place them in the holes where it is desired to set the limit of motion. The speed of wrist movement is set by changing the oscillation frequency of the control signal generated in the Arduino IDE. On the other hand, the pneumatic system has manual control valves of flow speed, which are at the value that allows a smooth and constant movement of the pneumatic cylinder. For emergencies, a stop button is placed to depressurize the cylinder chambers and stop the system.

2.3.2 Pneumatic system of the actuator

The Table 2.3 shows the characteristics considered for the selection of the cylinder used in this work. Fig. 2-16 will be used to describe the pneumatic system, as this is

where the pneumatic diagram is shown. Starting at the bottom, there is an air compressor as supply, then there is a water filter with pressure regulation. Afterwards, two flow speed control valves are connected, then tubing goes to the solenoid valves, in charge of pressurizing or depressurizing the double acting pneumatic cylinder connected to them.

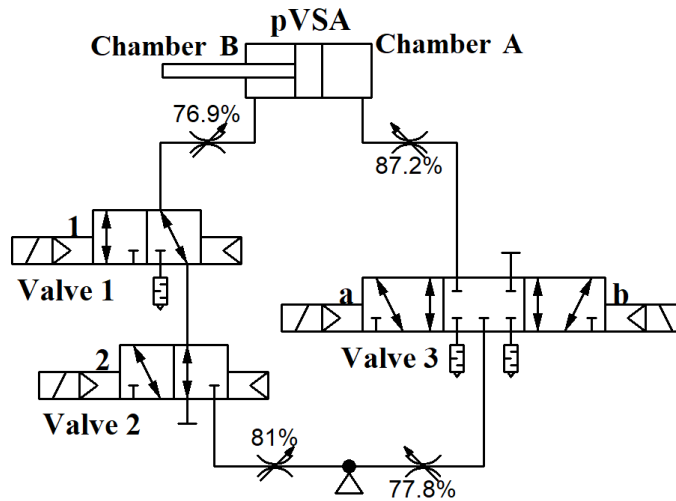


Figure 2-16: Pneumatic system diagram.

The pressure sensors and a flow speed control valve on each side are connected to the cylinder. The purpose of these valves and the previous speed control valves is to prevent air from flowing into or out of the cylinder too quickly, otherwise there would be a sudden oscillation in the rehabilitation device. For the independent control of the pressures in the chambers it is necessary to insert, release or restrict the flow of air in these, this is achieved with the use of 3-port, 3-positions solenoid valves for each chamber.

There are two solenoid valves for the chamber B, as only one would not have the option of preventing air flow. In other words, it is to build a 3/3 solenoid valve. The only disadvantage is that it takes two separate actions that can cause disturbances in the system.

Table 2.3: Cylinder characteristics.

Parameter	Value
Cylinder stroke	$100mm$
Cylinder inner diameter	$25mm$
Rod diameter	$10mm$
Max. operating pressure	$1MPa$
Min. operating pressure	$0.05MPa$

2.3.3 Electronic system of the rehabilitation device

The electronics are described in Appendix B, where the connections between the electronic components (shown in Table 2.1) are shown. The use of three Arduinos is due to the delay in controlling the pressure in the cylinder chambers. In addition to being suitable for a testing and education oriented prototype, at least until it becomes robust enough to be used in clinics. While with three it is possible to control the pressure of chamber A in one Arduino and the B in another, and the third Arduino is in charge of sensing and calculating the desired pressures. The power to the sensors and solenoid valves comes from a single source, but as the sensors need less voltage, a step down voltage Lm2596 is connected to the 24V source to obtain 5V. On the other hand, the Arduinos are powered from the computer's USB port.

2.4 Prototyping of the orthosis and its iterations

To make the prototype of the wrist orthosis, components were designed and arranged on a space according to the size of the parts, as shown in 2.2.1. Once the design was completed, it was proceeded to manufacture the non commercial components of the materials and characteristics seen in 2.1.1. When all the components were ready, they were assembled, creating the first prototype shown in Fig. 2-17. This prototype experienced issues at the base where all the components are mounted, due to weakness in their joints. This was observed as the collision of the mechanism with the safety pin exerted a force large enough to bend the base at its union points.

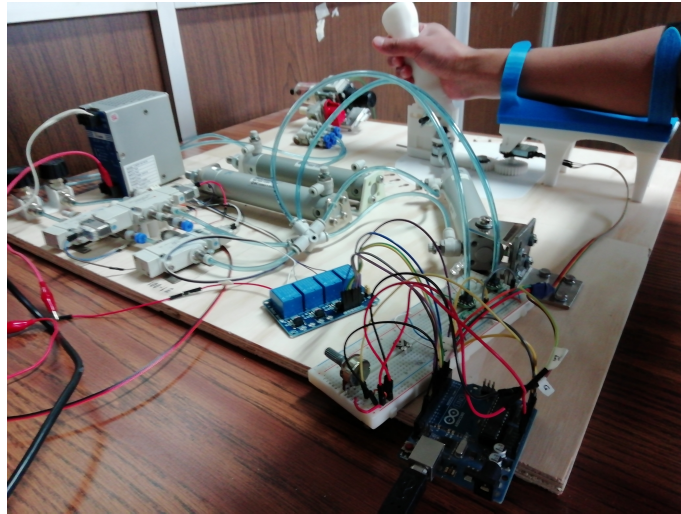


Figure 2-17: First orthosis prototype iteration.

Therefore, a second iteration was made (Fig. 2-18), where only the base was changed for one of smaller size. This meant that the disposition of the components also needed to be changed. Components to which access is not necessary other than for maintenance were placed under the base. While components such as the handle and forearm support are placed above, where the patient can use them freely.

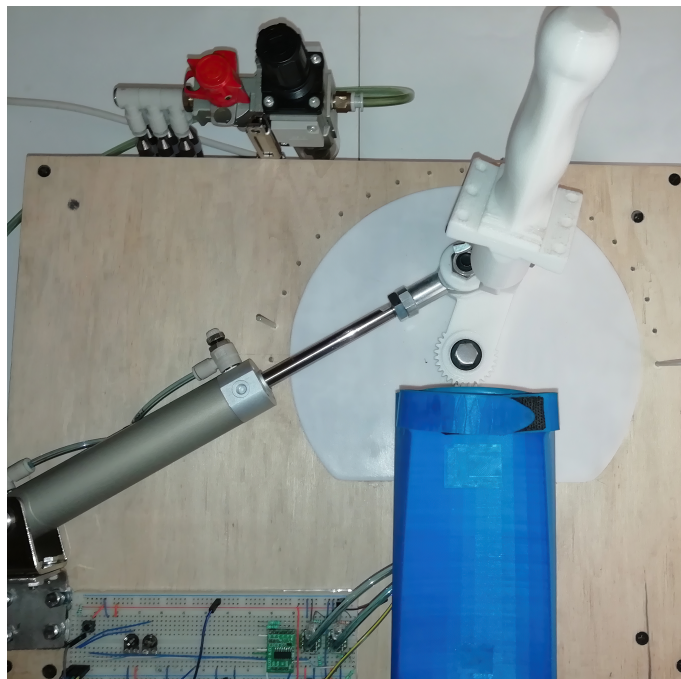


Figure 2-18: Second orthosis prototype iteration.

Changes were also made to the handle, as shown in Fig. 2-19. initially, the han-

dle (A) was ergonomically designed to allow for wrist flexion/extension movements. Later, improved ergonomics were added by making an interchangeable handle (D) with different sizes of TPU, giving a better grip due to its flexibility. Another improvement was the tongues (B) added to the sides of the handle, in order to be able to turn it 90°, and thus have an extra DOF in the orthosis, which gives the abduction/adduction movements of the wrist. In order to be interchangeable, a mortise and tenon joint was used. Since the pin could be weak, a steel insert (C) was used to give it strength. However, the joint allowed an unwanted twist of the handle, so the original idea of using a single piece (E) was used, but adding an extra DOF and strength.

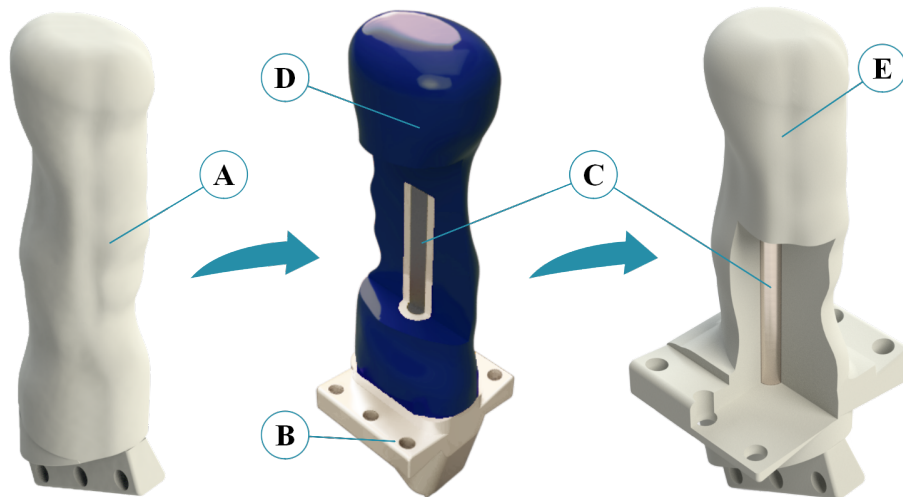


Figure 2-19: Handle iterations for the orthosis.

2.5 Chapter conclusion

The rehabilitation device was developed by satisfying requirements, analyzing parts and their construction, presented in this chapter in such a way that they can serve as a guide for the construction of a similar device. Safety, the pneumatic system and also the electronic system were not described in detailed as they are not the main focus of this work.

Chapter 3

Dynamic model and control of the device

In order to describe the relationships of length, volume, stiffness, pressure, position, among others of the WHO-DS is necessary to represent its variables, parameters and restrictions in a model that will help to control aspects of the system.

3.1 Modeling

The modeling of the WHO-DS is divided into two: the kinematics of the mechanism which gives the torque and range of motion ratios required for the rehabilitation of the wrist; and the dynamics of the pVSA which provides the movement, stiffness and position of the mechanism from the internal pressures of the pneumatic cylinder.

3.1.1 Model of mechanism

Synthesis

Guided by the kinematic inversion of the slider crank described in the atlas of mechanisms [30], showed in Fig. 3-1, since the torque applied to a link is transmitted to a distant point, in this project the wrist.

A sketch was made in SolidWorks® shown in Fig. 3-3, the rocker arm dimension of $50mm$ was chosen because at that distance the torque is considered safe for the

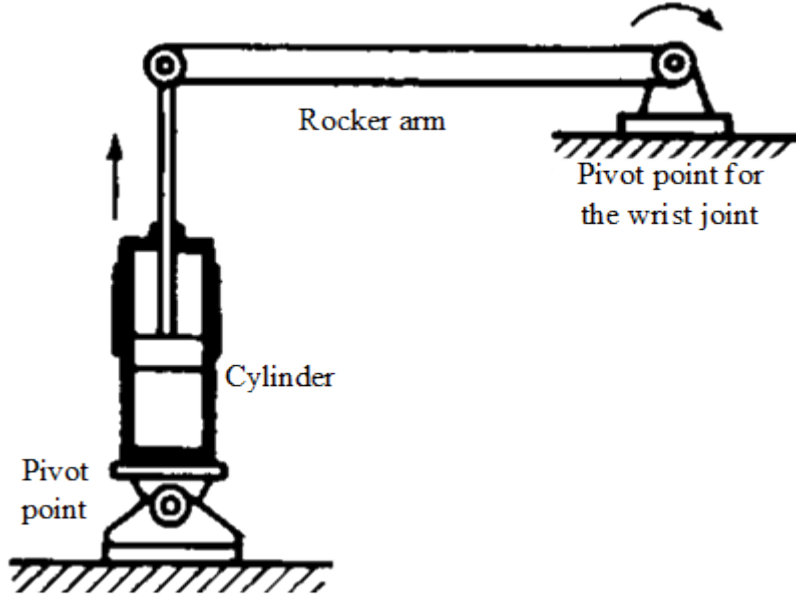


Figure 3-1: A torque applied to the shaft can be transmitted to a distant point [30], is the source of inspiration for the mechanism.

patient, considering that the maximum torque the wrist can generate is $4Nm$ [4]. The maximum moment is computed as the cross product of the length between the length l and the force applied to the mechanism, as seen in Equation 2.1 from section 2.1. Where a small length (half of the handle base piece) is considered to cause less torque, which helps keep the device secure. According to the $4Nm$ torque considered as safe, the maximum force that can be exerted by the wrist can be obtained from section 2.1 reorganizing the Equation 2.1

$$F_{max} = \frac{4Nm}{50mm(\sin(159^\circ))} = 223N$$

when ϕ is 90° the angle $\beta = 159^\circ$, without mentioning that, the range of movement of the WHO-DS was reduced by the increased stiffness, which occurs when the piston reaches the ends of the stroke. Also, because of this there is no greater β angle, which can also be seen in Fig. 3-2 (assuming a constant torque). This makes 159° the position in which the greatest force is applied.

Then for the pneumatic cylinder to generate a force smaller or equal to the maximum force which can be allowed to be safe, the pressures of each chamber are calculated. Knowing that the pressure of the chamber P_{ch} is the relationship of force

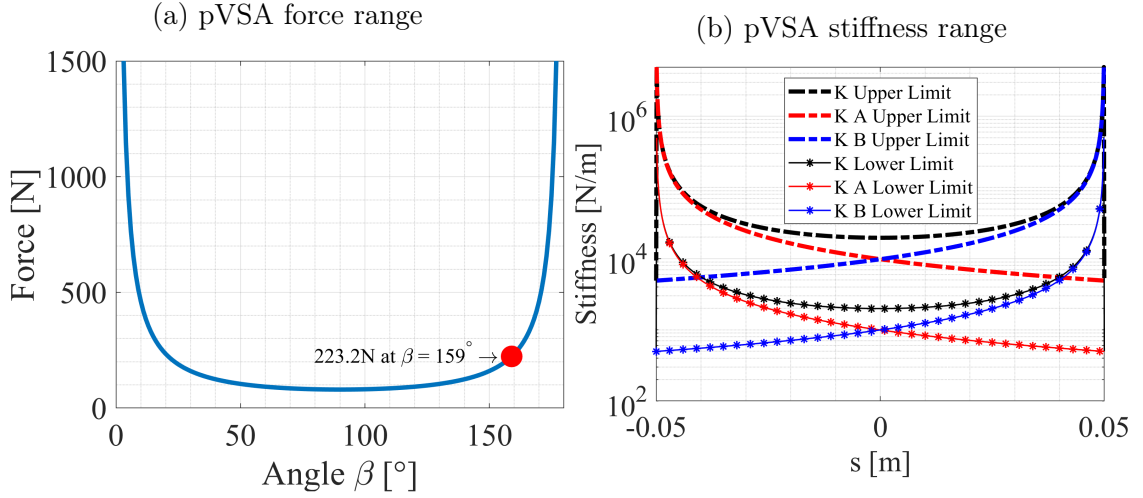


Figure 3-2: a) Force range with constant torque along rocker arm's range of motion. Range of motion limitation point to avoid banging due to abrupt pressure changes, because it tends to infinity at the stroke limits. b) Stiffness range for the different positions of the actuator stroke (vertical axis given in logarithmic scale). The stiffness tends to infinity when the volumes of the chambers A and B tend to zero (stroke limits), however, the stiffness decreases when the limits are reached.

F to the contact area of the chamber A_{ch} described in Equation 2.2, by substituting the values

$$P_A = \frac{4(223N)}{\pi(25mm^2)} = 0.454MPa$$

$$P_B = \frac{4(419N)}{\pi(25mm^2 - 10mm^2)} = 1.261MPa$$

the maximum safe pressures for the wrist are obtained.

The length of the pneumatic cylinder from the pivot A to the knuckle B was measured in the Fig. 3-3, to this measurement the stroke of the cylinder ($s = 100mm$) was added to have a sole dimension S in Fig. 3-5. It was observed that in order to have a 180° range of movement of the rocker arm, it had to measure half of the stroke (50mm) according to the layout of the sketch Fig. 3-3.

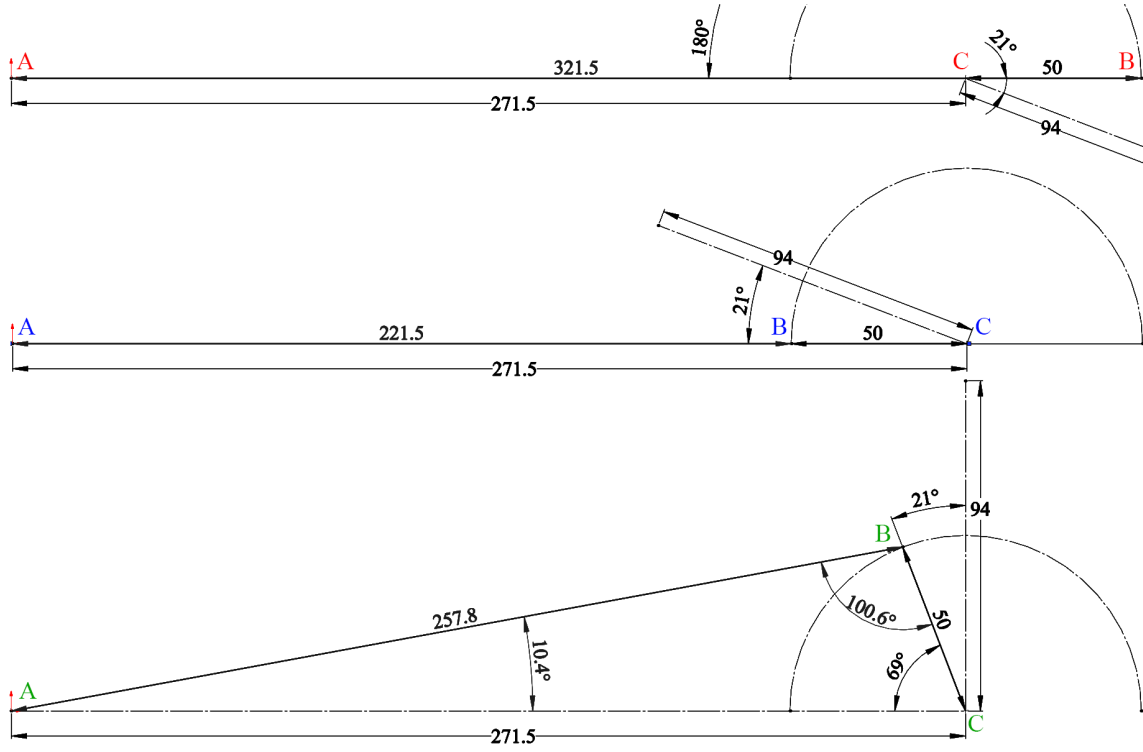


Figure 3-3: Graphic synthesis of the mechanism.

Analysis

The kinematic analysis of the four-link mechanism was performed in order to derive an appropriate model for PID control. The mechanism has a single closed loop whose equation can be obtained from the vector representation in Fig. 3-4.

$$\vec{q} + \vec{l} - \vec{S} = 0 \quad (3.1)$$

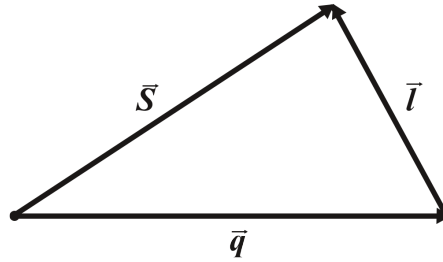


Figure 3-4: Vector representation of the mechanism.

- Equation 3.1 can be derived from Fig. 3-5 the position can be expressed in the cartesian form as the position is as follows

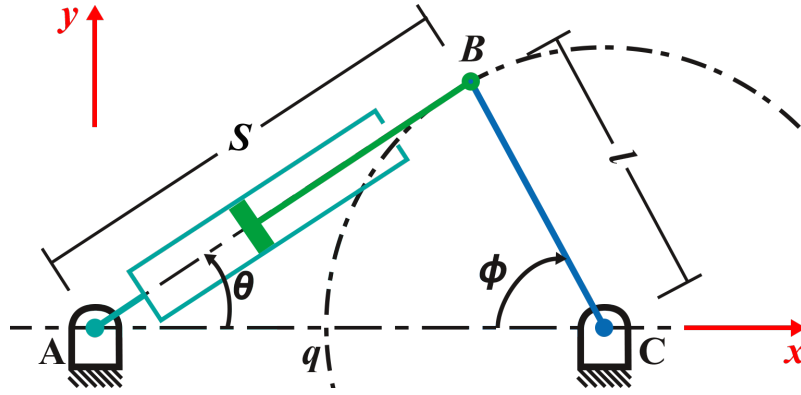


Figure 3-5: Kinematic diagram of the WHODS mechanism, where S is the cylinder stroke, rocker arm is l swings from the frame q to form ϕ .

$$q - l \cos \phi - S \cos \theta = 0 \quad (3.2)$$

$$S \sin \theta - l \sin \phi = 0 \quad (3.3)$$

which by reorganizing for S can be expressed as the following:

$$S \cos \theta = q - l \cos \phi \quad (3.4)$$

$$S \sin \theta = l \sin \phi \quad (3.5)$$

By squaring equations 3.4, 3.5 and adding them together in the same way as a system of equations we find:

$$S^2 = q^2 - 2ql \cos \phi + l^2 \quad (3.6)$$

hence, S is found when obtaining the square root of 3.6.

$$S = \sqrt{q^2 - 2ql \cos \phi + l^2} \quad (3.7)$$

then reorganizing equations 3.2 and 3.3 for θ

$$\cos \theta = \frac{q - l \cos \phi}{S} \quad (3.8)$$

$$\sin \theta = \frac{l \sin \phi}{S} \quad (3.9)$$

Using double arc tangent, to ensure that the solutions are in the appropriate quadrant

$$\theta = 2 \operatorname{atan} \left(\frac{l \sin \phi}{S + q - l \cos \phi} \right) \quad (3.10)$$

- To know the angular speed of the mechanism or the linear speed of the pneumatic cylinder rod, speed is derived from 3.2 and 3.3 with respect to angles and stroke

$$l\dot{\phi} \sin \phi - \dot{S} \cos \theta + S\dot{\theta} \sin \theta = 0 \quad (3.11)$$

$$\dot{S} \sin \theta + S\dot{\theta} \cos \theta - l\dot{\phi} \cos \phi = 0 \quad (3.12)$$

expressed in matrix form, and given that ϕ is known

$$\begin{bmatrix} -\cos \theta & S \sin \theta \\ \sin \theta & S \cos \theta \end{bmatrix} \begin{bmatrix} \dot{S} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -l\dot{\phi} \sin \phi \\ l\dot{\phi} \cos \phi \end{bmatrix} \quad (3.13)$$

can be solved as:

$$\dot{S} = \dot{\phi} l \sin(\phi + \theta) \quad (3.14)$$

$$\dot{\theta} = \frac{\dot{\phi} l \cos(\phi + \theta)}{S} \quad (3.15)$$

- The angular accelerations of the mechanism, the linear one of the pneumatic cylinder rod can be known deriving the speeds from 3.11 and 3.12

$$l\ddot{\phi} \sin \phi + l\dot{\phi}^2 \cos \phi - \ddot{S} \cos \theta + 2\dot{S}\dot{\theta} \sin \theta + S\ddot{\theta} \sin \theta + S\dot{\theta}^2 \cos \theta = 0 \quad (3.16)$$

$$\ddot{S} \sin \theta + 2\dot{S}\dot{\theta} \cos \theta + S\ddot{\theta} \cos \theta - S\dot{\theta}^2 \sin \theta - l\ddot{\phi} \cos \phi + l\dot{\phi}^2 \sin \phi = 0 \quad (3.17)$$

expressed in matrix form

$$\begin{bmatrix} -\cos \theta & S \sin \theta \\ \sin \theta & S \cos \theta \end{bmatrix} \begin{bmatrix} \ddot{S} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} l\ddot{\phi} \sin \phi + l\dot{\phi}^2 \cos \phi + 2\dot{S}\dot{\theta} \sin \theta + S\dot{\theta}^2 \cos \theta \\ -l\ddot{\theta} \cos \theta + l\dot{\phi}^2 \cos \phi + 2\dot{S}\dot{\theta} \cos \theta - S\dot{\theta}^2 \sin \theta \end{bmatrix} \quad (3.18)$$

solving gives

$$\ddot{S} = \dot{\phi}^2 l \sin \theta \sin \phi - \dot{\phi}^2 l \cos \theta \cos \phi - S\dot{\theta}^2 - \ddot{\phi} l \cos \theta \sin \phi - \ddot{\phi} l \cos \theta \sin \theta \quad (3.19)$$

$$\ddot{\theta} = \frac{2\dot{S}\dot{\theta} - \ddot{\phi} l \cos^2 \theta + \dot{\phi}^2 l \sin \theta \cos \phi + \dot{\phi}^2 l \cos \theta \sin \phi + \ddot{\phi} l \sin \theta \sin \phi}{S} \quad (3.20)$$

3.1.2 Model of pVSA

Knowing the stiffness and position behavior of the pneumatic cylinder requires obtaining the ratio of the pressures that will achieve them. Then they can be controlled by PID.

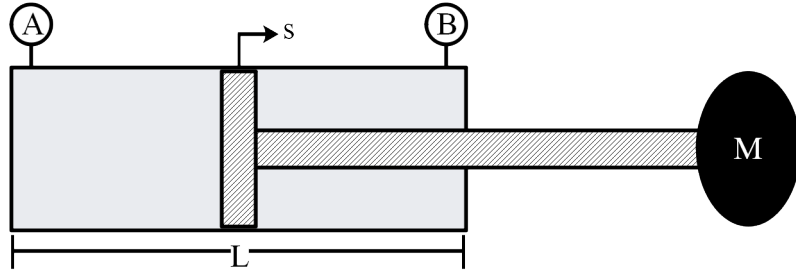


Figure 3-6: Pneumatic cylinder with L as the full stroke length, s is the zero displacement of the piston, M is the mass of the hand, handle, and A, B are the chambers.

The stiffness of a pneumatic actuator such as the one shown in Fig. 3-6 can be derived from the force F it exerts

$$F = P_A A_A - P_B A_B - P_{atm} A_r \quad (3.21)$$

where A_A and A_B are the cross-sectional areas corresponding to the cylinder chambers, P_{atm} is the atmospheric pressure, A_r is the area of the rod, P_A and P_B are the pressure of the A and B chambers respectively. Assuming that air is an ideal gas in

an isothermal process its behavior is governed by the following relationship:

$$P = \frac{mRT}{V} \quad (3.22)$$

Since the volume V is a function of the piston displacement and its cross-sectional area it can be computed as:

$$V = A \left(\frac{L}{2} \pm s \right) \quad (3.23)$$

the pressure inside the cylinder chambers can be expressed as

$$P_A = \frac{m_A RT}{A_A \left(\frac{L}{2} + s \right)} \quad (3.24)$$

$$P_B = \frac{m_B RT}{A_B \left(\frac{L}{2} - s \right)} \quad (3.25)$$

where m_A and m_B are the air masses inside the chambers, L is the full stroke of the pneumatic cylinder, R is the universal gas constant, T is the air temperature and s is the position of the piston. The partial derivative with respect to the displacement of the cylinder force is its stiffness K

$$K = -\frac{\partial F}{\partial s} \quad (3.26)$$

which is given by

$$K = RT \left(\frac{m_A}{\left(\frac{L}{2} + s \right)^2} + \frac{m_B}{\left(\frac{L}{2} - s \right)^2} \right) \quad (3.27)$$

3.2 Control

To control a system it is necessary to design a controller whose system output is used as the desired input for the controlled system, i.e. follow a reference signal [31].

As the objective of this thesis is not to implement a new controller to regulate the pressure of a pneumatic cylinder, and given its popularity, large documentation, simplicity, and satisfactory results [32] a PID controller will be implemented to

control the stiffness of the WHO-DS.

3.2.1 Ziegler-Nichols closed loop tuning method

Ziegler and Nichols were two engineers who proposed two tuning rules to determine the parameters of the PID controller. These rules take into account the transient response of the system to open or closed loop, the latter being used for our thesis project. The use of this methodology can be used when the model of the plant is known and also when not [31]. Since there are many variables and characteristics of the system to take into account, the mathematical model was not used in the WHO-DS to determine the parameters of the PID. The procedure for determining these parameters is as follows [33, 31]:

1. Stabilize the process by adjusting the flow control valves to prevent any sudden spikes.
2. Set the integral and derivative parameters to zero, while the proportional must have some value K_u .
3. Establish a step reference (pressure) and monitor the result.
4. If the process variable (the measured pressure value) does not oscillate, the proportional parameter must be increased until it does in a periodically stable way and with a constant amplitude.
5. If the oscillations are lost, the reference in step 3 must be changed.
6. When a constant periodic and amplitude oscillation is achieved, the measurement data must be saved to obtain the period manually, but if possible use a program that obtains the period accurately.
7. Try with different references, when observing a good behavior proceed to compute the K_u obtained in the equations of Table 3.1.

3.2.2 PID control

The stiffness of a pneumatic actuator is established by the sum of the pressures of each chamber; the movement of a pneumatic cylinder is given by the difference in pressure in the cylinder chambers. Therefore, it means that while the pressure of each chamber must be controlled independently, both pressures must be considered to obtain the desired stiffness. To achieve this, the relationship found in the research study by Zheng et al. [34] is used, which is obtained from the Equation 3.21 making it equal to zero, and substituting the equations 3.24 and 3.25 to compute the equilibrium force and thus the equilibrium or desired pressures

$$\frac{m_A RT}{\frac{L}{2} + s_{eq}} - \frac{m_B RT}{\frac{L}{2} - s_{eq}} - P_{atm} A_r = 0 \quad (3.28)$$

where s_{eq} is the desired or equilibrium position. From the previous equation and the Equation 3.27 it can be seen that they can be treated as a system of equations,

$$\mathbf{A} \begin{Bmatrix} m_A \\ m_B \end{Bmatrix} = \vec{B} \quad (3.29)$$

where

$$\mathbf{A} = \begin{bmatrix} \frac{RT}{\left(\frac{L}{2} + s\right)^2} & \frac{RT}{\left(\frac{L}{2} - s\right)^2} \\ \frac{RT}{\left(\frac{L}{2} + s_{eq}\right)} & -\frac{RT}{\left(\frac{L}{2} - s_{eq}\right)} \end{bmatrix} \quad (3.30)$$

$$\vec{B} = \begin{Bmatrix} K \\ P_{atm} A_r \end{Bmatrix} \quad (3.31)$$

to obtain the air masses from the chambers

$$\begin{Bmatrix} m_A \\ m_B \end{Bmatrix} = \mathbf{A}^{-1} \vec{B} \quad (3.32)$$

In other words, to control pressures, masses of air are used to add or decrease pressure at the chambers, where they are added or removed. Although, it is not possible to measure the air mass inside the cylinder directly, the equations 3.24

and 3.25 are used to replace the calculated masses to obtain the desired pressures

$$P_{Ad} = \frac{m_A RT}{A_A \left(\frac{L}{2} + s\right)} + P_{atm} \quad (3.33)$$

$$P_{Bd} = \frac{m_B RT}{A_B \left(\frac{L}{2} - s\right)} + P_{atm} \quad (3.34)$$

the addition of atmospheric pressure P_{atm} is necessary, because the absolute pressure P_{abs} has to be taken into account as follows:

$$P_{abs} = P_{A,B} + P_{atm} \quad (3.35)$$

To tune the PID, the Ziegler-Nichols closed-loop method and variants of it were used, shown in Table 3.1, whose results are shown in chapter 4.

Table 3.1: Tuning parameters considered in the orthosis control.

Rule	K_p	K_i	K_d
Ziegler–Nichols P	$0.5K_u$	-	-
Ziegler–Nichols PI	$0.45K_u$	$\frac{0.45K_u}{\frac{P_u}{1.2}}$	-
Ziegler–Nichols PID	$0.6K_u$	$\frac{0.6K_u}{\frac{P_u}{2}}$	$0.6K_u \left(\frac{P_u}{8}\right)$
Z-N Tyreus-Luyben PI	$0.31K_u$	$\frac{0.31K_u}{2.2P_u}$	-
Z-N Tyreus-Luyben PID	$0.45K_u$	$\frac{0.45K_u}{2.2P_u}$	$0.45K_u \left(\frac{P_u}{6.3}\right)$
Z-N Tan PID	$0.5K_u$	$\frac{0.5K_u}{P_u}$	$0.5K_u \left(\frac{P_u}{8}\right)$
Z-N Smith PID	$0.75K_u$	$\frac{0.75K_u}{0.625P_u}$	$0.75K_u (0.1P_u)$
Z-N Yu PID some overshoot	$0.33K_u$	$\frac{0.33K_u}{\frac{P_u}{2}}$	$0.33K_u \left(\frac{P_u}{8}\right)$
Z-N Yu PID no overshoot	$0.2K_u$	$\frac{0.2K_u}{\frac{P_u}{2}}$	$0.2K_u \left(\frac{P_u}{8}\right)$

As shown in Fig. 3-7, there are three Arduino controllers. The Arduino MEGA

takes readings of the current chambers pressures, angle of the mechanism, desired stiffness and desired position. With this data it calculates the desired pressures using the Equation 3.29, to send them along with the pressures measured to the Arduino ONE, which works as a PID slave. For better understanding see Fig. 3-7, Fig. B-1 and Fig. 3-8 self explain the procedure.

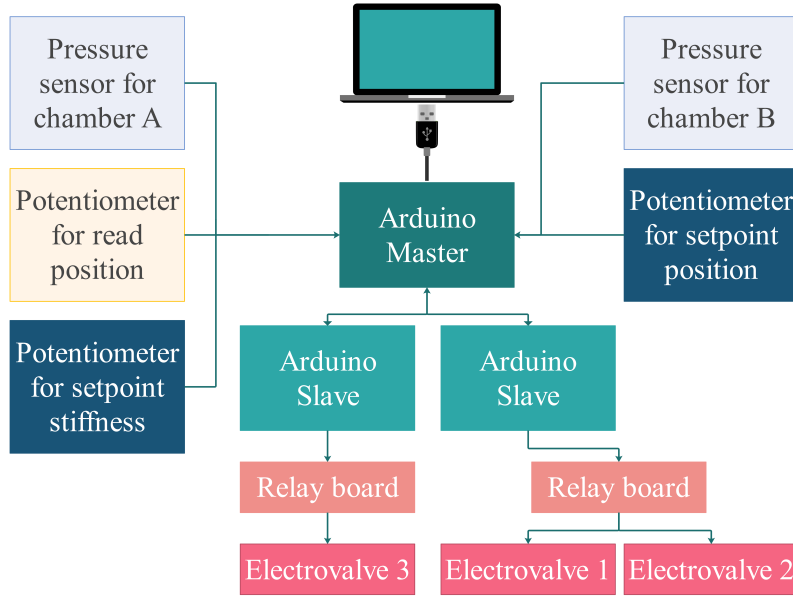


Figure 3-7: Electronic experimental setup.

3.2.3 On/off control

The PID slaves receive the input and reference, pressure measured and desired respectively. The code is based on the PID library developed by Beauregard [35] that, taking the information, makes the calculation of the output with the equation

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de}{dt} \quad (3.36)$$

$$e(t) = P_{Ad,Bd} - P(t)_{A,B} \quad (3.37)$$

where K_p is the proportional gain, $e(t)$, $e(\tau)$ is the error from the difference of setpoint (pressure of chambers A, B) with the process variable (desired pressure of

chambers A, B) in the instantaneous time, K_i is the integral gain, K_d is the derivative gain. The output consists of on/off switching similar to a PWM, but slow as it is for relays that activate the valve solenoids. The activation speed is given by a window that limits it and indicates by its minimum or maximum value, the opening or closing of the valves, according to the arrangement of the solenoid valves. Then, the output is the on/off time as can be seen in Fig. 3-9.

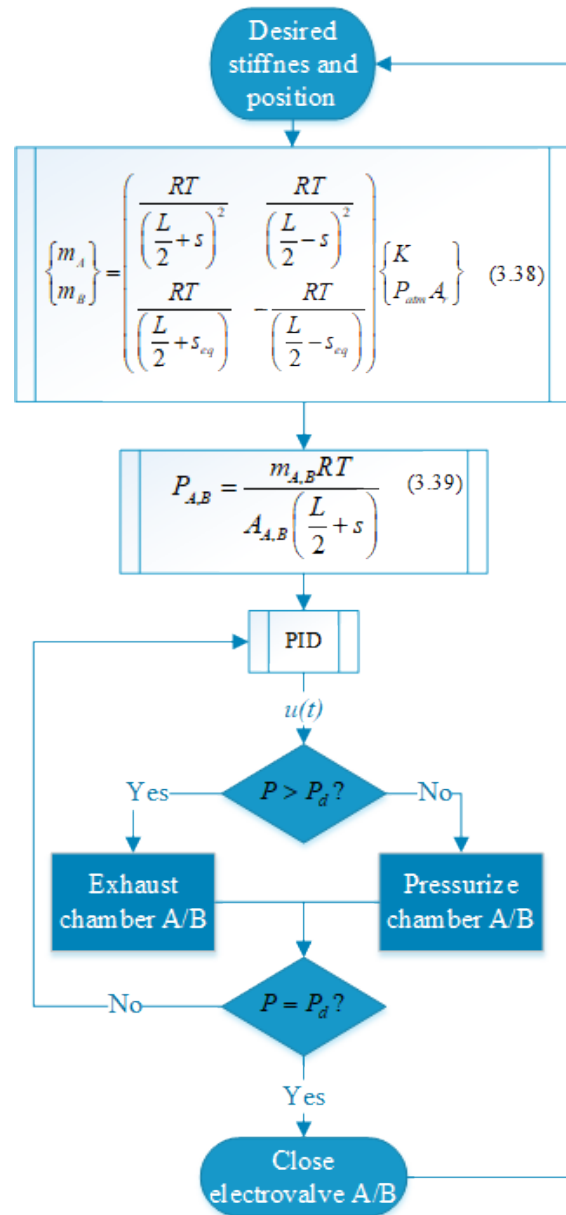


Figure 3-8: Desired pressure computation of equations (3.38) and (3.39) to control pressure in each chamber and thus achieve control of position and stiffness.

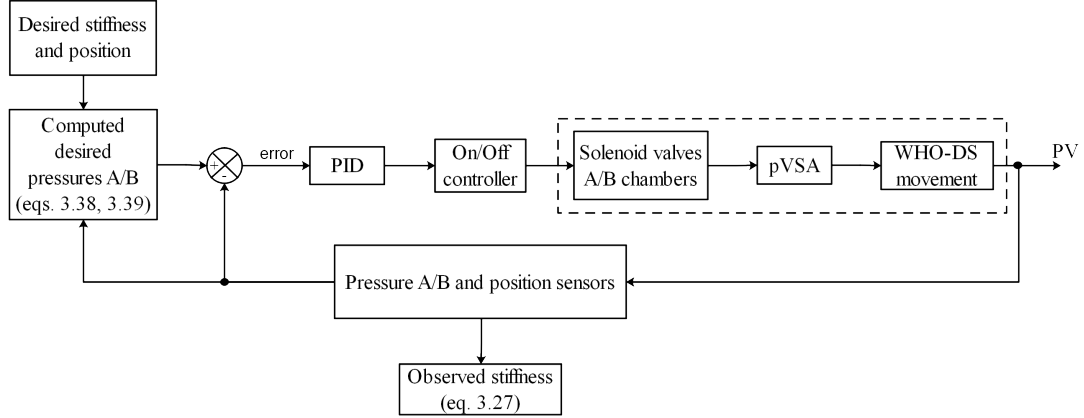


Figure 3-9: Control block diagram.

3.3 Chapter conclusion

For the control of a system it is necessary to know the output and input variables of this, for which the dynamic modeling of the pneumatic system and the kinematic modeling of the mechanism that is used by the first is shown in this chapter. As well as the PID controller and the low level on/off in charge of the pressurization and depressurization of the chambers, which result in a desired stiffness and position.

Chapter 4

Experimental validation of the device and its controller

Experiments with the device and analysis of the results are necessary to know if the device works. Therefore, this chapter presents how the tests were done, and the comparison of their results through the steady state error.

4.1 Experimental procedure

A mass of $1kg$ was fixed to the handle, in such a way for it to exert its force downwards. This is meant to simulate the hand and forearm of a patient. The compressor pressure was kept below $0.7MPa$, the percentage of opening of the flow control valves is shown in Table 4.2, all of the previous was considered in the experimentation.

4.1.1 Calibration for experimentation

To have a good behavior sensors and ultimate controller gain, which serve as feedback to the closed-loop control for the rehabilitation device must be calibrated.

Tunning the PID

In order to control the pressure of the chambers, a series of tests were carried out, varying the proportional parameter, also called ultimate controller gain (K_u) from

Table 4.1: Tested PI and PID gains in the WHO-DS.

Rule	Chamber A			Chamber B	
	K_p	K_i	K_d	K_i	K_d
Ziegler–Nichols P	0.075	-	-	-	-
Ziegler–Nichols PI	0.0675	0.20997	-	0.21076	-
Ziegler–Nichols PID	0.09	0.46661	0.0043398	0.46835	0.0043237
Z-N Tyreus-Luyben PI	0.0465	0.054791	-	0.054996	-
Z-N Tyreus-Luyben PID	0.0675	0.079535	0.0041332	0.079832	0.0041178
Z-N Tan PID	0.075	0.19442	0.0036165	0.19515	0.0036031
Z-N Smith PID	0.1125	0.46661	0.0043398	0.46835	0.0043237
Z-N Yu PID some overshoot	0.0495	0.25663	0.0023869	0.25759	0.002378
Z-N Yu PID no overshoot	0.03	0.15554	0.0014466	0.15612	0.0014412

0 to 20 in 0.1 increments. Each value of K_u was tested three times to avoid false positives. Following the Ziegler-Nichols method, when observing the results of these tests it was obtained that the control of the pressures was stable with a ultimate controller gain of 0.15. Which was found with the help of a code to obtain the period as required by the Ziegler-Nichols method, necessary for the computation of the PI and PID parameters. An interval of K_u between 0.1 and 0.19 could be considered, beyond that range the behavior of the control presented undesired variations that, moved away the controller from the reference.

As mentioned in section 3.2, Table 3.1, six methods of PI and PID tuning were tested. These methods are small modifications of the Ziegler-Nichols method that was also tested. Table 4.1 shows the parameters calculated from the K_u found when calibrating the proportional parameter.

Calibration

The pressure sensors were calibrated with the atmospheric pressure of the testing location at a temperature of 22°C. Adjustments were made in the mapping of bits to volts and of these to pressure in pascals as showed in the Arduino master code of Appendix C. For the position, the potentiometer was mapped from bits to volts and from these to degrees, with the help of the holes spaced by 10° in the device. Inside the full range of movement of the device which is 180°. However,

Table 4.2: Percentage of valve aperture

Valve	Aperture percentage	Comments
Flow control fitting	10	cylinder input
Throttle valve silencer	20	solenoid valve output
Flow control silencer	20	solenoid valve output
Flow control	14	air intake to the system

the experiments presented here the range of motion was reduced to 20° , to avoid reaching the cylinder stroke limits. The mappings are necessary, because the sensors only provide voltage values to the Arduino in charge of measuring them.

Flow control valves calibration

When performing the calibration of the ultimate controller gain, the air flow control valves were adjusted manually to find the value K_u . The regulation is somewhat arbitrary due to manual adjustment. Also, this adjustment prevents the device from banging, which happened before it was made to the valves, these settings are shown in Table 4.2. The use of two flow control valves (one at the inlet of the solenoid valve and one at the inlet of the cylinder) for chamber, is to obtain more accuracy of the air flow in and out of the pneumatic cylinder.

4.2 Experimental validations of the PI controller

Once the ultimate controller gain K_u capable of holding a periodic oscillation was found, was proceeded to compute the PI gains, like K_p and K_i . The reference value is $3000N/m$ for the stiffness and three positions in different tests (10° , 0° and -10°). The tests with a PI controller are for determining the suitability of its use against those of a PID controller. The way to know the stiffness of the device is by observing it through Equation 3.27, indirectly using the pressures and position read.

4.2.1 Results

Two tests with PI controllers were performed, specifically the gains were obtained by the Ziegler-Nichols method and others with the Tyreus-Luyben modification, both tests were performed with a 10° position reference. Results are presented below.

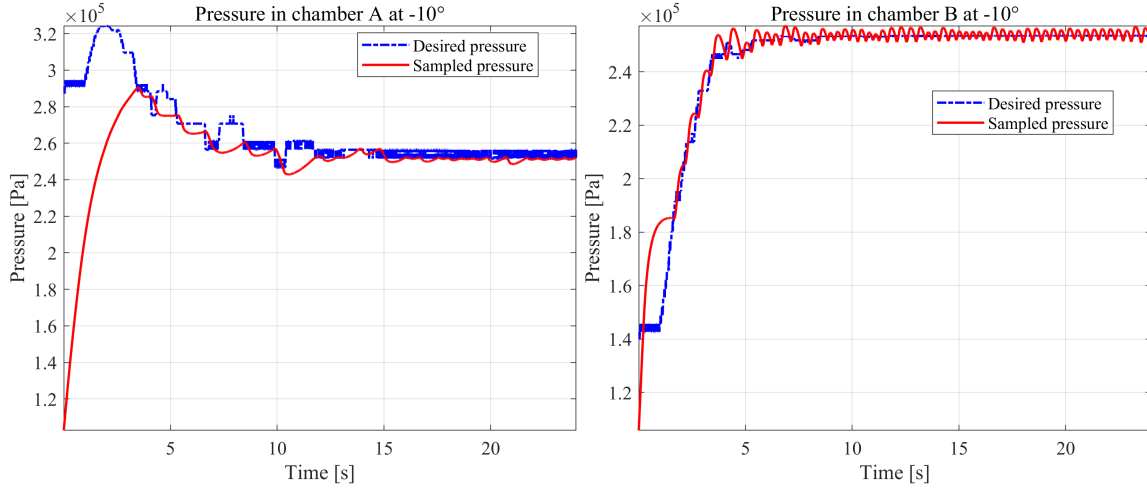


Figure 4-1: Results of the PI control by Ziegler-Nichols of pressures inside the chambers.

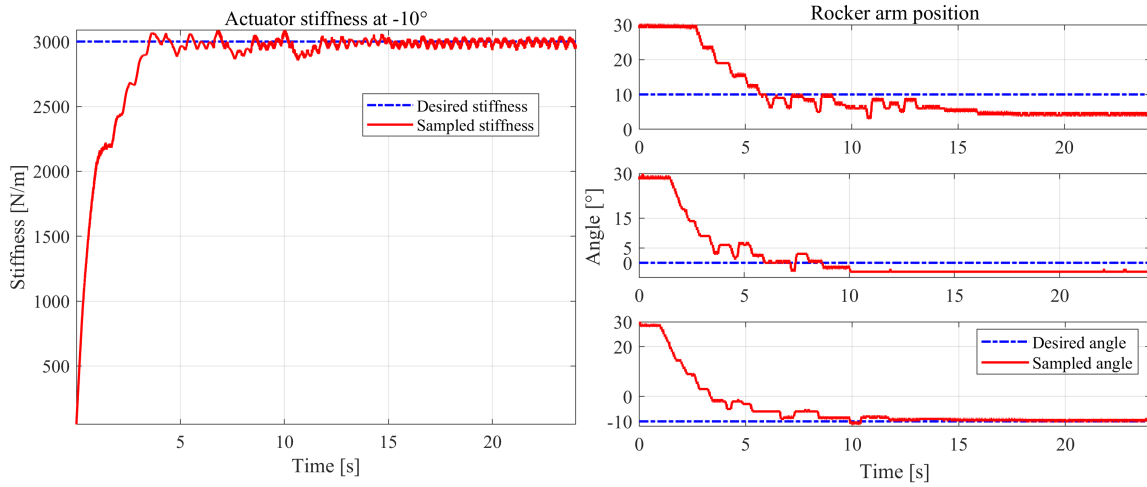


Figure 4-2: Results of the Ziegler-Nichols PI control of stiffness and position.

The pressures inside chambers A and B, and stiffness are only shown from this position (-10°) because they represent the position where the control behaves best at a stiffness of 3000N/m . While the results of pressures and stiffness of the 10° and

0° positions are shown in Appendix D. Pressures show a reading below atmospheric pressure, since a moving average filter was used. Due to the pressure values read during filter initialization, with values below atmospheric (not real), the stiffness shows negative values.

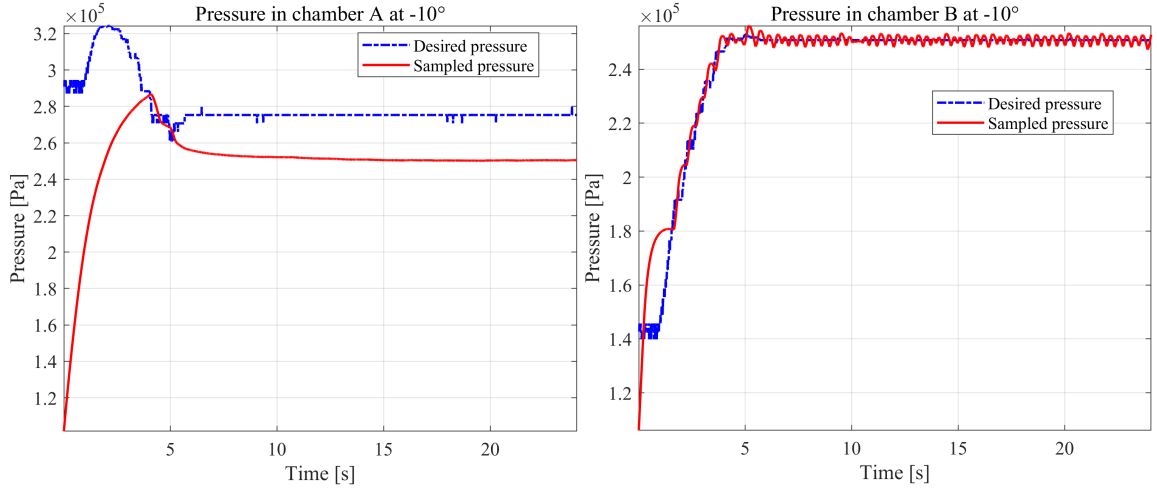


Figure 4-3: Results of the PI control by Tyreus-Luyben of pressures inside the chambers.

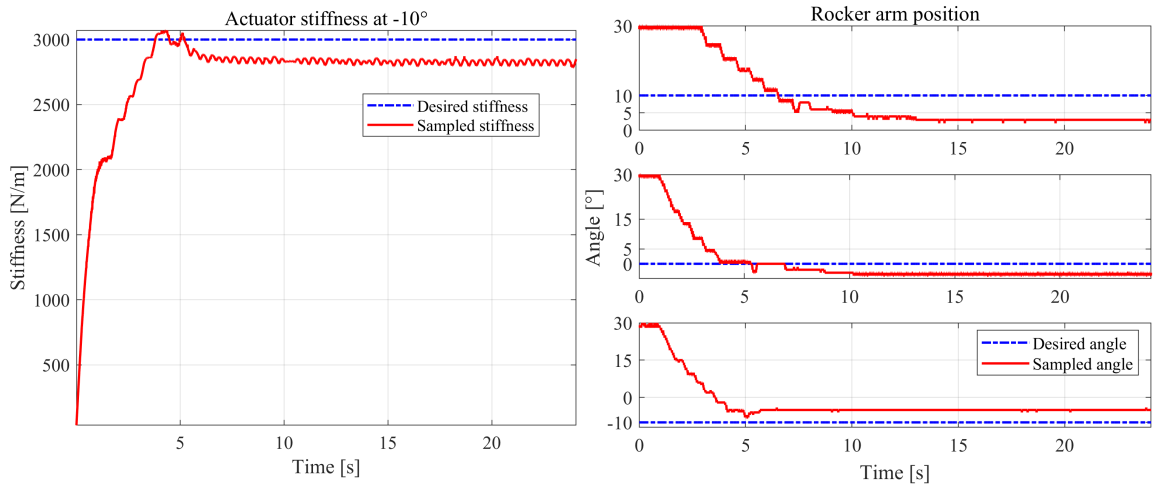


Figure 4-4: Results of the Tyreus-Luyben PI control of stiffness and position.

4.3 Experimental validations of the PID controller

With the same proportional parameter found, the PID gains of the different methods shown in Table 4.1 were computed. The references are $3000N/m$ for the stiffness and 10° , 0° and -10° of position in three different tests.

4.3.1 Results

Due to the fact that for each method ten graphs are obtained with results and to emphasise the best results, to avoid diverting attention only the results of the method with the best behavior are shown below (Yu no overshoot). Found the best PID control according to the steady state errors shown in section 4.4. While the remaining results are in Appendix D.

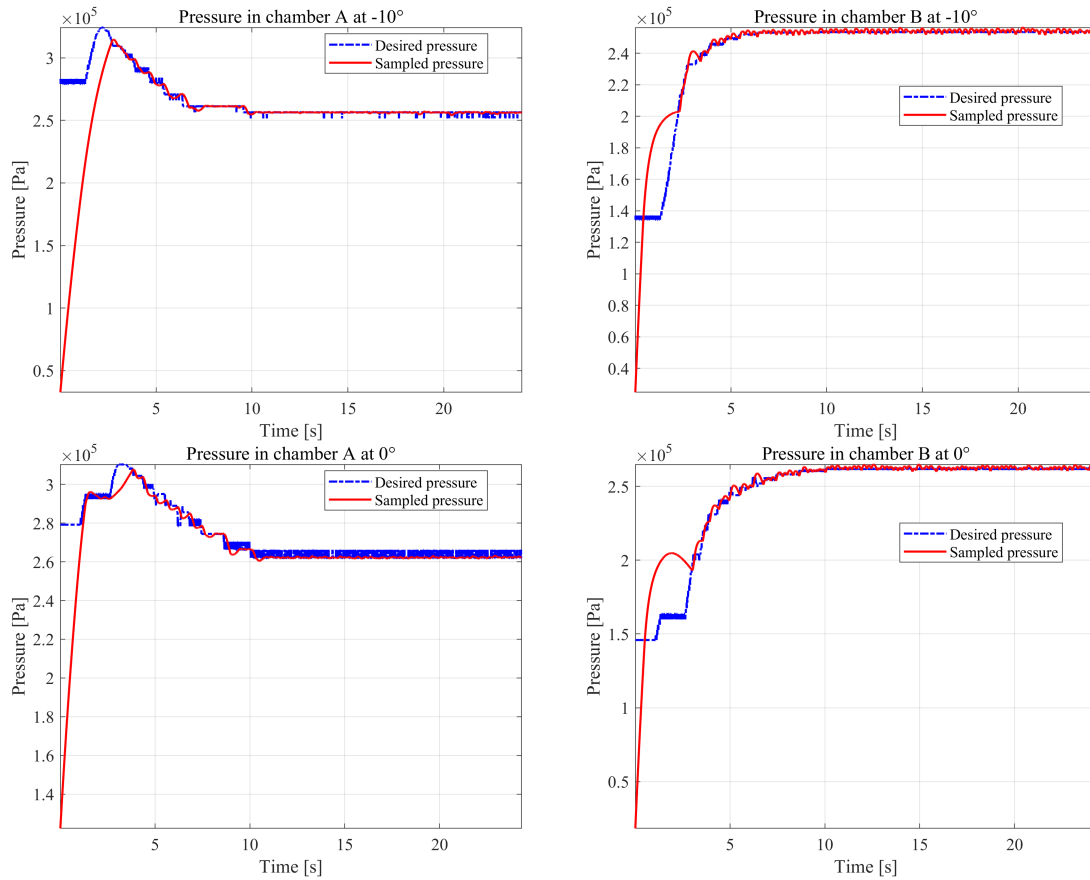


Figure 4-5: Results of the PID control gains by Yu (no overshoot) of pressures inside the chambers at -10° and 0° .

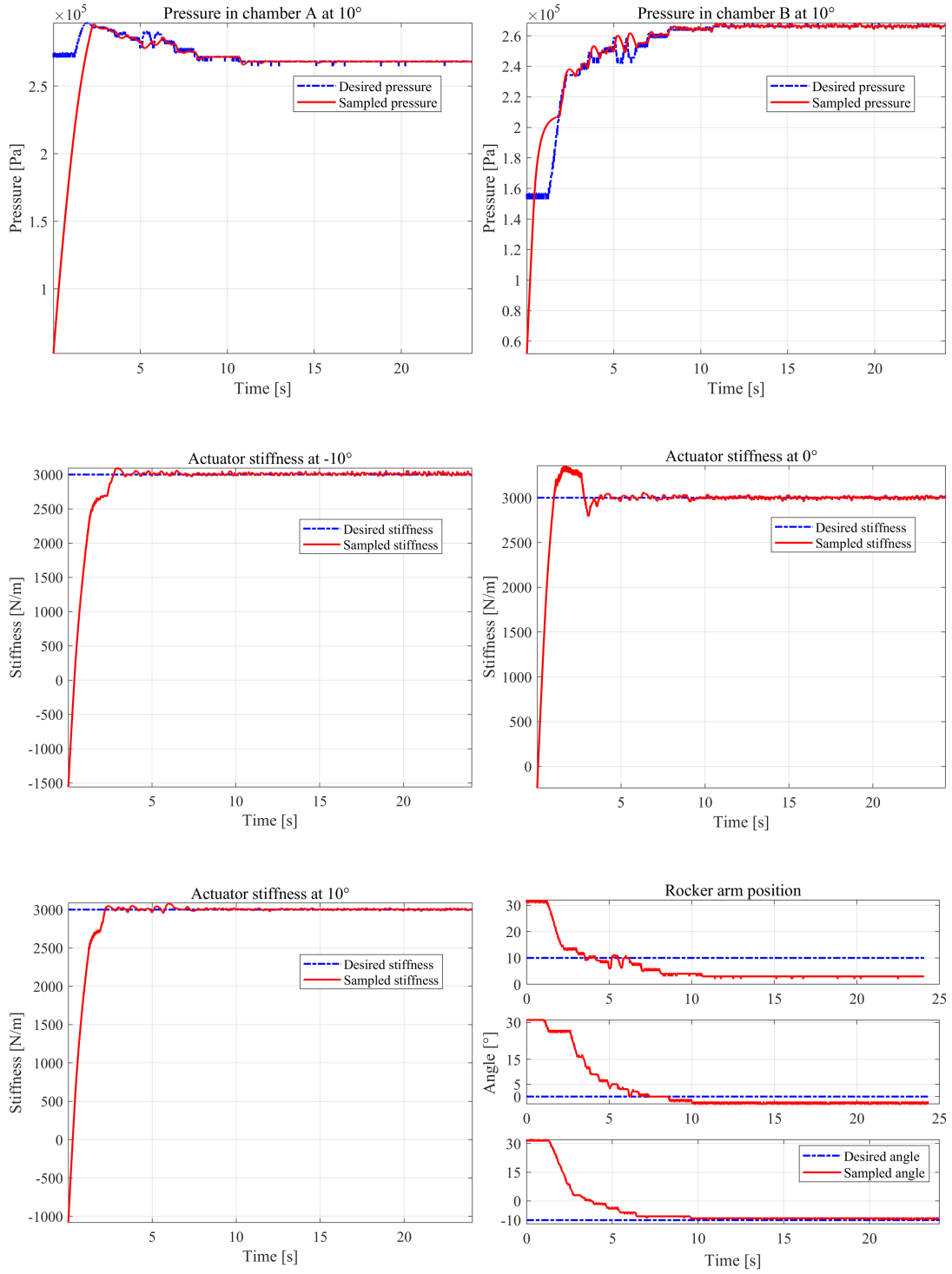


Figure 4-6: Results of the Yu (no overshoot) gains PID control of pressures inside the chambers at 10°, stiffness at -10°, 0° and 10° and three tests of positions.

4.4 Discussion

Multiple PID tuning methods were used to obtain the best system behavior. To know which one had better performance, a graphical analysis was made that compares the steady state errors between the different methods and tests. For better comparison of the errors in the control results, a the time interval corresponding to 20 to 22 seconds after the step-wise perturbation was applied is observed. In the cases of the pressures in chamber B this interval was reduced. The error is better appreciated in such intervals, because it is where most of the signals show good stability. With this interval the different errors in the methods can be differentiate between each other. The position control shows a higher error (Fig. 4-2, Fig. 4-4 and Fig. 4-6 at 10° of desired position) which is not significant because when compared to the full range of motion (138°) the error rate is less than 5%.

4.4.1 Minimum steady state error between methods used

Notice that in Figs. 4-7, 4-8 and 4-9 the PI and PID tuning method with the smallest steady state error in most of the results is the Yu (not overshoot) modification of the Ziegler-Nichols one. Closely followed are Yu (some overshoot) and Ziegler-Nichols PID and PI. This is distinguished by the trend of steady state error lines to 0 most of the time. There are error elevation peaks in all methods, attributed to the low level on/off controller. Also to the sensor noise, which causes a different desired pressure computation with each small variation. It is necessary to mention the small overshoots or small differences between the reference and the real values observed, are possibly due to the low frequency of air inlet and outlet of the solenoid valves, which impede a more stable continuity in the control of pressure.

For the position, was observed in Fig. 4-6 that the system is slow to follow the references, and takes about 5 seconds to reach the reference. It is also observed that, by increasing the value of the desired angle, a larger steady state error is observed. This is attributed to the fact that the desired stiffness can affect the correct positioning, along with small frictions in the system.

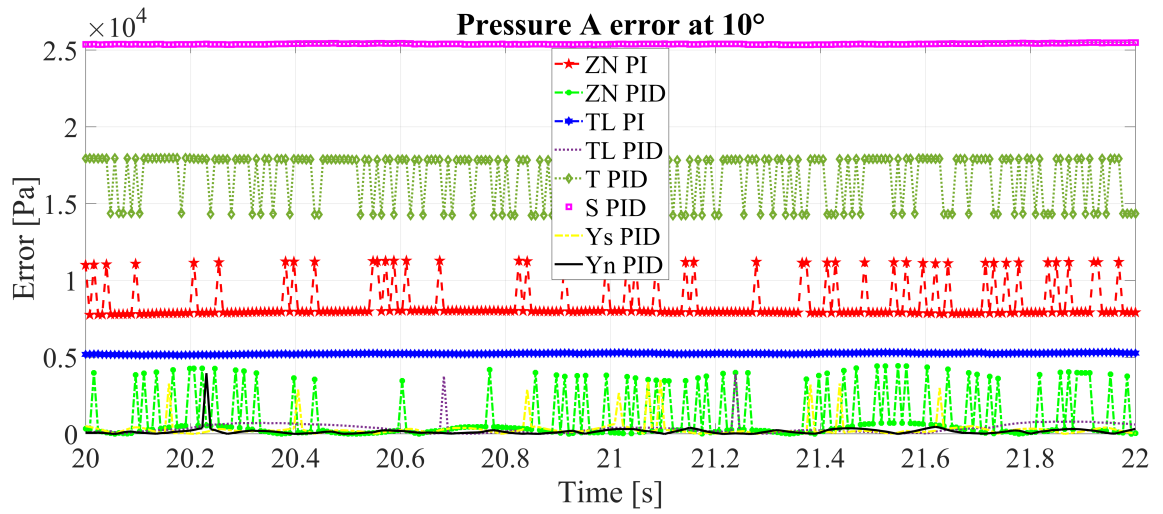
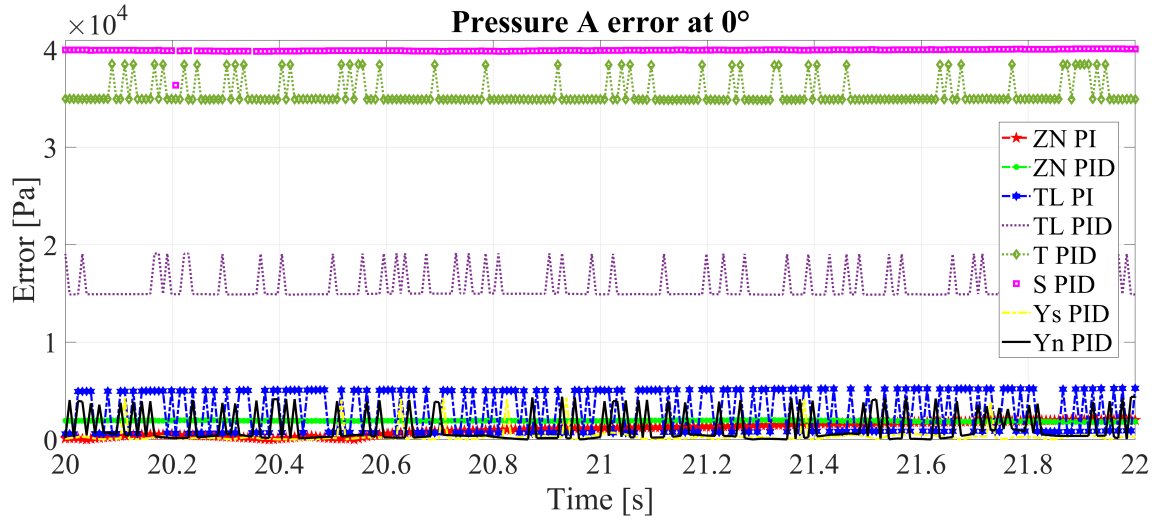
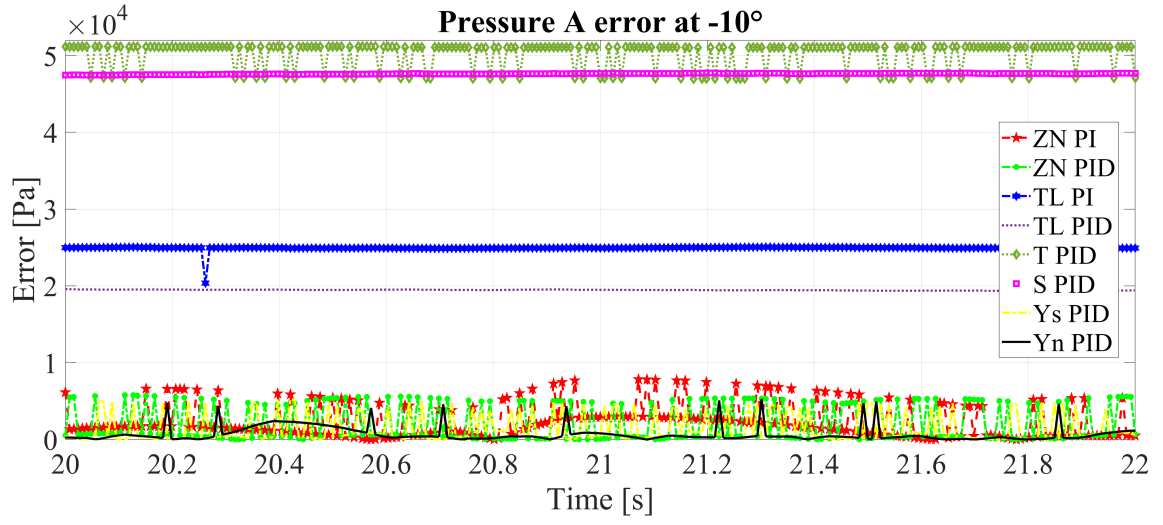


Figure 4-7: Steady state error of pressures in chamber A.

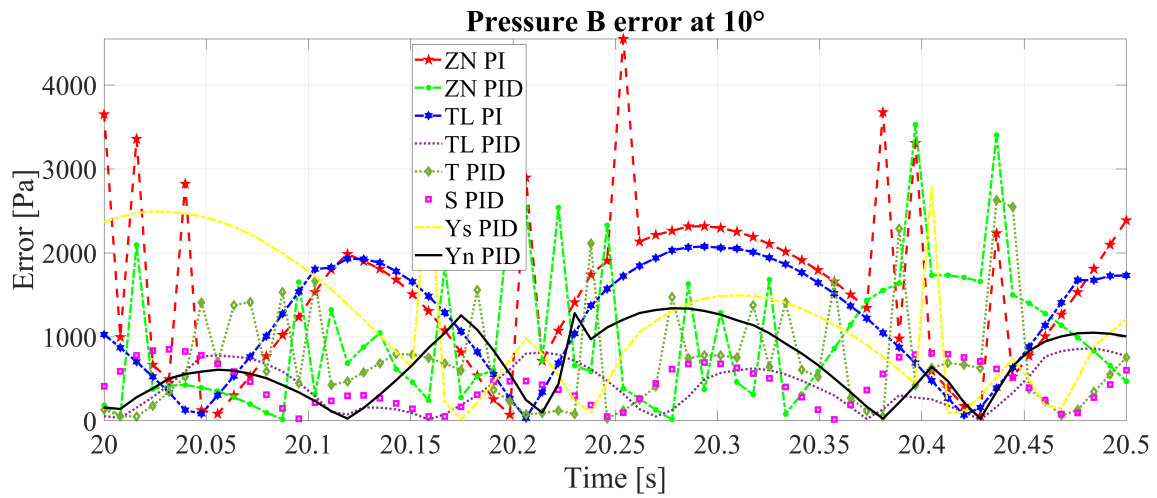
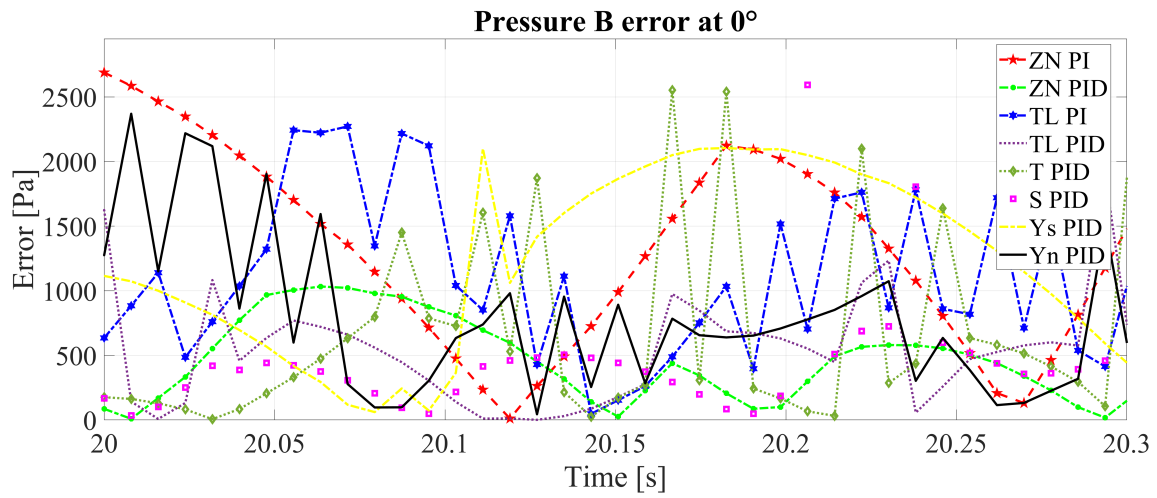
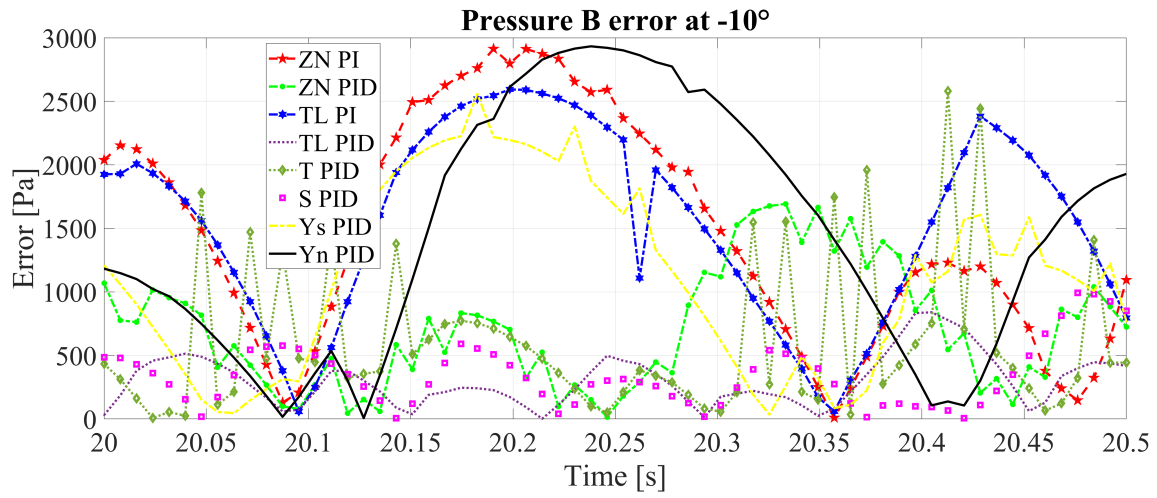


Figure 4-8: Steady state error of pressures in chamber B.

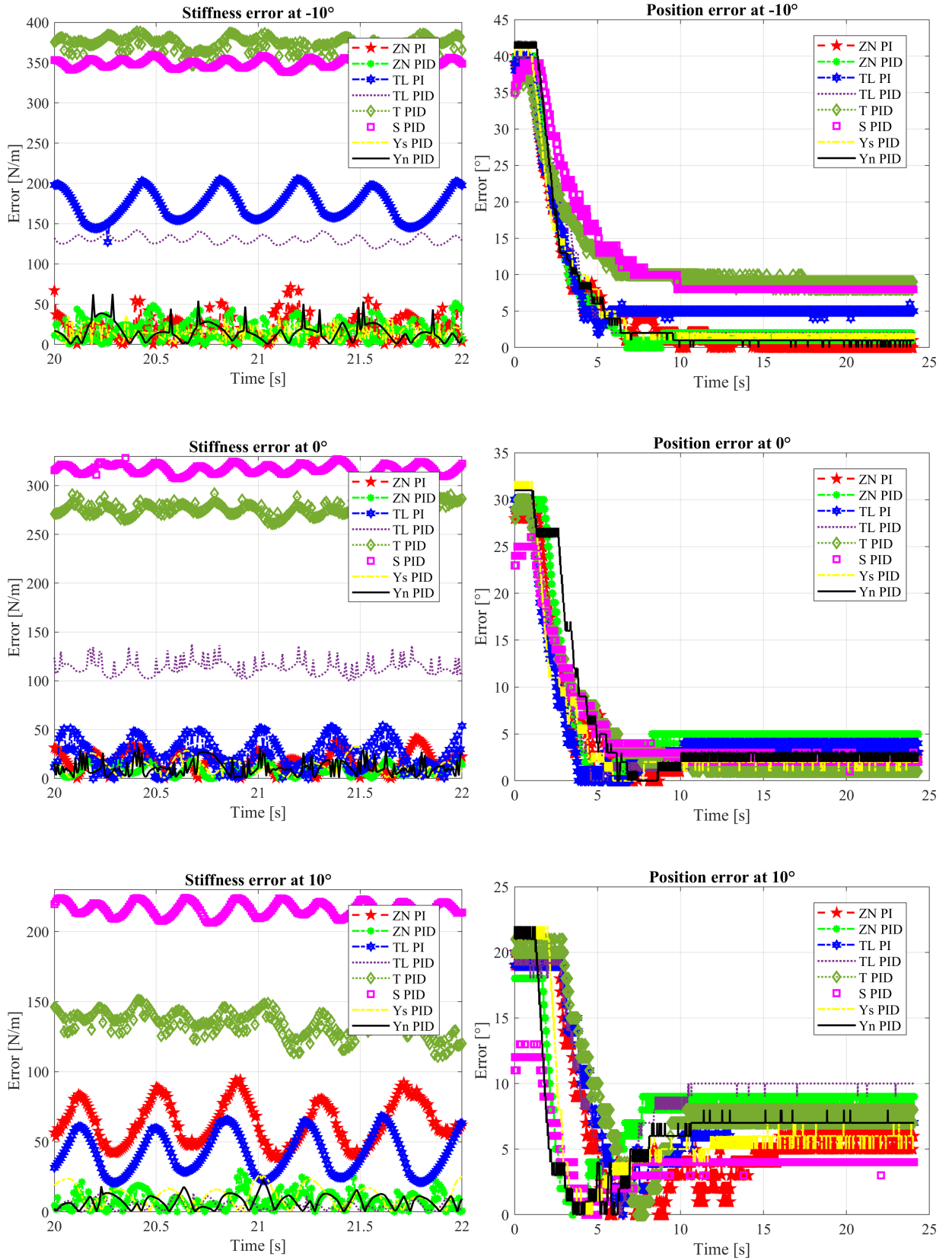


Figure 4-9: Steady state errors of stiffness and positions.

Clearly, the pressures in chamber B in Figs. 4-7 and 4-8 display very large variations, due to the hysteresis provided by a smaller chamber volume. The pressure in chamber B is supplied or released by two 3/2 solenoid valves that are configured to create a 5/3 solenoid valve as explained in subsection 2.3.2. The arrangement of the solenoid valves for the chamber B causes instability due to simultaneous changes in its state. And since there is only one 5/3 solenoid valve in chamber A, this chamber shows greater stability, whose small variations are caused by the chamber B.

4.5 Rehabilitation protocol

In the case of human testing, if it had been realized, it would have proceeded as follows:

- Establishment of collaboration with doctors or specialists in the area of physiotherapy, who will be responsible for providing one or more patients susceptible to physiotherapy intervention. Determining the risk level of the therapeutic complexity for the inclusion of the patient in the tests.
- If the patient's evaluation concludes that he/she needs therapy, the therapist will define the therapeutic plan. It will be verified that it can be performed by the WHO-DS.
- Later, the patient's permission (whose responsibility is his/her own) would be obtained to carry out the therapy with the device (in the test phase), and the supervision of professionals in the area would be arranged during the sessions. Afterwards, a follow-up would be done after the treatment was finished [36].

4.6 Chapter conclusion

This chapter shows the experimental validations of the rehabilitation device, with different sets of PI and PID gains. To know the best set of gains, a comparison of steady state error was made considering the pressures in chamber A, in chamber B,

stiffness of the actuator and its position. In addition, the results obtained were discussed, from the approach of the lowest steady state error obtained, and demonstrate that they can accurately reach desired position and stiffness simultaneously.

Conclusions

The development of soft robotics is vital for the interaction of robots with humans, because if one wants to comply with Isaac Asimov's three laws of robotics or simply for the safety of the human being and the robot. The robots must be provided with tools that prevent them from harming humans. One of these tools is the use of compliant actuators, such as the pVSA from WHO-DS. Created from the modeling and design developed throughout this project, which also provides the construction of a pVSA, the control of its stiffness and position.

The section 2.1 shows all the considerations taken and to be taken to present a stationary dynamic wrist orthosis. However, they also apply to any other type of orthosis, with the exception of the safety systems presented in subsection 2.3.1, as they may vary depending on the limb being targeted, and the actuator used. In other words, this thesis can be taken as a guide for designing orthotics, compliant or not. Or be replicated using the design parts detailed in Appendix A, the connections in Appendix B, and the programs used in Appendix C.

The results exceed the stiffness and position control on which they were based (system of Zheng et al. [34] equations), it is believed to be due to the lack of use of absolute pressure in the equations of Zheng et al. They used equations to predict pressure, but in this thesis work it was not used because of lack of equipment. However, it seems beneficial not to use the equations of prediction, because better results were obtained.

Despite it is believed that, solenoid valves should be used with a higher working frequency there is a positive part of the frequency handled in the WHO-DS (15Hz). Since Yu et al. mention that *"15Hz is more than sufficient for rehabilitation"*. But instead of the 5-port, 3-position (5/3) and the other two 3/2 valve arrangements,

one for each 3/3 chamber should be changed.

In the absence of human testing, the device handle was sometimes grasped to feel the change in stiffness by applying a force with the wrist and feeling the WHO-DS reaction, without recording the data.

Future Work and Recommendations

To prevent small oscillations in the pressure control which is responsible for ensuring position and stiffness. It requires the use of equal solenoid valves for each chamber, to avoid an arrangement of solenoid valves and with a higher working frequency capacity.

The device behaves in a way similar to human muscles, due to its variation in stiffness. It is essential to test in humans to know if the device is able to improve rehabilitation with respect to devices without variation of stiffness or conventional treatments.

For a behavior according to the patient's treatment needs, the use of sEMG sensors to mimic muscle stiffness in WHO-DS is recommended. This way the stiffness of the device will not exceed that of the patient, which could otherwise delay rehabilitation or damage the patient's wrist.

Publication

Design, Modeling and Control of a Variable Stiffness Device for Wrist Rehabilitation

- **Authors:** Oscar M. Flores, Jesus H. Lugo, Alejandro González, Mauro Maya, Matteo Zoppi, Emilio J. González, Juan A. Cárdenas.
- **Type of publication:** conference paper of COMRob 2020.

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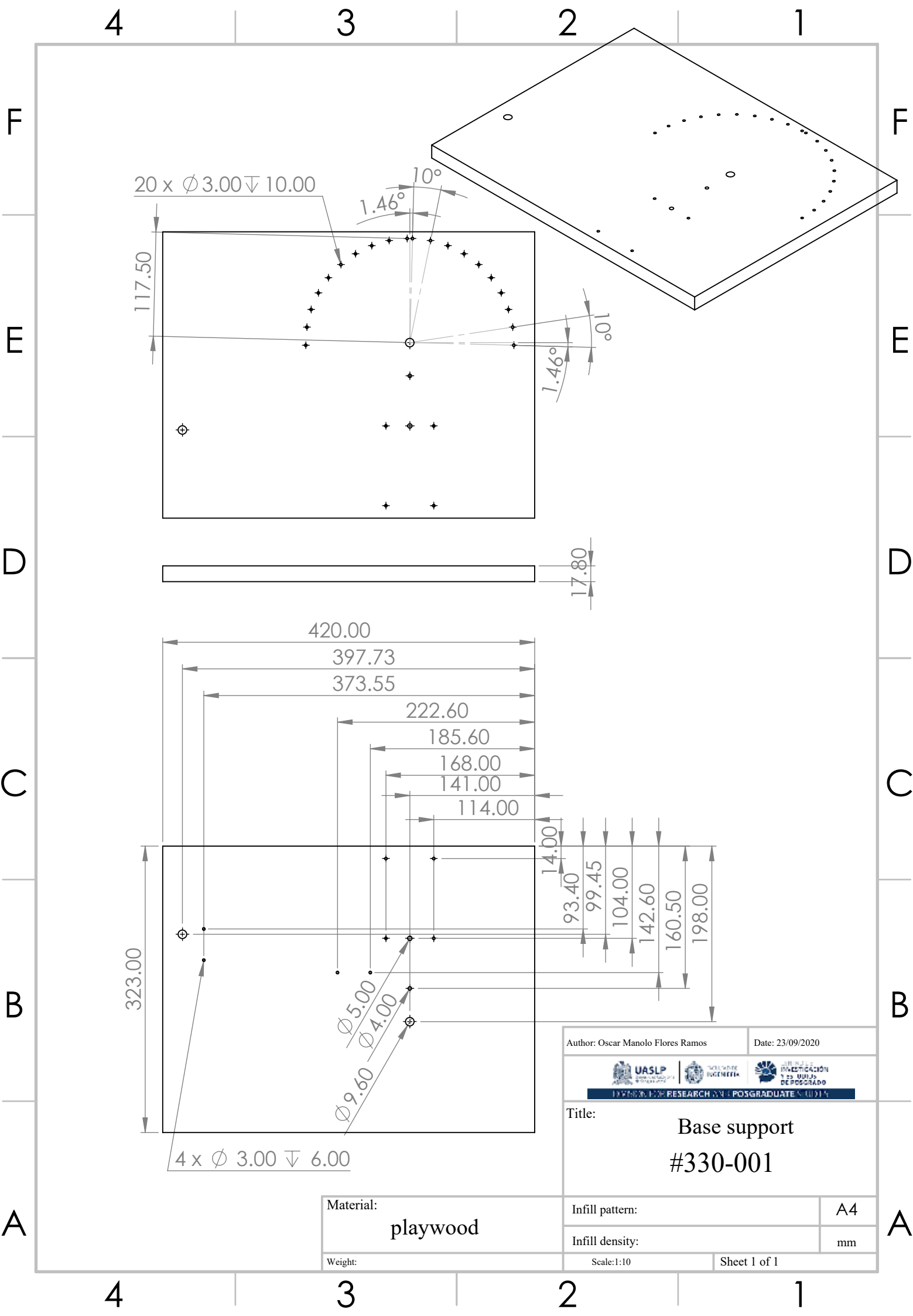
Appendices

Appendix A

Part drawings

In order to replicate the orthosis, detailed drawings of the designed components are shown below, whose 3D models can be found in the following link:

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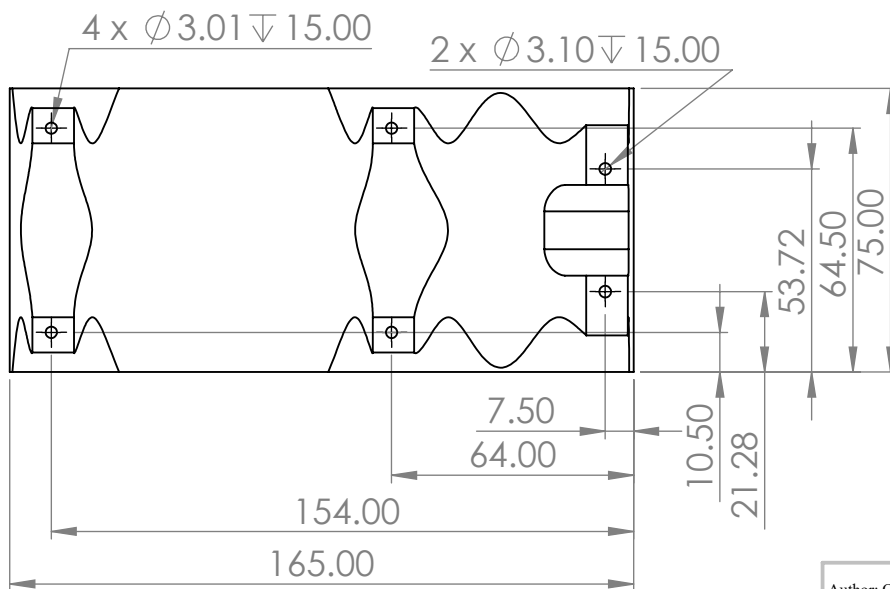
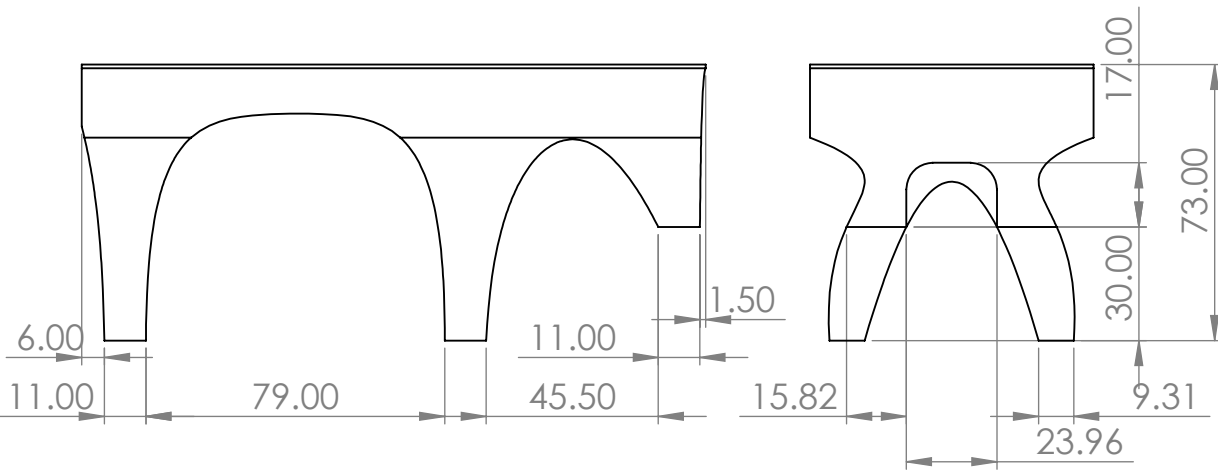
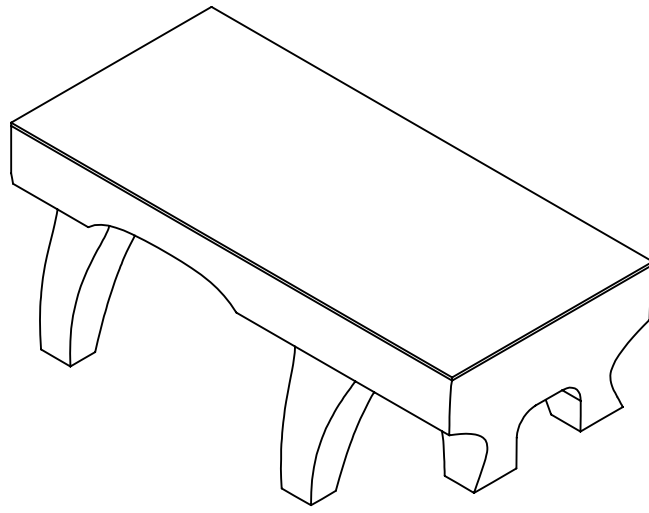
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B

B

A

A



Author: Oscar Manolo Flores Ramos

Date: 23/09/2020



Title: Forearm support
#330-017

Material: PLA

Infill pattern: Gyroid

A4

Infill density: 70%

mm

Weight:

Scale: 1:5

Sheet 1 of 1

4

3

2

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C

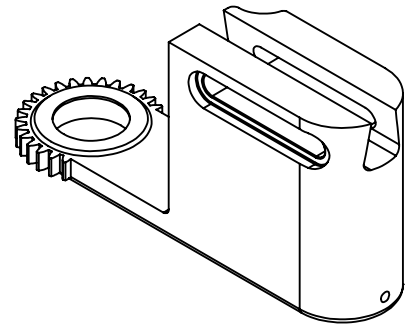
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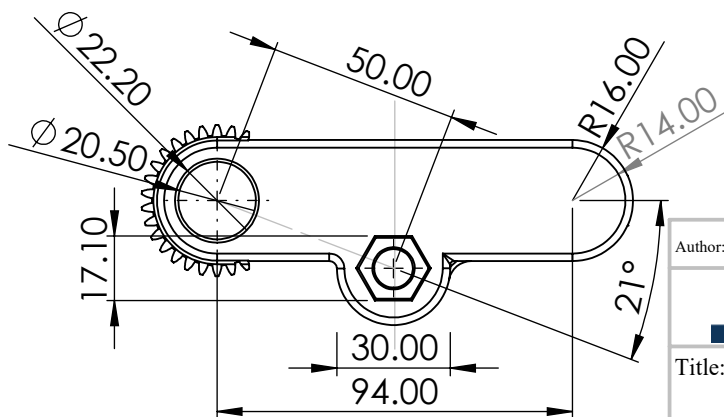
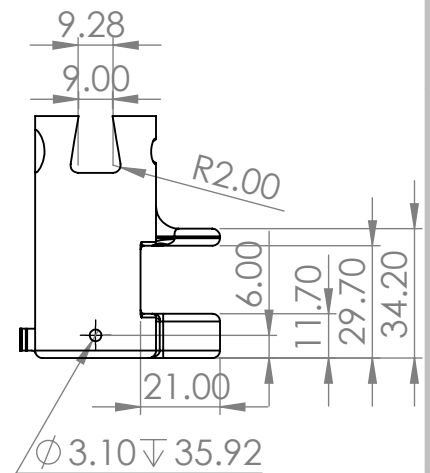
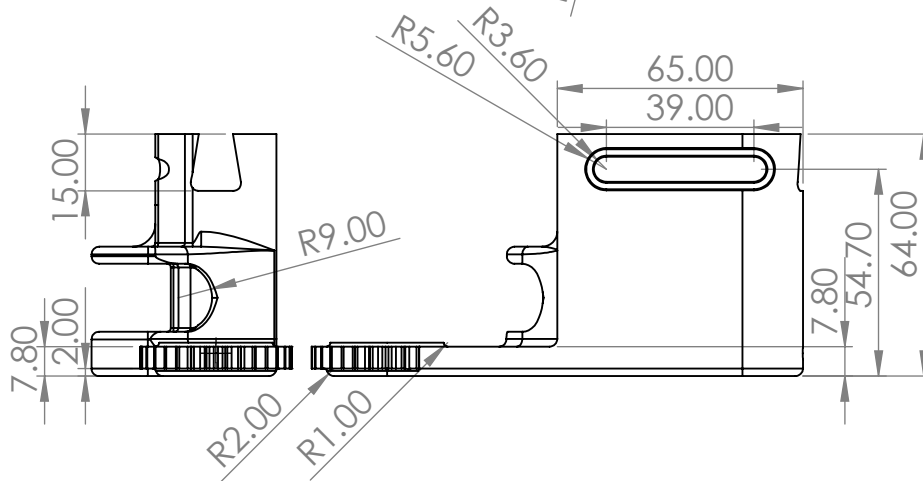
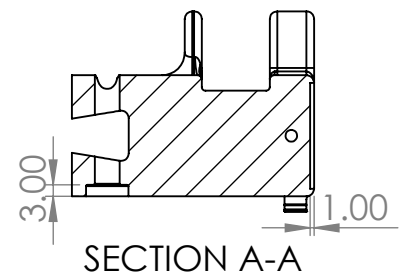
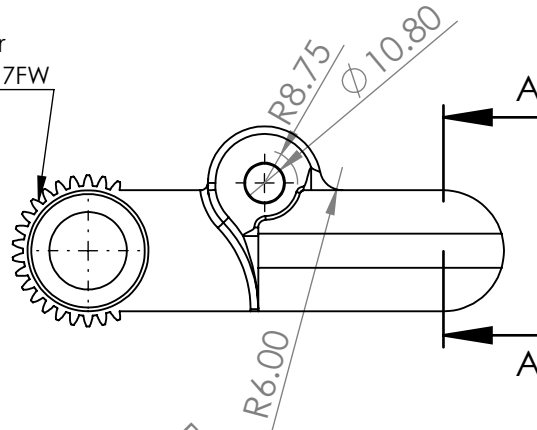
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A

A



JIS-Spur gear
1.25M 30T 20PA 7FW



Material:

PLA

Weight:

Author: Oscar Manolo Flores Ramos

Date: 23/09/2020



Title:

Handle base
#313-006

Infill pattern: Gyroid

A4

Infill density: 70%

mm

Scale: 1:2

Sheet 1 of 1

4

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4

3

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1

F

F

E

E

D

D

C

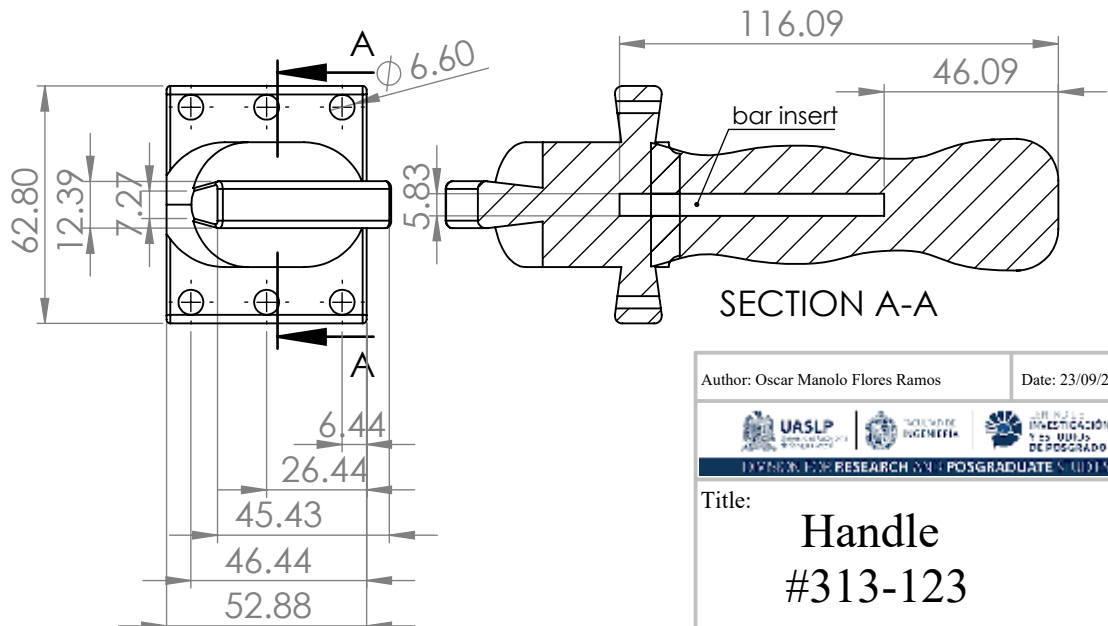
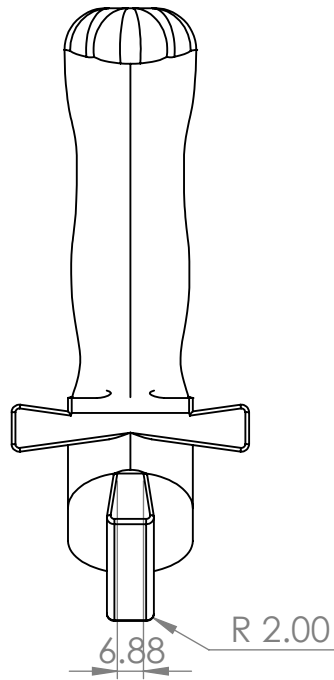
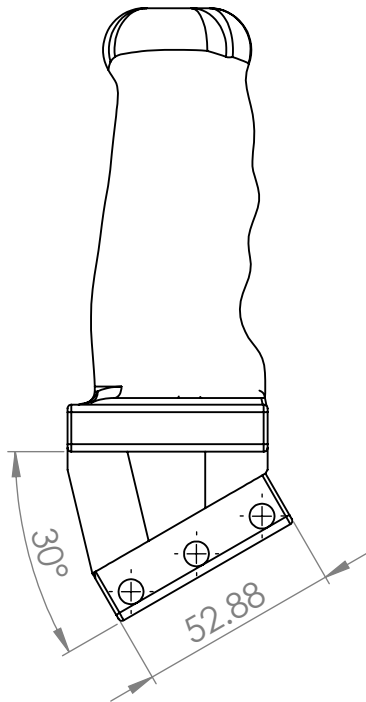
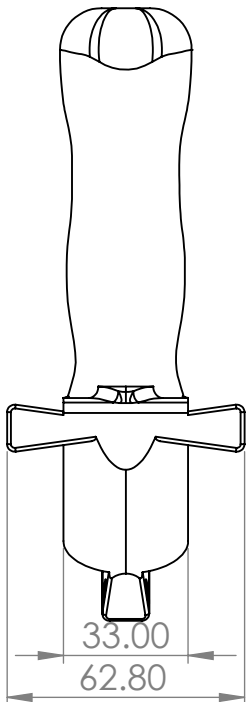
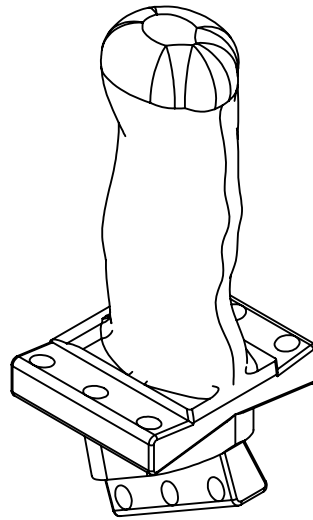
C

B

B

A

A



Author: Oscar Manolo Flores Ramos

Date: 23/09/2020



Title:

Handle #313-123

Material:

PLA

Infill pattern: Gyroid

A4

Infill density: 60% with steel bar insert

mm

Weight:

Scale: 1:2

Sheet 1 of 1

4

3

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1

Appendix B

Electronic system

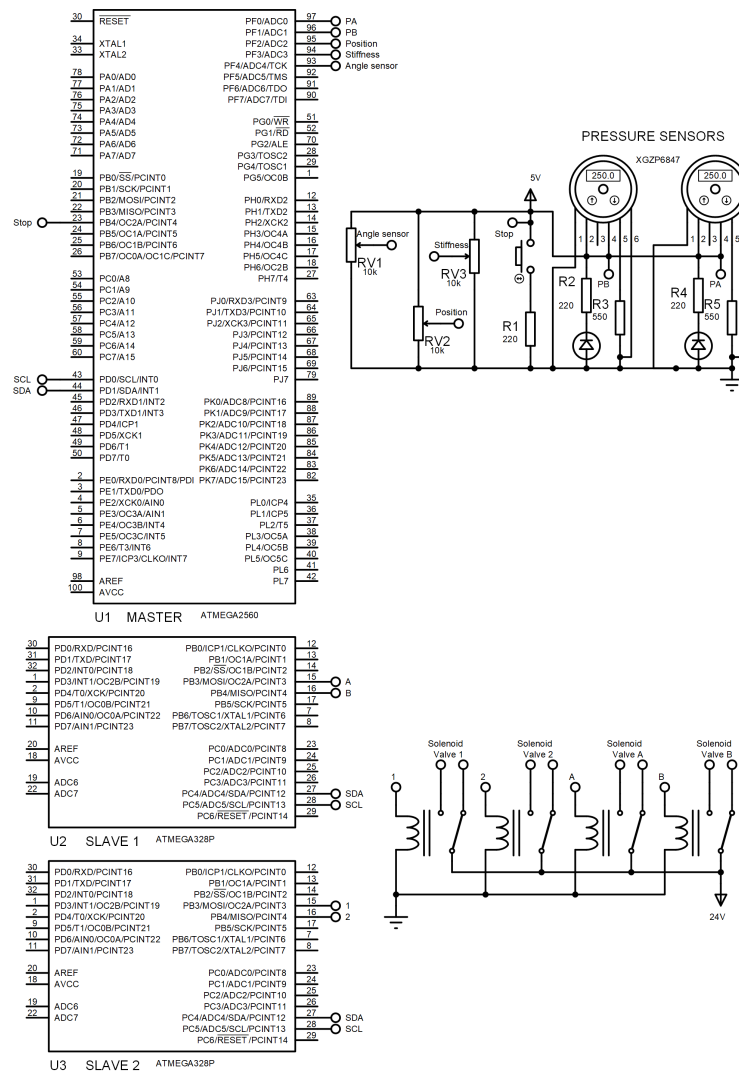


Figure B-1: Electronic system diagram.

Appendix C

Code

In the following link you will find the codes created to control the stiffness and position of the WHO-DS.

<https://www.dropbox.com/sh/48771yne61syjqs/AAAZ4g6YxpEGV4mZVJ6tHYfEa?dl=0>

Inside the MPS_08 folder, there is the code of the Arduino that acts as a master, in charge of reading sensors, making the desired pressure calculation and sending the data to the slave Arduino 1 (folder S1PS_05) and the slave Arduino 2 (folder S2PS_05). The slaves are in charge of the PID control of the pressure of each chamber.

Appendix D

Remaining results of the PI and PID rules tested

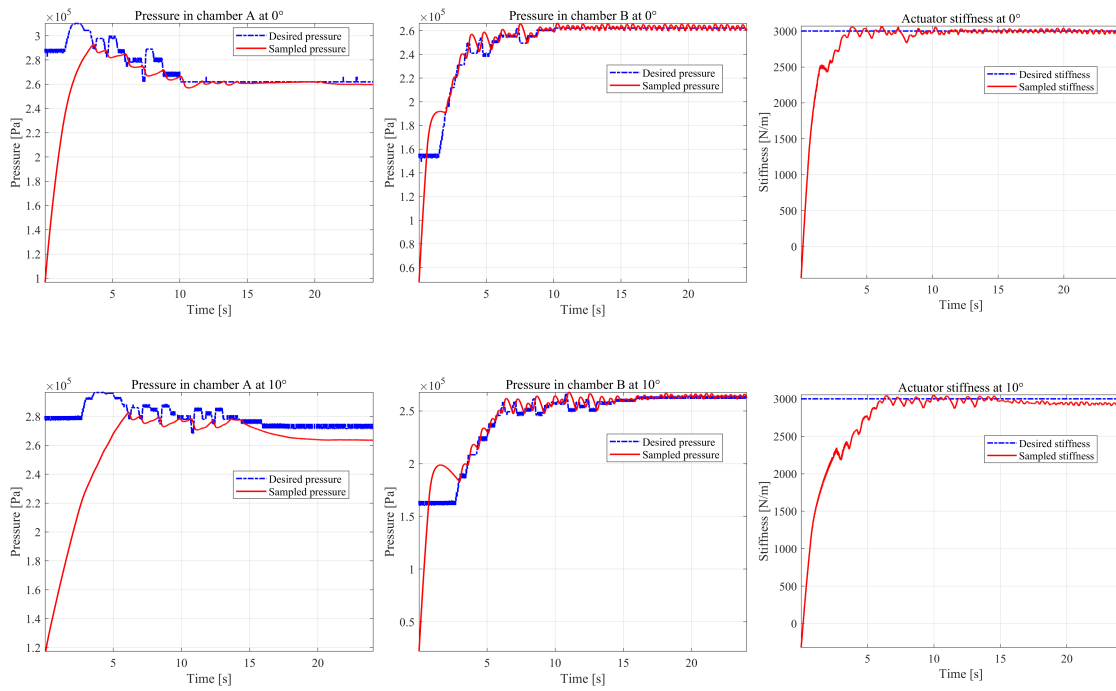


Figure D-1: Steady state errors of pressures and stiffness of Ziegler-Nichols PI controller at 0° and 10°.

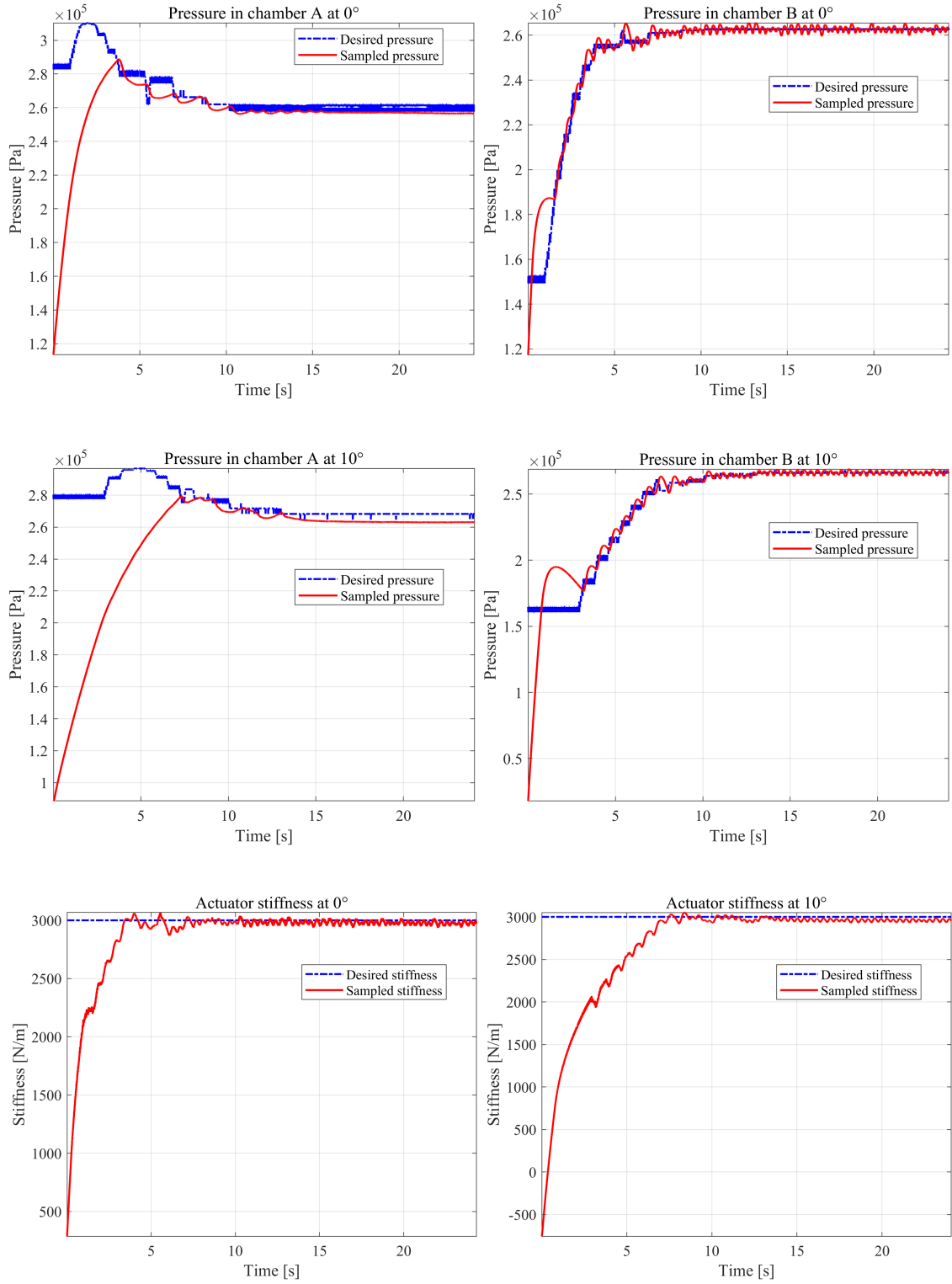


Figure D-2: Steady state errors of pressures and stiffness of Tyreus-Luyben PI controller at 0° and 10°.

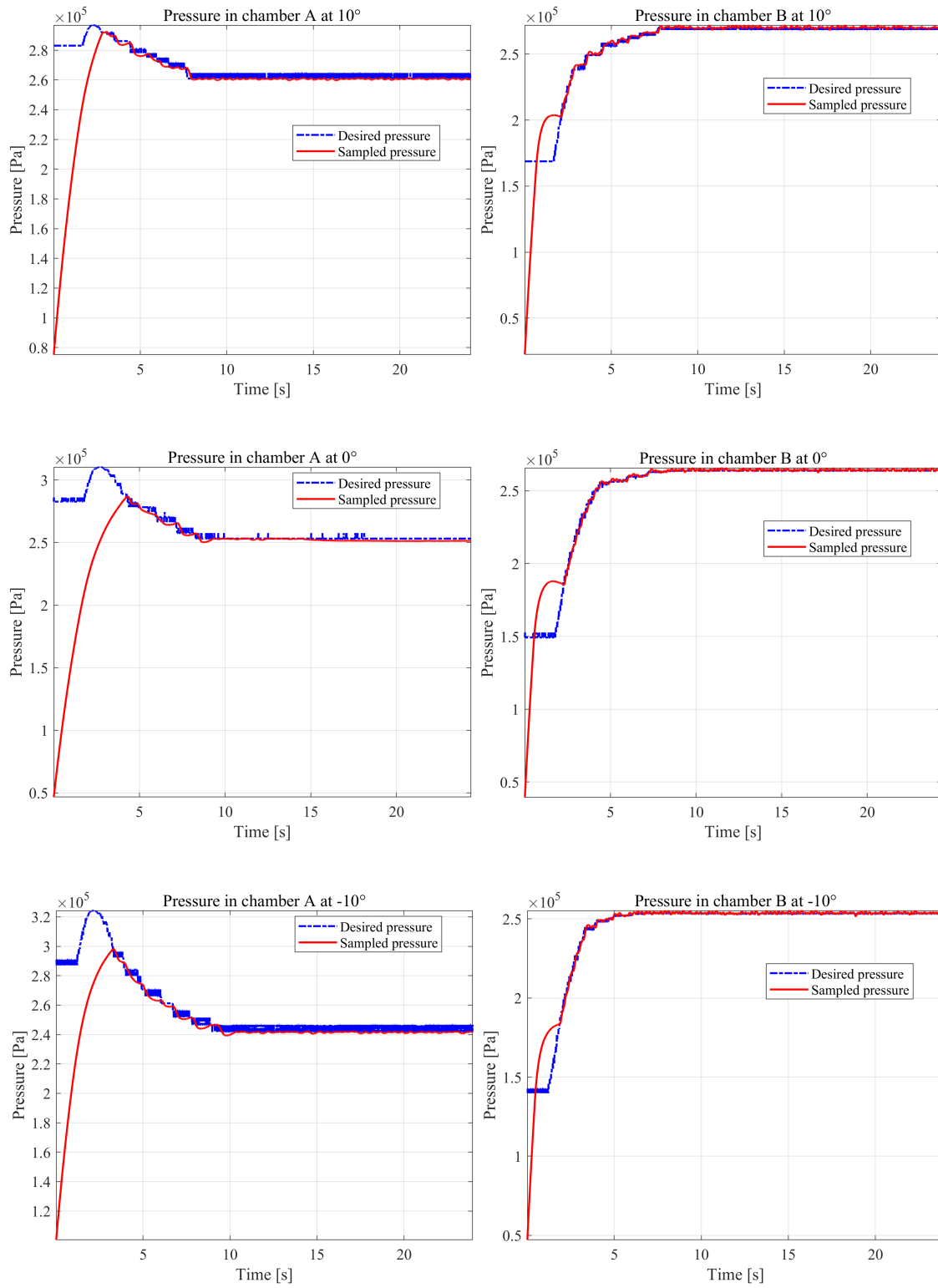


Figure D-3: Steady state errors of pressures of Ziegler-Nichols PID controller.

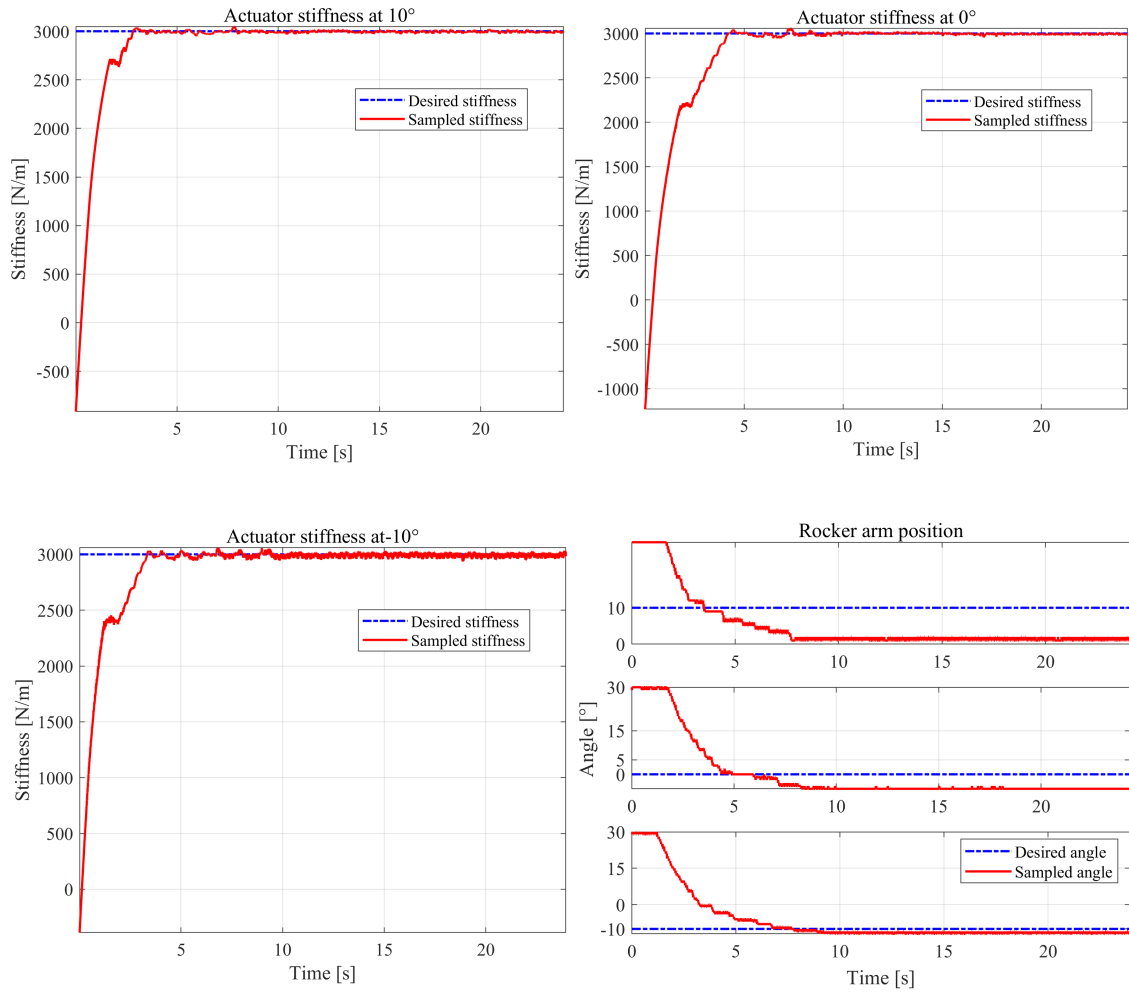


Figure D-4: Steady state errors of stiffness and positions of Ziegler-Nichols PID controller.

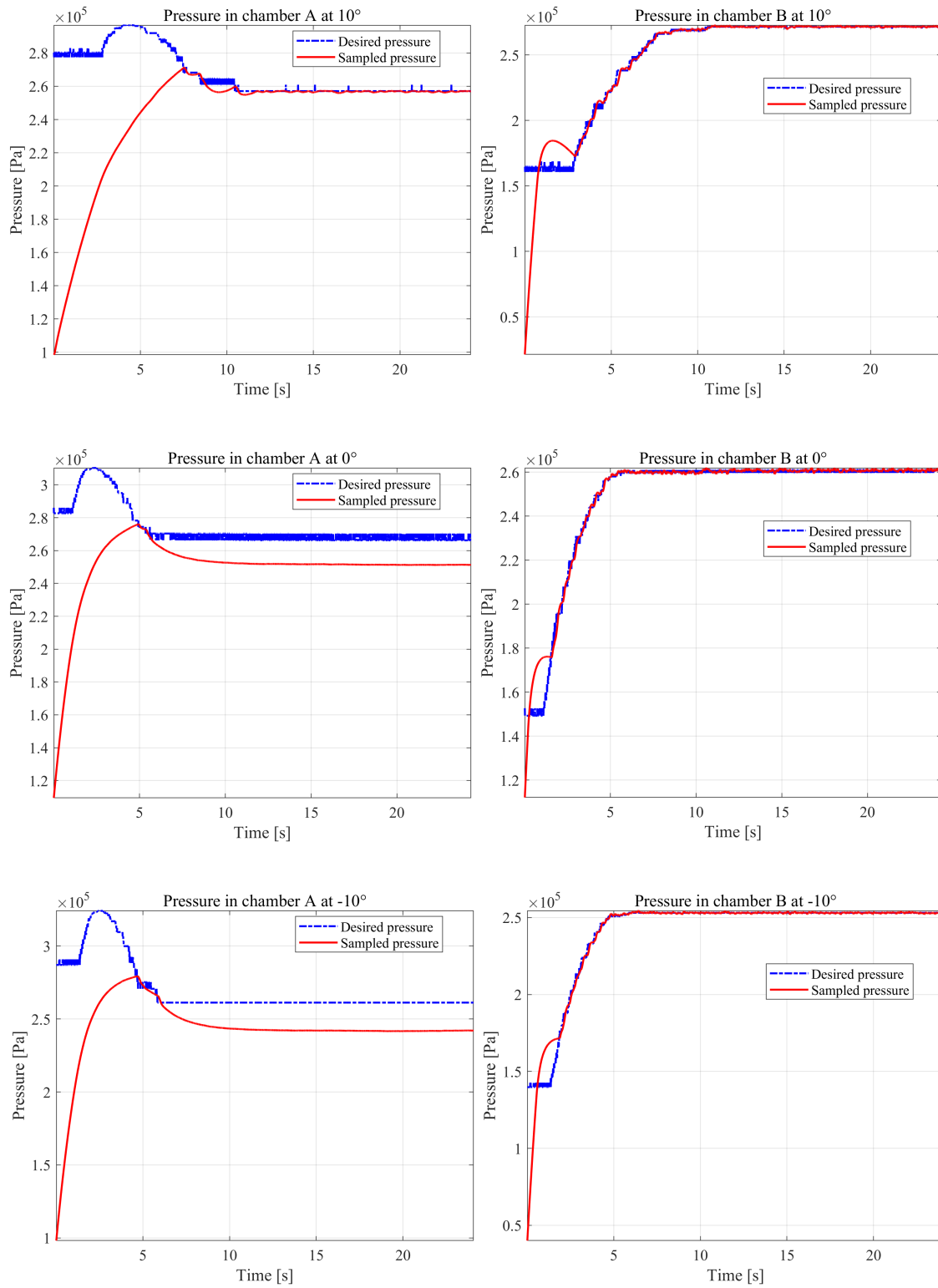


Figure D-5: Steady state errors of pressures of Tyreus-Luyben PID controller.

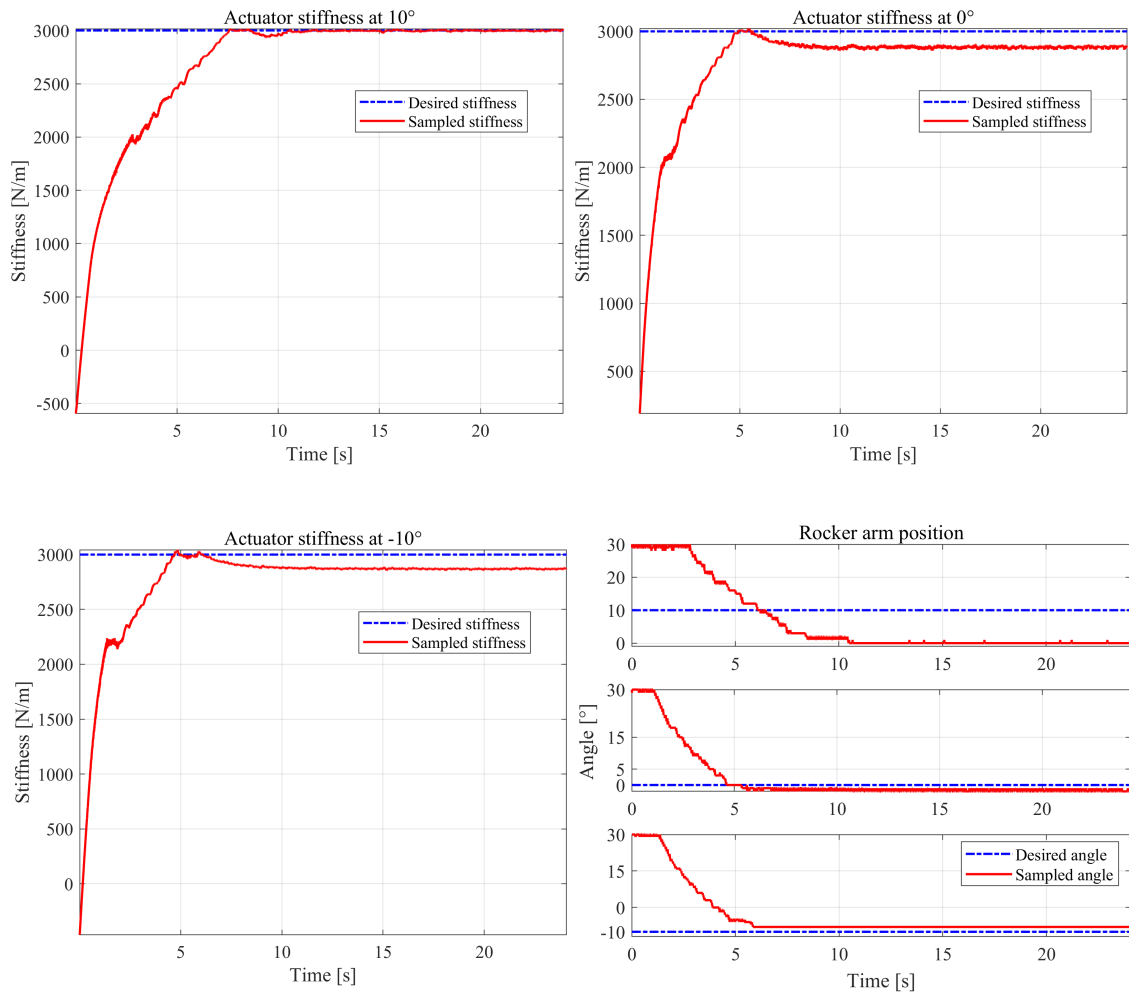


Figure D-6: Steady state errors of stiffness and positions of Tyreus-Luyben PID controller.

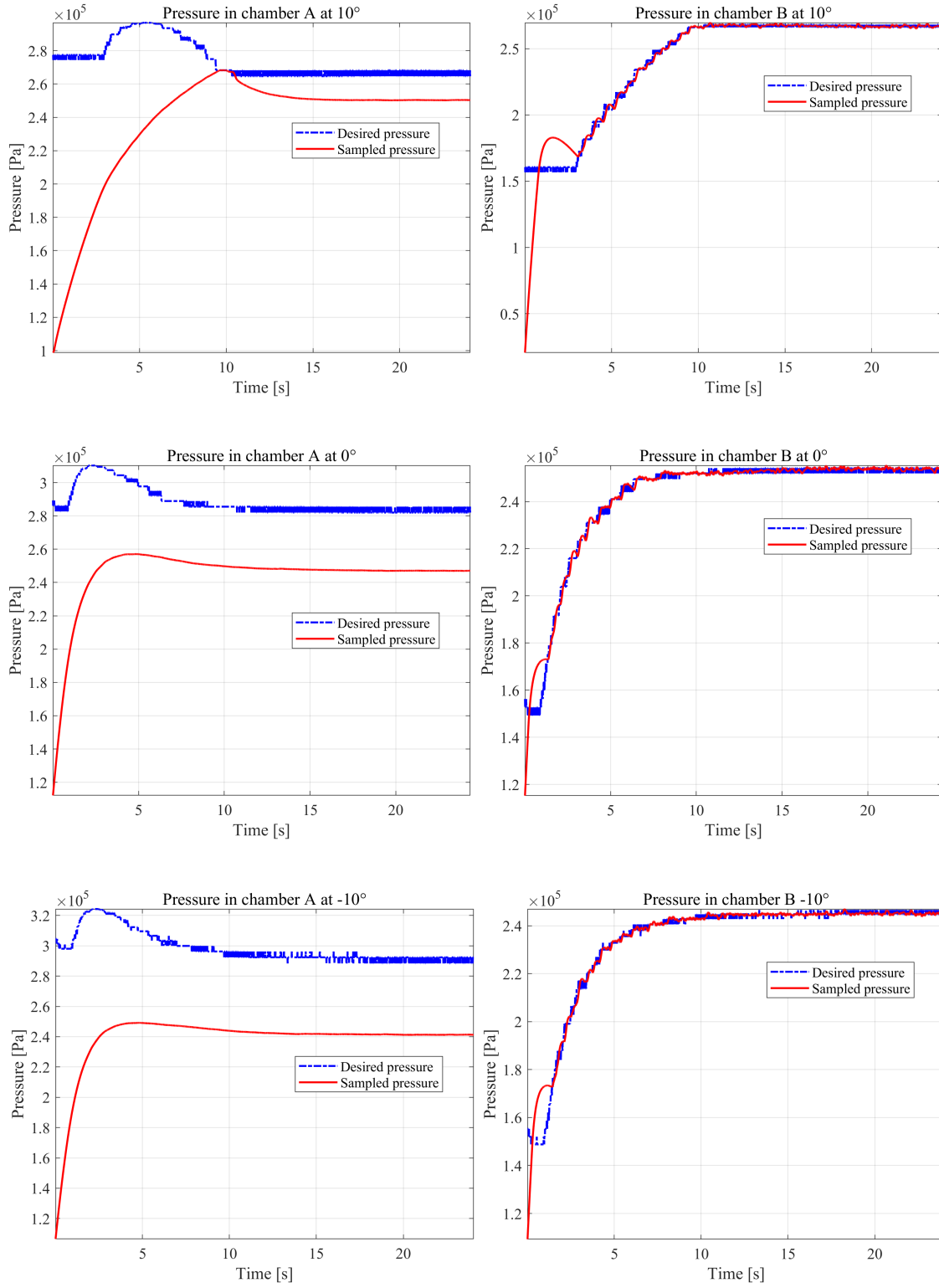


Figure D-7: Steady state errors of pressures of Tan PID controller.

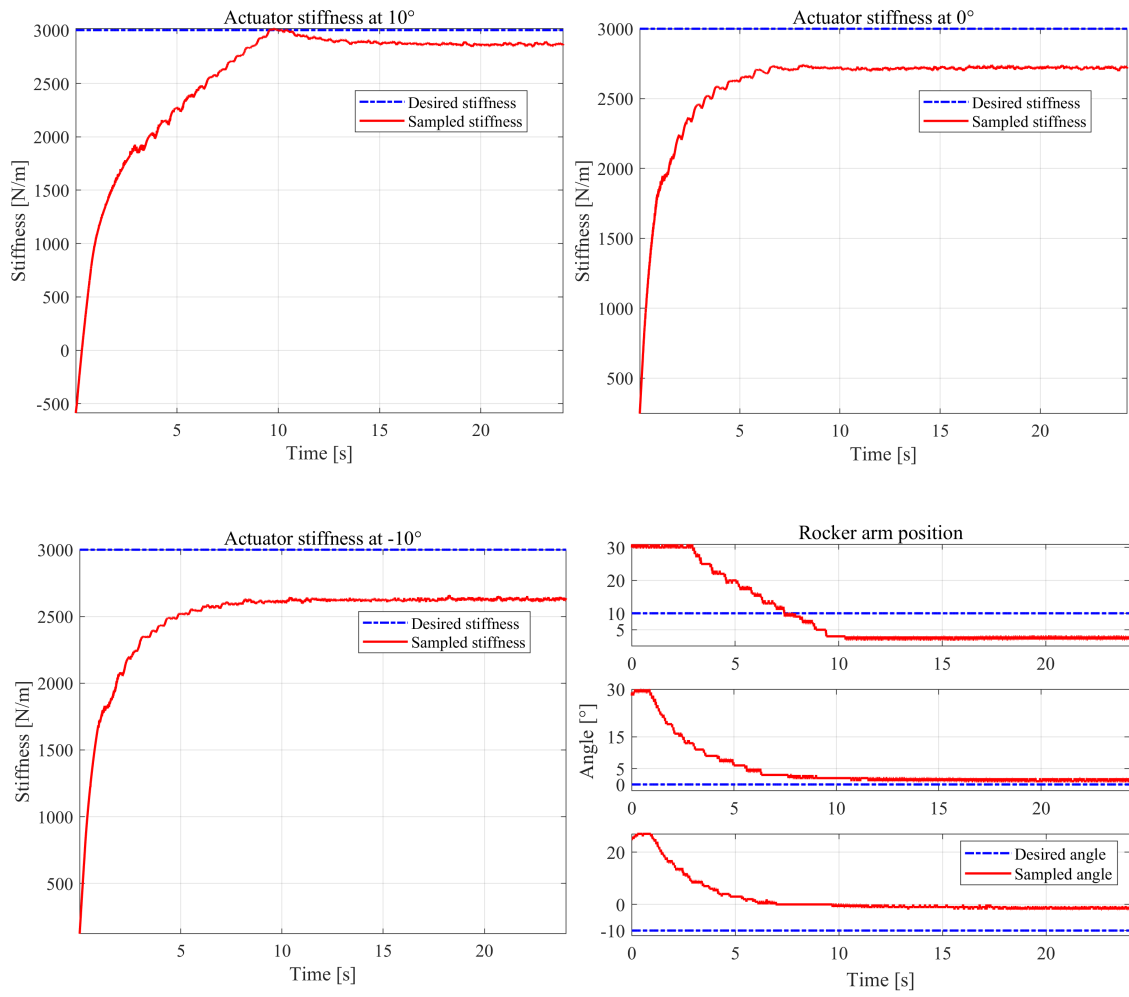


Figure D-8: Steady state errors of stiffness and positions of Tan PID controller.

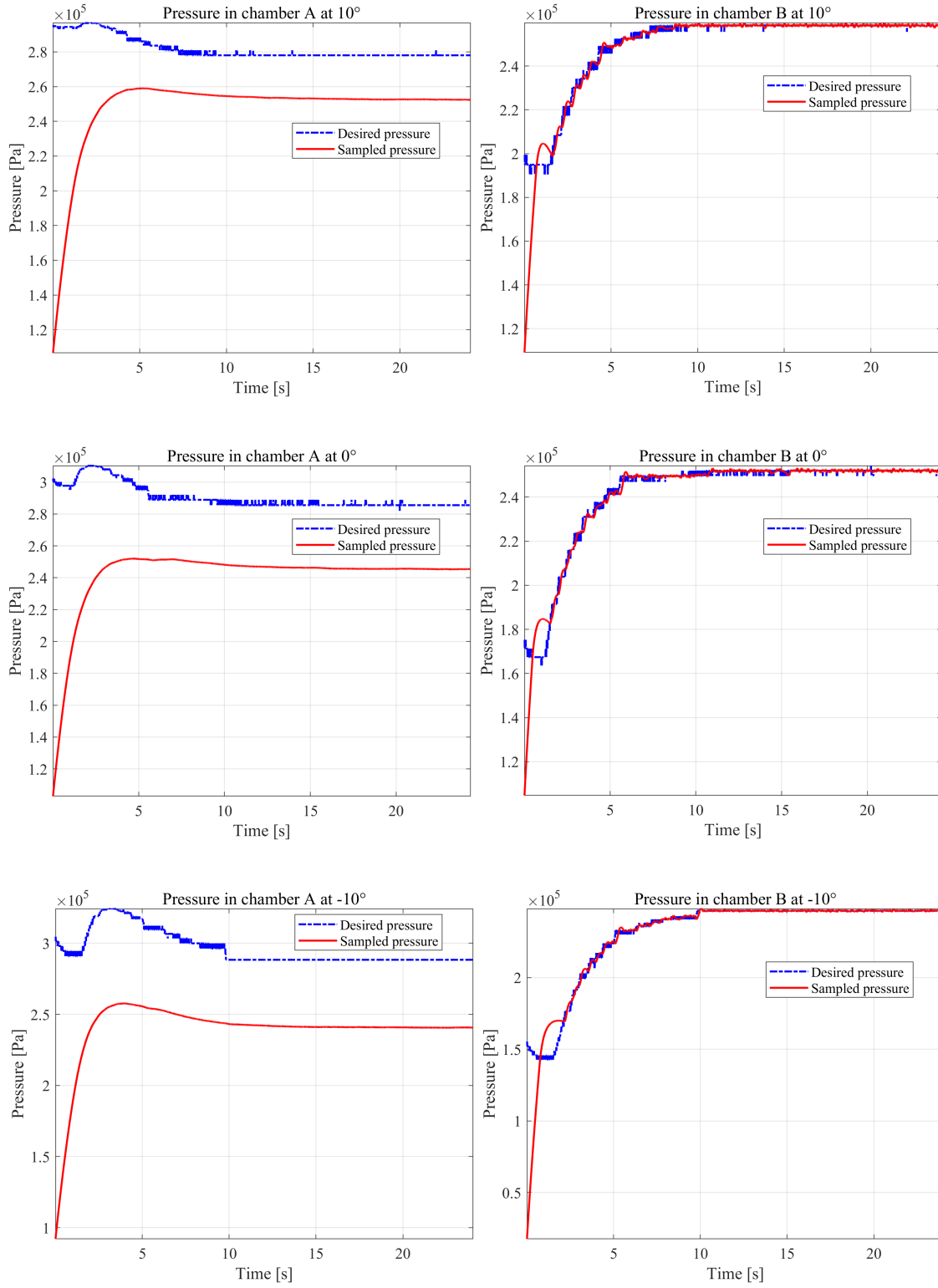


Figure D-9: Steady state errors of pressures of Smith PID controller.

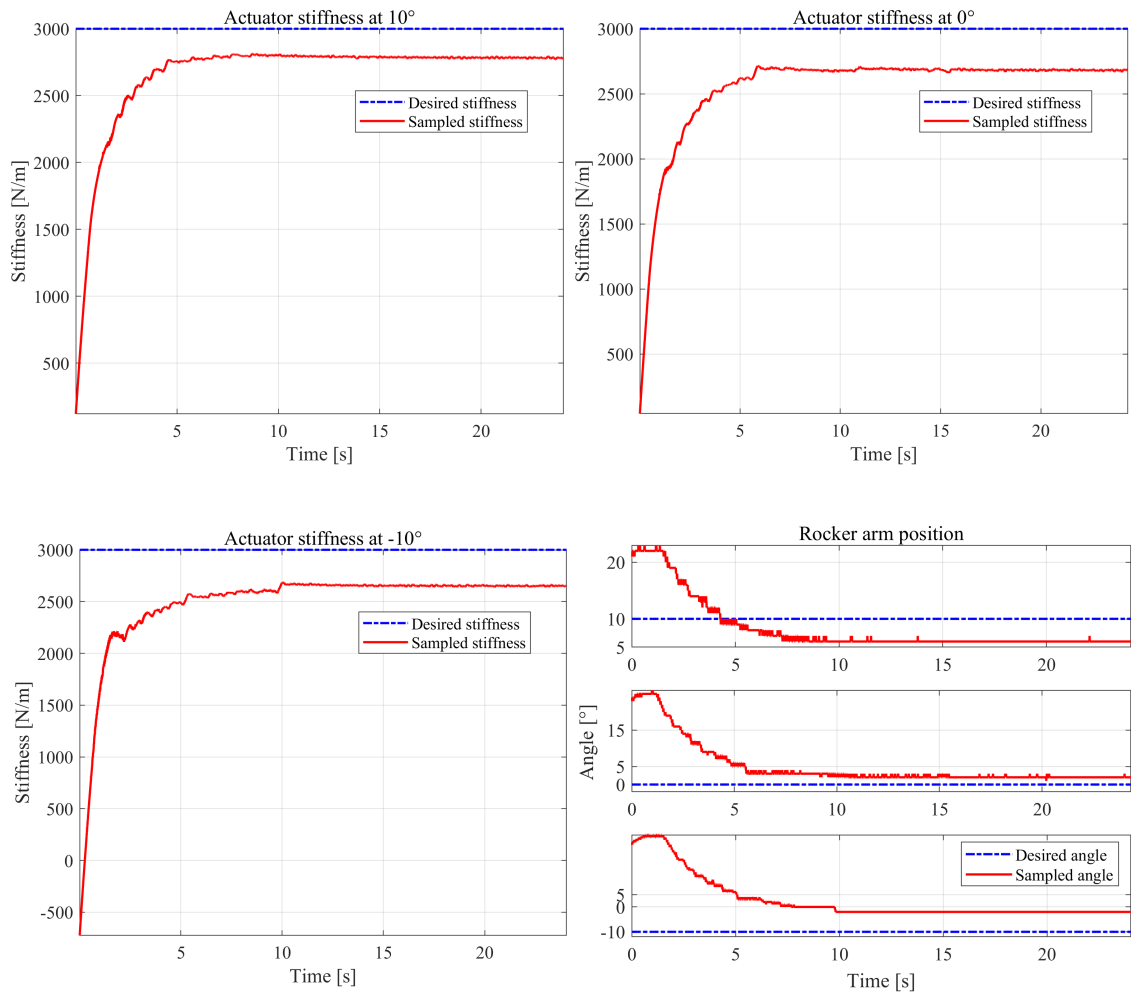


Figure D-10: Steady state errors of stiffness and positions of Smith PID controller.

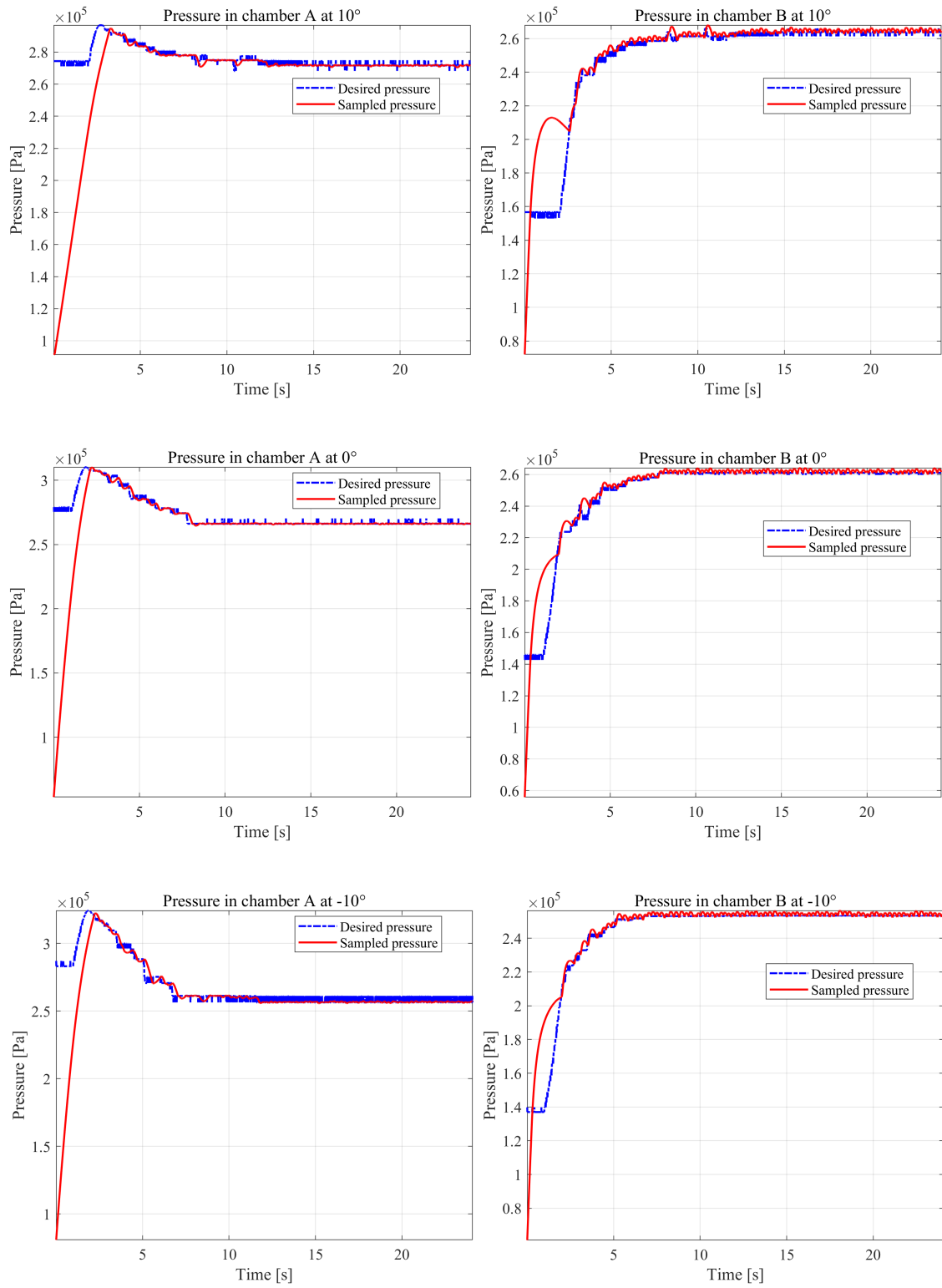


Figure D-11: Steady state errors of pressures of Yu (some overshoot) PID controller.

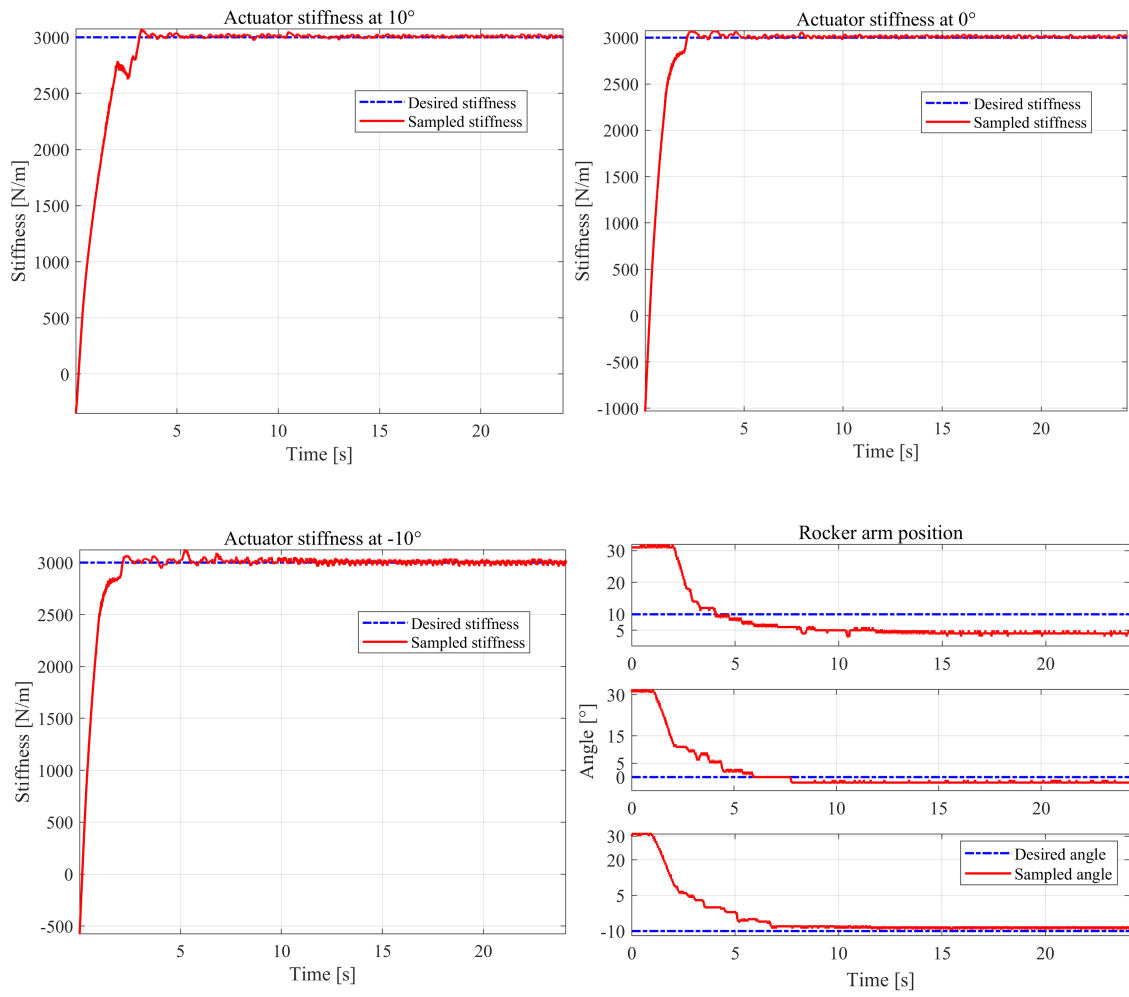


Figure D-12: Steady state errors of stiffness and positions of Yu (some overshoot) PID controller.