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University Degree in Biomedical Engineering

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Bachelor Thesis

"Design, characterisation and control of TCN artificial muscles"

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SUMMARY

Today there are several muscle weaknesses that hinder individuals from fully using their mobility. In attempts to solve these problems, several artificial muscles, so called actuators, have been invented to complement skeletal muscles. Yet, there is not a single actuator that covers all the characteristics of such muscles. In recent years, a new way of manufacturing actuators has made its way into the field. The actuators are manufactured by twisting and coiling silver coated nylon yarn and activated by sending a voltage through them.

This thesis covers research on the design, characterisation and control of Twisted and Coiled Nylon (TCN) actuators. It explains the manufacturing process, including the yarn to use, the number of twists to perform for the thread to coil and how to handle the coiled thread. It also describes how to manufacture a longer actuator. The characterisation and control are studied through testing the actuators with a control program written in MATLAB and comparing their behaviour due to several PID parameters together with a bilinear compensation and displacement reference.

The project also includes an introduction to a rigidifiable material where the actuators are applied to change the rigidity of a flexible material.

In conclusion, the result of the study of the design, characterisation and control shows that the material used, Shieldex® 235/36 dtex 2-ply HCB, does not reach new heights in the research on TCN actuators due to its force-to-strain ratio being lower than the ratio of previously obtained actuators. The actuators can still be used in the rigidifiable material, which gives them a future chance.

Keywords: artificial muscle, TCN, twists, coils, actuator, displacement, contraction, relaxation, control, PID, response, strain, rigidifiable

DEDICATION

During the work of this thesis I have received enormous support from people around me. I would first and foremost like to thank Professor Luis Moreno for introducing me to the interesting topic of artificial muscles. I would also like to express my gratitude for all the help, supervision and discussions that made this project possible.

Another important person I would like to thank is Dorin Copaci. An incredible help in form of answers to questions, explanations and practical problem solving enlightened the work of the thesis.

I am also very thankful for the never failing believe in me that my family and my friends have. Without them, the whole process would have been a lot harder. I am thankful for, that no matter how far away they are, I can feel them supporting me and cheering me on.

Throughout the practical work in the lab, there has not been one day when I have not been invited to a coffee break. Even though I have sometimes had to stay and work, I am beyond thankful for the endless invitations and the welcoming to enjoy community together.

I would also like to thank Jesus for His everlasting encouragement. Without Him, I would not have been able to complete this project.

Erika Bengtsdotter, June 2019

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1 INTRODUCTION

The human mobility is a complex interaction of cell activity. Through electric impulses in muscle tissue and neuro speedways to our brain, we can lift a phone to our ear, take a step forward or smile. Due to several illnesses or other causes, there are individuals who lack the ability to fully use their muscles.

To help and ease everyday life for those individuals, several artificial muscles have been invented. The artificial muscles work as a complement to skeletal muscles and their strength, movement and stability. Even though there are many good ideas to solve the problem, not a single artificial muscle has all the desired characteristics yet. The research on artificial muscles continues to make them more accessible, comfortable and safe for the users.

Researchers at Universidad Carlos III de Madrid have previously worked with Shape Memory Alloy (SMA) actuators and how to control them. [1], [2] Their research was successful regarding the control, but a problem of temperature remained. In the recent years, a new way of manufacturing artificial muscles has been introduced to the field. The idea is to twist silver coated nylon yarn until it coils and later activate the artificial muscle through a voltage. [3] A curiosity on the material, design and characteristics of these artificial muscles, called Twisted and Coiled Nylon (TCN) actuators, led to the work of this thesis.

This thesis will present research on the detailed design process, characterisation and control of TCN actuators and how they can be applied to create a rigidifiable material.

1.1 Objectives

The objective of this thesis is to study the design, characterisation and control of TCN artificial muscles for later continuous research to ease daily life activities and rehabilitation for individuals with decreased ability to use their muscles. This will be done through manufacturing and testing TCN actuators and through studying a method to use the TCN actuator to add rigidity to a flexible material.

The design of the TCN artificial muscle will be studied during the manufacturing of the actuator and will focus on

- Which of the available nylon materials to use
- Manufacturing steps such as the length of the material and the number of turns during twisting

The characterisation and control will partly be studied during the testing of the actuator. It will also be studied through the application of the actuator on a flexible material.

- The design of the PID controller used to control the contraction and relaxation of the actuator
- The behaviour of the activated TCN actuator
- Design of an application of the TCN actuator in a soft device

2 STATUS OF THE QUESTION

According to Bertrand Tondu, an artificial muscle is an actuator that contracts “in response to a chemical or physical stimulus”. [4] It is meant as a supplement or complement for muscles built up by living cells. An artificial muscle is in most cases compared to a skeletal muscle. The skeletal muscles in our bodies are critical for our survival and mobility.

2.1 How a skeletal muscle works

A skeletal muscle is a complex tissue and consists of a great number of different kinds of fibres. Firstly, the muscle is composed by long muscle cells, muscle fibres, that are fixed to the skeletal system through connective tissue in both ends. The muscle fibres work together to contract and relax the muscle. Inside the muscle fibres, thinner fibres, but with the same length, called myofibrils contain the active process for the contraction and relaxation. Myofibrils are triggered by impulses, so called action potentials, sent from the brain via alpha motor neurons. A terminal at the end of the neuron releases a transmitter substance called acetylcholine which is received by receptors on the muscle fibre and starts a chemical chain reaction in the fibre. [5]

Firstly, sodium channels are opened which leads to a domino-like spreading of action potentials along the membrane of the muscle fibre which results in more open sodium channels and a process of released calcium ions. [5] The released calcium ions disconnect a protecting protein from another protein inside the myofibril. The released protein, actin, together with two other proteins build-up a thin filament. Another protein, myosin, build up a thick filament. Together, the filaments are called a sarcomere.

When actin is released, it reacts with the myosin which creates a contraction of the sarcomere through a sliding process of the filaments. When many sarcomeres contract together, the myofibril contracts. When many myofibrils contract simultaneously, the muscle fibres contract and the result is a muscle contraction. [5] If the connective tissue at the ends of the muscle is fixed to two points on each side of a joint, the contraction of the muscle makes it possible to rotate around the joint.

The more actin-myosin reactions together with other necessary muscle fibre operations, such as the action potentials from the motor neuron and energy needed for the reaction in the sarcomeres, the stronger is the muscle. When we exercise our muscles, we increase the diameter of the muscle fibres and this work results in a stronger muscle. [6]

2.2 Muscle weakness

Unfortunately, there are several illnesses or work-related disorders that hinder human individuals from fully using their muscular system. These diseases often affect the force of the muscle by breaking down the muscle fibres resulting in a weaker muscle. In such cases, artificial muscles can be of important use.

2.3 Types of artificial muscles

Artificial muscles can be divided into different types depending on the contraction technique or the material they are made of. The contraction in an artificial muscle is called displacement and broadly means the change of the shape of a material. [4] Today there are several kinds of artificial muscles because yet, there is not a single artificial muscle that has all the characteristics desired. [7] A skeletal muscle has several characteristics that are imitated, or tried to imitate, in artificial actuators. Some of the most important characteristics are; density – the muscle's weight, strain – the possible stretch of the muscle, and stiffness – the ability of the muscle to obtain a rigid or flexible state. [4]

Several actuators of today will be mentioned in this thesis; the pneumatic actuator called the McKibben muscle, Shape Memory Alloy (SMA), Electroactive Polymers (EAP), Thermoactive Polymers (TAP), Hydrogels, and Super Coiled Polymer (SCP). The work of this thesis leads up to another artificial muscle called a Twisted and Coiled Nylon (TCN) actuator that is similar to the Super Coiled Polymer actuator.

2.3.1 McKibben muscle

The McKibben muscle is a pneumatic muscle that consists of a bladder made of a rubber tube covered with a braided case of threads with slight elasticity, a sheath. [8] When the bladder is exposed to a positive change of internal pressure, its diameter increases and causes the braided case to decrease the length of the muscle. The displacement of the length of the muscle is what gives the McKibben muscle its contracting characteristics.

The McKibben muscle was one of the first artificial muscles to be invented and started its process to the market in the late 1950s. [9] Even though it had great advantages in form of no friction, no critical alignment and a very light weight, its disability to produce a great force in combination with a necessary heavy gas tank hindered the muscle from really taking off on the field.

Pneumatic muscles were later improved and the force they could produce increased. The materials used for manufacturing the muscle had an economical price which resulted in an overall low cost. Although the great improvements of the McKibben muscle, unreliability regarding accuracy of the displacement and the force produced became a problem. [10]

Today there are new ideas to improve the McKibben muscle. [8] have studied the improvement of the characteristics of the McKibben muscle by adding shape-memory polymer to the manufacturing of the muscle. The shape-memory polymer makes the stiffness of the actuator more rigid during the low temperature-phase of the polymer. When the polymer is heated up, it becomes flexible again. Figure 2.1 below by [8] shows the improved actuator. With this improvement, only one actuator is needed in a joint, instead of two McKibben muscles without shape-memory polymer. The improved characteristics of the McKibben muscles come from the fact that two parameters are used to control the muscle; air pressure and temperature. A problem that still exists is the noise of the pneumatic device. [11]

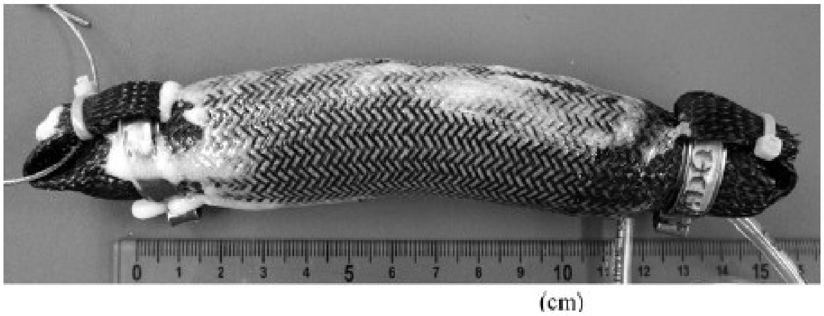


Fig. 2.1 The improved McKibben muscle with shape-memory polymer. The figure is taken from [8].

2.3.2 Shape Memory Alloy

Shape Memory Alloy (SMA) is very similar to shape-memory polymer. An alloy is a combination of metals, most often nickel-titanium (NiTi) in medical devices. [1], [12], [13], [14], [15] The main characteristic of the SMA is its ability to return to a previous shape when a positive change in thermal energy is applied. In an artificial muscle, the SMA actuator can be used by changing the form of the alloy, causing a displacement, before applying thermal energy. When heat later is given to the SMA, the alloy will remember its original shape and transform back to it. [2] In this process, the energy given to the alloy will through the reverse transform of its shape, be converted to mechanical work. [1]

To obtain a displacement of the SMA several methods can be used. In research made by [15] the displacement is obtained through wrapping the alloy around pulleys and attaching one end to an artificial tendon. When heat is applied, the result is a displacement of the tendon. Another design for an SMA actuator is the one researched by Universidad Carlos III de Madrid. [2] Here the alloy is wrapped around two pulleys, one at each end of a Bowden cable sheath, and runs through the Bowden cable, which can be seen in figure 2.2 below. One end is fixed while the other end can move flexibly. This causes displacement of the actuator when heat is applied. The displacement is, as previously stated, what produces the force. [1]

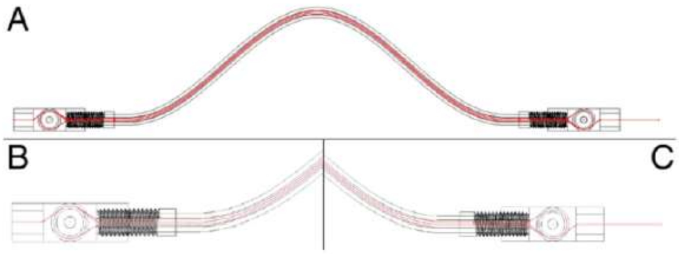


Fig. 2.2 The SMA actuator developed in previous research by Universidad Carlos III de Madrid. The figure is taken from [2].

Although SMA actuators have several advantages such as their small size, low mass, force-to-weight ratio and quietness, [1], [2], [15] they are also criticised for their low strain capability of a single wire, their short actuation periods due to the necessary cooling and the hard-to-control nonlinear behaviour. Successful attempts have been made to overcome the nonlinear behaviour, but the issue of the complexity of cooling down the SMA still exists. [2]

2.3.3 Electroactive Polymers

Electroactive Polymers (EAP) are a group of actuators that are triggered due to an electrical change. Within EAP the actuators are labelled according to what triggers their actuation. [16] The actuators are divided into ionic conductive EAP and electric conductive EAP.

For the ionic conductive actuators, the actuation is triggered by a change in ions. The ion change causes expansion and contraction. Ionic conductive actuators can be catheters that bend when an electric stimulus is given. Common materials used are ionic polymer-metal composites. [16], [17] Many ionic conductive actuators are made with hydrogels, which will be covered shortly. [16]

An example of an EAP actuator triggered by electric stimulus is a dielectric elastomer. The dielectric elastomer consists of a thin slice of a material with added electrons on the upper and bottom areas. When an external electric field is applied the charges between the electrons cause the material to decrease its thickness. This results in an expansion of the area of the material due to the conversion of electric energy to mechanic energy. [11], [16] The behaviour of the dielectric elastomer can be described by figure 2.3 below by [11] where a voltage is applied and causes the change of the shape of the material.

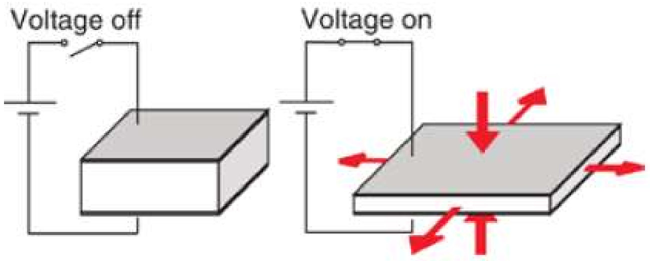


Fig. 2.3 The dielectric elastomer changes its shape when a change in electric energy is applied to the material. The figure is taken from [11].

There are several advantages with EAP actuators. They can obtain a great strength with a low voltage and are still very light. They are also quiet and often biocompatible which is a great benefit when working towards a future of implanted artificial muscles. [16] What speaks against EAP actuators being widely used depends a lot on their design but also on the specific material used. The actuators are complex and consist of several individual components without a general design which makes them more expensive to manufacture since they cannot be made in big batches. [18] Another disadvantage is that the actuators have a slow response time. Especially hydrogels have a slow response time, but also a certain electro-chemical instability.

2.3.4 Thermoactive Polymers

Another group of actuators are Thermoactive Polymers (TAP). As mentioned in their name, the contraction of the actuators is triggered from an applied change in temperature. Some polymers that have been used for this type of actuator have a similar design to Super Coiled Polymers which will be explained shortly. [19]

Just as EAP actuators, TAP actuators are noiseless and carry a light weight. Problems occur when the diameter of the manufactured actuators is too big. The actuator then conserves the heat better which results in a longer cooling-time. This limits the efficiency of the actuator since the activated time period will be longer.

2.3.5 Hydrogels

Hydrogels are sometimes used in EAP actuators since the material can be actuated with an electric stimulus. Just like dielectric elastomers, hydrogels are often used together with added electrons and their actuation depends on the electric charges between the electrons.

A common hydrogel is PVC, which bends when exposed to an electric stimulus. Another material that also bends is PPy/CB which can be seen in figure 2.4 below by [20]. PPy/CB bends when a voltage is applied.

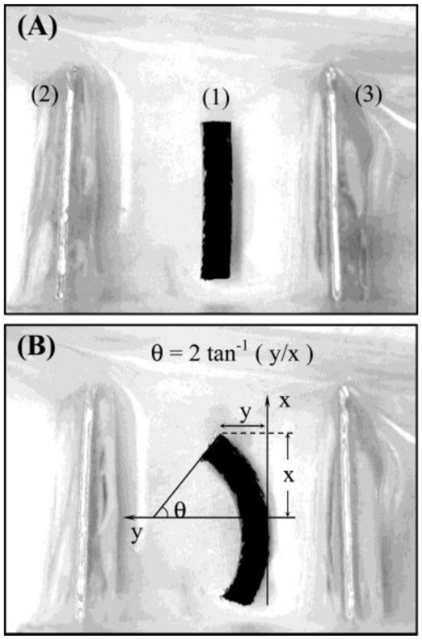


Fig. 2.4 The PPy/CB hydrogel is in resting state in (A). In (B) a voltage is applied which causes the hydrogel to bend. The figure is taken from [20].

A great advantage with hydrogels is that they bend back to their original position when the electric stimulus is interrupted. [11] A disadvantage that has already been mentioned is their slow response time which makes them less efficient in devices that require fast actuation.

2.3.6 Super Coiled Polymer

A Super Coiled Polymer (SCP) artificial muscle is an actuator that is manufactured through forcing twisting of a polymer wire until it twists itself, it coils. [7] The coiling of the wire makes the wire obtain the shape of a long helix (see figures 2.5 and 2.6 below by [7] and [19]) and this is where the name Super Coiled Polymer comes from. [7], [21] When the entire wire is coiled, it is folded in half and let to twist around itself until an equilibrium point is reached where the wire looks like a rope and is elastic. The rope-like structure can be seen in figure 2.5 below by [7].

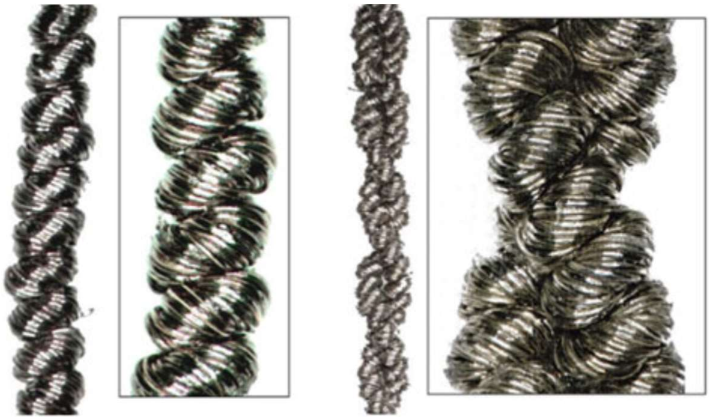


Fig. 2.5 The coiled actuator (the two left-hand pictures) is folded and let to self-twist and creates a rope-like wire (the two right-hand pictures). The figure is taken from [7].

Most SCP actuators are made of nylon fishing lines and sewing threads or polyethylene fishing lines, but today there are also twisted actuators made of shape memory alloys. [3], [22] Nylon threads can be purchased at a reasonable price which makes them very economically suitable and appealing for artificial muscles. [7] Another material used is silver coated nylon which enables actuation through Joule heating by sending a voltage through the actuator. [21]

Apart from the low cost of SCP actuators, they are also easy to manufacture. Together with these advantages come a large strain, fast relaxation, light weight and compliance. [21] Disadvantages for SCP actuators are the temperature reached when actuated and the cooling process. If the actuators are to be used in exoskeletons it is important that the user does not risk being harmed. The actuators can be cooled in several ways. If water is used, a problem occurs since nylon absorbs water. [3] Instead polyethylene can be used which does not absorb water.

Another challenge with SCP actuators is the complex computation required for control of the actuation. Successful attempts have been made to create an easier control model based on the material and physical characteristics of the thread, such as its coefficient of thermal expansion and its original length. [17]

The contraction of an SCP actuator is triggered through a positive applied change in temperature, mentioned as Joule heating earlier. The heating causes increase of the diameter of the coils in the radial direction which in turn causes contraction of the coils in the axial direction. Since the actuator is designed as a rope of double twisted coiled wires, the process results in a displacement of the length of the actuator. [3], [17] The contraction process can be seen in (B) in figure 2.6 below.

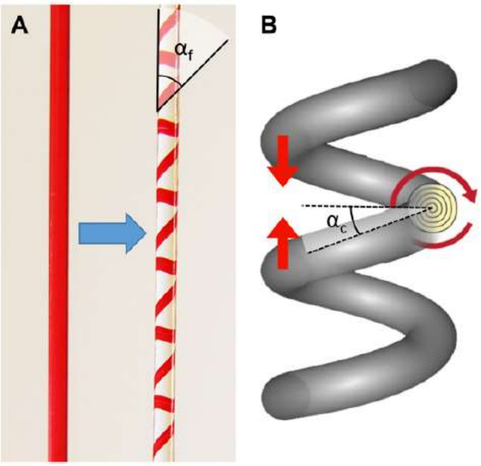


Fig. 2.6 A shows the coiling procedure of the thread. B shows the contraction behaviour of the actuator due to changes in axial and radial directions. The figure is taken from [19].

SCP actuators are mostly used in robotic applications such as hands, fingers, skin, exoskeletons and bending muscles. [17], [23] Today there is not a general name for the actuators that are designed through coiling. A few other names for SCP actuators are Twisted and Coiled Polymer (TCP) actuators, Twisted and Coiled Actuator (TCA) and Twisted and Coiled Nylon (TCN) actuators. [17], [23]

2.4 Control of the artificial muscle

Control engineering covers the engineering of how to control the output by a given input. It is used everywhere in our society, from deciding the temperature of a shower to the steering function in a car. In the medical field, control engineering is for instance used to adjust the disposal of medicine in syringe pumps. It is also used in artificial muscles to control the contraction and relaxation of the actuator.

One of the most used components in control engineering is a PID controller, due to its ability to be applied in many different applications. [24] The PID controller consists of three parts; one proportional, one integrational and one derivational part. To explain these, it is first important to be familiar with a control system and how it works.

2.4.1 Control systems

A control system consists of an input signal, a controller, a plant and an output signal. In this thesis, two types of control systems will be explained: one without feedback, an open loop control system, and one with feedback, a closed loop control system. Let us use the real case example of automatically filling a bucket with tap water. This can be done by both an open loop control system and a closed loop control system.

An open loop control system is a simple system but can sometimes result in a great error since there is no comparing of the output signal to the input signal, as can be seen in figure 2.7 below. The input signal in this case is the flow of water from the tap. The output signal is the amount of water in the bucket. The controller is the tap. For an open loop control system, the waterflow and the volume of the bucket need to be known. The next step is to calculate the time needed to fill the bucket with a desired volume of water with the known waterflow. If the waterflow is exactly what we assume, there will be no error. If the waterflow is greater than we assume, water will spill over the edge of the bucket. If the waterflow is less than we assume, the bucket will not be filled. See figure 2.8 below for visual understanding. There would also be an error if the volume of the bucket is greater or less than we assume.

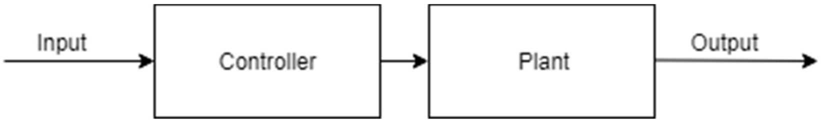


Fig. 2.7 An open loop control system does not provide a comparison of the output and input signals.

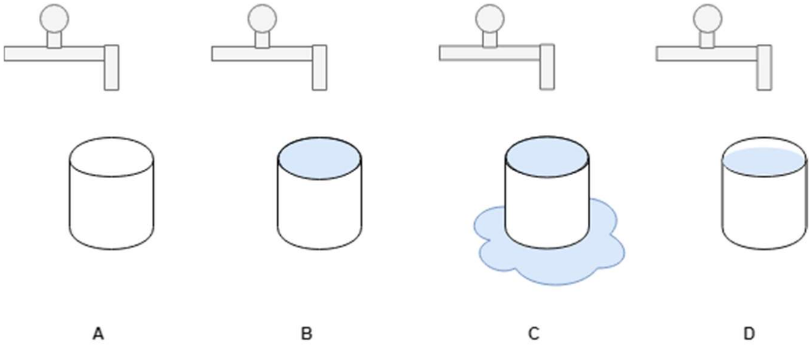


Fig. 2.8 Filling a bucket with tap water by using an open loop control system. A shows the tap and the bucket before we start filling the bucket with water. B shows an ideally filled bucket. C shows a bucket where water has spilled over the edge. D shows a bucket that is not filled.

With a closed loop control system, this error can be reduced through feedback. The idea is that the output is subtracted from the input and the difference is the error of the system. Figure 2.9 below shows the closed loop control system. This means that we do not need to know the exact waterflow or the volume of the bucket. Instead we send a signal of the volume of water in the bucket back to the tap. This will control the flow from the tap so that we will not overfill or underfill the bucket with water, hence we now have a control system with feedback. In an ideal case, there would not be an error with a closed loop control system, but since there are many components and parameters involved, the ideal case is hard to achieve due to their individual influence on the input and output signals. Therefore, the result can sometimes be similar to that in figure 2.8 above used to explain the open loop control system.

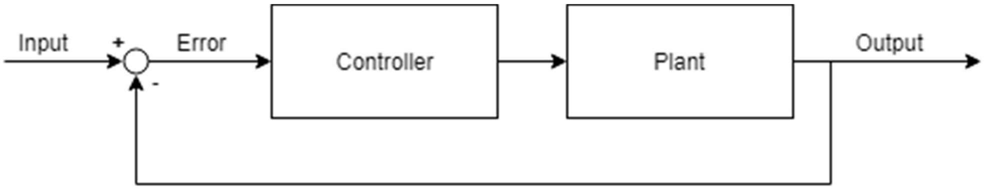


Fig. 2.9 A closed loop control system compares the input to the output through feedback.

Like previously stated, a PID controller is used in many applications where control of a signal is needed. It can for example be used as the controller in the cases above.

2.4.2 PID parameter computations

The idea of a PID controller is to obtain an output signal that follows the desired output with least possible error. To do this the parameters of the proportional, integral and derivational part can be set to wanted values. This process is called tuning.

The proportional part means that the error signal is multiplied with the value of the P parameter. The integrational part is based on the area under the error signal. In an ideal event, this area would be zero, meaning that the error is zero and also the I parameter. As with all existing systems, this will never be the case. The derivational part looks at the change of the error signal. The greater the change of the error signal is, the greater is the D parameter. The signal that goes out from the controller is the error signal that goes in multiplied with each parameter and later added together as follows, where $G_C(s)$ is the output from the controller, K_P is the proportional parameter, K_I is the integral parameter and K_D is the derivational parameter.

$$G_C(s) = E(s) * (K_P + K_I * 1 / s + K_D * s) \tag{1}$$

The formula above is for continuous control systems but can be converted to a discrete formula through various methods. The controller used in this thesis works in the discrete time domain, but the conversion of the PID parameters will not be covered in detail. The formula for the output from the controller in discrete time domain is the following.

$$G_D(z) = E(z) * [K_p + K_i / (1 - z^{-1}) + K_d (1 - z^{-1})] \tag{2}$$

To calculate the PID parameters in the continuous time domain, several methods can be implemented; Ziegler-Nichols, Root Locus and trial and error. Depending on the complexity of the whole system within where the PID controller is used, different methods are more suitable. [24]

- The Ziegler-Nichols method is well used in situations when the system is too complicated to mathematically compute the parameters. It is based on the idea to experimentally obtain a proportional gain and integral and derivative times from the transient response.
- In a more mathematically possible situation, the Root Locus method is used. With the Root Locus method, the parameters are calculated by studying the movement of the roots of the system.
- Trial and error means that several values of the parameters are tested. Depending on the resulting error, they are set differently to reduce the error. The parameters that best satisfy the desired output signal are the ones that are chosen.

In the case of this thesis, a BPID controller is used. The B stands for bilinear and complements the PID controller's ability to achieve a more linear output even if the plant would normally result in a nonlinear output. Universidad Carlos III de Madrid have previously used BPID controllers in research on the control of SMA actuators. [1] The system with a BPID controller can be seen in figure 2.10 below.

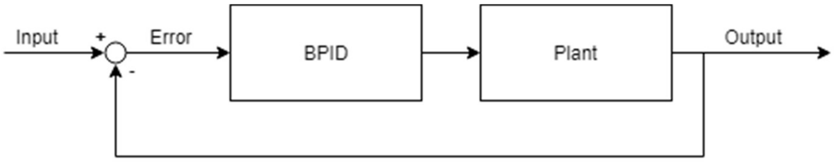


Fig. 2.10 A control system with a BPID controller.

2.5 Rigidifiable material

In the application of robotics in medical areas such as physical rehabilitation, there is also a need for multi-rigid materials. The human muscles do not only make lifting and grabbing possible but are also required to maintain rigid positions. Rigid positions are positions where static work is carried out. To be able to maintain these positions, the skeletal muscles have the characteristics of producing a force while keeping their stretch and shape.

Research projects have tested the existing actuators to obtain a rigid material for use in medical robotics. There are materials that can maintain a rigid state, such as SMP and electroactive gels, but disadvantages in form of long response time, energy inefficiency and lack of great change in rigidity have hindered a successful rigidifiable material. [25], [26] Ideas are that SMP actuators would be a good option for rigidity in artificial muscles, but the energy consumption and temperature reached together with the fact that the material is not conductive are obstacles that need to be solved before breakthrough. [25], [26]

Another attempt to obtain an actuator that changes its rigidity is by using a conductive elastomer cPBE embedded in PDMS. The elastomer is propylene-based and the PDMS is electrically insulating. The advantage of this is that the rigidity obtained is similar to the rigidity of skeletal muscles. [27] The elastomer used is activated electrically and reaches a temperature of 75°C which would be a problem in a device placed close to the user's skin.

Since the need for a material that can change its rigidity and possibly support a great weight still exists, an application of the manufactured actuator on a material to obtain these characteristics would be of great interest.

3 MATERIAL AND METHOD

3.1 Material

The material used for the manufacturing of the TCN actuators was purchased from Shieldex Trading Inc. which is a leading independent agent in providing conductive yarns, fibres and fabrics across the world. The products offered by Shieldex Trading Inc. are suitable for medical environments where a strict hygiene is required. Their products are coated with silver which has antibacterial characteristics and is thermally and electrically conductive. [28] A conductive material is a material that can lead a certain property, in this case temperature and electricity.

This thesis covers TCN actuators made of Shieldex® 117/17 dtex 2-ply HCB and Shieldex® 235/36 dtex 2-ply HCB (see figure 3.1 below). The yarn can be purchased through Shieldex Trading Inc. or their distributors and is bought in weight. For the two yarns used in this project, the weight is 234dtex respectively 470dtex. [29] dtex means the weight in grams per 10 km. The numbers 17 and 36 stand for the number of filaments in each yarn, which explained in more detail is the number of fibres used to make the yarn.

The cost of the yarns is very low. Shieldex® 117/17 dtex 2-ply HCB costs 320.10 € per kilogram yarn. Shieldex® 235/36 dtex 2-ply HCB costs 357.50 € per kilogram yarn. For both yarns, a 10 % MOQ-surcharge for purchases below 10 kg is included. Price per metre yarn is then 0.007 € respectively 0.017 €.

Fig. 3.1 The two different kinds of silver coated nylon yarn from Shieldex Trading Inc.. The left reel is Shieldex® 117/17 dtex 2-ply HCB and the right reel is Shieldex® 235/36 dtex 2-ply HCB.

For the manufacturing and testing of the actuator, a micro controller unit (MCU) from STMicroelectronics was used. The model is called STM32F407G Discovery and can be purchased for around 18 € from several distributors. Figure 3.2 below shows the MCU.

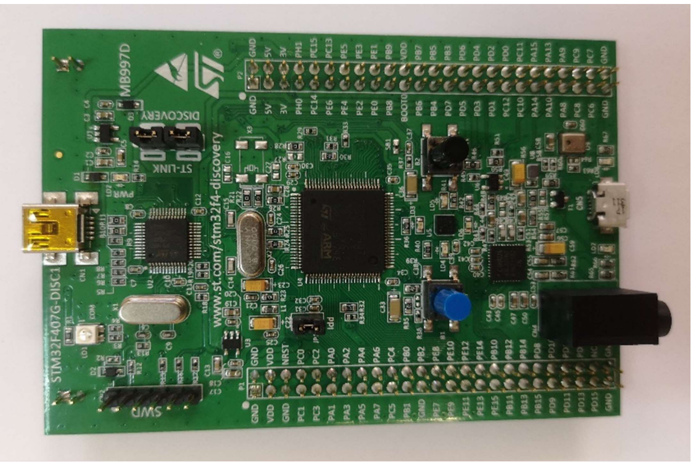


Fig. 3.2 The MCU used to manufacture and control the actuators.

3.2 Setup and components

When manufacturing and testing the TCN actuators, lab setups were built and used. The material was found in the RoboticsLab at Universidad Carlos III de Madrid.

3.2.1 Manufacturing setup

To manufacture the TCN actuator a temporary setup in the lab was built. The following components were used:

- Wooden plank on a tall cupboard
- Servo motor by Tower Pro, MG92B
- Paperclip
- Bulldog paperclip
- Dead weight
- Light rod
- Wires
- Micro Controller Unit (MCU), STM32F407G Discovery
- PC with MATLAB R2014b
- MATLAB program
- Silver coated nylon yarn from Shieldex Trading Inc.
- Analogue ruler with uncertainty 0.5 mm

The setup consists of a wooden plank as a base. On the wooden plank a servo motor is fastened. From the servo motor four wires are drawn to a micro control unit, MCU. Two wires are for power and ground. The power used is 5 V. One wire is for the control of the servo motor. One wire is for a potentiometer. All wires are connected to pins on the back of the MCU.

The MCU is also connected to a PC through USB which can be seen in figure 3.3 below. A MATLAB program written in the RoboticsLab at Universidad Carlos III de Madrid is built on the MCU. To further develop the program to count the number of turns carried out by the servo motor, a short loop is added. The loop variable “y” increases with one every time the servo motor has made one 360° turn. (The loop will be explained later in the results.)

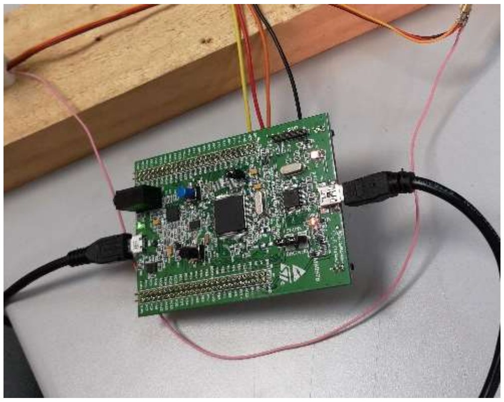


Fig. 3.3 The MCU is connected to the PC through the two black cables. The colourful wires connect the MCU to the servo motor through pins on the back of the card.

The servo motor has four wings. Between two wings across from each other, a loop is made through fastening the two ends of a stretched and bent paperclip in each of the wings. One side is easy to dislocate to be able to skewer a loop of the nylon thread.

To manufacture the TCN actuator, the temporary setup is placed on top of a tall cupboard, with the servo motor facing downwards, towards the floor, as can be seen in figure 3.4 below.

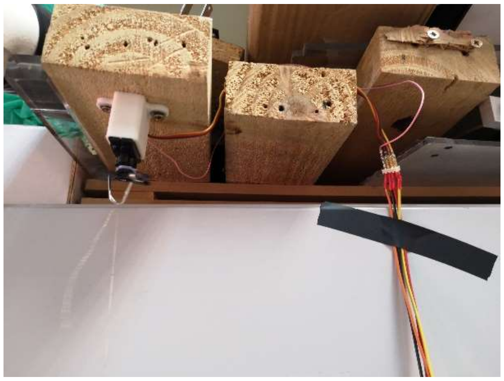


Fig. 3.4 The wooden plank with the servo motor is placed on top of a cupboard, facing downwards towards the floor. The wires to the right in the figure connect the servo motor to the MCU.

A measured and cut piece of nylon thread with two loops, one on each end of the thread, is attached to the servo motor. One loop is skewered onto the paperclip attached to the wings of the servo motor and the other loop is fastened to the hook on a dead weight. A light metal rod is taped onto the weight to hinder the weight from turning when the servo motor turns. See figure 3.5 below.

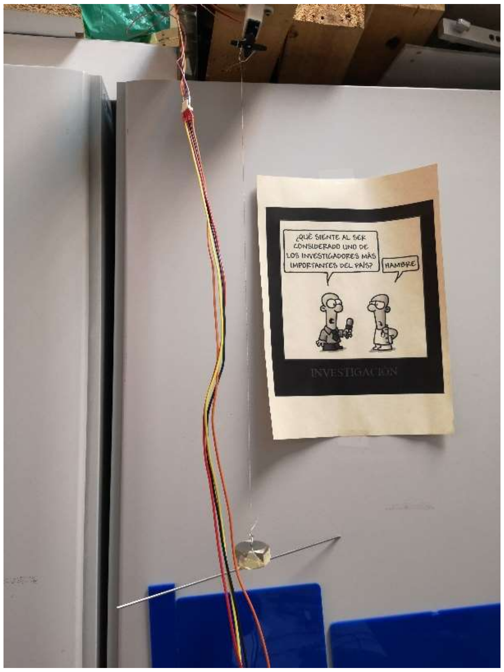


Fig. 3.5 The two loops of the thread are skewered onto the bent paperclip on the servo motor (top of the figure) and the hook on the weight.

To manufacture a longer actuator, the nylon thread is not cut. A loop is made at the end of the thread and skewered onto the bent paperclip on the wings of the servo motor. The thread is then measured to a certain length where a bulldog paperclip with a weight is fastened like a peg on the thread. See figure 3.6 below.

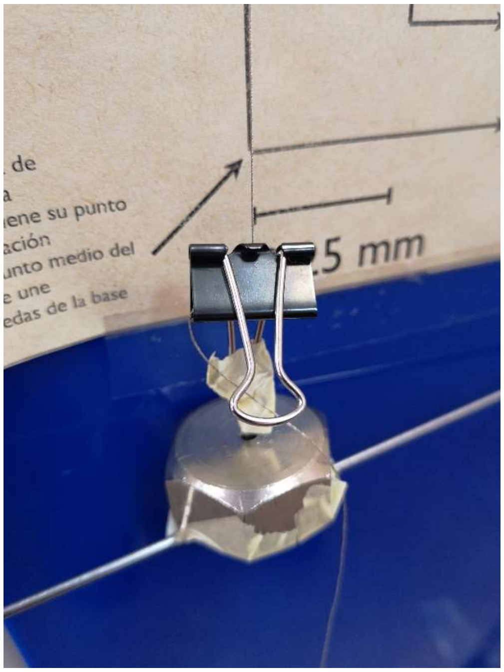


Fig. 3.6 A bulldog paperclip with a weight is fastened to the wire at a certain length.

The thread is then wired around the bulldog paperclip to avoid untwisting in case the thread escapes the grip. The reel with nylon yarn is placed besides the dead weight with a length of thread lying loose on the floor, see figure 3.7 below, to avoid any influence on the twisted thread. Such influence can be pulling the thread down or making the thread escape form the paperclip and untwist.

Fig. 3.7 The reel is placed on the floor besides the bulldog paperclip. A length of the yarn is lying loose on the floor.

3.2.2 Testing setup

To test the characteristics and control of the actuator an already built testing bench was used. The test bench was built in the RoboticsLab at Universidad Carlos III de Madrid. Small adjustments had to be made to make the setup suitable for the specific testing of the TCN actuator.

These are the components of the testing setup:

- Already built test bench
- Displacement sensor and activator
- Wires
- Micro Controller Unit (MCU), STM32F407G Discovery
- Driver
- Power supply
- PC with MATLAB R2014b
- MATLAB program
- Twisted and Coiled Nylon (TCN) actuator
- Dead weight

The testing setup consists of a hollow plastic box-shaped stand with a middle track where the actuator is to be fastened. One end of the actuator is fastened to a plastic piece that runs along the track. The other end on the actuator is connected, with a thread, to a strip inside a small hollow plastic box fastened on one end of the middle track. The thread runs with least possible friction inside the box.

Inside the box there is also a displacement sensor, a metallic strip and a wheel to help the thread move without friction. The metallic strip that the actuator is attached to works as the activator for the displacement sensor. On the other side of the strip, a weight is attached by a thread of nylon or titanium. To influence the displacement of the actuator with least possible friction, and therefore also the activating strip, the thread runs over a wheel.

The displacement sensor inside the small plastic box is controlled by an MCU and has a sampling time of 0.002 s and a data transmission time of 0.01 s. The MCU is loaded with a compiled program from a MATLAB program. For this, a MATLAB toolbox by Aimagin Co., Ltd is used with an extension by a former PhD student, Antonio Flores Caballero, at Universidad Carlos III de Madrid. [30] The MCU is connected to a PC through a mini USB port and also controls a switch for a power supply, called a driver. The power goes through the driver to both ends of the actuator, one end for the power and one end for the ground. The setup can be seen in figures 3.8 and 3.9 below.

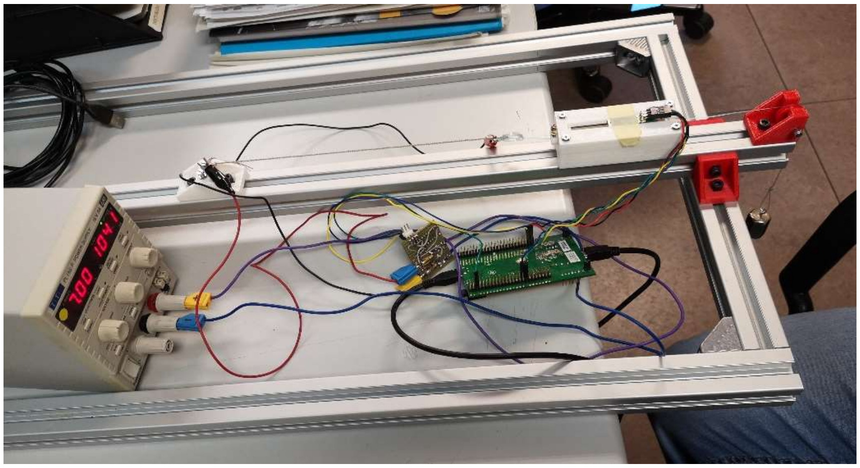


Fig. 3.8 The full testing setup. The power supply can be seen to the left, connected to the driver and further to the ends of the actuator. The MCU is connected to the driver to control the power to the actuator and to the PC through the black cables. The actuator is streched between the fastened plastic piece on the middle track and the activating strip in the small hollow box on the other end of the track. The dead weight at the right hand side hangs in a thread connected to the other side of the activating strip. On top of the hollow box, wires connect the displacement sensor to the MCU.

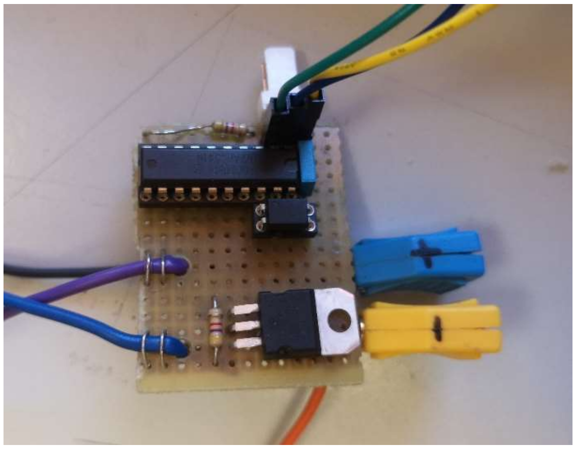


Fig. 3.9 The power is controlled by the MCU and a driver. The three wires in the top of the figure are connected to the MCU. The purple and blue wires are connected to the power supply. The red and black wires are connected to the ends of the actuator.

The contraction and relaxation of the actuator is controlled by the PID controller and a displacement reference signal in the MATLAB program.

3.2.3 Rigidifiable testing setup

To test the actuation of the rigidifiable material, the previous test bench was used together with a few additional components.

These are the components of the testing setup:

- Already built test bench
- Displacement sensor and activator
- Wires
- Micro Controller Unit (MCU), STM32F407G Discovery
- Driver
- Power supply
- PC with MATLAB R2014b
- MATLAB program
- Twisted and Coiled Nylon (TCN) actuator
- Dead weight
- Metallic rod
- 3D printed guiding device

In the setup for testing the rigidity obtained with the actuator, one end of the actuator is fastened to the plastic piece that runs along the middle track of the test bench. The other end is attached to a metallic rod through a thread. The metallic rod runs through the 3D printed guiding device that is placed on an eraser laid on the middle track. The other end of the metallic rod is attached to the dead weight through the activating strip in the small hollow plastic box fastened on one end of the middle track. The setup is showed in figures 3.10 and 3.11 below.

The MCU is connected to the PC as previously described in the testing setup. The power supply is also connected to each end of the actuator as previously described.

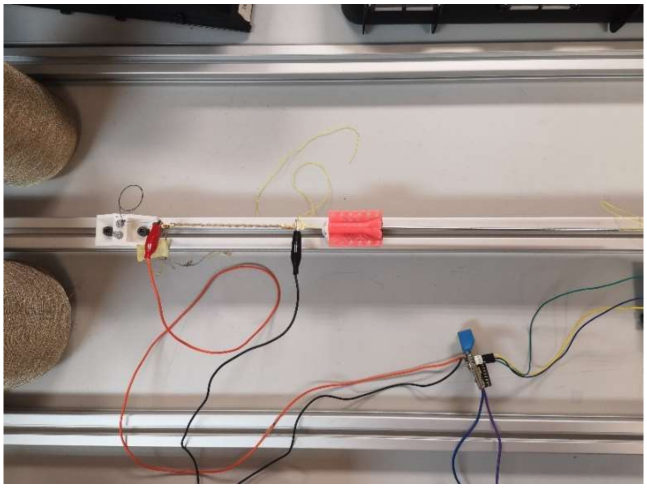


Fig. 3.10 The actuator is attached to the fastened plastic piece on the middle track and tied to the metallic rod. The rod runs through the guiding device that is placed on an eraser on the test bench. The power is connected to the actuator through the red and black wires.

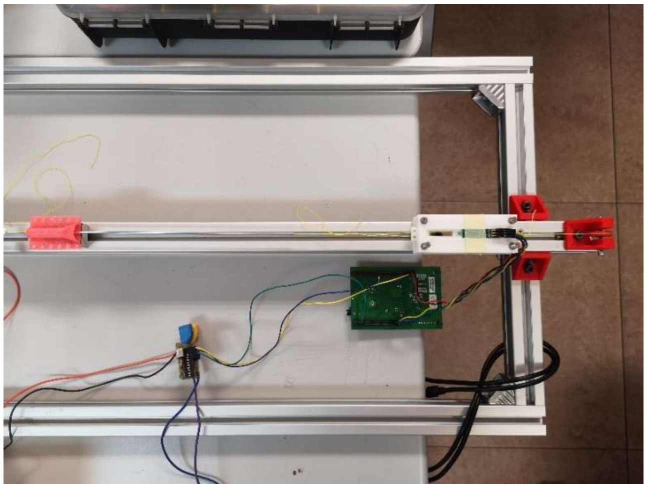


Fig. 3.11 The rod is connected to the activating strip inside the plastic box at the end of the middle track. A weight is connected to the other side of the strip and keeps the actuator streched. The weight cannot be seen in the figure, but hangs down from the red wheel on the righthand side as in figure 3.8.

3.3 Method

3.3.1 Manufacturing

PART 1: To manufacture the actuator, start with measuring and cutting a piece of silver coated nylon yarn. Then make two loops, one on each end of the thread. After that, skewer each loop onto the bent paperclip at the wings of the servomotor and the hook on the weight. Then start twisting the thread anticlockwise by running the MATLAB program and giving reference “4” to the servo motor.

Twist the thread until the whole thread is coiled. Pull the bottom end of the coiled thread outward and place two fingers halfway down the thread. While keeping the thread tense, fold it in half and let it twist itself between two fingers. When the twisting has found its equilibrium point, release the actuator from the hook on the servo motor. Crimp the ends with opened terminal ends. The terminal ends can be seen in figure 3.12 below.

Fig. 3.12 Opened terminal ends used to crimp the ends of the manufactured actuators.

PART 2: An actuator can also be manufactured with double thread. Skewer both loops onto the hook on the servo motor and hang the weight in the loop made of the thread. Then follow the twisting (coiling), folding, self-twist and crimping described above.

PART 3: To manufacture a longer actuator, take the yarn but do not cut it. Make a loop at the end of the thread and attach it to the hook on the servo motor. To hang the weight on the thread, use a bulldog paperclip. Twist the thread until the weight is above the length you would like to add. Stop the twisting and release the bulldog paperclip. While keeping the twisted thread stretched, add another part of the yarn. Again, attach the bulldog paperclip and the weight at the bottom of the chosen length of thread.

Repeat this method until the desired length of yarn has been reached. Then let the thread twist until coiled and repeat the procedure of folding, self-twisting and crimping the ends.

PART 4: To manufacture an actuator that is double the PLY of the already manufactured actuator, attach the ends of the actuator to the servo motor and the weight. Repeat the twisting (coiling) procedure explained in part 1. Then fold the actuator in half and let it self-twist. To finish, crimp the ends of the actuator.

Part 4 can also be performed with two separate actuators. Then, fasten the hooks on the crimps to the hooks on the servo motor and the weight so that the actuators hang down straight. Repeat the twisting (coiling) from part 1 and fold, self-twist and crimp the ends of the actuator likewise.

In each of the four parts, measure the resulting actuator as a final step.

Figure 3.13 below shows a flowchart of the manufacturing method.

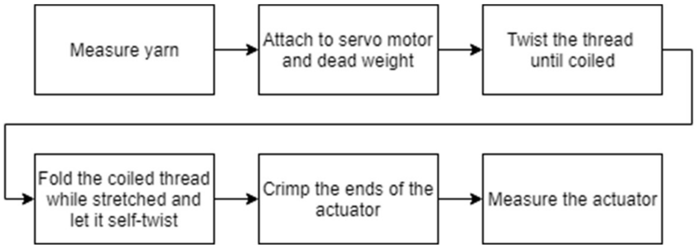


Fig. 3.13 The flowchart shows the different steps to follow when manufacturing an actuator.

3.3.2 Testing

Start with fastening one end of the actuator to the strip inside the hollow box. Then fasten the other end of the actuator to the freely running plastic piece. Fasten the plastic piece to the track so that the strip is just covered by the displacement sensor. Attach the power to one end of the actuator and the ground to the other end.

Disable the control in MATLAB and reset the displacement sensor through disconnecting and reconnecting the USB-cable to the MCU.

Choose the parameters of P, I and D in the Simulink window from the program in MATLAB, see figure 3.14. The bilinear parameter Kb is always set to 1 for the control tests in this thesis.

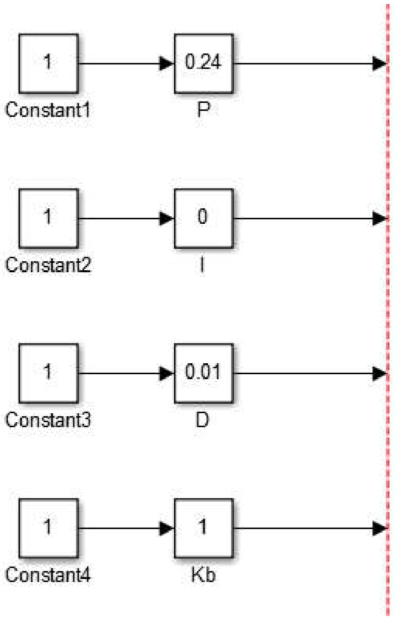


Fig. 3.14 Choose the PID parameters by changing each of the values in the three boxes labelled P, I and D. The bilinear parameter Kb is always set to 1 in the work of this thesis.

Choose also if the displacement reference should be given manually during the running of the test or be set beforehand. If the displacement reference is continuously given throughout the test, set the switch, to the right in figure 3.15 below, to the position reference. The value of the position reference can be changed when the program is running.

To set the displacement reference beforehand, set the pulse in the pulse generator in the figure below to the desired number of sensor units. Then set the switch as in the figure.

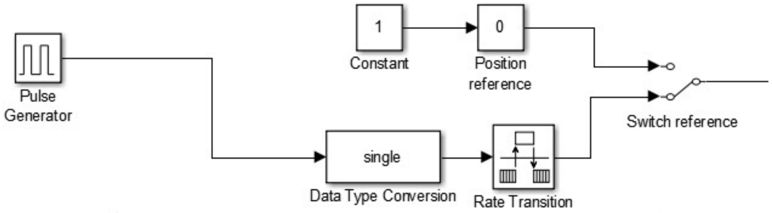


Fig. 3.15 The displacement reference is set as a value in the pulse generator (to the left) or the position reference. The switch decides whether the displacement will be given manually during the running of the test or set beforehand. In the figure, the switch is set to displacement reference chosen before the test is run.

Set the power supply to 7 V and 1 A. Enable the power supply by clicking the output button highlighted with an arrow in figure 3.16 below. When the power is enabled, the small indicating light by the point of the arrow will be red.

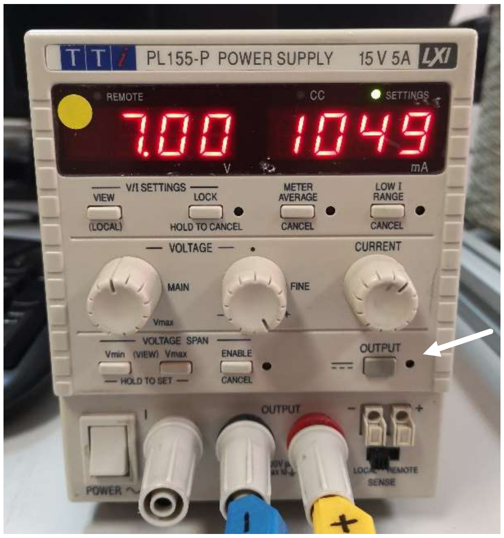


Fig. 3.16 The power supply is set to 7 V and 1 A. The power will be enabled when the buttom by the white arrow is pressed and the indicating light is red.

Enable the control in the Simulink window from the program in MATLAB through setting the switch in figure 3.17 below to 1. Run the program and study the movement of the actuator. Before making any further changes in the program for future tests, disable the control to avoid damaging the MCU.

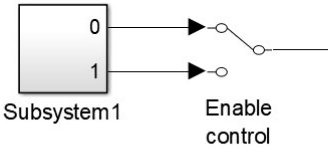


Fig. 3.17 The control is enabled by setting the switch to 1. The control is disabled when set to 0.

All variables obtained during a test will be available in the workspace in MATLAB. After a test, save the workspace data to later be able to compare responses from different actuators and tests. The displacement of the actuator will be the position block in figure 3.18 below. The reference is the displacement reference given to the actuator. During a test, the current displacements will be shown in a separate window called “Position”.

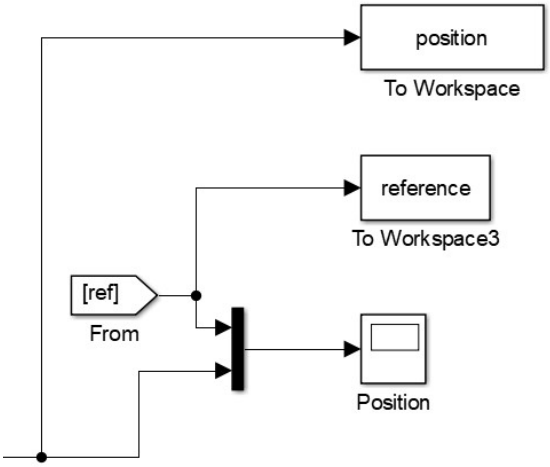


Fig. 3.18 The data recorded during the test will be showed as different variables in the workspace in MATLAB. It can later be compared to other test results if saved. The position in the bottom right corner will show the current displacement reference and displacement of the actuator during the test in a separate window.

Note that it is important that the activating strip does not touch the back end of the box. In such case, the actuator will not be fully stretched initially. Also, be familiar with where to quickest cut the power in case the experiment goes wrong. With the power supply used above, the power is cut quickest by clicking the output button or disconnecting the power and ground cables connected to the actuator.

Figure 3.19 below shows a schematic drawing of the control tests. Since the controller works in the discrete time domain, it is first converted to continuous time domain by a digital-to-analogue (D/A) converter and then later converted back by an analogue-to-digital (A/D) converter. PWM is the controlling signal that controls the power supply to the actuators through the driver. PWM (Pulse Width Modulation) modulates the width of the power pulses given to the actuator.

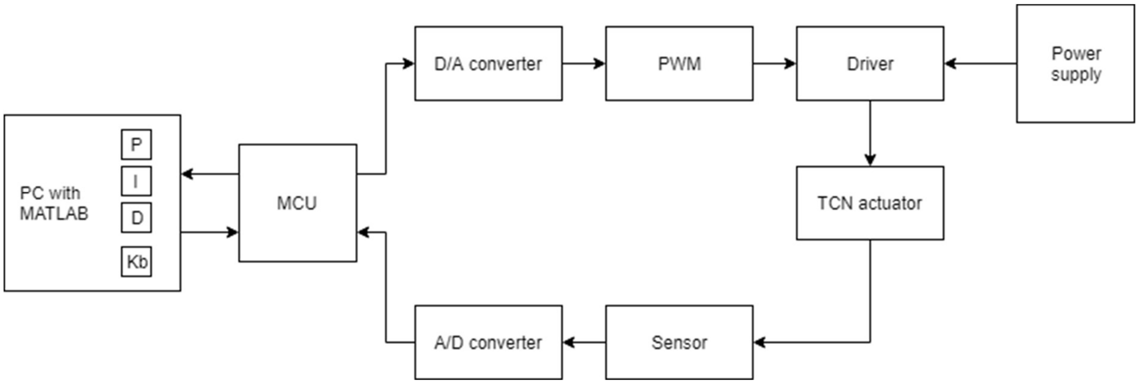


Fig. 3.19 The schematic drawing shows the control of the actuator.

3.3.3 Testing of rigidifiable material

Start with tying the metallic rod to one end of the actuator. Then put the rod through the guiding device and connect the other end to the activating strip. Continue with attaching the other end of the actuator to the freely running plastic piece and a dead weight to the other end of the strip. Fasten the plastic piece so that the actuator is stretched, and the back of the activating strip does not touch the wall inside the hollow box.

Place the guiding device so that the end of the metallic rod just rests on the bottom of the device as in figure 3.20 below. Connect the power to the ends of the actuator.

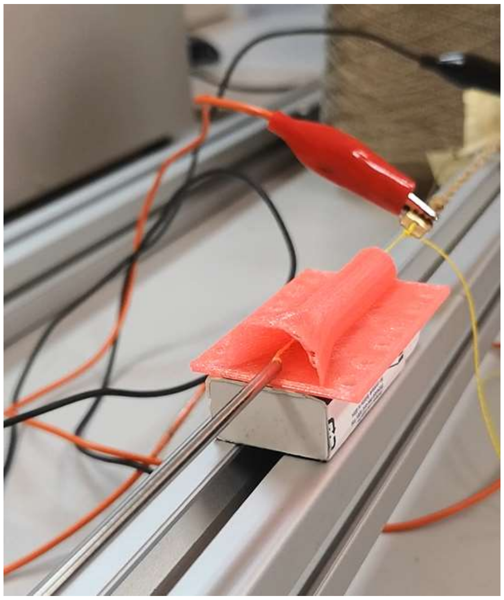


Fig. 3.20 The guiding device is placed so that the metallic rod just rests on the bottom of the device. The actuator can be seen in the background with the power (red) and ground (black) connected to its ends.

Follow the instructions for testing given above and make sure that the guiding device does not move. Study the movement of the actuator and the metallic rod.

4 RESULTS

The results of this thesis will be presented in three parts. Firstly, I will present the results of the manufacturing of the actuators. I will then continue with explaining the results of the testing with different PID parameters. Lastly, I will present the thoughts and practical results of the attempt to make a rigidifiable material by using a manufactured actuator and previously obtained PID parameters to control its behaviour.

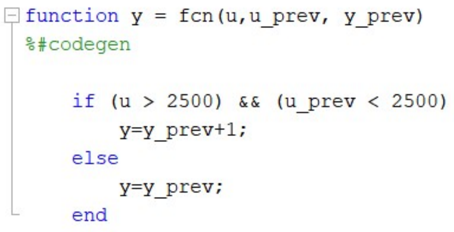
The results are also explained in the newly published report *Twisted coiled nylon-based actuators for robotic applications* by E. Bengtsdotter, D. Copaci, D. Serrano del Cerro, D. Blanco and L. Moreno. [31]

4.1 Manufacturing results

Several actuators were manufactured by twisting different lengths and numbers of threads from the silver coated nylon yarn. The thought was to use the two types of silver coated nylon yarn mentioned in material, but during the manufacturing process a decision to only use Shieldex® 235/36 dtex 2-ply HCB was made. Shieldex® 117/17 dtex 2-ply HCB has previously been used in research by [7], and therefore results of a yarn with more fibres would be interesting. The chosen yarn resulted in actuators that were slightly heavier, but still competing with other artificial muscles in the field through their low weight.

During the manufacturing process, several obstacles considering the setup and actual manufacturing arose and had to be solved. In the beginning, it was noted that it is important to use common sense and keep fastened wires away from turning tools to avoid breaking the equipment.

Firstly, a video by [32] of how to manufacture TCN actuators was studied. The video showed a setup and an idea of how to manufacture and prepare the actuators for actuation. The first thing to do was building the manufacturing setup, as has been explained previously in the manufacturing setup part. After that a short code to count the number of turns carried out by the servo motor was written and added to the already existing MATLAB program. The code can be seen in figure 4.1 below with a following explanation.



```
function y = fcn(u,u_prev, y_prev)
%#codegen

    if (u > 2500) && (u_prev < 2500)
        y=y_prev+1;
    else
        y=y_prev;
    end
```

Fig. 4.1 The code used to count the number of turns performed by the servo motor.

To count the number of turns, the signal from the servo motor was compared to a reference of 2500. If the signal from the servo motor was over 2500 and the previous signal was below 2500, the motor had made a full 360° turn and the output of the function increased with one. If not, the output remained the same.

The code was written in a function block that can be seen in figure 4.2 below. To be able to work with the signal from the servo motor, it had to be converted to datatype double. The signal (u) was then given to the function block and stored in a memory. At the same time, the current signal value in the memory (u_prev) was given to the function block and compared to the new input value. The output (y) was then displayed on the screen in the window “Counting” and stored in a memory to be increased if the motor made another turn (y_prev). Since the value for the previous input signal (u_prev) always was 0 when the counting started, it resulted in giving the output 1 before a full turn had been performed. To solve this problem, a constant value of 1 was subtracted from the output.

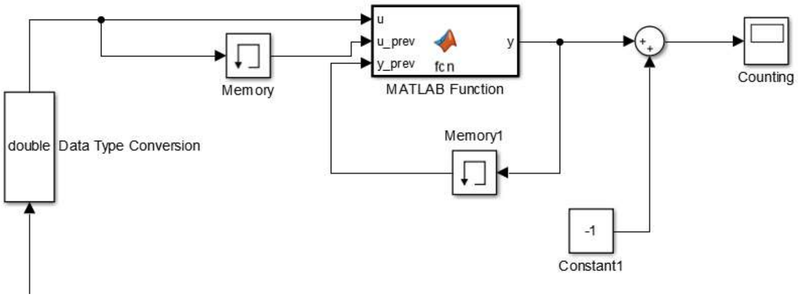


Fig. 4.2 The signal from the servo motor was first converted to datatype double and then stored in a memory and sent to the function block. The function block increased the output with one every time the servo motor made a full 360° turn. To get the correct number of counts, a constant of 1 was substracted from the output.

To study how the actuation depended on number of turns and length of yarn used, 11 actuators were manufactured out of 17 attempts and will be presented in chronological manufacturing order.

4.1.1 Single thread 4PLY actuators – actuators 2, 3

The first actuators manufactured were of type 4PLY. That means that single threads were twisted until coiled, then folded in half and let to self-twist under stretched circumstances.

During the first attempt, the thread was longer than the cupboard was tall which resulted in the thread lying loose on the floor and it detached from the hook on the servo motor. The thread used was 2.49 m long.

In the second attempt, the thread was shortened to 1.80 m and a weight of 200 g was used. The thread broke after a while of twisting due to a too heavy load for the fibres of the thread. In a try to save the actuator, the longer remaining part was folded in half and let to self-twist. The actuator obtained was very long and thin and can be seen in figure 4.3 below.

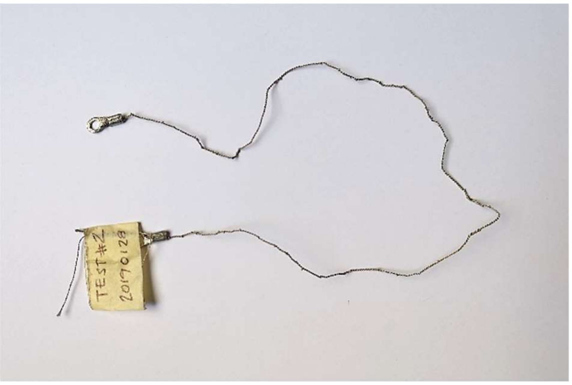


Fig. 4.3 The first manufactured actuator was thin and long.

A successful 4PLY actuator was obtained in the third attempt. The actuator was coiled, folded in half, although with some difficulties in the finger work, and later crimped at the ends. 1.90 m yarn was used together with a dead weight of 100 g. The resulting actuator (actuator 3) was elastic and can be seen in figure 4.4 below. A total number of 3173 twists were performed on the thread.

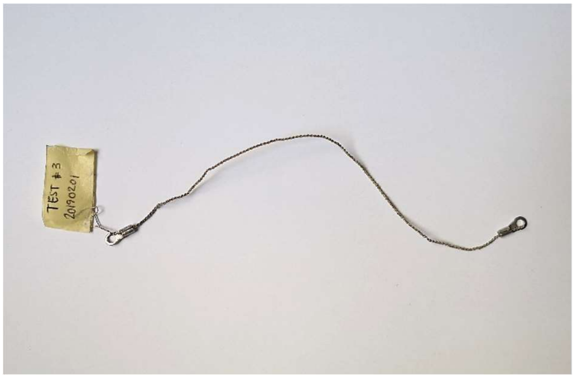


Fig. 4.4 Actuator 3 was a successfully manufactured 4PLY actuator.

Another actuator was manufactured with the same length of yarn and weight. From the previous actuator, the technique to fold and let the actuator self-twist was learnt, which resulted in a smoother and slightly more elastic actuator. The total number of turns performed by the servo motor was 3203. The actuator (actuator 4) was then used to make an 8PLY actuator and no photo was taken of it before.

4.1.2 Single thread 8PLY actuator – actuator 4

For the desire of an actuator that can produce a bigger force, actuator 4 was used to manufacture an 8PLY actuator. The actuator was folded in half and twisted first with a weight of 100 g. Due to that the actuator then started swinging back and forth, the weight was changed to 200 g. After the folding and self-twisting, the result was a very short and compact actuator with little elasticity. Figure 4.5 shows actuator 4. In the second twisting, 31 twists were inserted which made the total number of twists 3234 for actuator 4.

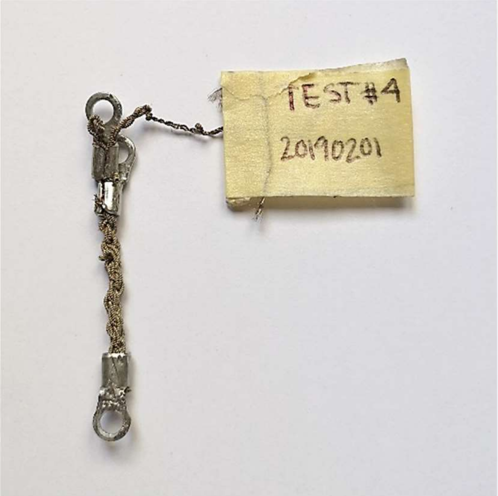


Fig. 4.5 The single thread 8 PLY actuator became very short and stiff.

4.1.3 Double thread 8PLY actuators – actuators 5, 6, 7, 8, 9, 10

To continue the idea to obtain an 8PLY actuator, attempts with double threads were performed. For the first double thread actuator, 3.90 m yarn was used together with a weight of 100 g. It was noted that before the thread was fully coiled, some coils started to group together and self-twist. An example can be seen in figure 4.6 below. This could be due to too many twists inserted or because the weight was too light. The coils grouping together continued being a problem throughout the manufacturing of future actuators.

Fig. 4.6 Before the thread was fully coiled, coils grouped together and self-twisted.

The groups of coils were straightened by either stretching the thread over the area of the coils or untwisting the groups of coils until the thread was straight again. The manufactured actuator (actuator 5) showed little elasticity after a total number of 1639 turns were performed by the servo motor. No photo was taken of actuator 5.

Another actuator was manufactured with the same length and weight but with less turns to avoid the coils to group together. That resulted in a non-elastic actuator. It was then twisted again with a weight of 100 g. During the second twisting, it was noted that the actuator untwisted before twisting again. This was because the second twists were inserted in the opposite direction to the twists on the actuator. The final actuator (actuator 6), which can be seen in figure 4.7 below, was tightly twisted and not very elastic with a total of 1125 twists.

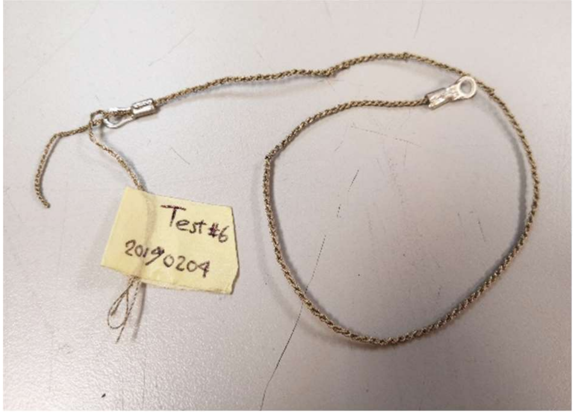


Fig. 4.7 Actuator 6 was tightly twisted and not very elastic.

In the seventh manufacturing test, the same procedure was followed, but during the second twisting a weight of 203 g was used. The actuator started self-twisting due to coils grouping together and was again untwisted before twisted. The final actuator (actuator 7) differed a little from actuator 6 in elasticity but was also very tightly twisted. Figure 4.8 below shows the actuator. In total, 1335 turns were performed by the servo motor.

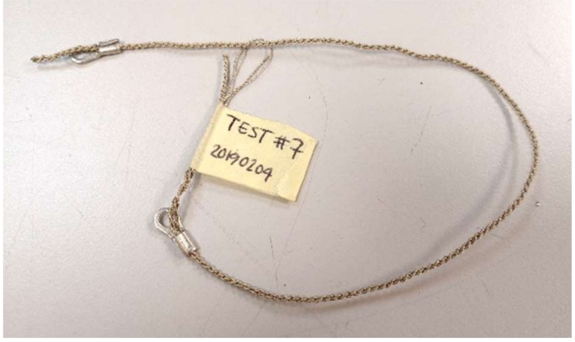


Fig. 4.8 Actuator 7 was slightly more elastic than actuator 6, but still very tightly twisted.

Another double thread actuator was manufactured with 3.90 m yarn and a weight of 100 g for the first twisting and 203 g for the second twisting. Reference “10” was given to the servo motor during the second twisting, which resulted in clockwise turns and no untwisting of the actuator. A third twisting with a weight of 100 g was performed on the actuator but gave no improved result. A total of 1550 twists were inserted on the final actuator (actuator 8). It was later used in testing by a colleague and no photo was taken before.

For actuator 9, again 3.90 m of thread was folded in half and twisted with a weight of 100 g. The actuator was folded and let to self-twist and later twisted again, this time with a weight of 200 g. Some of the coils grouped together resulting in an uneven actuator which can be seen in figures 4.9 and 4.10 below. The total number of twists performed on actuator 9 was 1332.

Fig. 4.9 Actuator 9 was uneven due to coils grouping together.

Fig. 4.10 A closer look at the groups of coils on actuator 9.

Another actuator with the exact same length and weights used for actuator 9 was manufactured. A total number of 1063 turns were performed by the servo motor. The result did not show any improvements in elasticity. To avoid the coils grouping together, less twists were performed. The final actuator (actuator 10) can be seen in figure 4.11 below and is more even than actuator 9.

Fig. 4.11 The result of actuator 10 was more even than actuator 9 but the elasticity was not improved.

4.1.4 Extended length 4PLY actuators – actuators 12, 14, 16

Another attempt to manufacture a 4 PLY actuator was by extending the length of a single thread. The steps during this manufacturing were a more difficult, but still easy to understand and carry out with experience from a few attempts. To extend the length resulted in a longer manufacturing time and a greater expectation on the fibres of the thread. Several times, this resulted in a thread that broke during the twisting. The thread then spun up towards the servo motor or down towards the weight which can be seen in figures 4.12 and 4.13 below.

Fig. 4.12 When the thread broke it spun up towards the servo motor.

Fig. 4.13 The bottom part of the thread spun down towards the bulldog paperclip.

For the first manufacturing test with an extended single thread, 1.95 m yarn was used to start. 2 m were then added through 1 m at a time. A weight of 100 g was used during the whole twisting process. After the fourth metre yarn had been added, the thread broke. The theory behind the thread breaking was that too many twists were performed on the fibres of the thread. In this case, a number of 6647 twists were performed before the thread broke. That is 1662 twists/m yarn.

In the second attempt, a total of 3 m yarn was used. Again, a weight of 100 g was used, and a successful actuator was manufactured. To avoid performing too many twists, the last coils were coiled by hand. The actuator (actuator 12) was later used to manufacture an 8PLY actuator and unfortunately no photo was taken before that. The total number of twists performed by the servo motor was 4645 resulting in 1548 twists/m yarn.

During the next manufacturing test of an extended single thread 4PLY actuator, the first twisting was performed with 2 m yarn and a weight of 100 g. Another metre of yarn was then added and twisted. Coils started to group together, and to straighten out the coils the thread was pulled downwards. Too much force was used and resulted in that the thread broke. When the thread broke, it has been twisted 4500 times. That is 1500 twists/m yarn.

A second successful extended length single thread 4PLY actuator was then manufactured with a total of 3 m yarn and a weight of 100 g. No problems were met, and the groups of coils were straightened with caution. Again, the actuator (actuator 14) was used to manufacture an 8PLY actuator and no photo was taken of it beforehand. The total number of twists performed on the actuator was 4826, resulting in 1608 twists/m yarn.

Another attempt of a total of 4 m yarn and a weight of 100 g was performed. 2 m were used to start with and then 1 m, 0.5 m and 0.5 m were added. When adding the last 0.5 m of yarn, it was noted that the thread started spinning very quickly against the inside of the bulldog paperclip. It looked like the fibres of the thread tore due to the heat produced by the friction between the thread and the paperclip. Because of this there was an expectation that the thread would break which also happened. When measuring the bottom broken part, it was about 0.5

m which confirmed that the thread broke around where the fibres had torn. The torn fibres can be seen in figure 4.14 below. When the thread broke, a total number of 5632 twists had been inserted. That is 1408 twists/m yarn.

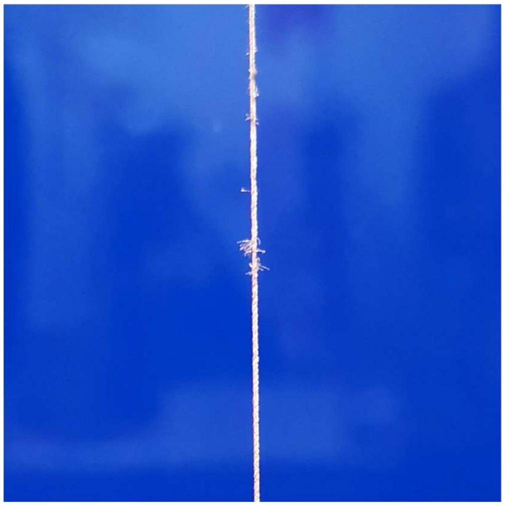


Fig. 4.14 It was noted that the fibres of the thread tore when the thread spun against the inside of the bulldog paperclip when adding more yarn.

In a final attempt to make a longer single thread 4PLY actuator, a total of 4 m yarn was used together with a weight of 100 g. When adding new yarn to twist, it was made sure that the thread did not spin against the paperclip. For the last 0.5 m help was given to the thread to coil faster by lifting the weight slightly. After folding and self-twisting, a final actuator (actuator 16) of 0.42 m was manufactured from a number of 6561 twists, resulting in 1640 twists/m.

Since there was a desire to manufacture an 8PLY actuator, the 4PLY actuator was folded in half and twisted again with a weight of 150 g. Unfortunately, the actuator broke, probably due to too many inserted twists. There are sadly no pictures of actuator 16 in its intermediate state before it broke.

4.1.5 8PLY actuator from two extended length 4PLY actuators – actuator 17

Actuators 12 and 14 were then used to manufacture an 8PLY actuator. A total of 50 turns were carried out with a weight of 100 g. Since the actuator became thicker than the previously manufactured actuators, a wider kind of terminal ends were used. The actuator (actuator 17) can be seen in figure 4.15 below and had a final length of 8.7 cm. In total, 9521 twists were performed on actuator 17. A total of 6 m yarn was used which resulted in 1586 twists/m.

Fig. 4.15 Actuator 17 was a successful single thread 8PLY actuator made of two extended 4PLY actuators.

In table 4.1 below, the total number of twists used to coil the successful actuators are presented together with the number of twists per metre yarn. It can be noted that the number of twists per metre yarn when a single thread was used are similar. The number of twists performed during the manufacturing with double threads were very different from the twists of a single thread. They were neither as uniform as the twists on a single thread nor reached the same number of twists per metre yarn.

TABLE 4.1 Number of turns performed by the servo motor on each actuator. Since actuator 2 broke, the number of turns is unknown.

Actuator	Length (m)	Total number of turns	Turns / m	PLY
2	1.80	-	-	4PLY
3	1.90	3173	1670	4PLY
4	1.90	3234	1702	8PLY - single
5	3.9	1639	420	8PLY - double
6	3.9	1125	288	8PLY - double
7	3.9	1335	342	8PLY - double
8	3.9	1550	397	8PLY - double
9	3.9	1332	341	8PLY - double
10	3.9	1063	272	8PLY - double
12	3	4645	1548	4PLY - single
14	3	4826	1608	4PLY - single
17	6	9521	1586	8PLY - single

4.2 Control results

To obtain a response as similar to the desired one as possible the parameters of the PID controller in the control program were set through trial and error. For the actuators to stand out to other types of actuators, a quick contraction and relaxation were wanted together with a large force and strain. All three of these characteristics were tested in the control setup.

The contraction and relaxation were tested through seeing how well the actuator could contract to a given displacement reference and how well it could relax when a displacement reference of 0 was given to the control. The force was tested by hanging different weights to one end of the actuator. The strain was tested through the maximum contraction and calculated with the following formula:

*Strain (%) = (Maximum contraction (mm)) / (Initial actuator length (mm)) * 100* (3)

The maximum contraction was computed by subtracting the minimum contraction value from the maximum displacement value. The original values were given in sensor units where 1 sensor unit was 0.488 µm. To obtain the maximum contraction in mm the following formula was used:

*Maximum contraction (mm) = (Maximum contraction (sensor units) * 0.488) / 1000* (4)

In total 77 tests were performed on five different actuators: actuators 7, 6, 4, 10 and 17. Before each test, the displacement sensor was reset. The starting current on the power supply was 1A. Throughout the testing, it was changed between 1A and 5A depending on the response of the actuators. Unfortunately, the current for each test was not noted, and will therefore not be evenly presented in the test results.

During the control tests, several problems were met and had to be solved gradually. They will be explained together with the tests in chronological order.

4.2.1 Actuator 7

Several PID parameters were tested to study the response of the actuator. The first test was performed on actuator 7 with a weight of 50 g, position reference of 10’000 sensor units, that is 4.88 mm, and the PID parameters P=3, I=0 and D=0.5. The initial length of actuator 7 was 237 mm, which gave the result of a contraction of 2.06 %. As can be seen in figure 4.16 below, the contraction response was rather quick, but the relaxation response became slower with time. In addition, there were errors just in the beginning moment of actuation and during the steady state.

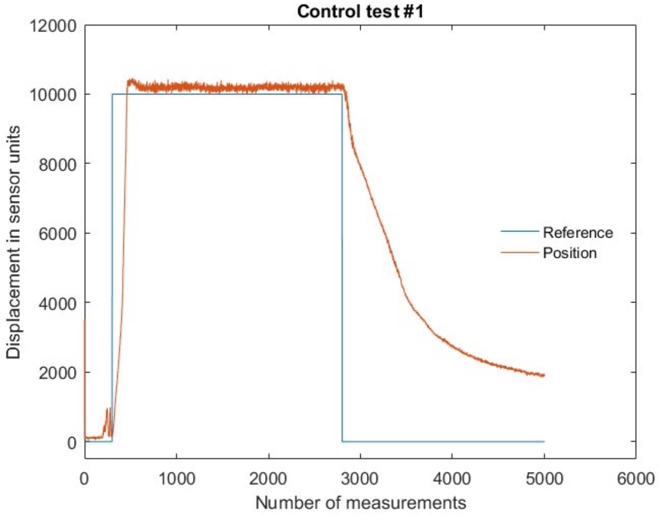


Fig. 4.16 Response result of the first control test where the contraction was quick, followed by an overshoot with errors and a relaxation that became slower with time.

Other PID parameters were tested with a weight of 50 g and showed similar results to the above. The errors were partly reduced by resetting the displacement sensor and adding a piece of tape on top of it to limit the influence of the surrounding light on the sensor (see figure 3.8 in the setup description). Table 4.2 shows the tested parameters below.

TABLE 4.2 PID parameters used together with a weight of 50 g on actuator 7.

Control test	P	I	D
2	2	0	0.5
3	1	0	0.1
4	4	0	0.01
5	3	0	1
6	5	0	0.01
7	5	0	0.001

The next results were obtained from a suggestion of PID parameters by Dorin Copaci. During a 25 s time period, actuator 7 was displaced 2.06% with a weight of 50 g and the parameters P=0.24, I=0 and D=0.01. The response was a quick contraction and slightly slower relaxation with a small overshoot. The overshoot still contained errors which can be seen in figure 4.17 below.

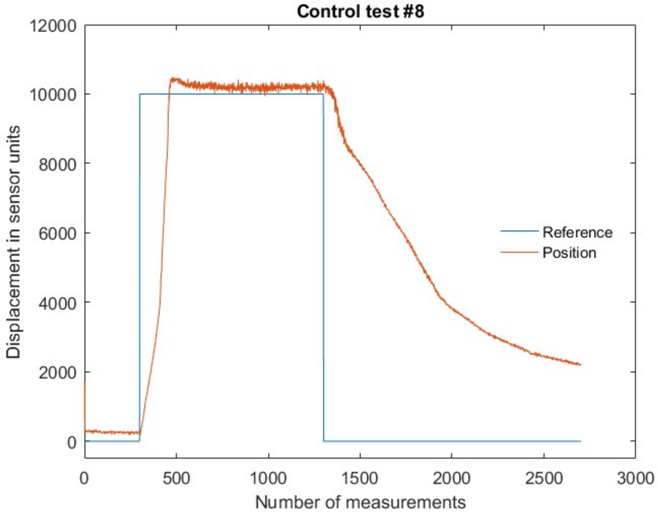


Fig. 4.17 Response result of actuator 7 showing a quicker relaxation but still an overshoot with errors.

The following tests had similar values of the PID parameters and the same weight of 50 g. The results were also similar, but several problems occurred. In various tests the actuator did not contract by itself but needed help with lifting the weight to start to contract. In such cases the result was a delay in contraction which is showed in figure 4.18 below. The parameters P=0.25, I=0 and D=0.01 were used in control test 9.

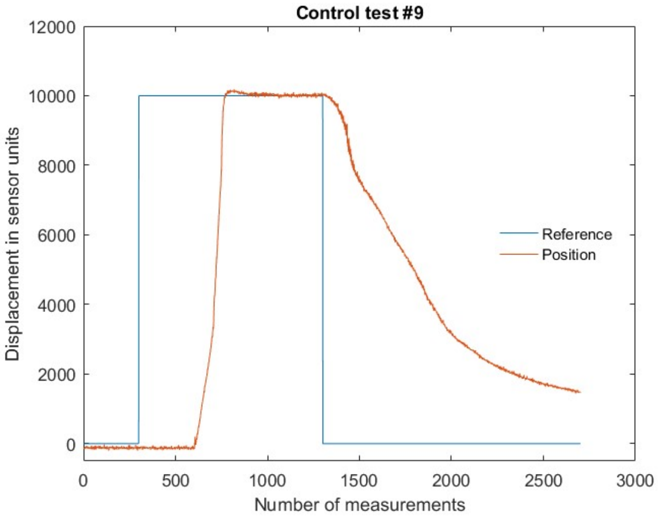


Fig. 4.18 The actuator needed help to start to contract. The relaxation was still good.

Other issues that were met were no response at all or very little displacement of the actuator. In control test 12, in figure 4.19 below, the parameters P=0.24, I=0 and D=0.01 were used together with a weight of 50 g. The actuator did not contract to the given displacement reference, and when the relaxation started it was very slow. It should be noted that there was no need to help the actuator to start to contract.

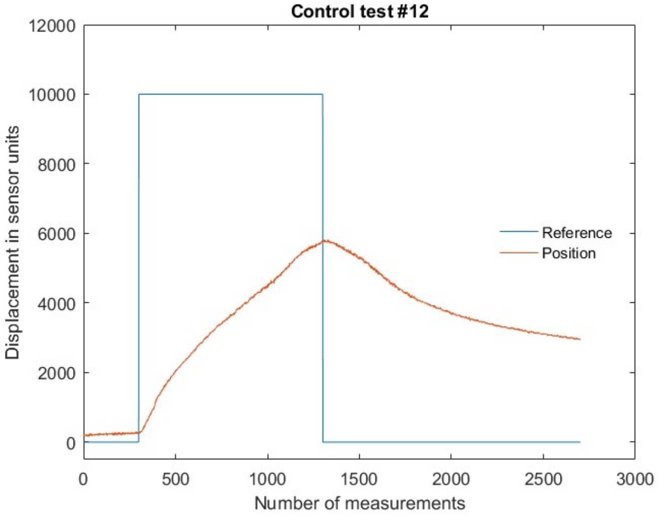


Fig. 4.19 Response result of actuator 7 showing the lack of contraction and slow relaxation of control test 12.

To solve these problems, the interface on the MCU was rebuilt. When there was still no good response, actions to reduce the friction inside the small plastic box were taken.

The nylon thread that was initially used to attach the weight to the activating strip was replaced by a titanium thread. Oil for reducing friction was used to reduce the friction between the threads and the plastic box. With these adjustments to the setup, the responses changed. The first response showed a great overshoot with a lot of errors. For that test the parameters P=0.19, I=0 and D=0.03 together with a weight of 50 g were used. The result is presented in figure 4.20 below. Control test 18 gave the maximum contraction of actuator 7, which was 5.6135 mm. The strain was 2.37 %.

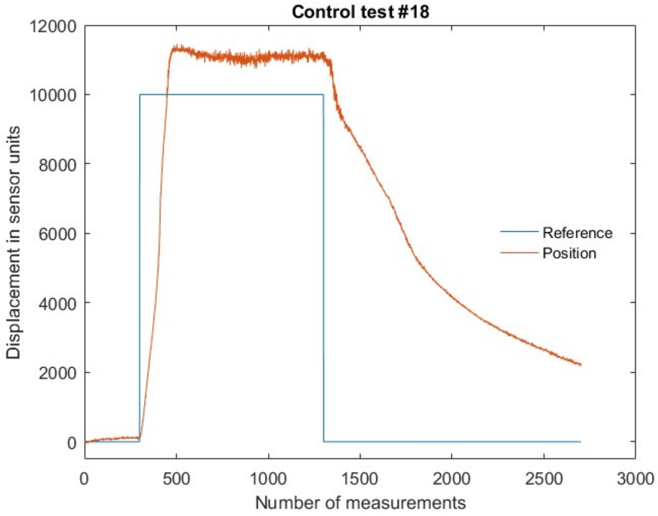


Fig. 4.20 First response of actuator 7 after friction reduction actions had been taken in form of a titanium thread and oil. The test shows a big overshoot with errors.

Another response after friction reduction showed a stair-like behaviour where the actuator did not contract to the given displacement reference. The stair-case behaviour looked like a jagged movement in reality. For the test, the parameters P=0.24, I=0 and D=0.01 were used together with a weight of 50g. The results can be seen in figure 4.21.

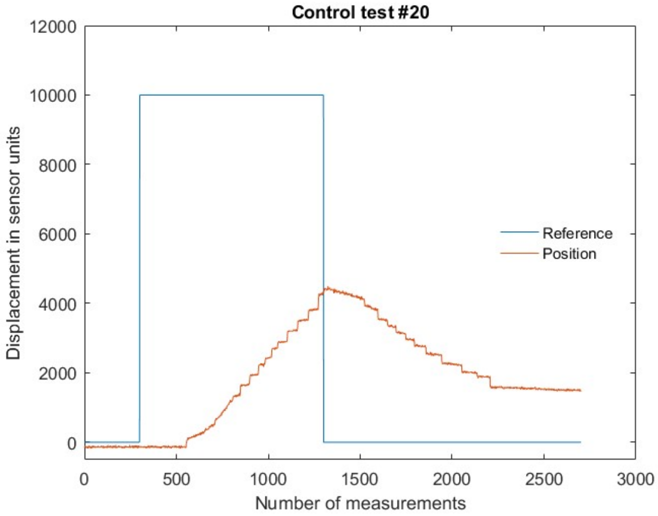


Fig. 4.21 Another test after friction reduction. Actuator 7 contracted and relaxed stair-like and did not reach the given displacement reference.

To eliminate the stair-like behaviour of the actuator, more oil and a lighter weight of 30 g were used. The same parameters as in the previous test then gave the result in figure 4.22. Improvements could be seen in the contraction, but the stair-like behaviour was not eliminated. The relaxation was slower than previously.

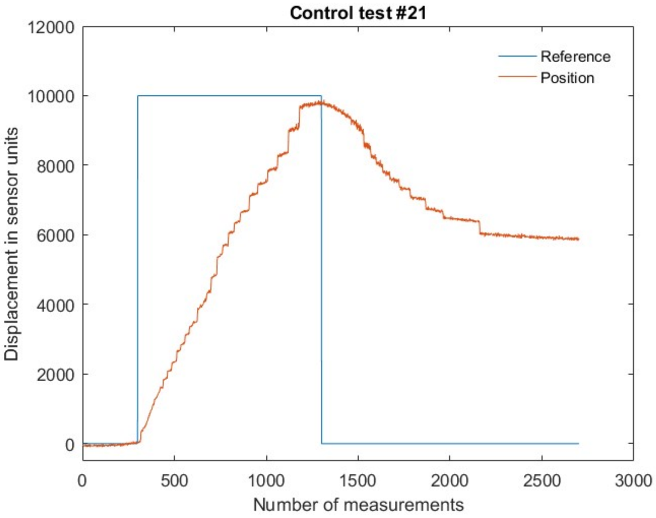


Fig. 4.22 The response of actuator 7 after further friction reduction with a lighter weight and more oil. The actuator now contracted more but kept the stair-like behaviour in both contraction and relaxation.

Another attempt with parameters P=0.24, I=0 and D=0.01 and a weight of 50 g was performed. This time the actuator contracted to the given displacement reference, but according to the sensor it was already partly contracted, which can be seen in figure 4.23 below. Because of the initial displacement given by the sensor, the maximum contraction was only 7598 sensor units. It should be noted that it was still more than in control test 20 where the maximum contraction was 4674 sensor units.

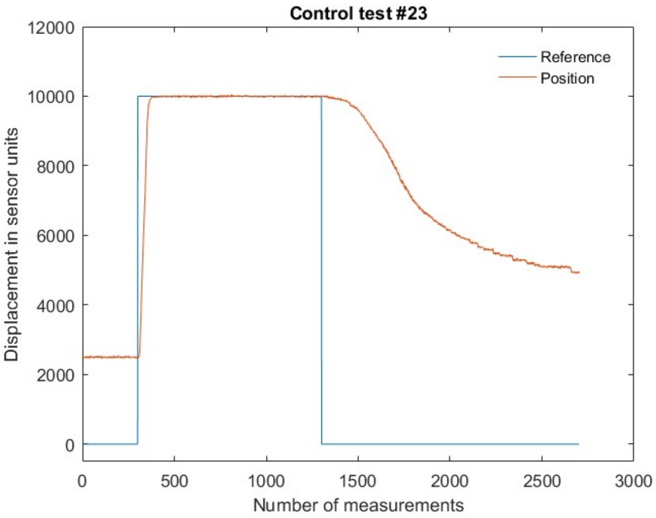


Fig. 4.23 Response result of actuator 7 where the sensor reported contraction before the power was sent through the actuator.

After control test 23 it was noted that the colour of actuator 7 had turned slightly yellow and the elasticity had decreased. Therefore, tests with another actuator were performed.

4.2.2 Actuator 6

The first control test on actuator 6 used the PID parameters P = 0.24, I = 0, D = 0.01 together with a weight of 50 g. For the actuator to start to contract, help was needed to lift the weight.

The contraction quickly increased but did not reach the displacement reference. The stair-like behaviour previously seen in the tests of actuator 7 was only noted in the end of the relaxation process. Figure 4.24 below shows the response.

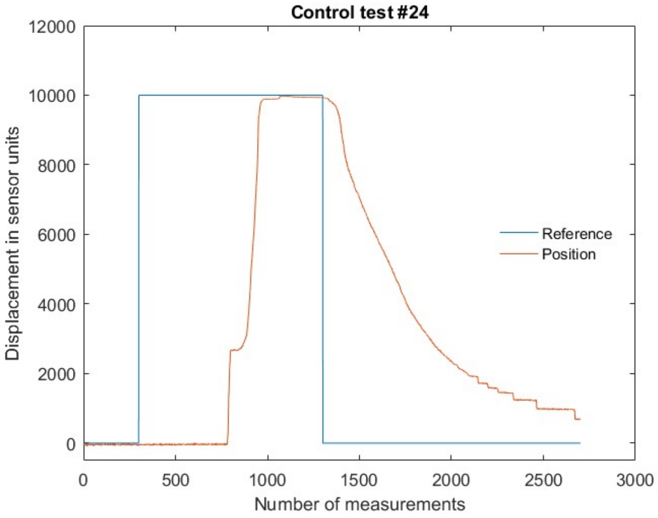


Fig. 4.24 Response of the first test on actuator 6 showing that the actuator needed help to contract and a stair-like behaviour in the end of the relaxation.

The next test performed on actuator 6 used the same PID parameters and weight as in control test 24. No help was needed for the actuation and the displacement was quick to increase and decrease. The relaxation still showed a jagging movement at the end. The results are shown in figure 4.25 below.

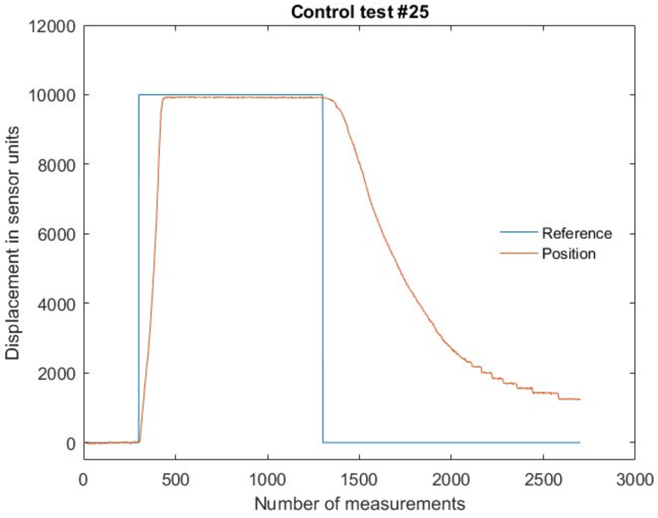


Fig. 4.25 Response results showing a quick contraction (without help) and relaxation, still with the stair-like behaviour.

To improve the steady state position of the actuator, the parameters in table 4.3 were tested with a weight of 50 g.

TABLE 4.3 PID parameters used to control actuator 6.

Control test	P	I	D
26	0.24	0	0.1
27	0.24	0	0.001
28	0.24	0	0.001
29	0.024	0	0.0001
30	0.024	0	0.001
31	0.24	0	0.002
32	0.024	0	0.1
33	0.24	0	1

Control test 27 and 28 were performed with the same PID parameters. In test 27 the actuator needed help to start contracting in form of lifting the weight slightly. In test 28, no help was needed for the actuator to start to contract. A connection between the temperature and performance of the actuator was noted. The following figure (figure 4.26) shows the comparison of control test 27 and 28. Test 28 was run straight after test 27. The contraction response was a lot faster in test 28 and the actuator did not need help to contract. The relaxation response was quicker in test 27 where the actuator also relaxed to a position closer to its initial position than in test 28.

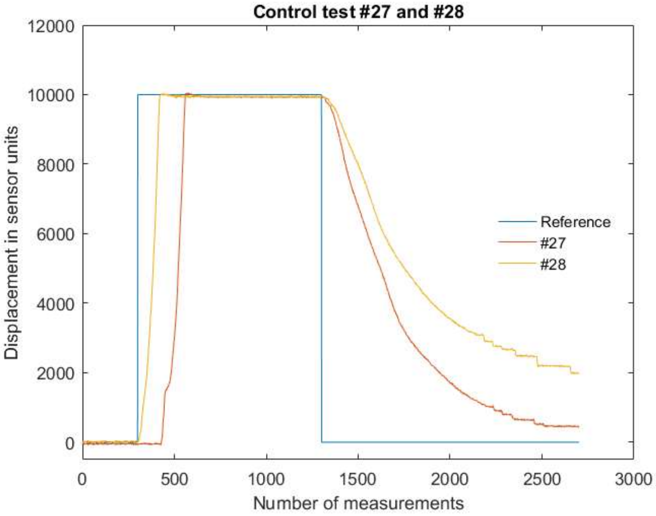


Fig. 4.26 Comparison between test 27 and 28 regarding the temperature and performance of the actuator. The contraction in control test 28 is quicker while the relaxation in control test 27 is quicker and more accurate.

Other results obtained from the tests in table 4.3 above included very slow contraction response, great overshoot and slow relaxation as can be seen in figure 4.27 below. The difference in response was due to changing the PID parameters but keeping the weight of 50 g. The slow relaxation was a result of decreasing the P component to 0.024 and the D component to 0.0001 in test 29. The slow contraction was a result of either decreasing the P component to 0.024 and keeping the D component as 0.1 in test 32 or keeping the P component as 0.24 and increasing the D component to 1 in test 33. The overshoots in test 32 and 33 were 1441 sensor units (0.703 mm) respectively 1702 sensor units (0.831 mm). That resulted in overshoots of 14.41 % and 17.02 %. In all three cases, the stair-like behaviour appeared in the end of the relaxation, but less in test 33.

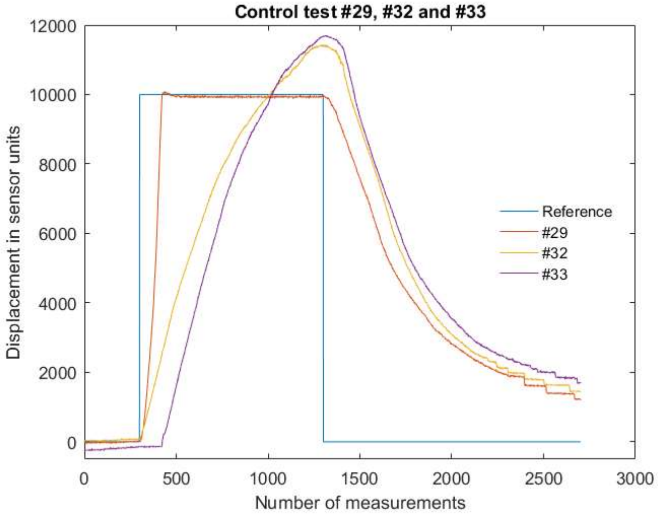


Fig. 4.27 Results of slow contraction, great overshoot and slow relaxation with a stair-like behaviour.

In control tests 34, the PID parameters P=0.24, I=0, D=0.01 and a weight of 50 g were tested to see that the actuator still worked as before. The response resulted in great errors and an overshoot when a displacement reference of 10'000 sensor units was given to the actuator. The result can be seen in figure 4.28 below.

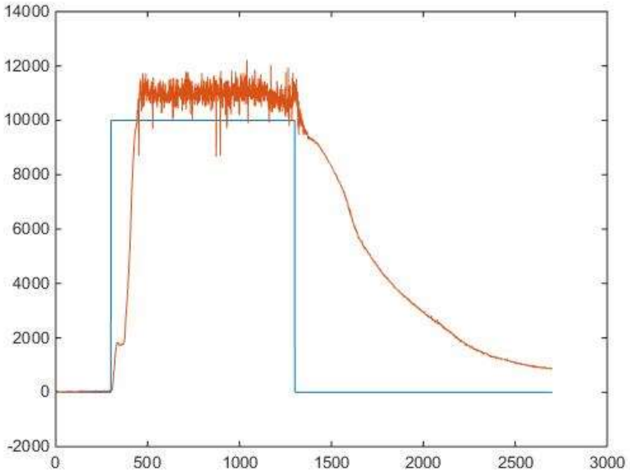


Fig. 4.28 The results of control test 34 showed great errors and overshoot. The x-axis presents number of measurements and the y-axis presents the displacement in sensor units. The blue curve is the displacement reference given to the actuator and the red curve is the response of the actutator.

The same PID parameters and weight were used in control test 35 and the response showed the previously seen behaviour of actuator 6. The contraction was quick and the relaxation slower but smooth, without any jagging movement. Figure 4.29 below shows the response of control test 35.

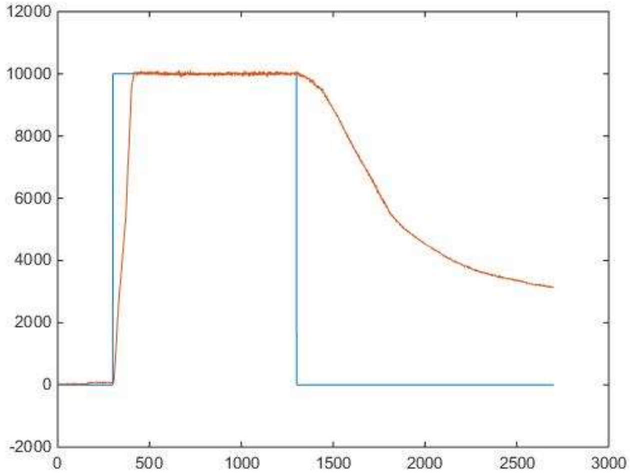


Fig. 4.29 Control test 35 showed the previously obtained response of actuator 6. The x-axis presents number of measurements and the y-axis presents the displacement in sensor units. The blue curve is the displacement reference given to the actuator and the red curve is the response of the actutator.

For control test 36, the displacement sensor delivered an initial position reference lower than the actual position. This resulted in that the actuator was contracted more than its maximum strain to satisfy the displacement reference. Therefore, the actuator became very hot, started smoking and eventually broke because the power was not cut in time. The remaining parts turned slightly yellow and became very stiff. To stop the contraction of the actuator, the easiest and quickest way is to cut the power, which was learnt from the test. It should be noted that the sensor was reset before every test, including control test 36.

Unfortunately, there is no saved data from control test 36 to be shown in a figure.

4.2.3 Actuator 10

With actuator 10 it took a few tests before the previous response was obtained again. During the first tests, the actuator contracted very slowly and did not reach the displacement reference, had errors when it reached the reference or seemed to contract again before relaxing when 0 sensor units were given as a reference. The several responses can be seen in figure 4.30 below and were all obtained with P=0.24, I=0, D=0.01 and a weight of 50 g.

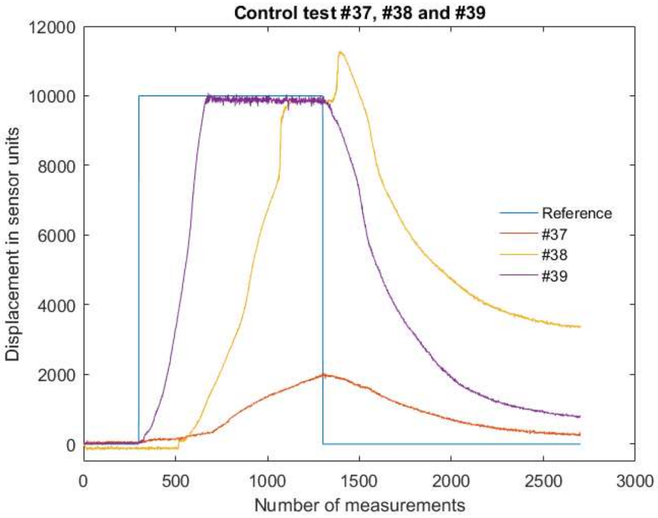


Fig. 4.30 Responses from the first tests on actuator 10. Issues such as small and delayed contraction, errors in the steady state and contraction in combination with relaxation occurred.

Other parameters that were tried were P=0.24, I=0 and D=0.1 with a weight of 50 g in test 43. The response showed a quick contraction and relaxation but did not fully reach the given displacement reference which resulted in a very small undershoot of 10 sensor units (0.1 %). The result is shown in figure 4.31 below.

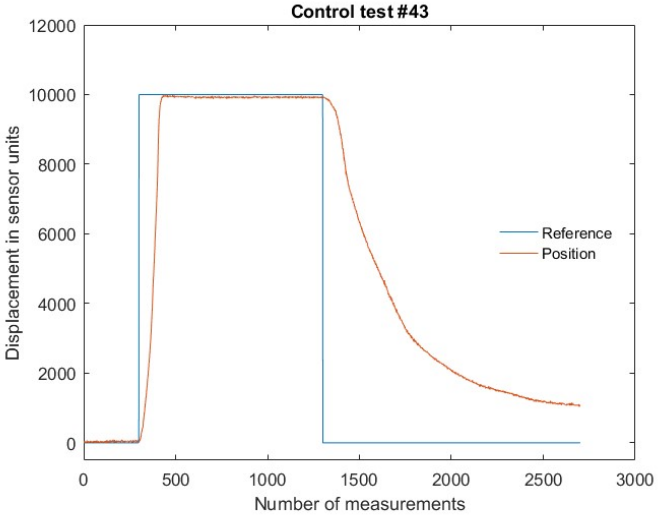


Fig. 4.31 Result of control test 43 showing a quick contraction and relaxation together with a very small undershoot.

In control test 44 the parameters P=0.24, I=0 and D=0.05 were tested with a weight of 50 g. The result showed a slightly slower contraction but about the same relaxation as in control test 43. Instead of an undershoot, a small overshoot of 115 sensor units (1.15 %) was obtained. The results can be seen in figure 4.32 below.

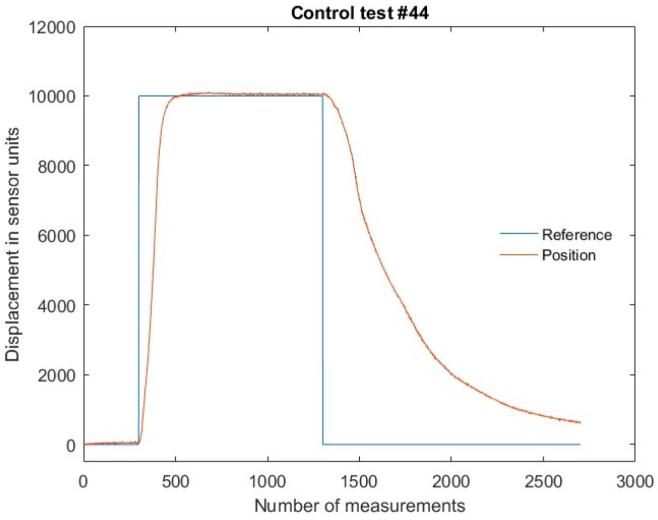


Fig. 4.32 Control test 44 has a slower contraction and a small overshoot. The relaxation was about the same as in control test 43.

Another test with the same P and I parameters and weight but D=0.02 resulted in that the actuator started smoking. At first, this was thought to be because the current was too big (5A) but was later discovered to be the sensor giving the wrong displacement to the control. When a displacement lower than 0 is given, the actuator should not be activated to prevent it from contracting too much. In this case it did not work, and the actuator was contracted past its maximum strain. The same problem was the reason that actuator 6 broke in control test 36.

4.2.4 Actuator 4

The next actuator that was tested was actuator 4. Since the actuator was very short, a small displacement reference of 500 sensor units was set in the control program. In the first two tests (control tests 46 and 47), no displacement was recorded by the sensor, but it showed a lot of errors. The PID parameters P=0.24, I=0 and D=0.01 and a weight of 50 g were used.

According to the sensor, there was displacement in control test 48, but since the actuator was so short, it was hard to detect with the eye. A lot of errors remained, and the steady displacement reached was about half of the given reference. Control test 48 was performed with the same PID parameters as test 46 and 47 but with a weight of 100 g. The results from control tests 46 and 48 can be seen in figure 4.33 below. The negative and positive displacement in test 46 was caused by pulling down and lifting the dead weight.

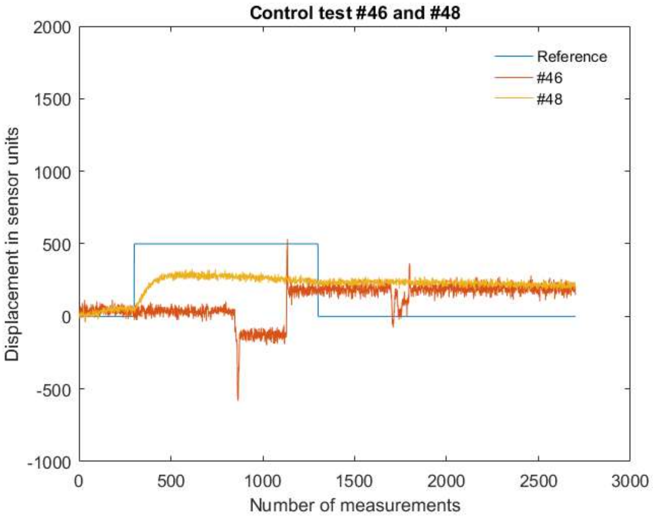


Fig. 4.33 Response from control tests on actuator 4. A lot of errors were recorded. In test 46, the actuator did not contract. In test 48, the actuator contracted but remained on a steady displacement around half of the given reference.

4.2.5 Actuator 17

Many tests were performed on actuator 17. During the first tests, a few problems occurred. Figure 4.34 shows the response of the second test on actuator 17. The sensor worked but delivered a lot of errors. It also showed no displacement for the actuator when it was activated. The different responses of the actuator in control test 50 were due to pulling or lifting the weight in a try to help start the contraction. A weight of 50 g was used together with the PID parameters P=0.24, I=0 and D=0.01.

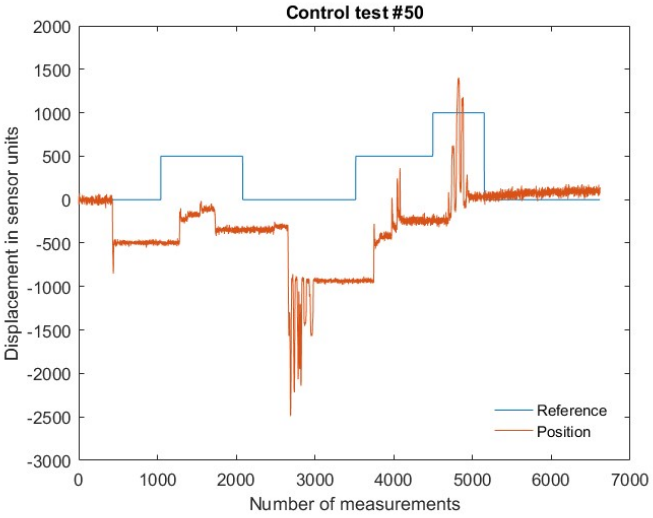


Fig. 4.34 Control test 50 showed no displacement of the actuator even though help was given in form of lifting the weight. The sensor gave a lot of errors.

In the next control test, the actuator contracted and relaxed depending on the displacement reference. No help was needed to start the contraction, and the actuator returned to its initial position after the relaxation. The great negative displacement at the end was due to pulling the weight down. Even though the actuator followed the displacement reference, a lot of errors were recorded by the sensor. The same weight and parameters as in control test 50 were used. The response can be seen in figure 4.35 below.

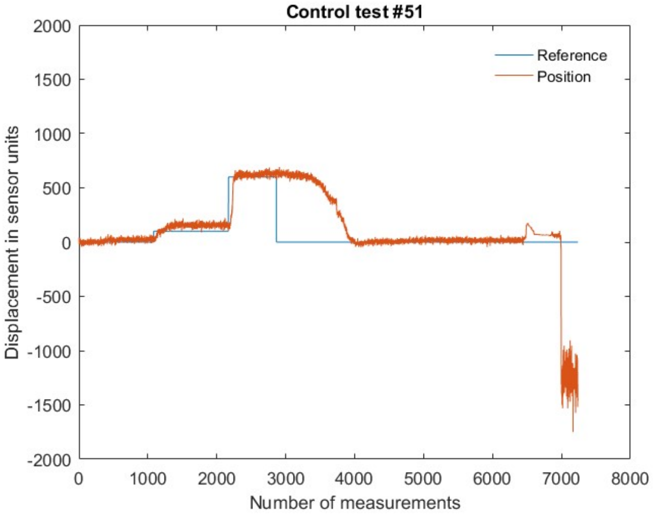


Fig. 4.35 Actuator 17 followed the displacement reference in control test 51, but a lot of errors were recorded by the sensor.

In figure 4.36 below, two weights were used: 100 g and 150 g. The actuator responded with an overshoot when 100 g was used and with an undershoot when 150 g was used. For the test, the PID parameters P=0.24, I=0 and D=0.01 were used. The big differences in displacement in the end of the test were due to pulling the weight down and releasing it.

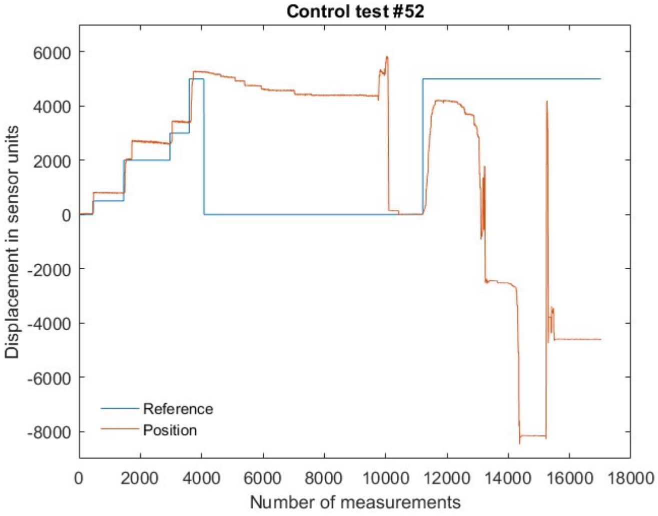


Fig. 4.36 For the first part (0-11000 measurements), a weight of 100 g was used. For the second part (11000-18000 measurements), a weight of 150 g was used. The actuator contracted with an overshoot in the first part, and with an undershoot in the second part.

To improve the response a weight of 125 g was used. The amplitude was set to 4000 with the same PID parameters as before. This adjustment gave a fast contraction but slow relaxation of the actuator. It was also noted that the actuator was very sensitive to movements in the table on which the test bench was placed. The table movements are the straight downwards relaxation falls in figure 4.37 below.

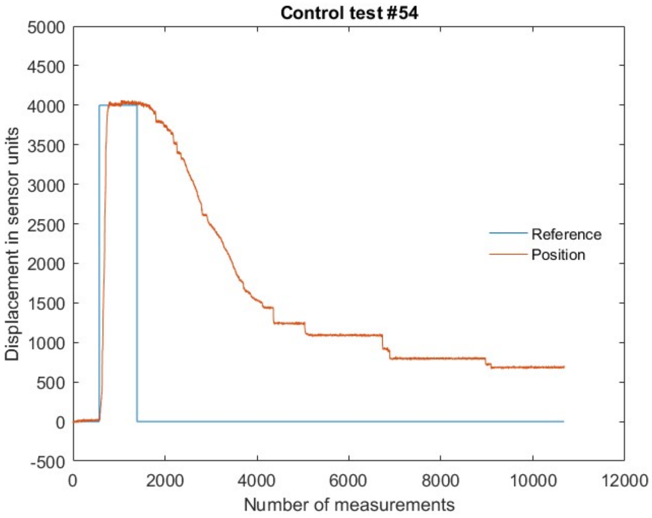


Fig. 4.37 The response shows a quick contraction and a slow relaxation that is interrupted by movement in the table that the test bench stands on.

In an attempt to further improve the response, the weight was changed to 130 g. The idea was that a greater weight would give a smoother and quicker relaxation. The same PID parameters as in the last tests were used. This resulted in a quicker relaxation, but the sensitivity to movements in the table remained. The contraction became slightly slower, which can be seen in figure 4.38 below.

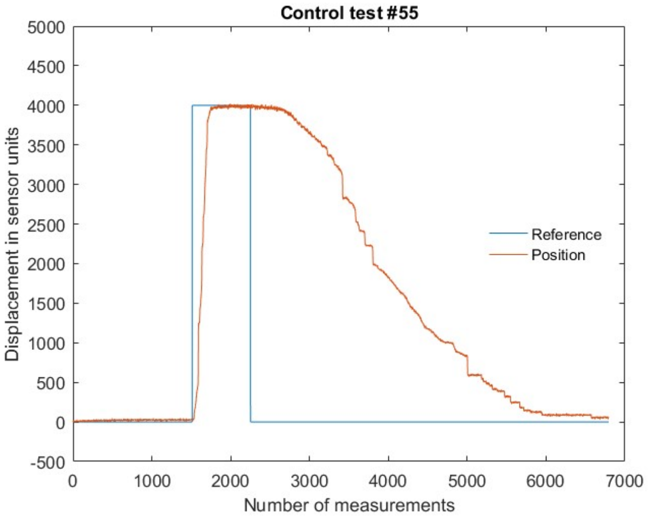


Fig. 4.38 When a weight of 130 g was used, the relaxation of the actuator was quicker, but the contraction was slightly slower. The drops are the actuator's sensitivity to movements in the table.

With a weight of 130 g and PID parameters P=0.24, I=0 and D=0.1 a quicker contraction was obtained but also resulted in a great overshoot of 12.40 % which can be seen in figure 4.39 below. The sensitivity to movements in the table remained.

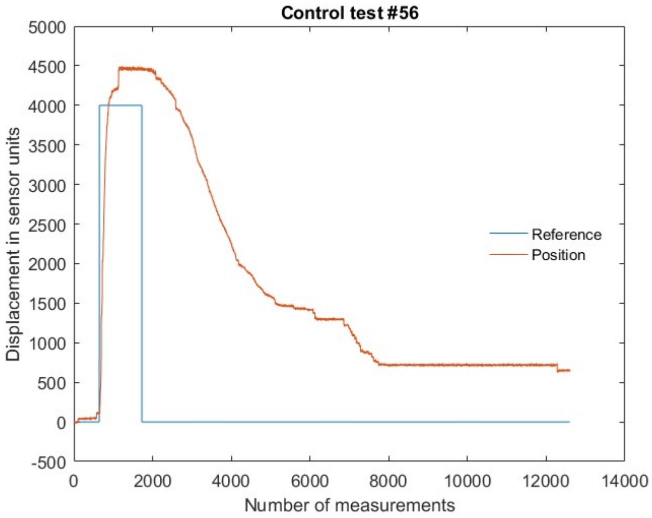


Fig. 4.39 Contraction and relaxation improvements but with a resulting overshoot.

With P=0.24, I=0 and D=0.05 and a weight of 130 g, a quicker relaxation was obtained but with a smaller overshoot of 4.18 % which can be seen in figure 4.40 below. Even here, the actuator was sensitive to movements in the table. It was also noted that the relaxation was slightly slower than in control test 55, and the actuator did not return fully to its initial position.

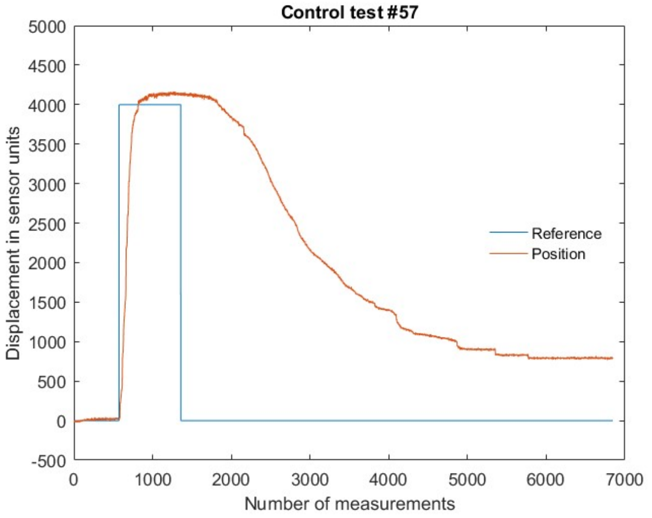


Fig. 4.40 In control test 57, the overshoot was reduced, but the actuator did not return to its initial positon.

A comparison between D=0.05 in control test 64 and D=0.01 in control test 65, both with P=0.24, I=0 and a weight of 130 g, shows that the actuator relaxes quicker with the first value of D. Although, it also results in a slightly bigger overshoot of 2.20 %. From this, it must be decided whether error in overshoot or relaxation time influences the desired response most. The overshoot means that the actuator risks contracting past its maximum strain, while a slower relaxation increases the response time. The comparison between the values of the D parameter are presented in figure 4.41 below.

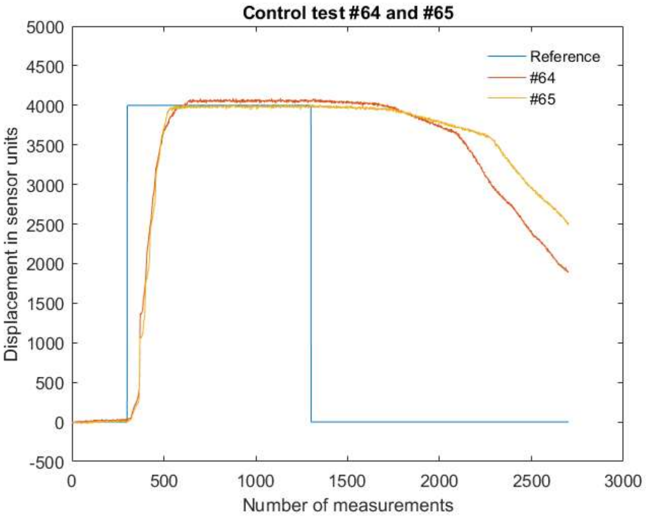


Fig. 4.41 Comparison of D=0.05 in test 64 and D=0.01 in test 65. The test showed that D=0.01 gave a smaller overshoot but a slower relaxation.

Other PID parameters were also tested with a weight of 130 g, but none of them gave a more satisfying result. Most tests showed a bigger overshoot and slower relaxation. The parameters are presented in table 4.4 below. The responses of the control tests in the table are divided into figure 4.42 and figure 4.43 below. Comments to the figures are given together with the parameters in the table.

TABLE 4.4 PID parameters used to control actuator 17 together with a weight of 130 g.

Control test	**P**	**I**	**D**	**Comment**
60	0.4	0	0.5	Quick contraction, overshoot, overshoot ok, actuator a little sensitive to table movements
62	0.6	0	0.05	Slower but smoother relaxation
63	0.9	0	0.05	Slower but smoother relaxation
67	0.1	0	0.05	Overshoot and slower relaxation, actuator sensitive in the end of relaxation
68	0.5	0	0.05	Slow relaxation, actuator sensitive to table movements
69	0.24	0	0.5	Big overshoot, cut power to save actuator, no smoke
70	0.24	0	0.5	Still contracted more than reference, stopped the test

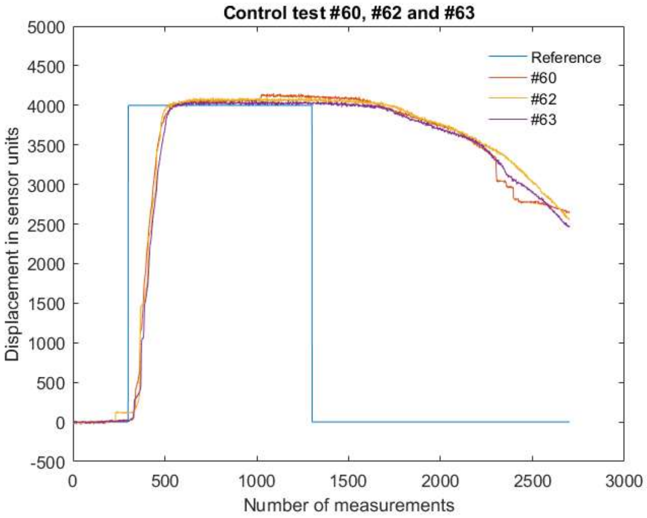


Fig. 4.42 Result of control test 60, 62 and 63 on actuator 17.

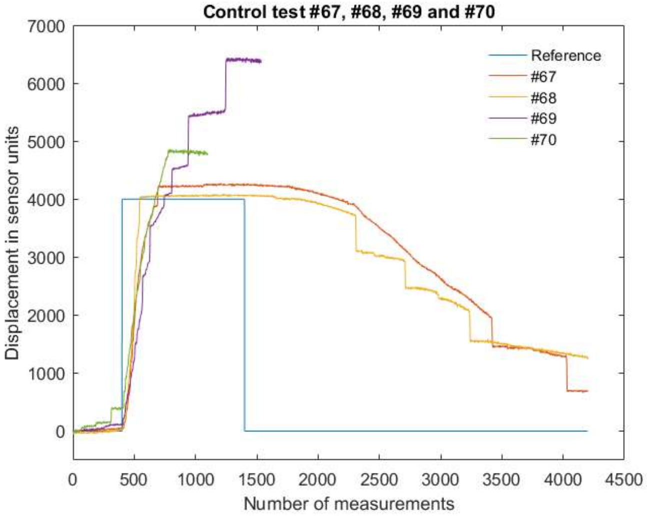


Fig. 4.43 Result of control test 67, 68, 69 and 70 on actuator 17.

Another comparison of the D parameter was made to confirm which gave the best result. In this control test, the result showed that D=0.01 gave a quick contraction, small overshoot and quick relaxation. In the comparison of the same D parameters in control test 64 and 65 (figure 4.41), it showed that D=0.05 gave a better relaxation. This could be due to temperature of the actuator, but also to the drop in displacement during the relaxation due to movements in the table. In figure 4.44 below, test 71 was performed with D=0.05 and test 72 was performed with D=0.01. In both cases, P=0.25 and I=0 were used with a weight of 130 g.

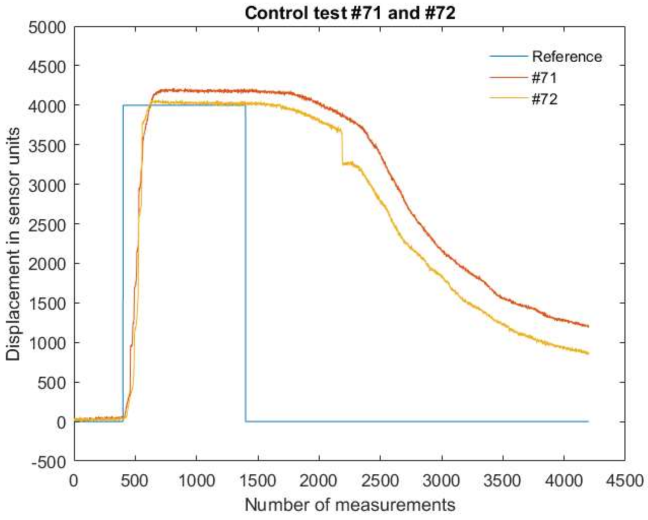


Fig. 4.44 In an additional comparison of the D parameter, D=0.01 in control test 72 showed a better overall response than D=0.05 in control test 71.

Control tests with 150 g and a displacement reference of 10’000 and 11’000 sensor units were also performed with PID parameters P=0.24, I=0 and D=0.01. The responses followed the characteristics previously obtained. In figure 4.45 it can be seen that the contraction became slightly slower, but the relaxation remained about the same as earlier.

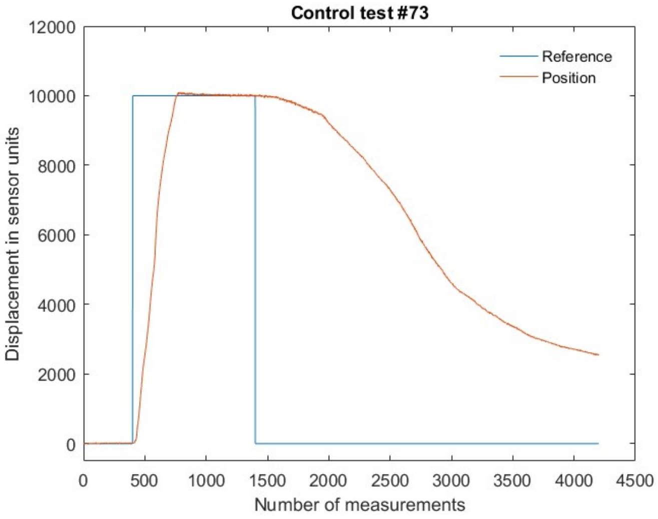


Fig. 4.45 Response of control test with 150 g and displacement reference 10'000 on actuator 17. The contraction was slightly slower than before while the relaxation was about the same.

It was noted that when the actuator was activated a second time without touching the weight between the tests, both the contraction and relaxation were better. This was because the actuator did not fully return to its initial position before being activated again. The sensor was still reset between the tests. A comparison of control test 75 and 76 can be seen in figure 4.46 below. The tests were run right after each other. Control test 76 show a quicker contraction and relaxation, but also a slightly bigger overshoot, than control test 75.

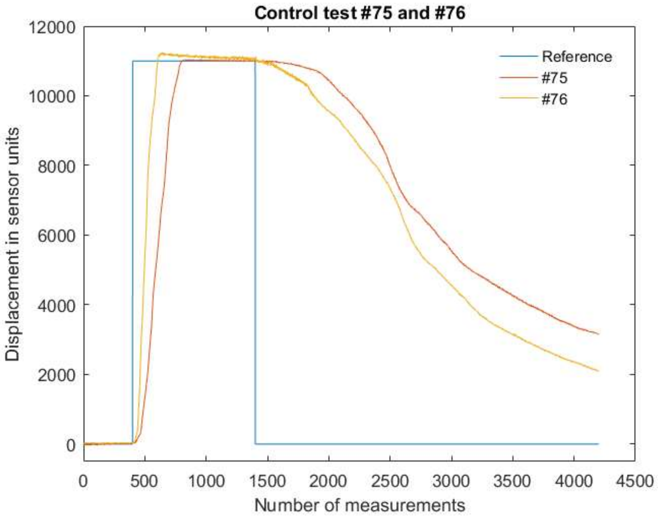


Fig. 4.46 Comparison between control test 75 and 76 that were run straight after each other. Control test 76 shows a quicker contraction, bigger overshoot and quicker relaxation than control test 75.

To test the maximum displacement of the actuator, a test was carried out with a displacement reference of 15’000 sensor units, a weight of 150 g and PID parameters P=0.24, I=0 and D=0.01. When the actuator contracted around 12’000 sensor units (5.86 mm) the actuator became very hot and started smoking. The power was cut, and the actuator was then kindly forced to return to its initial position by pulling the weight downwards. Figure 4.47 below shows the response.

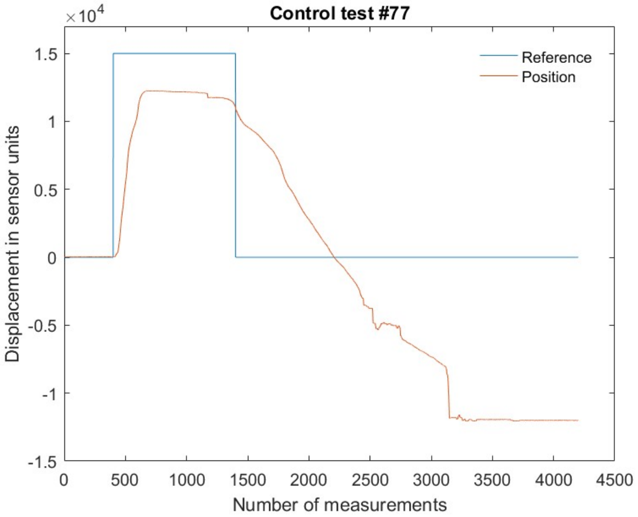


Fig. 4.47 When the actuator was given a displacement reference of 15’000 sensor units, it started smoking when it reached 12’000 sensor units. The power was cut and the actuator was relaxed by pulling the weight down.

4.2.6 Maximum strain

To compare the actuators characteristics, the maximum strain of each actuator was calculated. The strain was calculated as previously explained in the beginning of the control results and the results are presented in table 4.5 below.

TABLE 4.5 Maximum strain obtained for each of the tested actuators.

Actuator	Initial length (m)	Displacement (m)	Strain (%)	PLY	Weight (g)
4	0.02	0.0001698	0.85	8PLY - single	100
6	0.182	0.0058384	3.21	8PLY - double	50
7	0.237	0.0056135	2.37	8PLY - double	50
10	0.313	0.005255	1.68	8PLY - double	50
17	0.087	0.0054885	6.31	8PLY - single	150

4.3 Rigidifiable material

The idea was to obtain a small piece of rigid material that can be fastened to a flexible material, such as textile, and when working together with an actuator, change the rigidity of the device. The results of the rigidifiable material can be divided into two parts. The first part covers the design and manufacturing of the guiding device. For this, Solid Edge and a 3D printer in the RoboticsLab at Universidad Carlos III de Madrid were used. The second part covers the testing of the guiding device together with a previously manufactured actuator.

4.3.1 Design and manufacturing

The first manufactured guiding device was very tall and clumsy. To attach it to a flexible material would not be easy and it would stick out a lot. This would make the idea of a flexible and easy-to-wear-device harder to achieve. The first device can be seen in figure 4.48 below.

Fig. 4.48 First result of the manufactured guiding device for the rigidifiable material.

It is a compact piece with a flat bottom and rounded top. The idea was that the metallic rod should run through the channel, which can be seen in figure 4.52, in the guiding device. For the rod to not miss the hole, the hole where the rod would enter was made like a cone to ease the process. The tallness of the device comes from the diameter of the cone. Figure 4.49 shows the 3D drawn guiding device in Solid Edge in mm.

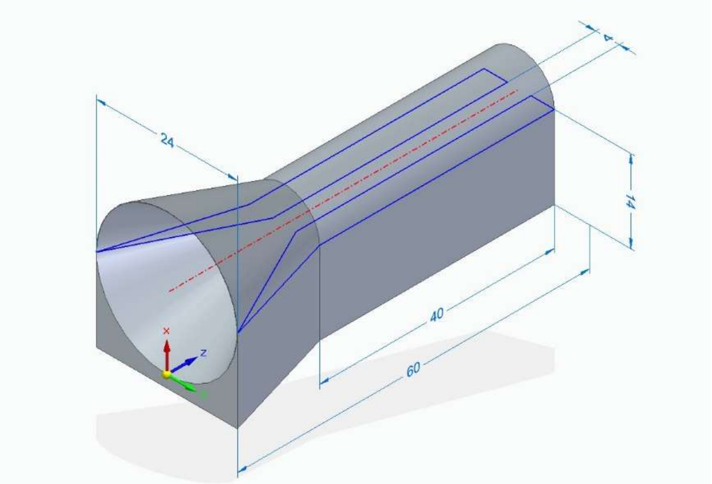


Fig. 4.49 Measurements in mm in scale 2 of the first guiding device.

To improve the design of the guiding device, another sample was drawn in Solid edge and later manufactured in the 3D printer. The new piece was made flatter and with holes to sow it onto a flexible material. It was also lighter than the previous guiding device. The result is presented in figure 4.50 below.

Fig. 4.50 Second result of the manufactured guiding device for the rigidifiable material.

The second device consists of a platform with holes to attach it to a flexible material through sowing. The channel in which the metallic rod will run, is placed onto the platform. One end is shaped as a cone, like in the previous device, to ease the guiding of the rod when entering the tunnel. It also supports a flexible movement of the rod when the material needs to be less rigid. The 3D drawn guiding device in Solid Edge can be seen in figure 4.51 below.

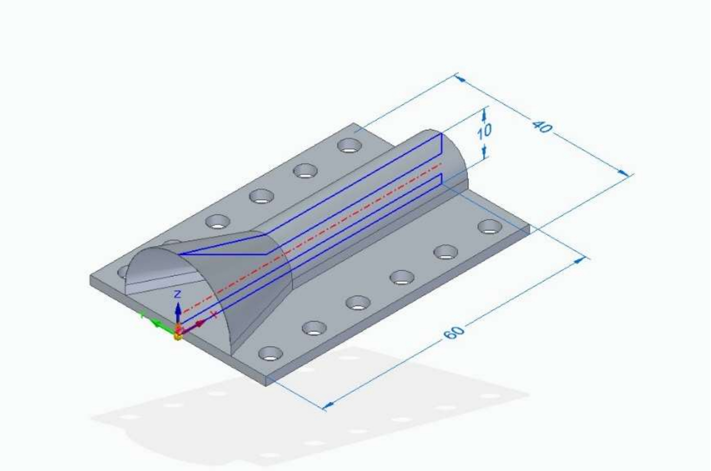


Fig. 4.51 The second guiding device in Solid Edge. The measurements are in mm.

4.3.2 Testing of rigidifiable material

The idea for the rigidifiable material can be seen in figure 4.52 below. In A the material is in a flexible state where the rod rests on the platform inside the cone (but outside the channel). The rod can move upwards and sideways. In B, the actuator is actuated and contracts, resulting in that the rod moves inside the channel. This makes the material rigid by limiting the movement of the rod.

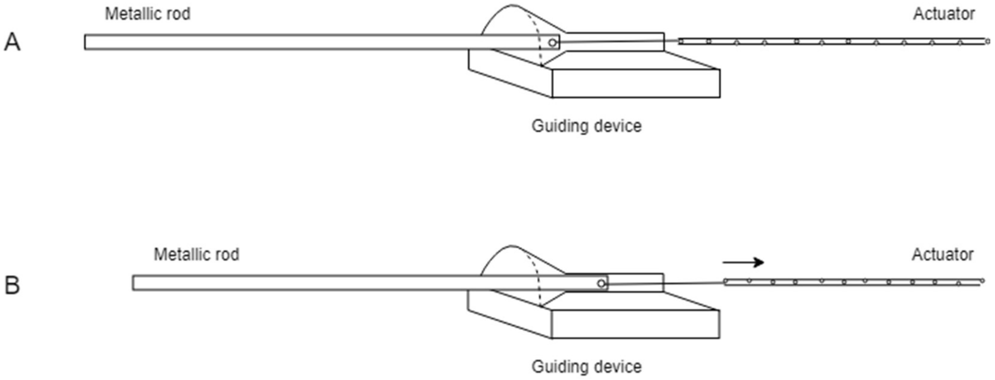


Fig. 4.52 A shows the rigidifiable material in a flexible state where the rod can move upwards and sideways inside the cone. B shows the rigid state of the rigidifiable material when the rod is inside the channel in the guiding device. The movement of the rod is cause by the contraction of the actuator.

To test the behaviour of the rod moving inside the device, a similar setup to the control setup was used. Again, 7 V were used as a power source and the same MATLAB control program. The rod and the guiding device were added to show the movement of the rod and rigidity obtained. In the tests of the rigidifiable in the lab, the rod was placed on the edge of the platform to study its movement. Figure 4.53 below shows the lab setup of the rod. Because of the distance between the rod and the channel of the guiding device, the rod never moved into the channel.

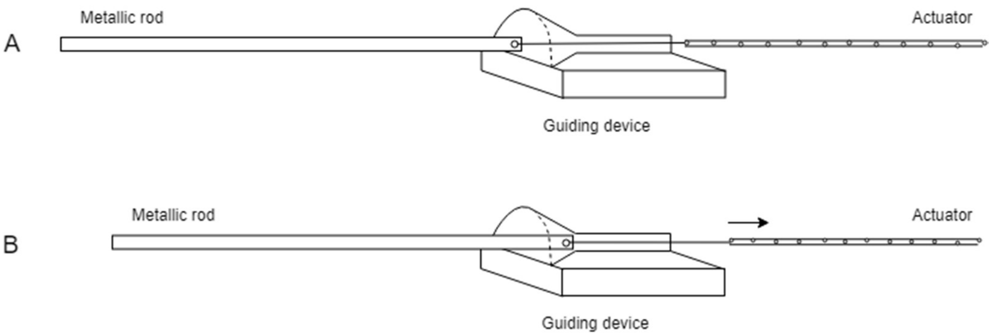


Fig. 4.53 During the tests, the rod was placed on the edge of the platform to study its movement. This can be seen in A. Because of the placement of the rod, it did not move into the channel as can be seen in B.

Since it had previously been concluded that the PID parameters P=0.24, I=0 and D=0.01 gave the best actuator response, these parameters were used for the rigidity tests as well. First, a weight of 130 g was used, but no movement was detected through the displacement sensor. Therefore, a weight of 50 g was used instead. Four tests were performed in total with actuator 17.

In the first test a reference displacement of 3000 sensor units was used. The actuator contracted slowly and a little unevenly. The behaviour was a consequence of the friction of the rod sliding against the bottom of the guiding device. When a displacement reference of 0 was given to the actuator, it did not relax. Instead the control was disabled and the power cut. In previous tests with actuator 17, the weight was at least 130 g. The 50 g weight together with the rod resting on the bottom of the device influenced the relaxation of the actuator. The result of the first rigidity test can be seen in figure 4.54 below.

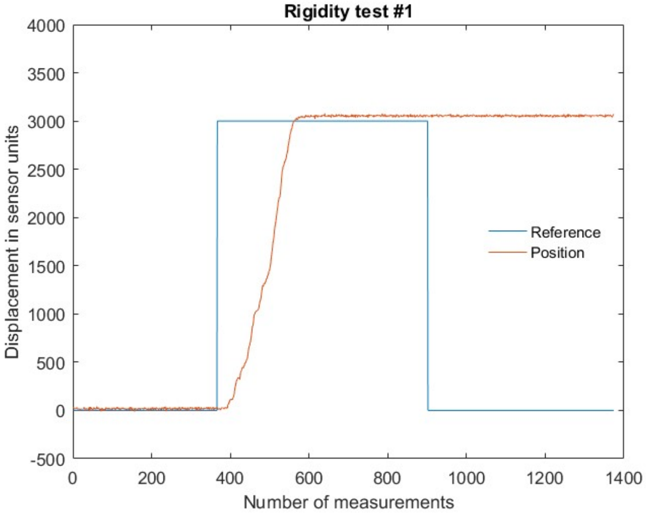


Fig. 4.54 Response of first test of rigidifiable material.

For the second test, three different displacement references of 1000, 3000 and 5000 sensor units were given to the actuator. To kindly introduce a greater contraction, they were given in steps, as can be seen in figure 4.55 below. The actuator contracted to all levels, with the same kind of slow and uneven result as in the first test. Again, the actuator did not relax when a reference of 0 was given.

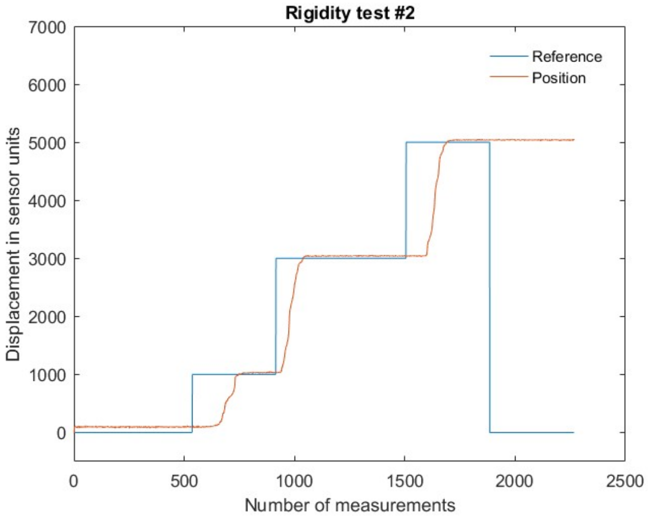


Fig. 4.55 Result of second test of rigidifiable material.

To increase the contraction of the actuator further, a reference displacement of 8000 sensor units was given in the third test. The consequences of the friction between the rod and the guiding device was very visible which also resulted in an even slower contraction than before. The actuator did not relax in the third test either. The results can be seen in figure 4.56 below.

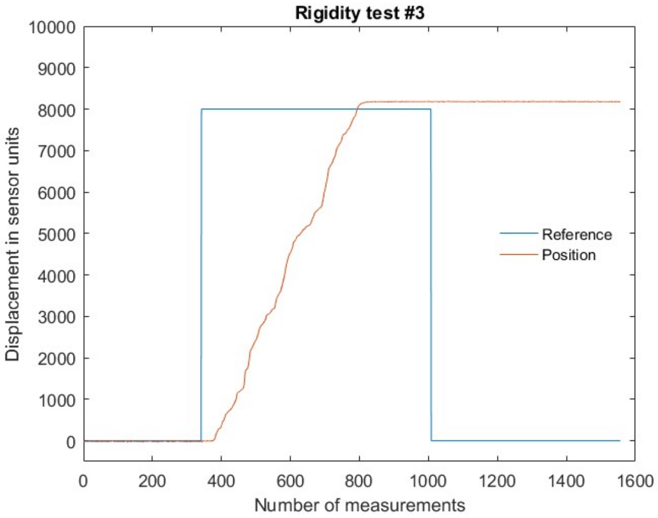


Fig. 4.56 Result of the third rigidity test.

In the last test, the actuator contracted more than the displacement reference given. The same behaviour in contraction and relaxation as before was noted. To help the actuator to relax, the weight was pulled down softly as can be seen in figure 4.57 below. A displacement reference of 10’000 sensor units was given to the actuator.

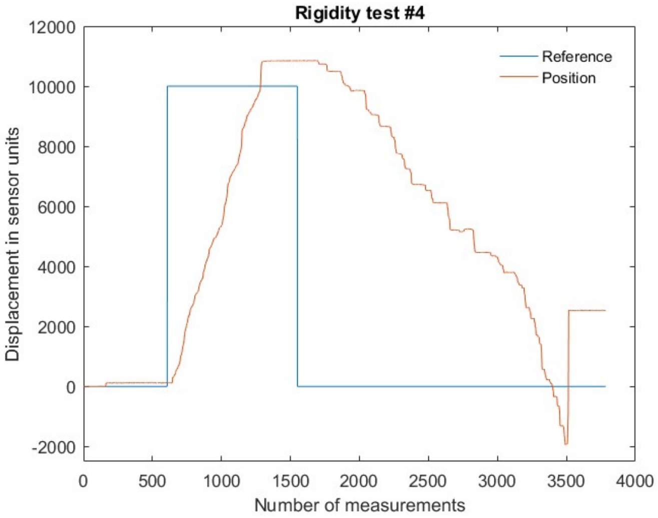


Fig. 4.57 Reference of the fourth rigidity test.

5 DISCUSSION

The results obtained through the manufacturing and testing of the actuators can be further discussed regarding several aspects: number of twists, manufacturing equipment and method, importance of a working displacement sensor, strain, force-to-strain ratio, behaviour related to temperature, sensitivities, PID parameters, material and price.

The work on the rigidifiable material can be further discussed regarding design and material.

A cost analysis of the manufacturing and testing of the actuators and the rigidifiable material can be seen in Appendix 1. A detailed project plan can be seen in Appendix 2.

5.1 Manufacturing and testing of actuators

For the manufacturing the number of turns per metre yarn can be compared to previous research on silver plated TCN actuators. From the manufacturing tests carried out in this thesis project several numbers of twists were obtained. For successful actuators manufactured with a single thread the average number of turns was 1623 per metre yarn. For successful actuators manufactured with double threads the average number of turns was 343 per metre yarn. If instead half of the total length of the double threads is considered the average number of twists is 687 per metre double thread. Previously Nylon 6,6 silver-plated multifilament sewing thread has been tested as the material for TCN actuators by [3]. The number of twists per metre obtained to coil the thread was 2430. The difference in twists most likely depends on the different materials. An advantage for Shieldex® 235/36 dtex 2-ply HCB is that the manufacturing will be faster since fewer turns are required. A disadvantage is that not as many twists can be inserted for the yarn in this thesis, which means that the thread is weaker than Nylon 6,6 and also results in weaker actuators.

During the actual manufacturing of the actuator, it is important to make sure that the equipment used does not tear the fibres of the yarn. When manufacturing an actuator by adding yarn, it is important that the twisted part is stretched from just under the bulldog paperclip to prevent the yarn from spinning against the inside of the bulldog paperclip and break. It is also important to use a weight proportional to the yarn. During the manufacturing, several actuators broke due to too heavy weights. Although, it was also noted that when manufacturing with a too light weight, the weight started swinging back and forth which brought an uneven load to the wings on the servo motor. In the long run, this would tear more on the equipment and the price for the servo motor would increase with the increased number of motors required.

A lighter weight also meant that the thread started building groups of coils that self-twisted and made the actuators uneven. The unevenness of the actuator would later influence the displacement of the actuator. Since the contraction is due to contraction in axial direction and increase of diameter in radial direction, the displacement would be interrupted by the groups of coils. Whether this would make a difference to the response of the actuator was not tested in this thesis.

Other aspects that could influence the response of the actuator is the measuring of the yarn during the manufacturing, of where the actuator is folded before it is let to self-twist and of the finished actuator. For the measuring to be exact, the yarn or the actuators would have to be equally stretched. As mentioned previously in the result, the actuators were elastic, which made it very hard for the producer to stretch them equally. This would later influence the computed strain of the actuators but could possibly be solved with an automatic measuring system. When the actuators were folded and let to self-twist, only the eye was used to measure the middle point of the coiled yarn. Even though not very likely, this could also influence the response of the actuators and be improved.

For an even response of the actuator, [3], [7], [32] performed annealing on the actuator before testing its actual response. The annealing meant activating the actuator several times in a row to maintain a stable structure of the coils and prevent a future uneven response of the actuator. The annealing in this thesis was not performed in the same way. Instead, the first few control tests on every actuator showed very different responses. In discussion, these tests can be seen as the annealing process, but were not performed in line with the annealing mentioned in the previous research on TCN actuators. It is very likely that the annealing process performed by [3], [7], [32] would make a difference to the behaviour of the actuator, and that this behaviour was not acquired due to the difference of annealing of the actuators in this thesis. A lack of understanding the importance of annealing the actuators before testing them resulted in a not entirely correct performed research which is important to criticise.

During the testing of the actuators it was recognised several times that it is important that the displacement sensor works properly. The importance lies in the maximum strain of the actuator and that if the maximum strain is surpassed, the actuator will become very hot and, if not deactivated in time, eventually break. To minimise the risk of the actuator breaking, a control threshold can be programmed, just as was the case in the program used for the control tests in this thesis. It can then be commented that even though a disabling control function exists, it does not eliminate all risks of the control being enabled incorrectly. To further prevent the actuator from contracting above its maximum, an interruption function can be programmed in the MATLAB program with a variable that can be changed for every test. Adding such a function would also mean adding another variable that the testing person would have to keep in mind and change, but in the end fewer actuators would break, and it would be and economical benefit as well as safer for a possible future user.

According to previous research by [3] the strain of Nylon 6,6 is up to 4 %. The maximum strains obtained in the results of this thesis were 0.85 % for actuator 4 (8PLY – single thread), 3.21 % for actuator 6 (8PLY – double threads) and 6.31 % for actuator 17 (8PLY – extended single thread). The maximum strains and strains per metre are presented in table 5.1 below and can be compared to the 4 % strain of Nylon 6,6. Neither of the actuators manufactured in this thesis project reached a strain of 4 %. That means that actuators of Shieldex® 235/36 dtex 2-ply HCB produce less strain than Nylon 6,6.

The maximum strains obtained can be compared to the maximum strain of 22 % obtained in research by [33] on actuator of Nylon 6,6. Again, it can be concluded that the actuators manufactured and tested in this thesis do not reach the same or higher maximum strain than previous research. Actuator 17 had the greatest strain of 6.31 % which is around 29 % of the maximum strain obtained by [33]. It might be possible that the actuators of this thesis could be contracted more, but in attempts to not displace the actuators past their maximum strain, greater contractions were not tested.

TABLE 5.1 The total strain and strain per metre yarn are presented for each of the tested actuators.

Actuator	Total length of yarn used (m)	Total strain (%)	Strain per metre yarn (%/m)
4	1.90	0.85	0.45
6	3.90	3.21	0.82

7	3.90	2.37	0.61
10	3.90	1.68	0.43
17	6.00	6.31	1.05

The obtained force-to-strain ratios for actuators 4, 6, 7, 10 and 17 can be explained through figure 5.1 below. The highest force-to-strain ratio in this thesis was for actuator 17 where the strain was 6.31 % with a force of 1.47 N. In another research on the control and characteristics of supercoiled actuators of Shieldex® 117/17 dtex 2-ply HCB, a maximum force-to-strain ratio of above 10 % was obtained with a force of around 1N (see figure 5.2). [7] Comparing the two results shows that even greater force-to-strain ratios can be achieved than the final ratio from the work of this thesis. It may have been possible to obtain a greater force-to-strain ratio for actuator 17 if the annealing of the actuator was performed in line with the annealing in [7]. This can only be tested and concluded if actuator 17 is annealed and tested again.

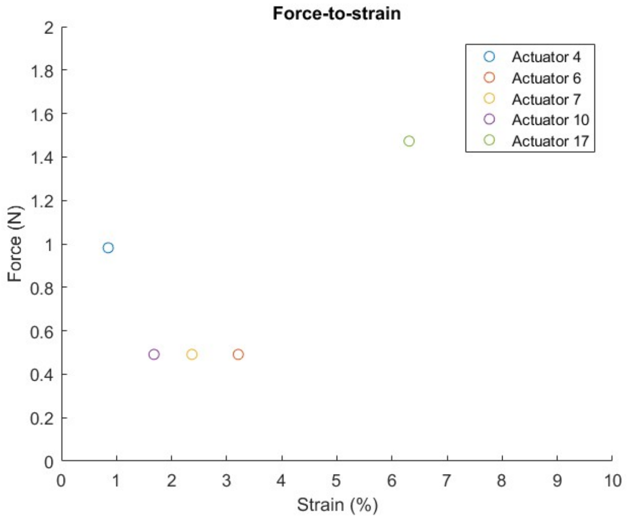


Fig. 5.1 The maximum force-to-strain ratios obtained for the tested actuators of this thesis project.

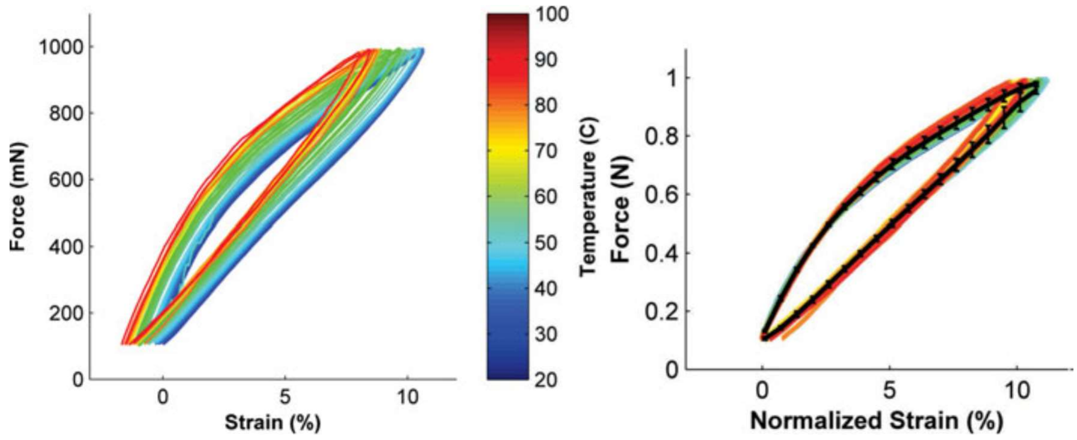


Fig. 5.2 Force-to-strain ratios of supercoiled actuators under different temperatures obtained in previous research by [7].

In [7], they also discuss the relation between maximum strain, annealing and temperature of the actuator. During the annealing process, the actuator is contracted until it smokes and then let to relax and cool down in temperature several times. When the actuator later is tested, it is said that its maximum strain is obtained when the actuator starts smoking. In the tests performed in this thesis the actuators started smoking several times. In such cases, the power was cut, and the actuator let to relax. When the power was not cut, the actuator eventually broke. This supports the idea that the actuators rise greatly in temperature when they are contracted past their maximum displacement, but also shows the moment when the actuators reach their maximum displacement. The line between over contraction and maximum contraction can be further studied by testing several displacement references.

Another temperature related matter that was noted during the testing of the actuators, was that the actuators contracted and relaxed easier when they were activated two times in a row. In such cases, the actuators were not touched between the tests (only the displacement sensor was reset). During the relaxation of the actuators, they did not always return to their initial length. That resulted in that the contraction during the second test was greater percentwise than the contraction during the first test. The initial length for the actuator during the second test was never measured, so a practical displacement cannot be presented percentwise.

For actuator 17, a critical characteristic noted was its sensitivity to movements in the table during testing. The sensitivity was slightly reduced by using a heavier weight, but still remained. Considering a real case where the actuator would be used as an artificial muscle in muscle rehabilitation or as a provided help for muscle weaknesses, its sensitivity to movements would be critical. Most of the time, muscles are used for movements such as walking and lifting. These movements are often smooth, but with actuator 17 they would be uneven in their relaxation if the actuator was under influence of, for example, two individuals bumping into each other. In many movement cases, this might not be a problem, but if the actuator is used in cases such as lifting and putting down a glass of water, the actuator might cause unpleasant results such as spilling water. Although, with the small force obtained with actuator 17, several actuators would need to be used to enable lifting a glass of water. An idea is that when several actuators are used together, they complement each other and the sensitivity to movements would be evened out amongst the actuators. In an unfortunate case of the actuators being synchronised in their sensitivity, the relaxation drops would amplify each other, and even more water would be spilled.

Considering the most suitable control of the actuation of the actuators, several aspects can be discussed. In the first control tests, the P and I parameters were greater than 0. That resulted in big errors, but a quick contraction of the actuator. The relaxation was quick at first but became slower with time. The big errors were also seen when parameters were greater than 0, but the difference between them was small (control test 5). Another interesting result obtained was when the D parameter was greater than the P parameter (control tests 32 and 33). In such cases, the actuators contracted a lot more than the given reference and resulted in very big overshoots. It was also noted that the contraction was extremely slow compared to contractions where the P parameter was greater than the D parameter. A third aspect to discuss is the transition of the position of the actuator between active contraction and static contraction. If the PID parameters P=0.24, I=0 and D=0.01 were used, the change between active and static contraction was quite sharp. If the D parameter was increased to D=0.05, the transition between the different states was smoother and slower (control test 44). It was also noted that the greater D parameter resulted in a slight overshoot in contraction, but a quicker relaxation. Since the ideal response would look exactly like a rectangular pulse, the smoothed transition between active and static contraction is of little interest. The slow relaxation can be solved with something pulling the actuator back to its original position and is less critical to the desired response of the actuator. This resulted in that the most ideal PID parameters obtained through the testing of the actuators were P=0.24, I=0 and D=0.01.

Since research previously has been made on Shieldex® 117/17 dtex 2-ply HCB as the material for supercoiled actuators, [7] a decision to only use Shieldex® 235/36 dtex 2-ply HCB was made in the beginning of this work. Interest was in if the latter could obtain a greater force-to-strain ratio. As has been discussed, the force-to-strain ratio did not increase with the new material, reaching the conclusion that it is not better. It is still important to consider other parameters during the manufacturing, such as set up quality and precision, that can influence the final result. When it comes to twisting and coiling the thread, it has been seen that the method is very detailed and requires caution and experience. In a more automated manufacturing setup, human errors can be reduced which in turn possibly can result in a better manufactured actuator. It is also important to recognise that both the materials from Shieldex Trading Inc. are low in weight and competing with other artificial muscles in that characteristic.

The yarn, Shieldex® 235/36 dtex 2-ply HCB, costs 0.017 € per metre and since the amount of yarn used for one actuator is only a few metres, the resulting cost is very reasonable. Of the actuators manufactured, actuator 17 uses the most yarn, 6 m. The final cost for the material for actuator 17 is then 0.10 €. On top of that, the MCU needed is 18 € and the servo motor is 8 €. The terminal ends cost between 0.15 € and 0.3 € depending on the size of the batch purchased. With only considering the yarn, MCU, servo motor and terminal ends, the final maximum cost for manufacturing one actuator, of the same type as actuator 17, would be 26.70 €. Further cost analysis can be seen in Appendix 1.

5.2 Manufacturing and testing of rigidifiable material

During the manufacturing of the guiding device, small problems with the scale of the sample drawn in Solid Edge were met. These were easily solved by scaling up the 3D drawing in the program for the printer. The two samples obtained had the same concept but different design. The idea was to let a rigid rod run through a channel in the guiding device due to a pull by a contracting actuator. When the rod was in the channel, it would create a rigidifiable material that would provide stability to muscles in rehabilitation situations.

From the printed 3D samples, it was concluded that it is important that the guiding device is not too tall. It would then stick out from the body and easily get stuck in objects that the user moves past. The height would also make a difference in the weight of the application since more material would be needed for the guiding device.

To easily apply the guiding device to a flexible material, such as a piece of fabric, the idea is to use sowing. The second guiding device was therefore manufactured with a platform with holes. The platform also provides stability for the material by resting in line with the muscle underneath.

Since it was previously noted that the actuator did not return fully to its initial length, that would mean that the rod would still be in the channel inside the guiding device. In such cases, it would be easier for the application to break when there is a requirement for flexibility, since the material would still be rigid. This can be solved with attaching an elastic thread, for example a rubber band, to the other side of the rod. When the actuator relaxes, the elastic thread would pull back the rod to its original position outside the mouth of the channel.

The rod is placed resting on the platform just outside the mouth of the channel. Because of the position of the rod, possible errors of the rod getting stuck on the edge of the platform are reduced, but the flexibility of the rigidifiable material is limited to the cone. The size of the cone would then have to be decided considering the required flexibility of the material, but also, as mentioned before, the kind of material used for the guiding device and the external risks of the device getting stuck.

Further research would include more specific situations where the rigidifiable material would be used, the material for the guiding device and the rod, the reliability in the response of the actuator and how and when to trigger the actuation of the actuator. An idea for how the rigidifiable material could be attached to a piece of fabric is shown in figure 5.3 below. This would increase the rigidity of the material and produce a stronger force.

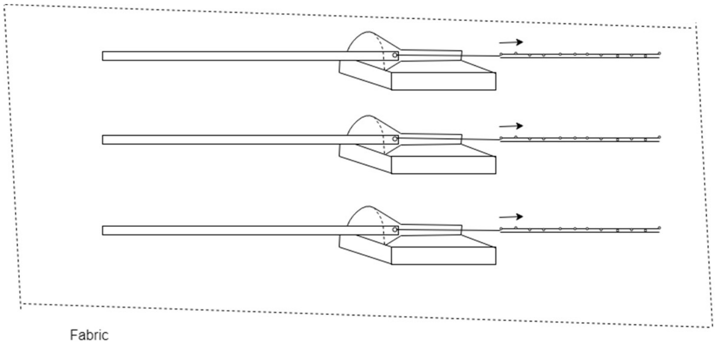


Fig. 5.3 The rigidifiable material could be added together with others on a piece of fabric.

To continue the idea of the rigidifiable material, one example is to make it into a sleeve. The sleeve can later be put around a muscle such as a thigh or the torso. This would provide the muscle with stability and help to keep it rigid in situations when it is necessary. Such situations can be when the foot pushes off the ground in a step or when sitting straight while driving a car.

6 CONCLUSIONS

The work of this thesis project resulted in a conclusion that Shieldex® 235/36 dtex 2-ply HCB does not add a new aspect to the field and research on silver coated Twisted and Coiled Nylon actuators.

Since more successful results have been obtained through previous research on Shieldex® 117/17 dtex 2-ply HCB by [7], the wiser would be to continue using that material for silver coated TCN actuators. If Shieldex® 235/36 dtex 2-ply HCB in the future is found to produce more ideal characteristics regarding force-to-strain ratio and response behaviour, it would be considerable to manufacture TCN actuators with that material. Both yarns are very similar in price, and in addition very inexpensive. That means that whichever material is used for the actuators, would result in actuators that are competitive on the market compared to other current actuators regarding manufacturing cost.

The manufacturing steps for TCN actuators are easy to follow, require little equipment and can be adjusted to the amount of yarn used to manufacture the actuators. It is important that the steps are carried out with caution to not damage the yarn and that the equipment is well maintained to last longer in a production line. A single actuator was made with a maximum of 3 m continuous yarn. Another actuator was made with a total of 6 m yarn, but of two actuators of 3 m each.

A manufacturing difference between previous TCN actuators and actuators of Shieldex® 235/36 dtex 2-ply HCB is the number of twists that are required to coil the thread. The resulting number of twists per metre yarn in the work of this thesis is less than the number achieved for previous actuators. This makes the manufacturing of Shieldex® 235/36 dtex 2-ply HCB less time-consuming.

Over 70 different control tests led to the conclusion that the PID parameters P=0.24, I=0 and D=0.01 give a response closest to the ideal response. With them, a bilinear compensator with parameter Kb=1 is to be used. The final response of the actuator showed a quick contraction and very little, if any, overshoot but a somewhat slower relaxation. The slower relaxation can be complemented with an elastic thread that pulls back the actuator to its initial position.

Also with the actuation of the TCN artificial muscle, it is important to be careful. The actuator tends to become very hot when contracted past its maximum contraction. It also starts smoking, and if not deactivated in time, it eventually breaks. It was also concluded that the actuator is more sensitive to disturbing movements the lighter the weight used during testing is. The critical aspects on the behaviour of the actuator can be a problem when the actuator is used in practical applications.

The idea of a new design to apply TCN actuators to create a rigidifiable material was also initiated. It was shown that together with a guiding device and a rigid rod, the actuator can be used to change the rigidity of a flexible material, such as fabric. This can be used in applications for rehabilitation of individuals with muscle weaknesses and would offer a new, rather inexpensive product to the market. For the rigidifiable material to be widely used, further research and improvements will have to be made.

7 FUTURE

In the future, several steps in the manufacturing of the TCN actuators can be improved to make the production line less time-consuming, cheaper, more automated and more reliable. To reduce the time of the manufacturing, a set length of yarn can be twisted from both sides of the thread. It would require that one twisting end is flexible and can move towards the other end when the thread coils, and the resistance is equal to the dead weight in the manufacturing setup in this thesis. When manufacturing an actuator by adding yarn continuously, this can be done automatically by the setup pulling yarn from the reel. The improvement would require less personnel, making the manufacturing less expensive. Less human involvement would also reduce the risks of damaging the material and make the manufacturing more reliable and precise.

Since the design of a rigidifiable material was only introduced in this thesis, there is a lot that can be further researched regarding material, cost, application and user comfortability. For the material, the most important parameters are rigidity and weight. The cost of the rigidifiable material will depend on the material together with the actuator. Further research can also be made considering how to apply the guiding device to a flexible material in the best possible way, as briefly mentioned in the discussion. It will also require an idea of how to activate the rigidifiable material. This will further lead to adjusting the application for the user comfortability and make it accessible for everyone.

Another important aspect that needs to be considered is the regulations regarding medical devices. Several regulations on national, European and international levels need to be met for the actuators and rigidifiable material to be released on the commercial market.

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APPENDICES

Appendix 1 – Cost Analysis Actuator and Rigidifiable Material

The estimated cost for this project if it was carried out by a biomedical engineer including purchasing the material and production equipment would be a total of 10 840.94 € with all taxes included. The cost analysis confirms that the material cost for the actuators and the rigidifiable material is very low. What adds to the total cost of the project is the production equipment and personnel.

The tables below show the estimated costs for the material and production of the actuators and the rigidifiable material. Two micro controller units are used to be able to manufacture and test actuators at the same time.

TABLE A.1.1 Material costs for the project.

Material cost	**Quantity**	**Price**	**Total cost**
Shieldex® 235/36 dtex 2-ply HCB	55 m	0.017 €/m	0.94 €
Terminal ends	30 un	0.3 €/un	9 €
Filament for 3D printer (material)	0.2 kg	50 €/kg	10 €
Metallic rod (1 m)	1 un	2 €/un	2 €
			21.94 €

TABLE A.1.2 Production costs for the project.

Production cost	**Quantity**	**Price**	**Total cost**
Biomedical engineer	350 h	15 €/h	5250 €
Supervisor	40 h	25 €/h	1000 €
Second supervisor	50 h	25 €/h	1250 €
Servo motor	1 un	8 €/un	8 €
Dead weights (pack of 8)	1 un	50 €/un	50 €
MCU	2 un	18 €/un	36 €
Power supply *	1/18 un	560 €/un	31 €
PC with monitor	1 un	800 €/un	800 €
MATLAB License	1 un	800 €/year	800 €
3D printer **	1/24 un	500 €/un	21 €
Other equipment costs			50 €
			9 296 €

*Used approximately 2 months, warranty ~ 3 years

**Used approximately 1 month, warranty ~ 2 years

TABLE A.1.3 Total project cost.

Project cost	**Total cost**
Material cost	21.94 €
Production cost	9 296.00 €
	9 317.94 €

Appendix 2 – Project Time Plan

The approximated time spent to complete this thesis project was 350 h. The hours were divided between research, practical work, studying of results, report writing and supervision. The table below shows the hours broke down for each part.

TABLE A.2.1 Time division for the project.

Part of Project	**Time (h)**
Literature research	20
Manufacturing and testing of actuator	110
Design, manufacturing and testing of rigidifiable material	30
Report writing and comparison of results	150
Supervision	40
Total	350

Appendix 3 – Glossary

BPID	Bilinear PID
cPBE	Propylene-based elastomer
EAP	Electroactive Polymer
MOQ	Minimum Order Quantity
PDMS	Polydimethylsiloxane
PID	Proportional Integral Derivational
PPy/CB	Polypyrrole/Carbon Black Composite
PVC	Polyvinyl Chloride
SCP	Super Coiled Polymer
SMA	Shape Memory Alloy
TAP	Thermoactive Polymer
TCA	Twisted and Coiled Actuator
TCN	Twisted and Coiled Nylon
TCP	Twisted and Coiled Polymer