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Automatisk håndtering av fisk ved bruk av kraftregulering og griperoptimalisering

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Master i kybernetikk og robotikk
Innlevert: juli 2015
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SINTEF

ROBOTIC HANDLING OF FISH WITH POSITION CONTROL
- FORCE FEEDBACK and GRIPPER OPTIMIZATION

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Master thesis in Engineering Cybernetics
Trondheim, July 2015

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Thesis support: SINTEF Fisheries and Aquaculture

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NTNU Norwegian University of Science and Technology

SPECIALIZATION PROJECT in ENGINEERING CYBERNETICS

ROBOTIC HANDLING OF FISH
WITH POSITION CONTROL
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Faculty of Information Technology,
Mathematics and Electrical Engineering

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Master thesis written at NTNU/SINTEF, 2015

Printed by Fagtrykk Trondheim AS

Abstract

For the reader to directly see the main results of the thesis and the discussion of these, it is advised to go to part V - Discussion and Conclusion.

As the world's population grows with rapid speed, the demand for food grows every day. To accommodate this frightening problem, something has to be done. How can we utilize an already efficient food industry? How can we expand the production without causing too much impact on mother earth?

The questions above are big questions with possibly bigger answers which are not to be discussed in this paper. However it is important to have a sence of understanding of the deeper meaning of what we try to achieve in our goal in making the food production more efficient. How much automation can we put into a production line without causing thousands of people to lose their jobs?

This thesis is written with focus on gripper optimization for robotic handling of fish. The motivation is the widely practice of humans in Norway's fish industry which manually moves fish. There are two reasons for humans moving fish: quality control and the diversity and compliancy of the fish. Quality control is a task which requires good image processing. This is under development as we speak (or as I write). To grasp a fish humans use good eye-hand coordination as well as good force feedback from fingers. This thesis will investigate the possibility of optimizing a gripper in terms of local force feedback. Experiments with force measurements on fish as well as gripper design is presented in this thesis.

Acknowledgements

I want to acknowledge my supervisor at NTNU, *Anton Shiriaev*, for valuable inputs along the way. You have done a great job in guiding me in the right direction. Also I would like to thank *Leonid Paramonov* for inputs on gripper design. Thank you *Terje Haugen* at the workshop for Engineering Cybernetics for producing the gripper prototypes. I want to hand out a big thank you to *SINTEF Fisheries and Aquaculture* for giving me the oppurtunity to use their facilities for practical testing as well as guidance and economical support. To *Elling Ruud Øye*, *John Reidar Mathiassen* and *Aleksander Eilertsen* at SINTEF Fisheries and Aquaculture; thank you for supervising me, and showing genuine interest in my work. Thank you *Alekander Eilertsen* for helping me drawing the gripper prototype.

Without you guys, this thesis would have been much tougher. Not only have you helped me scientifically, but also the platform you have given me practically has been a great kick-start for this thesis. I would like to thank *Pernille Nguyen Johansen* and *Christian Søderholm Johannessen* for giving me valuable motivation.

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PART I

INTRODUCTION

Abstract – This part discusses the importance of automation in food production, with a focus on the fish industry in Norway. A lot of the same issues are common in all of the world's fish industry, however due to the economic differences, automation is more important in countries such as Norway. The project assignment is described in more detail in this part, listing up what is thought of as main challenges.

Due to the expensive labor force in Norway, there are increasing demands for ways to save money in Norwegian and other western countries' industry. Food industry is world wide a huge industry. However the food industry is very little automated compared to many other industries. There are many reasons for this. As mentioned in the next part, robots are good at things that are structured. Food can have different sizes, different species of both plants and animals, there could be anomalies and food is compliant. A human's ability to see, decide, touch and feel are still greatly superior to that of a robot.

> *Fishing is much more than fish. It is the great occasion when we may return to the fine simplicity of our forefathers.* - Herbert Hoover

Why could a company be interested in using a robot in the production line? Time is money – a robot could decrease the production time for each food unit. Except for a robot's need for maintenance, it never gets tired. No coffee breaks, no sleeping and no complaining about a sore back. Today most of the world's food production happens in countries with cheap labor forces. So why invest a lot of money in food production in countries such as Norway?

Chapter 1

Fish Industry

1.1 Motivation

It is important to understand the motivation for further investigation on automation of the fish industry, especially in Norway where the salary is very high. SalMar is a Norwegian company which produces farmed salmon. SalMar has taken place as one of the worlds biggest and most efficient producers of farmed salmon. After visiting SalMar's factory at Frøya, outside the coast of middle-Norway, one thing was standing out: Along with sophisticated technology, many parts of the process there were humans moving fish in the same direction. The reason for this was the diversity of directions and positions of the salmon coming from the conveyor belt as well as the need of human quality control.

Automated quality control of the fish is currently under development, however there is not much focus on how to move the fish efficiently and in a failsafe way. Because of the compliance and the slippery consistency of the salmon, it is even for a human quite difficult to grip the salmon properly. Usually the operators use pebbled gloves which minimizes the friction. Another important aspect of the human way to grab the fish, is the force feedback from the fingers gripping the fish. It is a balance between gripping the fish firm enough to prevent slip as well as not to deform the fish. This will be investigated in this thesis in a way of imitating a human grabbing a fish in terms of force feedback as well as gripper optimization.

1.2 Worldwide point of view

Worldwide the biggest fish export countries are China, Norway and Thailand based on numbers from 2012 [11]. China exported for 18.228 million US dollars, while Norway as the second biggest fish export country exported for 8.912 million US dollars. Norwegian fish industry has a big challenge ahead, and the challenge seems closer than earlier anticipated. Norwegian labor force is one of the most expensive worldwide. China still has a cheap labor force even though they have one of the fastest growing economy in the world. China may some day face the same problems Norway are facing now, however they still have a long time ahead to plan their automatic controlled fish industry. For Norway to maintain its position as one of the world leading fish export countries, the fish industry has to go through massive changes. This is where we will come to play with our robotics.

1.3 Norwegian point of view

Norway has got a 103.000 km long coastline. Note that the equator is approximately 40.000 km long. Thus one can easily understand that fishing and aquaculture has strong roots in Norway. The fish industry in Norway has a long history, however it has not been technologically revolutionized. Norwegian seafood industry includes four value chains: Fishing, aquaculture, fish processing and export/trade. It is thought that the Norwegian seafood industry has a great development potential and some have predicted that it is designated to replace the oil sector as the main export industry in the future. The importance of fishery and aquaculture in Norway is stated in [10]. Figure 1.1 shows an overview of the 14 industry groups with the highest value added per man-year in Norway in 2010. In total, the Norwegian seafood industry, added values in terms of contribution to GDP of about 46.5 billion NOK in 2010. One can clearly see that values coming from the oil industry makes a huge contribution to GDP. Furthermore it is clear that the Norwegian oil adventure can not last forever. The oil does not last forever. Removing oil- and gas-related value chains from figure 1.1, we can see that the seafood industry plays an important role today, and maybe an even more important role in the future.

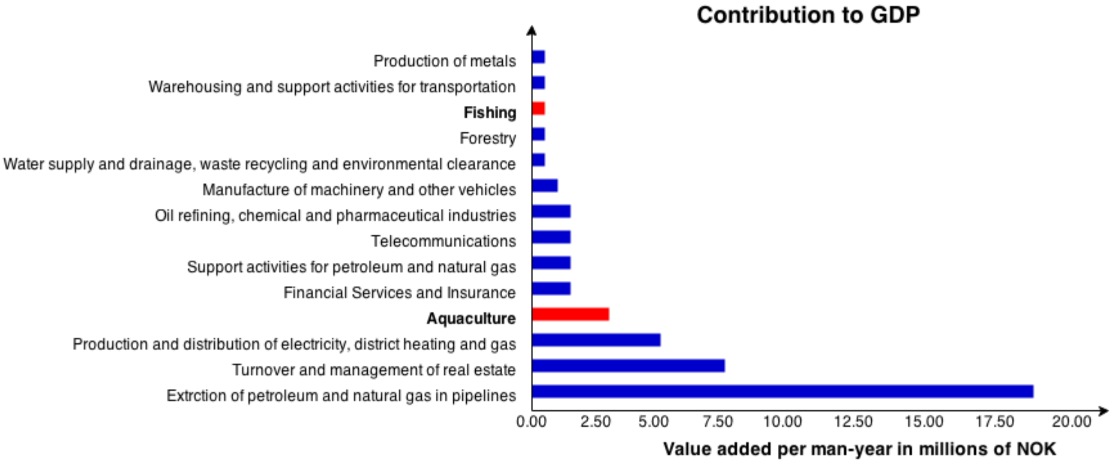

Figure 1.1: Overview of the 14 industry groups with highest value added to GDP per man-year in 2010 [10].

In 2010 the seafood industry had an employment equivalent to 44.000 man-year. What will happen to the employment when parts of the industry becomes automated? One other important factor is that the seafood industry in Norway is mostly a district industry. Therefore a lot of logistics is required as well. There are both pros and cons with large scale logistics. For transport companies this results in added employment, while someone has to pay for the transport. The environment is also affected by huge logistic operations. All this are also affected by an growing act of urbanization throughout the country. There is a job culture in Norway which makes it difficult to fire people without a very good reason. Hopefully, when robots replace humans in food production, people would not get fired.

Chapter 2

Robotic handling of fish

Automatic handling of fish is a growing field in the fish industry. Today there are mainly mechanical handling of fish, while robotic handling is more rare. However the industry are welcoming new innovations continuously. In general the production line have one or more points where humans manually move fish, thus the future is open for a robotic revolution.

2.1 Grippers in fish industry

Today there are few pure fish grippers or grabbers. Fish grabbers can be used in many different processes. On fishing vessels of different sizes as well as different types of factories. When moving fish automatically, often a mechanical solution is employed. This can be

- Opening a hatch. This results in the fish dropping from one level above down onto for example a conveyor belt or into separate buckets.
- Pushing device. A mechanical push-plate can push the fish in a new direction or adding speed to the fish down the production line.

The above mentioned methods are the most common mechanical ways of moving fish. Fish grabbers and future possible usage of them are discussed below.

2.1.1 Areas of use

The Salmar factory at Frøya uses robotic grippers, however not to move fish itself, but to move styrofoam boxes containing fish. The robot grabs the boxes from a conveyor belt and stack them onto a pallet for further transportation. This gripper is a pneumatic tool, and it is very important to apply the correct pressure due to the characteristics of styrofoam boxes. They can easily break, and the pressure must be big enough to hold the box containing quite heavy fish.

In some processes it is important that the fish has a certain orientation. This is done manually by rotating the fish by hand. For a gripper performing this task it is important with a rigid structure capable of handling high torques due to rotating heavy fish in high speeds.

Another important case is during quality control. Today quality control is performed by humans where the task is two-sided: visual quality control and manual transfer between parts of the process. In this case a gripper with form- and/or force-closure ensuring no-slip is important.

A more futuristic vision is dynamic robotic handling of anomalies in the process. This can be fish stuck somewhere in the process or fish which has fallen down. In this case the same gripper as described above is needed. No-slip is important.

2.2 Previous work by thesis author

In the case of fish rotation both a prototype gripper and a second version has been tested. The prototype shown in figure(2.1) was lacking the compliance in order to perform satisfactory. Most trials ending in failure was due to wrong fish height measurement, causing the gripper to either generate too much force in negative z-direction or too little force was applied which caused slip. Another important issue was the material which was in contact with the fish. It is desired to being able to rotate and move the fish both without slipping and damaging it.

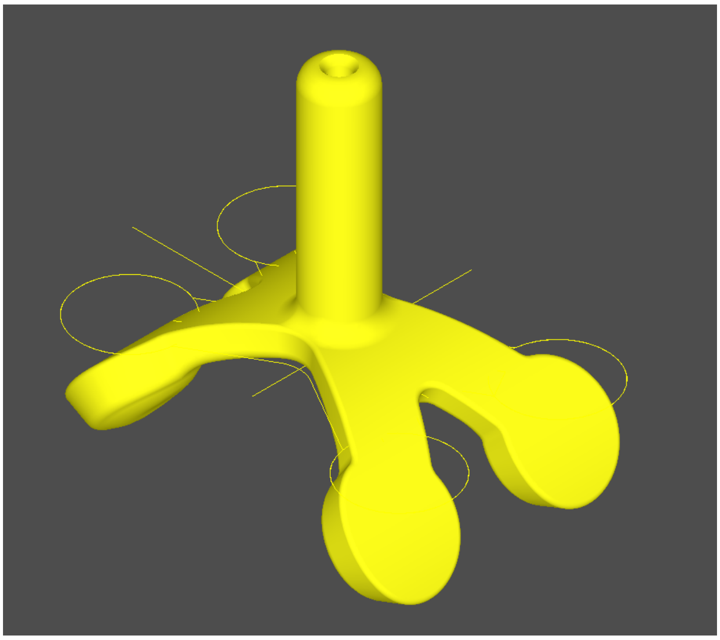

Figure 2.1: 3D image of fish gripper prototype.

The second version of the gripper had a spring mechanism which allowed us to get a more damped force between the gripper and the fish. The new version has also the ability to use force sensors or other embedded systems.

Trials with the four-fingered gripper where done as shown in figure (2.3). The transformation between camera and robot coordinates are quite simple in this case since only x- and y-coordinates are considered. The workspace is therefore a two-dimensional plane, the XY-plane.

The way this application works is in short terms: Kinect detects the position of the fish on a conveyor belt. After a transformation to robot coordinates, the robot moves to a point directly above the center of the fish. A kinect module which detects the position and orientation of the fish

Figure 2.2: Version 2 of fish gripper.

is running in parallel with the robot control algorithm. When the robot has reached the point above the fish center, the robot moves in negative z-direction and puts pressure on the fish body with the gripper.

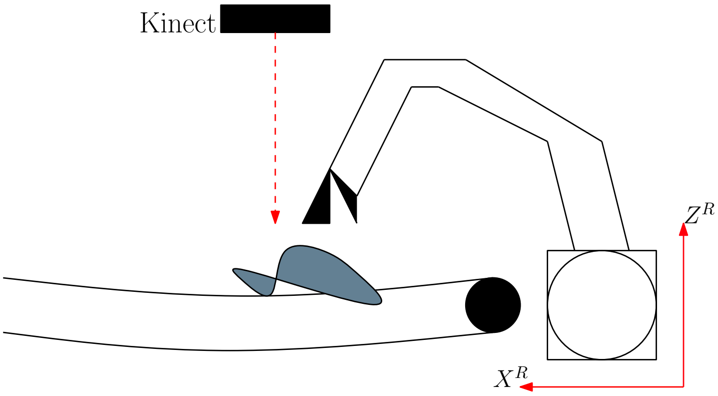

Figure 2.3: Lab setup for fish handling.

According to the fish orientation, the robot will rotate the fish and move it to a given exit. The fish can be sent to two different exits depending on the orientation of the fish and which exit is closest. Each of these exits is split into two exits, so in practice we have four exits. The goal is to send the fish to an exit such that the head points in the direction of the motion as well as the belly of the fish should point in positive Z-direction after sliding down a chute. In other words, the fish should after initially laying sideways, naturally slide down a chute where the belly points upwards at the end of the chute.

2.2.1 Chicken fillet harvesting

A small notice of the work done in chicken fillet harvesting is also worth mentioning. The reason for mentioning this is that there are several similarities between the applications. Compliance characteristics is important taking into consideration, and gripping both chicken fillet and fish has many of the same challenges. A challenge when gripping chicken fillets was slipping when displacement in the chicken meat was too big.

Chapter 3

Problem description and setup

3.1 Problem statement

In general words, the problem presented in this thesis is to imitate the human grasping of a fish in terms of force feedback and finding a satisfactory way of gripping the fish without too much deformation.
There are two main focuses in this thesis:

1. *Force measurements.* This includes finding a satisfactory region of force applied on a fish as well as experiments with both continuous force feedback position control of gripper and force measurement to detect contact.

2. *Gripper optimization.* Design and documentation of gripper.

3.2 Software

LabVIEW

The software used for this project is mainly LabVIEW. LabVIEW has libraries for use of the DENSO robot. Data acquisition is obtained with a NI-DAQ, which has support through LabVIEW. LabVIEW and certain modules in LabVIEW are used to control the robot as well as the gripper.

Arduino 1.6.3
Arduino software is used along with an arduino board to program and test the motor and motors.

Google SketchUp
Used for prototype design of grippers.

SolidWorks
Used for prototype design of grippers.

3.3 Hardware

DENSO VS-087
The robot used for this project is a DENSO VS-087 which has 6 revolute joints.

Arduino Duemilanove
Arduino board with ATMega328P-PU microcontroller. Motor driver is connected to the arduino board. This is used to program and test motors.

Futek LSB200 Miniature Load Cells

Two sensitive compression and tension sensors were used to measure compression continuously. One has a maximum load of 44 [N]. The other has a maximum load of 22 [N].

Data acquisition

A 4-channel NI 9237 analog input module mounted in a cDAQ-9171. This is used to read and process the output from the load cells.

3.4 Thesis summary

Chapter 1 presents the motivation for researching this subject. Some mathematical and physical background for better understanding the contents of this thesis are presented in chapters 4 and 5. Chapters 6 and 7 presents the part goals and setup for experiments done. Chapter 8 gives the reader the main results of the research, before chapter 9 and 10 concludes and discusses the results. Lastly, the aftermath in chapter 11 shows some thoughts about the future regarding this subject.

PART II

BACKGROUND

Abstract – This part is divided into two main focuses: The physics of the problem, and technical theory.

Dictionaries describe the word background as ”the ground or scenery located behind something” or ”The circumstances and events surrounding or leading up to an event or occurence”

> *Robots are good at things that are structured* – Vijay Kumar

Humans are good at interacting and dealing with compliant objects. We have a very complex way to feel and see compliant objects. Let us think about fish – We can easily see differences in many species, we can see differences in size and orientation. We can also interact with the fish in many ways by feeling with our hands. We can try to grab the slippery fish, and if we fail we may try to grab harder or in a different way. How can we implement such features in robots? A good way to start is to make the robot so good at recognizing and grabbing, that it doesn't fail at all. The next step is to have feedback information from the interaction point to the robot. Bottom line, **it is difficult to design a control system for robotic handling of compliant objects**.

Chapter 4

Compliance modelling and observations from the nature

This chapter will shine light on the nature of compliant objects. How can such objects be described mathematically? A precise model is often difficult to find due to the shape of the object and the difficulties of finding precise parameters, such as stiffness and viscosity. For a fish these parameters can be especially difficult to find when handling it as whole, with meat, skeleton and guts. As we will see, a approximation can be developed for the mathematical model for mechanical behavior.

4.1 Mathematical model

Compliance is the inverse of stiffness, typically measured in units of meters per newton. As shown below the parameter for stiffness is used in the mathematical model for the mechanical behavior of deformable objects. *Tan et al.* [1] suggests as an approximation, the mechanical behavior of all deformable solid objects can be expressed as

$$f = F_s + Kx + B\dot{x} + M\ddot{x} \tag{4.1}$$

where f is the total force applied on the object with the displacement x, velocity $\dot{x}$ and acceleration $\ddot{x}$. K is the linear stiffness, or the change in force divided by change in displacement. B is the viscosity. Viscosity is often used when talking about fluids, while elasticity is more common when talking about solids [2]. Fluids will often have the same properties as solids and vice versa. Such objects/materials can be described as having both elasticity (reaction to deformation) and viscosity (reaction to rate of deformation). F_s is frictional force and M is the mass of the object.

4.2 Physical interpretation

As will be discussed later, the compliance of a fish and the stiffness of a spring can be closely related. The use of words in this matter can be confusing. To make this clear: For a body with one degree of freedom the stiffness k is

$$k = \frac{F}{d} \tag{4.2}$$

where F is the force applied to the body which yields the displacement d in the same direction as the force applied. The inverse of stiffness is often referred to as compliance or elastic modulus [4]. Elasticity or compliance is in general used for deformable object, and stiffness is used in terms of structure. Of course on molecular level every materials are deformable, however talking about the elasticity or compliance of for example steel is not common. One property of a steel structure is stiffness, not compliance. *Rotational stiffness* is a rotational force, or moment, M over the angular distance θ:

$$k = \frac{M}{\theta} \tag{4.3}$$

However rotational stiffness is not relevant in the scope of this text other than the focus on rotational forces during the design of gripper 2 shown later. Given an object deformed by an element with length L and cross-sectional area A the stiffness is

$$k = \frac{AE}{L} \tag{4.4}$$

where E is the elastic modulus, often referred to as *Young's modulus*.

4.2.1 Force acting on an elastic half-space

Often contact problems are described as one force or a distributed force acting on an infinitely large half-space [7]. The elastic half-space will get deformed when acted upon by a force.

When a force acting at the origin in the positive z-direction (figure (4.1)) we get the following equations for the displacement u in x-, y- and z-direction:

$$u_x = \frac{1+\nu}{2\pi E}\left[\frac{xz}{r^3} - \frac{(1-2\nu)x}{r(r+z)}\right]F_z, \tag{4.5}$$

$$u_y = \frac{1+\nu}{2\pi E}\left[\frac{yz}{r^3} - \frac{(1-2\nu)y}{r(r+z)}\right]F_z, \tag{4.6}$$

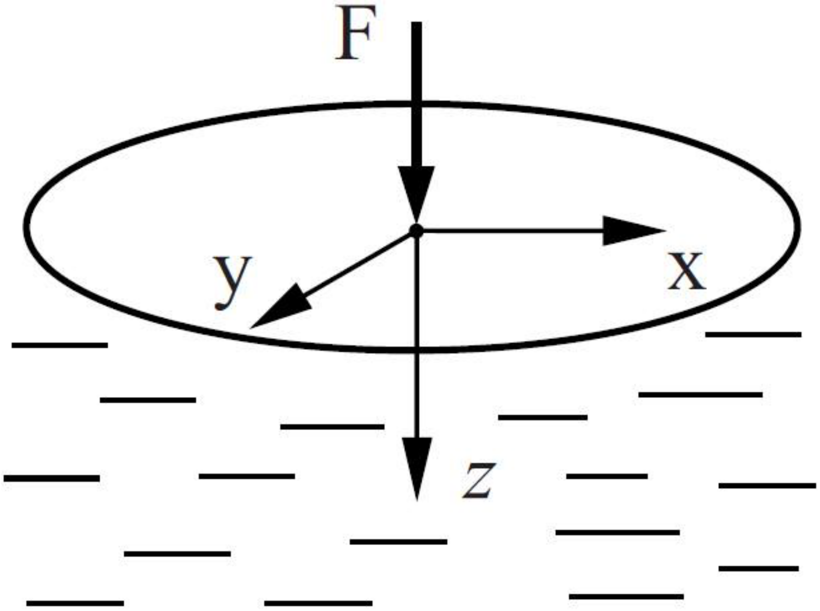

Figure 4.1: Force acting on an elastic half-space.

$$u_z = \frac{1+\nu}{2\pi E}\left[\frac{2(1-\nu)}{r} + \frac{z^2}{r^3}\right]F_z, \tag{4.7}$$

where $r = \sqrt{x^2+y^2+z^2}$. Furthermore

- ν = Poisson's ratio. It is dimensionless. This parameter is a measure of the Poisson effect which is the phenomenon when a material is compressed in one direction, it will often expand in the directions perpendicular to the direction of the compression.

- E[Pa] = Young's modulus. It is defined as the ratio of stress to strain.

Then for the free surface, $z = 0$ we get

$$u_x = -\frac{(1+\nu)(1-2\nu)}{2\pi E}\frac{x}{r^2}F_z, \tag{4.8}$$

$$u_y = -\frac{(1+\nu)(1-2\nu)}{2\pi E}\frac{y}{r^2}F_z, \tag{4.9}$$

$$u_z = \frac{(1-\nu^2)}{\pi E}\frac{1}{r}F_z, \tag{4.10}$$

where $r = \sqrt{x^2 + y^2}$.

4.3 How animals grip

There are different ways that animals and insects (from here on when referring to animals, it includes both animals and insects) employ gripping and grasping features. Some features are for climbing, other for stable walking. Some animals also grasp objects and use them as tools, and some grasp their food similar to how humans grasp food with their hands. One important observation made from the nature is the *passive* gripping abilities of many animals.

Scientists at University of California Riverside has done research on the gripping abilities of geckos [22]. It is very interesting how they can climb vertical surfaces seemingly with no effort. Even with smooth surfaces such as glass, they can easily climb vertically. The question was then – are these amazing gripping abilities passive or active?

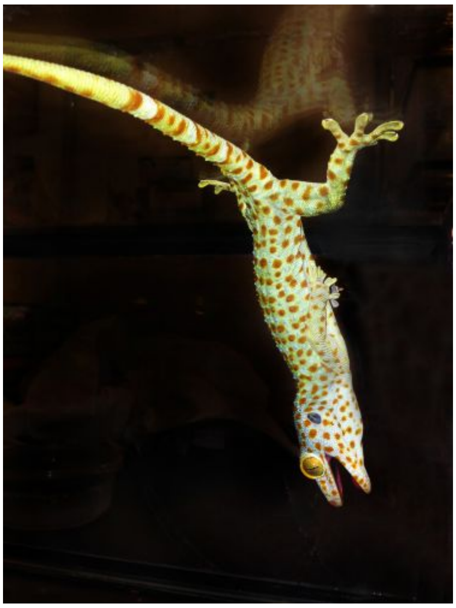

Figure 4.2: Gecko climbing vertically on a smooth surface.

To test their hypothesis they measured shear forces before and after death of the gecko. This was measured vertically with a force measurement device as well as with cameras. It was found that the gecko's gripping ability can support 20 times their own weight.

Figure 4.3: Foot of the gecko.

Important aspects of the gecko foot are the symmetry of the toes as well as the toe pads. These toe pads are found to be inherit by microscopic hair-like structures. These structures are thought to be the source to the gripping strength.

A very important result was that the gecko has equally good gripping abilities after death has occurred. This confirms the hypothesis of passive gripping. Author of [22], Timothy Higham, said “The idea that adhesion can be entirely passive could apply to many different kinds of adhesion. This is clearly a cost-effective way of remaining stationary in a habitat. For example, geckos could perch on a smooth vertical surface and sleep for the night – or day – without using any energy.”

The evolution is a great process, which has over time made some amazing features. Why is this passive gripping so rare then? It is important that this feature is balanced. If the stickyness is too big, this can also affect the motion of an animal by creating too much friction. Observing monkeys, which also are climbing animals, they have almost completely active climbing abilities. If the monkeys had such gripping abilities as the gecko, the monkey would still be to heavy to climb vertical surfaces because of the small contact area. It would also cause unnecessary stickyness when walking.

Chapter 5
Technical Theory

5.1 Pulse Width Modulation

Pulse Width Modulation (PWM), is used in a wide variety of applications. Several of the most common modulation methods employed in measurement devices and signal amplifiers implies a discrete reproduction of a signal [14]. Since analog signals can be difficult to tune, and may drift over time, it is important to be able to control analog signals digitally. In other words, an analog circuit can often be economically inefficient without a digital control. Therefore most applications with analog circuits today, has a digital control.

The digital control of analog circuits results in more efficient power consumption [15]. In short terms, PWM makes sure analog signals are digitally encoded. A modulated duty cycle of a square wave ensures the encoding of a specific analog signal level. Since the DC signal is either on or off, the PWM is digital. The whole idea behind PWM is being able to adjust the on-time/of-time of the signal. With a sufficient bandwidth, a good reproduction of the analog signal can be made.

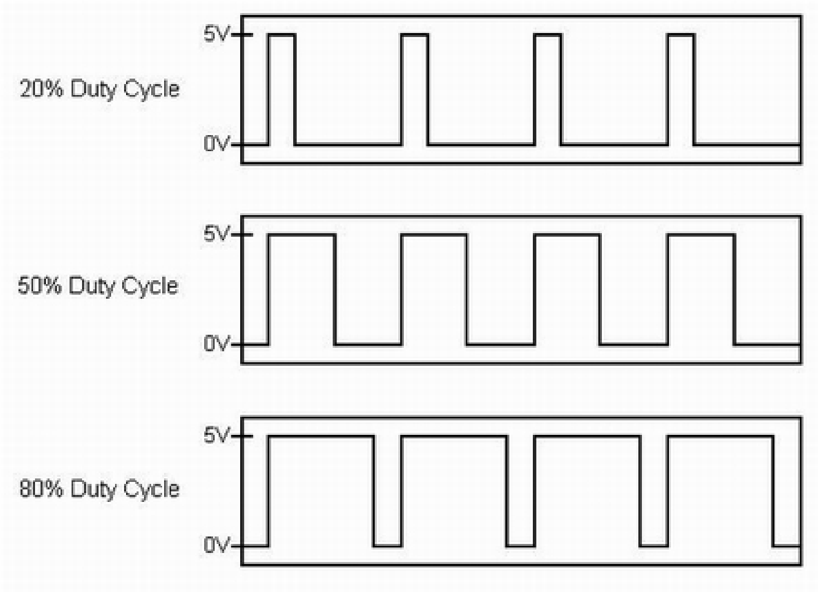

Figure 5.1: Pulse Width Modulation with different duty cycles.

If the clock frequency of the PWM is very slow, this corresponds to turning the signal to maximum for a while, and off for a while. Intuitively one can think of a light bulb being switched off and on. If a 9V power supply is connected to a light bulb with a PWM-switch in between, and a slow clock frequency, i.e. 2 Hz, the light bulb will switch between completely off and on. If the the bulb is controlled by a PWM with 50% duty cycle, 100 Hz and a 9V power supply, the resulting light will be as if the bulb was connected to a 4.5V power supply (50% of 9V). As will be seen later in this thesis, PWM is used to control the speed of a DC motor by controlling the voltage applied to the motor in the same manner as described for the light bulb.

Mathematically one can describe PWM as follows: Consider a rectangular pulse waveform $f(t)$ with period T, low value y_{min}, high value y_{max} and a duty cycle D. Then the average value of $f(t)$ is

$$\bar{y} = \frac{1}{T}\int\limits_0^T f(t)dt$$

$f(t)$ is a pulse wave, thus

$$f(t) = \begin{cases} y_{max} & \text{for } 0 < t < D \cdot T \\ y_{min} & \text{for } D \cdot T < t < T \end{cases}$$

then we get

$$\begin{aligned} \bar{y} &= \frac{1}{T}\left(\int\limits_0^{DT} y_{max}dt + \int\limits_{DT}^{T} y_{min}dt\right) \\ &= \frac{D \cdot T \cdot y_{max} + T(1-D)y_{min}}{T} \\ &= D \cdot y_{max} + (1-D)y_{min} \end{aligned}$$

and since often $y_{min} = 0$ this can be simplified to $\bar{y} = D \cdot y_{max}$. Thus the direct dependency of the duty cycle can be seen.

5.2 Force measurement

As force measurements are a very important part of this thesis, a short description is given on the subject. There are several different ways of measuring force. The easiest way of measuring force is with a weight and the fact that the gravitational constant is $g \approx 9.81[\mathrm{m/s^2}]$. The history of force measurements is long. From Archimedes who discovered the force-amplifying capability of a pulley, and the discovery of the difference in displaced water when submerging the same weight of silver and gold to Stephen Hawking who unified Einstein's relativity theory with modern quantum theory [16]. The force measurement theory in this thesis originates from somewhere between those two.

The most common ways of measuring force is by measuring strain, load, torque or piezoelectric. Often load cells and torque sensors use the physics of strain and piezoresistivety. The force sensor used in this paper is a strain gage load cell. It has a shear beam, and can measure both tension and compression. Note that strain gages are also called strain *gauge*. The gages are bound to a beam that deforms when weight is applied. Often four strain gages are connected to each other, where normally two are in tension and two in compression [17].

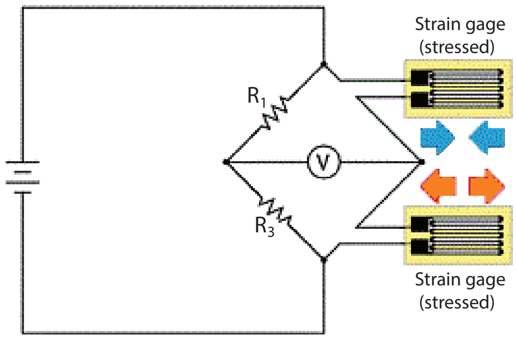

Figure 5.2: Half-bridge.

In a half-bridge configuration, the load cells have two strain gages connected on opposite arms. Compared to the full bridge, the change in signal is halved for the same amount of strain.

Since resistors have variable resistance for different temperatures, the performance of the half-bridge is less accurate than the full-bridge.

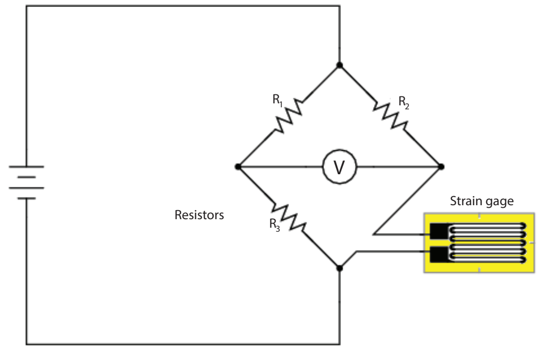

Figure 5.3: Quarter-bridge.

The quarter-bridge is the least expensive bridge configuration, it also have the worst performance in terms of accuracy and signal strength.

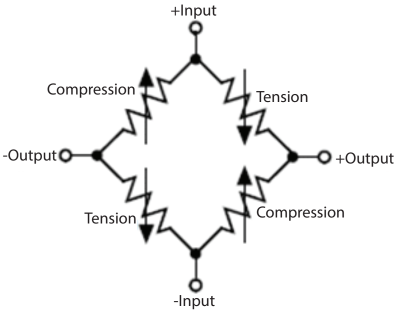

Figure 5.4: Full-bridge.

The full-bridge configuration has strain gages on all four arms of the Wheatstone-bridge. This results in the highest output signal and the most accurate signal. Noise are coupled such that it gets cancelled out.

The full bridge has a good compensation for temperature differences as well.

5.3 Control theory

Since a control objective in this thesis is to control the position of gripper fingers by measuring force, some control theory are presented. The most relevant controllers for this thesis are the bang-bang controller, P-controller, PD-controller and PID-controller. The control theory are found in [14], [18], [19] and [20]. Some of the most common controllers in todays industry are

- *Bang-bang control.* This is a logic controller, and the easiest controller. Often used in temperature control of water and air-temperature indoor. The principle can be described using the temperature control example: If temperature is too high → turn off oven. If temperature is too low → turn on oven.
- *Proportional control.* The P-controller is used where simple control is needed, that is not too accurate control is needed. This is a cheap controller which is easy to implement. The P-controller is in reality an amplifier with an adjustable gain. When the difference between measured state and desired state, from now on called the *error*, goes towards zero, the controller input goes to zero, which results in a steady-state error.
- *Proportional-Integral control.* The PI-controller has an advantage of being able to integrate the error, and thus removing the steady-state error completely. The PI-controller is therefore a common controller when accuracy in the desired state is needed. The PI-controller can be slow in terms of reaching the desired state.
- *Proportional-Derivative control.* The PD-controller is rarely used in industry. It can sometimes be seen in control of servomotors. The added derivative of the error results in a

higher bandwidth and a faster response. The steady-state error leads to inaccurate control.

- *Proportional-Integral-Derivative control.* The PID-controller is often used because when tuned properly, it can be fast, without overshoot and accurate. This controller is more difficult to implement, and is more difficult to tune because 3 tuning parameters must be taken into consideration.
- *Linear Quadratic Control.* Often referred to as LQR - Linear Quadratic Regulator. When the cost of operating a system is important, the LQR is often used. When optimal control of a dynamic system is needed, by describing the dynamic system by a set of differential equations, and the cost is described by a quadratic cost function, the problem is known as a Linear-Quadratic problem.
- *Model Predictive Control.* MPC are typically used for systems with slow dynamics. It can be difficult to implement, and often a big computational power is needed for each loop of the control algorithm. As its' name says, this is a controller which uses what it knows of the model to control the future state - it predicts.

For the scope of this thesis, and more important, since the handling of fish is very difficult to do with a big precision, the most relevant controllers are Bang-bang control and P-control. The integral action to remove the steady-state error is not needed since the position accuracy of the gripper fingers shown later in the thesis is good enough with a bang-bang controller or a

P-controller. A PD-controller can be relevant to make the response faster. Some of the advantages and disadvantages of the three controller parameters K_p, K_d and K_i are summarized in the table below.

Parameter	**Rise Time**	**Overshoot**	**Settling time**	**S-s error**
K_p	Decrease	Increase	Small change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Small change	Decrease	Decrease	No change

Table 5.1: Controller parameters summary.

PART III

IMPLEMENTATION

Abstract – This part presents the part goals on the way to the final solution. This part will be as a timeline with description and solution of the different steps. The lab setup and hypothesis are also described for the different experiments.

For a computer engineer *implementation* normally means coding of an application. Wikipedia states the definition of implementation as : "Implementation is the realization of an application, or execution of a plan, idea, model, design, specification, standard, algorithm, or policy.” Implementation in this thesis means coding, wiring and realization of each part goal.

> *It’s not necessarily size that matters, it’s how fast you move that implement.* - Bryan Clay

The reason that part goals has its own part in this thesis, is the iterative way the solution is found with many small goals to reach before the final solution is found.

Chapter 6

Iterative solution

6.1 Solution proposal

The goal of this thesis is to do research on gripper optimization as well as position control of gripper fingers by measuring force applied to the fish. Experiments applying load on the fish belly while observing deformity is the first part goal. This is to establish a region of force applied to the fish which is satisfactory. To call it satisfactory, it needs to be a force region where the fish does not slip as well as the deformity while gripping should not be permanent.

The most general system description for the solution proposal is the following;

- The robot has the gripper attached to the end effector.
- The gripper has two load cells attached. One for continuous force measurement while grasping the fish, and one to detect contact with the fish.
- Two motors attached to the gripper. One for each of the two gripper fingers.

As described more thoroughly later, two grippers are designed and produced. Only the last gripper has motors attached to it. This means for the first gripper the main system components are the robot and the load cell. For the second gripper the system components are the robot, load cells and motors as well. To deal with the communication between these components programming will be done in LabVIEW. LabVIEW has good ways of dealing with data acquisition as well as motor control.

The reason why designing two grippers are as follows; The first gripper is designed to find a satisfactory force region in terms of deformity. Here one load cell is attached to measure load while the robot pushes the gripper in negative z-direction in robot coordinates, or directly downwards onto the fish. Pictures of the experiment are shown in chapter 8. The second gripper is designed to use this force region found with gripper-1 as a setpoint for the position control of the gripper-2 fingers.

6.2 Load cell - robot interaction

The interaction between the robot and the load cell is important to secure a failsafe experiment. It is also convenient to just start one application which controls both the robot and measures the force from the load cell. When the robot pushes onto the fish in negative z-direction, there are three possibilities to stop the robot: hit the emergency stop button, use the embedded collision detection in the robot or read the load cell continuously and set a maximum allowed force applied to the fish on which

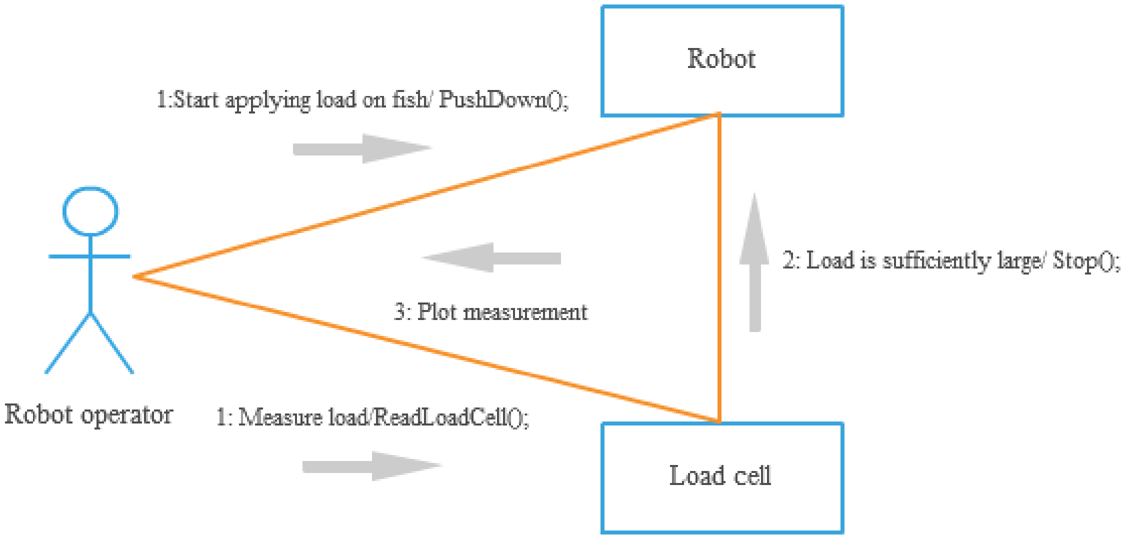

Figure 6.1: UML diagram showing the system for gripper 1.

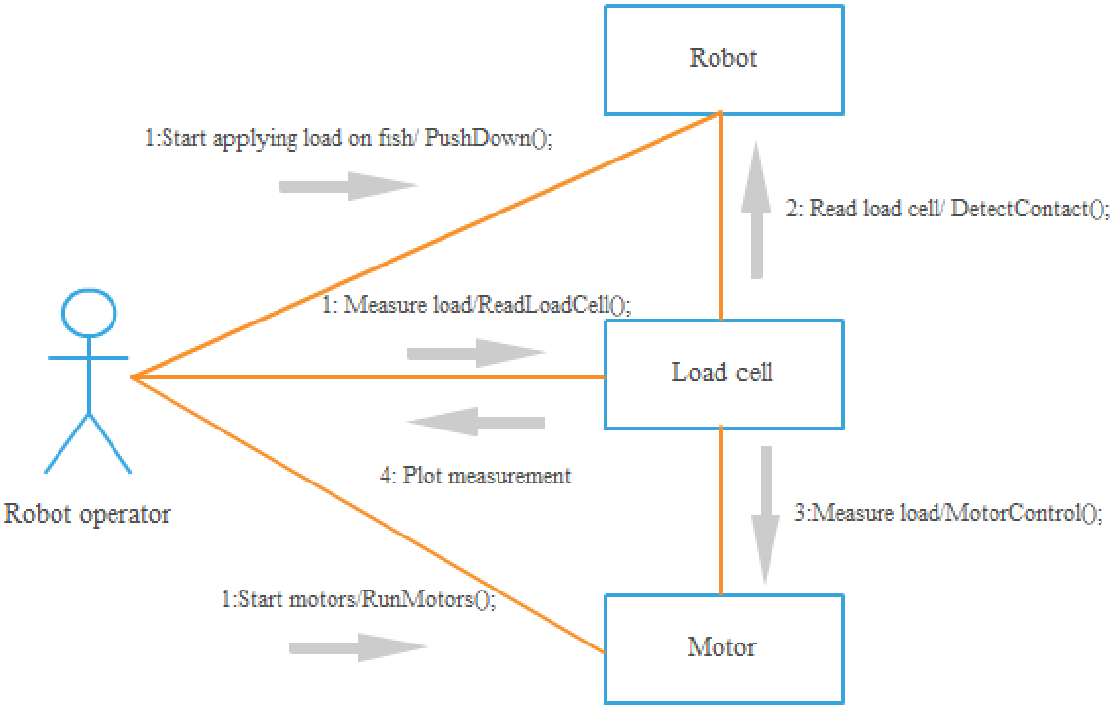

Figure 6.2: UML diagram showing the system for gripper 2.

the robot stops. The latter is the best idea, because altering collision detection parameters to control the robot position is not a good idea. The principle by doing so is much the same, since both the collision detection and the load cell measures force. However the collision detection parameters are set to prevent collision, and should be used only as the last safety line.

6.3 Gripper prototyping

It was clear early the need of designing two grippers. One for experiments on fish to determine compliance characteristics as well as finding a satisfactory region of force applied to the fish. And one for the complete action with grasping the fish with force feedback and motor control.

6.3.1 Gripper 1

The gripper for measuring force in one direction needed to be simple. The goal is to measure force when applying load onto the fish with as little disturbances as possible. One important parameter is the area of contact with the fish. The solution was to design a gripper with rather big area of contact, due the nature of the fish. The compliance can be very different from parts of the fish. Therefore with a big contact area, one can get an average picture of the compliance.

One aspect when using a big contact area is that the load has to be equally distributed over the area of contact. This can be practically difficult to achieve. Figure 6.3 shows the first

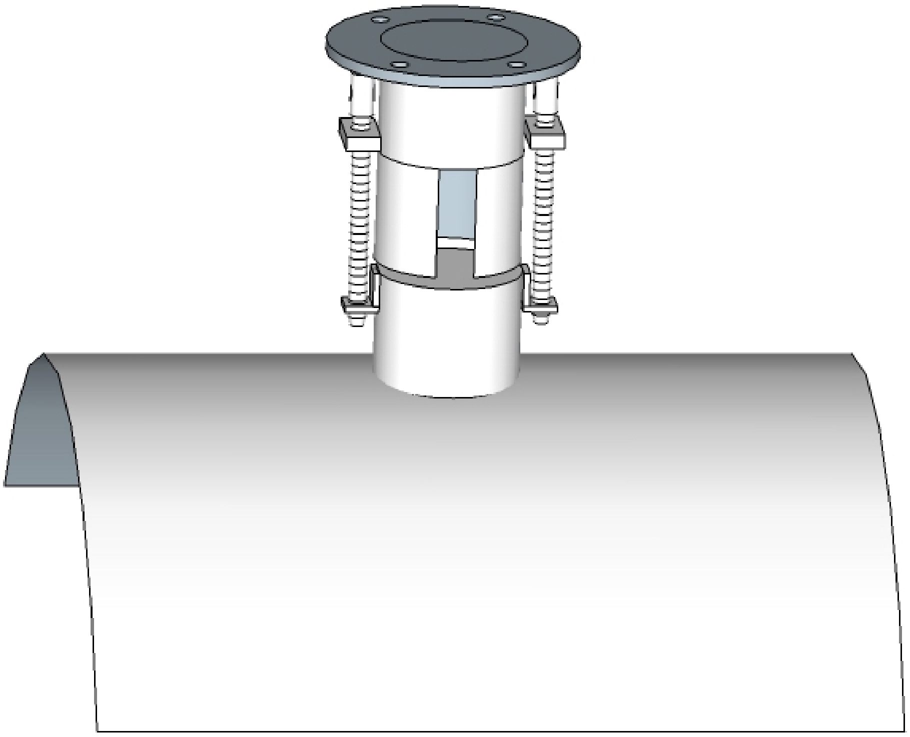

Figure 6.3: First prototype 3D-drawing of gripper 1.

conceptual design of gripper 1. The fish is supposed to fit inside the half pipe and a load sensor is placed inside the "sensor house" in the middle of the gripper. The top of the sensor house is attached to the robot. More drawings and pictures of the gripper are shown in appendix C. Observing the 3D-drawings in the appendix and comparing it to the real life images shows some differences in the final design.

6.3.2 Gripper 2

Gripper 2 is more complex than the first one. It has two DC motors attached and two load cells. One load cell on the top has a purpose of detecting contact with the fish, and one load cell on the side of the gripper measures force continuously. The motors drive each of the two gripper arms.

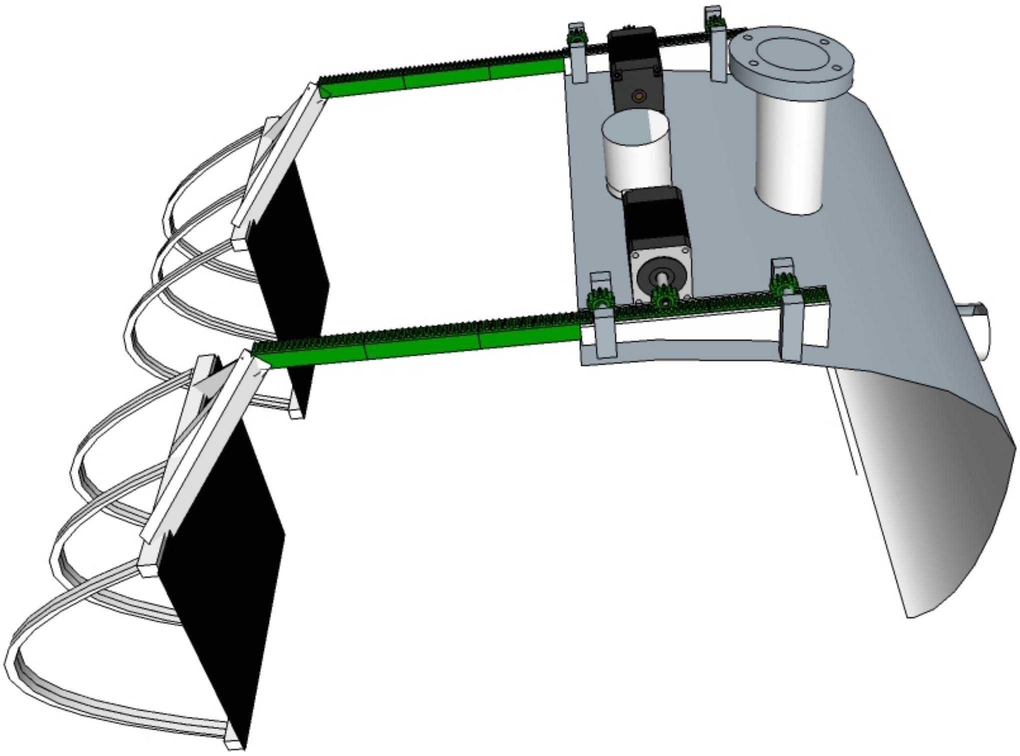

Figure 6.4: First prototype 3D-drawing of gripper 2.

One big challenge with gripper 2 is the moving parts. They need to be strong and rigid because of the relatively big force applied for a fish measuring approximately 4-6 kg.

As figure (6.5) shows, a solution to make the gripper arm more rigid was to add two support beams for each of the motor axles. The first goal for gripper 2 was making the gripper arms compliant, but due to the complexity the arms were designed rigid.

The motors used are two powerful DC motors with an operating voltage from 6-12 VDC, torque of 21 kgf·cm and a no-load

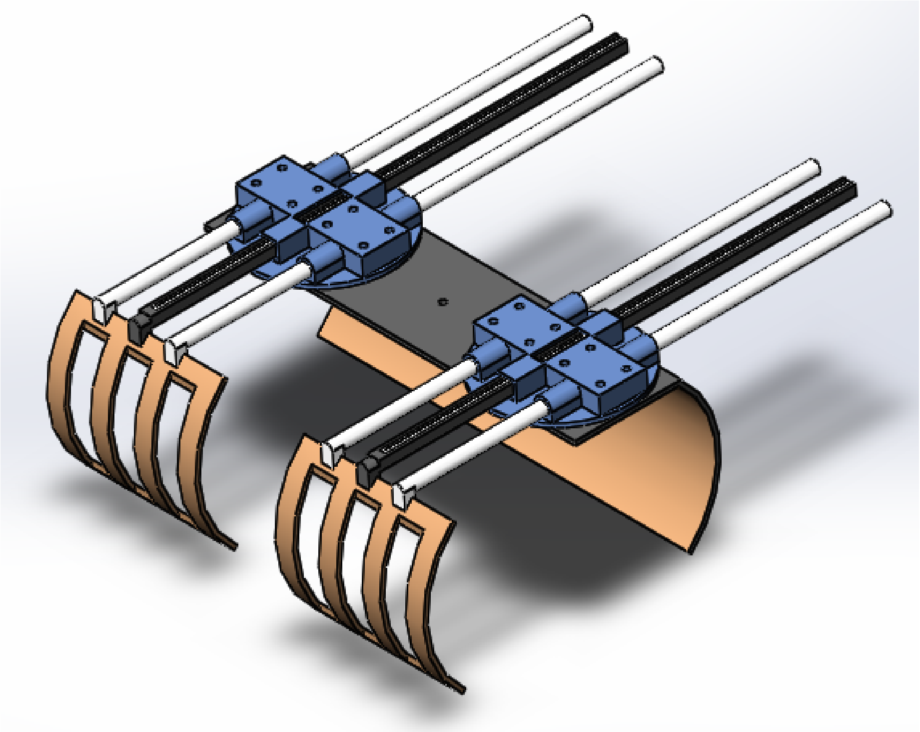

Figure 6.5: Second prototype 3D-drawing of gripper 2.

speed of 45 rpm.

The two arms can be adjusted for different angles of attack. This can be desirable when handling fish of different sizes. More drawings and pictures of gripper 2 are shown in appendix C.

6.4 Robot - motor interaction

After the communication between robot and load cell was set, it was important to fill in the missing piece, namely the motor. For the final solution communication between three main components are needed: Robot - load cells - motors. Guidance in this subject is found in [9]. To run the motors through Arduino from LabVIEW the LINX library for LabVIEW was installed.

The motor driver used is a Arduino Duemilanove which is capable of driving 4 motors.

Since the motor shield for the Arduino Duemilanove uses a latch, it is not trivial to program the Arduino using LabVIEW. The solution to this was to bypass the latch, and disconnect the microcontroller from the motor shield and connecting it to a breadboard (figure (6.6)).

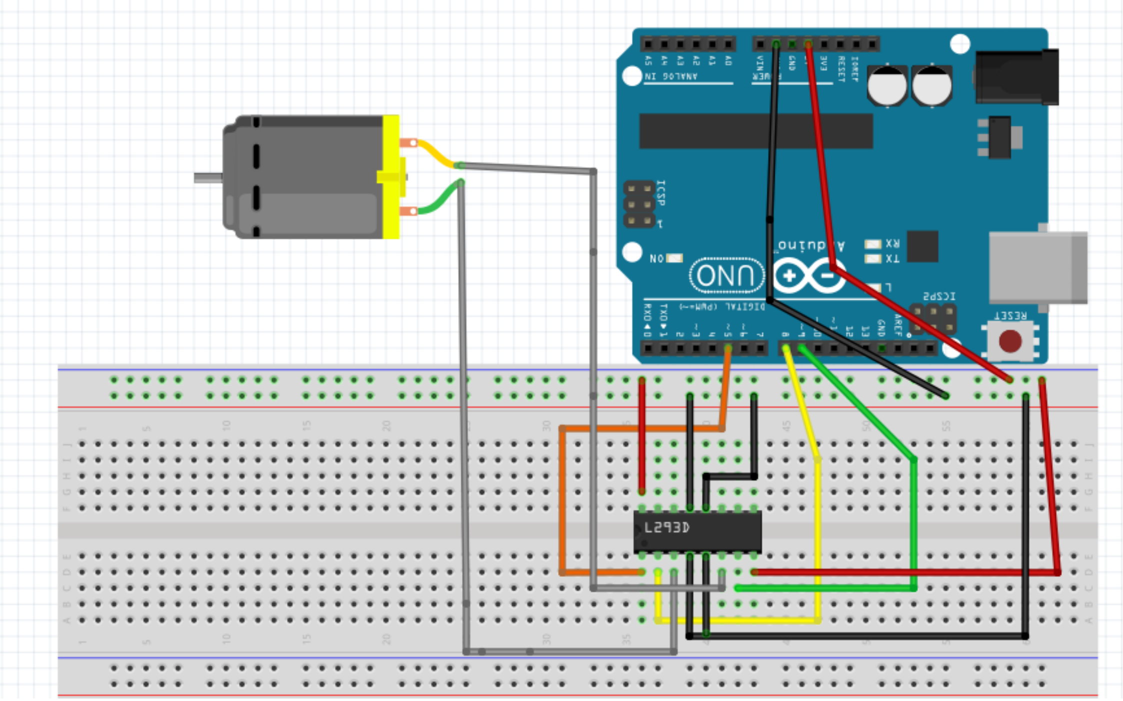

Figure 6.6: Connection diagram for motor control using LabVIEW and Arduino.

The Arduino has a 5 VDC supply which is not enough to power the DC motors (range 6-12 VDC). Therefore an external power supply is connected to the breadboard to supply enough voltage.

To control the speed of the motors Pulse Width Modulation (PWM) is used. This is an embedded feature in the Arduino.

6.5 Load cell - motor interaction

When the load cells as well as the motors communicate with LabVIEW, one can control the motors using load cells through LabVIEW. A program for this was written using a bang-bang control algorithm based on a P-controller. The control algorithm is shown below.

Algorithm 1 Bang-bang P-controller

```
Input: Setpoint $SP$ and force $F_z$
Output: Motor speed and direction
Initialize motor and load cell communication
while true do
    read $F_z$
    $error = K_p(SP - F_z)$
    if $error > 5$ then
        Motor direction = Close Gripper, Motor speed = MAX
    else if $error < -5$ then
        Motor direction = Open Gripper, Motor speed = MAX
    else if $-5 < error < -0.5$ then
        Motor direction = Open Gripper, Motor speed = 50%
    else if $0.5 < error < 5$ then
        Motor direction = Close Gripper, Motor speed = 50%
    else if $-0.5 < error < 0.5$ then
        Motor direction = STOP, Motor speed = ZERO
    else
        "ERROR!"
Close communication to motor and load cell
```

The LabVIEW program is attached in appendix C.

Chapter 7

Experiments

This part describes the setup and hypothesis for the experiments. The results are shown in part IV.

7.1 Determining force region and compliance characteristics

7.1.1 Experiment description

The purpose of this experiment is to observe the response from a force measurement with respect to time and displacement. A gripper tool attached to the robot has an attached load cell. The robot will push downward (negative z-direction in robot coordinates) while continuously logging the force measurement. The experiment are split into *three* parts:

1. Manually jog the robot in negative z-direction onto the fish belly to determine a maximum force applied before the deformation is too big.
2. Continuous force measurement while robot applies a force

from 0 newtons to the maximum force found in the previous part of the experiment.

3. The same as part 2 of the experiment with different speed of the robot motion.

7.1.2 Hypothesis

It is expected that the resulting force response with respect to time has an exponential growth. As the compliant material is contracted enough the force response is expected to linearize. However the experiment has no aim in applying too much force due to robot and load cell limitations. It is expected that when applying a certain force and given a constant displacement, the measured force will decrease due to the complex nature of the fish. It is believed that the insides will naturally have a motion away from the contact point of the gripper, causing a decrease in measured force.

7.1.3 Setup

The lab setup contains a drain-shaped structure made out of blue foam. This structure makes sure the fish lies steady with the belly pointing upwards. Furthermore the gripper has a load cell attached, whereas the gripper is attached to the robot. The robot performs a motion directly downwards onto the fish belly until the force is equal to the maximum force allowed. Plots of the resulting responses are logged. This program is written in LabVIEW.

Figure 7.1: Lab setup for experiment 1.

7.2 Determining scaling factor for force measurements

To validate results from the previous experiment, it is important to see if a scaling factor is necessary to correct the measurements. Treating the fish as a spring with unknown stiffness k, and comparing measurements on a spring with known stiffness can give an indication if a scaling factor is needed.

7.2.1 Experiment description

The experiment is very similar to the previous experiment, replacing the fish with a spring. Measuring force with respect to both time and displacement can show similarities and/or differences from measuring force applied to fish. For the case when measuring force with respect to time, one can compare the plots with those from the previous experiment. Measuring force with respect to displacement and comparing the values to

$$k = \frac{F}{d}$$

since k is known for the spring, one should measure the same k as given from the manufacturer.

It will be done trials using different speeds on the robot.

7.2.2 Hypothesis

Due to the more complex nature of the fish it is expected to observe some differences in the measurements on the spring. It is also expected to find some different values for k compared to the given k from the manufacturer.

7.2.3 Setup

A spring is attached to a solid non-deformable surface. To stabilize the spring, a tool is made for this (figure (7.2) and (7.3)).

The robot performs a motion applying force in negative z-direction until the force equals the maximum allowed which was found in part 1 of the first experiment. The load cell is attached to the robot which along with LabVIEW provides force-time and force-displacement plots.

Figure 7.2: Spring setup for experiment 2.

Figure 7.3: Spring setup for experiment 2.

7.3 Observing area of contact characteristics

In order to observe characteristics of the area of contact, measurements when applying force on the fish with a small contact area are conducted. This is important both to observe if the characteristics found when using the gripper with big contact area are still prominent as well as the similarity of setup with the spring experiment.

7.3.1 Experiment description

The experiment are similar to the previous experiments. Now the contact area is close to the same as for the case with the spring. A measurement for the stiffness, k, can be estimated by analyzing the response in the linear (or close to linear) region.

7.3.2 Hypothesis

The expectation concerning the force response is for it to show much of the same characteristics as for measuring force on fish with big contact area, except that the displacement would be bigger when the contact area is smaller.

7.3.3 Setup

The setup is the same as for the other experiments, except the half cylinder is removed from the gripper in order to decrease the contact area. The gripper without the half cylinder applies force onto a fish in negative z-direction.

7.4 Force closure using position control of gripper fingers

This is the last experiment, and this experiment has a purpose of observing the behavior of the fish when grasped by the gripper. Now gripper 2 is introduced with two motors and two load

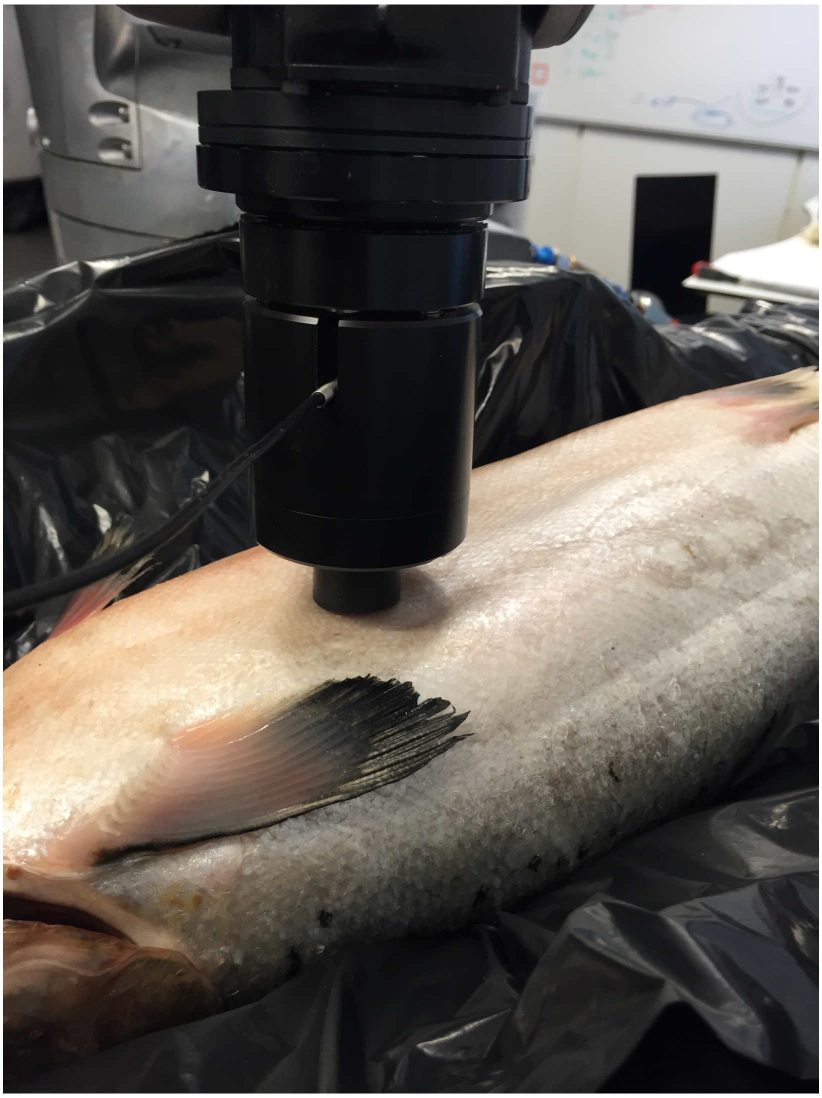

Figure 7.4: Lab setup for experiment 3.

cells.

7.4.1 Experiment description

This experiment has two main focuses:

1. Test the behavior of gripper 2 and the control algorithm. Observe and optimize performance of robot, load cells and

motors.

2. When grasping the fish, observe force response when robot performs different motions in different speeds.

For the first part of the experiment, the goal is to set the robot end effector in an initial position placed above the fish, lower the robot arm until one load cell attached to the gripper detects contact. When contact is detected, the motors will start to contract the gripper fingers while the second load cell measures force continuously. When the force is big enough, the motors holds the fingers in position.

For the second part, observing the behavior of the gripper is the goal. This includes analyzing the force needed to hold the fish using a satisfactory force, and observing the force response and behavior when trying to lift the fish, and moving it back and forth with different speeds.

As a safety precaution, the voltage applied to the motors are measured. This way one can find the torque, and have two measurements for the force applied, both from the motors and from the load cell.

To deal with the differences between the motors, encoders are installed to keep track of the position of each motor. This is another failsafe mode to ensure that for example the force control loop does not start until gripper fingers are in synchronized position.

7.4.2 Hypothesis

Some problems that are likely to occur are different performance of motors. Each motor is controlled by measurements from one load cell. Since the two grippers has different contact points on the fish with different compliance characteristics in may be necessary to scale one of the motors. It is expected that the performance of the gripper when the robot has different motions are varying.

7.4.3 Setup

Initial position of the gripper is with the fingers in a completely open state. The robot end effector is placed directly above the fish laying on a horizontal plane. When decrementing the robot z-coordinate, the fish will fit inside the open gripper. The first application written in LabVIEW will perform this from an initial position above the fish, until the robot has lowered the gripper, and closed the gripper until a set point for the force is reached. Then the application is aborted.

For the second part of the experiment, the gripper starts in a closed state with the fish inside. Then different motions programmed will be executed while plots are made of the force response. Videos for observations are recorded.

PART IV

RESULTS

Abstract – This part includes results from four main experiments. Three of them are more theoretically based using gripper 1, while the last is more practical in terms of observing the performance of gripper 2.

According to `thefreedictionary.com` the word result is from Middle English *resulten*, from medieval latin *resultare*, to leap back. The definition is ”to happen as a consequence” or ”to end in a particular way".

> *It is common sense to take a method and try it. If it fails, admit it frankly and try another. But above all, try something.* – Franklin D. Roosevelt

Results can be both a failure or a success. A failure can also be a success when the failure of achieving according to the given hypothesis, makes valuable change in the understanding of the system.

Chapter 8

Experiment results

For each of the three first experiments, a summary of trials is shown in a table. For each of these trials there are plots shown in appendix B.

8.1 Determining force region and compliance characteristics

As described in the previous part, this experiment consists of three focuses. For convenience these are given below:

1. Manually jog the robot in negative z-direction onto the fish belly to determine a maximum force applied before the deformation is too big.
2. Continuous force measurement while robot applies a force from 0 newtons to the maximum force found in the previous part of the experiment.
3. The same as part 2 of the experiment with different speed of the robot motion.

The results and observations are the following.

8.1.1 Determining maximum force

After joging the robot and applying force directly onto the fish belly the maximum allowed force was found to be 30 Newtons. This result was found after applying different loads and observing the deformity of the fish afterwards. The maximum force was however increased to 37 N to get a better analysis of the displacement, and to match the trials done on a spring (section 8.2).

8.1.2 Obtaining plots from force measurement

Figure (8.1) shows the resulting response after applying force onto the fish with a speed of 0.1 mm/sec.

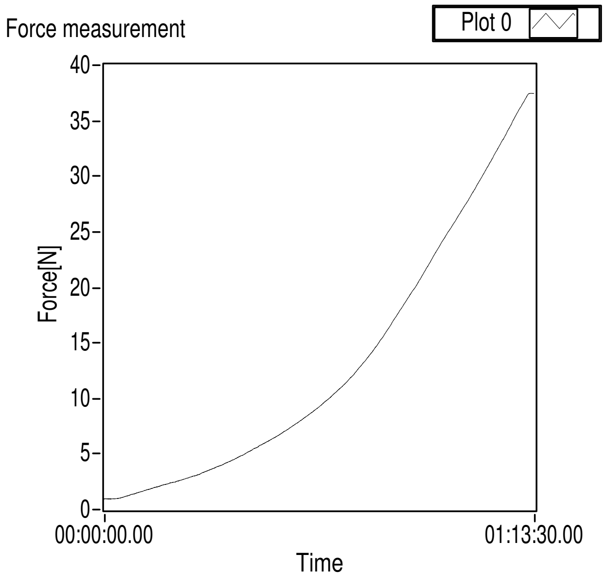

Figure 8.1: Force-time response when applying a load from 0 N to 37 N at 0.1 mm/sec. Corresponds to trial 1.

The hypothesis is confirmed concerning the exponential growth of force over displacement. The linearity after the force

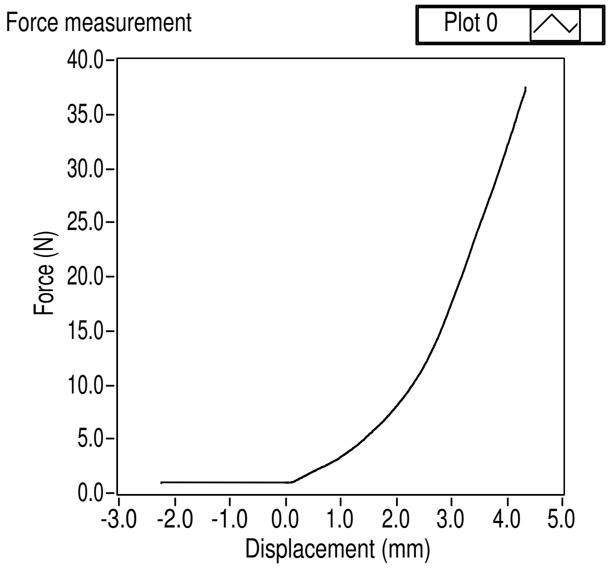

Figure 8.2: Force-displacement response when applying a load from 0 N to 37 N at 0.1 mm/sec. Corresponds to trial 1.

grows big enough is also confirmed.

8.1.3 Force measurement with different speeds

Table 8.1 summarizes the different measurements shown in the plots below. Note that the terminal force in the table points to the force when force measurements are concluded. One interesting result is that the robot stops applying force to the fish at almost the exact same spot every trial, no matter the speed of the robot. The robot is not programmed to stop at the same spot, but to stop when the force is greater than or equal to 37 N.

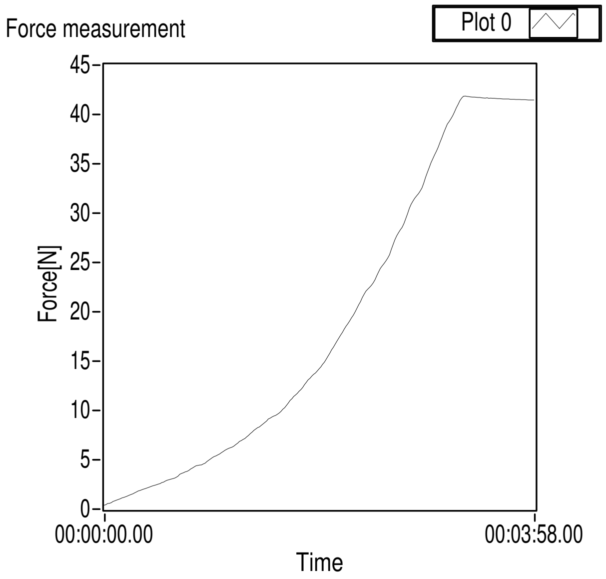

Figure 8.3: Force-time response with a speed 2 mm/sec. Corresponds to trial 4.

It is a big difference in the maximum force measured with different speeds. At slow speeds the robot stops at 37 N and the maximum force measured is also close to 30 N. At higher speeds the maximum force measured is as high as 40-42 N (figure 8.3 and 8.4). Another interesting results at high speeds is that the force measured decreases several newtons after the robot has stopped applying load to the fish (figure 8.4).

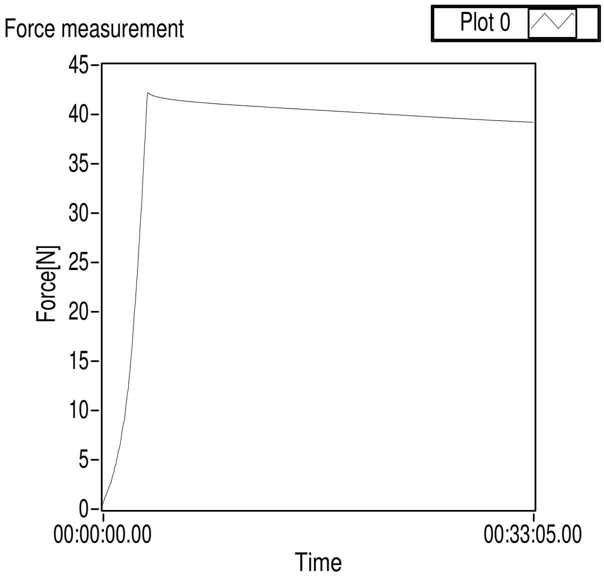

Figure 8.4: Force-time response with a speed 2 mm/sec. Note the response after robot has stopped applying load to the fish. Corresponds to trial 5.

Trial	Displacement [mm]	Terminal force [N]	Speed
1	4.4	37.38	0.1 mm/sec
2	4.1	38.01	1 mm/sec
3	3.9	38.24	1 mm/sec
4	3.7	41.38	2 mm/sec
5	3.95	39.12	2 mm/sec
6	4.4	49.66	6 mm/sec

Table 8.1: Experiment summary for force measurement on fish with gripper.

8.2 Determining scaling factor for force measurements

The results after applying load to a spring with known stiffness, k, are summarized in table 8.2. A spring should be linear within a region. In an attempt to get as similar measurements as possible compared to measurements on the fish, the spring is pushed close to its maximum compression. Normally a spring would lose its linear features close to maximum compression. This can be seen in figure (8.5) and (8.6)).

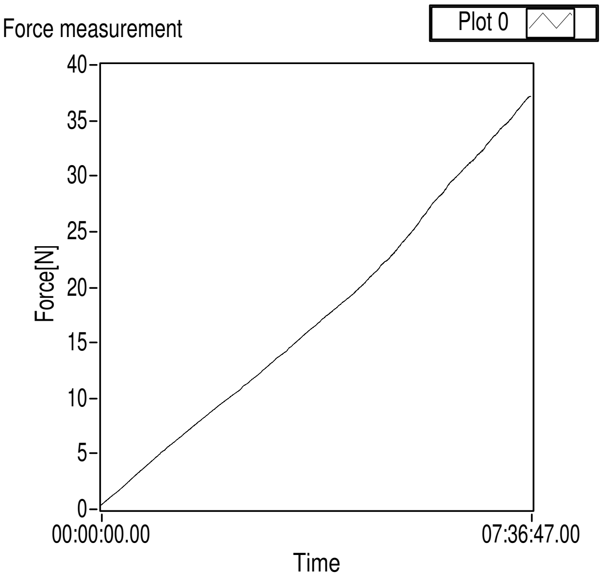

Figure 8.5: Force-time response with a speed 0.1 mm/sec. Corresponds to trial 1.

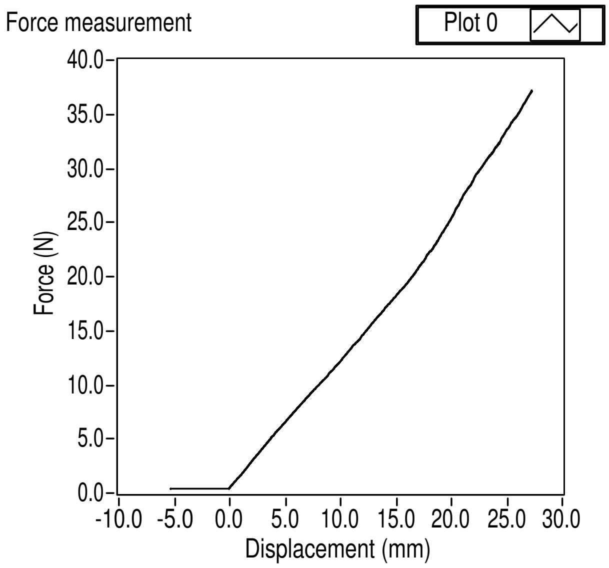

Figure 8.6: Force-displacement response with a speed 0.1 mm/sec. Corresponds to trial 1.

One can see that the spring loses some of its linearity when the displacement grows big enough. As seen in figure (8.7) the overshoot in force is not as big as observed for the case with fish and a big contact area. It is thought that this is due to the bigger displacement when applying force on the spring compared to the fish.

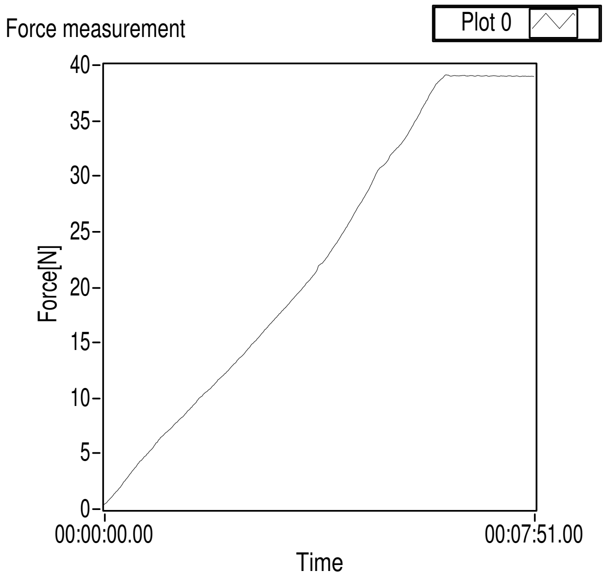

Figure 8.7: Force-time response with a speed 10 mm/sec. Corresponds to trial 8.

Trial	Displacement [mm]	Terminal force [N]	Speed [mm/sec]
1	27	37.09	0.1
2	27	37.17	1
3	27	37.04	1
4	27	37.41	2
5	27	37.31	2
6	28	38.80	6
7	28	38.50	6
8	27	38.90	10

Table 8.2: Experiment summary for force measurement on spring.

8.2.1 Stiffness

The stiffness in a body with one degree of freedom is from equation 4.2

$$k = \frac{F}{d}$$

Then for the spring the following stiffness are found by the measured force, F, and displacement, d:

Trial	**Displacement [mm]**	**Force [N]**	**Stiffness, k [N/mm]**
1	27	37.09	1.37
2	27	37.17	1.38
3	27	37.04	1.37
4	27	37.41	1.39
5	27	37.31	1.38
6	28	38.79	1.39
7	28	38.51	1.38
8	27	38.90	1.44

Table 8.3: Spring stiffness.

The given spring stiffness from the manufacturer i $k = 1.42$. The measured k compared to the given spring stiffness from the manufacturer shows a small deviation. The measured k lays 2-3 N/mm below. The results suggest rather than using a scaling factor for the measurements, it is important to optimize robot position control because of the overshoot in force.

8.3 Observing area of contact characteristics

For a better comparison between force measurement on a spring and the fish, one experiment was conducted without the lower part of the gripper. This results in a much smaller contact area between the rigid gripper and the compliant fish. The measurements are summarized in table 8.4. The characteristics with the decreasing force seen when using a gripper with big contact area is much more prominent for less contact area (figure(8.8)). Note that the maximum force applied is again set to 30 N because the small contact area can result in penetration of the fish tissue. The spike in the displacement response in figure (8.9) is due the robot having constant position while the force steadily decreases. This decrease in force is due to the movement of the fluids and guts inside the fish.

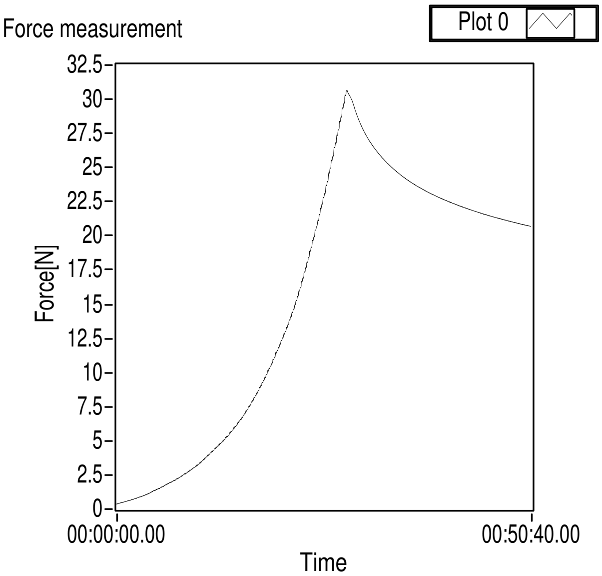

Figure 8.8: Force-time response with a speed 1 mm/sec. Corresponds to trial 3.

These results shows the importance of the area of contact in the model.

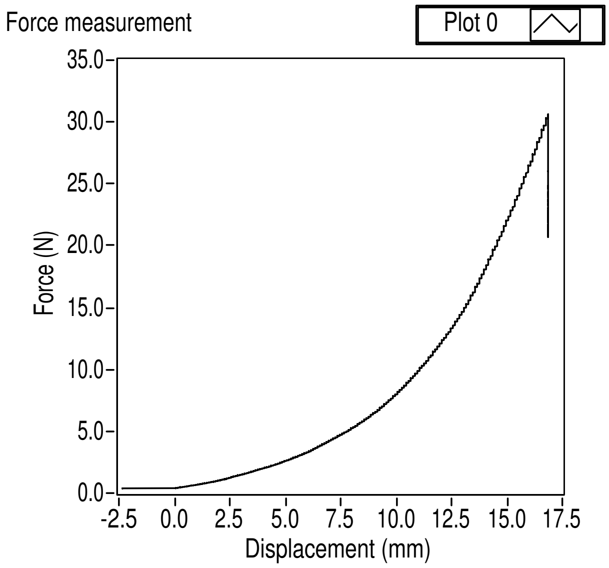

Figure 8.9: Force-displacement response with a speed 1 mm/sec. Corresponds to trial 3.

Trial	**Displacement [mm]**	**Terminal force [N]**	**Speed [mm/sec]**
1	19.00	29.95	0.1
2	16.75	30.41	1
3	16.75	20.64	1
4	18.00	31.05	2
5	16.75	19.57	2
6	16.75	31.64	4
7	16.50	18.62	4

Table 8.4: Experiment summary for force measurement on fish without gripper.

8.3.1 Stiffness

Di Wu et. al. [21] found a stiffness of salmon meat to have values between 2.53 to 5.88 N/mm. Their lab setup was much the same as in this experiment, however the area of contact was a 50 mm in diameter circle in their case, while a 20 mm in diameter circle was used in this setup. By observing the linear region of the force measurements on the fish, the stiffness was found. In all trials the linear region was seen approximately from a force of 15 N to maximum force applied. The stiffness found in trials had values between 2.85 N/mm to 5.60 N/mm, which has a good fit with the values found in [21].

Trial	**Displacement [mm]**	**Force [N]**	**Stiffnes, k [N/mm]**
1	5.25	14.95	2.85
2	4.15	15.41	3.71
3	4	15.19	3.80
4	5.25	16.05	3.06
5	2.75	15.39	5.60
6	4	15.64	3.91
7	4	38.51	3.81

Table 8.5: Salmon meat stiffness.

8.4 Force closure using position control of gripper fingers

Experiments showed that the gripper was able to perform the given tasks. The communicating parts, as well as the structure of the gripper worked well together. It was discovered that the gap between the static part of the gripper and the gripper fingers was too big when fully closed. Therefore it was added extra thickness to the gripper fingers. This made the gripper more robust against changes in the size of the fish (figure (8.11)).

The fish used for the experiment was a 5.85 kg salmon. This is a rather big fish for this gripper. The second part of this experiment was to do different motions after the gripping action

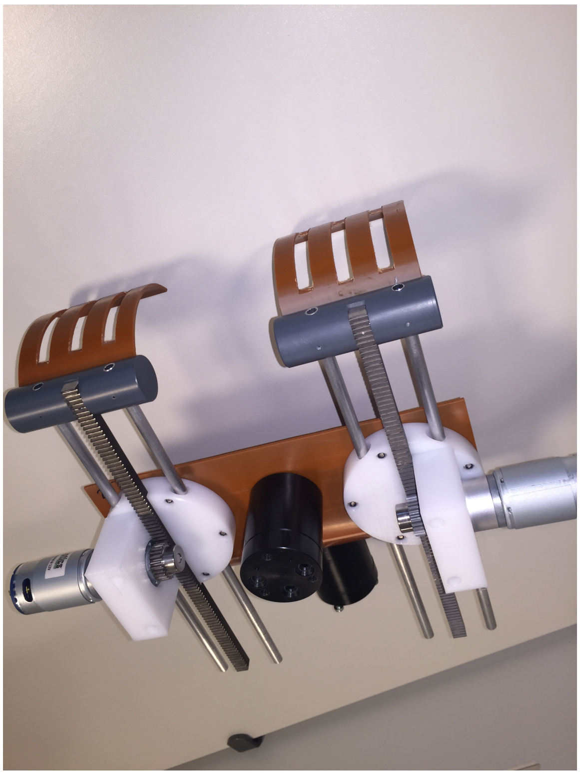

Figure 8.10: Gripper 2 prototype

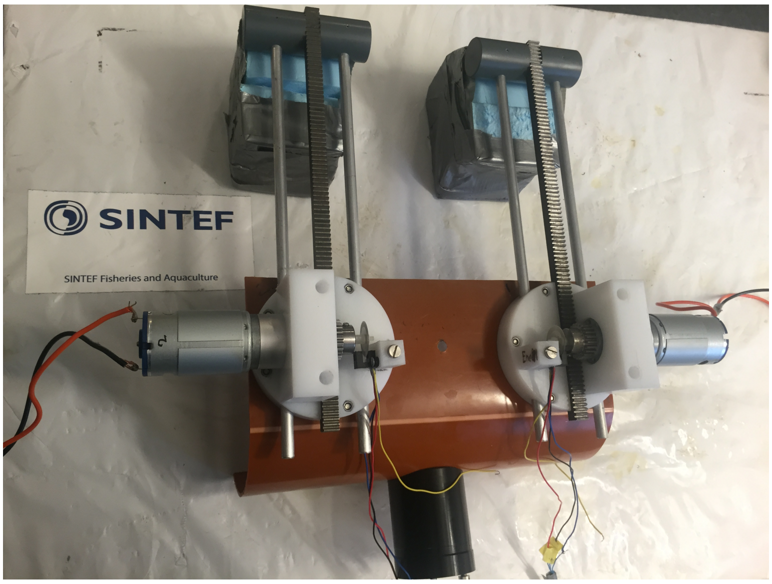

Figure 8.11: Gripper 2 prototype with extra thick gripper fingers

is complete. The fish was somewhat too big for this motions due to gripper limitations. The gripper performed well on the sequence: 1. Lower the robot arm until contact with fish is detected, 2. Synchronize motors, 3. Grasp fish while continuously measuring force applied, 4. Hold gripper fingers in a steady position when force setpoint is reached. The fifth part of the sequence was to rotate or move the fish back and forth. The last part was done with not too good results. This was due to big friction between fish shells and surface. Figure (8.12) shows the belly of the fish when grasping algorithm is finished.

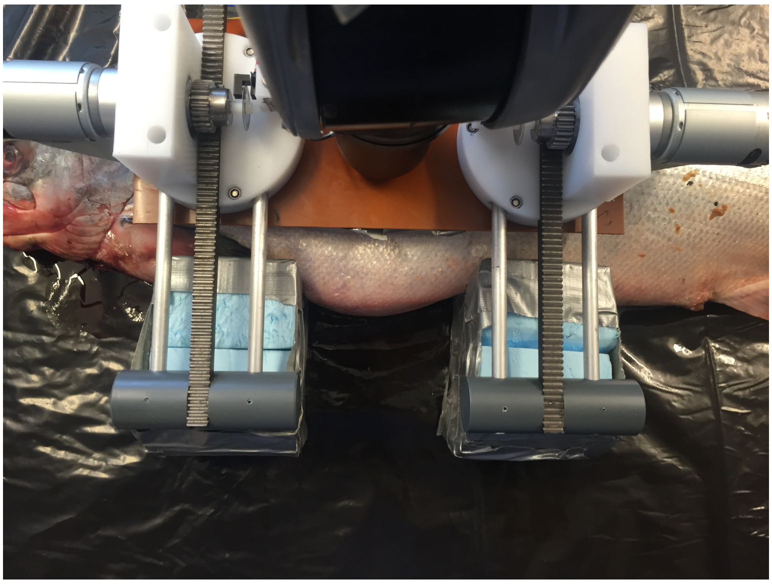

Figure 8.12: Grasping complete.

PART V

DISCUSSION AND CONCLUSION

Abstract – This part includes, as it is written with big letters, the discussion and conclusion of this paper. The discussion is seperated in two parts – one for each of the grippers.

Conclusion is from latin *concludere* - to end. In many cases this part is the most important part. Results from trials are discussed, and thoughts around the results are presented. To get a first impression of the text, and with as little reading as possible, this part is good to start with.

> *I think and think for months and years. Ninety-nine times, the conclusion is false. The hundredth time I am right.* - Albert Einstein

As Mr. Einstein clearly states, a conclusion does not always have to be a solution to a problem. An equally good conclusion could be one which states the failure of obtaining desired results.

Chapter 9

Discussion

The discussion is split in two parts - one for each of the grippers and the corresponding experiments.

9.1 Part 1 – Gripper 1

An important result is the characteristics concerning the gripping at high speeds. When the desired force is reached it is observed that the maximum force gets an overshoot. When this overshoot occurs, the period after the robot has stopped applying force, the measured force decreases. Could this result in slip when moving the fish? It was thought that this decrease in force is due to the compliance of the fish. The bluefoam which holds the fish in place could also affect the measurement. Measurements using the same program for the execution was done both on metal (figure 9.1) as a reference and on the bluefoam (figure 9.2).

As expected the force response when applying load on metal is linear. It is close to linear for the case of the bluefoam as well. Measurements on metal and bluefoam together with measure-

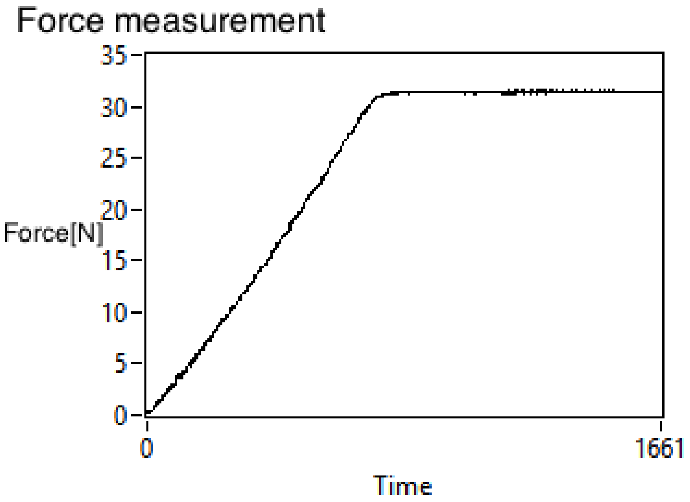

Figure 9.1: Force response applying load on metal.

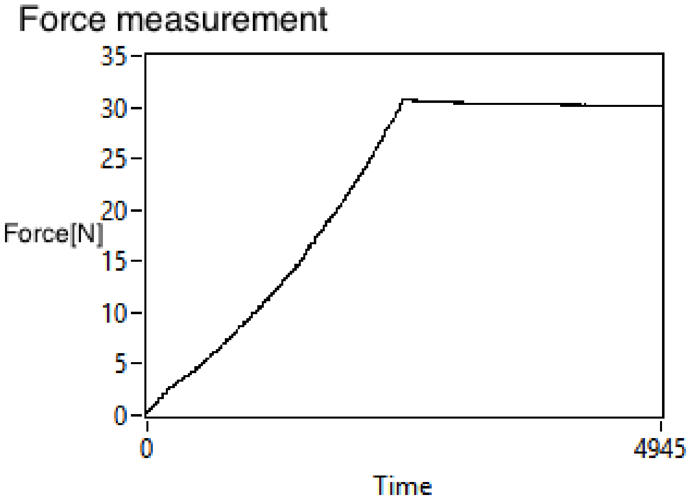

Figure 9.2: Force response applying load on bluefoam.

ments on the spring with known stiffness, it was shown that the compliant characteristics in the force response stems from the fish only.

9.2 Part 2 – Gripper 2

The work done in this thesis has a purpose of acting as a proof of concept. The way the gripper is designed shows a clear indication of which parts of the design that should be redesigned or improved. Pros and cons after the experiments are given in the table below. The most important notes on gripper design is the gap between the static part and the gripper fingers. This was modified for the experiments using bluefoam. Another important modification was to add a plate of different thickness according to the size of the fish underneath the load cell for contact detection. Suggestion for redesign in the case of handling different fish size is to add a very elastic material, such as soft silicon, underneath the contact detection load cell. The purpose is to ensure both contact with the fish before grasping as well as contact between the ground and gripper at the same time.

The controller used for the experiments was a PI-controller with $K_p = 50$ and $K_i = 0.3$. After studying responses from the load cell using different filters, a Bessel-filter was chosen to smooth the signal from the load cell. The responses from different filters are shown in appendix A.

Positive	Negative
Easy to implement.	Redesign of gripper fingers was needed to handle smaller fish.
Two seperate motors for adjustment concerning the shape and physics of the fish.	Encoders are needed to control the position of the motors as well as keeping them in sync.
Alot of information can be used by only one continuous force measurement. The second load cell is used only for contact detection.	The height of the gripper is critical. That is the distance from the ground to the detection load cell when gripper finger touches ground. When handling small fish, one can experience no contact detection at all, while with big fish the gripper fingers may not reach the ground when contact is detected.
Rigid design capable of handling the motion when moving big fish well.	When rotating fish, the part that connects the gripper to the robot has to be modified. This is due to only one contact point between the gripper frame and the part connected to the robot.
Partly compliant fingers is more smooth against the fish body. In the case of faulty measurement from the load cell measuring continuously, this compliancy relaxes some stress on the motors when too big force is applied.	

Table 9.1: Pros and cons with gripper 2

Chapter 10

Conclusion

It can be concluded that a good fish gripper can be realized with fairly non-complex components. This thesis shows an iterative solution from economic motivation to the final product with resulting experiments. It is shown that fish has compliant characteristics that are important to consider when modeling the system for control purposes.

Experiments with gripper 1 did show both satisfactory results as well as some surprising results. Especially the effect of a rapid decreasing force when applying a constant displacement is important. Experiments with gripper 1 gave good understanding for designing the control system for gripper 2.

Experiments with gripper 2 were satisfactory in the way it showed very clear what is good design, and what needs to be redesigned. Without very big changes, an industrial fish gripper is possible producing.

PART VI

AFTERMATH

Abstract – The following part discusses the importance of future work in this matter. This part has a timeline shape where the future work is presented with the work thought to lie in the closest future first, and more extensive work which maybe needs huge steps in technology progress towards the end.

The aftermath is often a word describing the conclusion of a war. It describes the facts from the past, and states the challenges for the future. `www.dictionary.com` describes *aftermath* as ”something that results or follows from an event, especially one of a disastrous or unfortunate nature; consequence”. Hopefully this paper is not a disastrous event. The word origin is from after + -math, a mowing, cutting of grass. Originally a second crop of grass grown after the first had been harvested.

> *There’s always some aftermath, good and bad, makes-me-happy or makes-me-unhappy, for anything we choose to do.* - Richard Bach

The aftermath in this paper does not mean a conclusion, but in this context more like thoughts of the future after the results achieved.

Chapter 11

Future Work

This part are only considering gripper 2. Presenting the future work iterative with the simpler solution first, the following are possible areas of research: The first change of design is the gap between the fully opened gripper. To handle smaller fish the gap has to be much smaller than for the gripper prototype used in the experiments. This can be solved by either minimizing the minimal gap mechanically possible using the original gripper finger design, or similar to the modification done for the last experiments - making each finger thicker.

A second change is a different solution for detecting contact with the fish. To being able to handle different sizes, the gripper should be more compliant when a negative z-direction motion is performed. It should still be able to have a big contact area, no matter the size of the fish (of course within reasonable sizes).

Being able to rotate fish is important. Similar to each gripper finger being designed to withstand rotational forces, the gripper itself needs to be designed to withstand rotational forces as well. Instead of each gripper finger being attached normal to the static part of the gripper, with both fingers pointing more inward with a certain angle, better gripping can be achieved.

For industrial standards, the grasping has to be done faster. This can either be solved by faster motors, or maybe better, well controlled pneumatics. Using air pressure can give a much faster grasping motion, however it can be more complex to control the air pressure in a good way.

Continuously measuring the force applied while moving the fish can prevent slip. This is complex due to disturbances of force measurements when moving the whole gripper. This causes the meat to vibrate and displacement in the guts are likely.

Referring to section 4.3, about how animals grip, the definitive future solution is much better passive gripping. With nanotechnology materials for super gripping features such as for the gecko can be achieved. As well as the material itself has gripping features, mechanical passive gripping is also preferable.

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Declaration

I herewith declare that I have produced this work without the prohibited assistance of third parties and without making use of aids other than those specified; notions taken over directly or indirectly from other sources have been identified as such. This paper has not previously been presented in identical or similar form to any other Norwegian nor foreign examination board.

The thesis work was conducted from January 2015 to July 2015 under the supervision of Anton Shiriaev at Norwegian University of Science and Technology, and SINTEF Fisheries and Aquaculture - Process technology.

TRONDHEIM - NORWAY, 29th of July 2015

Asle Hammerdal

Asle Hammerdal
29th of July 2015

APPENDICES

Abstract – This part includes responses from testing of different filters, plots from the experiments, figures from gripper prototyping, datasheets and some LabVIEW code.

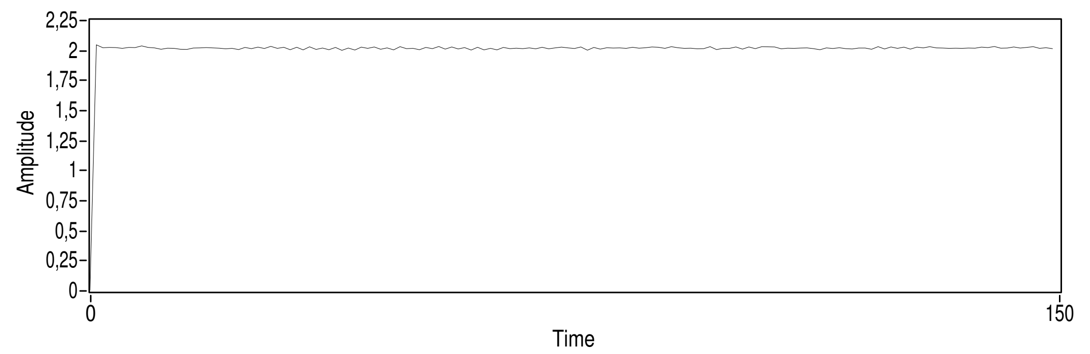
Appendix A

Filters

Some of the filters tested for the motor control with force measurement. The graphs presented are measurements from the load cell, with constant load.

A.1 Measurement with initialization period

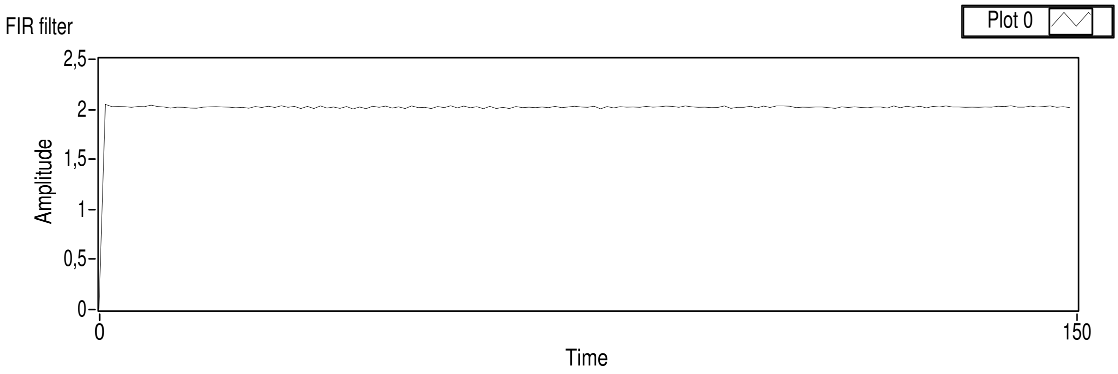
The graphs shows the measurement where the load cell stabilizes including the initialization period.



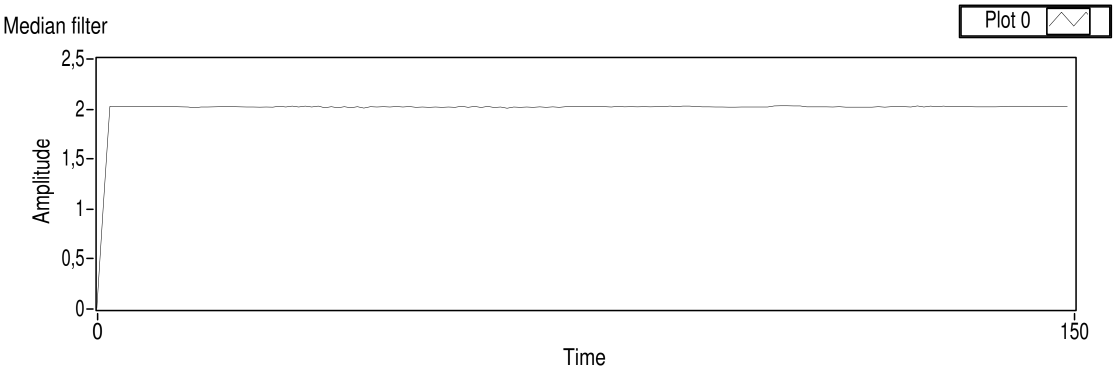

Butterworth
Plot 0
2,5
2
1,5
1
0,5
0
Amplitude
0
150
Time

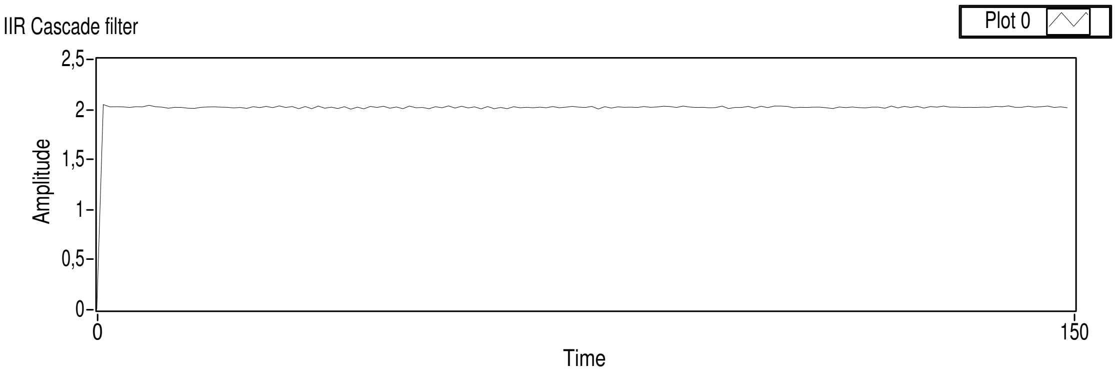

Chebyshev
Plot 0
2,5
2
1,5
1
0,5
0
Amplitude
0
150
Time


Bessel
Plot 0
2,5
2
1,5
1
0,5
0
Amplitude
0
150
Time


FIR filter
Plot 0
2,5
2
1,5
1
0,5
0
Amplitude
0
150
Time


Equi-Ripple Lowpass
Plot 0
Amplitude
2,5
2
1,5
1
0,5
0
-0,5
0
150
Time

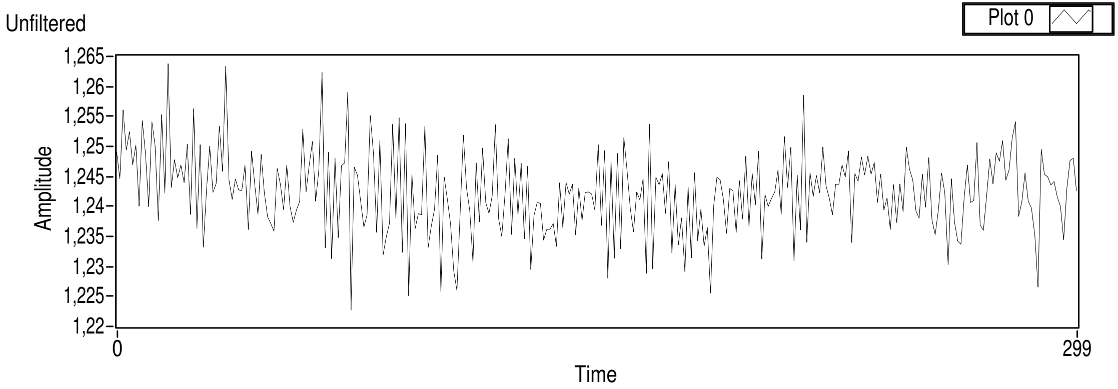

Median filter
Plot 0
Amplitude
2,5
2
1,5
1
0,5
0
0
150
Time

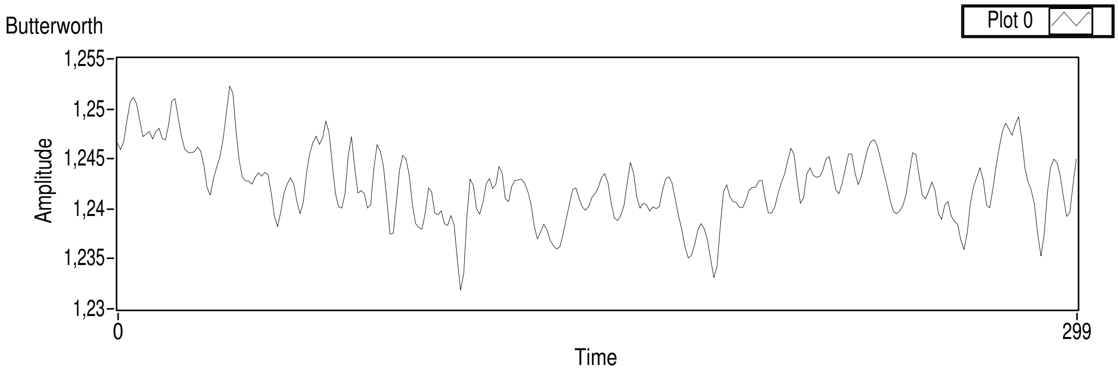

IIR Cascade filter
Plot 0
Amplitude
2,5
2
1,5
1
0,5
0
0
150
Time

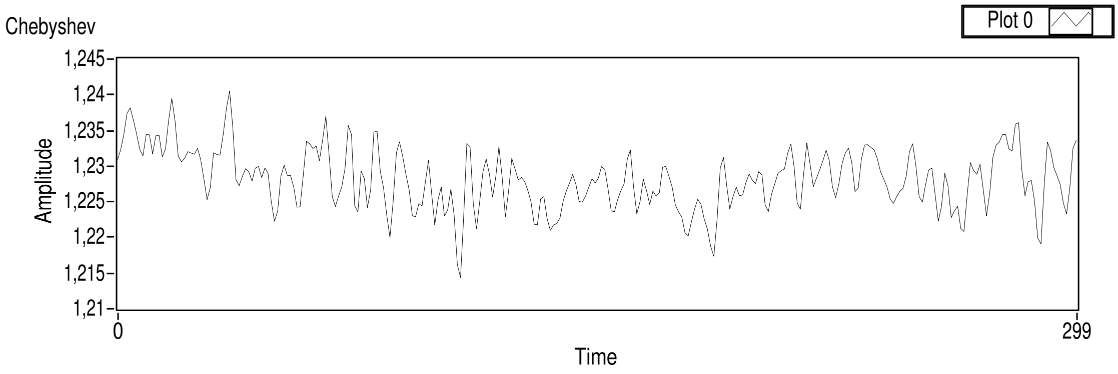

Savitzky-Golay
Plot 0
Amplitude
2,5
2
1,5
1
0,5
0
-0,5
0
150
Time

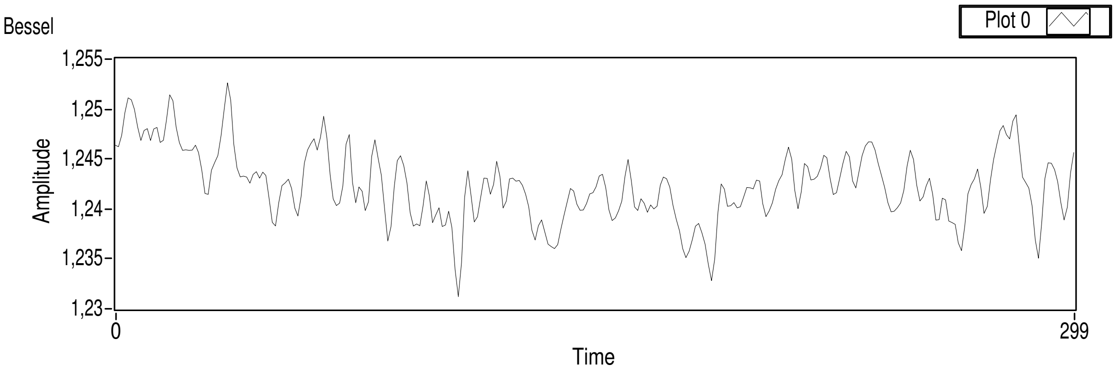
A.2 Steady state measurement

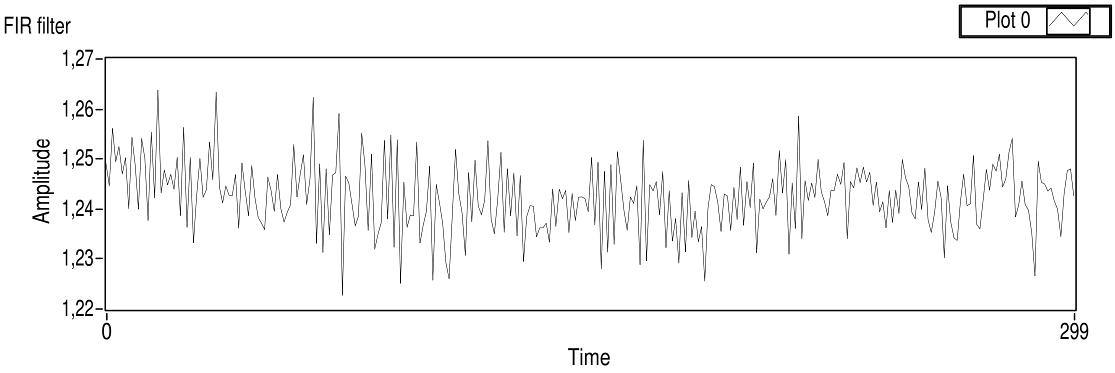
The graphs shows the measurement where the load cell has stabilized after initialization.

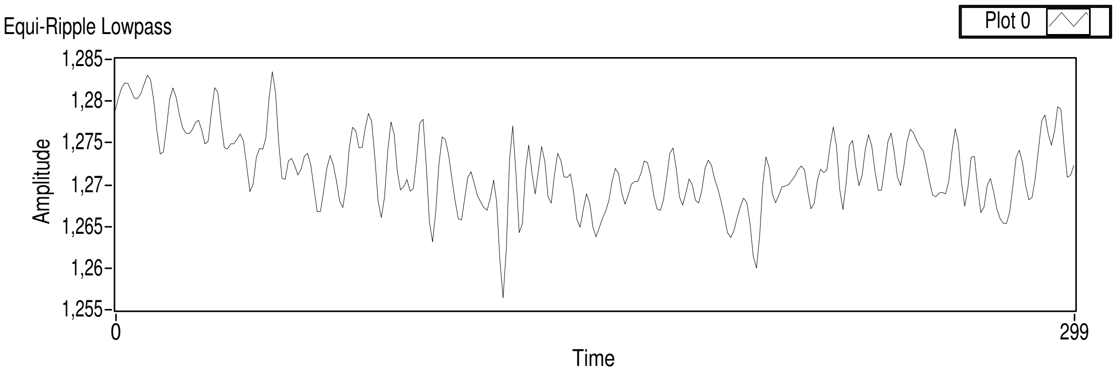


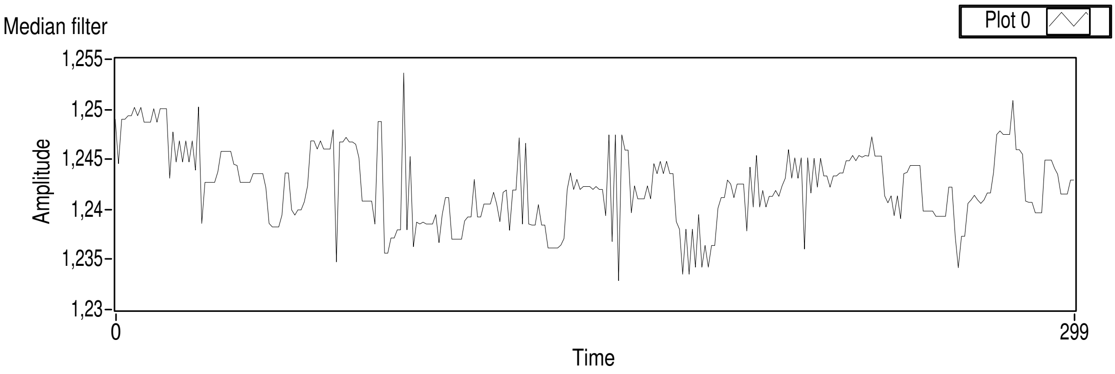


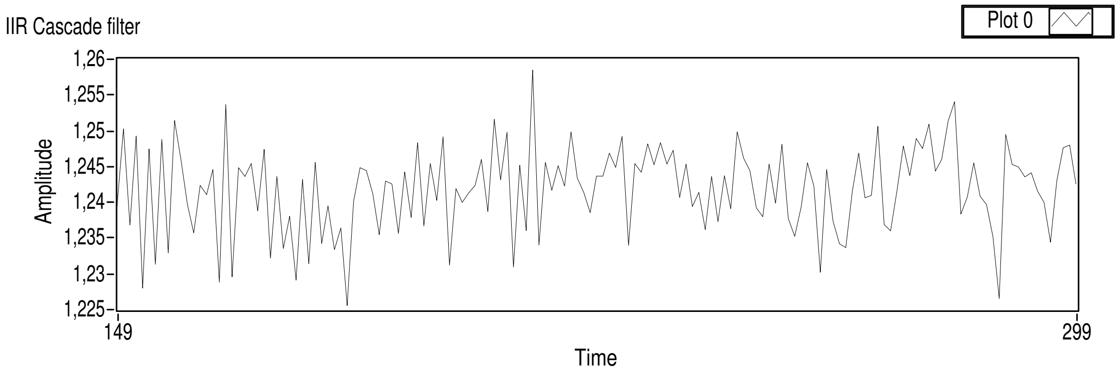


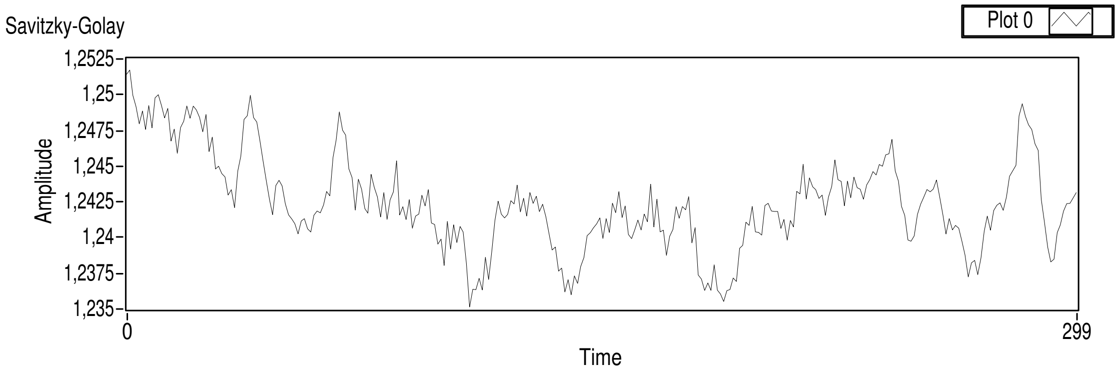

Bessel
Plot 0
1,255
1,25
1,245
1,24
1,235
1,23
Amplitude
0
299
Time


FIR filter
Plot 0
1,27
1,26
1,25
1,24
1,23
1,22
Amplitude
0
299
Time


Equi-Ripple Lowpass
Plot 0
1,285
1,28
1,275
1,27
1,265
1,26
1,255
Amplitude
0
299
Time


Median filter
Plot 0
1,255
1,25
1,245
1,24
1,235
1,23
Amplitude
0
299
Time


IIR Cascade filter
Plot 0
Amplitude
1,26
1,255
1,25
1,245
1,24
1,235
1,23
1,225
149
299
Time


Savitzky-Golay
Plot 0
Amplitude
1,2525
1,25
1,2475
1,245
1,2425
1,24
1,2375
1,235
0
299
Time

Appendix B

Plots from experiments

B.1 Experiment 1 - Fish with big contact area

The plots below shows the force response from the trials when applying force in negative z-direction. The plots are presented in the same order as presented in table 8.1. Both displacement-plots and time-plots are shown.

B.1.1 Force - time response

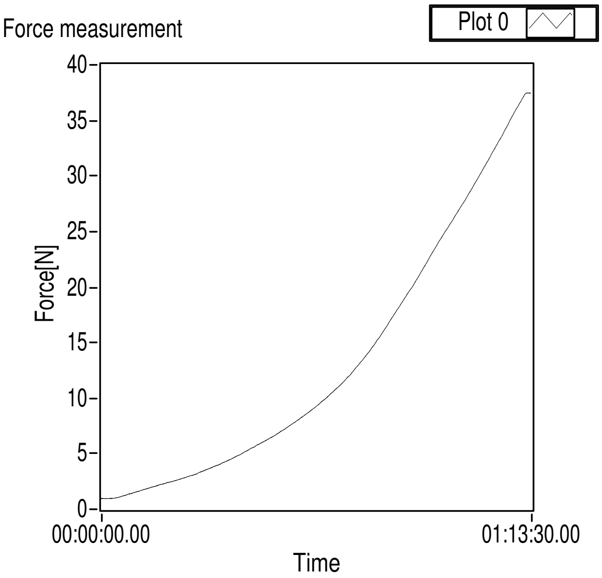


Figure B.1: Force - time response number 1.

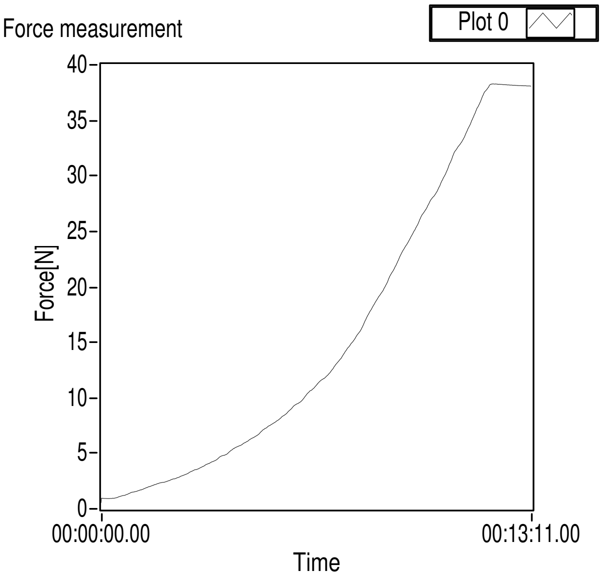


Figure B.2: Force - time response number 2.

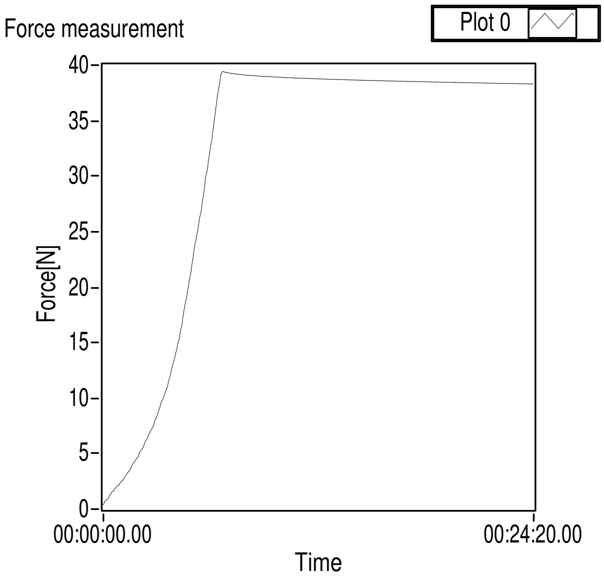


Figure B.3: Force - time response number 3.

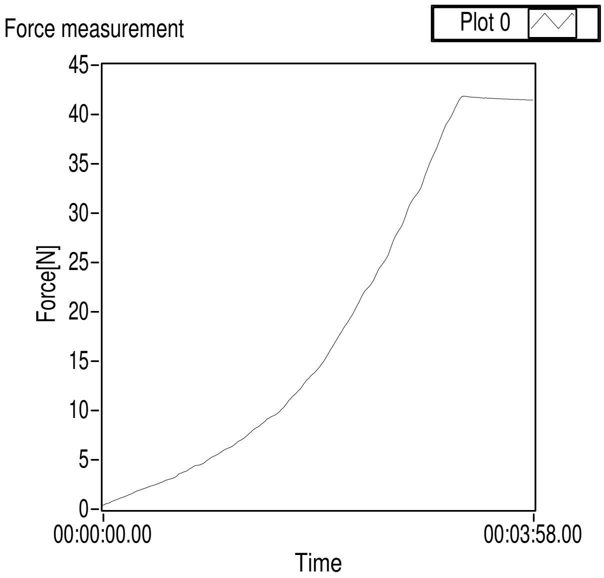


Figure B.4: Force - time response number 4.

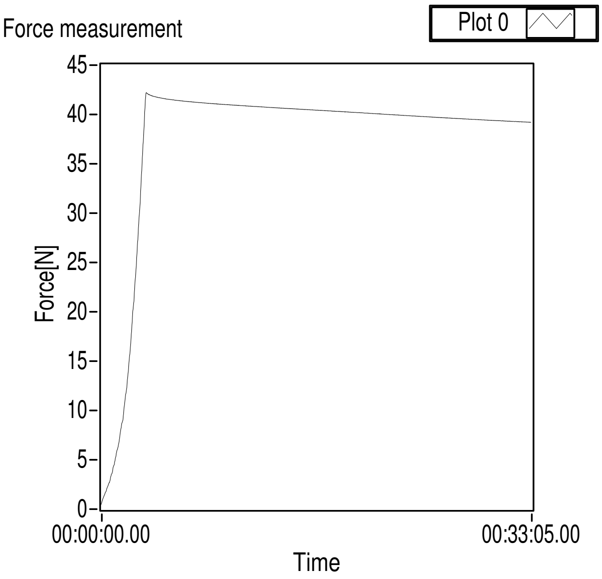


Figure B.5: Force - time response number 5.

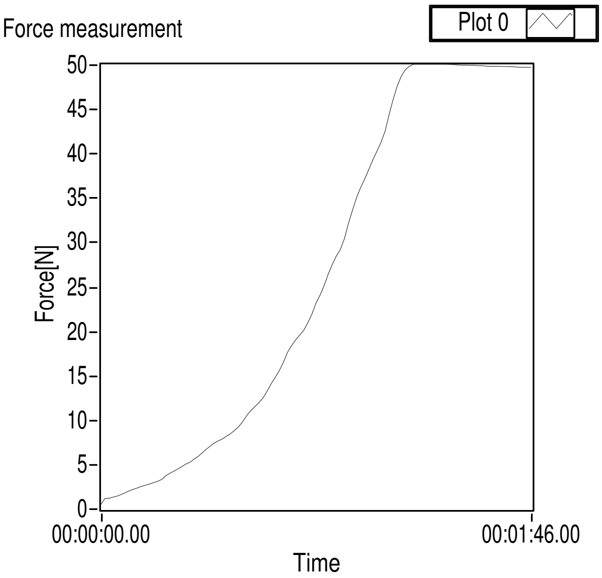


Figure B.6: Force - time response number 6.

B.1.2 Force - displacement response

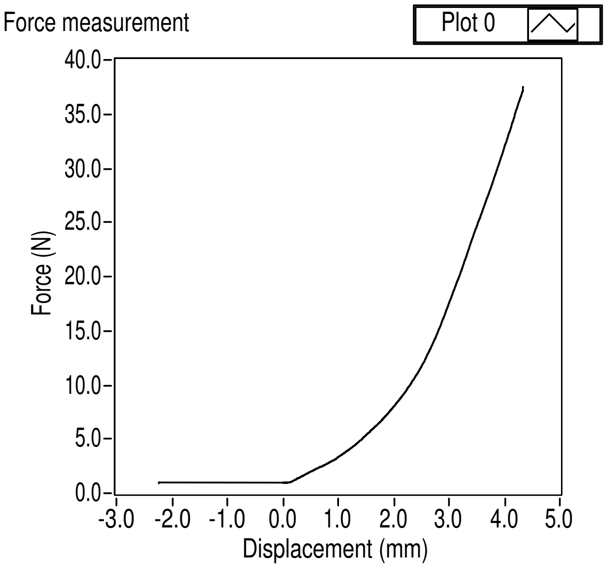


Figure B.7: Force - displacement response number 1.

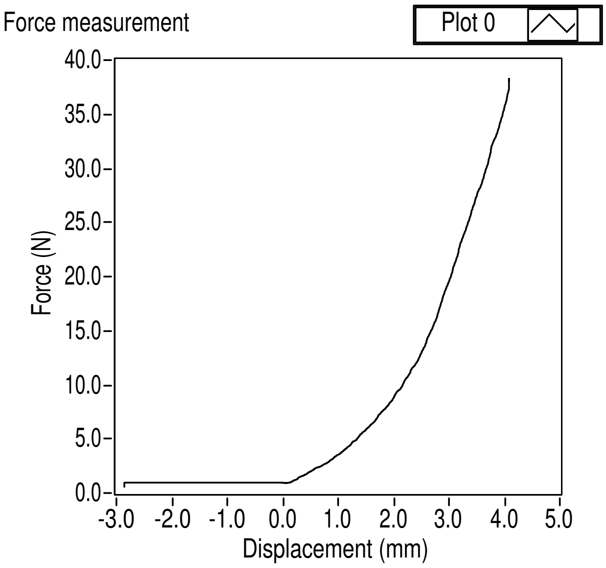


Figure B.8: Force - displacement response number 2.

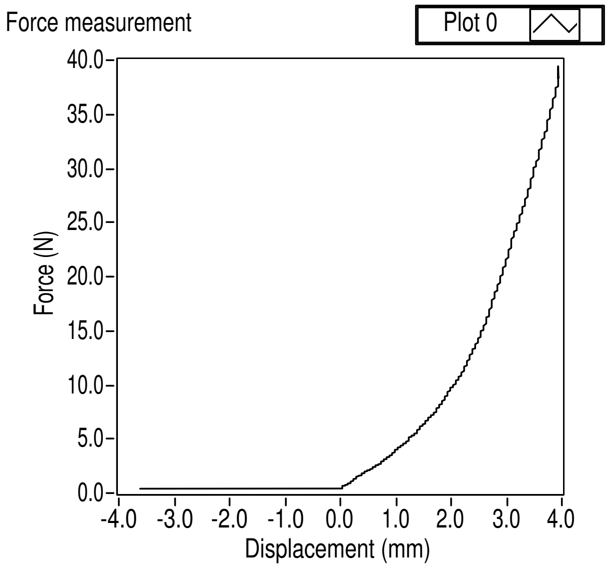


Figure B.9: Force - displacement response number 3.

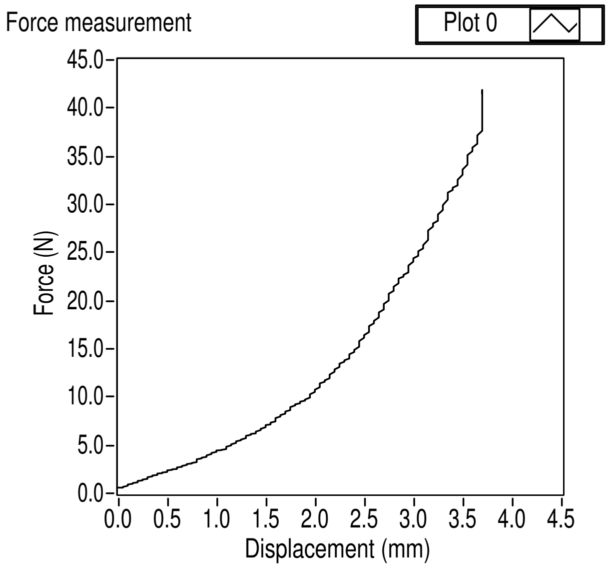


Figure B.10: Force - displacement response number 4.

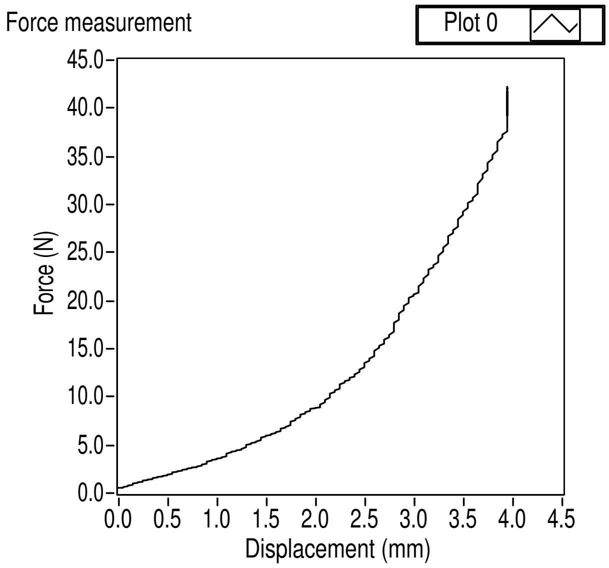


Figure B.11: Force - displacement response number 5.

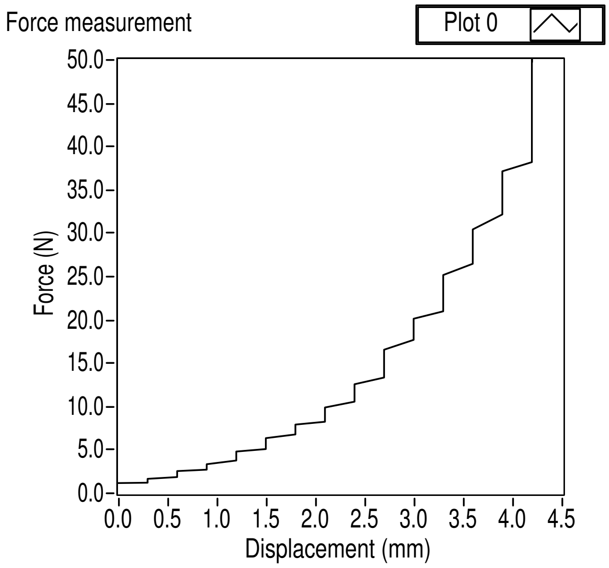


Figure B.12: Force - displacement response number 6.

B.2 Experiment 2 - Spring

The plots below shows the force response from the trials when applying force in negative z-direction. The plots are presented in the same order as presented in table 8.2. Both displacement-plots and time-plots are shown.

B.2.1 Force - time response

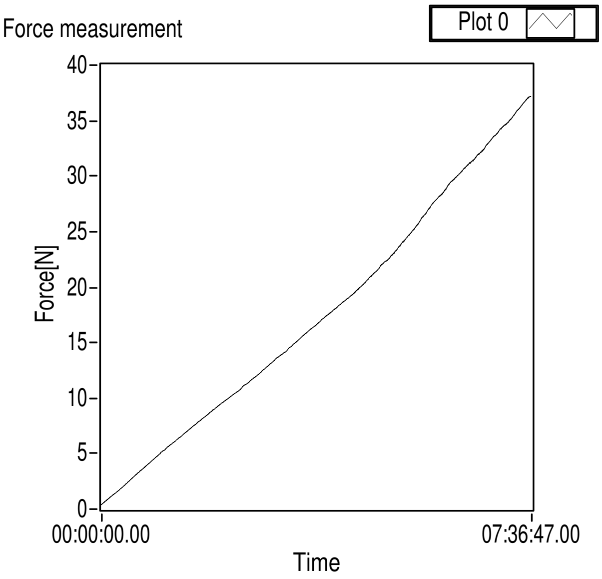


Figure B.13: Force - time response number 1.

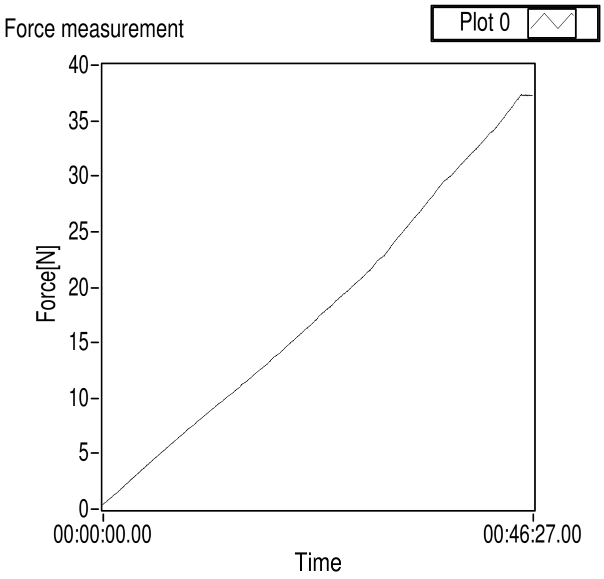


Figure B.14: Force - time response number 2.

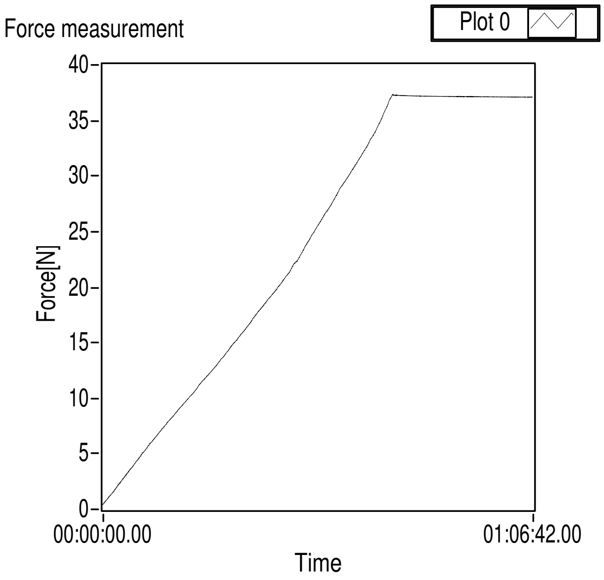


Figure B.15: Force - time response number 3.

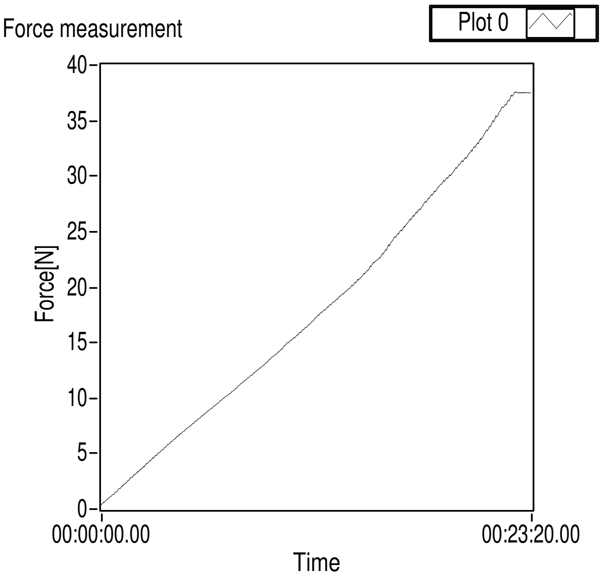


Figure B.16: Force - time response number 4.

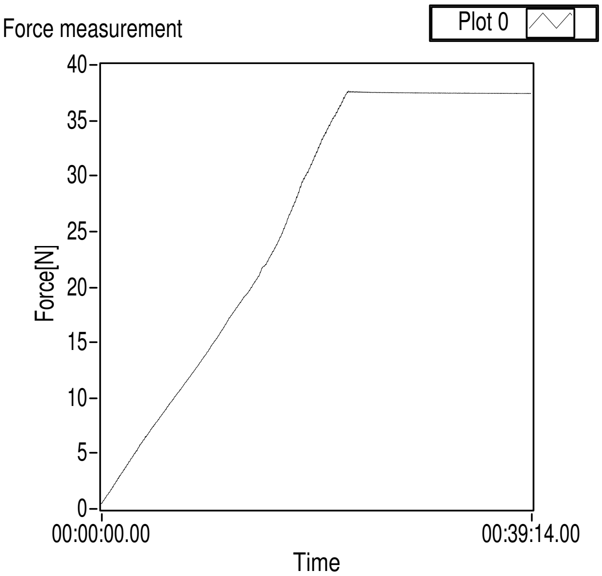


Figure B.17: Force - time response number 5.

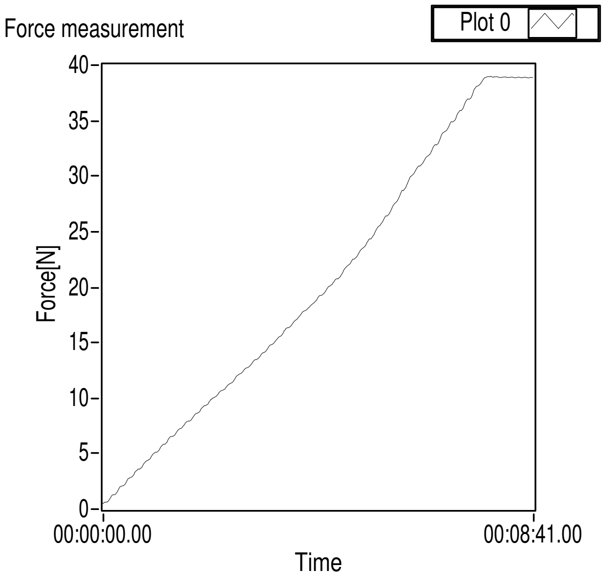


Figure B.18: Force - time response number 6.

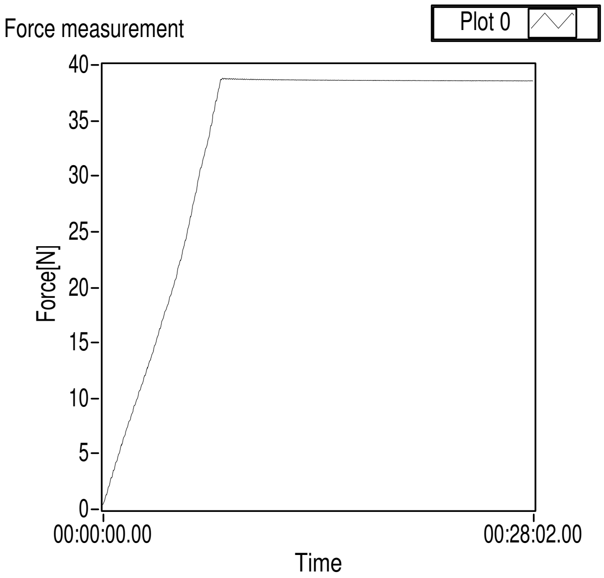


Figure B.19: Force - time response number 7.

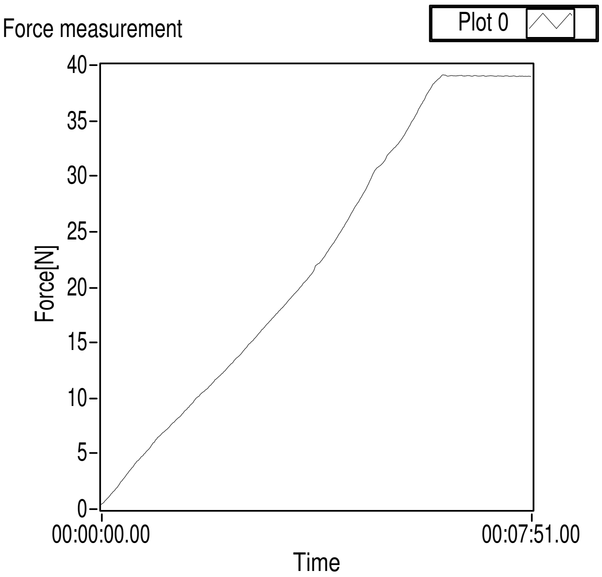


Figure B.20: Force - time response number 8.

B.2.2 Force - displacement response

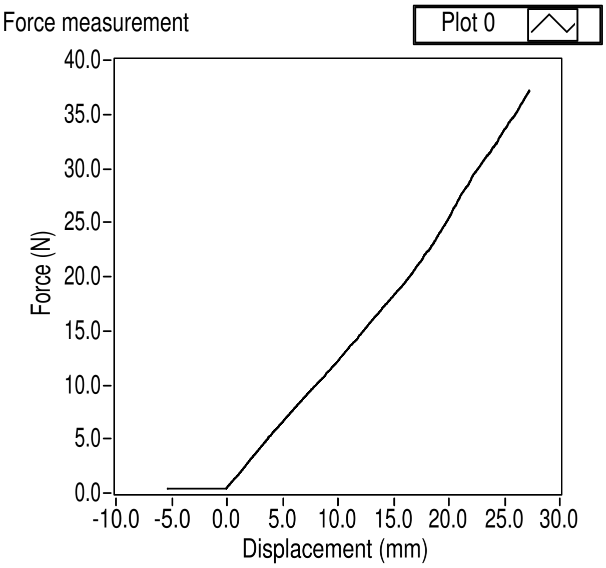


Figure B.21: Force - displacement response number 1.

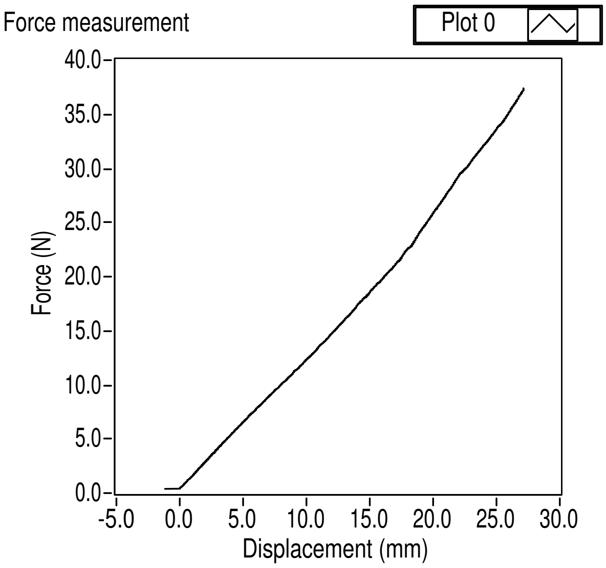


Figure B.22: Force - displacement response number 2.

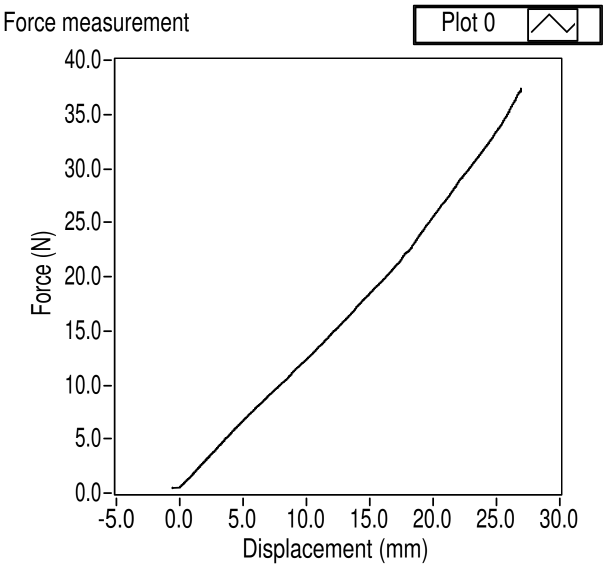


Figure B.23: Force - displacement response number 3.

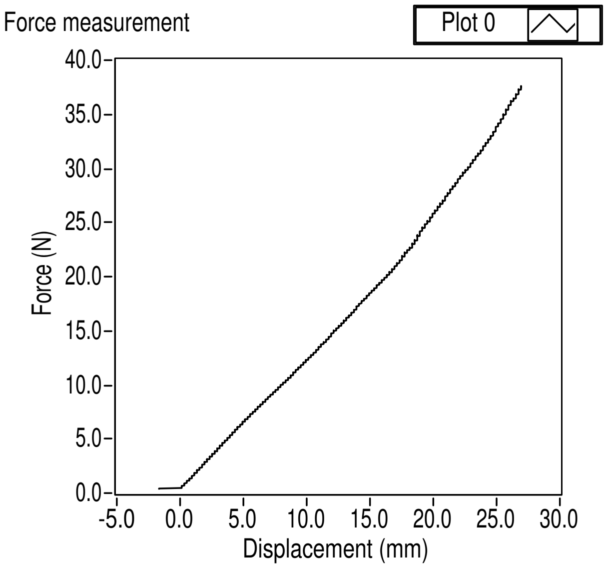


Figure B.24: Force - displacement response number 4.

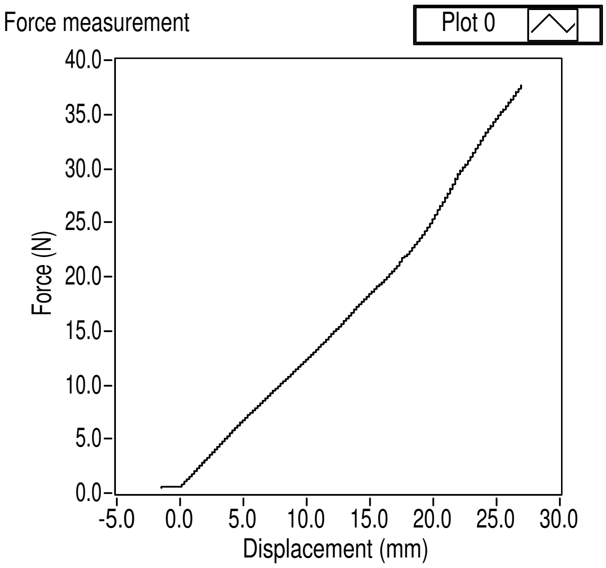


Figure B.25: Force - displacement response number 5.

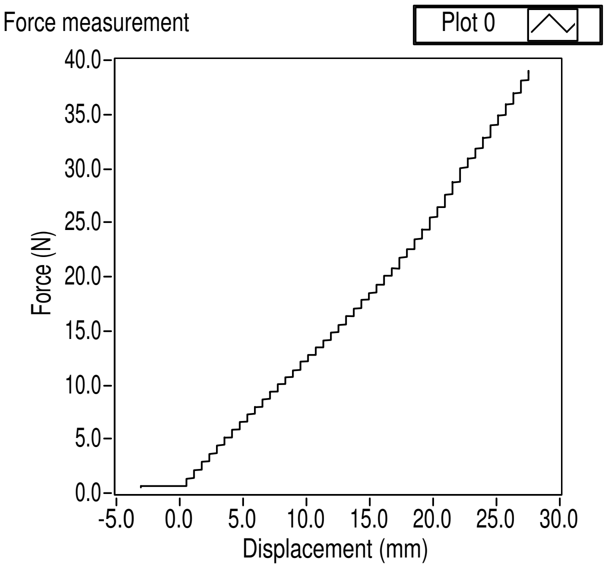


Figure B.26: Force - displacement response number 6.

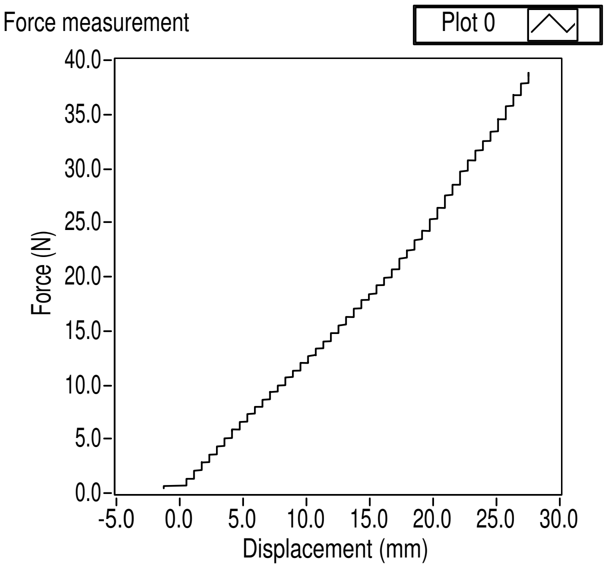


Figure B.27: Force - displacement response number 7.

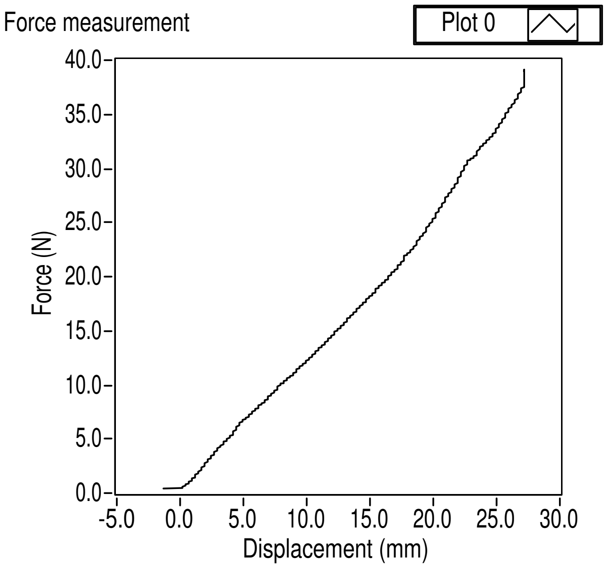


Figure B.28: Force - displacement response number 8.

B.3 Experiment 3 - Fish with small contact area

The plots below shows the force response from the trials when applying force in negative z-direction. The plots are presented in the same order as presented in table 8.4. Both displacement-plots and time-plots are shown.

B.3.1 Force - time response

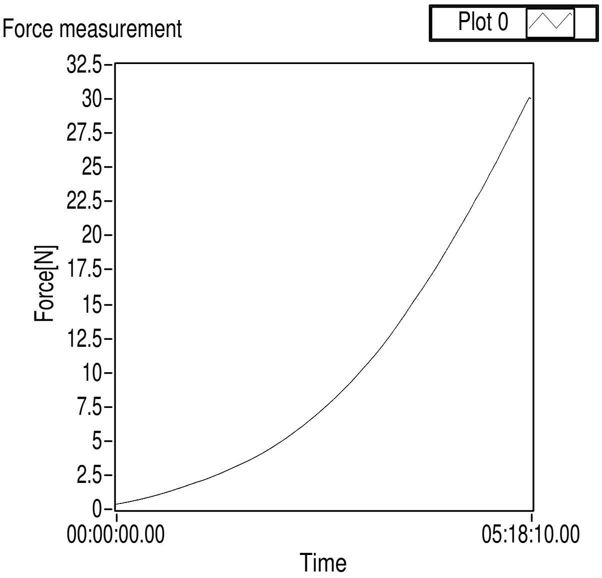


Figure B.29: Force - time response number 1.

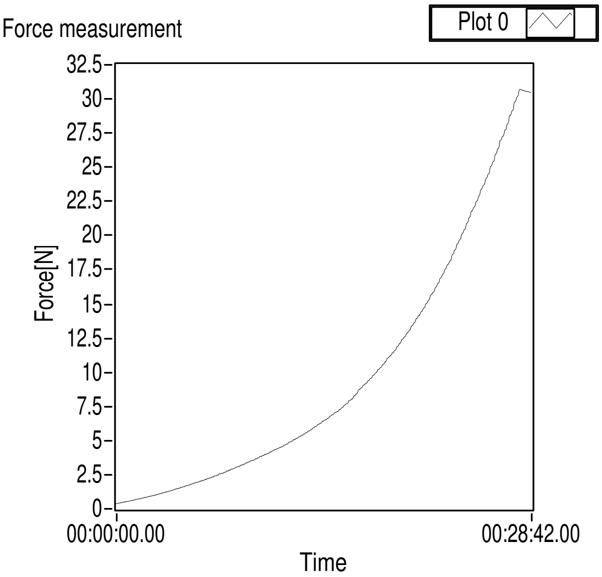


Figure B.30: Force - time response number 2.

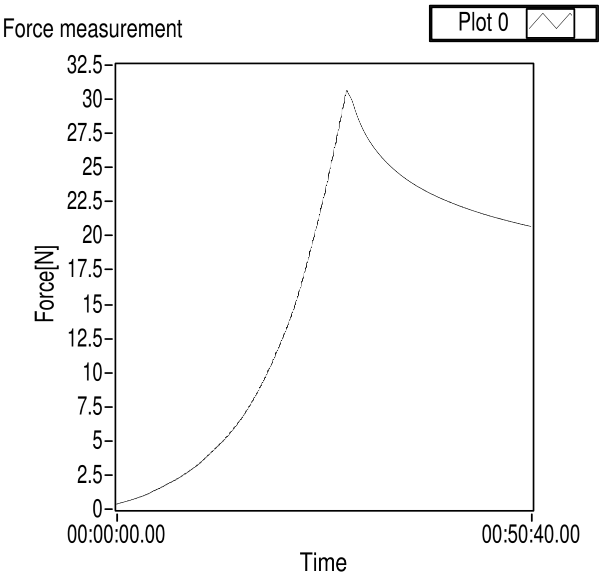


Figure B.31: Force - time response number 3.

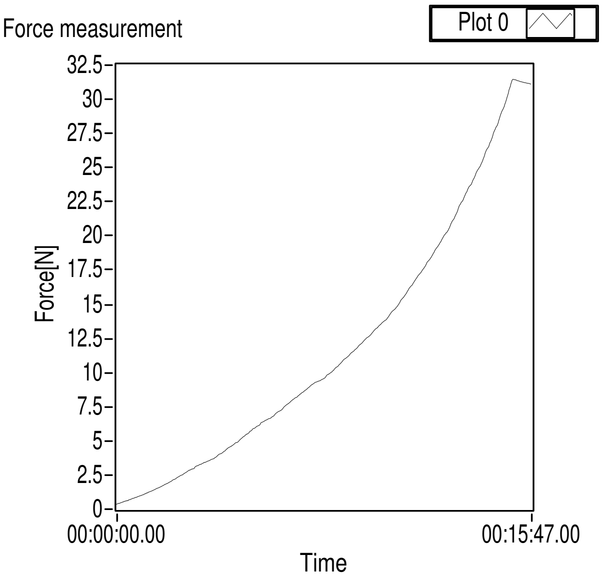


Figure B.32: Force - time response number 4.

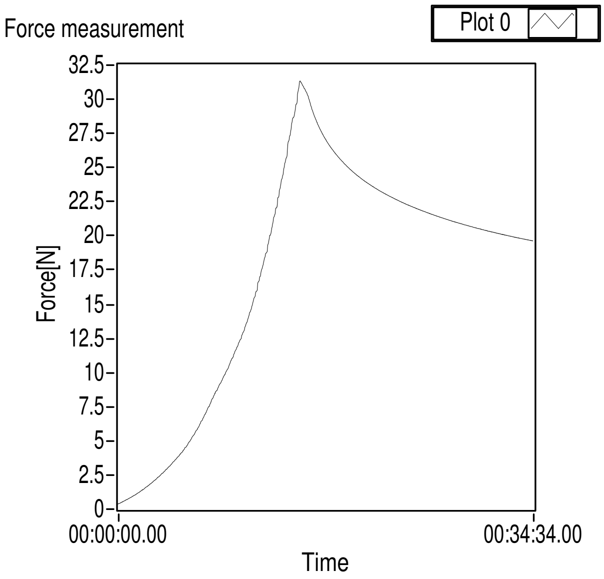


Figure B.33: Force - time response number 5.

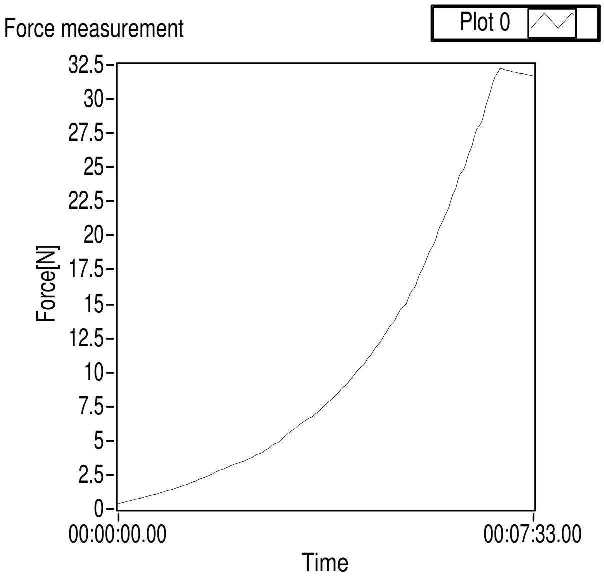


Figure B.34: Force - time response number 6.

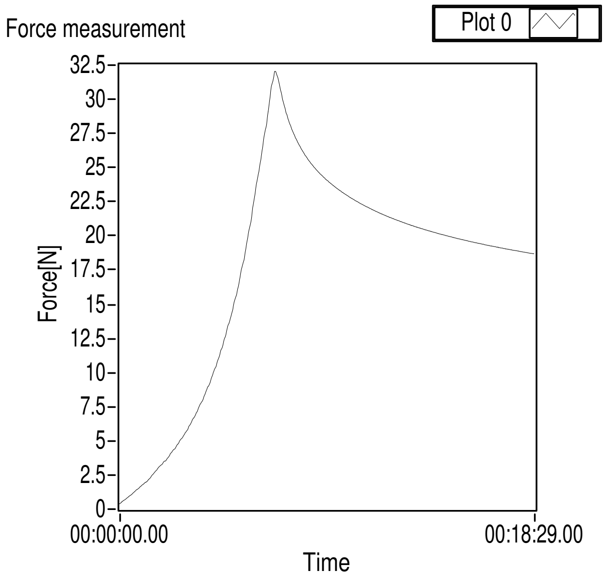


Figure B.35: Force - time response number 7.

B.3.2 Force - displacement response

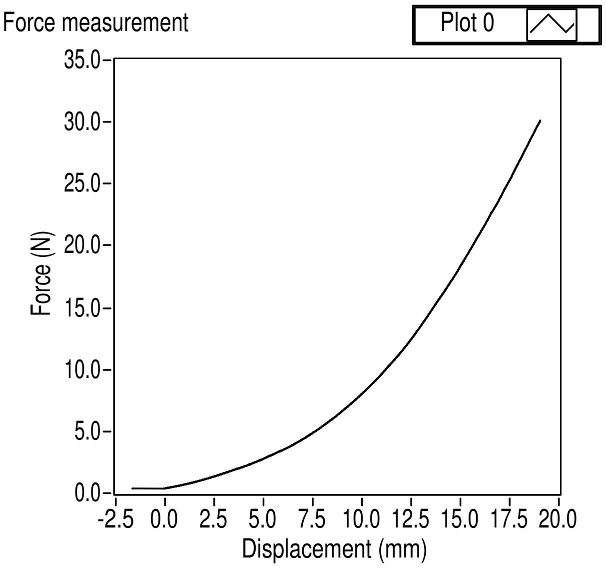


Figure B.36: Force - displacement response number 1.

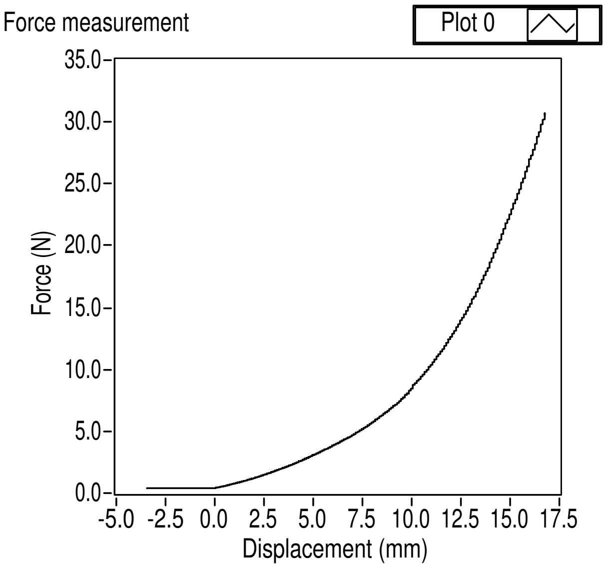


Figure B.37: Force - displacement response number 2.

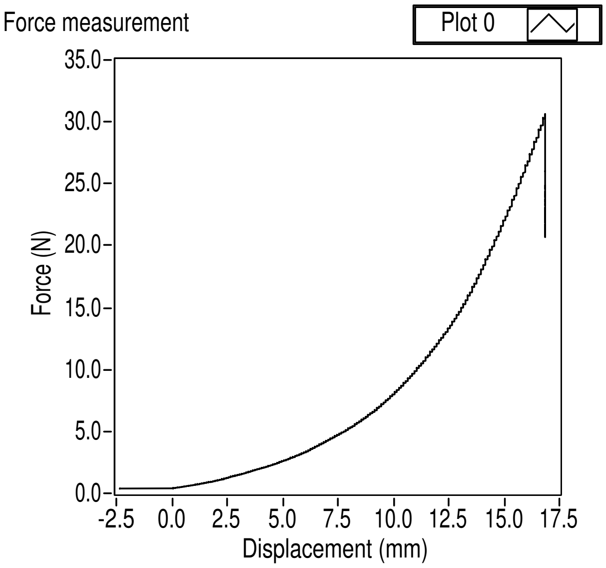


Figure B.38: Force - displacement response number 3.

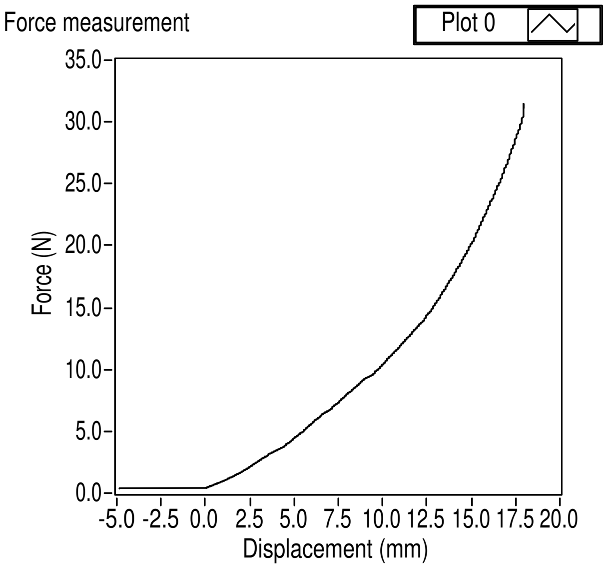


Figure B.39: Force - displacement response number 4.

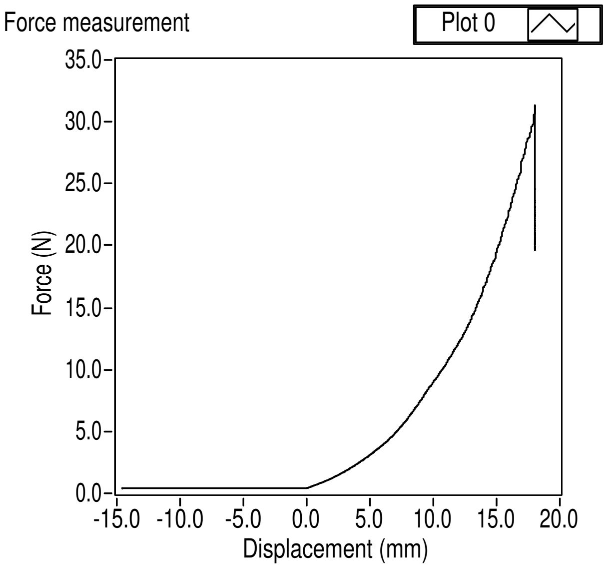


Figure B.40: Force - displacement response number 5.

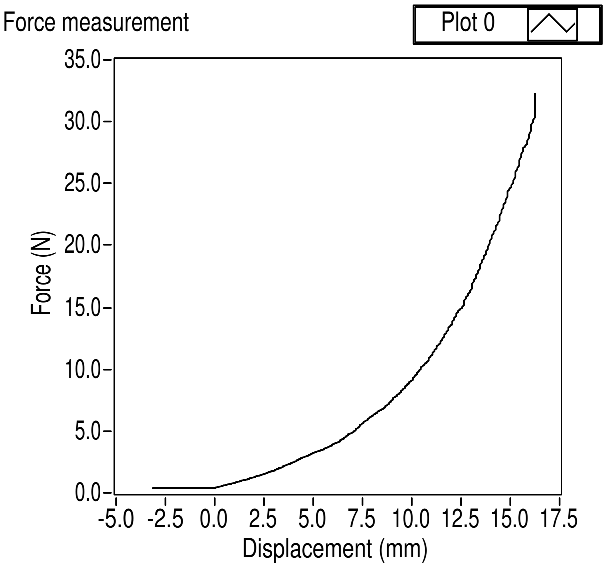


Figure B.41: Force - displacement response number 6.

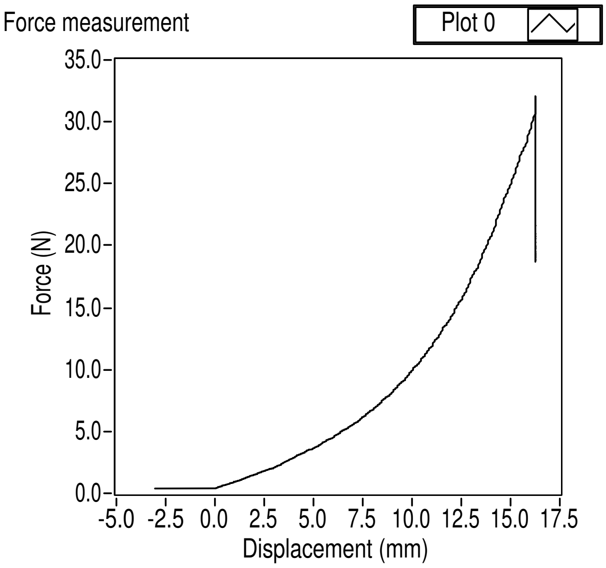


Figure B.42: Force - displacement response number 7.

Appendix C

Gripper Prototyping

C.1 Gripper 1

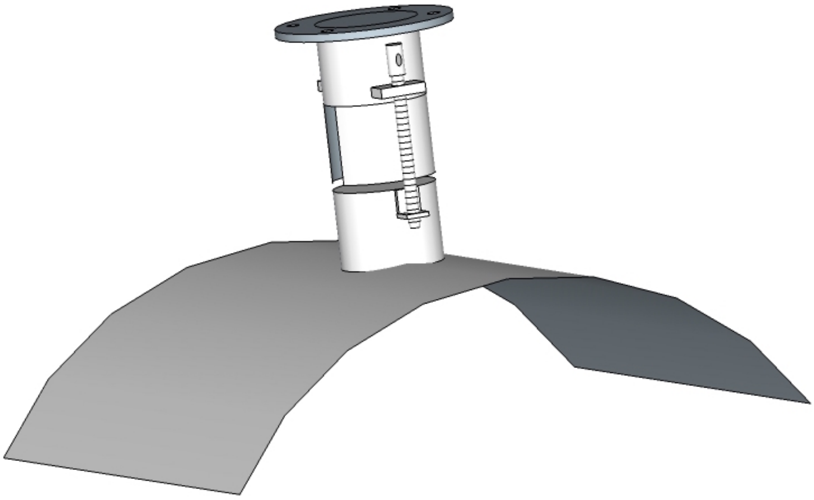


Figure C.1: Gripper 1.

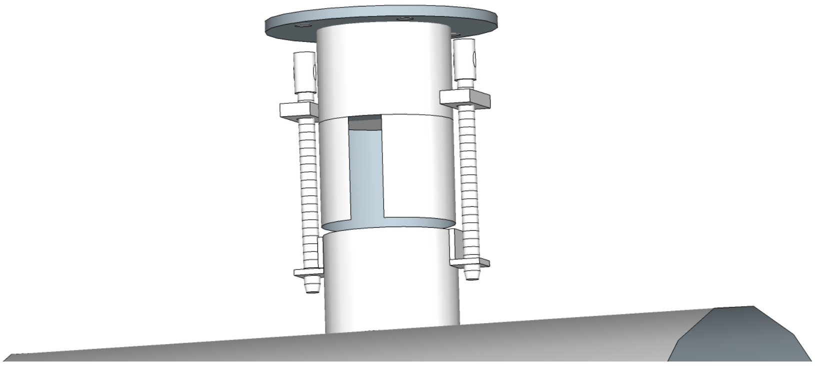


Figure C.2: Gripper 1 sensor house.

Figure C.3: Gripper 1 during experiment.

Figure C.4: Gripper 1 sensor house including load sensor.

Figure C.5: Gripper 1 sensor house.

C.2 Gripper 2

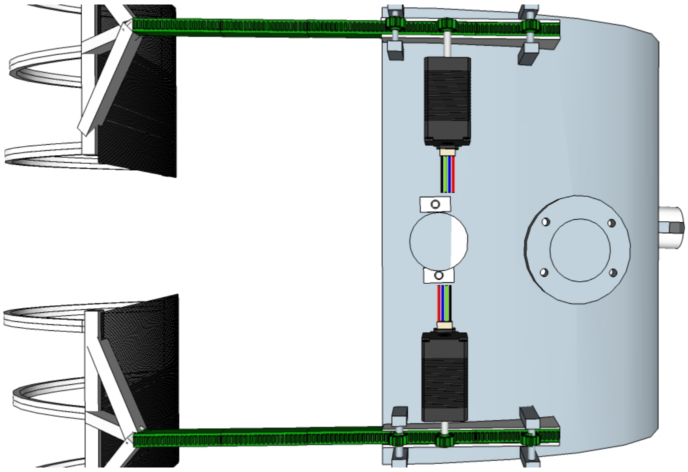


Figure C.6: Gripper 2 seen from above.

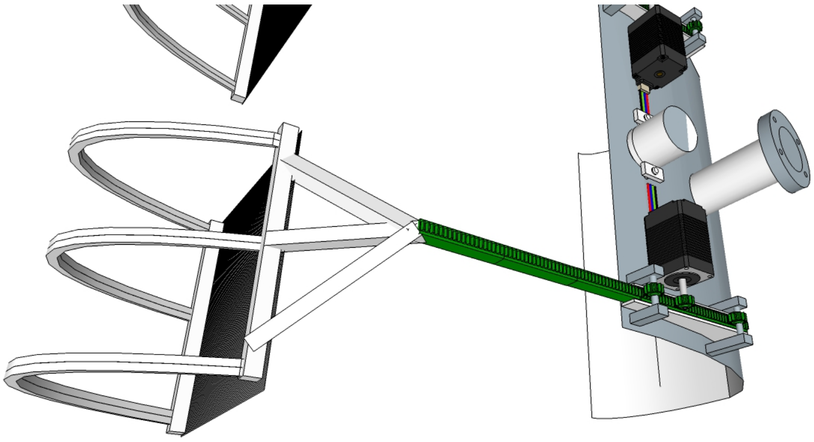


Figure C.7: Gripper 2 arm.

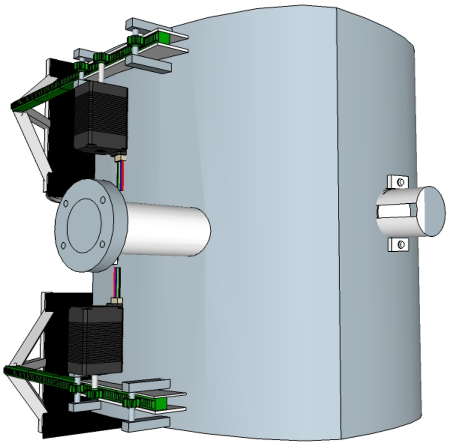


Figure C.8: Gripper 2 seen from behind. The load cell measuring continuously is attached here.

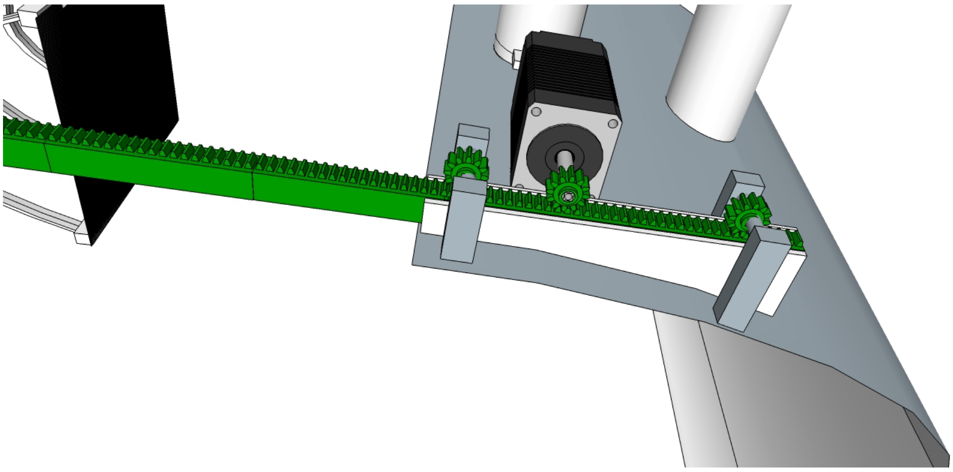


Figure C.9: Motor attached to gripper 2.

Appendix D

Datasheets

D.1 Arduino Motor Shield

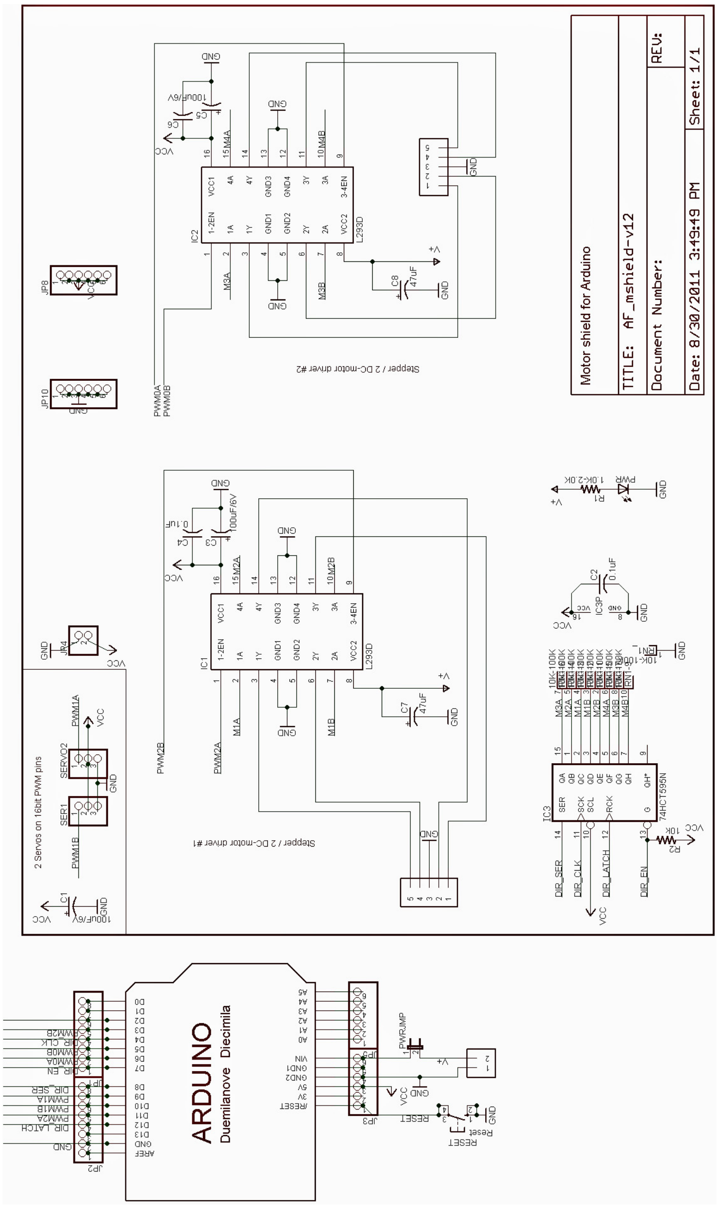
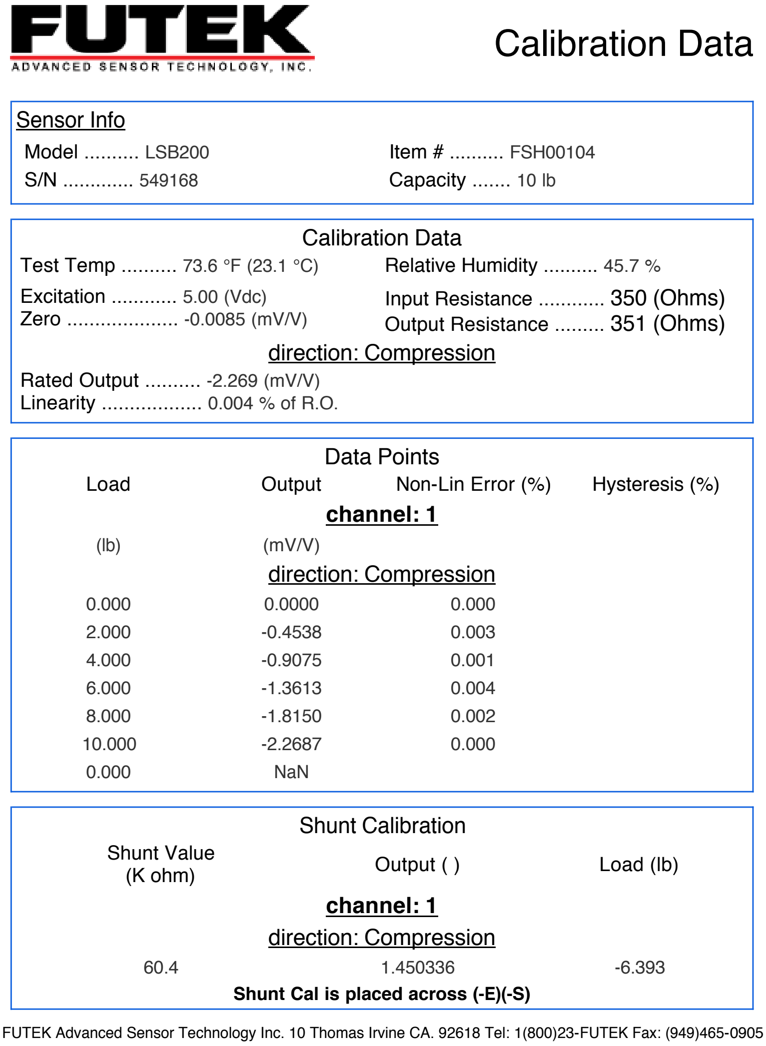


Figure D.1: Datasheet for Arduino Motor Shield.

D.2 Load Cell Calibration



FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

Calibration Data

Sensor Info

Model LSB200	Item # FSH00104
S/N 549168	Capacity .... 10 lb

Calibration Data

Test Temp .... 73.6 °F (23.1 °C)	Relative Humidity .... 45.7 %
Excitation .... 5.00 (Vdc)	Input Resistance .... 350 (Ohms)
Zero .... -0.0085 (mV/V)	Output Resistance .... 351 (Ohms)

direction: Compression

Rated Output .... -2.269 (mV/V)
Linearity .... 0.004 % of R.O.

Data Points

channel: 1

direction: Compression

Load (lb)	Output (mV/V)	Non-Lin Error (%)	Hysteresis (%)
0.000	0.0000	0.000	
2.000	-0.4538	0.003	
4.000	-0.9075	0.001	
6.000	-1.3613	0.004	
8.000	-1.8150	0.002	
10.000	-2.2687	0.000	
0.000	NaN		

Shunt Calibration

channel: 1

direction: Compression

Shunt Value (K ohm)	Output ( )	Load (lb)
60.4	1.450336	-6.393

Shunt Cal is placed across (-E)(-S)

FUTEK Advanced Sensor Technology Inc. 10 Thomas Irvine CA. 92618 Tel: 1(800)23-FUTEK Fax: (949)465-0905

Figure D.2: Calibration sheet for FUTEK Load Cell

Appendix E

LabVIEW code

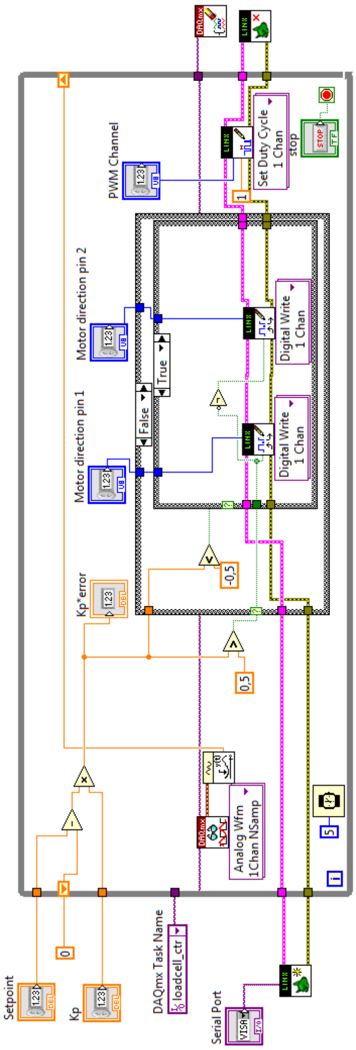


Figure E.1: LabVIEW code for Bang-Bang Motor Control Algorithm.

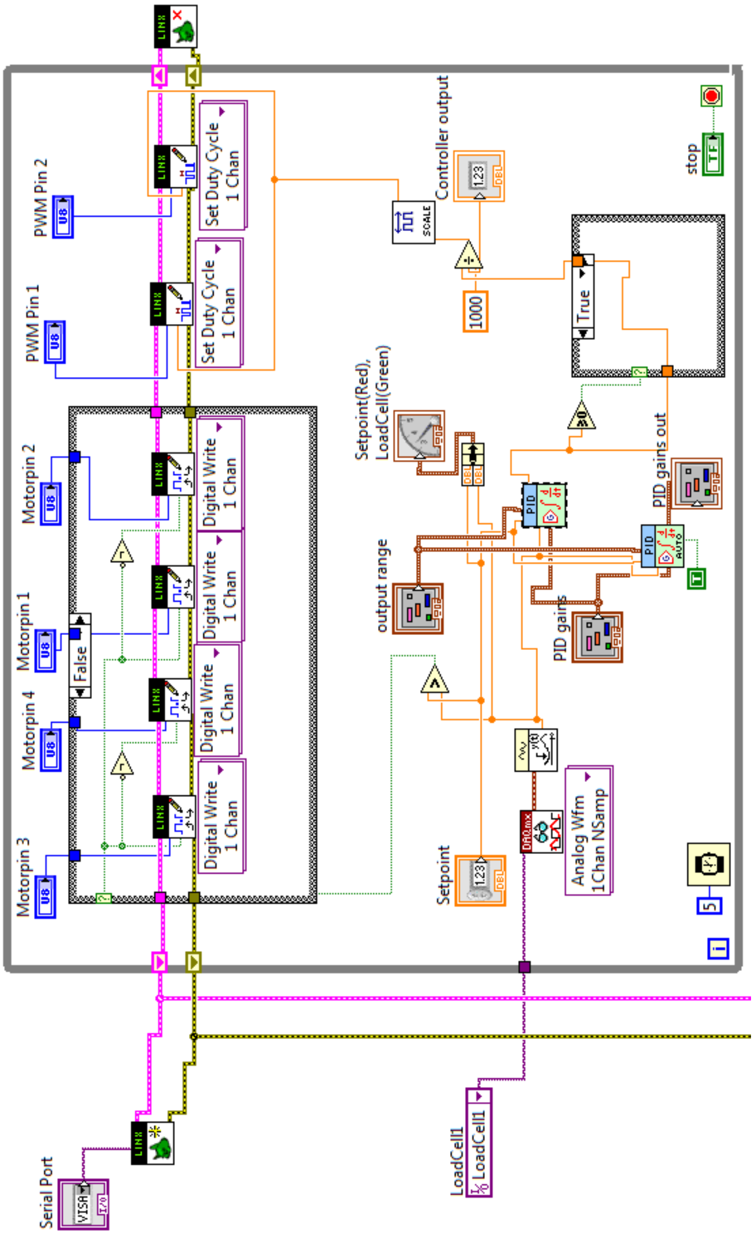


Figure E.2: LabVIEW code for PID Motor Control Algorithm.

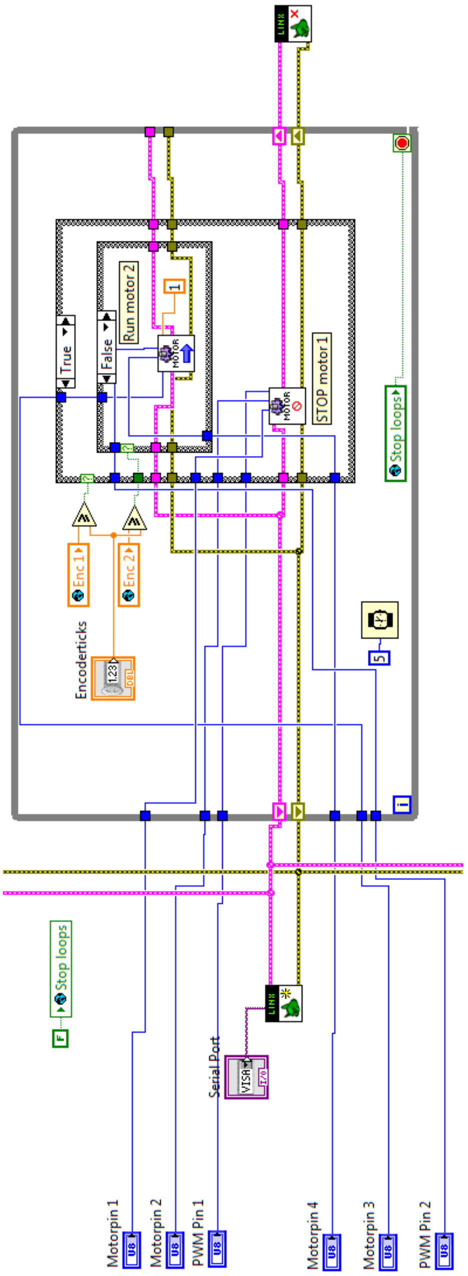


Figure E.3: LabVIEW code for synchronization of motors using encoders