Designing a cost-effective robot gripper with force-feedback

AX-18A Robotic Arm by Crustcrawler

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1 Abstract

The aim of the integration project is to design a responsive force-feedback gripper for AX18A robot arm by Crustcrawler at the DTPA laboratory of the Rijksuniversiteit Groningen. A parallel gripper is designed and a control program written based on the load reading of the AX18A servomotor. The controller uses both the load reading and the moving speed which is used in the current control program to regulate the grasping force. A validation experiment is conducted to test the performance and is concluded to be successful as the of the combined product does not damage or drop the workpieces used.

Contents

2 Introduction

The importance and potential of industrial robots have been increasingly investigated over the last years and have proven to be beneficial in terms of for example cost-efficiency, safety and adaptability (Tai, El-Sayed, Shahriari, Biglarbegian, & Mahmud, 2016). These days primarily large multinationals are using collaborative robots to assist with for example pick-and-place operations in production today, nevertheless, this is changing with the introduction of industry 4.0. (Bragança, 2019) The gripper of the robot is the direct link between the handling equipment and the object to be lifted and thus greatly affects the prehension ability of the robot as a whole.

In this research, the possibility of improving the Crustcrawler AX-18A simplistic robotic arm gripper is explored. Utilizing the load reading inferred by the implemented servomotor, a force feedback control loop is presented. The finalised robotic gripper prototype is created using additive manufacturing. The combined product is tested in real-life experiments.

This paper is structured as follows, first the problem is introduced in which the problem owner, the system and its components are discussed. Followed by relevant theory on robot grippers and force-feedback control. Afterwards the new design is discussed force-feedback controller introduced. Thereafter the solution results to the tested solution is given and discussed. The report is finalized by some final remarks and suggestions for further research.

3 Problem analysis

In this section the problem context is thoroughly explained. This entails the problem to be solved, the problem owner as well as a description of the current system and it components. Moreover, the different software programs used to control the robot arm are introduced.

3.1 Problem definition

The AX18A robot, as visible in figure 1, is the AX18A robotic arm manufactured by Crustcrawler (Crustcrawler Inc., 2013). However, The construction of the arm itself collapses when a weight over 0.5 kg is lifted and the promised repeatability of the manufacturer of 2.5 mm is not met. The current one, is a two-fingered active gripper, is complementary with the AX-18A robot. The gripper is not able to fully encompass an object whilst clasping, for the fingers of the gripper only close at the tips.

A new physical robot gripper is to be designed to replace the complementary gripper that comes with the robot free of charge. The current gripper does not suffice as the gripper under-performs in terms of retention ability and stroke. Moreover, in order to prevent on the one hand surface damaging and on the other the risk of dropping the workpiece; especially when handling delicate objects, the force exerted by the gripper on said object needs to be controlled. The current software only allows the gripper to move to predetermined positions. Therefore, the program regulating solely the speed of the gripper needs to be expanded.

Figure 1: Image of the AX18A Crustcrawler robotic arm

3.2 DTPA Group

The problem owner of the project is the DTPA research group of led by Prof. dr. ir. Jacquelien Scherpen. The DTPA is in turn part of the ENTEG (Engineering and Technology institute Groningen) of the Rijksuniversiteit Groningen.They are specialised areas such as robotics, mechatronics and sensor systems and have 35 current ongoing projects at the moment. (Current projects.2021). The Discrete Technology Production Automation research group, from now on DTPA, has adjusted the off-the-shelf robot arm in terms of hardware, mechanical drives and has created control programming to control and direct the arm. A few of these adjustments are:

- Creating a new base for the robotic arm which allows for better rotation and provides stability to the arm
- The servomotor controlling the first degree of freedom (the bottom servomotor on the picture above) has been replaced for a stronger and bigger one.

The DTPA researchers are continually improving the hardware, updating software as these robots are used for research projects and in courses given by DTPA professors to Rijksuniversiteit master students. An example of a research project performed by the DTPA group is robots mounted on vehicles and ordering the robots to pick an object up in unison.

For this research project, the problem owner has given specific requirements for this project: The new gripper must be able to prehend a boiled egg and a paper coffee cup without damaging or dropping the object by means of a force-controlled program.

3.3 System

The current gripper is part of a mechatronic system controlling the movements of the two fingers of the robotic gripper by means of a gear attached to servomotor 8 of the robotic arm, see figure two. The seven other servomotors controlling the rotation of the robotic arm are regarded outside the scope of the project. In addition, the scope of the project is limited to the gripping of the object and the arm of the AX-18A robot is positioned correctly. Hereby, finding and positioning the object for the robot is not included in the project.
Goal position commands are sent to the servomotor via the controller using the PuTTY program. The gripper is driven by an AX-18A servomotor, which makes the right gear and thereby the whole gear train of two rotate. The jaws of the grippers are fastened to the gears and such the gripper opens and closes. The gripper has two options; opening (CW) and closing (CCW), for which the pulse length is recorded by the keyboard of the PC and translates to a corresponding increase or decrease in the goal position. A P-controller adjusts the speed based on the difference between the desired and current position of the servomotor.
The output of the system is the kinetic energy from the gears as well as noise and heat.

Moreover, noise and heat produced by the servomotor and along with live readings of various parameters such as present load, present temperature, present speed and present voltage (ROBOTIS e-Manual AX-18A, n.d.).

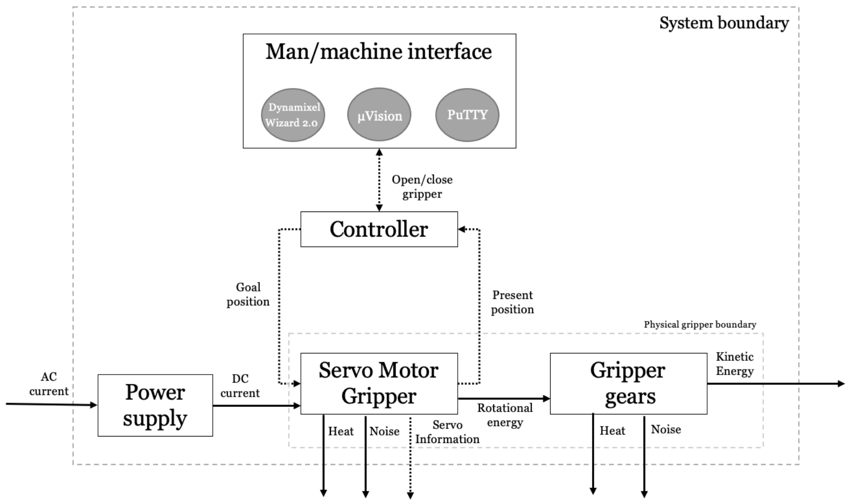


Figure 2: Overview of the current system without force feedback.

3.3.1 Electrical overview

The electrical overview of the system is visible in figure 3. The keyboard is connected to the PC by a USBc cable and the LCD screen by means of an HDMI cable. The programmer and the controller are both connected to the PC by USB. The programmer and the AX controller are connected using a JTAG cable. The eighth different servomotors are connected by serial bus interfaces with RS422 and RS232 cables, of which the latter is longer and is only in use by servomotor 1. Both cables transmit electric current and allow for communication.

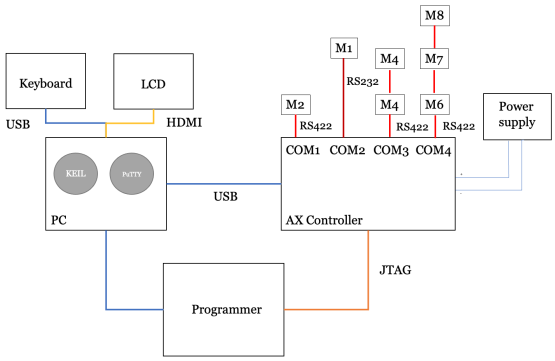


Figure 3: Electrical overview of the current system

3.3.2 Relevant individual items

Current gripper As mentioned previously, the current gripper is complementary with the AX18A robot by Crustcrawler and can be seen in figure 4. The gripper is made with strong anodized brushed finished aluminum and high adhesion rubber is mounted on the surface of the gripper fingers to enhance the grip. Moreover, the cylindrical gear train consists of two items with 60 straight teeth each. (Crustcrawler Inc., 2013). The gripper has a stroke of 6cm and further dimensions can be seen in the figure below. The lengths are taken from bolt to bolt. The links connecting the gripper finger to the gears and servomotor are fastened to a plate below this construction. A specific place on this plate is reserved for the servomotor by means of a hole in which the servomotor can be fastened.

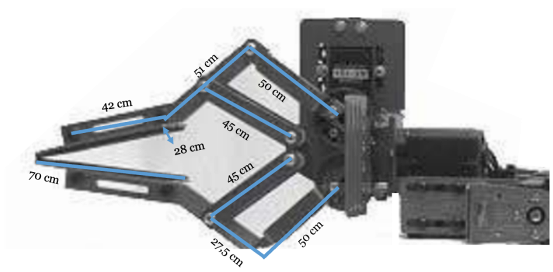


Figure 4: Overview of the electrical system

Controller The AX Controller used for the AX18A robot is built in-house by the DTPA lab in 2021 with the intend to replace the Dynamixel controller that comes with the AX-18A robot arm. This was crucial when servomotor 1; motor type MX-106 of the robot arm was introduced and replaced the former AX-18 motors that stood at its place. The schematics of the controller can be found in Appendix D. Some further characteristics (Busman, 2020) of the controller are:

- A motor communications check after activating the motors of the arm
- The implementation of basic kinematics that prevent collisions
- Four strings of motors are connected to 4 serial interfaces to support faster control loops and allow for the addition of more motors
- The implementation of default control loops that prevent sudden motor movements which may damage the robot
- A ROS serial mode to read and control motors
- An interactive mode, to setup, test and calibrate the robot manually

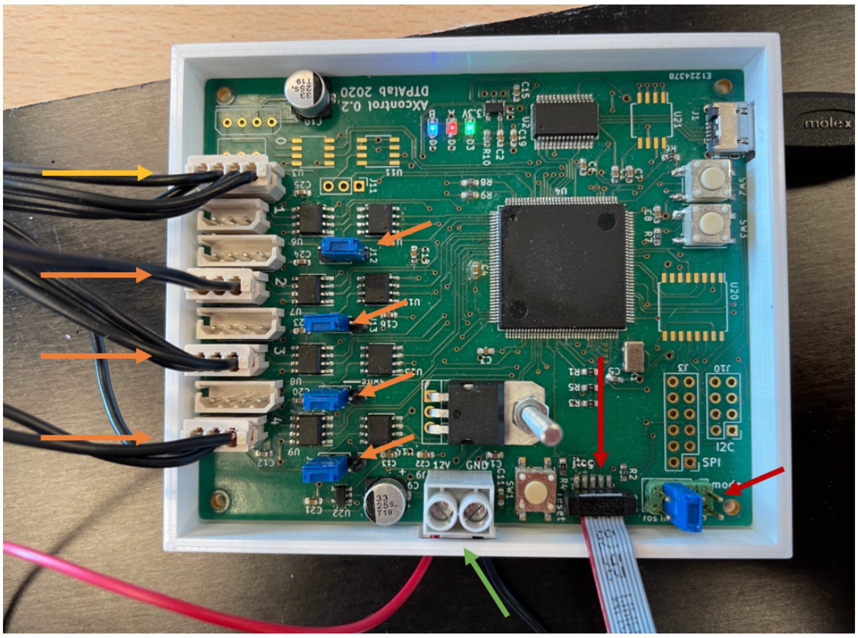


Figure 5: Inside of the AXcontroller built by the DTPA labrotory

For the arrows in figure 5:

- The orange arrows: RS232 cable (long) and its corresponding jumper on the electrical circuit (short)
- The yellow arrows: RS422 cable (long) and its corresponding jumper on the electrical circuit
- The red arrows: JTAG cable (long) and its corresponding jumper on the electrical circuit
- The green arrow: The cable connecting the controller to the power supply

AX-18A servomotor The AX-18A servomotor is produced by Dynamixel. Before the robot was altered by the DTPA lab staff, all motors of the arm were this type. The servomotor of the gripper is currently controlled by the goal position input, which ranges from 0-1023 and thereby turns 300°. (ROBOTIS e-Manual AX-18A, n.d.).

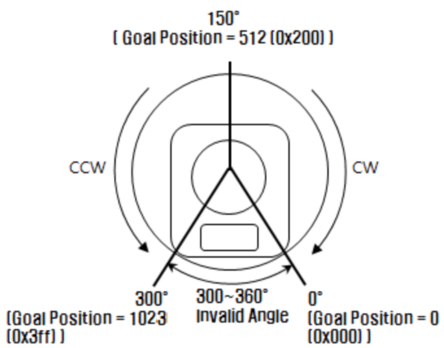


Figure 6: Front view of the Dynamixel AX-18A servomotor in terms of the goal position

Some other specifications (ROBOTIS e-Manual AX-18A, n.d.) include:

Weight	55.9 [g]
Dimensions	32 X 50 X 40 [mm]
Stall Torque	1.8 [N.m]
Feedback	Position, Speed, Temperature, Load and Voltage

Table 1: Table displaying servomotor AX18A specifications

Fixture to robot arm The gripper is attached to the robot arm via the plate below. Four M3 holes around the larger middle one are used to fix the gripper hardware to the rest of the robot using nuts and bolts. The plate can be seen in figure 7 below.

Figure 7: Photo of the attachment plate of the robot arm and the gripper

3.3.3 Communication

In the section describing the system above the program PuTTY was mentioned when explaining the communication from the PC to the controller. There are two other programs which may be used used to send commands to the targeted servomotor.

1. µVision : This program is used to write the software for the entire robotic arm in the programming language C. This has already been executed by the DTPA staff for all servomotors of the robot arm for controlled movement based on goal position. The robot is not live directed from this program. When wanting to make a change to the control dynamics of the robot, this has to be done in µVision and then downloaded via the programmer to the AX controller. Afterwards, PuTTy can be used to send terminal tasks to the controller.

2. PuTTY: This program is a terminal emulator. Contrary to the other software listed above, this program is merely used to pass signals to the controller from the keyboard by the user and cannot process any information on its own. It is important the AX Controller is put in interactive mode when using PuTTY.

3. DynamixelWizard 2.0: This is the software provided by the manufacturer and can be used to directly control one of the servomotors of the robot arm using a USB to serial converter with a FTDI-232 chip. This program needs to be used with caution, as limits (maximum torque, goal position) put in place in the µVision programming are not activated. This may result in e.g. sending the servomotor to a goal position which will damage the hardware of the gripper.

4 Literature research

In this section relevant theory on robotic grippers and on how to design them is given. Moreover, basic control systems theory provided as well as force-feedback control methods applied in other research.

4.1 Gripper design

4.1.1 Classification robotic grippers

The selection of the right gripper is dependent on multiple factors. These are the task, the robot, the environment and the workpiece which needs to be prehended (Pham Yeo, 1991). In the same article, the class of grippers that is suitable for gripping multiple parts are called universal grippers. A distinction can be made between active and passive universal grippers:

1. Passive grippers
   These types of grippers will adapt to the grasping object automatically and generally do not require energy to maintain the grip (Crooks, Rozen-Levy, Trimmer, Rogers, Messner, 2017). However, a disadvantage of passive grippers is the low gripping accuracy of the object. Generally, this type is thus solely used for practices where positional accuracy is not called for.

2. Active grippers
   Active grippers aim to achieve maximum gripping ability by mimicking the performance of a human hand. Nevertheless, the number of fingers may vary. A high level of adaptability is achieved by increased complexity for both the design as control program of the gripper.
   In the book Robot Grippers (Monkman, Hesse, Steinmann, Schunk, 2007) four different types of active grippers are introduced. These four distinctions between types of grippers ask for a property for prehension:

   I Ingressive: asks for surface damaging by hackles and needles

   II contiguous: asks for chemical or thermal adhesion

   III Astrictive: asks for magnetic or electrostatic forces between the object and the gripper

   IV Impactive: asks for a compressing force between jaws and workpieces

The impactive gripper design is the most widely used (Monkman, Hesse, Steinmann, Schunk, 2007) and the outcome of this research project will be an impactive mechanical gripper. Hence, more information on mechanical grippers is required. The mechanical motion of the impactive gripper relies on two basic fundamentals:

i. The motion of the gripper jaws must be coupled directly to the drive element

ii. The gripper jaws must be directed in a well-defined manner.

   The closure of the gripper jaws can be achieved in three different approaches of jaw rotation:

   A. circular motion around a fixed point

   B. Planar motion of the gripper jaws

   C. parallel motion (circular, curved or linear path)

Most impactive grippers can use stereomechanical prehension to hold an object. This describes the symmetrical movement of the individual grippers in relation to the centre axis of the gripper. The fingers can also move along a curved rotational path, also known as scissors gripper or move in parallel to eachother. A parallel gripper combined with too long gripper fingers can cause instability in the balance of the gripping forces (Monkman, Hesse, Steinmann and Schunk, 2007).

The chosen prehension strategy depends on three factors. The gripping location of the object, the accessibility of the prehension location and whether the gripping process is pre-programmed or adaptive to the situation. The gripping force in turn depends on: spatial setting, resultant force as a vector sum of all forces, the geometry of the object, design of the gripper jaws, material and surface of the gripper jaws and environmental vectors. Most impactive grippers use one of the following electrical drives:

- Stepping motors
- Servo motors
- Linear motors
- Piezoelectric drives

4.1.2 Stability of grip

An impactive gripper can enclose an object by either line, point, surface, circular or double line contact contact, see the figure below. The number k in the figure denotes the number of contact points between the workpiece and the gripper fingers. By either increasing the number of contact points or enlarging the acting active surfaces a high retention stability can be realised. Moreover, this allows for using a lower gripping force. (Monkman, Hesse, Steinmann, Schunk, 2007)

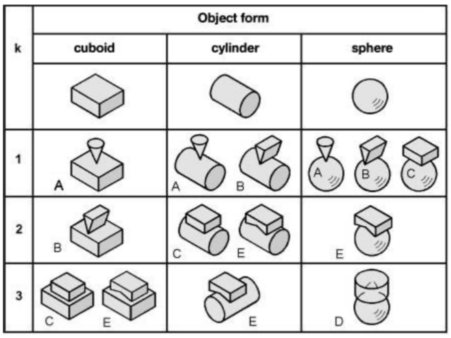


Figure 8: Overview of the different types of contact between a gripper and the workpiece

In the figure below, examples are given for the prehension of a workpiece using a two-fingered gripper and the degrees of freedom left unaccounted for. The degree of freedom F denotes the rotational and translational axes that are not matched by forces of the gripper. These axes indicate the direction of misalignment of the workpiece when for example the gravitational force working on the workpiece surpasses the frictional forces at the fingers. Whereas increasing the gripping force on the object and it is than held with a too high pressure, surface damaging to both the object and the end-effector may be the result. In an ideal grip, all the degrees of freedom are suppressed.

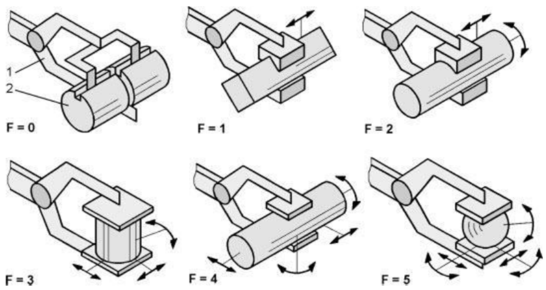


Figure 9: The different possibilities for suppressing the degree of freedom K for a workpiece

4.1.3 Prehension force calculation

The designed impactive gripper relies on frictional forces for the prehension of the workpiece. The calculation of the gripping force is dependent on the number of fingers and/or prehension points. In the book Robot Gripper the following formula is given:

$$F_g = \frac{m * g}{\mu * n} \tag{1}$$

with:
m = mass (gr)
g = gravitational acceleration (m/s^2)
µ= friction coefficient (dml)
n = number of contact points (dml)

This formula is derived by equating the following force balances:

$$\sum F_y := G = n * F_r = 0 \tag{2}$$

$$F_r = F_g * \mu \tag{3}$$

with:
G = Gravitational force of the workpiece (N)
F_r = Friction force (N)
F_g= Gripping force (N)

The different possibilities for contact points between the gripper and the workpiece are presented below for multiple shapes. The shape of a paper cup has been simplified to a cilinderical shape.

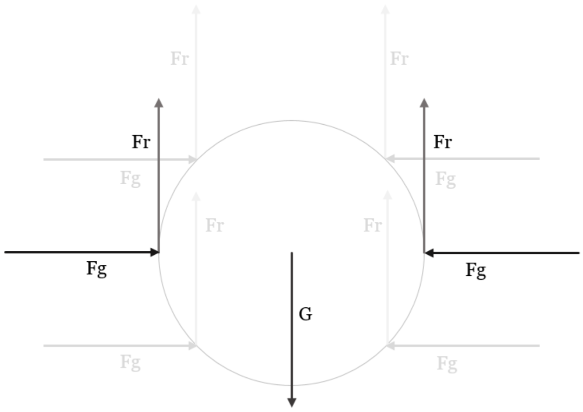


Figure 10: The different possibilities for suppressing the degree of freedom K for a workpiece from the book Robot Grippers

4.2 Controller design

4.2.1 Control theory

There are two different interpretations of the term system descriptions (Liu, 2018):

1. The external description: the input-output description
2. The internal description: the state-space description

The external description encompasses three elements: The system's input, the system or plant itself and the output of the system. Without describing the system itself by means of mathematical models of the internal structure, the casual relation ship driving the response is analysed. (Liu, 2018)

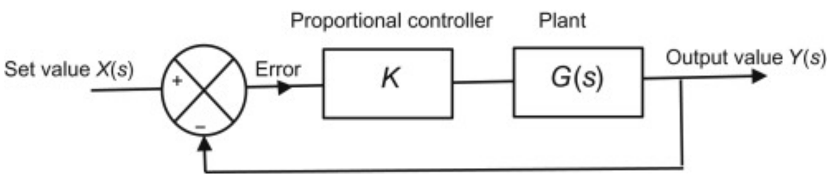


Figure 11: The different possibilities for suppressing the degree of freedom K for a workpiece from the book Robot Grippers

In figure 11 a basis schematic is given for a proportional controller. Ideally, the steady-state value of a system; which is the the value the system converges to , is equal to the input set value (Bolton, 2021).

4.2.2 force-feedback control

Multiple studies in force feedback control for end-of-arm grippers use a Force Sensitive Resistor (FSR) to generate a force-feedback signal. The electronic sensor relates the pressure to measured resistance. (Kumar, Kumar, Aravindan, and Arunachallam, 2020)

FSR force-feedback In a study conducted by Kumar, Mehta, and Chand in 2017, the objective was to find a low-cost force feedback system for a robotic gripper as well. The two-fingered parallel gripper already possessed an intelligent vision system and kinematics algorithm based on a multi-layered feed-forward artificial neural network. A force feedback system is created within Simulink using a Flexi-Force FSR. Firstly, the sensor was calibrated and thereupon experiments with uniformly shaped objects were performed to assess the coefficient of friction.
In another study using a dual parallel gripper, a FSR sensor is again used to develop a force feedback system (Kumar, Kumar, Aravindan, Arunachallam, 2020). This is mounted on one of the fingers and the measured force is compared to the current of the servo motor using a load current servo. A control system is built using both parameters.

Load reading feedback In a study performed by J.D. Tedford in 1991, for cost-effective reasons it was decided to obtain control by feedback from both position and used current from the servomotor. First experiments with a strain-gauged load cell were conductec and revealed a linear relationship between applied force and armature current (Tedford, 1991). Therefore, it was decided to be a valid force-feedback parameter. Using an optical encoder attached to the drive shaft of the servo motor, positional feedback is generated. A PI controller is used and written in turbo-pascal 4.0

5 Methods

In this section the design two-fold deliverable is discussed. First, the conceptual design of the gripper is finalised and next the embodiment design of the new gripper is introduced. By first stating the requirements going into the design phase and thereafter explaining specific important choices made, the design is then presented. Following the design, an examination of the forces within the gripper is supported by means of a free-body diagram. Next, the design of the force-feedback control program is discussed including the design procedure and the programming C code.

5.1 Design of the gripper

The design process is guided by the steps suggested by Pahl Beitz in their book Engineering Design. In this book a systemic approach is introduced for tackling a technical design project. A mechatronic system incorporating the mechanical, electronic and information technology domain is considered fluid and should no be regarded as definitive (Pahl & Beitz 2007). The same approach is adopted in the design process of the robot gripper, as all three domains are considered and have an impact on both the phyiscal and controller design.The design steps of Pahl and Beitz which are to be followed are:

1. Task clarification: broadening the problem formulation and developing product requirements.

2. Conceptual design: establishing function structures, creating an overview of all working principles and selecting the correct variant.

3. Embodiment design: creating a free-body-diagram with all relevant forces within the product, material selection and assemblability.

4. Detail design: The detail design consits of the part drawings, the bill of material and the cost price.

5.1.1 Task clarification

The problem analysis in the chapter two expanded on the scope of the system. By working with the robotic arm first-hand, the stroke; the maximum width of the gripper fingers, proved to be too small. The maximum width the current gripper can reach is only 60 mm. For the retention of differently shaped objects, a wider stroke is desired. For comparison, a stroke of 60 mm is not wide enough for the gripper jaw to prehend a paper cup from the middle. In the new design the stroke ought to be wider. Moreover, the gripper must be able to provide a gripping force which is at least 15N, see section 6.2.1. If choosing to buy the force feedback strip along with the standard gripper excluding a servomotor offered by CrustCrawler, total costs would amount to 138,82 euro's, shipping costs not included. Hence, the solution to the project should cost less this total price. The gripper is to be 3D printed at the laboratory using PLA and hence these requirements. For the required handling see chapter 5.3, validation process.

Stroke	> 70 [mm]
Weight	+/- 150 [gr]
Gripping force ability	15 [N]
Price	< 140 euro's
Production method	Additive manufacturing
Material	PLA
Required handling	Egg, paper cup, wooden cube, ping-pong ball and plastic flask

5.1.2 Conceptual design

Due to timing constraints, the following two choices are made:

1. The decision is made not to design a new gripper, but to alter the current design to meet the wishes of the problem owner.

2. The method of generating the force-feedback signal highly impacts the chosen design and is therefore chosen before the design process.

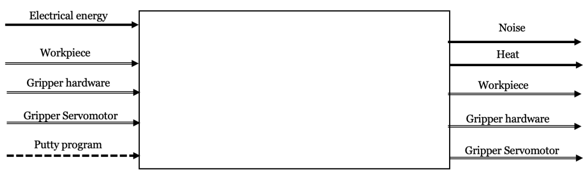


Figure 12: A mei diagram of the gripper system with force-feedback

Understanding the working principles In all technical systems, material, energy and signals are channelled and converted (Pahl, Beitz, 2007). Pahl and Beitz propose to first create a blackbox to gather all material, energy and signal flows, see figure . This is called a MEI-diagram. Consequently, the MEI-diagram is filled in with the gripper's working principles and forms a function structure. This diagram gives an overview of the functions performed by the technical product and how the conversion of energy within a product is tied in with it. The function structure below is created for the newly designed gripper with force-feedback. For more information on the force-feedback, see chapter 6.

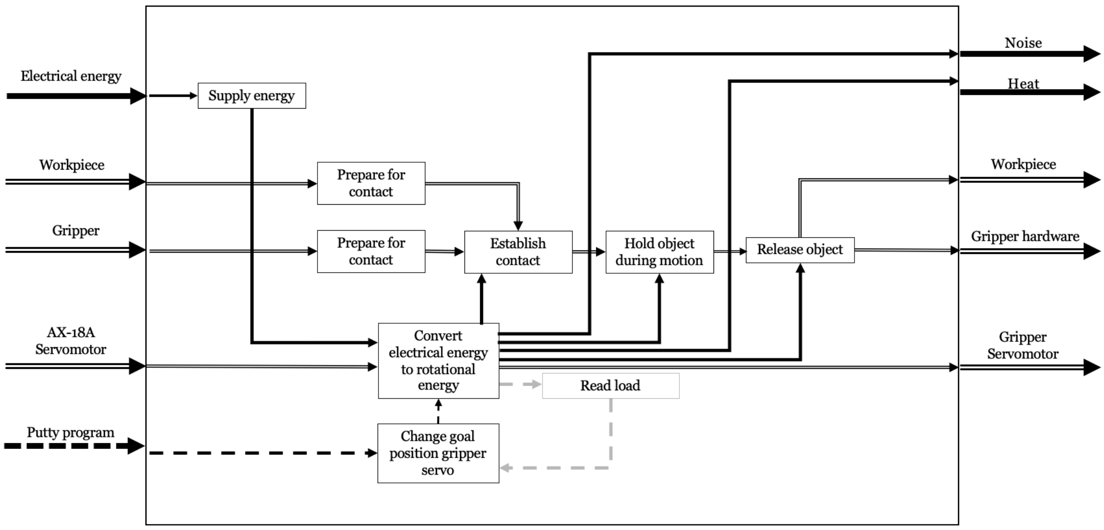


Figure 13: A function structure of the gripper system with force-feedback portraying the functions of the gripper and the conversion of energy

Concept selection The different options for the chosen design are portrayed in the table below. On the vertical axis, the different functions of the function structure are listed beneath each other. For each function, different solutions are given horizontally. The chosen solution is highlighted in the diagram.

Functions	Option 1	Option 2	Option 3
Supply energy	Electrical charge		
Prepare for contact	Planar motion	Parallel motion	Rotary motion
Establish contact	Gear train	Screw gear	
Hold object during motion	Line contact	Surface contact	Multi-point contact
Measure force	Sensor	Load reading servomotor	
Change goal position	Putty, µVision and DynamixelWizard 2.0 software		

Figure 14: A textual morphological overview of the gripper's functions and its possible solutions

The darker colour is assigned to the supply energy, establish contact and change goal position functions. This is due to the fact that these solutions were not chosen and are pre-established before the design process. These are:

- The same RS422 wire will be used to supply energy to the servomotor.
- The same software will be used to control the robot albeit with modifications.
- The gear train of the current design is best suited to convert the rotational energy of the servomotor into translational energy for the gripper jaws and hence a similar technique will be applied the current design

The other design choices are made specifically for this project:

- The gripper jaws of the current gripper, move towards the object in a angled motion toward the tips. In the book Robotic Grippers, this is also called a planar motion. This is most suitable for gripping round objects axially. However, parallel grippers are able to grip and lift both round and square shaped objects radially and axially (Guelker, 2011) . The workpiece is better suited to be gripped by means of force matching, when the forces are parallel to each other (Monkman, Hesse, Steinmann, Schunk, 2007). Hence, it is chosen to implement a parallel gripper in the design.
- Due to the parallel motion of the gripper jaws, the fingers will maximize the active prehension points and will result in a gripper using either:

  - square shapes: surface contact with degree of freedom: F=3

  - circular shapes: line contact with degree of freedom: F=5

- The solution to the measure force function is explained in chapter 6.

5.1.3 Embodiment design

In figure 15 the final design is visible in the Solidworks environment. The detailed design can be found in Appendix A including the part drawings and the bill of material.

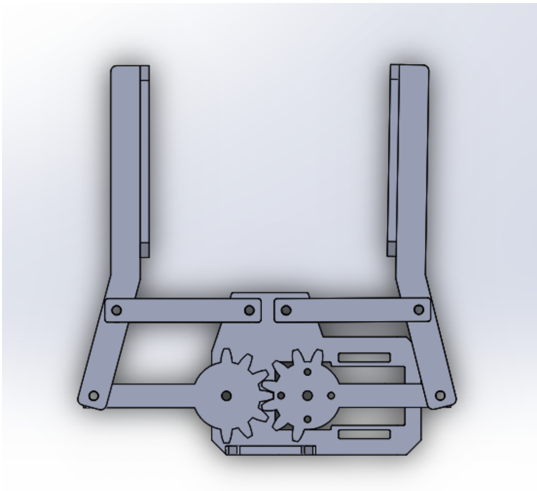


Figure 15: Chosen gripper design.

Design specifics

Kinematics The design process starts with measuring the lengths and widths of the current gripper, as the new one should be similar in size. This is taken as the base of the design. Thereafter, the integration of parallel gripper jaws is explored. Designing a gripper of which the fingers remain parallel at all times is quite complex and relies on the following two principles:

1. The lengths of the parallelogram are of fixed length (Bélanger-Barrette, 2016)

2. Through trial and error it is found that the angle on the outside of the gripper is equal to 180-α for which α is equal to the angle between the two fixtures of one parallelogram. For this gripper α is equal to 15°as visible in the figure below.

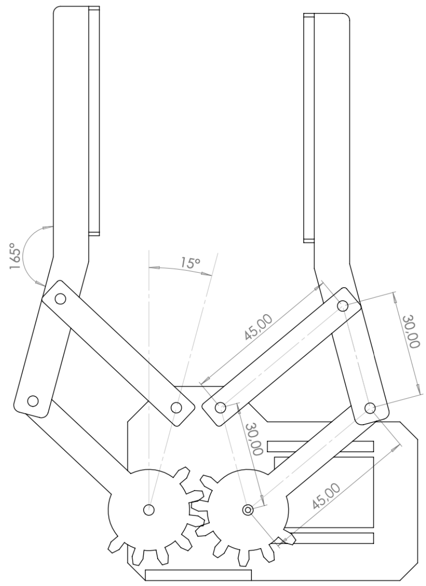


Figure 16: Solidworks drawing showing the values which ensure the parallogram shape

Fixture to the robot In figure 17 the connector to the robot arm is visible. The gripper is fastened similarly to the current gripper using bolts and nuts.

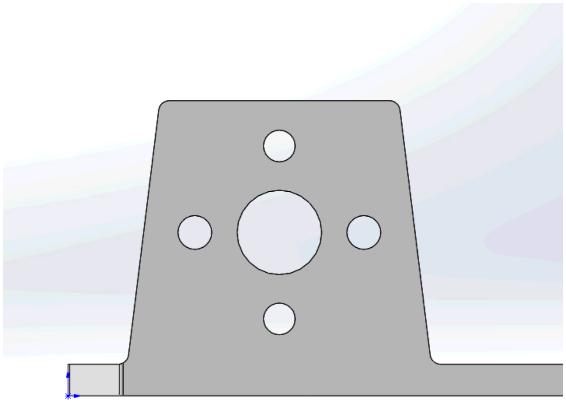


Figure 17: The part of the gripper base which will be assembled to the arm in the Solidworks environment

Gripper gears The spur gears of the gripper are designed according to known gear dimensions (Calculations of gear dimensions, 2021). From the parallel gripper design, a centre distance of 28 mm between the gear functioned as input for the gear design. Next the gear module and the pressure angle are chosen.

- The module is the ratio between the reference diameter and the number of teeth. The larger the module the larger the gear teeth. Through trial and error a few modules are tried and the final module 2 is chosen. This resulted in 14 teeth which are well in proportion to the reference diameter. Of these 14 teeth only half would be used, as only half of the gears are used to move the gripper jaws in- and outwards.
- The most common pressure angles are between 14.5°and 25°of which the 20 °is the most widely used (Moreau, Mevel, 2014). Hence, this angle is tried and has proven to give nice results. Therefore, a pressure angle of 20°is chosen.

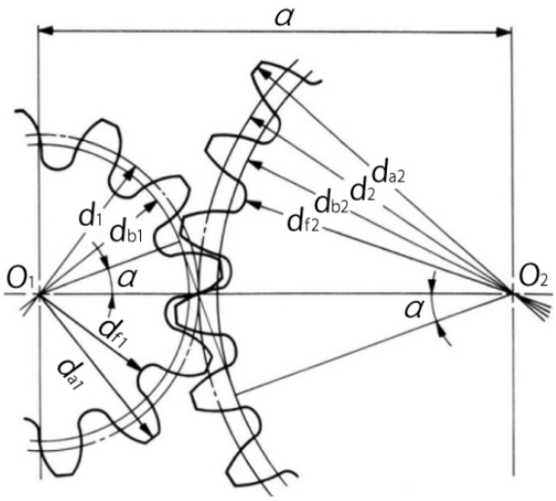


Figure 18: Gear dimension theory

The rest of the gear dimensions are as follows:
module: $m = 2$
Reference pressure angle: $\alpha = 20°$
Center distance: $a = \frac{(z+z)*m}{2} = 28$
Whicht results in: Number of teeth: $z = 14$
Reference diameter: $d = z * m = 2 * 14 = 28$
Base diameter: $d_b = dcos\alpha = 28cos20 = 26,31$
addendum: $h_a = 1 * m = 2$
Tooth depth: $h = 2,25 * m = 4,5$
Tip diameter: $d_a = d + 2 * m = 28 + 4 = 32$
Root diameter: $d_f = d - 2,5 * m = 23$
Tooth thickness: $s = \frac{(\pi * m)}{2} = 3.141$

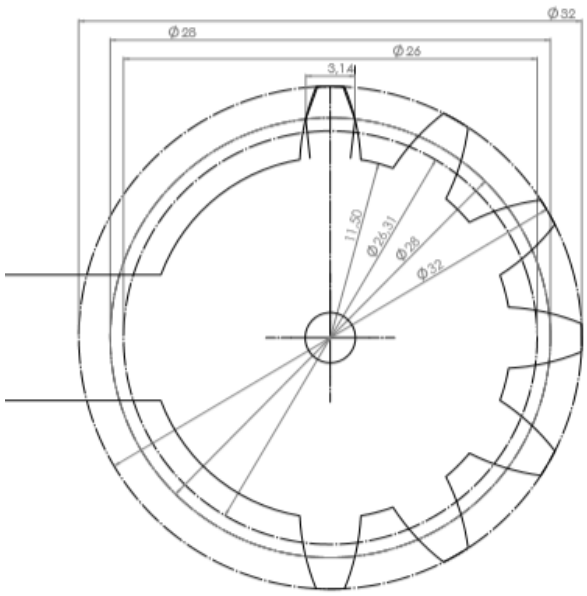


Figure 19: The diameters of the designed gripper

Free-body-diagram A free-body-diagram is created to display and calculate the forces within the gripper when the object is subject to the torque provided by the servomotor and the resulting gripping force on the workpiece. In figure 20, the forces are visible.

1. The orange arrows: The resultant force Ft perpendicular to the arm of the torsional moment created by the servomotor.
2. The yellow arrows: The force F1 is the resultant force of the torque in the direction of the gripper jaw. F2 is the force in the direction of the link between the base and the gripper jaw.
3. The green arrows: the gripping force on the workpiece due to the torque provided by the servomotor

Then, the angels a, b and c of the figure can be measured in Solidworks and the forces Ft, F1, F2 and Fg for one jaw of the gripper is calculated using the following formula's in Matlab for different positions of gripper jaws:

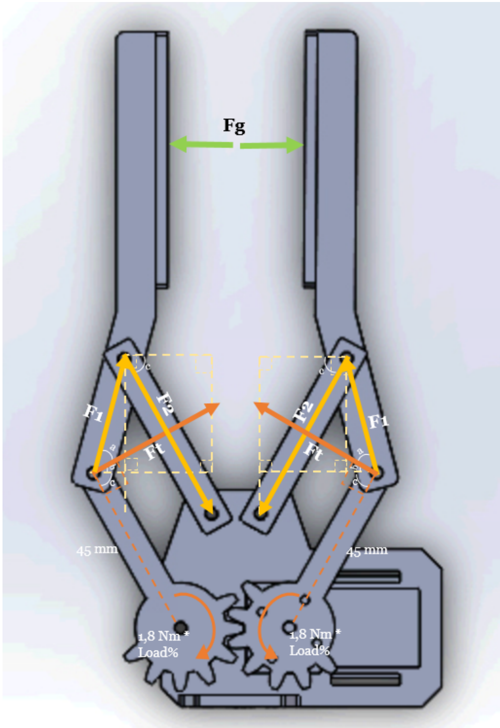


Figure 20: Free-body-diagram of the gripper

$$T = (1.8 * Load)0.5 \tag{4}$$

$$Ft = T/0.045 \tag{5}$$

$$\sum F_x := -F_{1,x} - F_{2,x} + F_g = 0 \tag{6}$$

$$\sum F_y := F_{1,y} - F_{2,x} = 0 \tag{7}$$

The torque used for the calculation is equal to reference load used for prehension in the final experiment; which is equal to the maximum load multiplied by the desired percentage. This value is multiplied by 0.5, as half of the torque is used to actuate one of the gripper jaws.

5.1.4 Manufacturing and assemblability

Manufacturing technique The DTPA lab of the Rijksuniversiteit Groningen is in possession of an Ultimaker 2+ additive manufacturing machine, which is used to produce the end-of-arm tooling. Ultimaker is a Dutch company focusing on the production and constant innovation of their 3D printers. The company was founded in 2010 and launched their first product, the Ultimaker in 2011 (About ultimaker. n.d.). The company values rapid innovation and strives to achieve this by releasing open-source files. The blueprints of their 3D printers are free to the public to spark engagement and collaboration (Ultimaker releases open-source files of their 3D printers,2015).

In 2016 the Ultimaker 2+ was put on the market. The printer has a building area of 23 by 22.5 cm and can reach a height of 20.5 cm (Ultimaker 2+, 2 extended+ and GO review.2016). By means of additive manufacturing, the different parts of the final product is to be created. 3D printing is the process of automatically producing from three-dimensional CAD data by means of multi-layer manufacturing. All AM projects adhere to the same process chain. Firstly, the 3D CAD model is 'sliced' and this will return a data set containing contour data, thickness data and and the layer number. This is done in the program Cura, which is the open-source slicing software by Ultimaker. By means of an SD-card, the data-set is sent to the printing device which firsts generates the layer and thereafter connects them. These steps are the same for all AM devices however the manner in which the layers are generated and fastened differ amongst them (Gebhardt, Kessler and Thurn, 2018). For the Ultimaker 2+ this is achieved by fused filament fabrication (Ultimaker 2+, n.d.).

Figure 21: Picture of the Ulitmaker 2+

Assemblability After the printing job is finished, the different parts need additional work before the gripper can be assembled. In figure 22, a picture is shown on how the parts come out of the printer. The additional required steps are:

1. Separating all the parts from the thin layer underneath
2. If the thin layer has not come completely of the sides of the separate parts, the sides are polished using a handheld manual sander.
3. As the gripper fingers are slanted and differ in height, the extra material is printed underneath the slope of the gripper jaw. This is removed using a manual jigsaw with the gripper clasped in a bench vice.
4. After the additive manufacturing is finished, the material shrinks. In the design, this effect is considered, however, not enough. All the holes are widened using a handheld drilling machine.
5. The smooth surfaces of the gripper fingers, are sanded down using the same sanding tools mentioned above to increase the friction force at the gripper fingers when prehending objects.

Hereafter, the gripper is assembled in approximately 20 minutes using bolts and locknuts with a synthetic inner lockring, which prevents the loosening of the nut due to vibrations.

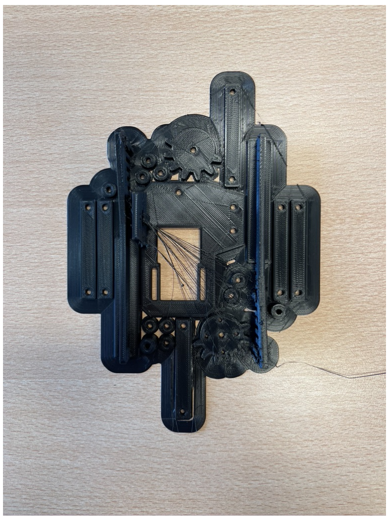


Figure 22: Photo of the gripper parts directly after additive manufacturing

5.2 Control of the gripper

Once the chosen method for generating the force-feedback signal is chosen a controller must be designed. As there is no transfer function known for the dynamical system determining the movement of the gripper, the gains of the controller cannot be calculated. Hence, the correct ones ought to be found heuristically by trial and error. In order to guide this process a step-by-step plan is formulated beforehand.

5.2.1 Load reading AX-18A

The chosen method for generating the force feedback signal is the load reading of the servomotor of the gripper; the Dynamixel AX-18A. This means that without the usage of any additional hardware, a force feedback loop can be generated, which complies with the aim of a cost-effective gripper from the problem owner. As visible in the system overview below, the only adjustment to the old situation is the exchange of the present load to the controller.

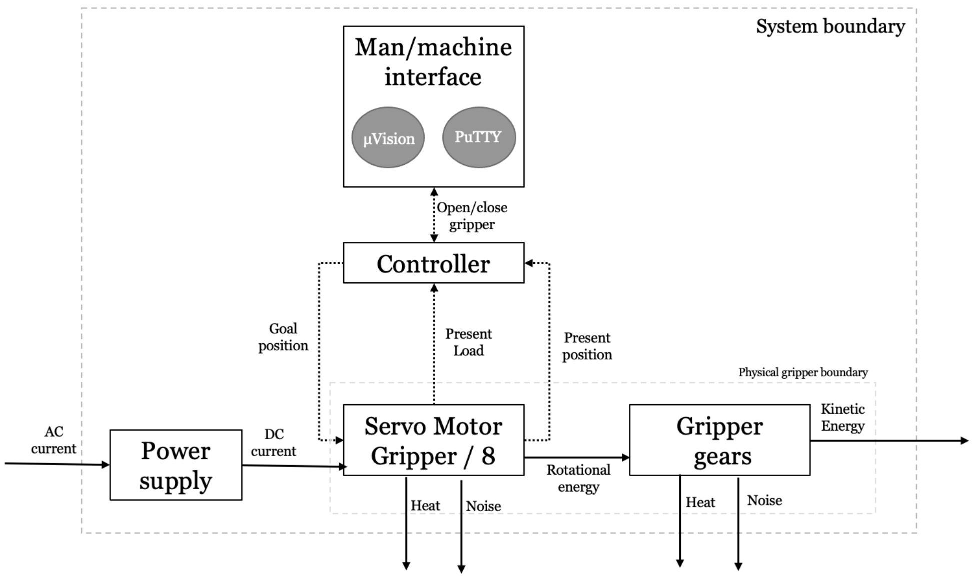


Figure 23: Overview of the proposed force feedback system.

The parameter used for the feedback control is present load of the AX-18A servomotor, which means the currently applied load (ROBOTIS e-Manual AX-18A, n.d.). This is the electrical current the motor uses to perform the desired changes in present position. The load as described in the e-manual ranges from 0 to 2047. From 0 to 1023, the servomotor applies load in a counter clockwise motion and from 1024 to 2047 a clockwise motion. The value of the load indicates the percentage of torque used in comparison to the maximum torque. A load of 256 implies 25 percent of the maximum torque used in the counter clockwise motion. The present load reading is therefore an indicator in direction and size (ROBOTIS e-Manual AX-18A, n.d.).

5.2.2 Force-feedback controller

A P-controller is designed to control the motion of the servomotor, see figure 24 below. The already existing control loop in place that direct the motion of the servomotor does put a limit on the possibilities, as the new controller should be compatible with the ones already in place.

Design procedure An intuitive controller is designed based on basic control systems theory (Bolton, 2021) and tuned heuristically.

1. Before beginning with the design of the controller, the desired response of the system is determined. In this case, the aim is for the gripper to continue to close around the object until a certain torque also load, has been provided by the servomotor.

2. Thereafter, the design process starts with finding the right output to close the open-loop system. As described above, the current load reading of the servomotor will act as the process variable.

3. The error signal is then the current load subtracted from a desired reference load.

4. The next step is deciding the variable which needs to be adjusted using the calculated error signal. As the gripper needs to stop closing, which is essentially increasing the current position. The goal position is taken as the control variable.

5. As the gripper jaws need to adjust the goal position based on the current position, the output of the controller; the goal position, is defined as the current position plus the error times a proportional gain Kp.

6. The system response is recorded for different Kp's by trial and error. The two parameters on which the response is tested are whether the system converges to a steady-state-error and how much the system oscillates.

7. As the load reading is only an inferred value and changes in steps of 32, boundaries are set in place to help the system converge to a steady-state response.

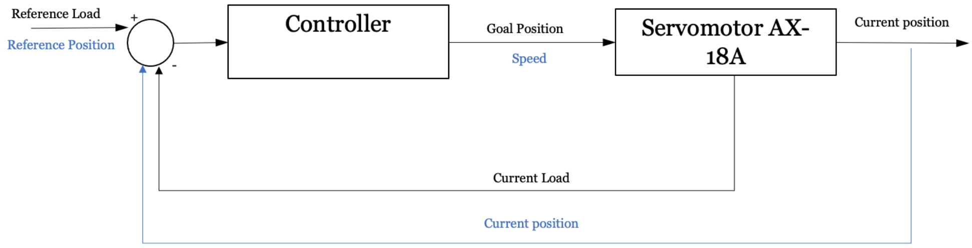


Figure 24: Overview of the entire controller, including the new force-feedback control loop .

5.2.3 C script control program

The current script Currently, the code for all eight AX-18A servomotors of the robotic arm is written in the program µVision in the programming language C. In order to incorporate force-feedback, the majority of the script can remain untouched. However, the section describing the speed and goal position of servo number 8 requires modification.

The code can be found in Appendix B. Firstly, the moving speed of the gripper is determined. When the difference between the current and goal position is greater than 10x0.111 rpm, the speed will be two times the difference. If not, the speed will be 5x0.111 rpm. At the moment, the gripper moves very quickly. In combination with wider stroke in the new design the gripper may not read the load fast enough and respond with the desired action of stop increasing the goal position. Therefore the speed for position errors¿10 is changed from 5 to 2.

Secondly, the script ensures there is no unnecessary exchange of data if the present moving speed equals the goal moving speed. Thereafter, the script specifies the derivation of the new goal position for the servo motor. These two parts will not be altered.

Introduction force-feedback P-controller A P-controller is implemented within the excising control loop with a proportional gain of 0.128. A limit equal to 64 (two load steps) has been put in place to help converge the system to the steady state error.

```
/* Load P-control */
if ((-32<LoadError)  && (LoadError <= 32)) {
ServoState[SERVO8].pos_goal_user = ServoState[SERVO8].pos_current; }
else {
```

```
ServoState[SERVO8].pos_goal_user = ServoState[SERVO8].pos_current + LoadError / 8; }
```

Force PI-controller The code for an additional PI controller is written to remove the steady-state error and help it converge to zero.

```
Z* Load PI-control */
dTms = PIT1_Counter - PrevTimeMs;
LoadErrorSum += LoadError * dTms;
PrevTimeMs = PIT1_Counter;
```

5.3 Validation process

The end-product which consists of the 3D printed robot gripper as well as the designed force-feedback controller, is tested by performing a prehension job with five different workpieces. In addition to the requirement of the problem owner; which states that the gripper must be able to take an egg and a paper cup without dropping it, three more objects are added to the list due to increase the desired versatility of the gripper. The challenge will now lie on making a gripper which is suitable to prehend all differently shaped workpieces: Hence, the validation objects are selected based on differences in size, weight and material.

	Workpiece	Weight [g]	Width [mm]	Photo
1.	Plastic flask	85	70,3	
2.	Boiled egg	64,2	55	
3.	Paper cup	4,9	46,1	
4.	Wooden cube	18,5	34,75	
5.	Pingpong ball	1,90	39,55	

Table 2: Overview of the different selected validation workpieces

6 Experiments

In this section the two performed experiments for the project are described. The first is an experiment concerning the load reading of the servomotor and the second the validation experiment of the whole project.

6.1 Servomotor load experiment

An experiment is conducted to examine the relationship between the the force applied by the gripper jaws and the present load reading of the servomotor. If a correlation is found, this would validate the design choice to use the load reading as a force-feedback signal.

6.1.1 Experimental setup

Servomotor 8 of the AX-18A robotic arm is directly connected to the PC with a USB to serial converter with a FTDI-232 chip. The motor is controlled via the program DynamixelWizard 2.0, which is the software provided by the producer. Before using the kitchen scale the torque limit is set to 500, which is approximately 50 percent of the maximum torque. A kitchen scale is placed on its side between the fingers as visible in the image below by setting the goal position equal to 680, of which goal position has a unit value of 0.29°. The kitchen scale is then set on tare, to ensure all experiments begin with a measured weight of zero. The goal position is then increased by five with each iteration and the present position, present load and measured weight recorded. This is carried out for ten iterations.

Figure 25: Picture of the experimental setup of the servomotor force experiment.

6.2 Validation experiment

In order to test the combined product; the 3D printed gripper and the force-feedback program, an experiment is executed using the various workpieces previously mentioned. The control program allows the user to provide the reference load as input for each trial. The reference input for each workpiece is selected by prehension force calculations.

6.2.1 Gripping force determination

In the table below the prehension force is depicted for a gripper with 2,3 and 4 points of contact. The necessary force is largely determined by the gripper friction coefficient (Monkman, Hesse, Steinmann and Schunk, 2007) (Friction and friction coefficients, n.d.). The values below are assumptions based on literature as not every material combination has a known friction coefficient.

	Weight [g]	Friction coeff. [DML]	2 point [N]	3 point [N]	4 point [N]
Flask	85,0	0,08	5,21	3,47	2,61
Egg	64,2	0,1	3,15	2099	1575
Cube	18,5	0,3	0,30	201	151
Cup	4,9	0,5	0,05	0,05	24
Pingpong ball	1,9	0,2	0,05	31	23

Table 3: Overview of the required gripping force for 2,3 and 4 point prehension

The Matlab code in Appendix C is used to determine the correct percentage of the torque of the motor to be used for each workpiece. A reference load which resulted in a gripping force that equals three times the above calculated prehension force, with a minimum of 0,2Nm is taken. This is due to the fact, that the controller is not fully stable and therefore oscillates. The gripper must still be able to hold the weight of the workpiece and not drop it. On top of this, the calculated gripping force based on the FBD is theoretical and does not take into account any friction that may occur when the different parts of gripper set into motion.

Workpiece	Load%	Stroke [mm]	Ft [N]	F1[N]	F2[N]	Fg[N]
Flask	0.45	70.2	10.0	9.7	19.3	19.2
Egg	0.5	54.9	10.0	8.6	11.7621	10.4
Cube	0.3	34.9	6.0	4.2	4.6	3.3
Cup	0.2	46.1	4.0	3.2	3.9	3.1
Ping-pong ball	0.2	39.6	4.0	2.9	3.4	2.5

Table 4: Overview of the forces within the gripper when prehending the validation workpieces

6.2.2 Experimental setup

The AX-18A robotic arm is connected to the PC via the controller and the PuTTY program is opened. The µVision script is updated with the new force-feedback controller, according to the lines stated above. The robot arm is put in the up-position for the prehension experiment by choosing option 3: up position, in the PuTTY program. Then, the logging is switched on for all output and the correct file selected for the generated text file. Afterwards, option 16: gripper load test, set max. load , is chosen to select the force-feedback program. The program will ask for the desired reference load. After pressing the 'enter' button, the gripper jaws immediately start to close. Therefore, it is important to keep in mind that the workpiece needs to be positioned correctly when hitting enter. After 30 seconds, stop the option 16 program by pressing cntrl+c and stop the logging to generate the output text file. This is carried out ten times for all five workpieces.
For every workpiece this looks as follows:

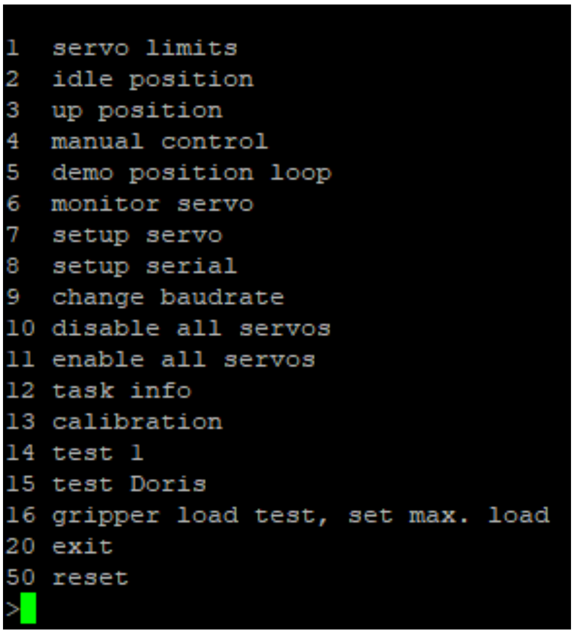


Figure 26: Screenshot of the PuTTY interface

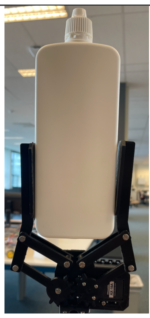
	Workpiece	Load [DML]	Photo
1.	Plastic flask	460	
2.	Boiled egg	515	
3.	Wooden cube	310	
4.	Paper cup	205	
5.	Pingpong ball	205	

Table 5: Overview of the gripper prehending the validation objects

7 Results and discussion

In this section the results of the load experiment and the validation experiment are presented.

7.1 Results

7.1.1 Servomotor Load experiment

The two graphs below display all the collected date from the servomotor load experiment. On the left one the weight in grams is set against the load and on the right the force in Newtons, which is the weight divided by the gravitational acceleration)

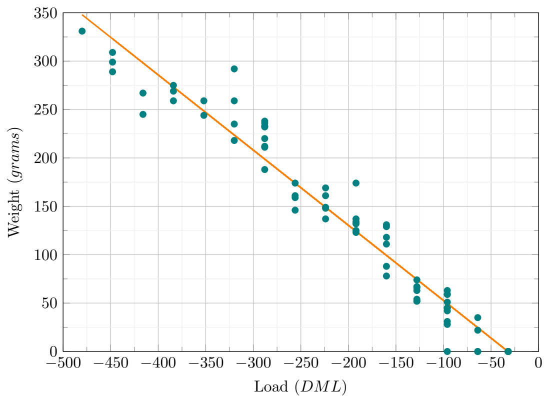


Figure 27: Graph visualizing the measured weight set against the load reading of the servomotor.

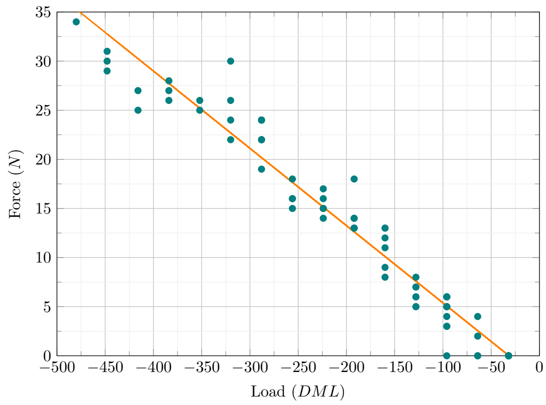


Figure 28: Graph visualizing the calculated force set against the load reading of the servomotor.

7.1.2 Validation experiment

For all the ten iterations for all five objects, the current load is displayed in the graph to portray the response of the system.

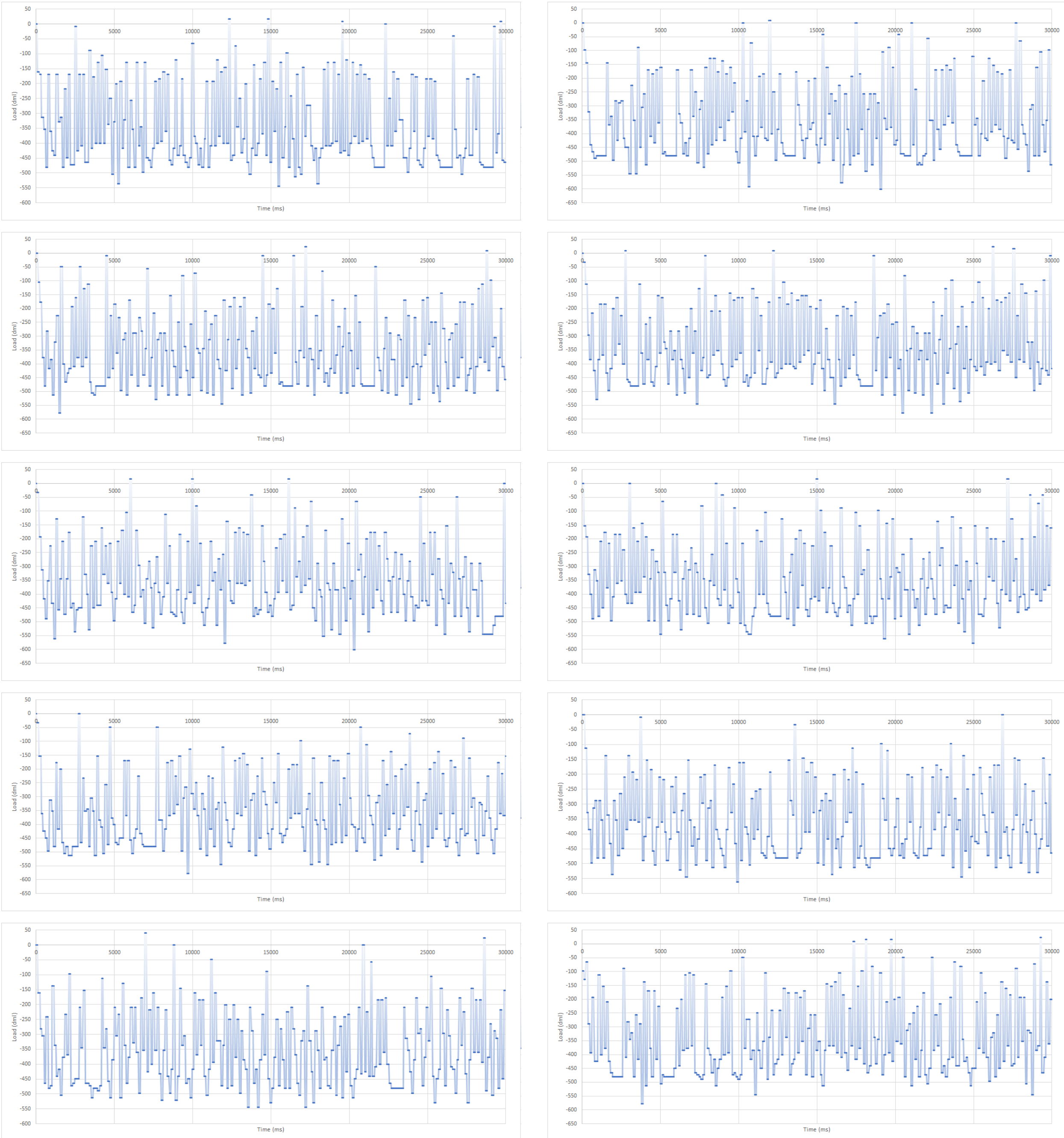


Table 6: Flask prehension iterations 1-10

Response of the system prehending the plastic flask

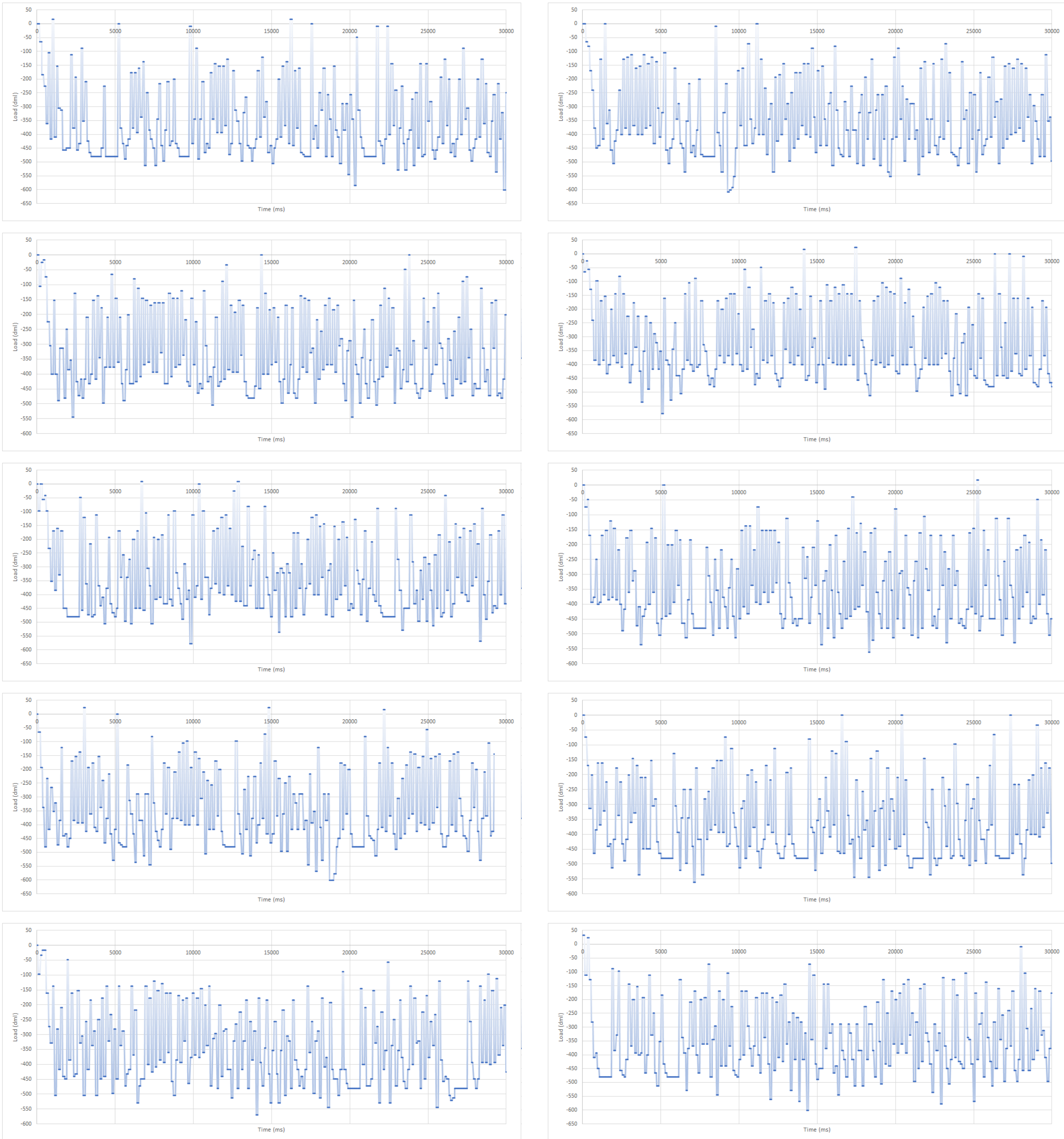


Table 7: Egg prehension iterations 1-10

Response of the system prehending the boiled egg

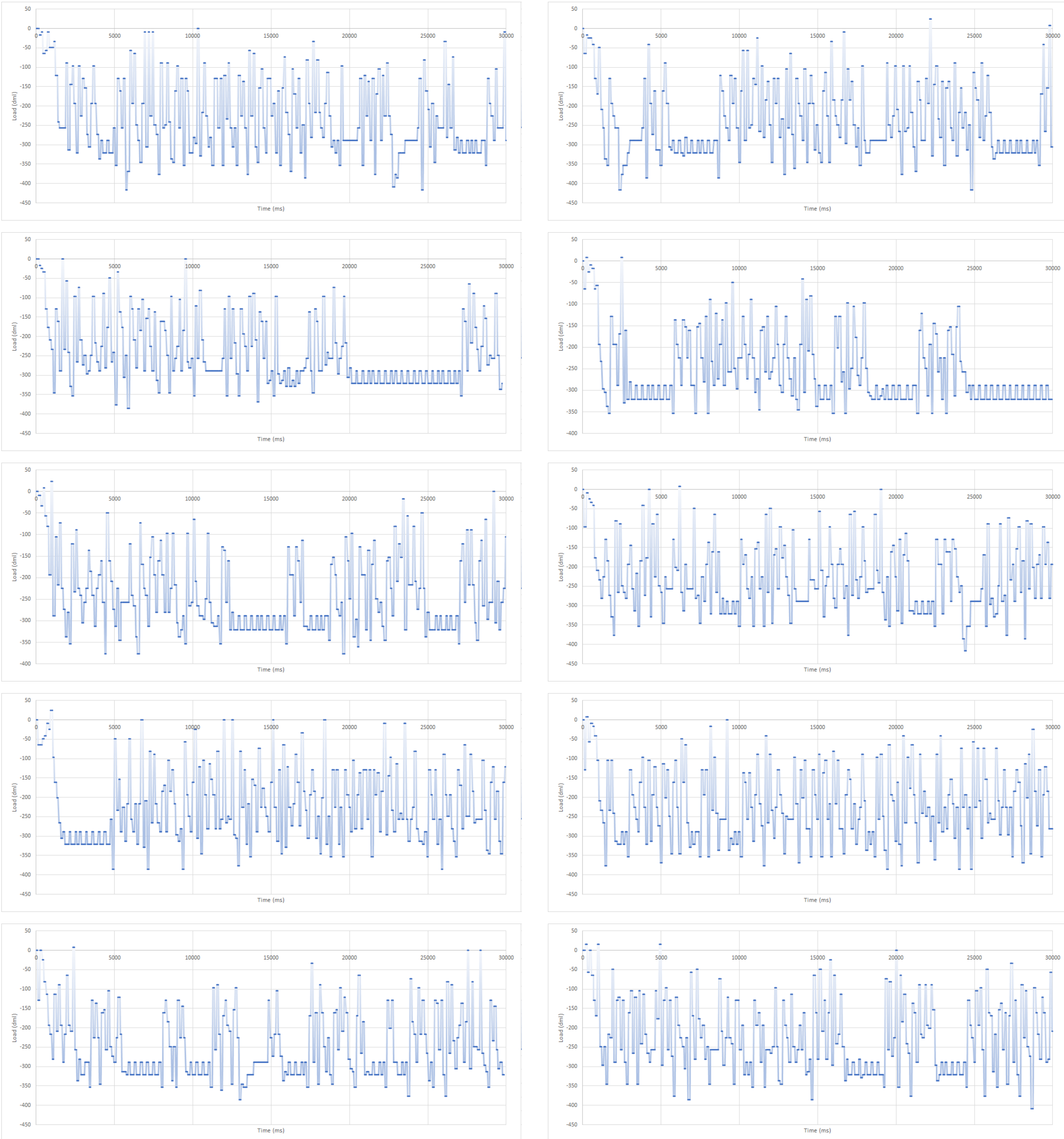


Table 8: Cube prehension iterations 1-10

Response of the system prehending the wooden cube

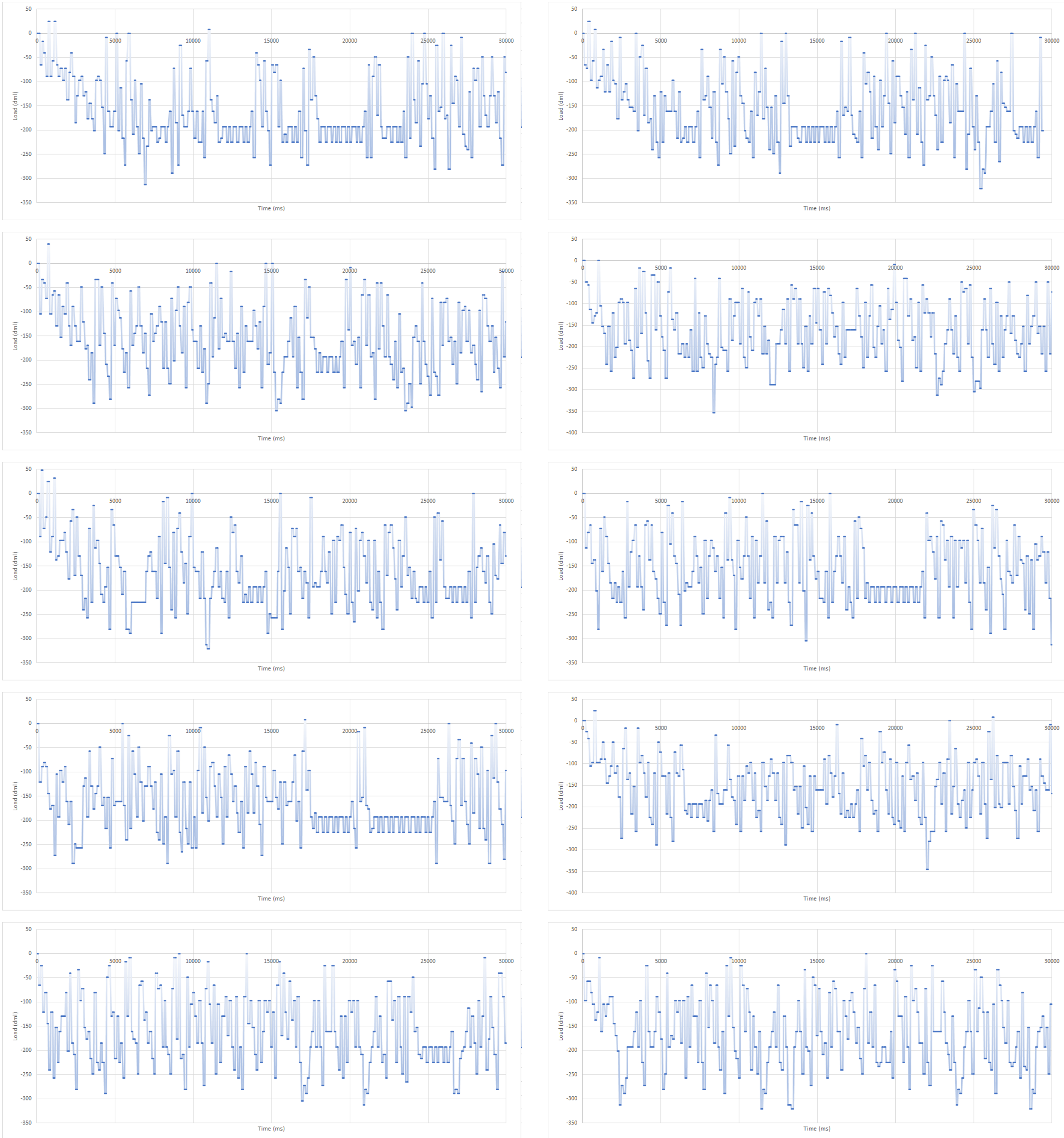


Table 9: Cup prehension iterations 1-10

Response of the system prehending the paper cup

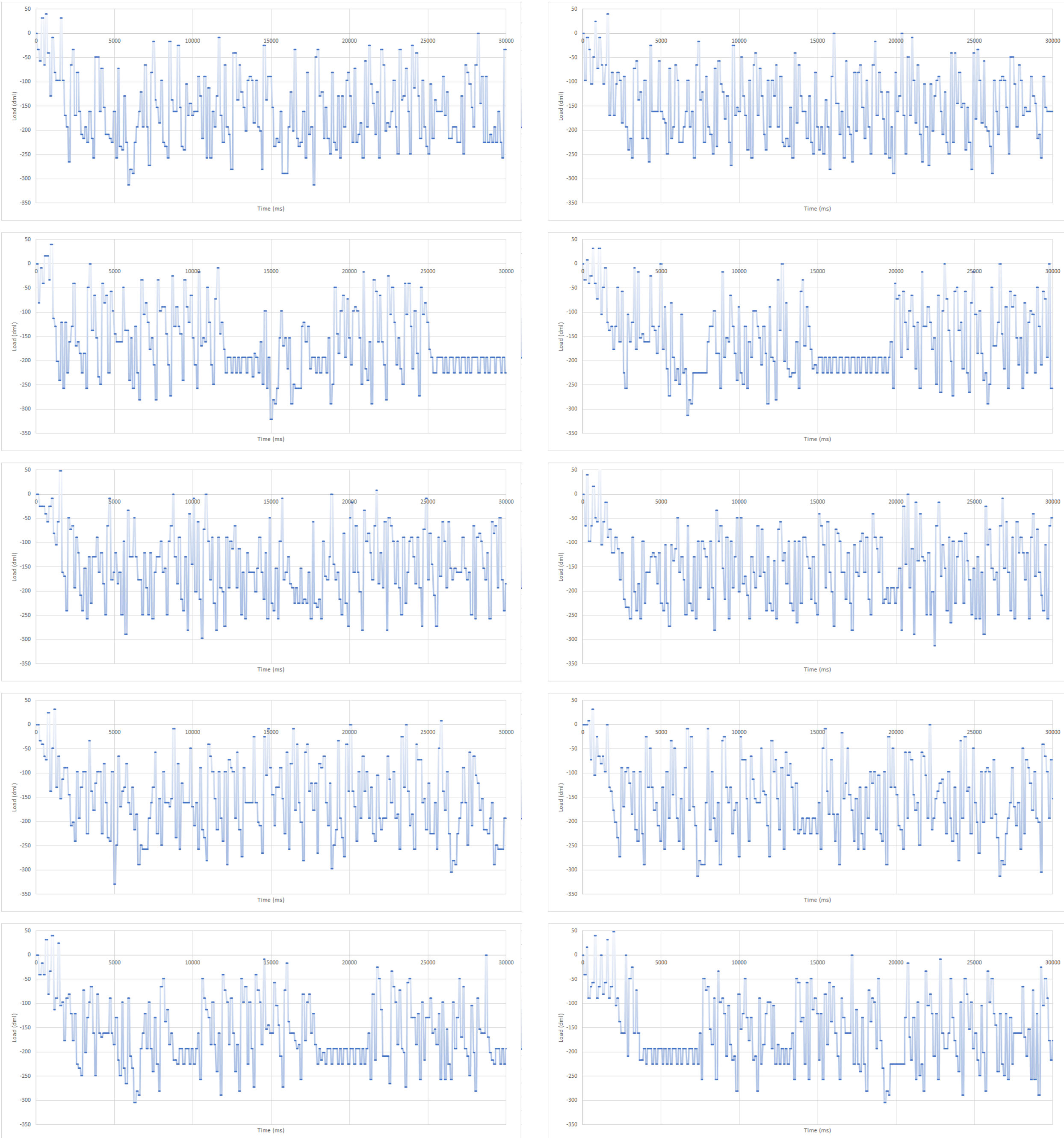


Table 10: Ball prehension iterations 1-10

Response of the system prehending the ping-pong ball

7.2 Discussion of results

7.2.1 Servomotor load experiment

The results of the experiment are visualized in Figure 27; which depicts the measured weight by the scale and in figure 28 the applied force. The computer processes the counter clockwise motion of the servomotor as negative, hence the negative value of the present load.
Noteworthy, is the intervals in which the load readings present themselves. This is due to the digital conversion of the analogues reading of the servomotor using 5-bits. As visible on the graph there is a strong negative correlation between counterclockwise applied load and measured weight by the kitchen scale. Therefore, the load reading is concluded to generate a valid force-feedback signal and is continued to work with during the project.

7.2.2 Validation experiment

The experiment with the newly designed gripper fastened to the robot arm in combination with the new force-feedback control program is carried out. Notable, is that the new gripper moves with more difficulty than the complementary gripper of Crustcrawler.
The current load of the servomotor does oscillate during all expirements, however, in real time this translates to slight twitches Nevertheless, all workpieces are prehended with success; without any damage or dropping the object.

Performance of the gripper design The parallel gripper is assembled with success and is effective in prehending differently shaped objects as aimed. However, A couple of remarks can be made on the design of the gripper at the end of the project. The design of the gripper performs as a parallel gripper in the Solidworks environment. Be that as it may, after assembling the gripper the parallel function is lost. This causes the gripper to be highly sensitive to the placement of the workpiece during the experiment, as the forces do not counteract oneanother anymore.(Monkman, Hesse, Steinmann and Schunk, 2007). This is partly due to human errors when manually drilling the holes in order to expand them. 3D printed PLA has a shrinkage of approximately 2 to 2.5 percent (Spencer, 2020). After manual drilling, especially the right upper hole of the base was too wide and allows too much movement of the bolt.
Moreover, to minimize friction, the bolts and nuts holding the gripper parts can not be fastened too tightly. This also results in the gripper parts being looser than preferred and thus allowing more movement. Therefore, the very specific requirements (lengths and angles) of the the parallelogram is not met and its shape lost.

Performance of the force-feedback controller A couple of conclusions can be drawn from the data collected in section 9.1.2 by the PuTTY program during the validation experiment.

- From the figures, it can be clearly seen that when using higher loads of 45% and 50%, the egg and the flask respectively, the current load oscillates for the entire 30 seconds and does not fluctuate around the reference load in comparison to when a load of 20% and 30% is used.
- From the figures it can be concluded that the controller tries to stabilize around the reference point for the cube, the cup and the pingpong ball. As mentioned above, to the parallel shape of the gripper is lost. The conclusion is drawn that due to the wrong placement of the workpiece in relation to the gripper, the system is not able to stabilize, as all further factors in the experiment are constant and unchanged.
- When comparing the graphs of the different workpieces, the controller perfroms the best for the prehension job of the wooden cube. This is in line with the theory described in chapter 4. The cube was prehended by with an active surface area with the lowest degree of freedom F=3 of all the workpieces.

8 Concluding remarks and further research

The design project has successfully delivered a robot gripper design and an accompanying force-feedback P-controller. After the validation experiment with five objects that differ in weight and size, the objective of not dropping and damaging the objects is accomplished.

For future research regarding the design the following desing options may be considered:

- Another option for further research would be to explore the impact of incorporating either double-sided or single-sided prismatic gripper jaws. This causes a self-centering effect of the workpieces and allows for a smaller gripping force due to multiple active prehension points.
- An additional feature for the gripper would be to glue an anti-slip material to the gripper fingers' surface. The effect of the higher friction force would allow for a smaller gripping force and the outcomes are interesting to explore.
- Further research may be done in exploring the effect of shrinkage on the 3D printed objects and sizing them accordingly. Following this method would result in perfectly shaped holes and a sturdier gripper and may cause the gripper to attain its parallel shape.
- Another remark for the the design of the gripper, is the length of the gripper fingers. This may also play a role in the gripper not holding its parallel shape. The length of these gripper fingers are based on the current design, however, this might have not been the best option. As the parallel shape was not wholly intact and a small change in an angle due to the manual drilling can cause also cause this, it may be interesting to explore whether the length of the grippers caused this.

The chosen controller for this project is a P-controller with implemented limits and a gain of 0.125. However, due to time constraints, there was no time to find the right limits and the gains of the controller. These are needed as PI-controllers are very sensitive to gains (Sreekumar Jiji, 2012). As there is no transfer function available for the system, this proved to be too time-demanding for the current project. Further research into the force-feedback control program may look into changing the P-controller to a PI-controller by introducing an integral term and its corresponding limits to ensure a stable system.

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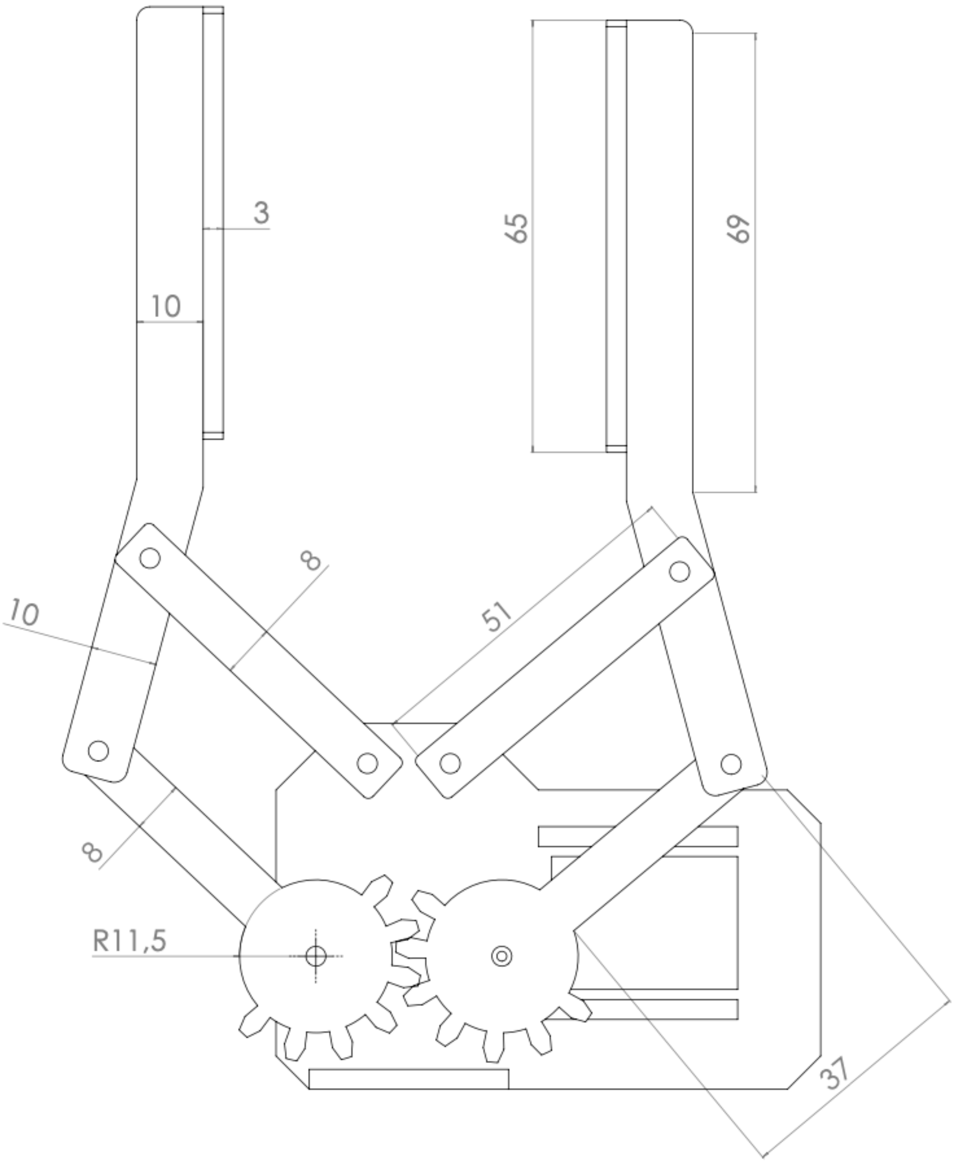
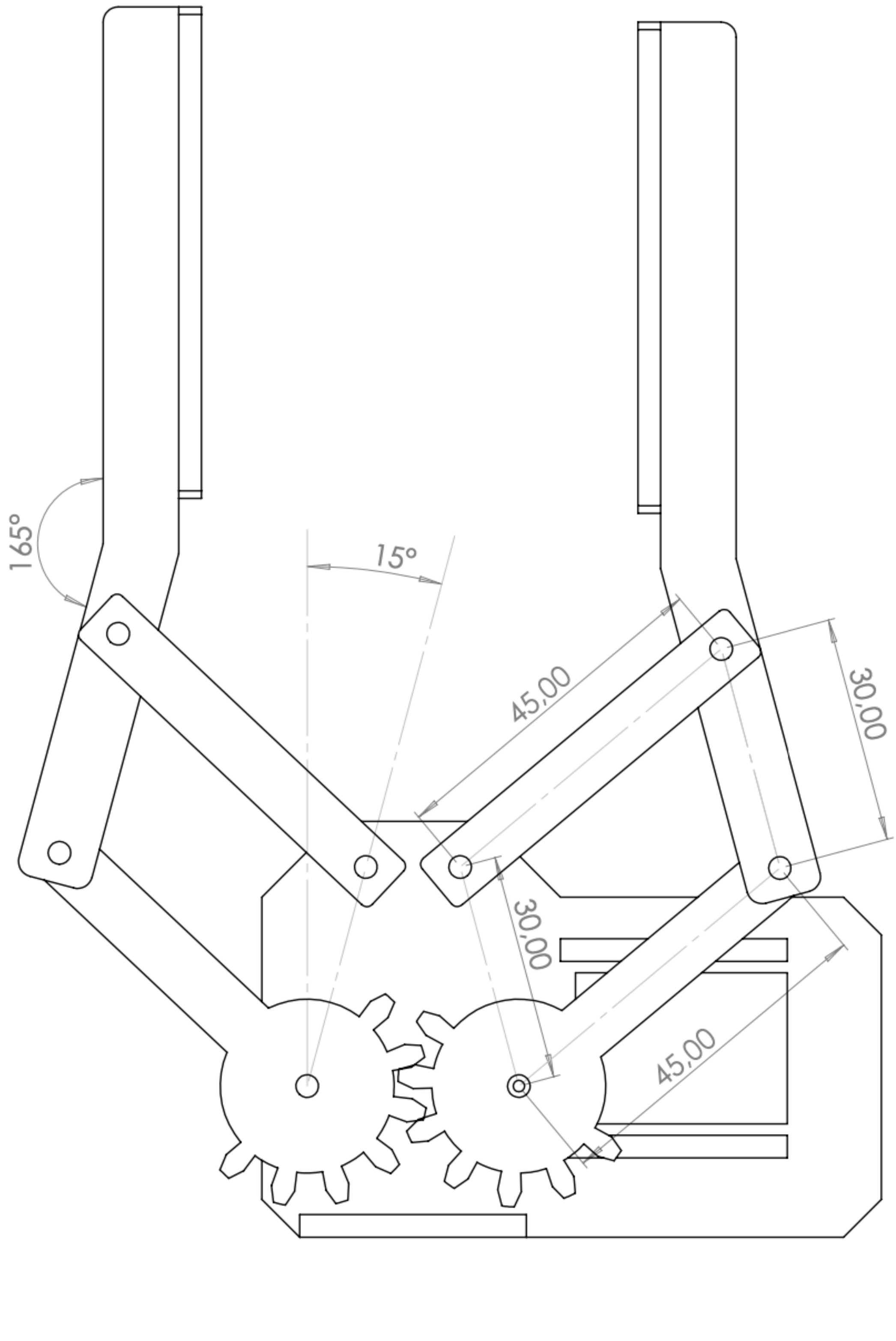
1 Appendix A

1.1 Details gripper design




165°
15°
45,00
30,00
30,00
45,00

1 Appendix B

1.1 Controller C script

```
/* speed by P-control */ {
ServoState[SERVO8].speed_reduced = ServoState[SERVO8].speed_user;
if (ServoState[SERVO8].pos_goal_user > ServoState[SERVO8].pos_current) {
PositionError = ServoState[SERVO8].pos_goal_user - ServoState[SERVO8].pos_current; }
else { PositionError = ServoState[SERVO8].pos_current - ServoState[SERVO8].pos_goal_user; }
if (PositionError < 10) {
ServoState[SERVO8].speed_reduced = 5; }
else {
ServoState[SERVO8].speed_reduced = PositionError * 2;
if (ServoState[SERVO8].speed_reduced > ServoState[SERVO8].speed_user) {
ServoState[SERVO8].speed_reduced = ServoState[SERVO8].speed_user; } } }

/* set the new moving speed */ {
if (ServoState[SERVO8].speed_reduced != ServoState[SERVO8].speed_set) {
WriteMovingSpeed(SERVO8, ServoState[SERVO8].speed_reduced, &return_value);
if (return_value > 0) {
ServoState[SERVO8].com_error_var++; }
else {
ServoState[SERVO8].com_error_var = 0;
ServoState[SERVO8].speed_set = ServoState[SERVO8].speed_reduced;
Com4Wait(&waittime); } } }

/* set the new goal position */ {
if (ServoState[SERVO8].pos_goal_user != ServoState[SERVO8].pos_goal_set) {
ServoState[SERVO8].pos_goal_user_deg = SERVO8_CAL * ((((float)ServoState[SERVO8].pos_goal_user) - 512.0) / (1024.0 / 360.0));
ServoState[SERVO8].pos_goal_user_rad = SERVO8_CAL * ((((float)ServoState[SERVO8].pos_goal_user) - 512.0) / (1024.0 / 6.283185307));
if ( (ServoState[SERVO8].pos_goal_user >= ServoState[SERVO8].pos_cw_angle_limit) &&
(ServoState[SERVO8].pos_goal_user <= ServoState[SERVO8].pos_ccw_angle_limit) ) {
WriteGoalPosition(SERVO8, ServoState[SERVO8].pos_goal_user, &return_value);
if (return_value > 0) {
ServoState[SERVO8].com_error_var++; }
else {
ServoState[SERVO8].com_error_var = 0;
ServoState[SERVO8].pos_goal_set = ServoState[SERVO8].pos_goal_user;
ServoState[SERVO8].pos_goal_set_deg = SERVO8_CAL * ((((float)ServoState[SERVO8].pos_goal_set) - 512.0) / (1024.0 / 360.0));
ServoState[SERVO8].pos_goal_set_rad = SERVO8_CAL * ((((float)ServoState[SERVO8].pos_goal_set) - 512.0) / (1024.0 / 6.283185307)); } } }
Com4Wait(&waittime); }
```

1 Appendix C

1.1 Matlab Gripping force code

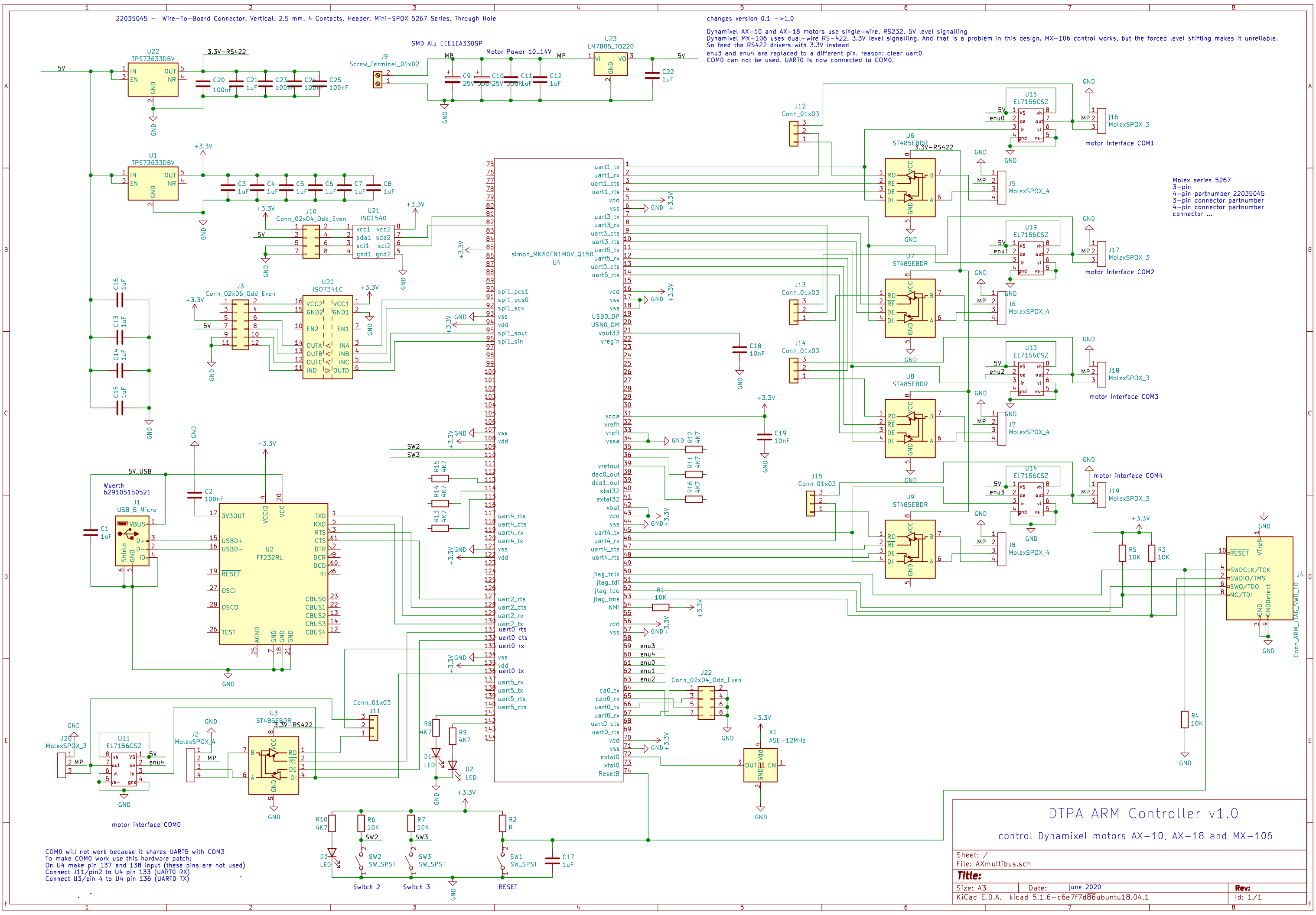
```
%%%%%%%%%%%%%%%%%%%%%%%%%%% Flask  %%%%%%%%%%%%%%%%%%%%%%%%%%
Sflask = 70.23;
Lflask = 0.45;
a = 15;
b = 61;
c = 29;

T = 0.5*1.8*Lflask;

Ft = T/0.045 ;
F1 = Ft*cosd(a) ;
F2 = (F1*sind(a+b))/sind(c);
Fg = F1*cosd(a+b)+ F2*cosd(c);

Flask = [Sflask, Lflask]
Fflask = [Ft, F1; F2, Fg]

%%%%%%%%%%%%%%%%%%%%%%%%%%% EGG  %%%%%%%%%%%%%%%%%%%%%%%%%%
Segg = 54.91;
Legg = 0.5;
a = 31;
b = 45;
c = 45;

T = 0.5*1.8*Legg;

Ft = T/0.045 ;
F1 = Ft*cosd(a) ;
F2 = (F1*sind(a+b))/sind(c);
Fg = F1*cosd(a+b)+ F2*cosd(c);
```

```
Egg = [Segg, Legg]
Fegg = [Ft, F1; F2, Fg]


%%%%%%%%%%%%%%%%%%%%%%%%%%% CUP  %%%%%%%%%%%%%%%%%%%%%%%%%%
Scup = 46.05;
Lcup = 0.2;
a = 38;
b = 38;
c = 52.5;

T = 0.5*1.8*Lcup;

Ft = T/0.045 ;
F1 = Ft*cosd(a) ;
F2 = (F1*sind(a+b))/sind(c);
Fg = F1*cosd(a+b)+ F2*cosd(c);


Cup = [Scup, Lcup]
Fcup = [Ft, F1; F2, Fg]


%%%%%%%%%%%%%%%%%%%%%%%%%%% ball  %%%%%%%%%%%%%%%%%%%%%%%%%%
Sball= 39.55;
Lball = 0.2;
a = 43;
b = 33;
c = 57.5;

T = 0.5*1.8*Lball;

Ft = T/0.045 ;
F1 = Ft*cosd(a) ;
F2 = (F1*sind(a+b))/sind(c);
```

```
Fg = F1*cosd(a+b)+ F2*cosd(c);


Ball = [Sball, Lball]
Fball = [Ft, F1; F2, Fg]


%%%%%%%%%%%%%%%%%%%%%%%%%%% CUBE  %%%%%%%%%%%%%%%%%%%%%%%%%%
Scube= 34.91;
Lcube = 0.3;
a = 46;
b = 29;
c = 61;

T = 0.5*1.8*Lcube;

Ft = T/0.045 ;
F1 = Ft*cosd(a) ;
F2 = (F1*sind(a+b))/sind(c);
Fg = F1*cosd(a+b)+ F2*cosd(c);


Cube = [Scube, Lcube]
Fcube = [Ft, F1; F2, Fg]
```

1 Appendix D

1.1 AxController schematics


22035045 – Wire-To-Board Connector, Vertical, 2.5 mm, 4 Contacts, Header, Mini-SPOX 5267 Series, Through Hole
changes version 0.1 ->1.0
Dynamixel AX-10 and AX-18 motors use single-wire, RS232, 5V level signalling
Dynamixel MX-106 uses dual-wire RS-422, 3.3V level signalling. And that is a problem in this design. MX-106 control works, but the forced level shifting makes it unreliable.
So feed the RS422 drivers with 3.3V instead
enu3 and enu4 are replaced to a different pin. reason: clear uart0
COM0 can not be used. UART0 is now connected to COM0.
Molex series 5267
3-pin
4-pin partnumber 22035045
3-pin connector partnumber
4-pin connector partnumber
connector ...
motor interface COM0
motor interface COM1
motor interface COM2
motor interface COM3
motor interface COM4
COM0 will not work because it shares UART5 with COM3
To make COM0 work use this hardware patch:
On U4 make pin 137 and 138 input (these pins are not used)
Connect J11/pin2 to U4 pin 133 (UART0 RX)
Connect U3/pin 4 to U4 pin 136 (UART0 TX)
DTPA ARM Controller v1.0
control Dynamixel motors AX-10, AX-18 and MX-106
Sheet: /
File: AXmultibus.sch
Title:
Size: A3
Date: june 2020
Rev:
KiCad E.D.A. kicad 5.1.6-c6e7f7d86ubuntu18.04.1
Id: 1/1