MSc Project

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DESIGN, MODELING AND CONTROL OF AN UNDER-ACTUATED GRIPPER

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Synopsis:

This report will go through the considerations and the methods of design and control of an under-actuated adaptive multi-functional robot gripper. The gripper is designed around a novel grasping method using an under-actuated four-bar linkage in each of it's three fingers. The fingers can be easily positioned around the "palm" of the hand-like gripper, to optimize grasping patters for a cylindrical, spherical or pinch-like grasp. The fingers are all driven by a single brushless DC motor, offering positional feedback, and torque control, thus control of the gripping force. This report will model and characterize the gripper compliance, and do an experimental validation of the compliance model for the real system. Finally, a design and implementation of a controller for the new motor and electronics will also be made and tested.

Preface

Reading Instructions
Throughout this report source references will appear as numbers in brackets, e.g. "As described in [1]", and will be gathered in a reference list at the end of the report, according to the appearance in the report. Figures, tables and noticeable equations are numbered, referring to the chapter, that is the first figure in chapter 3 is numbered 3.1, the second numbered 3.2 and so on. Describing texts for figures and tables can be found under the figures and tables. In the report English number notation is used, e.g. that a dot(.) is used as a decimal separator, whereas a comma (,) is a thousand separator: 10,000.00 is ten thousand.

I would like to give special thanks to Muhammad Raza Ul Islam for providing help with smart human interface control for intention detection.

Contents

1 Introduction

With ever increasing automation, the ability for robots and machines to pick up and manipulate objects plays a more vital role than ever before. But what sort of objects do we expect machines to handle? And how can these objects effectively be manipulated?

This project attempts to answer many such questions, and cover the theory and considerations involved in the process of designing, modeling, controlling and testing a novel multi-functional three-finger under-actuated robotic gripper, shown in figure 1.1.

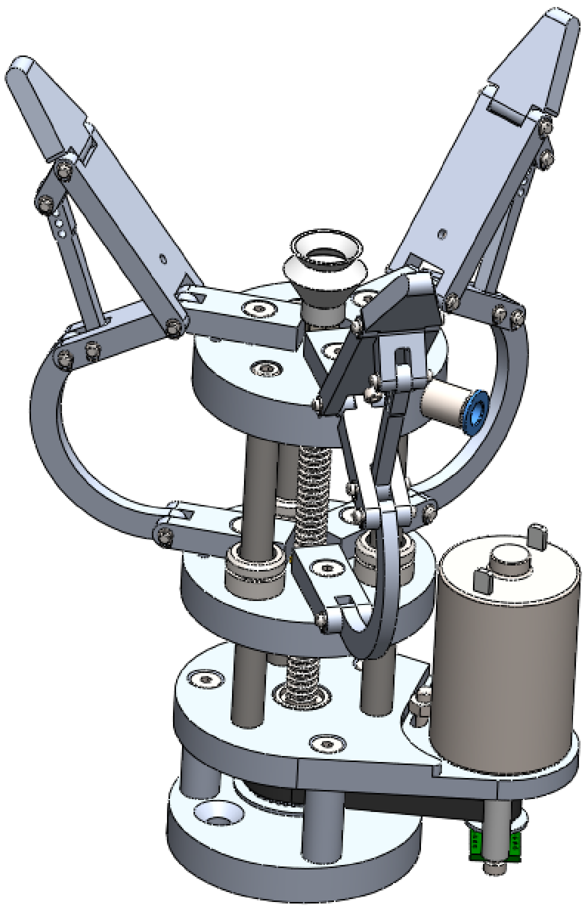


Figure 1.1: The gripper developed in [1]

A prototype of the shown robotic gripper has been designed, fabricated and finally tested in previous years student project [1]. The gripper has three human-like fingers, driven by one motor only, to help lower the cost and complexity. The fingers adopt elastic elements in their mechanism, allowing for adaptive grasping. Thus, advanced mechanics modeling for the mechanical compliance is needed to describe it, which is this projects primary goal, as well as designing a motion controller, implementing, testing and validating the results.

1.1 Robotic Arms and End Effectors

Robotic arms have come a long way since the first industrial robotic arm was introduced in 1961. Today they serve as a vital part of many big industries, ensuring high speeds, high consistency, with fine tolerances, taking loads off human workers and thus lowering the cost of many high quality products. They are used today in almost all industries from making vehicles to meat processing in several manufacturing applications, most notably:

- Welding.
- Spray Painting.
- Machine loading.
- Packing.
- Palletizing.
- Precision pick and place operations.

Depending on the task, different robot arms will use different end effectors, in other words, the tools that these arms will be using. For many applications, these end effectors are directly linked with the application; welders for a welding robot, spray nozzles for a painting robot.

However, most robotic arms are used in assembly lines for various tasks, but most prominently welding in the automotive industry, and "material handling", whether it be moving heavy loads to pallets, or placing tiny hundreds of tiny electronic components on motherboards for assembly, these robot arms need ways to interact with the objects they are manipulating. In most of these cases, this is achieved using some sort of gripper.

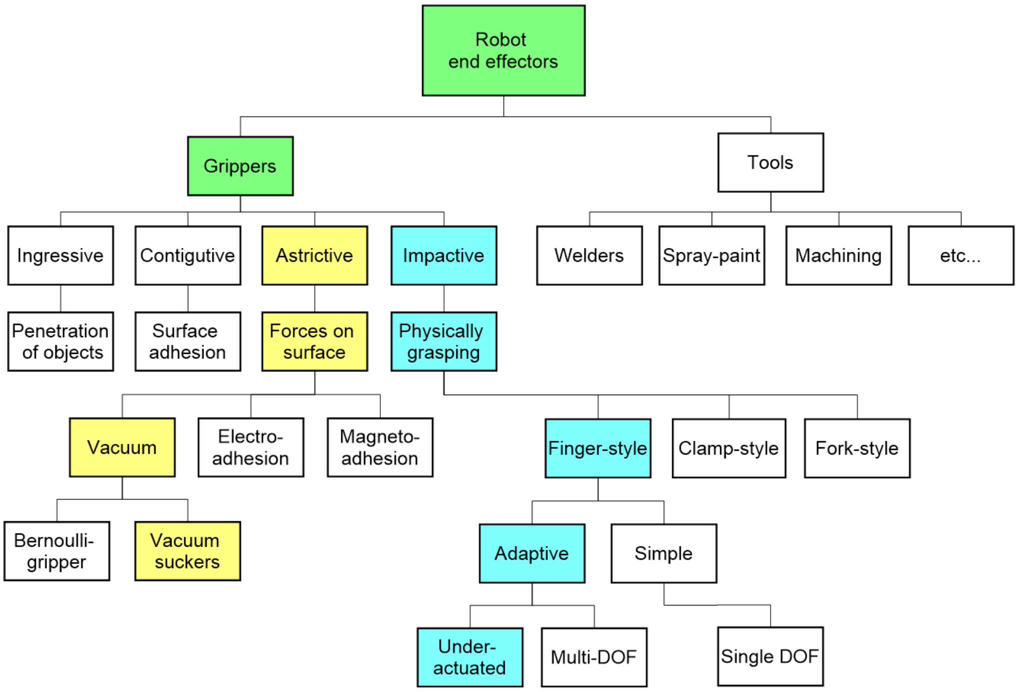


Figure 1.2: Branching family tree of types of endeffectors, showing the the lineage of the multifunctional novel gripper design.

On figure 1.2 a family tree type diagram shows where grippers align with other tools, as well as a variety of different kinds of grippers that exist. Furthermore the highlighted fields show where the novel multifunctional gripper of this report lands, which is in two categories thanks to its ability to grasp as well as lift with its integrated suction cup.

1.2 State Of the Art

Before elaborating the design considerations of the gripper, a review of the state of the art on robotic grippers will be given.

1.2.1 Grippers Today

To manipulate objects use grippers

A typical gripper consists of a base structure, some sort of moveable jaw or fingers, and a way to actuate these jaws or fingers. Thus allows for the gripper to be attached to the robot arm as an end effector, and manipulate objects.

- Custom made task-specific grippers
- Clamp grippers
- Adjustable grippers
- Adaptable grippers
- Compliant grippers

1.2.2 Industrial Adaptability

With increased automation in many industries, most of the production can be taken care of by machines and conveyors alone, however, there is often a few places where certain tasks were still done by humans, often material handling or tasks that requires some form of unique action that was not economic to design a machine to do. Furthermore, it is important for producers to be able to adapt to future changes to their products. The automotive industry, for example, needs their production lines to adapt to the changes between different car models every few years.

A single robot arm can offer the versatility and adaptability that previously made automation of these tasks uneconomic. With six degrees of freedom, most industrial robot arms are able to reach almost any point within their workspace from almost any angle. Thus, the same model of robot arm can find it's way into a number of different industries, because they offer the agility and versatility to replace human workers in a huge array of applications. This is the trend that has been observed the many past years and statistics suggests that it will continue in the future, as described in World Robotics' "Industrial Robot Report" [2]. This also shows the strong motivation why it is still relevant to develop and research more robotics. Robotiq has been making commercially available adaptable grippers as seen on figure 1.3a adn 1.3b, with increasing popularity due to it's advantages, especially in combination with collaborative robots that's are understood as one that is intended to work alongside or directly interact with humans, such as Universal Robot's arms.

(a) Two finger design (b) Three finger design

Figure 1.3: Examples of adaptable industrial grippers from Robotiq

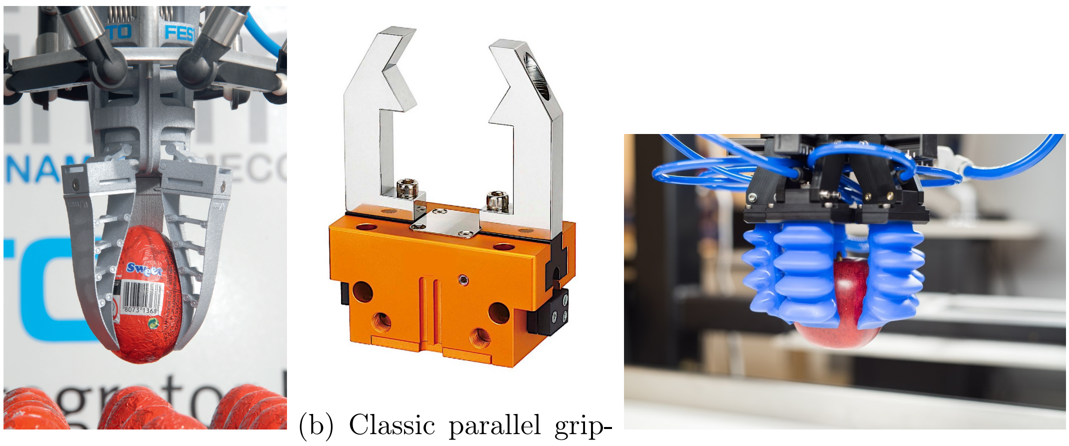
Depending on the task, load, and desired workspace, the size and exact type of robot arm will be picked accordingly, of course. The only thing otherwise, that is likely to change between applications, is the endeffector.

Often times one will also see what seems to be unlikely combinations, very big robotic arms doing small tasks, and this is usually due to small tasks requiring high precision, and larger robot arms offering more structural rigidity and so is able to do small tasks more effectively.

Different grippers offer different advantages and disadvantages. Festo has been experimenting with a compliant spline finger design for a while as seen on figure 3.2.4. Compliant mechanisms has big advantages in the way part count can be significantly reduced, as well as also completely eliminating backlash.

A more classic design is one such as 1.4b which is a pneumatic parallel gripper. It does not adapt to the shape but it can be reconfigured relatively easily with new jaws that fit the objects it's intended to pick up.

Finally a movement in so-called "soft robotics" technologies has also been appearing more and more, to the point where it is commercially available and used in a number of applications. Instead of a typical pneumatic piston, these robots use flexible inflatable bellows, and geometric shapes that mimic function of the hydraulic limbs seen on many sea creatures such as an octopus.



(a) Festo spline finger (b) Classic parallel gripper (c) New soft robotics

Figure 1.4: More examples of industrial grippers

From both the consumer and the producers point of view, offering production tools that are adaptable or configurable is an advantage; The consumer can change his production and simply adjust his or her equipment accordingly. Meanwhile the producer gets a wider range of customers that are able to buy the same product, in this case an adaptable gripper.

But adaptability isn't only relevant for industrial applications, as will be elaborated in the next section.

1.2.3 Grippers for Prosthetic Limbs

With the technological advancement in industrial robot arms, many of the same advancements carry over to prosthetic limbs. The ultimate end effector can be said to be the human hand, as it has ultimately created everything we know and use today. Losing a hand therefore is a big handicap, and where a a hundred years ago you might get your missing hand replaced with a metal hook, today it is possible to closely replicate a normal hand again, and these are almost always adaptable to mimic how a human grasps objects.

Not only is the technology getting better, it is also getting more affordable, which may be said to be a crucial detail, as the places same places that have a lot of amputees are also often too poor to afford the technology that could best replace lost limbs.

The design of the novel gripper in this report is made to be very low-cost, making it relevant to reflect on potential use cases for that sort of endeffectors.

Problem Analysis 2

The problem presented in this project is set by Aalborg University, which are among the ...

Before the problem statement can be crafted, the problem must be defined. It is human nature to want to begin working on a solution as soon as possible and neglecting the definition of the true problem to be solved. However, a poorly defined problem increases the risk of implementing a solution that does not fully meet the expected results. A problem cannot be solved if it is not completely understood.

2.1 Problem Statement

How can the benefits of under actuation be utilized to design a low cost universal gripper and what control protocols are advantageous for it to function with optimal speed and sensitivity?

2.2 Problem Specification

In order to successfully solve the problem stated above, it can often be beneficial to divide the task into a set of well-defined subquestions. The questions are defined in regard to a morphological solution approach:

- What mechanical and actuational components are most suitable for building a low cost gripper and how will they affect each other?
- Which aspects must be considered in the design process to satisfy the desired low cost, performance and functionality?
- What components will be necessary for actuationg and controlling the gripper and how will these interact and be implemented within the design?
- How can an under-actuated system be modelled, simulated, and controlled accurately by utlizing a numerical approach?
- How can the performance of the gripper validated and to what extend does the performance compare with the model predictions?

2.2.1 Outline

When studying robotics, there are often many aspects to cover; degrees of freedom, mechanical linkages, actuation, kinematics, control, human-machine interface, end-user experience, safety, maintenance etc., all contributing to the overall design and functionality of the product. However, due to limited time and resources, the scope of this project is limited to the following tasks:

- Design review of a robotic gripper
- Kinetics modelling and simulation
- Control design and implementation
- Performance validation

Design and Development 3

Before modelling, control and validation of the gripper, this project will look into the background and explain how it was designed. This will be done using an iterative analytic method called morphological analysis in an attempt to find the best design solution to fulfil the design criteria that was specified in [1].

3.1 Concept

The concept of an under-actuated gripper for this project was inspired by previous work done in [1], where a similar under-actuated gripper was made and a prototype was made for testing. The construction of this previous gripper had much room for improvement in terms of complexity and cost savings, due it's use of a central worm drive and integrated teeth cut in each finger. While reducing part count, this design choice unfortunately massively increases the production complexity and cost of these parts. The alternatives will be thoroughly considered in the morphological analysis.

3.2 Morphological Analysis

The morphological analysis is used to determine the best combination of compatible options to produce the functional gripper. This is performed as a study of splitting the overall goal product into it's functional components, methods, technologies. The significance and importance of mayor choices will be considered, and the analysis will a top down approach by determining the feature choices that will be the most influential on the rest of the design. Then the combinations and alternatives will be considered for each functional part of the design, along with the pros and cons of these. These may be found by means of brainstorming and mind-mapping methods. Depending on their practicality and functionality in combination with other solutions, only the more suited options are kept for final consideration while the rest are omitted.

In order to quantify these choices, the scoreboard method from [3] is used. Here the options are given scores based on the different design criteria and the desired weighing of these criteria. One may for example chose to weigh low cost more than reliability or ease of maintenance, and solutions that are favor this will result in a higher total score. Thus it is used to evaluate of the characteristics of these combinations in order to find the best solution based on the desired characteristics from the total score of each.

In this project the weighing importance multiplying factor will range from 3 to 1, and will be scored on the following criteria:

- Solution possible using more low-cost components, with a multiplier of 3.
- High simplicity, with multiplier of 2.
- Solutions that don't limit design options, with a multiplier of 2.
- High accuracy, with a multiplier of 2.
- Low weight, with a multiplier of 1.

These criteria were chosen in order to arrive at a design that naturally favours the initial criteria of the design specifications in the 2016 report. Each of the design options will then be scored 5 to 1 on how well they satisfy the above criteria. The scores for each criteria is multiplied respectively, and the sum of resulting scores for each solution is added up resulting in a total score for each design. The design with the highest score will be chosen for final design considerations.

Besides a scoreboard, many lesser design choices were also taken by considering the pros and cons of a variety of suitable options, and choosing the solutions that are best for the design criteria in combination with the existing choices.

3.2.1 Grasping Method

There are many different ways to grasp an object. The overall design of the gripper will mostly be affected by the type of type of movement and type of fingers that the gripper will utilize. These will therefore be the first to be considered.

There are three overall movements that are considered for the design of this gripper; Rotating, Translating and Combined Movement, as illustrated on figure 3.1. Table 3.1 lists the pros and cons for each of the options.

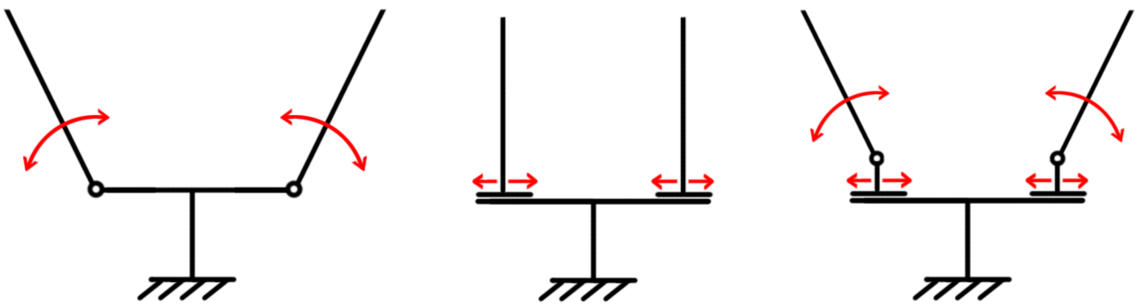


Figure 3.1: Rotating, Translating and Combined Movement. [1]

	Pros	Cons
Rotating finger	Easy movement to produce. Suited for under-actuated fingers.	Not suited for regular shaped objects. (e.g. Boxes.)
Translating finger	Suited for regular shaped objects.	Less suited for under-actuated fingers. Difficult movement to produce.
Combined movement	May be more suited for both regular and irregular objects.	More difficult to produce. Higher cost.

Table 3.1: Table comparison of finger movement options.

In order to pick a method it is very beneficial at this point to also consider how these options combine with each other, and then evaluating these combinations of design options, as mentioned earlier in this report, rather than just the individual design options by themselves.

The next mayor design choice is the type of finger that should be used for the gripper. Three finger design types are considered for this project and can be seen in figure 3.2 and the differences are compared in table 3.2. The three types are as follows:

- Stiff type fingers, will pinch objects like chopsticks do.
- Under-actuated type fingers, uses internal spring and linkages to adapt to the shape of object being picked up.
- Flexible type finger, uses its own flexibility to adapt to the shape of the object being picked up.

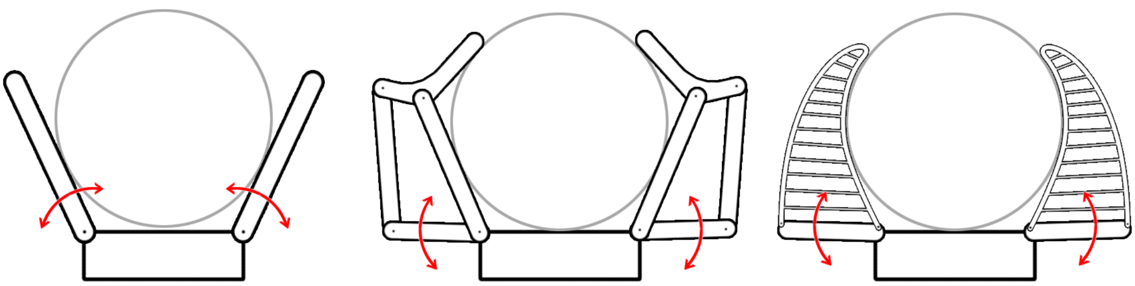


Figure 3.2: Stiff, under-actuated and flexible fingers grasping round objects.[1]

	Pros	Cons
Stiff finger	Very Simple. Very low cost.	Does not adapt to the shape of objects.
Under-actuated	Roughly adapts to the shape of objects being picked up.	More complex design. Higher cost.
Flexible	Continuously adapts to the shape of objects picked up.	Complex design. Higher cost. Must be flexible material.

Table 3.2: Table comparison of finger type options.

The combinations of these finger and movement types are now examined. Their approximate performance is evaluated in table 3.3. This evaluation is considering the options based on how well they perform in grip and cost. The grip is scored according to how well an object can be held in place as well as the gripping strength it can produce. The cost is estimated from the complexity of the different parts. The score is given in words from; Poor, OK, Good and Excellent for grip, and low, medium and high for the cost, with plus'es(+) indicating a superior score.

Prioritizing low cost, it can be seen on table 3.3 that the gripper with rotating under-actuated type fingers is evaluated with the best qualities, followed closely by the rotating flexible type finger gripper. The deciding difference is the assumed grip strength, and the complications that may be involved using flexible material for the fingers, compared to a linkage-based finger, however the flexible design may still be very valid for future considerations. The rest of the design will now be decided with the winning design combination in mind.

3.2.2 Movement Generation

With a finger and movement type chosen, this part of the design process will now determine the best solution to generate the rotational movement for the fingers.

To do this the scoreboard method is used, with points (1 - 5) based on how well the solutions fulfills the respective criteria. Furthermore each criteria is weighed with factors (1 - 3), since some criteria are more important than others. In the case of this design the criteria and weight factors, seen in square bracket, are as follows:

- Low-cost [3]: Lower price gets higher score.
- Simple [2]: Simplicity in terms of few parts and ease of manufacturing.
- Options [2]: Freedom of design options, such as motor placement, part shape, size, power-source.
- Accuracy [2]: Accurate in terms of minimal backlash and position.
- Weight [1]: Lower weight gets higher score.

These criteria and weight factors have been chosen in order to arrive with a design that is low-cost and allows for efficient design, as well as favouring solutions that are low weight, since the gripper will be an end effector and high unnecessary mass on the end of a robot arm is best avoided.

	Rotational	**Translational**	**Combined Movement**
Stiff finger	Poor grip Low-cost++	OK grip Low-cost	OK grip+ Medium cost
Under-actuated	Excellent grip+ Low-cost	Good grip Medium cost	Excellent grip++ High cost
Flexible	Excellent grip Low-cost	Excellent grip Medium cost	Excellent grip+ High cost

Table 3.3: Combination evaluation for finger type and movement.[1]

The following possible solutions, on figure 3.3, are then chosen for consideration:

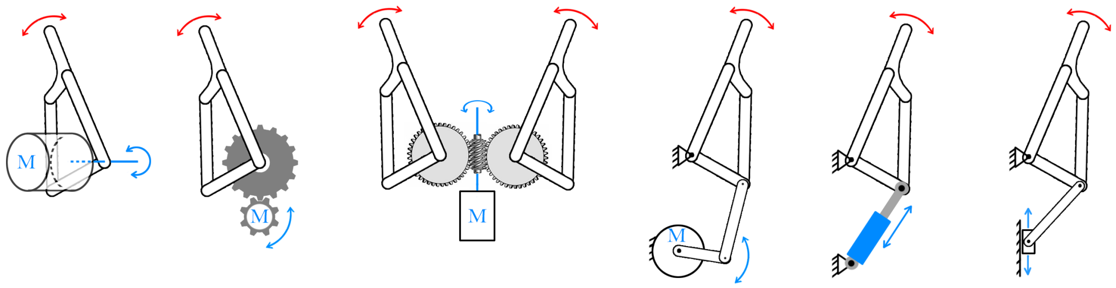


Figure 3.3: Direct, Gear-train, Central gear, Four-bar-linkage, Crank-style and Crank-slider drive.[1]

Direct drive: Finger rotation is driven directly by individual motors. Each finger thus gets a degree of freedom which may be advantageous when gripping some objects. The position of the motor is however restricted, and the amount of motors needed makes it more expensive.

Gear-train: Similar to direct drive, except each motor is moved to a more convenient location by means of gears or pulleys. The output can be given a custom gear-reduction if desired. This comes at the cost of introducing more complexity in the form of parts and also backlash in the case of gears.

Central gear: One motor drives all fingers through a system of pulleys or gears, for example a worm-gear in the middle of a flower arrangement of gears leading to the fingers. This reduces the need of multiple motors and may result in a much simpler gripper depending on how the motor drives each finger.

Four-bar linkage: Rotation from rotation. Using a four-bar linkage, the power-source of the rotation may be moved to a more convenient location, similar to rotation through gears or pulleys in the gear-train method.

Crane-style: Rotation from linear actuator. Similar to the movement of a hydraulic crane. This solution is very space-efficient and may be ideal if the rest of the system, in which the gripper is to be used, is hydraulic or pneumatic. This solution also requires one linear actuator for each finger.

Crank-slider Rotation from translation. Similar to the four-bar linkage solution, it is possible to use a crank slider mechanism. This allows every finger to be driven by a shared moving plate driving all fingers. The linear isn't easy to produce, however there are many open design possibilities.

The different possible combinations of solutions are compared in table 3.4 and rated.

	Low-cost [3]	Simple [2]	Options [2]	Accuracy [2]	Weight [1]	**Total**
Direct drive	2	4	1	3	3	**25**
Gear-train	1	2	3	4	3	**24**
Central gear	4	3	2	3	4	**32**
Four-bar linkage	1	3	3	3	3	**24**
Crane-style	1	4	2	5	3	**28**
Crank-slider	3	3	4	4	3	**34**

Table 3.4: Scorecard evaluation of the design options.

At 34 points, the crank-slider mechanism wins, and is chosen for further development. Using the crank-slider plate, a single translation can move all fingers at once, while having no expensive parts and potentially very low backlash for high accuracy. Another possible feature is the ability to arbitrarily place the fingers on the gripper as long as they are anchored to the top and the moving plate.

3.2.3 Actuation Design

Now that the mechanism of the design is chosen, the remaining development will now consider options to make the gripper work.

The first necessary thing to consider is the actuation method to drive the central moving plate up and down. This can be achieved in a number of ways. For this project the following, figure 3.4 was considered, their pros and cons compared below:

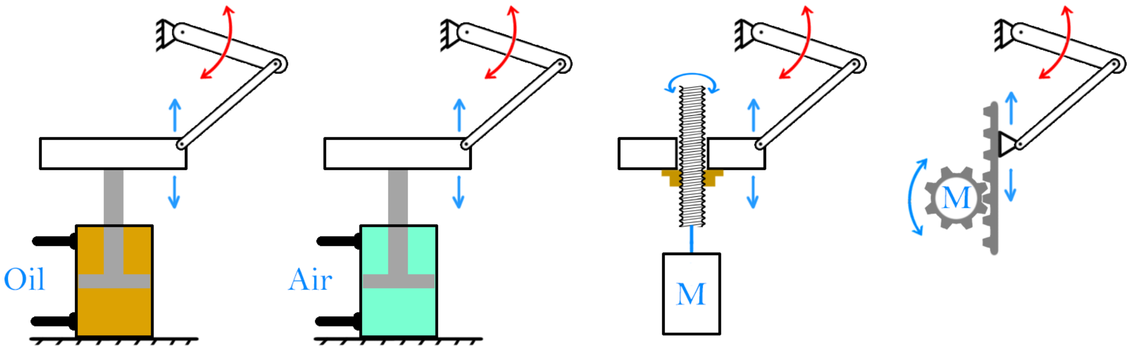


Figure 3.4: Different systems to generate the crank-slider motion.[1]

	Pros	Cons
Hydraulic piston	Powerful and accurate. Power source may be moved far away from actuator. Space efficient.	Requires oil system. Very expensive.
Pneumatic piston	Very fast. Power source may be moved away from actuator. Space efficient.	Requires air system. Not very accurate.
Lead screw	Cheap motor options. Low backlash. Uses readily available power sources.	Not space efficient.
Rack and pinion	Cheap motor options. Some built-in gearing. Uses readily available power sources.	Expensive. Has backlash. Not space efficient.

Table 3.5: Table comparison of actuator options.

The lead screw option is chosen since there are many options to implement it, and it is low cost which is one of the mayor goals of the design of this gripper. It is also possible to use in electrical systems with no additional elements for pneumatic or hydraulic actuation.

After the lead screw chosen, the type of motor to drive it was chosen. Three options are considered; Brushed DC motor, Brushless DC motor, and Stepper motors, each with their advantages and disadvantages, which are as follows:

Brushed DC motor: Pros: Best Power-to-price. High speed. Low noise. Cheap to control. Cons: Poor at holding constant position.

Brushless DC: Pros: Good at holding constant position. Cons: Expensive. Difficult to control.

Stepper motor: Pros: Great at holding constant position. High torque. Cons: Expensive. Noisy.

It should be mentioned that brushless DC motors have been gradulally falling in price, likely thanks to more widespread usage and more production, for instance due to it's frequent usage in commercial drones and quadcopters. This makes the brushless DC motor more worth considering, as it brings a lot of useful options to table and outperforms the DC motor except in price.

This summarises the main design considerations. The method then goes on to iterative design in CAD, exploring different methods and ways of combining the chosen technologies.

3.2.4 Different design consideration

For conventional mechanisms, scale-independant fabrication tolerances lead to increased backlash relative to the assembly size, decreasing accuracy. However, this is not the case for compliant mechanisms [4], as there are no bushings or bearings or pins to cause this, and parts can often be designed in such a way that they have 2D simplicity, and could thus easily be manufactured by injection molding or even extruded and cut to width.

In the case of this project this is true for the grippers fingers, which potentially be reduced from 27 parts each, to just one. And this would stay true even if another phalanx segment is added to the finger, or even having a continuous flexible spline like on the festo gripper from the previous figure , although it a spline is just one solution.

There are of course advantages and disadvantages too to this method, and it is not the focus of this report to redesign the fingers. However, reviewing the essentials of the design chapter is should be mentioned for future considerations.

3.3 Electrical System

In order to power and control the gripper, an electrical system is needed. It is desirable for this system to be easily configurable for different use-cases, and for it to interface in a simple manner with external commands, as well as providing feedback.

There are multiple ways to achieve this but the most common and cost-effective method is to use a simple microcontroller for controlling inputs and outputs, and integrate it with a motor driver. This is also true, for the gripper as well, however the components used have been changed significantly since the original gripper design, and the current one.

3.3.1 Original Electrical System

The original electrical system used an Arduino Uno, which is based on the ATmega328P 8-bit AVR microcontroller. This has the advantage of being low power and low cost, operating at 16MHz.

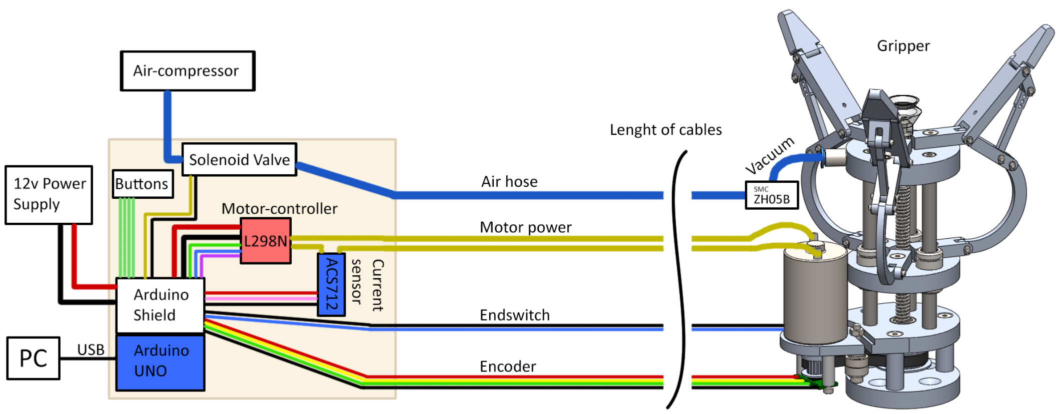


Figure 3.5: Original electrical system.

This system used a DC motor interfaced with the AS5040 magnetic encoder for position feedback, and uses a L298N full-bridge driver IC to control the motor direction and speed. It also used an in-line ACS712 current sensor to measure the current used by the motor, as this is proportional to the torque and thus necessary for controlling the gripping force. Finally there is also an endswitch which the gripper uses during startup to zero itself to a known position, as well as function as an emergency stop in case the gripper unexpectedly bottoms out.

The interface consists of a few buttons for determining if the gripper should open or close, and knob inputs deciding the allowed gripping force as well as the desired closing position.

The pros of this system is the extremely low cost of the component choices. The cons however is that the system has limitations on performance, since the microcontroller needs to do many calculations while keeping track of the encoder which pulses 512 times per single revolution of the motor.

3.3.2 Upgraded Electrical System

Some significant changes have been made to the system, most prominently the DC motor has been upgraded to a brushless or electronically commutated (EC) motor instead. This has the advantages of being much smaller and more power dense than a DC motor of similar power specs. The EC motor has three phase coils internally which requires a more advanced driver and control scheme to use. In this case the EC motor is a Maxon EC397172 motor with a built-in encoder, used along with a compatible Escon 50/5 driver module on an Escon module motherboard.

These provide an interface that reads a desired setpoint, for either current or speed, as well as an enable and direction input. It then proceeds to do the motor regulation internally using it's built-in control scheme that is tuned for the motor and system's parameters. Finally it outputs analog signals for actual current and actual speed, which can be used to interface and integrate this system in a bigger control loop with a microcontroller.

The pros of this system is a potentially much higher system performance, and it handles an internal control loop, reducing the load of whatever microcontroller it used along with it. The cons of this is a much more expensive system, as well as some limitations in design and control freedom due to the proprietary nature of integrating these systems. Although the system already has a built-in encoder, the Escon driver offers no access to this, so the previous AS5040 magnetic encoder still has to be used in order for the outer control loop to know the system's position.

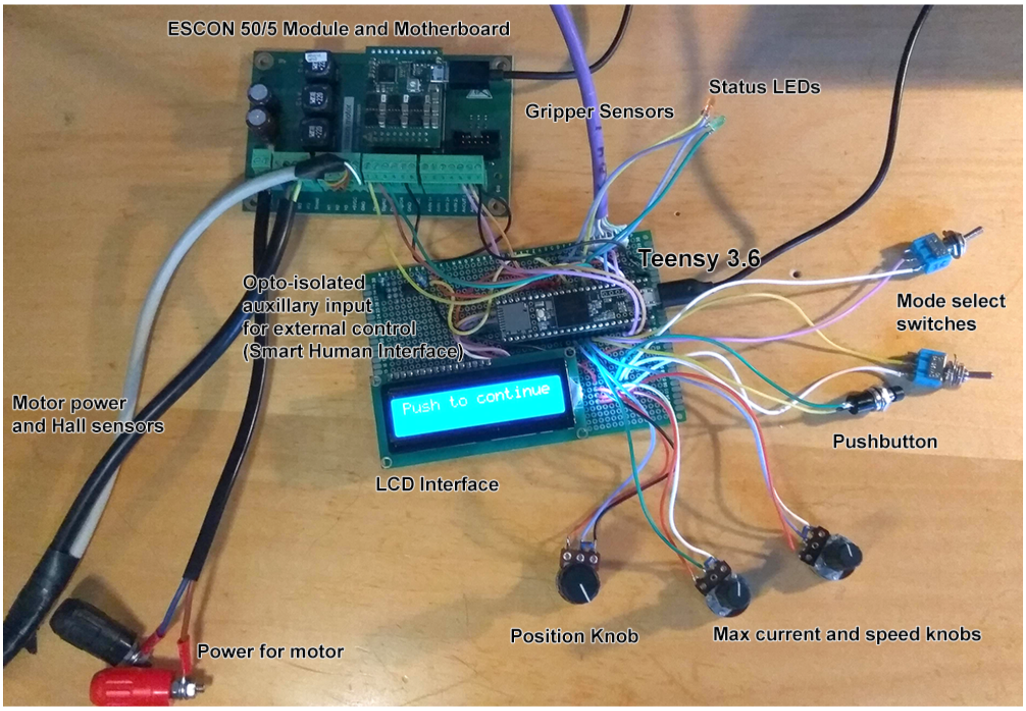


Figure 3.6: The new electronics to drive the gripper.

The somewhat limited options with Maxon motor and Escon driver is however not negative, as they generally make prototyping easier. For later development however it may be beneficial to look into a generic brushless DC motor and a three phase motor driver or variable speed inverter (VSI), as this by itself can be controlled much more freely. With position feedback it is potentially possible to control the motor using Field Oriented Control (FOC) to efficiently achieve fine and smooth control of the current used by the motor and thus the torque produced, which is very useful in an application such as the gripper where this is proportional to grasping force.

With the potential performance now offered by the new hardware, it was decided to also drastically upgrade the microcontroller to take advantage of this potential, using a Teensy 3.6, which is based on the 32-bit 180 MHz ARM Cortex-M4 processor, which proves to be a significant improvement over the old Arduino Uno, not only thanks to a clock frequency more than 11 times higher, but also much higher memory and offering many more I/O features.

This time to interface, it is chosen to also have an LCD screen, for improved human control interface. The system has two buttons, one for mode select and one for open/close. It also has 3 knobs; one for end position, one for max speed and one for max torque. The three knobs are read using the analog values of potentiometers, and steps have been taken this time to eliminate noise, both physically with an RC filter, as well in software where hysteresis on the input is simulated to omit edge value changes. This ensures that the setpoint for these options will not cause jitter after the gripper has moved, and allowing the gripper to continuously read new setpoints.

Thanks to the high processing speed of the Teensy it is furthermore possible to increase the loop time of the PID controller that is programmed herein.

To reflect the design changes, the CAD model has also been updated with an accurate model of the new motor as seen on figure 3.7.

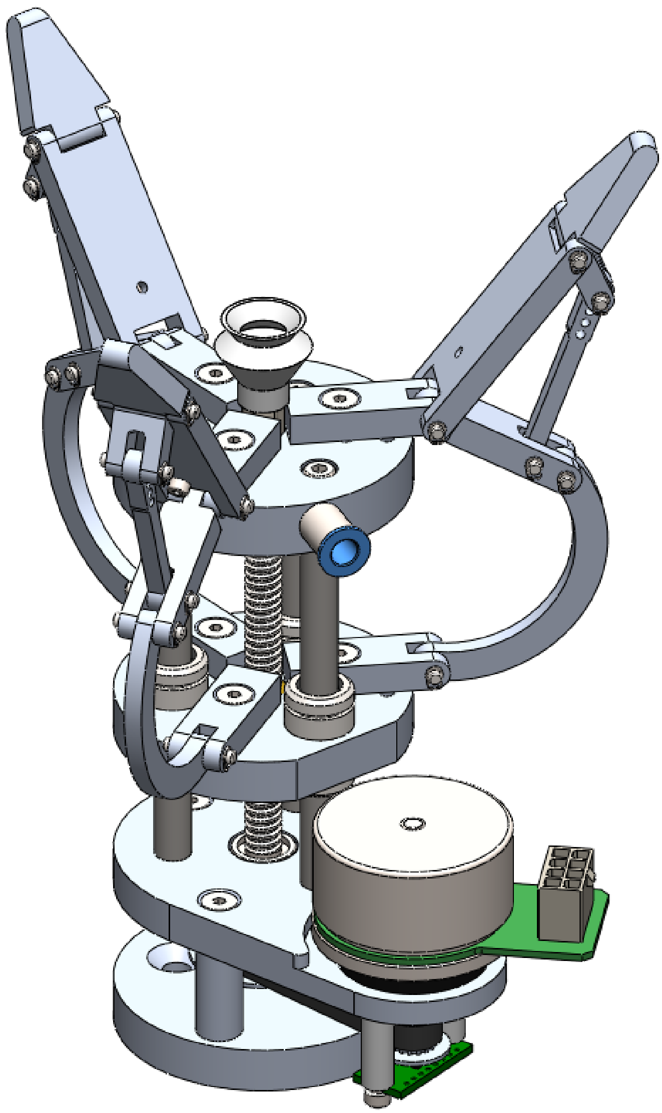


Figure 3.7: Updated CAD model to account for the new motor.

However, due to the larger diameter of the motor, using the old motor mount now makes the outer rotating case of the motor and the moving slider of the gripper overlap, limiting how much the gripper can move before it will start to destroy itself. A simple solution to this was thought out, which consists of removing 2mm material on the moving ring where it faces the motor, as shown in blue on figure 3.8. However this was not done in time and results in further complications in the control, testing and validation, as this limits the total movement of the gripper.

However the important part of the grippers total movement is preserved enough that the validation tests should be comparable.

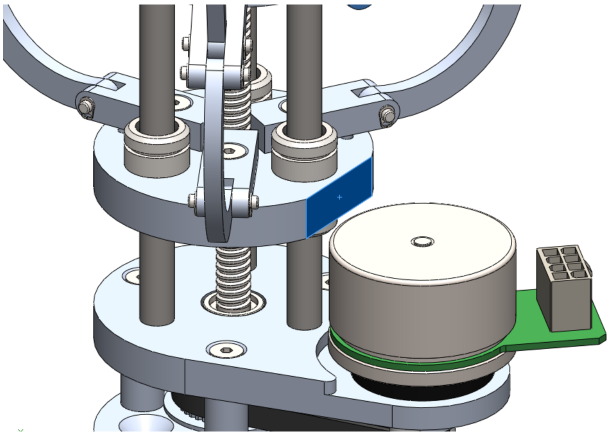


Figure 3.8: Upgraded electrical system.

Summary

The upgraded electronics have a higher cost, but offers higher performance and while offering new possibilities for control. This is excellent for prototyping but more cost effective solutions exist and should be considered at a later stage.

3.4 CAD Design

To aid in the design process, CAD software was used to quickly go through multiple design iterations, while more easily and intuitively being able to visually inspect and correct the design quickly. Having the design digitally also allows for the design to me made into work drawings for prototyping and production, or even exported as a 3D object and fabricated with rapid prototyping such as 3D printers for physical examination.

CAD is also extremely useful for design as it directly allows for mechanical properties to be examined, for instance the movement behaviour of the finger linkage was tuned by adjusting the lengths of the links in Solidworks, and structural analysis can also be carried out, such as finite element analysis for a specific load case.

4 Modelling

This chapter was intended to addresses the establishment of a kinematic and kinetic representation of the gripper. However, the geometry of the system will initially be described to determine the further modelling procedure.

4.1 Multibody Mechanical Systems

The gripper falls under the category of multibody systems as it is composed of a number of different mechanical components. Together they make up a system of linkages between points that facilitate predictable movement based on known inputs also called 'forward dynamics'. Oppositely, when system movement is used to determine the inputs, the analysis i called 'backwards dynamics'. There are a number of ways to obtain descriptions of this movement mathematically, but within the field of multibody dynamics, the Nikravesh method seem to be one of the more recognized approaches. As a result, this chapter will also focus on the principles from [5], where three universal approaches for multibody modelling are introduced. However, these all rely on the general assumption that all linkages can be considered to be infinitely stiff. This means that deflections due to strain in the structural members of the system are neglected. This is also why these methods are not applicable for systems designed with compliant mechanisms.

The gripper covered in this project is fundamentally a three-dimensional mechanism, where all fingers work together in order to grasp a spatial object. This would normally implicate that the entire system must be determined in three directions and three orientations. However, due to the symmetric configuration of the gripper, the individual fingers can be observed as separate two-dimensional systems. The transformation from spatial to planar coordinates simplifies the modelling process drastically, as the number of system equations goes from being cubed to being squared. More specifically will the number of calculations be reduced by a factor of two, since only two directions and a single orientation has to be determined.

4.2 Kinematics

The field of kinematics is used to describe positions, velocities, and accelerations of objects in motion. The determination of these parameters are essential in order to further calculate forces and reactions. Any kinematic analysis starts with an illustrative geometric representation, where the system at hand is introduced. The kinematic scheme of a single gripper finger is shown in figure 4.1 with O as origin of the fixed XY reference frame. The red dots represent the position of the joints, while the blue dots corresponds to the center of mass for the links.

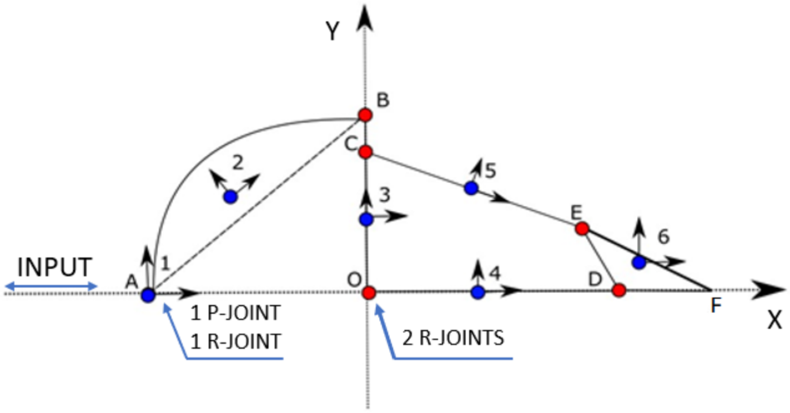


Figure 4.1: Kinematic representation of a single finger, [6].

It can be seen that the mechanism is comprises of two concatenated planar linkages; the PRRR linkage (A-B-O) and the RRRR linkage (O-C-E-D). The first consists of one prismatic and three rotational joints, commonly called a slider-rocker mechanism, while the second consists of four rotational joins, also known as a four bar linkage. In order to allocate the position, velocity, and acceleration of the the individual links in regard to the global coordinate system, kinematic vectors are is introduced for each of the six bodies as shown in equations 4.1, 4.2, and 4.3.

$$\mathbf{r}^i = \begin{bmatrix} r^i_{(x)} \\ r^i_{(y)} \end{bmatrix} = \begin{bmatrix} x_i \\ y_i \end{bmatrix} \tag{4.1}$$

$$\mathbf{v}^i = \dot{\mathbf{r}}^i = \begin{bmatrix} \dot{x}_i \\ \dot{y}_i \end{bmatrix} \tag{4.2}$$

$$\mathbf{a}^i = \dot{\mathbf{v}}^i = \ddot{\mathbf{r}}^i = \begin{bmatrix} \ddot{x}_i \\ \ddot{y}_i \end{bmatrix} \tag{4.3}$$

Six additional body frames are then introduced locally in each of the centers of mass by the transformations matrix shown in equations 4.4 resulting in an array of coordinates as shown in equation 4.5.

$$\mathbf{R} = \begin{bmatrix} \cos(\phi) & -\sin(\phi) \\ \sin(\phi) & \cos(\phi) \end{bmatrix} \tag{4.4}$$

$$\mathbf{c} = \begin{bmatrix} x \\ y \\ \phi \end{bmatrix} = \begin{bmatrix} x & y & \phi \end{bmatrix}' \tag{4.5}$$

The local body coordinate systems facilitate the definition of points in regard to the local axis ξ and η as illustrated on the figure 4.2. Here it can be seen how the vector $\mathbf{s}$ can be used to define any point in the body regardless of overall orientation.

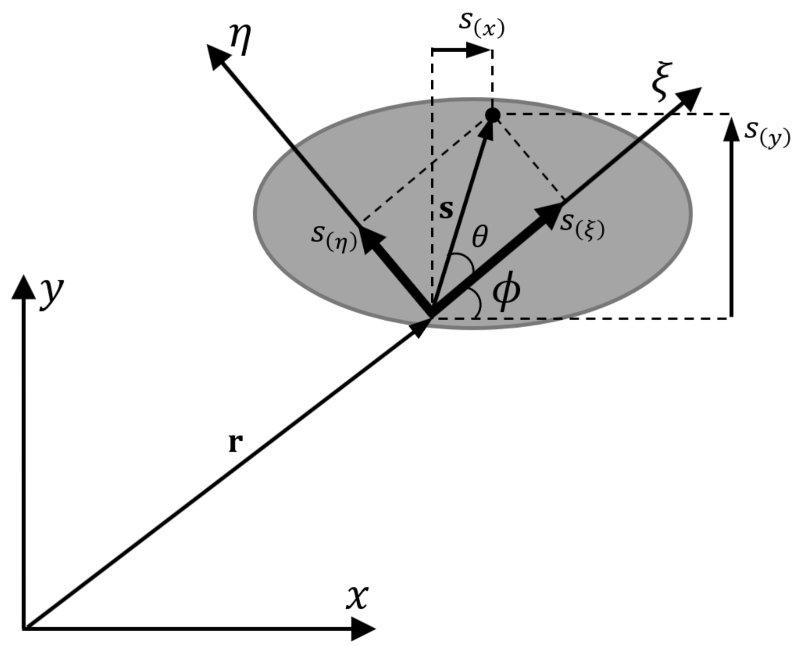


Figure 4.2: Components pf a vector attached to a body, inspired by [5].

Utilizing linear algebra the local position vector $\mathbf{s}$ can be define either equation 4.6 or 4.7 depending on the reference system.

$$\mathbf{s}_{(\xi-\eta)} \equiv \not{\mathbf{s}} = \begin{bmatrix} s_{(\xi)} \\ s_{(\eta)} \end{bmatrix} \tag{4.6}$$

$$\mathbf{s}_{(x-y)} \equiv \mathbf{s} = \begin{bmatrix} s_{(x)} \\ s_{(y} \end{bmatrix} \tag{4.7}$$

This facilitates the calculation of any fixed point P on a body with only the global coordinates as equations 4.8 and 4.9.

$$\mathbf{s}^P = \mathbf{A} + \not{\mathbf{s}}^P \tag{4.8}$$

$$\mathbf{r}^P = \mathbf{r} + \mathbf{s}^P = \mathbf{r} + \mathbf{A}\not{\mathbf{s}}^P = \begin{bmatrix} x^P \\ y^P \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} \cos(\phi) & -\sin(\phi) \\ \sin(\phi) & \cos(\phi) \end{bmatrix} \begin{bmatrix} \xi^P \\ \eta^P \end{bmatrix} \tag{4.9}$$

This can also be written on expanded form as shown in equations 4.10 and 4.11.

$$x^P = x + \xi^P \cos\phi - \eta^P \sin\phi \tag{4.10}$$

$$y^P = y + \xi^P \sin\phi + \eta^P \cos\phi \tag{4.11}$$

The velocity of a body or time derivative is defines as $\mathbf{v} \equiv \dot{\mathbf{c}} = (\dot{x} \quad \dot{y} \quad \dot{\phi})'$. For this a time derived rotation matrix is defines as equation 4.12.

$$\dot{\mathbf{A}} = \begin{bmatrix} -\sin(\phi) & -\cos(\phi) \\ \cos(\phi) & -\sin(\phi) \end{bmatrix} \tag{4.12}$$

Now the instantaneous velocity of a fixed point on a body can be calculated by equation 4.13.

$$\dot{\mathbf{r}}^P = \dot{\mathbf{r}} + \dot{\mathbf{A}}\not{\mathbf{s}}^P \tag{4.13}$$

And finally the acceleration is defined as $\dot{\mathbf{v}} \equiv \ddot{\mathbf{c}} = (\ddot{x} \quad \ddot{y} \quad \ddot{\phi})'$ where $\ddot{\mathbf{A}}$ is defined as equation 4.14 prescribes.

$$\ddot{\mathbf{A}} = \begin{bmatrix} -\cos(\phi) & \sin(\phi) \\ -\sin(\phi) & -\cos(\phi) \end{bmatrix} \tag{4.14}$$

With this a number of constrain equations can be defined in order to mathematically describe the allowable workspace for the mechanism. However, the degrees of freedom will initially have to be determined, which can be done with the Grübler formula shown in equation 4.15.

$$\text{DoF}_{mechanism} = \text{DoF}_{plane} \cdot n - \text{DoC} \cdot c_1 = 3 \cdot 6 - 2 \cdot 8 = 2 \tag{4.15}$$

Although the Grübler equations specifies two degrees of freedom, the gripper is utilizing the concept of under actuation, saving the use of an extra actuator. This allows the structure to be easier to control and cheaper to manufacture.

These methods have been carried out for the gripper in the original design report [1] as well as in the later [6], where the different modes of operation have also been characterised and simulated.

Due to limited time the focus now is to implement control on the new system and validate the simulations.

Control 5

For most systems it is desirable to have accurate and responsive control of the output that the system produces, and the gripper is no exception. In order to control it, it is necessary to develop a control scheme, the method by which it will be controlled, as well as how the system can be tuned for the desired output responses.

5.1 Control Design

Because of limited resources and time in this project, it is decided to use a cascade control loop scheme with PID regulation for this input. In order to tune the PID later, a variation of the heuristic Ziegler–Nichols tuning method to achieve the final control parameters.

5.1.1 Control Scheme

Since the motor used now is a brushless DC motor, this gives options for much higher performance controls, for instance it is very suited to control accurately using Field Oriented Control (FOC) scheme.

However due to the nature of the maxon motor, the internal access is limited, and that has both advantages and disadvantages. But for this project it is decided not to look further into the technical control of such a three phase motor.

Instead the control will follow a simple cascade control with an inner current loop and an outer speed, force or position loop depending on the desired mode of operation.

Ziegler–Nichols tuning method is meant to give PID loops best disturbance rejection, however it yields aggressive gains and overshoot, which is not wanted in a case such as the gripper, as this could potentially destroy whichever object it being attempted picking up. Instead, a variation is used, based on the same tuning principle, the parameters are given gains of different fractions of the measured response, as described in Ziegler–Nichols Tuning Rules for PID by Microstar Laboratories [7], which then yields regulation for the outer control loop without overshoot.

A similar method is used in the ESCON Studio software used to configure the ESCON 50/5 module that drives the motor. Here an oscilation is similarly induced, and the inputs causing this as well as the system behaviour is used to determine the control parameters for the inner current control loop for the motor using the software, providing a stable general purpose regulation.

5.2 Control Implementation

In order to implement the control on the Teensy, some code had to be written. Not only to run the control loop, but to also keep track of input and give the necessary outputs to peripherals. In an attempt to best elaborate and explain the difficulties and challenges presented with regards to implementing this, the following sections reflect the way the code is set up, starting with it's start-up routine, the inputs and the control loop itself.

5.2.1 Start-up routine

The first thing done in the program for the gripper, is declaring all the names and variables that is used throughout the code, as well as importing any libraries used - in this case one library is used to communicate with the LCD screen.

For the practical implementation of the control on the Teensy, it is necessary at all times to know the position of the slider in order to reach the desired open and closed gripper positions, as well as to not cause damage to itself. So the next thing is to start the Interrupt Service Routine (ISR) that will receive the quadrature pulses from the encoder. This allows the gripper to immediately keep track of any position changes from this point onward. However it still does not know where it is positioned relative to the maximum and minimum allowed positions.

To do this, during start-up the gripper will zero itself by opening to its fully open position. Once this position is reached the position can be registered to a known "zero". This could effectively be done in two ways:

- With known torque, drive the carriage until it hits the bottom.
- Use an end-switch to register when a certain position is reached.

By applying a constant current low enough, self damage can be avoided letting the gripper open until it hits its own bottom, and registering when the movement stops. This has the advantage of not requiring any additional components. However, uneven friction or a stuck object could give a false reading resulting in a false zero position which is an issue. By using an end-switch to register when the slider carriage reaches a certain position is a more reliable solution, and was the chosen method.

The gripper zeros itself it moves to the bottom twice. Second time slower than the first. This ensures that if the gripper starts in the bottom position, after moving up a little and slowly down the second time, the gripper will still have the same reference.

To also make this safe and user friendly, for demonstration, the gripper displays a pushbutton request before it returns the slider carriage to zero, so that no movement is initiated automatically when power is supplied.

After zeroing, the program continues into the main loop where it stays indefinitely.

5.2.2 Main Loop

Once the gripper knows where it is, it goes into the main loop where it does primarily three things:

- Check if it is time to compute and update the PID output. Otherwise wait.
- Read and store user input values to variables for later computations.
- Update the display if any of the displayed values have changed.

The first step is in order to calculate the PID at a fixed sample time. This has several benefits, as will be discussed in the next section.

5.2.3 PID Implementation

The general formular for a proportional–integral–derivative controller is as such:

$$Output = K_P e(t) + K_I \int e(t)dt + K_D \frac{d}{dt} e(t) \tag{5.1}$$

Where

$$e = Setpoint - Feedback \tag{5.2}$$

However implementing it on a microcontroller changes a few things, as this is now discrete time. This has some advantages, however, once implemented correctly the computation can be done fairly easily. For instance, if called at a regular interval, the behaviour of the PID is very consistent and the computing the derivative and integral parts of the output can be simplified, since they're both dependent on the change in time, which, ideally, will be constant between each computation.

To ensure that the PID is called at a regular interval, a simple time checking function gets called every cycle, and based on a pre-determined sample time, the main loop decides if it should compute the PID again or return immediately. Alternatively an ISR could also be configured with a timer that will run the PID at a fixed rate.

Another issue to take into account is to eliminate the phenomenon knows as "Derivative Kick". The issue has been illustrated on figure 5.1, which shows how a change in the setpoint causes a causes an instantaneous change in error due to the equation 5.2. The derivative of an instantaneous change is theoretically infinity, while in practice it winds up being a really big number, since dt isn't 0. This number gets fed into the PID equation 5.1, which results in an undesirable spike in the output.

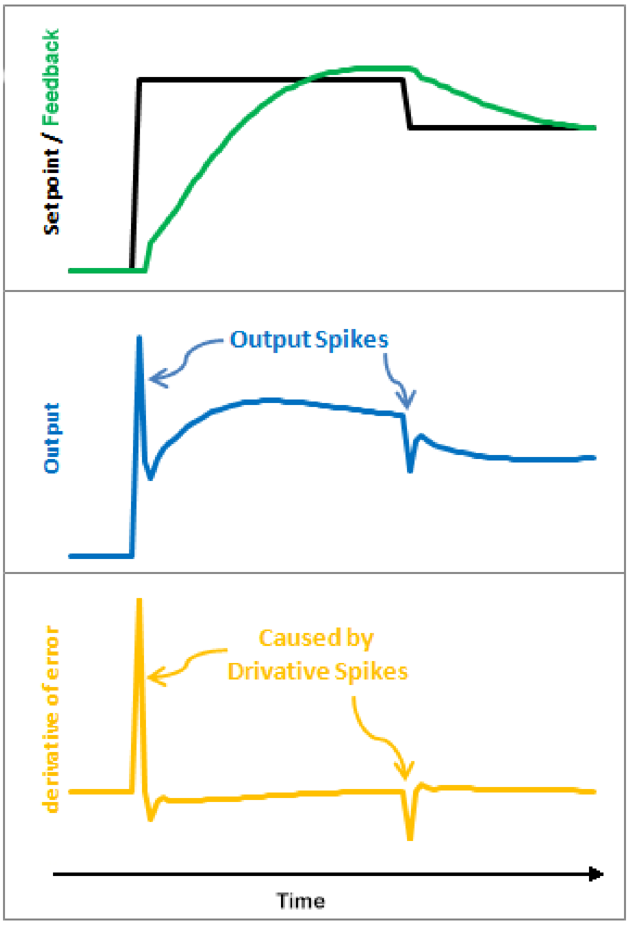


Figure 5.1: Derivative Kick caused by instantaneous change in setpoint and error.

To solve this we observe as in equations 5.3 and 5.4 that except when the setpoint is changing, the derivative of the error is equal to negative derivative of input. So instead of adding $K_D\frac{dError}{dt}$, we subtract $K_D\frac{dFeedback}{dt}$. This is known as using “Derivative on Measurement”.

$$\frac{dError}{dt} = \frac{dSetpoint}{dt} - \frac{dFeedback}{dt} \tag{5.3}$$

When setpoint is constant this gives:

$$\frac{dError}{dt} = -\frac{dFeedback}{dt} \tag{5.4}$$

Finally the code also takes into account anti windup of the integral part. Once an output limit is reached, the output is clamped and the and the PID is told to stop summing (integrating). This way, the PID is actually produces the output that is sent, not just something that is limited by the system. If this were not done, The

PID would be confused trying to push a higher and higher output with no impact. When a new setpoint is set, however, this huge value from the integral part would cause lag before the PID could accurately respond to the new goal.

5.2.4 Smart Human Interface Compatibility

It was part of the project proposal to look into controlling the gripper using a smart human interface, such that the setpoint for the gripper is given based on the intention of the user. Such a system is described in [8]. Here it works using sensor bands attached to the user. After training, the algorithm will have learnt what different combinations of sensor feedback correspond to different intentions, and these known intentions can then be used as inputs to drive a system.

By having the opto-isolated auxillary input as part of the new electronics, as seen previously on 3.6, it it possible to switch to an operating mode where the setpoint of the gripper is controlled using human intention detection, and it was decided to include this because of the many possibilities it gives the system for further future development and implementation.

Validation 6

One of the main goals of this project is the experimental validation of the compliance model for the real system. In this chapter it is explained how a method of data acquisition for this purpose is proposed and tested, and compared with the simulated results.

6.1 Testing Methods

In order to effectively validate the simulated results, it would be ideal to record the position and rotation of all bodies during movement. One way of doing this would be to fit sensors in each joint of the linkages to record the rotations and then use forward kinematics to compare the position data. However the amount of sensors and the accuracy needed would make this scenario expensive to carry out, as well as the size of the sensors may end up being so bulky it would interfere with the movement or functionality of the gripper, which goes against the point of validating the performance.

Another way is to track the movement of the fingers in space using cameras. However this method requires some consideration as well. The biggest issue with using a camera is the distortions caused by perspective, which would cause errors in the perceived distances. Another issue besides perspective is the lens distortion, the

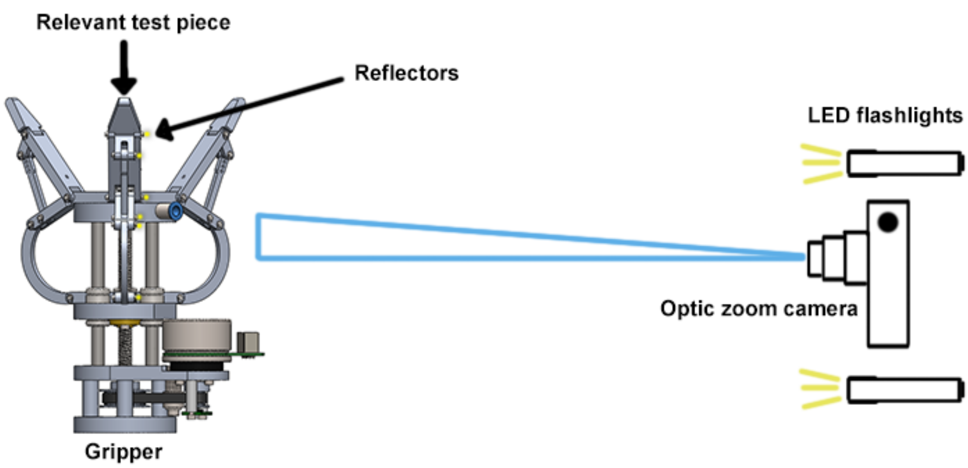


Figure 6.1: Experimental setup for compliance model validation.

extreme example being well known as the "fish eye lens" effect. In order to avoid lens distortion, a rectilinear lens should ideally be used, which is in practice the opposite of a fish eye lens, designed re preserve straight lines as well as angles wherever they occur.

In order to deal with the perspective, there are two practical options:

- Use multiple cameras and computer vision to triangulate the positions without perspective error.
- Record from a high distance to approximate 0 angle of view and minimize the perspective distortion.

The second option is the one used in this project, as it is more straight forward using only a single camera, the only requirement being optical zoom. Furthermore, with enough distance a rectilinear lens is also not necessary as all incoming light will approximate an isometric view. In practice there will always be a slight deviation, although given enough distance and zoom the difference may be negligible.

The experimental setup is illustrated in figure 6.1, illustrating the described method of data acquisition.

6.1.1 Implementation

In this project, in order to track and validate the behaviour of the gripper, a single camera with optical zoom is placed as away from the gripper as possible, on a stable tripod, while zoomed having the gripper in frame. In order to more clearly see the points we wish to track, reflective markers are placed on the end of each joint axle, as seen on figure 6.2

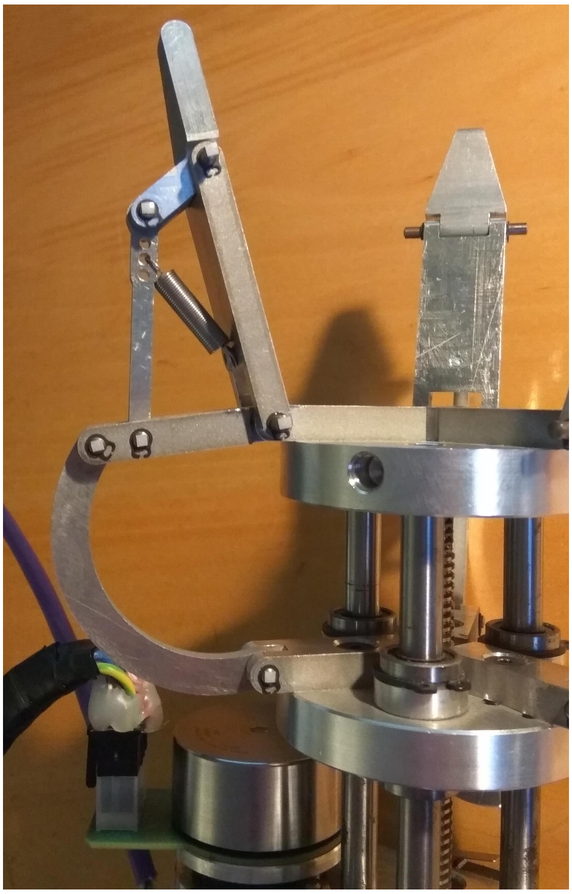


Figure 6.2: Tiny reflective markers on the joints.

To make use of these reflective markers, two powerful flashlights are placed right next to the camera, so that scattered reflections from the flashlights will be picked up by the camera.

In order to test the gripping modes characterized in [6], it is necessary to have physical objects that result in the same sort of responses as the ones simulated. Therefore in this validation, 6 cylindrical test pieces were designed in such a way that gripping these will stop the inner phalanx at the simulated angles $10°$, $5°$ and $-5°$ to validate power grip, and three other test pieces were made so that the gripper centrally grips a cylinder of radii $5mm$, $15mm$ and $26mm$. The test pieces were designed to be mounted fit in the screw hole previously used for a suction cup, thus securing their central position as well. The test pieces can be seen on figure 6.3

Figure 6.3: Gripper with the 3D printed testing pieces.

6.2 Results and Discussion

After the experiments are performed, they are analysed the free video analysis and modeling tool Tracker, which is built on the Open Source Physics (OSP) Java framework. This section will present and comment on the results found in the previous chapters.

Because of technical difficulties the validation got delayed significantly in regards to what had been planned. So only one validation is shown in this report, although preparations had been made to be able to validate all of the simulation results with the control, test setup and 3D printed test pieces.

6.2.1 Simulation Results

The report refers to [6] for the simulated behaviours. Although it was intended to include it here and overlay the simulated with the experimental results, it was not achieved in time.

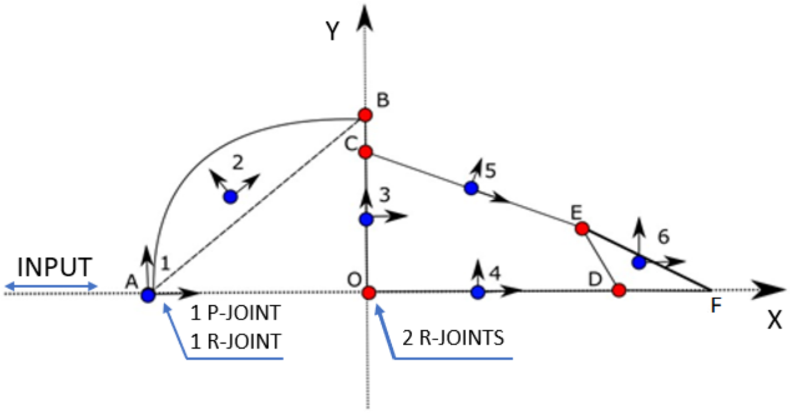


Figure 6.4: Kinematic representation of a single finger, [6].

6.2.2 Validation Results

The following on figure 6.5 is the footage overlaid with a coordinate system aligned with the axis of the gripper and zero in joint O, at the base of the finger. This is so that the joints follow the same convention used in [6] as illustrated on figure 6.4, in order to later be able to directly compare the results (although unfortunately no time was available at this point to realise this).

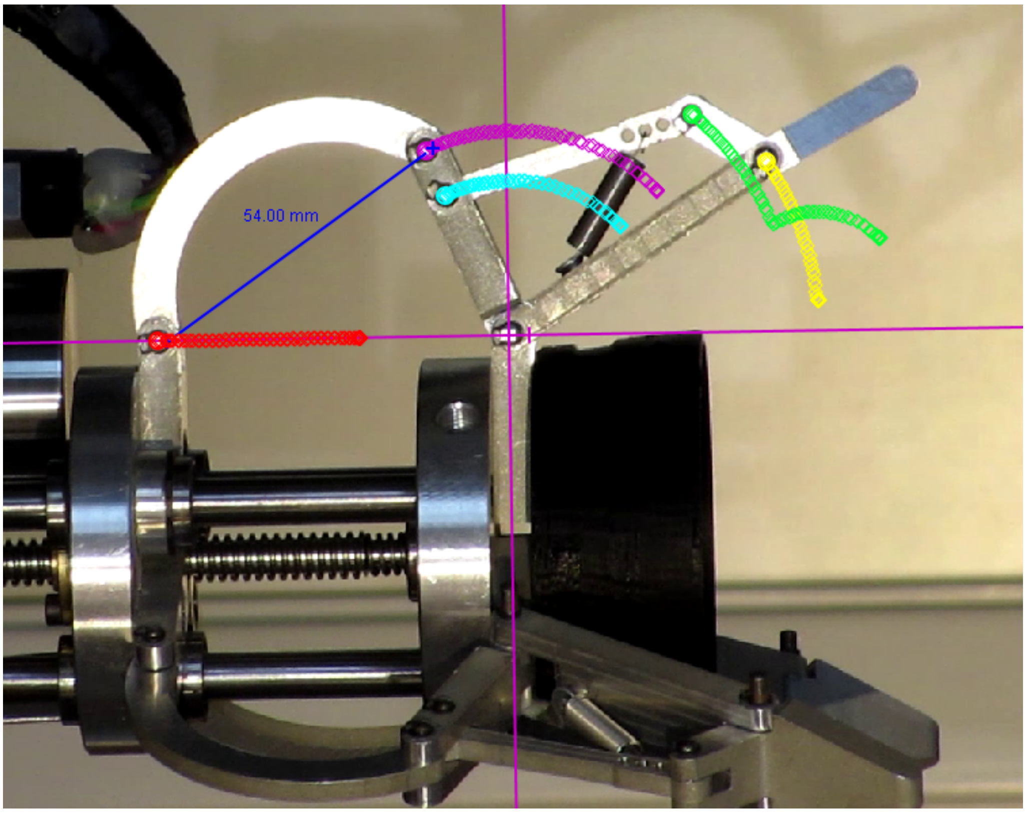


Figure 6.5: Tracked footage as seen in Tracker software

The system was given the movement seen on figure 6.6 as input. On top of the footage the trace of each joint's position can be seen for each frame as also seen on figure 6.5 and isolated on 6.7.

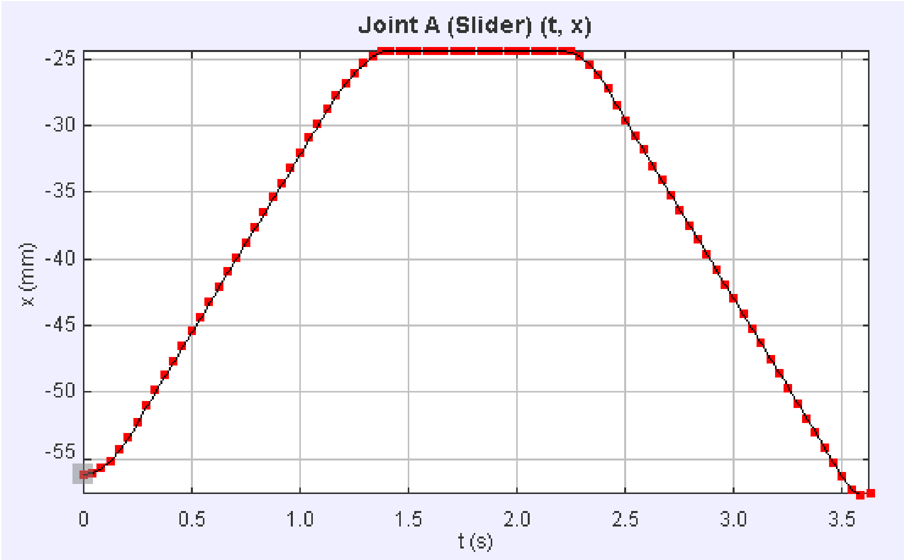


Figure 6.6: Input given to the slider (A).

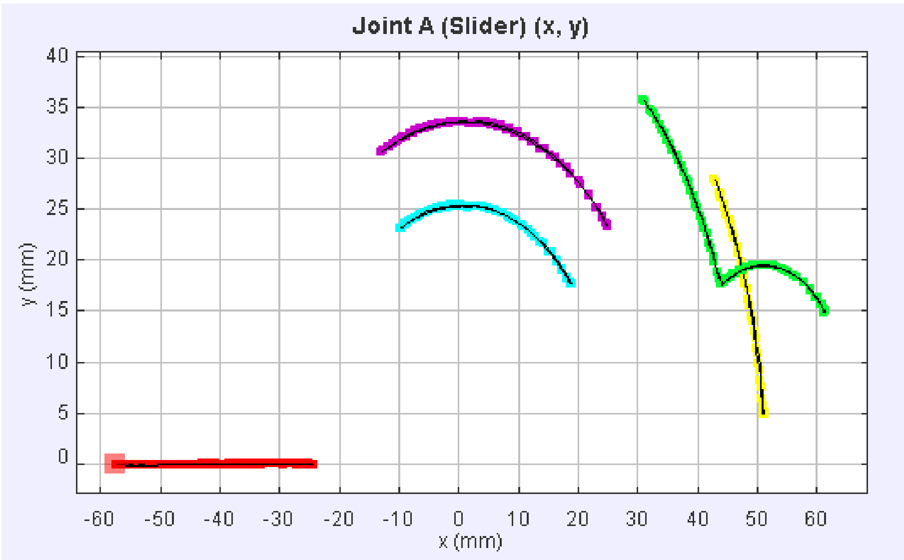


Figure 6.7: Plot of the joint's movements in x-y space. Legend: Red; A, Purple; B, Cyan; C, Yellow; D, Green; E,

The last thing to do to is to overlay these data with the output data from the simulation for a direct comparison, and repeat for all cases that wish to be tested for.

Conclusion 7

This report reviews the development and design process of the novel design and modeling of the gripper in this report. An upgrade has been made on the motor as well as implementing control on the gripper using a brushless motor and a new microcontroller, the implements of which is only an improvement to the potential performance from the system. Although complications were had, this was successful, however not well described in the report as focus was instead focused on executing and including some of the validation, as this was one of the main goals of this report. For validation, a method of testing the gripper is developed in order to validate the grippers performance using a video camera and reflective markers for post-process tracking. The video tracking was successful and using a known reference and realigning the coordinate system, it was possible to get results that may be directly compared to simulated outputs for true validation, however this was not achieved whithin the given time.

7.1 Future Works

It is directly significant and relevant to finish the validation and compare the results of these. Furthermore it could be of interest to look into a finger-design using compliant mechanisms to decrease the part count and the backlash of the fingers.

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