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Applied Mechanics - Functional Design

Prof. Ing. Massimo Maria Foglia

Title:

Transition from Parallel Gripper to Adaptive Gripper: Design and 3D Simulations

Students:
Francesco Di Chio
Nicola Saltarelli
Francesco Stasi

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Abstract

This study aims to conduct a comparative analysis between two types of grippers used in robotic manipulation: a 3-finger parallel gripper and a 3-finger adaptive gripper. The research will begin with a description of the development of the parallel gripper and will continue with the design of an adaptive phalanx that will convert the developed parallel gripper into an adaptive gripper. Additionally, the analysis will include a thorough evaluation of the performance of both devices, with particular emphasis on their manipulation capabilities.

Through a series of experimental tests, the performance of the two grippers will be examined in different operational contexts to provide a detailed analysis of their features and advantages. The objective is to provide an in-depth understanding of the performance differences between the two devices.

The 3D modeling will be carried out using SolidWorks software. This process will be documented in the report to ensure a clear understanding of the model development process and the methodologies employed.

Contents

Introduction

Human labour has always been associated with the acquisition of specific skills, methods, and tools making the work and its environment easier and more effective. Increasing competition from industrial robots for tasks normally carried out by human hands has led to the need for more effective handling equipment, especially prehension tools (more commonly called "grippers"). However, industrial robots are not simply a substitute for people. Their relevance is more often in applications beyond the normal ability (physical or temporal) of conventional manpower. Examples include dirty, hazardous and repetitive work. Just as human hands are the organs of human manipulation, so are robot grippers usually the only parts in direct contact with the workpiece.

Among the wide types of end-effectors, grippers are largely used thanks to their relative simplicity and efficiency in part-handling applications and grasping any physical object, according to the design of the gripper, that can be also manipulated by human hands.

These are the main reasons behind the project, focused on the complete design of two grippers. Starting from the parallel configuration, an adaptive gripper based on the parallel one will be implemented, showing the process of switching from one configuration to another and benefits.

The paper shows all the most important characteristics and steps done in order to develop the grippers.
After a brief introduction and the various classifications that can be made on the robotic grippers, the parallel gripper's design process will be presented, showing the base mechanism of the gripper, the fingers displacement and the degree of freedom analysis and the design of all parts of the gripper, realized using the SolidWorks software.
The report therefore focuses on the transition to adaptive configuration, showing the new custom parts developed and the main choices made regarding the DC motor and the linear springs to be used.
These choices are important because they have a very close consequence on the operation of the gripper and on the simulation and experimental results obtained in SolidWorks, on which the successive part of the report is focused.
The last part of the papers aims to analyse the results from the SolidWorks simulations, showing advantages and disadvantages of using the two different configurations in terms of applied forces variations, adaptability and forces distribution.

1 Robotic grippers

A robotic gripper is an essential component of a robotic manipulator. It serves as the robot's hand and allows the robot to manipulate objects. Recently robotic gripper is widely used for different tasks in various fields. Variety of robotic grippers is developed in high flexibility and multi-function. This project is aimed to study current existing robotic grippers, focusing on the distinction between adaptive grippers and parallel grippers, using a model with three fingers and two phalanges.

1.1 Classification

The wide range of shape, size and weight of objects to be manipulated in a production process led to designing of a various types of grippers, that has to be properly selected for a specific task. Therefore is important to distinguish and knowing the grippers types in order to do the correct choice when needed.

1.1.1 Configuration-based classification

According to their configuration, grippers can be distinguished in terms of:

- *number of fingers* : the base configuration of a gripper needs two fingers, sufficient to do the majority of production and manipulating tasks, such as assembly or pick and place. By incrementing the number of fingers one can achieve configurations with multiple fingers for more accuracy and precision in grasping sensitive and fragile objects.

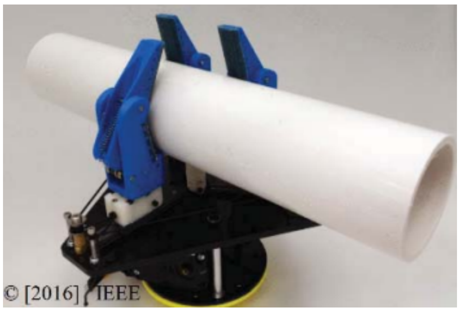

Figure 1: Adaptive three-fingered gripper.

- *shape of gripper* : grain-filled flexible ball grippers and bellow grippers works changing the shape of the end effector in real time changing the amount of air in the balloon that, in this case, rappresents the gripper. These grippers are also called "Air-Hand" grippers.

1.1.2 Actuation-based classification

From the actuation point of view, grippers can be divided in terms of:

- *Mechanical actuation* : mechanical fingers, that are integral part of the mechanism, are actuated by the main mechanism to grasp objects.
- *Cable-driven or sensory feedback actuation* : This type of gripper is equipped with a lot of sensors for control purposes. In this type of gripper the design of the robotic arm and the end effector has to be done in order to match with wiring requirements.
- *Vacuum grippers* : the high level of flexibility of this gripper, while providing a good grip of an object, is due to the use of a rubber or foam suction part to hold the object.

Figure 2: Mechanical gripper.

- *Hydraulic actuation* : using hydraulic pumps one can produce more grasping force compared to other actuations. The disadvantage of hydraulic grippers is that they need constant maintenance.
- *Pneumatic actuation* : the fingers movement and displacement is made by changing the air pressure in the valve. Small dimensions and low weight are key factors to pay attention to when this type of gripper is used.
- *Servo-electric actuation* : Using servo-motors used to control the fingers ensures high flexibility and low maintenance costs.
- *Magnetic actuation* : Making use of the principles of magnetism, these are used for holding ferrous objects.

1.1.3 Stiffness-based classification

This important classification in based on the material's stiffness. In particular the main division is relative to:

- *Rigid grippers* : these are the traditional ones and they are largely used in industrial applications, in which high precision and less flexibility of fingers is required.
- *Soft grippers* : the fingers are made by flexible material, allowing to grasp object with very different shapes. These types of grippers and robots are currently important areas of interest for scientists and engineers, especially for medical applications. Grain-filled flexible ball grippers and bellow grippers belongs to soft robots, such as the universal grippers.

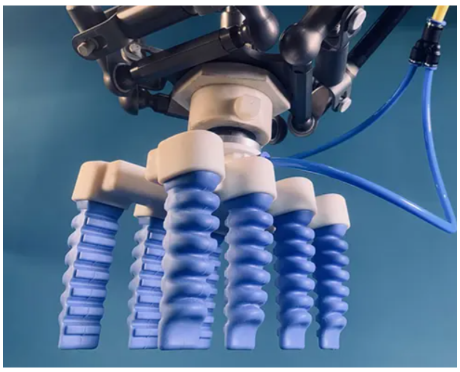

Figure 3: Soft gripper.

1.1.4 Application-based classification

Grippers are not only used in industrial applications, but they also works in:

- *Surgical application* : especially for Minimally Invasive Surgery (MIS), small grippers and soft grippers are the main choice.
- *Assistive application* : there are a lot of grippers designed for people with disabilities or, for example, mounted on Unmanned Aerial Vehicle (UAV).
- *Research application* : a big area of interest is also linked to underwater or underground researches.

1.2 Case study

As previously mentioned, the primary objective of this study is to conduct a comparison between parallel and adaptive grippers. Therefore, this subsection will outline the main differences between these two types of devices to facilitate understanding of the results obtained from this research.

1.2.1 Parallel grippers

Due to their simplicity of control and relatively low cost, parallel grippers have been widely utilized as end-effectors in industrial robotic systems. Particularly, parallel grippers with fingers moving along a single linear trajectory are notably easy to use. This is because the position of both fingers relative to the linear trajectory remains consistent and constant throughout. This feature greatly simplifies the control process and ensures precise repeatability of operations.

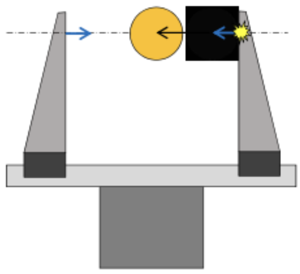

Figure 4: Gripper with linear guide mechanism (Kobayashi et al., 2019).

The collision free space of the motion of the robot which the gripper is attached to depends on the dimensions of the gripper. When grasping objects with different dimensions is performed using a single gripper, the width of the gripper is determined by the largest dimension of the objects; on the other hand, a gripper with large width is undesirable from the collision free space of the robot motion point of view. Because of this issue, the parallel grippers have been usually utilized for tasks to handle the same or a similar dimensions of objects, not for tasks to handle of objects with different dimensions. Grasping of the same or a similar dimensions of objects can be realized by a compact gripper with a compact linear guide mechanism having short stroke.
(Kobayashi et al., 2019) [4] addresses the issue of parallel grippers using the linear guide mechanism and proposes a new parallel open-close gripper.
The width of the proposed gripper depends on the fingers opening width, that is, the gripper becomes small when it grasps a small object and becomes large when it grasps a large object. The proposed gripper can be applied to tasks handling objects with different dimensions without restricting the collision free motion space.

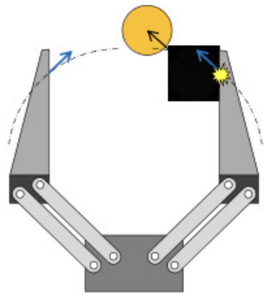

Figure 5: Gripper with parallel four bar mechanism (Kobayashi et al., 2019).

With this mechanism, the gripper can open and close fingers with keeping their orientations constant. Normally, the grasping flat surfaces of fingers are parallel to each other. The width of the gripper with four bar parallel linkage can be designed smaller than its finger stroke.

1.2.2 Adaptive grippers

An adaptive mechanical system is one in which some form of intelligence is embedded into the mechanics. In such a system, no sensors or complex controllers are required to perform the main task since the mechanical system itself will provide the required adaptive behavior.
In many robotic applications, the manipulation of objects with very complex mechanical hands is not essential and grasping devices are sufficient. However, simple grippers are not appropriate in most cases because they are not capable of adapting to the shape of different objects.
Hence, the development of versatile robotic hands which are capable of grasping a wide variety of objects with a very simple control structure is of great interest for many applications.
It is clear that robot hands based on the latter principle are adaptive mechanical systems since they can adapt to the shape of the objects simply by the mechanical action of their components. Since this behaviour implies that motion takes place without control actions, underactuation must be introduced.
An underactuated mechanism is one which has fewer actuators than degrees of freedom (dof)s. When applied to mechanical fingers, the concept of underactuation leads to mechanical adaptiveness. Mechanically adaptive fingers envelope the objects to be grasped and automatically adapt to their shape with a limited number of actuators usually one and without complex control strategies. The implementation methods of underactuated mechanisms are generally classified into three types: using tendon [6], linkage mechanism [7], and mechanical elements such as gears [8].Most of the research of the underactuated mechanism is focusing on reducing the control complexity of multi fingered robot hands.

2 Parallel gripper design

The proposed gripper consists, as shown in the Figure 6, of three identical fingers equally spaced along a circumference, dividing it into three equal parts. The fingers displacement is realized thanks to a quite simple mechanism driven by a single actuator : a small DC motor, having its own screw shaft, moves in a linear way the gripper's palm connected to it and, thanks to a rods system, this displacement generates the opening and closing fingers' movement.

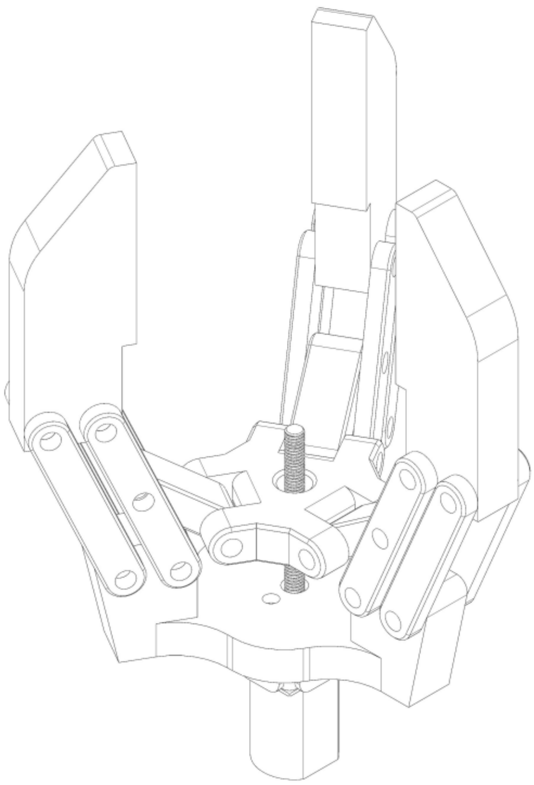

Figure 6: Model of the three fingers parallel gripper

The proposed solution is especially suitable for the grip of spherical or cylindrical objects, on which the grip is firm and the pressure applied is uniform thanks to the three contact points.
The main advantages that characterize the gripper are in terms of efficiency, ease of implementation and costs thanks to the reduced number of parts.

2.1 Degree of freedom analysis

Focusing on a single finger, one can demonstrate that the mechanism allowing the movement is characterized by one degree of freedom. This is an important feature, because it allows a fairly simple study of the kinematic behavior of the entire gripper.

In order to demonstrate this, the *Grübler's formula* can be used, which states the number of degrees of freedom of a mechanism can be calculated in the following way:

$$dof = m(N - 1 - J) + \sum_{i=1}^{J} f_i \tag{1}$$

where:

- dof : degrees of freedom of the mechanism;
- m : equal to 6 for spatial bodies, 3 for planar;
- N : number of bodies, including ground;
- J : number of joints;
- f : degrees of freedom of each joint.

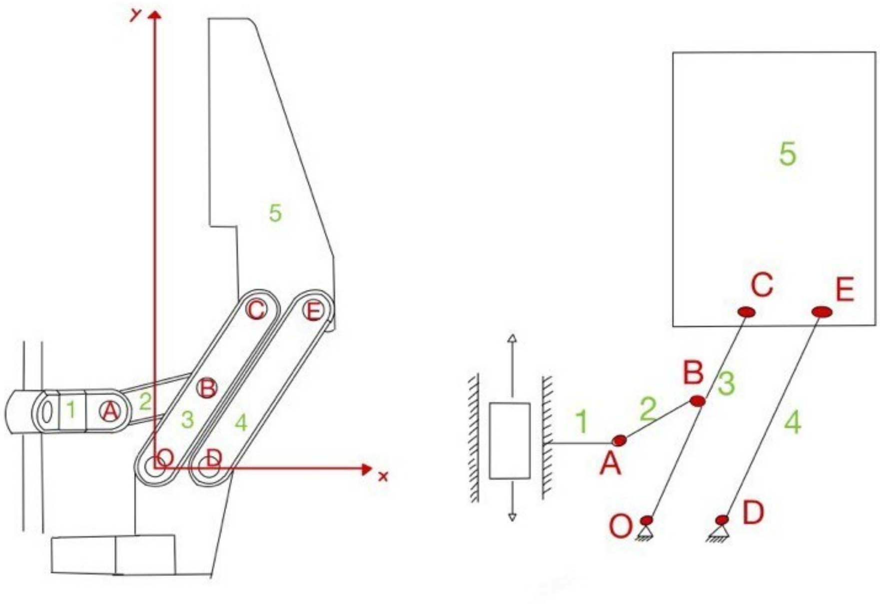

Figure 7: Constraints analysis

According to the Figure 7, one can see that every finger mechanism is characterized by five bodies (six with the ground), six revolute joints (A,B,C,D,E,O) and one prismatic joint to which the body 1 is subject. In addition, the movement of each finger can be seen as a planar motion.
For this reasons one can stated that m is equal to 3, N is equal 6, J is equal to 7 and the and the sum value is equal to 7 because for every joint there is one degree of freedom.
Applying this values to the Grübler formula one can have:

$$dof = m(N - 1 - J) + \sum_{i=1}^{J} f_i = 3(6 - 1 - 7) + 7 = 1 \tag{2}$$

2.2 Finger displacement analysis

The chosen approach for studying the kinematic behavior of the finger mechanism makes use of the complex numbers in order to generate the so called *closing equation* in 2D. Following this method, the mechanism is outlined through vectors expressed as complex numbers, so in terms of magnitude and phase. Using the Euler formula, a non linear system of equations can be obtained and its resolution allows to have a general understanding of the possible displacement of the mechanism.

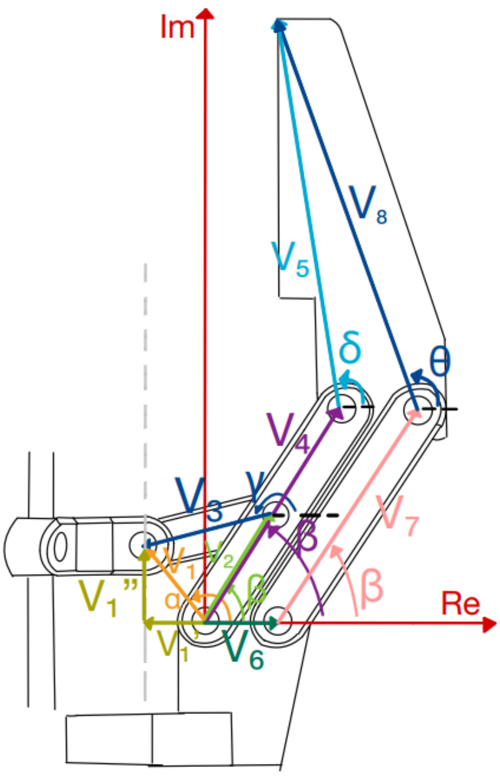

Figure 8: : Closed kinematic chains

In order to study the mechanism two closing equations have been developed.
The first one states that:

$$\overline{V_1} - \overline{V_2} - \overline{V_3} = 0 \tag{3}$$

Expressing the vector $\overline{V_1}$ as sum of $\overline{V_1'}$ and $\overline{V_1''}$ the final closing equation is:

$$\overline{V_1'} + \overline{V_1''} - \overline{V_2} - \overline{V_3} = 0 \tag{4}$$

Expressing the equation (4) in terms of amplitude and phase one can obtain :

$$V_1' e^{-j\pi} + V_1'' e^{j\frac{\pi}{2}} - V_2 e^{j\beta} - V_3 e^{j\gamma} = 0 \tag{5}$$

Using the Euler formula $e^{jx} = cos(x) + jsin(x)$, one can divide the closing equation into two equations, one for the real part and one for the imaginary one. In this way one can obtain a non linear system of two equations in two unknowns, that in this case are the angles β and γ.

The feasible range of variation of $V_1^{''}$ was experimentally deducted from SOLIDWORKS. The range of variation used in Matlab for the non linear system resolution is therefore:

$$V_1^{''} = [-1.79 : 11.2] \tag{6}$$

expressed in mm and referred to the origin.

The same method was used also for the second closing equation :

$$\overline{V_4} + \overline{V_5} - \overline{V_6} - \overline{V_7} - \overline{V_8} = 0 \tag{7}$$

Expressing the equation (7) in terms of amplitude and phase one can obtain:

$$V_4 e^{j\beta} + V_5 e^{j\delta} = V_6 e^{j0} + V_7 e^{j\beta} + V_8 e^{j\theta} \tag{8}$$

After simplifications and using the Euler formula you obtain another non linear system of two equations.

The obtained results are shown in the following figures :

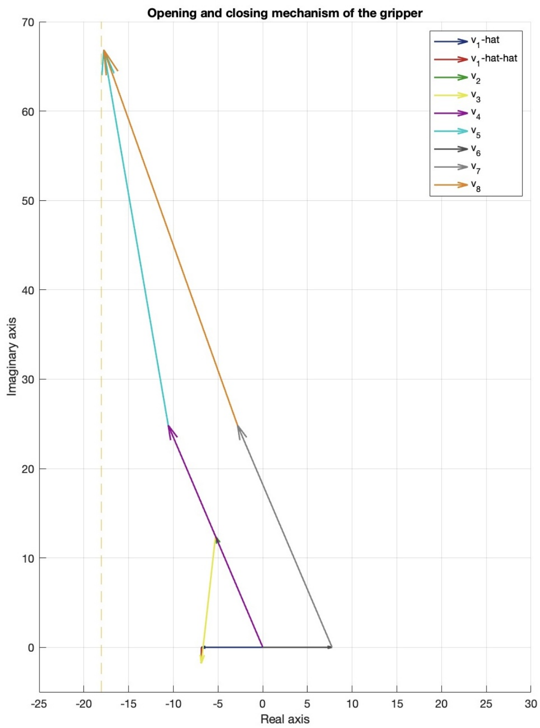

Figure 9: Initial position of the mechanism

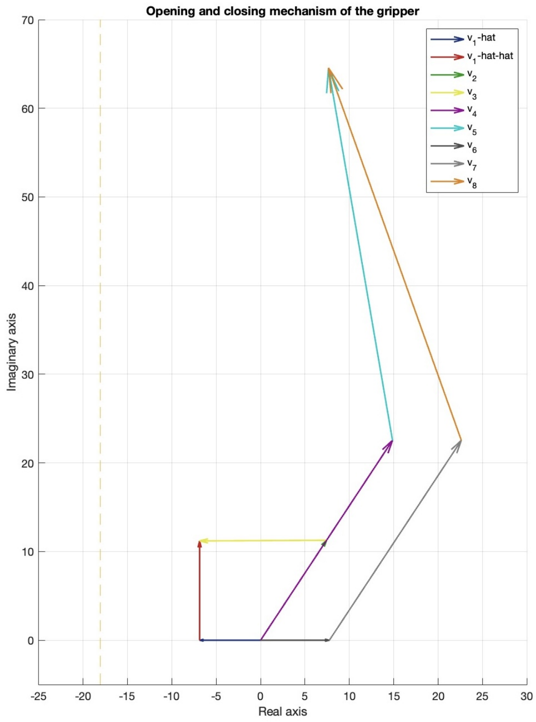

Figure 10: Final position of the mechanism

2.3 SolidWorks 3D model

The 3D model of the designed gripper was developed using SolidWorks, a very powerful software useful also for the contact forces analysis.
The design process started with the creation of fully customized individual parts which were later assembled thought concentricity and coincidence constraints, thus generating the final model.

2.3.1 Base part design

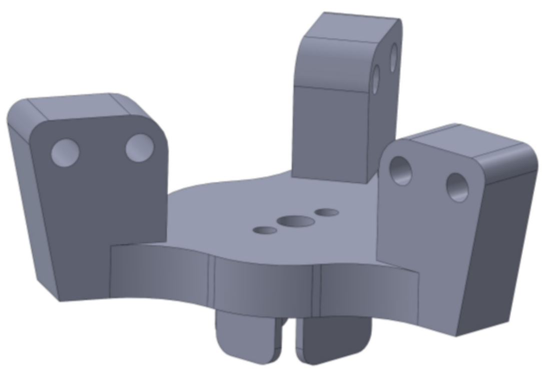

Figure 11: Base part design

The base is mainly composed of a flat main extrusion and three external along the circumference on which there are holes for the connecting rods between the base and the finger. The base is also provided by a central holes and an adapter in the lower part to accommodate the motor and the shaft.

2.3.2 DC motor enclosure

The chosen actuator is the *12 GA Miniature DC Gear Motor Screw Shaft*. The developed casing ensures a good protection against external agents, increasing the reliability of the gripper.

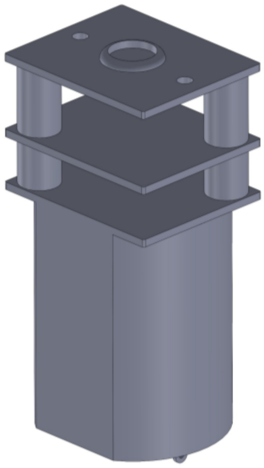

Figure 12: DC motor enclosure

2.3.3 Threaded shaft design

Figure 13: Threaded shaft

The opening and closing fingers movement is possible thanks to a threaded shaft, to which the palm of the gripper is attached, moved by the DC motor. The construction parameters of the shaft are height (32 mm) and pitch (0.5 mm).

2.3.4 Palm design

The central element of the gripper mechanism is the fully customized palm. The central hole accommodate the DC motor shaft, while the six external holes generate the revolute joints connecting the palm with the rods.
The design of the palm required much attention in order to have a contact-free slide between the palm and all other parts of the gripper, especially with the base.

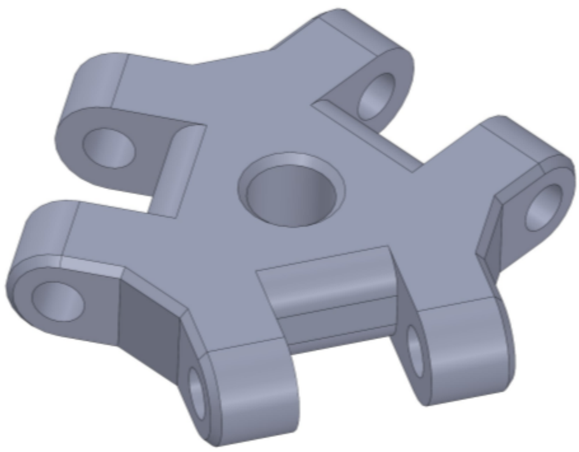

Figure 14: Gripper palm

2.3.5 Connection rods

Three types of rods are used in order to realize the opening and closing finger movement.

The first type of rods makes possible the connection between the base and the finger. In particular, these rods have two holes : one creates the revolute joint with the external hole of the external extrusion of the base, while the second hole generates the external revolute joint on the finger.

The second type of rods is characterized by the same dimensions of the first type rods, but with an additional central hole. The two external holes have the same function of the first type rods ones, while the central one makes the connection with the third type rods.

The third type rods are are shorter and thicker with respect to the other types rods. These rods create a connection between the palm and the central hole's second type rods.

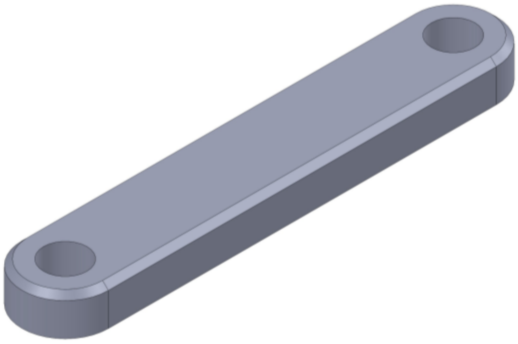

Figure 15: First type rod

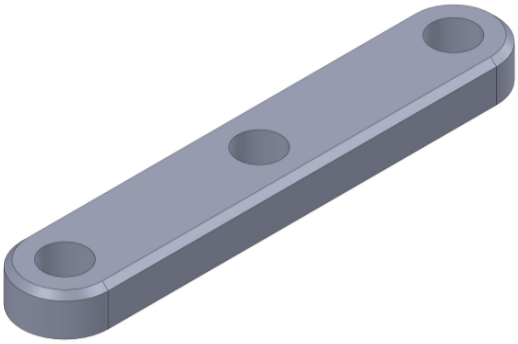

Figure 16: Second type rod

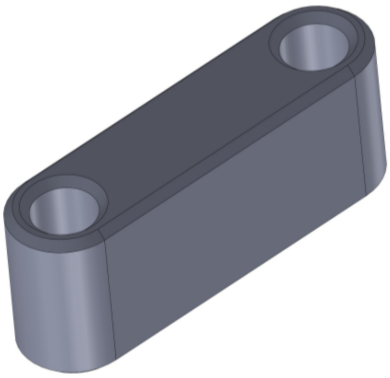

Figure 17: Third type rod

2.3.6 Finger design

The finger is quite simple single part, obtained with a simple extrusion. You can notice that that flat internal part make contact with the object to be grasped. The flat design allows to grasp spherical object with different size a very solid way.
The holes realize the revolute joint with the first and second type rods.

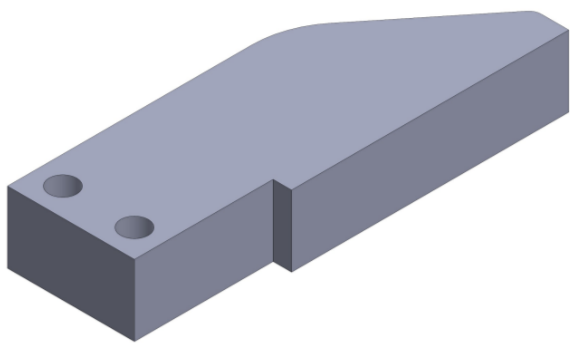

Figure 18: Gripper finger

3 Adaptive finger design

To enable the transition from a parallel gripper to an adaptive one, a specific modification was made to the non-adaptive phalanx, avoiding alterations to the entire model. This strategy allowed us to obtain an adaptive gripper simply by modifying the final phalanx of the parallel gripper, while keeping the palm and the opening and closing mechanism unchanged. This approach was chosen with the objective of comparing the two models, as described in the project abstract.

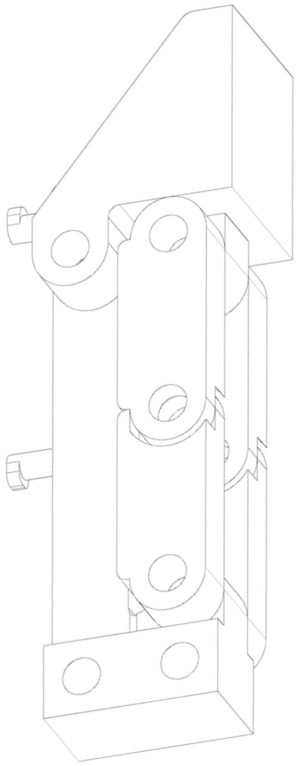

Figure 19: Adaptive finger's sketch

For simplicity, in this section we will focus exclusively on describing the adaptive phalanx model of the gripper, as it would be redundant to describe again the base and palm of the gripper. Thanks to this adaptive phalanx, it is now possible to grasp objects by adapting the phalanx to the shape of the object. All of this is made possible through the use of springs.

When the phalanx comes into contact with an object, the four front segments, as depicted in Figure 19, move and conform to the surface of the object, enabling a secure and flexible grip. The springs assist in restoring the phalanx to its original position once the object is released, ensuring that the phalanx always returns to its initial configuration, ready for the next gripping operation.

Utilizing an adaptive phalanx offers numerous advantages:

- Greater Flexibility: The ability to adapt to various shapes and sizes of objects makes the gripper highly versatile.
- Secure Grip: Automatic adaptation to the object's surface enhances grip stability and security, reducing the risk of slippage.

- Simplicity of Design: Using springs for restoring the original position is a simple and effective solution that does not require complex control systems or additional actuators.

These advantages make the adaptive gripper an efficient and versatile solution, significantly enhancing the capabilities for grasping and manipulating objects.

3.1 Degree of freedom analysis

In this subsection, the degrees of freedom of the adaptive phalanx will be determined, following the method previously used to analyze the opening and closing mechanism of the parallel gripper. This calculation quantifies the number and nature of independent movements that the adaptive phalanx can perform.

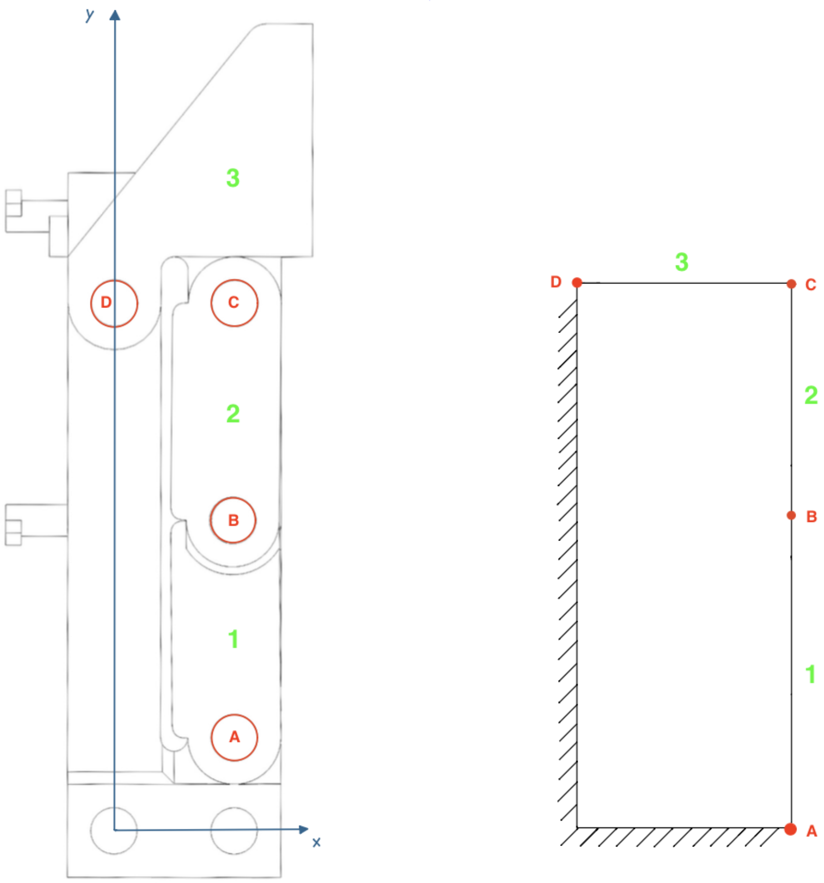

Figure 20: adaptive finger's dof analysis

In Figure 20, on the left, a technical side view of the adaptive phalanx is shown, while on the right, a simplified schematic representation facilitates the calculation of its degrees of freedom. The phalanx is equipped with 4 revolute joints and consists of 3 bodies. Therefore, the degrees of freedom of the phalanx are:

$$dof = m(N-1-J) + \sum_{i=1}^{J} f_i = 3(4-1-4) + 4 = 1 \tag{9}$$

3.2 SolidWorks 3D model

3.2.1 Fixed part of the adaptive finger

The fixed part of the adaptive finger in Figure 21 is designed in an L-shape. This part connects the tip of the finger with the bars, which in turn are connected with the base and palm of the end-effector.
The part is designed not to collide with the movable phalanges during closing and opening. A spring attachment is also added, as well as a slide rail (a channel that only allows elongation and compression while preventing it from moving laterally).

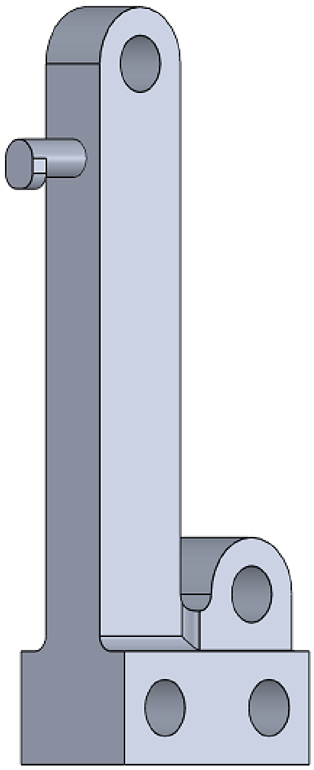

Figure 21: fixed finger part

3.2.2 Mobile phalanges

Phalanges are composed of the same repeated part so that assembly is less complex. In particular, they are made similarly to the connection bars of the static model, but with some tricks to maintain a reduced thickness by modifying the connection between upper and lower phalanges.
In addition, a knocker necessary to prevent reverse rotation of the bars is added. This knocker implies a rotation limitation between the constraints during simulation.
Figure 22 shows the connection between upper and lower phalanges, made with the same repeated part.

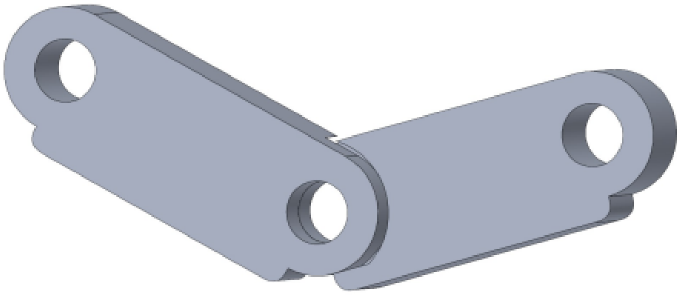

Figure 22: mobile phalanges parts

3.2.3 End part of the finger

The terminal part of the adaptive finger (figure 23) must connect the fixed part with the movable phalanges. Care is taken to avoid creating intersections during movement. The profile is made from the static model of the end-effector. The second hook of the spring is then inserted.

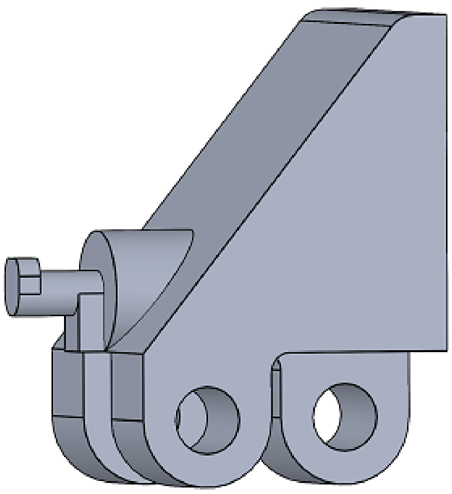

Figure 23: terminal finger part

3.2.4 Parts assembly

The finger, which will be directly substituted for the three fingers of the static model, is thus assembled; the spring brings the end-effector to the rest configuration.
Figure 24 shows the finger assembly with a bending test and the addition of the spring for a dynamic study test, while a complete assembly of the new adaptive end-effector can be seen in figure 25.

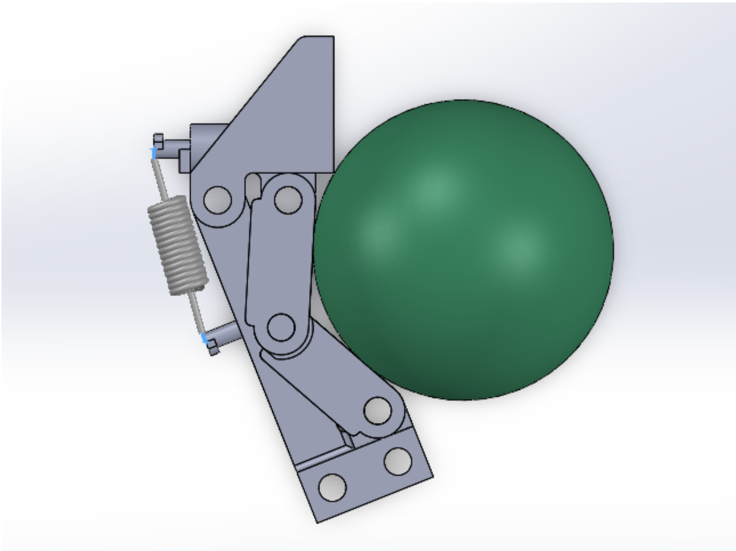

Figure 24: finger assembly

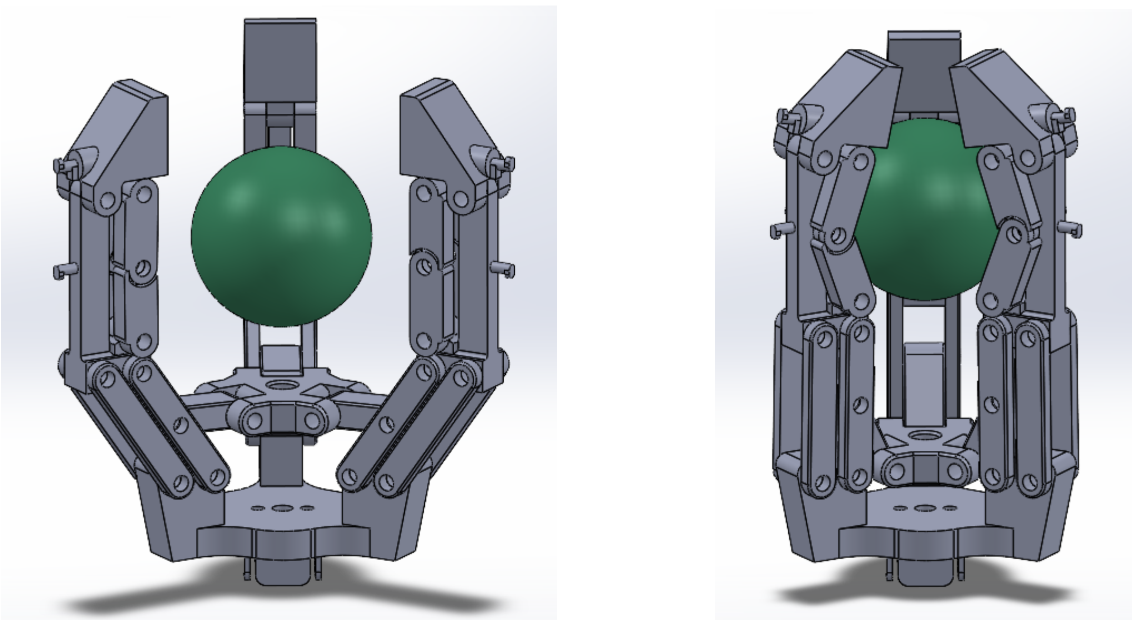

Figure 25: Complete assembly

4 Experimental Results

In this section of the documentation, the results of simulations conducted using Solidworks Motion will be presented. The tests were performed to compare the contact force generated by a gripper in both parallel and adaptive gripper configurations.

The object used for the gripping tests is an aluminum sphere 3.0205 (EN-AW 1200) with a variable diameter. Three spheres of different diameters were employed to analyze how the contact force varies with changes in the diameter and mass of the sphere. Aluminum was selected as the material for the sphere due to its mechanical properties, such as lightness and strength, which make it ideal for simulations aimed at obtaining an accurate and representative response under the given load conditions.
It should be noted that the images presented in this section depict the gripper in a simplified version, excluding the motor and threaded rod necessary for the opening and closing mechanism. In the simulation, the motor's function, opening and closing the fingers, was replaced by a constant force of 55 N applied to the palm of the gripper, enabling the closing and gripping of the object.

4.1 Gripping force calculation

This subsection will demonstrate how to calculate the minimum gripping force required to grasp an object, given the coefficient of friction between the object and the rubber applied to the gripper's phalanges, as well as the mass of the object itself. The use of rubber pads on the phalanges is particularly beneficial as it enhancing the grip and reducing the risk of the object slipping.

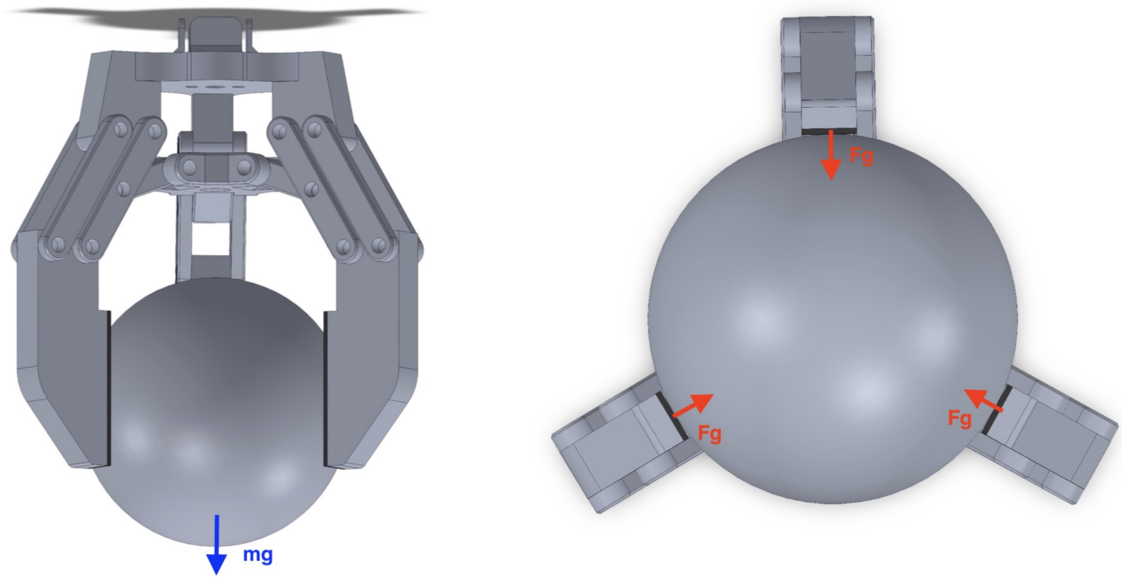

Figure 26: Parallel gripper in contact with a large sphere.

As shown in Figure 26, the left side displays a front view of the parallel gripper while grasping a sphere, which is the object used for the simulation. On the right side, a bottom view is provided, where the directions of the gripping forces necessary to hold the sphere in place are indicated. Therefore, the gripping force required to grasp the object on each phalange is:

$$F_g = \frac{mg}{\mu N} * S \tag{10}$$

where F_g is the gripping force to be applied to each phalange, m is the weight of the object to be grasped, g is the gravitational constant, μ is the coefficient of friction between the materials in contact, N is the number of gripper fingers and S is a safety factor, typically set to 2.

4.2 Choice of linear spring

As shown in Figure 24, each finger of the adaptive configuration requires a linear spring that allows the finger to adapt correctly to the object to be grasped, also ensuring the return to the vertical position of the finger when the palm of the gripper is fully raised.
For these reasons the choice of the spring to be used is extremely important, having important consequences for the behaviour and functionality of the gripper.

The chosen spring is a cheaper one, easily available and purchasable on the web, shown in the Figure 27 :

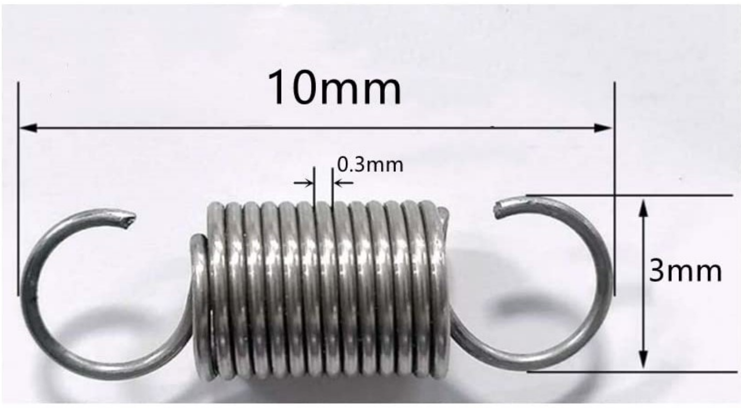

Figure 27: Linear spring's parameters

In order to carry out the simulations on Solidworks Motion, the elastic constant and the free length of the spring have to be known.
The free length can be derived from the Figure 27 (10 mm), while the elastic constant is not provided, so is necessary to calculate it.
In order to do it, the following equation [9] can be used :

$$k = \frac{Gd^4}{8nD^3} \tag{11}$$

where :

- G is the spring material stiffness module ;
- d is diameter of the spring wire ;
- n is the number of active coils ;
- D is the average diameter of the spring.

By taking these parameters from Figure 27 and setting G = 79 GPa, a typical G-value for steel, you obtain, using the Formula 11, that the elastic constant of the spring is equal to 2.9 N/mm.

This result is acceptable and shows that the spring has a good elasticity. As consequence of this, the finger is characterized by a good adaptability to the objects to be grasped, regardless from the

object size. In addition, if the spring constant is too high, the finger will not be able to bend, thus losing its adaptive behaviour.
Summing up, the great adaptability that can be achieved and the availability of the spring makes make this choice in line with the project's objectives.

4.3 Choice of electric DC motor

The choice of motor is crucial since it determines the maximum gripping force applicable by the endeffector and also the closing and opening speed. Among the various types, the DC motor is chosen, which, having a linear torque characteristic, makes it easy to deduce the force that can be obtained from the feed-forward construction parameters, as shown below:

$$T = K \cdot \phi \cdot I_a \tag{12}$$

The obtained torque T thus depends only on a constant K given by the construction parameters, magnetic flux ϕ and armature current I_a.

Figure 28: motor with gearbox

This DC motor must also respect the small size of the system while maintaining a torque capable of making the system functional, even introducing a gearbox to have the right compromise between torque and speed obtained. It is also necessary to transform the rotary motion of our motor into a linear motion suitable for the movement of the palm in our endeffector.
We therefore choose the type of motor shown in Figure 12 that meets the following characteristics, where the M3 threaded rod ensures linear motion.

Then we go on to choose the gearbox to calculate the force of our motor on the palm. Looking at the datasheets of these motors gives indicative tables.
We choose a supply voltage of 6V, with a gearbox that allows a torque at rated load of $4,903 \cdot 10^{-3} Nm$ and a speed of $100,531 rad/s$.
Considering these data, the force transmitted to the palm through the threaded rod can be calculated by the following formula [10]:

$$F = \frac{2 \cdot \pi \cdot T \cdot \eta}{P} \approx \frac{2 \cdot \pi \cdot 4,90 \cdot 10^{-3} \cdot 0.9}{0.5 \cdot 10^{-3}} \approx 55N \tag{13}$$

where :

- F is the resultant force placed on the palm of the endeffector ;
- T is the torque produced by the motor ;
- η is the efficiency set to 0.9 ;
- P is the pitch of the threaded rod equal to 0.5mm for a diameter of 3mm.

In this formula we take into account an efficiency set by us and neglect the friction produced in the movement, however, the value obtained is only indicative of a force that can be used in the simulation phase, this value in fact will always be modifiable by going to check the power parameters of the motor.
To calculate the linear velocity of the palm displacement we can use the following formula where ω is the angular velocity and p is the pitch of the threaded rod. Knowing that the excursion made by the part we can calculate the time taken for the complete opening and closing of the endeffector.

$$v = \omega \cdot p \approx 50 \cdot 10^{-3} mm/s \tag{14}$$

4.4 Simulations with Large Sphere

In this subsection, the results obtained from the simulation of the parallel and adaptive gripper interacting with a sphere of $26mm$ radius and approximately 200 g mass will be presented.

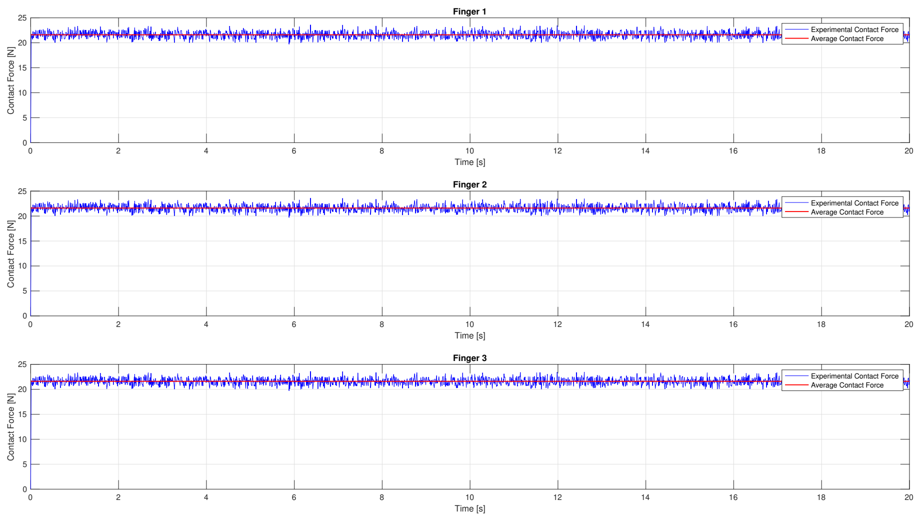

Figure 29: Contact force between the phalanges of the parallel gripper and the sphere.

Figure 29 illustrates the variation in contact force between the phalanges of the parallel gripper and the sphere. It can be observed that the contact force is approximately 22 N, which is higher than the gripping force required to hold the object. Specifically, an aluminum sphere 3.0205 (EN-AW 1200) with a radius of 26 mm has a weight of about 200 g. Given that the static friction coefficient between rubber and aluminum is 0.25, applying Formula 10 yields a gripping force of approximately 5.5 N.

Figure 30 shows the trend of the contact force between the phalanges of the adaptive gripper and the sphere. The graphs highlight that two phalanges per finger come into contact with the sphere. The 'lower phalanx' refers to the phalanx closest to the palm, while the 'upper phalanx' is the one situated between the lower phalanx and the outermost phalanx, which is the third and final phalanx of the adaptive finger. It can be observed that once the gripper grasps the object, the contact force is approximately 3.5 N for the lower phalanx and 5.5 N for the upper phalanx.

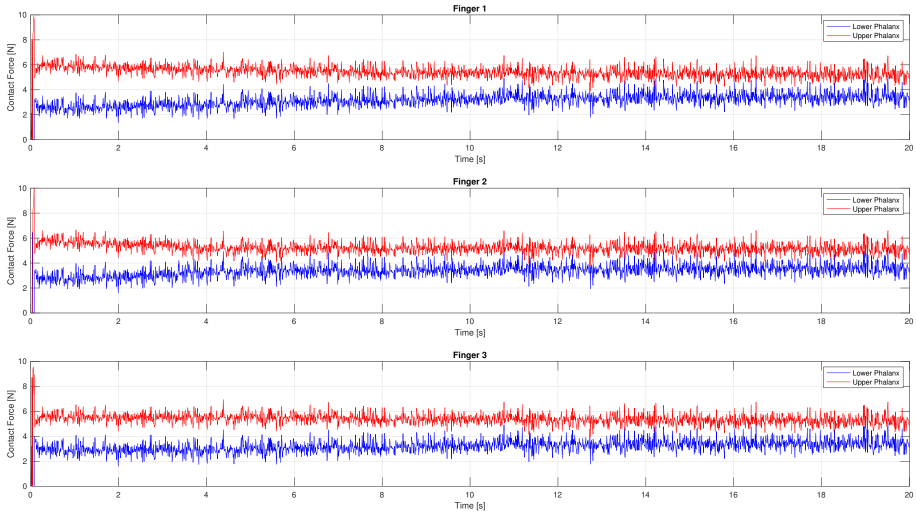

Figure 30: Contact force between the phalanges of the adaptive gripper and the sphere.

4.5 Simulations with Medium Sphere

By reducing the size of the sphere to a $22mm$ radius, we obtain a body with an approximately $120g$ mass, and we can repeat the previous simulations for the parallel endeffector and the adaptive one.

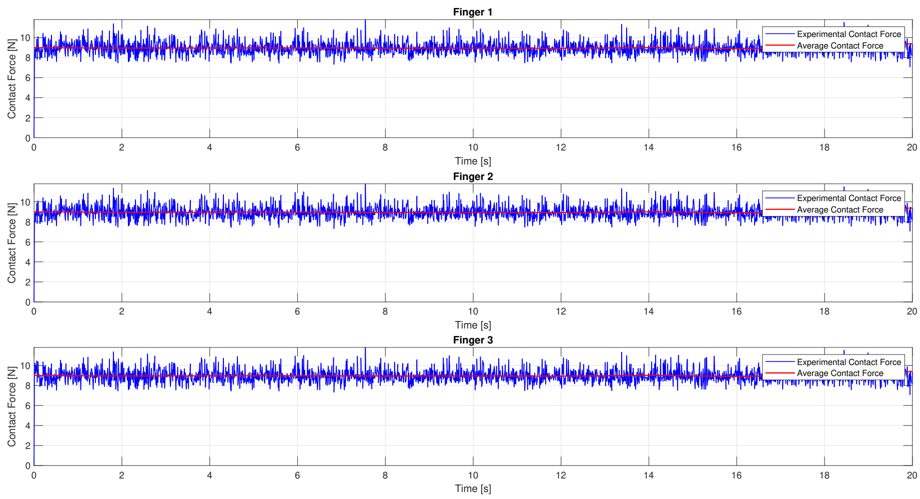

Figure 31: Contact force between the phalanges of the parallel gripper and the sphere.

Figure 31 shows the simulation results for the parallel endeffector. It can be seen that decreasing the radius also decreases the contact force between phalanx and sphere, specifically the resulting average contact force is about 9 N.
Considering the mass obtained from Solidworks evaluation, and considering Formula 10, we get a gripping force of about $3.15N$. So the force exerted is sufficient to grip the chosen object.

Figure 32 shows the contact forces between the upper and lower phalanges with the ball for each of the three fingers. We note that after a transient due to the initial conditions of endeffector position, which allow repositioning of the sphere, steady-state contact forces are achieved.
These forces average less than in the previous case. In particular, a force of about $4N$ is obtained for the upper phalanx, and slightly more than $2N$ for the lower phalanx. This difference is due to the consideration of the force of gravity in the simulation, which, by pushing the ball toward the upper phalanges, increases its contact forces.

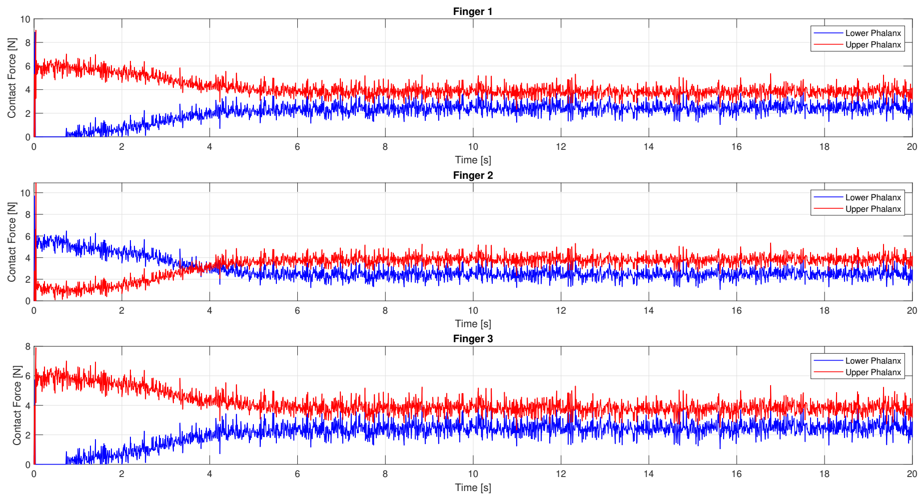

Figure 32: Contact force between the phalanges of the parallel gripper and the sphere.

4.6 Simulations with Small Sphere

In order to have a general understanding of the gripper behaviour, simulations with a sphere of $18mm$ and approximately 60 g have been done, both in parallel and adaptive gripper configuration.

Figure 33 shows the contact force generated between the fingers and the small sphere in case of parallel gripper. It can be observed that the contact force for each finger-sphere contact oscillates around an average value of about 6 N. In particular, the little spikes around the average value are due to the simulation parameters settings in Solidworks.
This result is acceptable according to the Formula 10 which states that, for this specific small sphere aluminium object, the minimum gripping force required is approximately 1.6 N

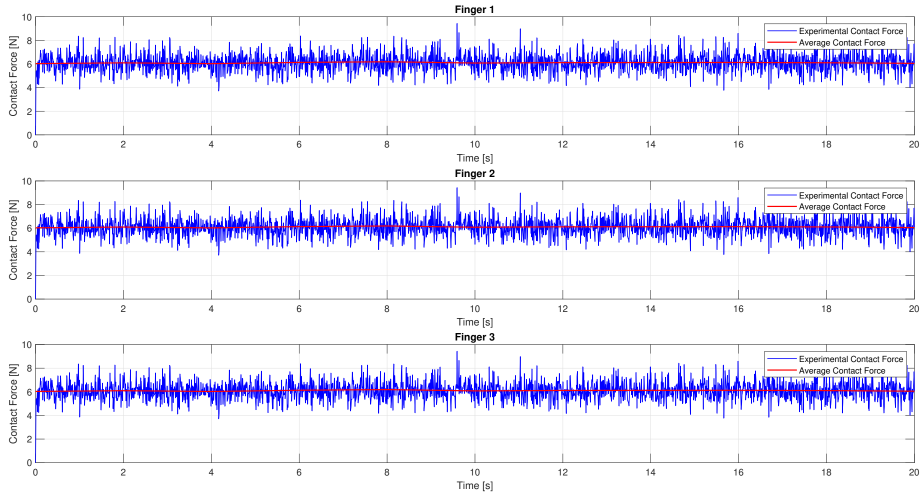

Figure 33: Contact force between the phalanges of the parallel gripper and the small sphere.

Figure 34 shows the trend of the contact forces generated for the fingers-small sphere contact. It should be noted two phases : in the firsts four seconds there is a fingers settling phase which lead the fingers to adapt correctly to the sphere, while in the successive seconds the situation is stable, indicating that the gripper has correctly grasped the ball.
It can observed, focusing on the second phase, that the average contact force is approximately 3 N for upper phalanx and 2 N for the lower one.

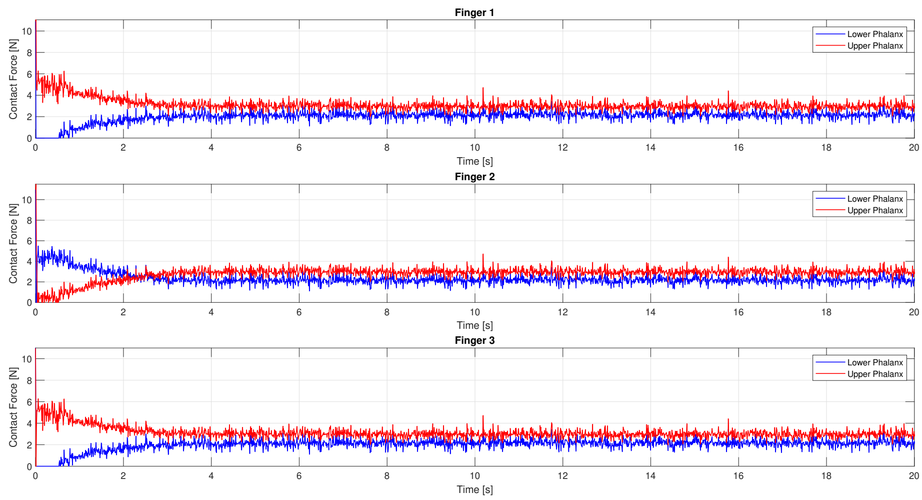

Figure 34: Contact force between the phalanges of the adaptive gripper and the small sphere.

4.7 General Conclusions on Contact Force Analysis

Analyzing the contact force charts you may notice some recurring elements both focusing on the graphs relating to the same sphere and by seeing the whole.

From the comparison of the two graphs generated for the same sphere, it can be observed that in the parallel gripper each finger makes contact with the object at a single point, while in the adaptive gripper contact occurs at two distinct points. This characteristic of the adaptive gripper can be considered advantageous, as distributing the contact over multiple points allows for a more uniform and adaptable grip on objects with irregular shapes and surfaces, reducing the risk of damage.

Moreover, it is evident that the contact force between the sphere and the phalanges is, adding all the components, greater in the parallel gripper compared to the adaptive one. This can be explained by the fact that the parallel gripper exerts a concentrated pressure on a single contact point, which can result in a more intense and robust grip. However, this concentration of force may also increase the risk of damaging the object, especially if it is delicate or has an irregular surface. In contrast, the adaptive gripper, with its force distributed over two contact points, tends to apply a more uniform pressure, reducing the risk of damage and improving handling of objects with complex geometries or sensitive surfaces.

In addition, you can notice a general decreasing of the contact force, both in parallel and adaptive gripper configuration, as the size of the sphere decreases. This could be explained, focusing on the parallel gripper configuration and referring to the Figure 7, by the increasing of the linear distance between the point A and the contact point between the finger and the sphere as the dimension of the sphere increases.
In fact, the smaller the sphere is, the closer to the palm will be to the base, increasing that linear distance. Using the principle of levers or moments balance it can be easily seen that the contact force is inversely proportional to the distance between the point A and the contact point, thus confirming the results obtained from the simulations.

Conclusion

In this study, we conducted a comparative analysis of the performance between a parallel gripper and an adaptive gripper to evaluate their effectiveness in object manipulation. Using SolidWorks, we modeled and simulated both grippers based on an analysis of degrees of freedom and a study of displacements through closure equations. The simulations revealed significant differences between the two configurations.

In summary, parallel grippers offer advantages such as a higher concentrated gripping force, simplified design which reduces production costs, and ease of control and precision due to predictable movement, which minimizes complexity compared to adaptive grippers. On the other hand, adaptive grippers provide uniform force distribution, adaptability to irregularly shaped objects, and a lower risk of damaging delicate items, making them more versatile in handling a variety of objects.

This analysis provides a solid foundation for future development and optimization of grippers, with potential applications across various sectors, from industrial robotics to automated handling in unstructured environments. Future developments for this project include:

- FEM Analysis (Finite Element Method): This phase involves using finite element analysis to simulate material and structural behavior under specific loads. FEM analysis is crucial for optimizing design and predicting the structural performance of the component before physical production.
- 3D Printing: Based on the results of the FEM analysis, 3D printing will be carried out using the same material used in the simulation. This step allows for the production of physical prototypes that reflect the characteristics predicted in the simulation.
- Experimental Validation: Finally, tests will be conducted on the printed grippers to verify the alignment between simulated results and real-world performance. This phase is essential for confirming that the FEM simulations accurately reflect the component's behavior in practice.

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