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Gripper design and development for a modular robot

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1. Introduction

Since the humanity was born, hands have been the most essential parts of the body for our interaction with the environment. It would make no sense to receive a huge amount of information through the senses and processing it incredibly fast in the brain if then you cannot perform consequently. And just as human hands are the organs of human manipulation, if we make the comparison with a robot, their prehension tools are what is commonly called "grippers". As the end of the kinematic chain, is usually the only part in direct contact with the work piece as well. It can be defined as:

Grippers: *"Subsystems of handling mechanisms which provide temporary contact with the object to be grasped. They ensure the position and orientation when carrying and mating the object to the handling equipment. Prehension is achieved by force producing and form matching elements. The term "gripper" is also used in cases where no actual grasping, but rather holding of the object as e.g. in vacuum suction where the retention force can act on a point, line or surface."* Definition from (1).

Human hands are capable of grasping objects of an enormous range of sizes, shapes and weighs. This is a difficult achievement for a robot gripper and it is only possible due to the greatest variety of designs for either specific tasks or general ones than can be found nowadays.

Matching the necessity of a robot to be able to pick up objects with the increasing trend of DIT (Do it yourself), a modular robot with a gripper module will encourage people to build their own robot learning in different fields as mechanics or programming while enjoying their time.

1.1. Fable system

Fable is a robotic modular platform that due to its flexibility and accessibility is engaging for the user in the experimental process of building and programming. It is designed focusing on user's needs as a classroom of kids, after-school clubs nut also hobbyists/makers and even researchers (See Figure 1 from (2)).

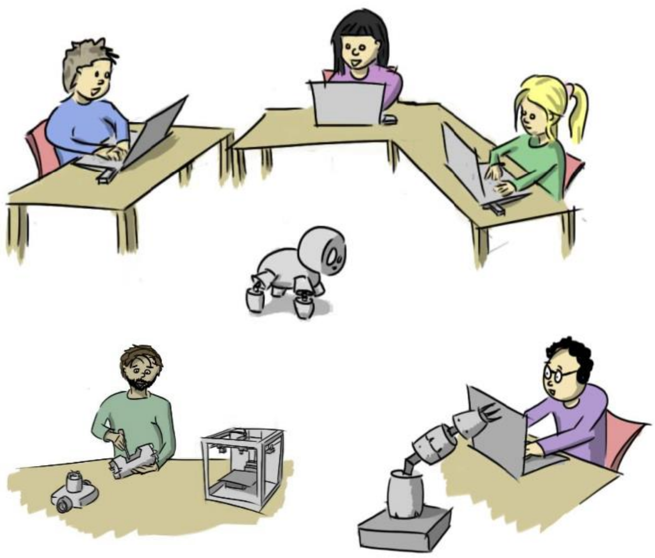


Figure 1: Users of Fable system: Students, Maker and Researcher.

The main characteristic is that the robot can be assembled in seconds and can be programmed with Blocky, Python and Java, what supports this diversity of users.

The Fable system is divided in active and passive modules that can be magnetically assembled. Active modules with functionalities as actuation and sensing contain electronics, onboard power, and they communicate with the PC by radio. Passive modules consist of a variety of shapes made out of empty plastic shells to give the robot structure and shape.

1.2. Aim of the project

The project consists on designing and building a new module for Fable that enables it to grasp daily items that you can easily find at home. The gripper will be considered good enough if it can pick up at least nine out of the ten objects seen in the Figure 2 without causing them any damage. The gripper will need to deal with different shapes (spherical, cuboid, cylindrical, irregular...), made of different materials (plastic, metallic, textile, ceramic...), and with different sizes and weights. The items are numbered from 0 to 9 for future applications.

Figure 2: Ten items that Fable should grasp: 0.5L bottle, can, egg, shoe, orange, cardboard box, Fable's brick, cup, marker and teddy.

For achieving the purpose of the Fable system, all users' necessities must be kept in mind during the design process. For example, in the educational application, an easy grasping mode would be useful for the younger learners and providing it with sensors would be appreciated by researchers.

Secondly, as it is thought to be commercialized one day, the cost of the fabrication process and its complexity as well as the price of its components is something to take into consideration for a success in the market together with the importance of aesthetics.

1.3. Scope of the project

Before the final version comes to the end, different prototypes must be done. This project consists in the evolution from the simplest version to a functional prototype that approaches as far as possible the final one.

Although the final design will be made by injection modeling in order to reducing costs when serial production, the prototype is made by 3D printing and laser cutting due to its low cost and rapid execution that allows to do variations in the design while checking its functionality.

1.4. Motivation

The creation of this new module will provide Fable with a large number of new functionalities, from a robotic arm as an SCARA robot (Selective Compliance Articulated Robot Arm) or a six degrees of freedom arm. It can also be assembled to any kind of walking robot that will be able to carry objects from one place to another.

1.5. Design procedure

Starting with the simplest possible design, the idea is to consider different prototypes learning from the errors of the previous one in an iterative way. Also adding sensors and increasing the complexity of the mechanism as the design process goes forward until it gets to achieve the final purpose.

2. Background

The grippers' world is as extended as one can imagine and before starting the design is essential to know more about the existing types and what are they used for to make sure that the right one is chosen.

2.1. Classification of grippers by gripping methods

To deal with the different tasks that an end-effector is in charged, grippers use diverse methods that can be categorized in the four following main groups.

- **Impactive gripper.** It is a mechanical gripper where the prehension force is achieved by the impact against the surface of the object from at least two directions. Are the most widely used in the industry for picking rigid objects using, for example, clamps or tongs.
- **Ingressive gripper.** It consists in the penetration of the work piece by the prehension tool. It can be intrusive when it literally permeates the material, for example pins, needles and hackles and on the contrary it can be non-intrusive when using other methods as hook and loop, for example Velcro. They are commonly used with flexible objects as textiles.
- **Astrictive gripper.** Direct contact is not needed at the beginning of the prehension and the binding force can take form of air movement for vacuum suction, magnetism or electroadhesion and it is applied in one single direction. This gripping method can only acquire particular objects: non-porous and rigid materials are required for the vacuum suction, for magnetoadhesion ferrous materials are needed and electroadhesion is only useful for light sheet materials and micro components.
- **Contigutive gripper.** The surface of the object and prehension means must make direct contact without impactive methods in order to produce the grasping force from one direction. Depending on the kind of force used the contigutive grippers can be classified in chemical adhesion as glue, thermal adhesion as freezing or melting and surface tension as capillary action.

Once all the gripping methods have been presented, the most suitable for picking the ten daily objects can be chosen. Taking into consideration that not all the items are metallic, light sheet or non-porous, the astrictive method can be discarded. In the same way, as the ingressive one only works with a few of them as the teddy bear because it is made of textile, it is definitely not the best option. Neither the contigutive gripper is a good choice due to the particularities of the method. In conclusion, the best choice is using an impactive gripper because it is able to grasp all the objects mentioned with their versatility of shapes and materials.

2.2. Impactive grippers

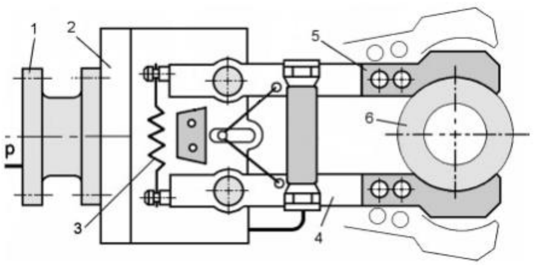
Mechanical grippers are the most frequently used in the industry field due to its great variety of applications. They may possess between two and five fingers usually with a synchronously movement. They require extensive or simple mechanisms related with the physical effects of classical mechanics as the amplitude of the friction cone between the two contact surfaces.

The complexity of the gripper lies partly in the degrees of freedom, understanding it as the required number of independent actuators that are needed for a completely defined motion of all links. The simplest one only requires one actuator but the number of degrees of freedom grows with the difficulty of the task to perform.

Parts of end-effector

An impactive gripper normally consists of drive chain placed in the gripper housing and the kinematic chain formed by the fingers that go from the housing of the gripper to the jaws. They are which are actually in contact with the work piece. All that parts are depicted in the Figure 3.

Kinematics



1 - Flange
2 - Gripper housing
3 - Tension spring
4 - Gripper finger
5 - Gripper jaw
6 - Workpiece

Figure 3: Parts of the en-effector of an impactive gripper (1)

The shape that the fingers must have for a determined purpose is determinate by studying the kinematics of the mechanism. There is a huge diversity of designs for the kinematic chain in order to transform rotational or translational motion into a particular jaw motion. Focusing in that, grippers can be distinguished between:

- **Parallel motion** (Jaws can follow whether a curve or lineal trajectory but always remaining parallel, i.e. without rotate)
- **Rotational motion** around a fixed point
- **General planar motion** of the jaws, for example rotation around a not-fixed point.

It is essential to know the transmission ratio of the kinematic chain to control the jaw travel from the motor motion. The jaw position can only be controlled by knowing the position of the actuator needed. This relation is reflected in the gripper stroke characteristic curve that gives the position and orientation of the jaw for each position of the actuator.

Knowing the dependence of the gripping force and the torque in the motor is also important when selecting the gripper mechanism or even the appropriated motor, at least to make sure that it is capable to do the force that is required.

Drive chain

The first component of the drive chain is always the motor which is the responsible for providing movement from electric power. There are several different types of motors in the market and for the right choice is necessary to balance their characteristics with the necessities as the accuracy in the control of the position or the maximum torque provided. The following motors may be suitable:

- **Stepper motors:** brushless DC electric motor that divides a full rotation into a number of equal steps. The motor's position can then be commanded to move and hold at one of these steps without any feedback sensor (an open-loop controller). Application in low-cost systems.

- **Servo motors (synchronous motors):** rotary actuator that allows for precise control of angular position, velocity and acceleration. It consists of a suitable motor coupled to a sensor for position feedback. Application when sensitive force and position regulation is required.
- **Linear motors:** an electric motor that has had its stator and rotor "unrolled" so that instead of producing a torque (rotation) it produces a linear force along its length. Applicable to proportional operation at high speeds.
- **Piezoelectric drives:** electric motor based upon the change in shape of a piezoelectric material when an electric field is applied. Applicable for extremely light objects and high speed handling. Their reliability and lifetime is very long but the achievable stroke is limited.

The motor is attached to the guidance gear which brings the motion to transmission gears. The second ones are used for transferring the movement from one place to another or to reduce its angular speed and finally moving the fingers.

Contact methods

The design of the jaws is totally determinant for a proper prehension because it is responsible of the distribution of the grasping force and it must be taken into consideration to ensure the stability.

The movement of an object in the three dimensions of space can be disaggregated in 6 velocities corresponding to rotation and translation around the three axes. The contact between the work piece surface and the gripping area of the jaw restrict a specific number of those velocities (also called degrees of freedom, k). An object will only be completely subjected when none of their velocities are possible.

Figure 4 illustrates different ways of restricting *k* degrees of freedom for a cuboid, cylinder and sphere. For impeding one velocity only one point of contact is needed, for two a beeline or two points of contact are necessary and any other planar contact method will restrict three velocities.

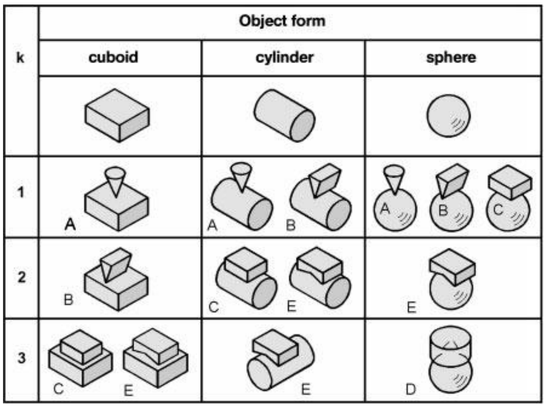


Figure 4: Shape of the jaw depending on the object form and the number of degrees of freedom that it restricts (k) (1)

The active surface of a gripper is what actually is in contact between the jaw and the object and it is related to the geometric shapes used in the designs of jaws. It is designated as: A point contact, B line contact, C surface contact, D circular contact, and E double line contact.

Besides the importance of the total retention of the work piece, the stability of the prehension must also be ensured by the compensation of all the forces and moments on the object. Misalignment of grasped components should not be possible as a result of their weight or inertia.

A reduction in the gripping force with an improvement of retention stability at the same time is possible enlarging the active surfaces or increasing them in number by using more fingers or more adequate profiles. Figure 5 show some examples of the combination between one to three fingers and one, two or multi-point of contact.

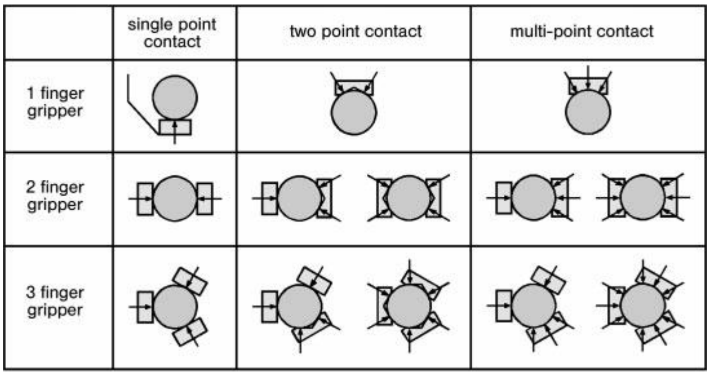


Figure 5: Distribution of the prehension force depending on the number of points of contact. (1)

2.3. State of the art

Before starting with the design of the new module, the related work is reviewed in order to find out what is being used at the moment to grasp objects. The grippers will be categorized in three main groups: industrials, hobby or leisure and others.

Industrial grippers

- Adaptive robot gripper

Used in industrial applications, they have two or three fingers with two degrees of freedom. They are compatible with all major industrial manufacturers and enable you to manipulate a wide variety of objects. They are designed to facilitate part ejection and part seating. Some applications are machine tending, collaborative robots and assembly.

  - 2-FINGER 85 (3)

Although it can grasp a large variety of objects, it is perfect for items with two parallel faces or cylindrical ones using its encompassing mode due to its two degrees of freedom.

Figure 6: Adaptive robot gripper 2-FINGER 85

- 2-FINGER 200 (3)

With a stroke of 200 mm and a payload of 23 kg, this sealed and programmable Robot Gripper can handle a wide variety of parts. The main differences with the previous one is that it can also grasp objects from inside a hole and the objects can be much heavier.

Figure 7: Adaptive robot gripper, 2-FINGER 200

- 3-FINGER (3)

Provides hand-like capabilities to the robots and it has reliability in unstructured environments. It is suitable for R&D projects although it is also used in various industrial applications. It is designed for advanced manipulation tasks.

Figure 8: Adaptive robot gripper, 3-FINGER

- Pneumatic grippers

AGI pneumatic grippers have a wide range of sizes, jaw styles, and gripping forces for almost any industrial application. The three major types of pneumatic grippers are parallel gripper, angular gripper, and custom units such as O-ring assembly machines. These products are used in various industries such as Aerospace, Automotive, Appliance, automated industrial O-ring systems, Electronic, Medical and Packaging.

- Compact Low Profile Parallel Gripper (4)

It is ideal for small parts handling. It has long stroke and light weight designed for robotic applications where weight is an issue.

Figure 9: Pneumatic grippers, compact low profile

- Single Jaw Parallel Gripper - One Fixed Jaw Style (4)

It is made for use in tight spaces needing large payloads. It is ideal for situations where the zero position of one jaw is need. This gripper has a T-slot bearing design that is supported the length of the body to carry heavy loads.

Figure 10:Pneumatic grippers, Single jaw parallel

- Dual Motion Gripper (4)

Automated seal and O-ring assembly made for small to large O-ring or part pick and seat applications. Spread and place seals with these dual motion automatic O-ring placement assembly machine. It is designed to facilitate part ejection and part seating.

Figure 11: Pneumatic grippers, dual motion

Hobby or leisure

- Bioloid gripper

Bioloid is an educational robot kit which who you can learn the basic of structures and principles of robot joints and expand its application to the creative engineering, inverse kinematic, and kinetics. It is also for hobbyists who enjoy building customized robots.

- Simplest model (5)

A gripper can be easily assembled with two metal frames and one single servo. In this case one of the frames is directly fastened to the servo case and only the second one is moving. It is mainly useful for large objects.

Figure 12: Simplest model of bioloid gripper

- AX-12 Dual Robotic Gripper (6)

This robotic arm gripper design is ideal for a numerous robotic arm manipulation tasks that can be applied to all types of shapes. The two servos can move synchronously having one degree of freedom or independently having two degrees of freedom.

Figure 13: Bioloid gripper with two servos

- Lego Mindstorms gripper

Lego Mindstorms is a kit that contains software and hardware to create customizable, programmable robots. They include an intelligent brick computer that controls the system, some modular sensors, motors and Lego parts to create the mechanical systems. Its application is mainly educational. There are two versions: NXT is the first one and the second one is EV3 with the same characteristics but more powerful and with larger variety of sensors.

- NXT simple gripper (7)

With some Lego parts, some gears and a single motor, an angular gripper can be assembled without big difficulties.

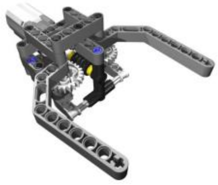


Figure 14: NXT simple gripper

- NXT crane (8)

With the same NXT kit much more complex grippers can be assembled. This one not only can close and open the gripper but also position it in the right place. It also has an infrared sensor to detect if an object is ready to be grasped.

Figure 15: NXT gripper in crane

- EV3: GRIPP3R (9)

Using EV3, the more powerful version of Lego Mindstorms, a wheeled robot as this one can be built. The GRIPP3R robot is constructed for some heavy-duty lifting. It has got the muscle to grab and drop a can of soda with its powerful grasping grippers.

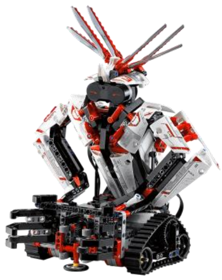


Figure 16: EV3 gripper robot

Others

- Universal gripper (10)

The universal robotic gripper is based on the jamming of granular material. Individual fingers are replaced by a single mass of granular material that, when pressed onto a target object, flows around it and conforms to its shape. Upon application of a vacuum the granular material contracts and hardens quickly to pinch and hold the object without requiring sensory feedback.

Figure 17: Universal gripper with granular material

- Makeblock robot gripper (11)

It is made from a heavy duty but lightweight PVC and it has extra anti-slip material on the inside of two fingers. It comes with four standard M4 thread holes on the bottom for easy assembly to any other robot.

Figure 18: Makeblock gripper

3. Analyses

3.1. Study of the motion of some mechanisms

In order to choose the design of the best mechanism for the purpose of the project, it is necessary to study the different possibilities.

The study consists of a first simplification of the grip to the kinematic chain using the program PAM (12). All the simplified designs are exactly the same size to be able to make a reliably comparison of the results afterwards. Then the grasping action is simulated and the displacement and forces plotted. In all the following grippers, a rotational motor has been considered for each degree of freedom of each finger but with symmetric movement for the two fingers. The grippers simulated can be divided in two main groups depending on the degrees of freedom that they have.

One degree of freedom

Following the classification of the kinematics chain, three types of grippers can be found. The rotational motion is option A (13). In parallel motion two possibilities are contemplated: using a parallelogram that will remain its sites always parallel two by two that is option B (14) and a movement with a guide that ensures the parallelism and restrict not only the rotation of the jaws but also their vertical motion, option C (15). Finally a combination of rotation and translation is shown as planar motion is option D (16). (See Figure 19)

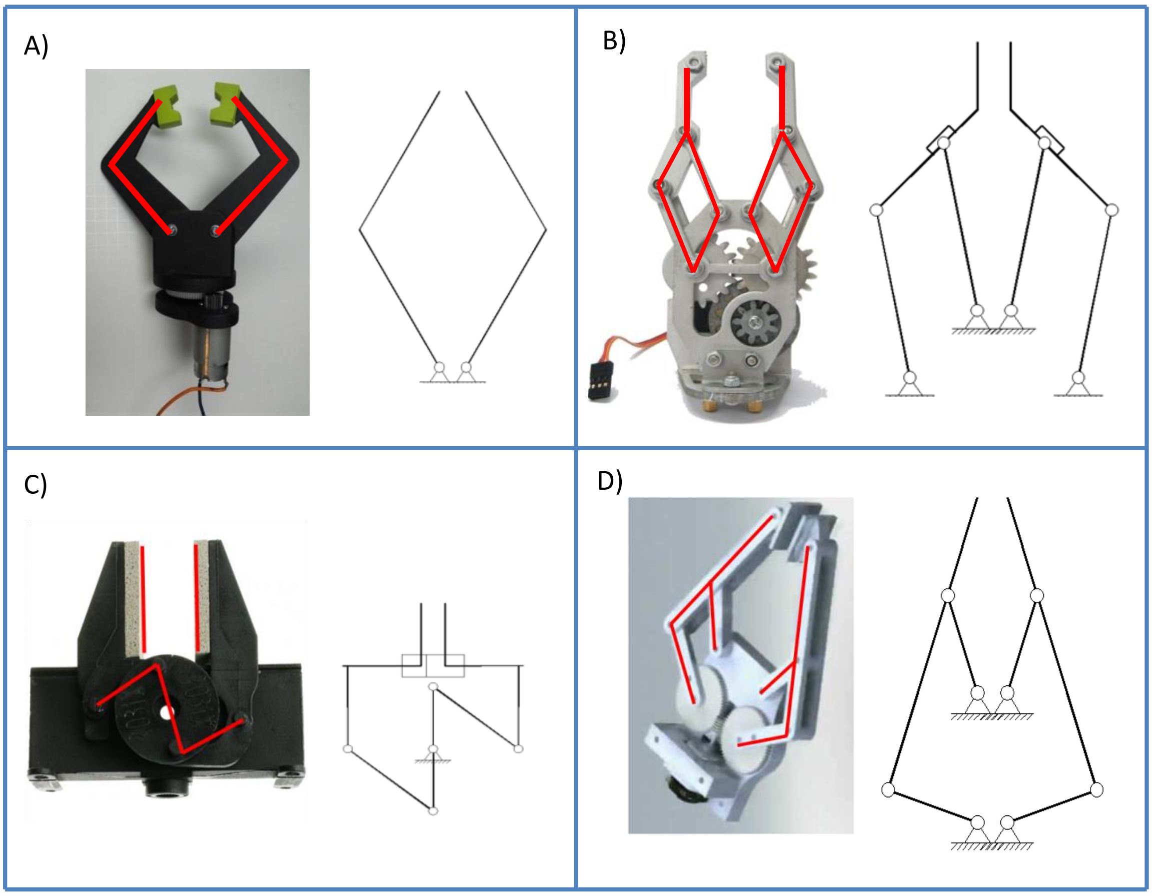


Figure 19: Grippers examples of one degree of freedom and simplifications. Top-left is angular, top-right is parallel with a parallelogram, bottom-left parallel with a guide and bottom-right is planar motion

Every mechanism is simulated by rotating one radian the actuator from the maximum opening to its closure holding a 1 cm object. This way it is obtained the stroke curve that shows, for each position of the motor, the position and orientation of the left jaw, knowing that the right one has a symmetrical motion. Its function is to control the jaws motion from the actuator motion and it is illustrated in Figure 21. Obviously, in option B and C the jaws do not have any rotation and it can be seen that the maximum jaw horizontally displacement is achieved in option A, the angular motion.

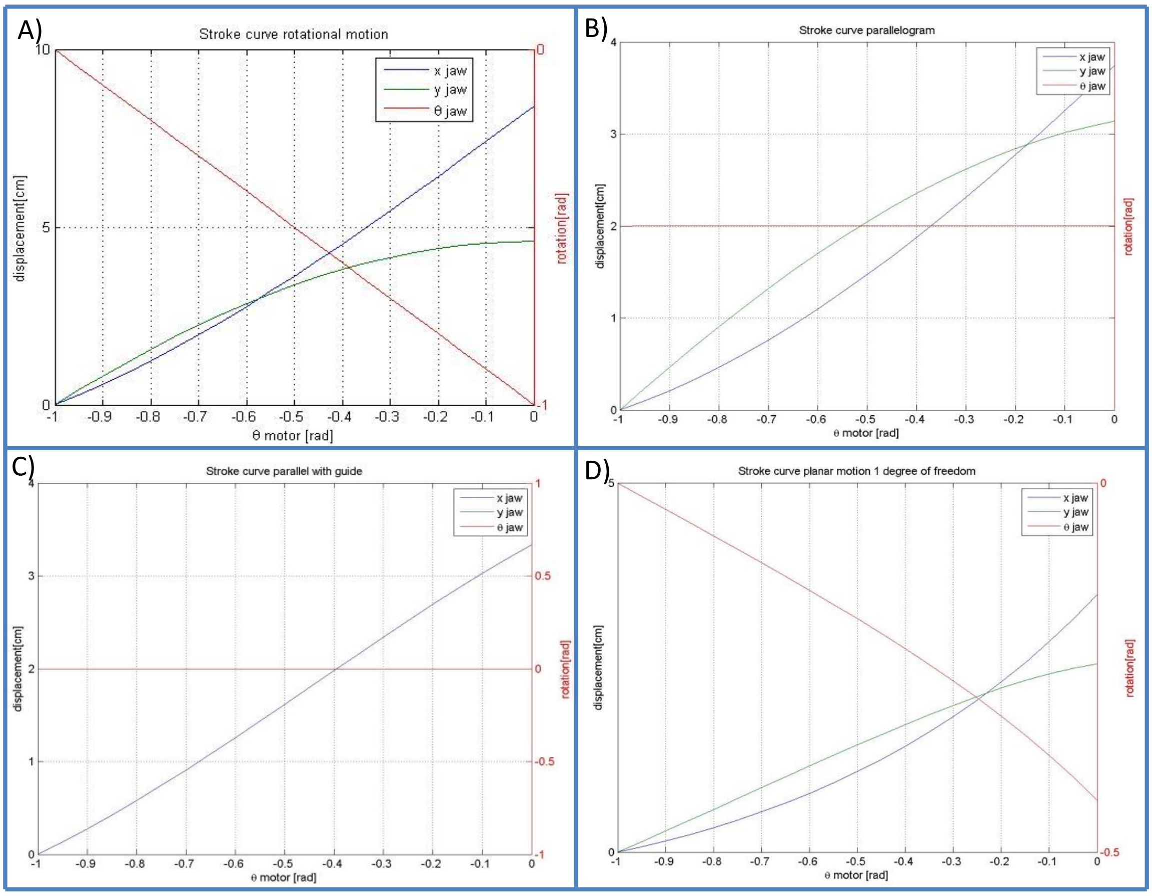


Figure 20: Force curve of the four mechanisms

To compare the torque that is needed in each of the mechanisms previously mentioned, 1N has been horizontally applied to each jaw during the simulation. The torque that the actuator needs to do in each position of the motor is plotted in Figure 20, knowing that each position of the motor is equivalent to a size of the object grasped. For the simulation one actuator has been placed in each finger so in case of using just one motor the torque would be twice the one in the graph. It is important to take into consideration that, as the force applied in the jaws and

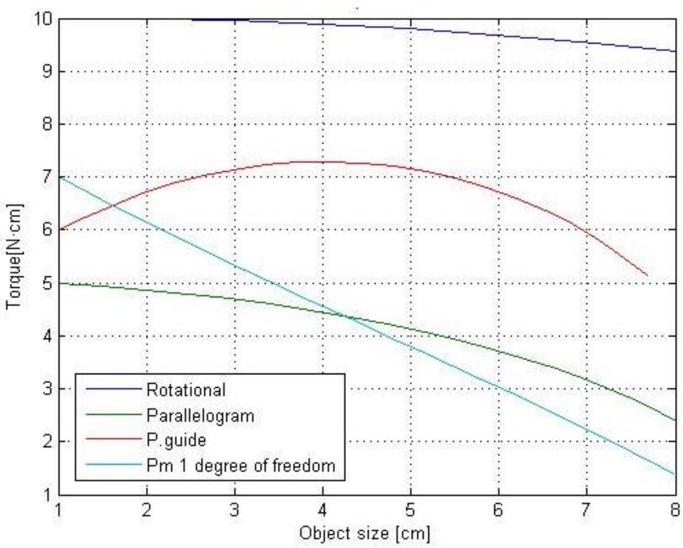


Figure 21: Stroke curves of the four mechanisms

the torque needed are linearly dependents, by multiplying the force curve per the real grasping force, the real torque is obtained. It can be seen that the rotational (option A) one requires an enormous torque and the ones which need a lower torque are the parallel using a parallelogram (option B) and the planar motion of 1 degree of freedom (option D).

Two degree of freedom

The complexity of the mechanisms can increase as much as wanted. In the case of two degrees of freedom a wide variety of motions can be achieved from parallel motion to an enclosing one. The motion depends on the relation between the speeds of the two actuators as well as the initial position of both of them. It is also possible to control one of the degrees of freedom with the motor and live the second one free to allow the gripper to adapt to the object shape.

Figure 22: Example of a two degrees of freedom gripper (3)

In order to compare this mechanism with the previous ones, two motions have been simulated and its stroke curve as well as its force curve is illustrated in Figure 23. The graphs on the left correspond to a parallel motion and the ones on the right to an encompassing motion.

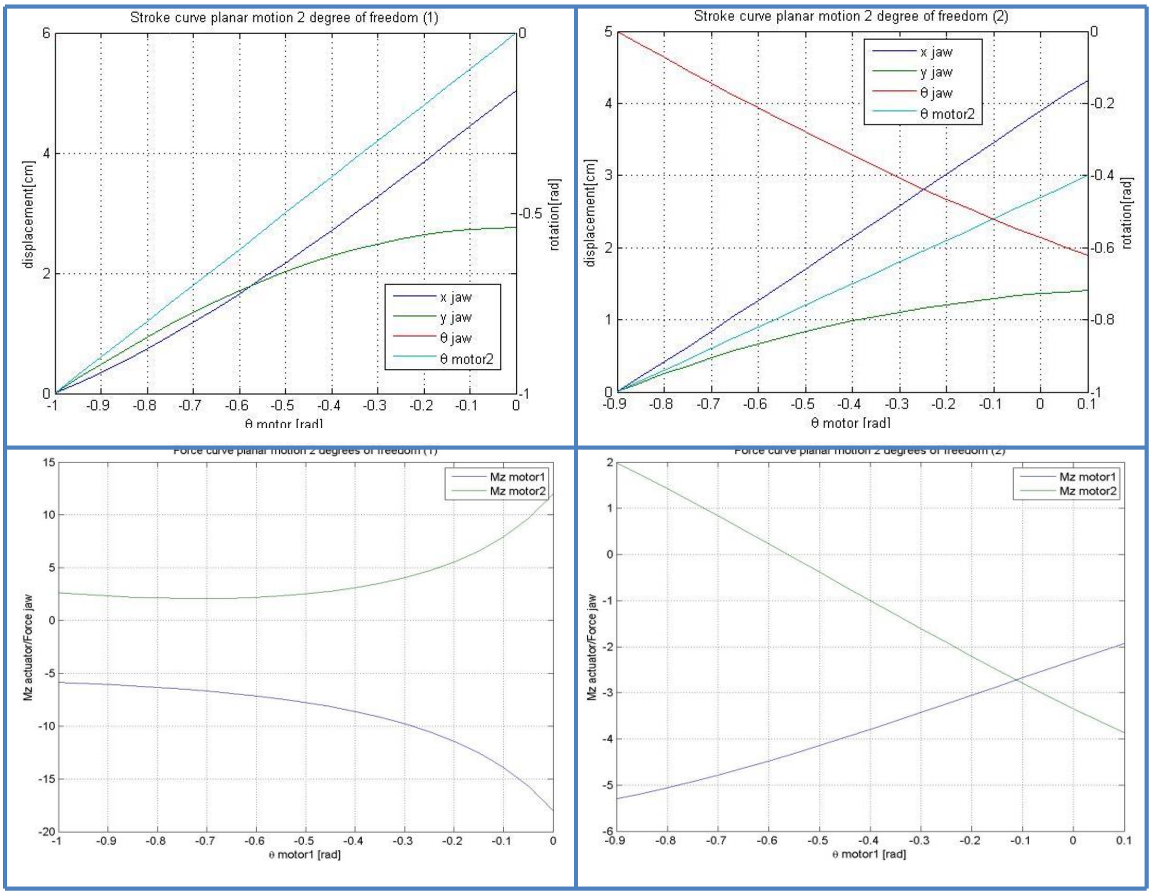


Figure 23: Top: stroke curve of parallel motion (left) and encompassin (right); bottom: force curve of parallel motion (left) and encompassin (right)

In the stroke curve can also be found the rotation of the second motor that is needed in order to achieve the desired movement of the jaws. In the force curve each line represents one actuator. In the parallel motion, it is shown that more than 10 $N \cdot cm$ and 15 $N \cdot cm$ are needed on the two motors just to hold the item with 1 N force. On the other hand, in the encompassing option less than 6 $N \cdot cm$ are required. Both motions are depicted in Figure 24 from (17).

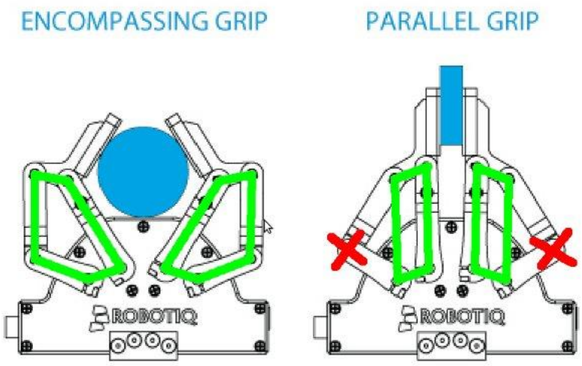


Figure 24: Encomapssing mode and parallel mode in the two degrees of freedom gripper

Discussion of the simulations

Once all the mechanisms have been simulated they can be compared in order to choose the one that fits better for the Fable's gripper. The decision will be made focusing on the stroke of the mechanism to ensure that all the objects can be gasped; the torque that is actually transmitted from the actuator to the jaws and finally the building simplicity of the mechanism. For that purpose, the results of the simulations are summarized in the Figure 25. In the first place it contains the size of the biggest object that can be grasped calculated from the horizontal jaws position. Secondly the torque range that is required in the actuator during the simulation of a rotation of 1 radian. Thirdly, to compare the torque's needs of all the mechanisms in the same position, the torque needed when holding a beverage can with a diameter of 6.63 cm (18) is also in the following table.

Type	A) Rotational	Parallel		D) Planar 1 DOF	Planar 2 DOF	
		B) Parallelogram	**C) Guide**		**Parallel**	**Other**
Max object size [cm]	17.8	8.4	7.6	8	11	9.6
Torque range [N·cm]	[5.4, 10]	[1.9, 5]	[1.4, 7]	[1.4, 7]	[5.9, 18] (motor1)	[1.9, 5.3] (motor1)
					[2.6, 12] (motor2)	[0, 3.9] (motor2)
Can torque [N·cm]	9.55	3.38	6.37	2.51	7.8 (motor1)	3.4 (motor1)
					2.5 (motor2)	1.6 (motor2)

Figure 25: Table of the summmarized results of the simulations

About the one degree of freedom, it can be seen that, although the rotational option is the one that can grasp the biggest object is also the one that needs the highest torque so it can be definitely discarded. Secondly the parallel motion using a guide is not useful neither because it has the smaller stroke and such a big torque. The remaining options would be B and D.

When comparing them to the mechanism of two degrees of freedom, it can be seen that the benefits in the stroke and torque are not gigantic but it is more about its flexibility of movements. On the other hand this flexibility implies an increase in the building, design and control difficulty.

3.2. Requirements

Before start to enumerate all the requirements it is necessary to make a distinction between the prototype and the final version. This project consists on designing the first prototype of a gripper for the Fable system but it will continue evolving until it reaches the optimized prototype that completely meet with all the necessities that are expected in it. That is why the real requirements are not exactly the same ones as the expected at this point. They are both listed in the Figure 26 adding to the list that it must fit with Fable's connectors.

	Prototype	Final version
Maximum distance between jaws	12 cm	
Modeling	3D printing	Injection molding
Robustness	2 hours between consecutive breaks	1000 hours between consecutive breaks
Price	<= 200$	<= 50$
Stability	>= 2 points of contact between jaw and work piece	
Grasping assistance	Distance to the object and force control	
Holes at the housing	<= 1cm^2	<= 0,1 cm^2

Figure 26: Table of requirements for the prototype and for the final version

The maximum distance between the jaws is obtained by measuring the largest object from the ten set that is the Fable's brick.

The modeling will be 3D printing during the designing iteration due to the low cost for one piece and its rapid execution but always having a design compatible with injection modeling because when serial production the cost is importantly reduced.

The robustness is not really important at this point but it will definitely be of several importance in the final version as well as the price.

Obviously it must fit with Fable's connectors to be able to assemble the new module with the other ones.

To ensure the grasping stability each jaw and the item should always have at least two points of contact and the applied force and the distance to the next object must be under control to make the grasping action as easy as possible without damaging the object.

Finally there should be almost no access to the inside of the housing of the gripper to avoid breaks in the driving chain or injuries of the users.

4. Design and implementation

The design starts choosing the best option between the studied ones that matches with the requirements for the first version. The module can be divided in the kinematics chain and the driven chain and the choice as well. The prototypes are designed in SolidWorks and its parts and assemblies can be found in the attached CD.

- Kinematics chain

The chosen mechanism is option B, parallel motion with a parallelogram. The main reason to avoid choosing the mechanism of two degree of freedom is because its complexity makes it not suitable for the first steep although it should be considered in the future. Between the one degree of freedom ones, and focusing on the results of the simulations, two of them were not discarded: the parallelogram and the planar motion. They are similar but the reasons to choose the parallelogram are:

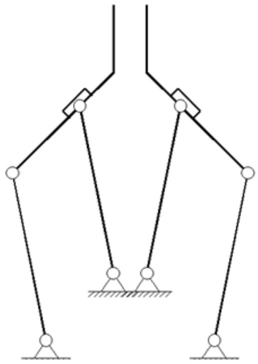


Figure 27: Chosen mechanism

  - It can grasp larger objects
  - It reaches lower torque necessities when grasping small objects. To have low torque is relevant because a less powerful motor will be required and its batteries will last longer so it has a direct impact in the price of the gripper.
  - It is also much simpler to control the gripper if the jaws only have displacement and not rotation.
  - The most important reason is that, as the jaws will always remain parallel, the grasping forces will be compensated and the object will be better subjected. (See Figure 28)

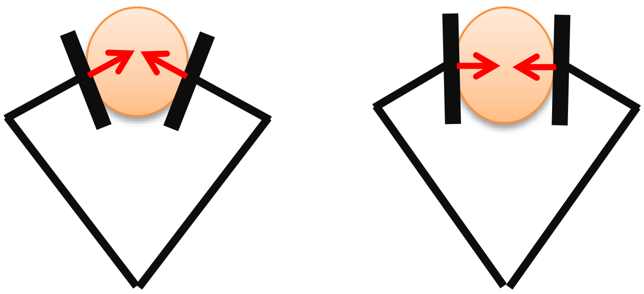


Figure 28: Grasping force for not parallel gripper (left) and parallel gripper (right)

- Driven chain

The chosen actuator is a servomotor because it allows an accurate control of angular position as well as velocity and acceleration due to its feedback sensor. The market has a huge variety of servomotors that change in specifications, size and price.

Figure 29: Chosen motor

The best one at this point is DYNAMIXEL AX-12A from ROBOTIS of Figure 29 (19) but it is suitable to be changed in the future due to its high price and size. It has been chosen because, besides the usual control of the servomotors it also includes torque limit and it will be really useful to control the force applied to the items. This model is the “Join Mode” that can achieve lower speeds than AX-12W (with a lower gear ratio) but higher torque that will be needed to overcome the friction between the gears and with the axis. Its main specifications are 300º of operating angle, a stall torque of 15,3 $kg \cdot cm$ (ROBOTIS recommends that using 1/5 or less of the stall torque to create stable motions) and 59 RPM of maximum speed.

- Contact method

As said in the requirements, in order to ensure the stability at least two points of contact between the jaw and the object are necessary. To have a symmetric distribution of the forces when having a gripper of two fingers, the design of the gripper should be something similar to Figure 30.

Figure 30: Chosen contact method

4.1. Prototype 1

As said before the first prototype consists on a parallel motion mechanism of two fingers connected with a driving chain of four gears, one of them attached to the motor. It has a total of 14 plastic pieces that have been laser cut in acrylic of 5 mm plus three more for the subjection of it all. Ten screws of metrics 4 and 2 cm of length are used as axis together with their nuts. In Figure 31 can be seen the main parts of the prototype; the fingers, bars, central and external gears and the servomotor.

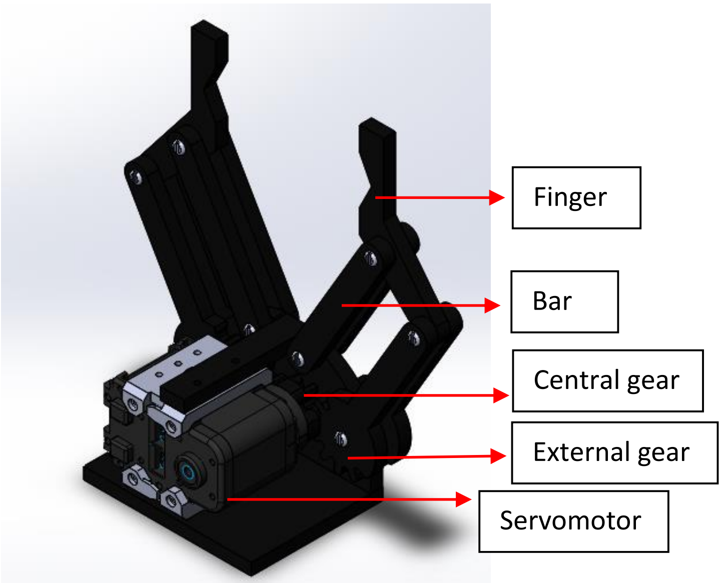


Figure 31: First prototype with its components

Design of the kinematic chain

The gripper mechanism is the one shown in Figure 32 and it consists of two fingers (in yellow) and eight bars, four in each site to give greater resistance. The red and green bars represent the parallelogram that is actually the basis of the mechanism where the bars from the same color must be the same size. As the green bars will always remain parallels and one of them is fixed, the other one will never rotate and neither will the fingers. The bars are articulated with eight joints and each of them are subjecting together three plastic pieces.

In can also be seen the design of the mechanism in its closure position and its maximum open position. As it was required, the maximum separation between the jaws is 12 cm when the bars have rotated 90º as it is depicted.

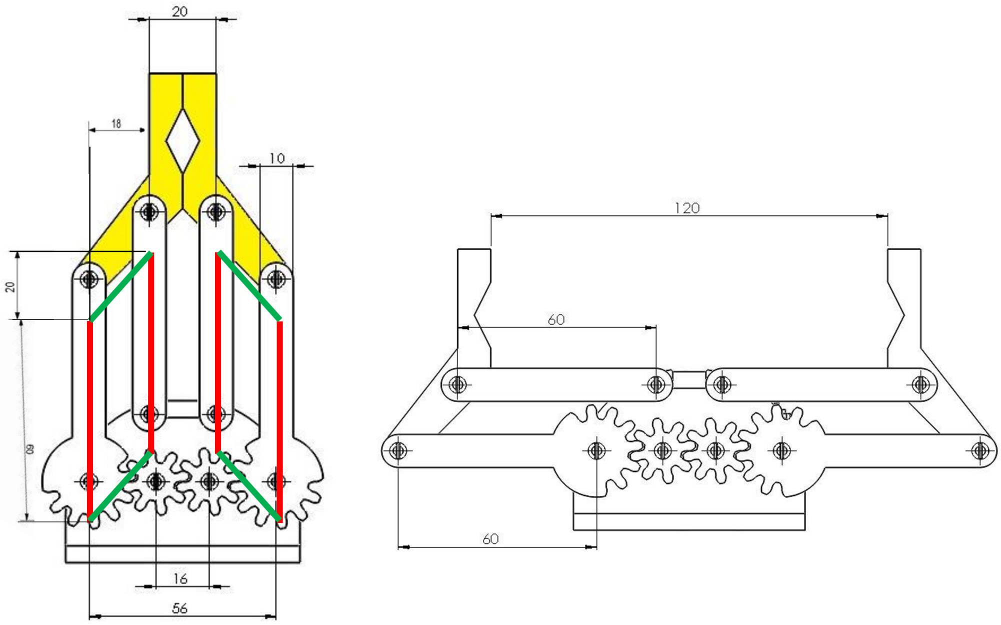


Figure 32: Design of the first prototype in its closed position (left) and its open position (right)

Design of the driven chain

The drive chain usually consists on a servomotor and at least two gears to move both fingers synchronously. For this particular mechanism design, the fingers are separated 56 cm so two gears of 28 cm would be needed. It is necessary to reduce the size of the gears and to place the motor as centered as possible so the best solution is to use four gears instead of two and attach the motor to one of the central ones. Again, in order to give greater resistance, four other gears are placed in the other site of the fingers.

To take more advantage of the 300 º of operating angle of the servo, the internal gears are smaller than the external ones because if they were the same size the motor would only use 90º. This increases the precision of the position control.

To design the gears, the first step is to choose a pitch. It is defined as the distance between the beginning of a tooth and the beginning of the consecutive one and two gears must have the same pitch in order to mesh properly. Another parameter that can be used to describe a gear is the module and they are both calculated as follows (Eq.1).

$$\left.\begin{aligned} pitch &= \frac{pitch\ diameter \cdot \pi}{number\ of\ teeth} \\ module &= \frac{pitch\ diameter}{number\ of\ teeth} = \frac{pitch}{\pi} \end{aligned}\right\} \quad \text{(Eq. 1)}$$

A gear has three characteristic diameters; the pitch diameter is the middle one and when two gears are meshing their pitch diameters are always tangent. Then there is an external diameter that is defined as the end of the teeth and an internal one at the beginning of the teeth that is calculated as the external one less the whole depth. (See Figure 33 from (20))

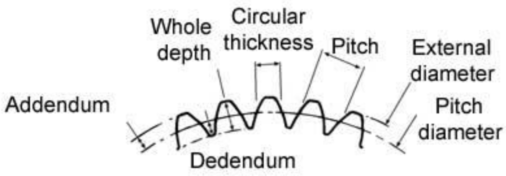


Figure 33: Illustration of the gear characteristics parameters

In order to design the gears properly they should be (21):

$$\left.\begin{aligned} external\ diameter &= pitch\ diameter + 2 \cdot module \\ Whole\ depth &= \frac{13}{3} \cdot module \end{aligned}\right\} \quad \text{(Eq. 2)}$$

The gear ratio establishes a linear relation between the number of teeth of two gears and their angular speed, or what is the same, the angular rotation.

$$\left. ratio = \frac{N_A}{N_B} = \frac{w_B}{w_A} \right\} \quad \text{(Eq. 3)}$$

In this first prototype the central gears have 8 teeth and are smaller than the external ones with 12 teeth as said before. Then knowing the ratio with the number of teeth and the required rotation of the external gears, it can be found the rotation of the central gears. It results a total rotation of 135 degrees and that is obviously also the rotation of the motor.

$$\left. ratio = \frac{8}{12} = \frac{90}{w_A} \right\} \quad \text{(Eq. 4)}$$

They will both have a module of 2 because is one of the most extended in the industry for this size of gears so its pitch and all their parameters can be easily calculated and are summarized in the following table (Figure 34).

	External gears	Central gears
number of teeth	12	8
pitch	6.283	6.283
pitch diameter [mm]	24	16
external diameter [mm]	28	20
whole depth [mm]	8.67	8.67

Figure 34: Characteristic gear parameters for the first prototype

Attachment of both chains

This first prototype does not meet the requirement of fitting with Fable's connectors yet. As the motor is placed on one side of the mechanism it does not present any symmetry and the gripper is going to be in one side of the module. It may have some benefits as increasing the versatility of grasping items because there are two different ways to approach it but the misalignment with the center of the module can produce some torsion forces and once the object is grasped it increases the inertia of the set if a rotation is required. In this first prototype the motor is attached to the mechanism in three ways. The first one is to provide the motion using a special gear (in red) that is directly screwed to the driven gear of the servo. The other and are used to subject the servo with the motionless part of the mechanism and are fixed to the servo case with a Bioloid frame (in blue). They are all shown in Figure 35.

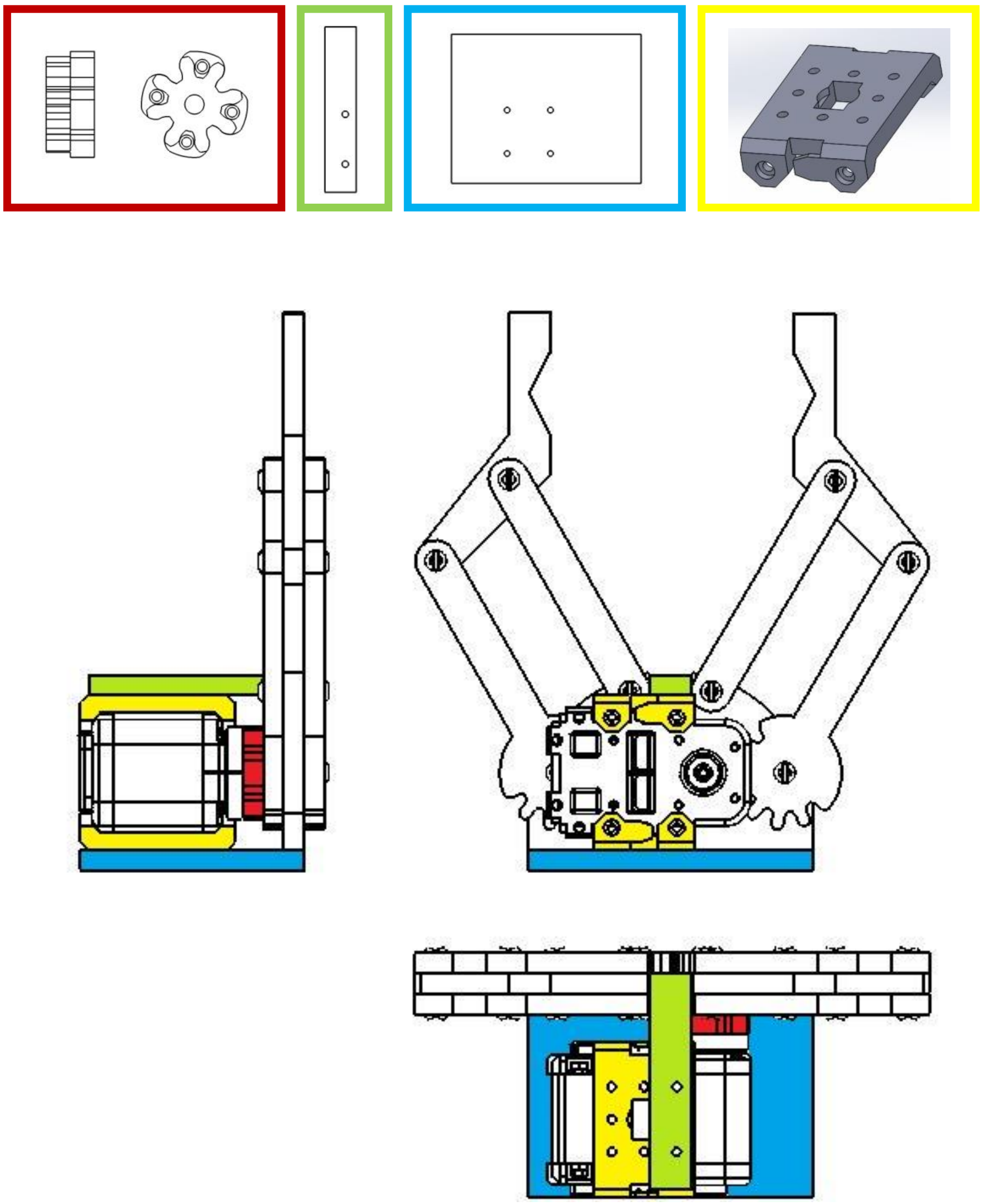


Figure 35: First prototype with identification of the subjection elements

Design of the contact method

Figure 37: Desing of the jaw in the first prototype

The jaw needs to be carefully designed taking into consideration the different shapes of the objects that are going to be grasped, having always at least two points of contact. In this first prototype the jaw is divided in two main parts. The central one is for cylindrical or spherical objects and the two external parts are for objects with 2 or more parallel faces as depicted in Figure 37. The irregular objects will adapt somehow two the central part having also two or more points of contact. The final result can be seen in Figure 36.

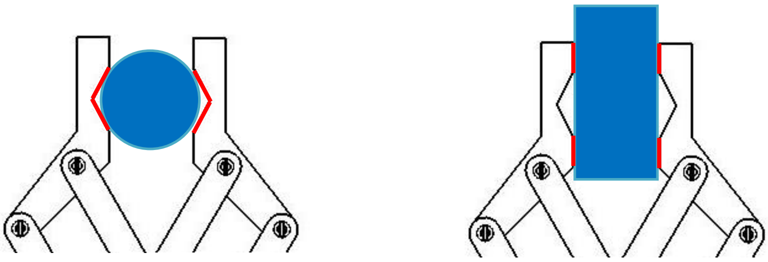


Figure 36: Contact methods for a cylindrical and cubical object in the first prototype

Images of the built first prototype

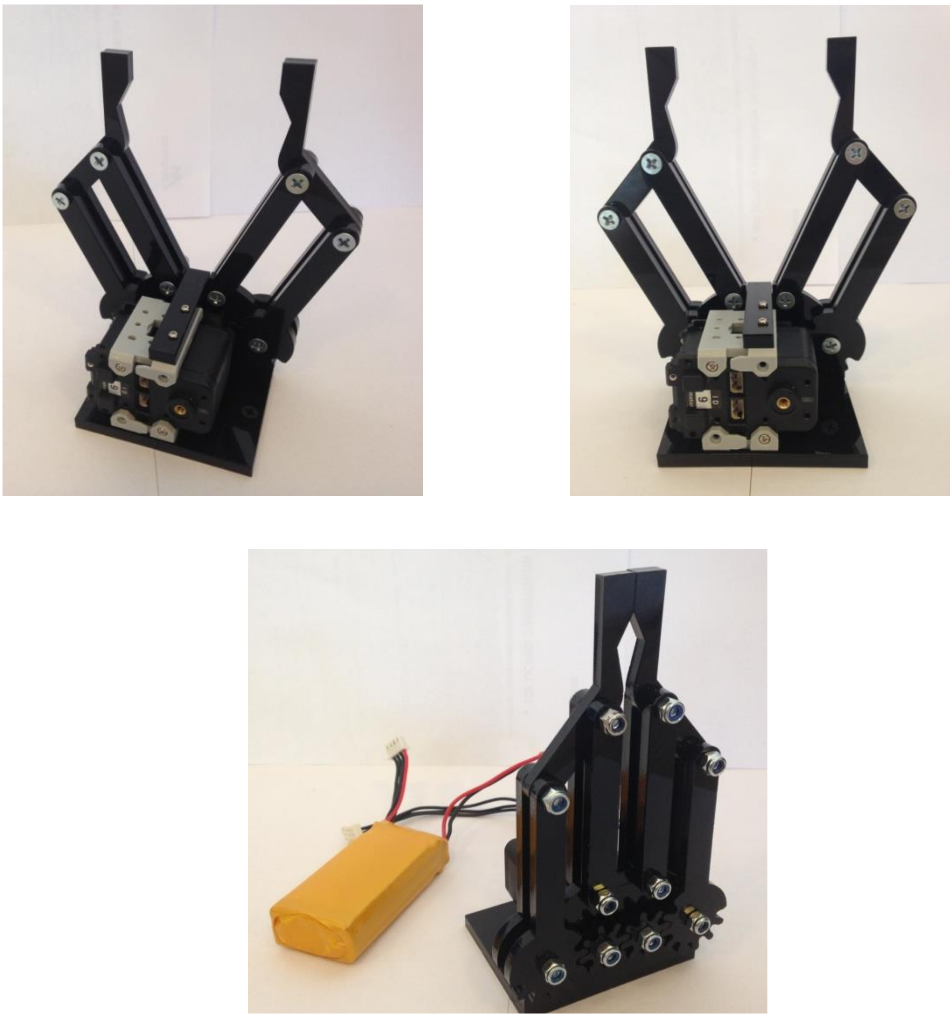


Figure 38: Pictures of the first prototype

4.2. Prototype 2

After doing the experiments that will be seen in the chapter 6, the main failures of the first prototype has been detected and tried to solve in this second prototype. The main problems faced in the first prototype were:

- Not fitting with Fable's connectors
- The most heavy and rigid objects felt because they slide.
- There driven chain was not covered yet

It also needs to meet the requirements of Fable's connectors and having a closed housing for the driven chain, as well as incorporate the needed senor. The final result can be seen in Figure 39. In this prototype some of the plastic pieces have been laser cut in 5 mm black acrylic as the previous one but some others have been 3D printed.

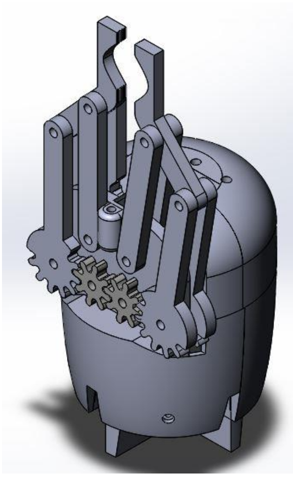


Figure 39: Design of the second prototype

Design of the kinematic chain

The kinematic chain has not suffered any changes in this prototype because it was working well enough. The four bars are laser cut.

Design of the driven chain

There is neither almost any problem detected in the driven chain. The only issue is that, as the gears were laser cut, they were some tenths of a millimeter smaller than expected. It allows a small rotation of one gear while the other one is stopped. To solve the problem simply the gears has been now designed taking into consideration the amount of material that the laser eliminates using gears one quarter of millimeter bigger than before. The four external gears and the three internal gears are also laser cut. The fourth one that is attached to the motor is 3D printed.

Attachment of both chains

The main difference between the two prototypes is the shell. Inside it is placed the servomotor, the battery of 12V, the IR sensor and the connector. Four of the gears are not included inside the shield because it provides and educational interest to see how the driven chain works. The shield is divided in two parts for an easy assembly as it is shown in Figure 40; front shield and back shield, both 3D printed. The electronics are outside of the shell although the next version should include them inside. There is a hole in the back shield where all the cables will exit the housing. The servomotor is subjected with a Bioloid F3 frame and five screws, one of them in the front shield and the other four in the back one. They are signposted with a red circle.

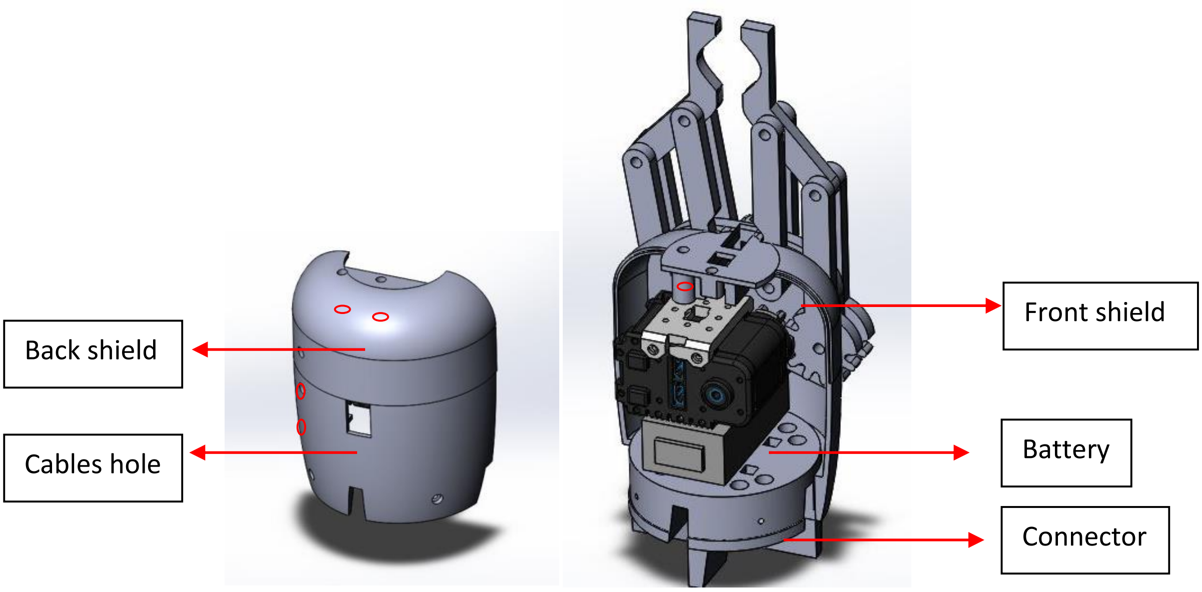


Figure 40: Design of the second prototype with its parts

The entire shield has a thickness of two millimeters (See Figure 41); this is made thinking with the future injection modeling because it is important to have homogeneity in the thickness for a good distribution of the molten plastic. Both parts of the shield are subjected with:

- A lip and groove with a small inclination as illustrated in the right image of
- The screws that are used to subject the servomotor also subject the two part of the shield on the top of it.
- The four screws that are used to subject the connector subject again the shield on the underside.

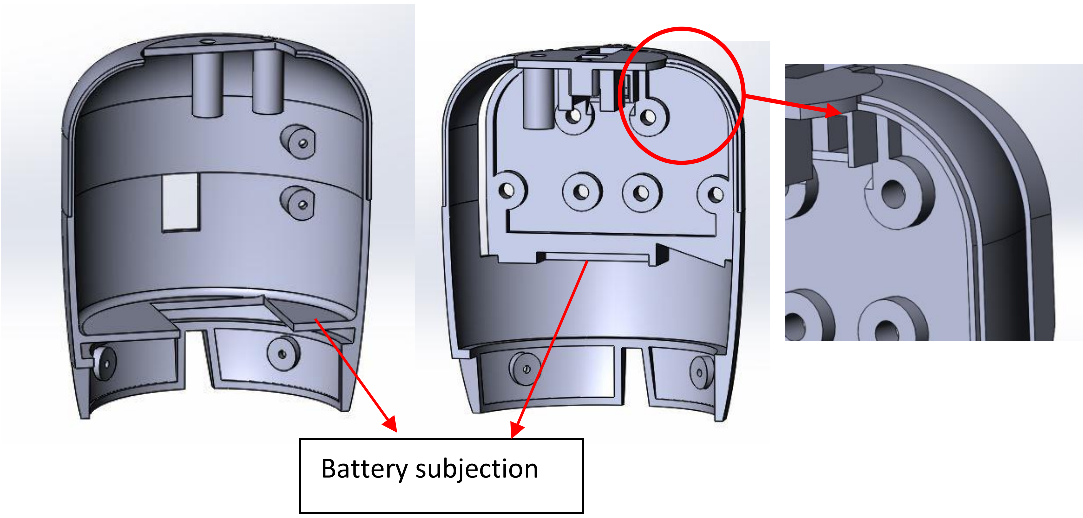


Figure 41: Design of the back and front shield

Finally the IR sensor is subjected with two screws, one in each side. It is placed in the front shield between the two fingers and has only two rectangular holes for the two diodes; the rest of it is hidden (See left and middle images of Figure 42). As the internal bars where interfering with the IR sensor their design has slightly changed to the one seen in the image on the right.

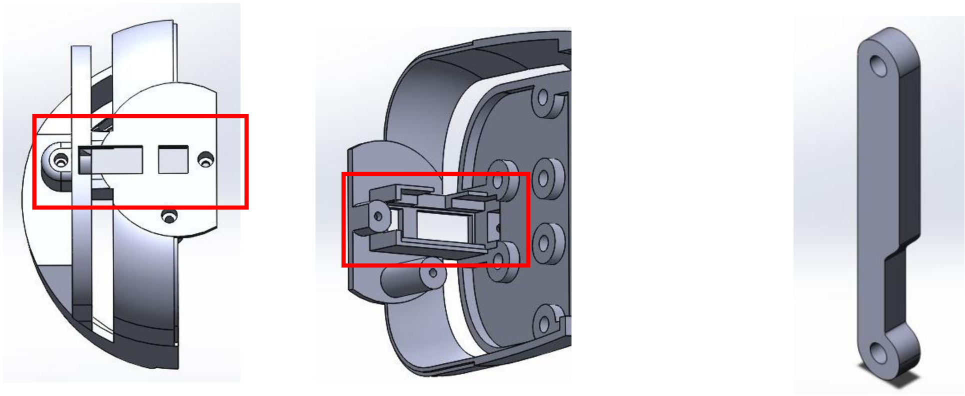


Figure 42: Adaptations in the second design for the IR sensor

Design of the contact method

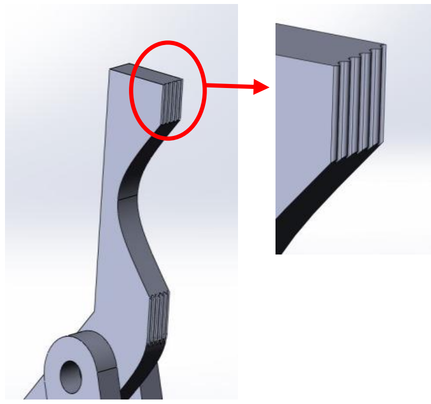


Figure 43: New design of the jaw

In order to avoid the slide of some of the objects suffered in the first prototype the design of the jaws has undergone some changes. The first one is with the material. It is now made with 3D printing that is with a softer plastic than acrylic. This will increase the contact area between the jaws and object surface because the jaw will suffer a small deformation and it will lead on a higher friction force. Secondly there has been incorporated some rails in the opposite direction of the slide of the objects to difficult it as depicted in Figure 43. Finally the central part of the jaw, dedicated for cylindrical or spherical objects is now bigger to ensure that the objects with a large diameter will also have no less than two points of contact.

Images of the built first prototype

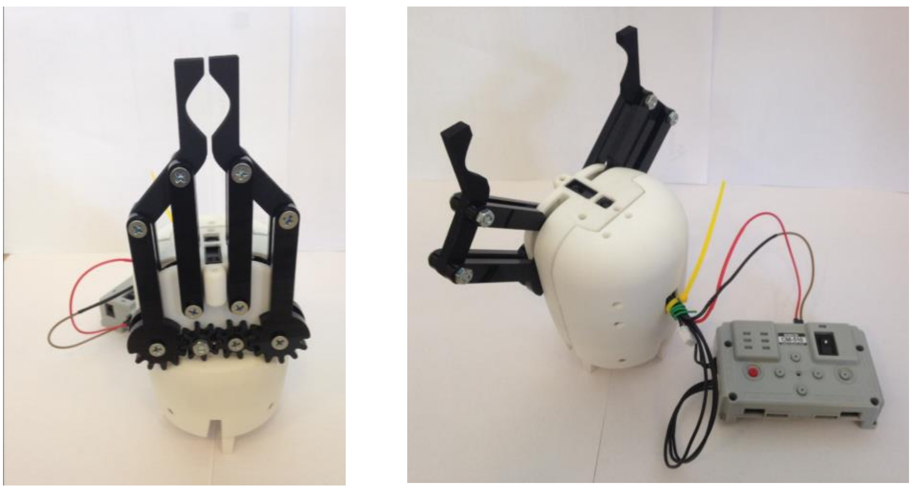


Figure 44: Pictures of the second prototype

5. Control of the gripper

Once the mechanic design has been completed the next step is to control its motion to achieve the griping task. Also it is useful to control the amount of torque that it is doing to ensure that the surface of the grasped object is not being damaged.

5.1. Distance measure (22)

In order to assist the gasping action, for example programming that the gripper closes automatically when the object is in the right position, a distance sensor is required. It is placed between the two fingers at the end of the shell. There are two possibilities for measuring the short distances: infrared sensors (IR) and ultrasonic sensors (US). To choose the best one, it is needed to know how they work.

- Infrared sensor

The infrared sensors can be used in several applications and one of them is short distance measurements. The most extended IR sensors for this purpose are called SHARP (See Figure 45).

Figure 45: Example of SHARP IR sensor

There are two major types of Sharp's infrared sensors based on their output: analog rangers and digital detectors. The first ones provide information about the distance to an object in the ranger's view. Digital detectors provide a high or low indication of an object whether if it is closer than a predefined distance or not.

These sensors use triangulation and a small linear CCD array to compute the distance or presence of objects in the field of view. In order to triangulate, a pulse of IR light is emitted by the emitter. The light travels out into the field of view and either hits an object not. In the case of no object, the reading shows that no light is reflected. If the light reflects off an object, it returns to the detector and creates a triangle between the point of reflection, the emitter and the detector as it is shown in Figure 46.

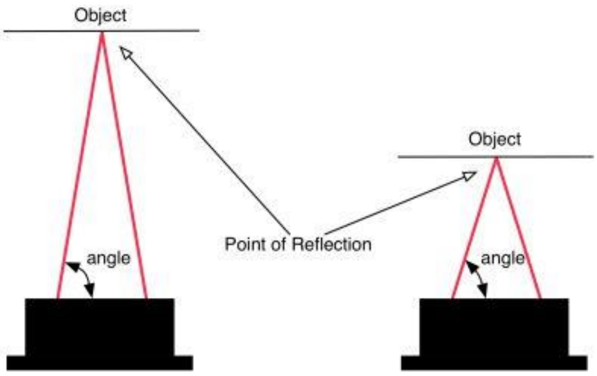


Figure 46: Distance measurement of IR sensors

The incident angle of the reflected light varies depending on the distance from the sensor to the object. The receiver led of the IR sensor is a precision lens that transmits reflected light onto various portions of the enclosed linear CCD array. The CCD array can then determine the incident angle, and thus calculate the distance to the object. This method of ranging is very immune to interference from ambient light and it is not affected by the color of the object that is being detected.

- Ultrasonic sensor

Figure 47: Example of ultrasonic sensor

The ultrasonic sensor (see Figure 47) radiates a sound pulse signal to the object and then receives a reflection sound signal ("echo"), back to sensor. The distance will be measured by calculating the reflection time interval between the target and sensor. Its actuating mechanism is illustrated in Figure 48.

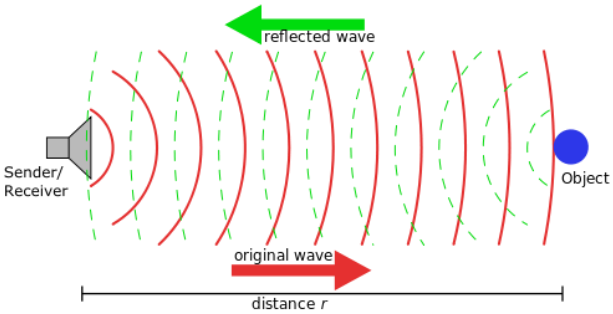


Figure 48: Distance measurement of ultrasonic senors

Ultrasonic sensing technology is based on the principle that sound has a relatively constant velocity. The time for an ultrasonic sensor's beam to strike the target and return is directly proportional to the distance to the object.

- Comparison (23)

Usually the ultrasonic sensors are more useful for larger distances than the infrared and in this case the minimum distance that should be measured is approximately 5 cm so it seems that IR will work better. In the table Figure 49 are summarized some specifications of the most extended two commercialized sensors. As said the IR measure shorter distances with better resolution but the most important thing is the beam width.

Sensor	MaxSonar LV EZ1	Sharp GP2Y0A02YK0F
Range	0.15 – 6.45m	0.2-1.5m
Resolution	2.54cm	1cm
Beam Width	± 30º	10º
Weight	4.3g	4.8g

Figure 49: Comparison table of ultrasonic and IR sensors

The sensor will be placed in the middle of the fingers it is essential not to detect them as if they were a grasping object. That is why the smaller beam width turns IR the best option. (See Figure 50).

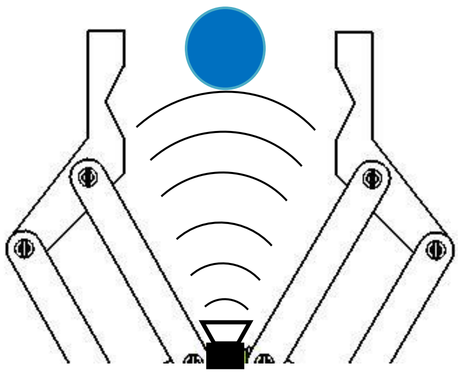


Figure 50: Distance sensor placed between the fingers

Once the IR has been chosen as the most suitable option, the different types of SHARPS are represented in Figure 51 and they mainly differ in the scope of vision.

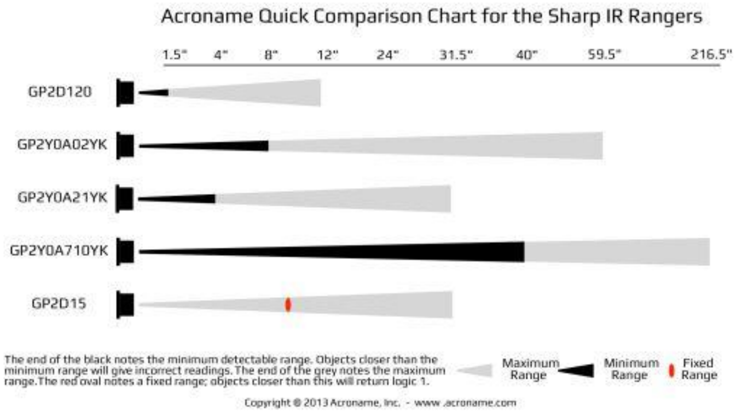


Figure 51: Comparison of the types of SHARP

They all have the minimum distance from where they start being effective and the maximum one that can discern, from there on non-object is detected. This two distances can be understood looking the output distance characteristics of Figure 52 where the result is not reliable before the peak of the curve. Although the GP2D120 would be more suitable, the GP2Y0A02 is being used because of availability issues and its datasheet can be found in the annex CD.

The read output of this sensor goes from aproximately 40 points when nothing is detected until aproximately 650 points when the object is 10 cm far from the sensor. Then the output value decreases again. The problem is that if the value is for example 400, there are two possible distances one before 10 cm and one after 10 cm and the user must know which one is it. Usually to avoid this problem the shorter distance sensor would be used but it can also be used if paying attention to this fact.

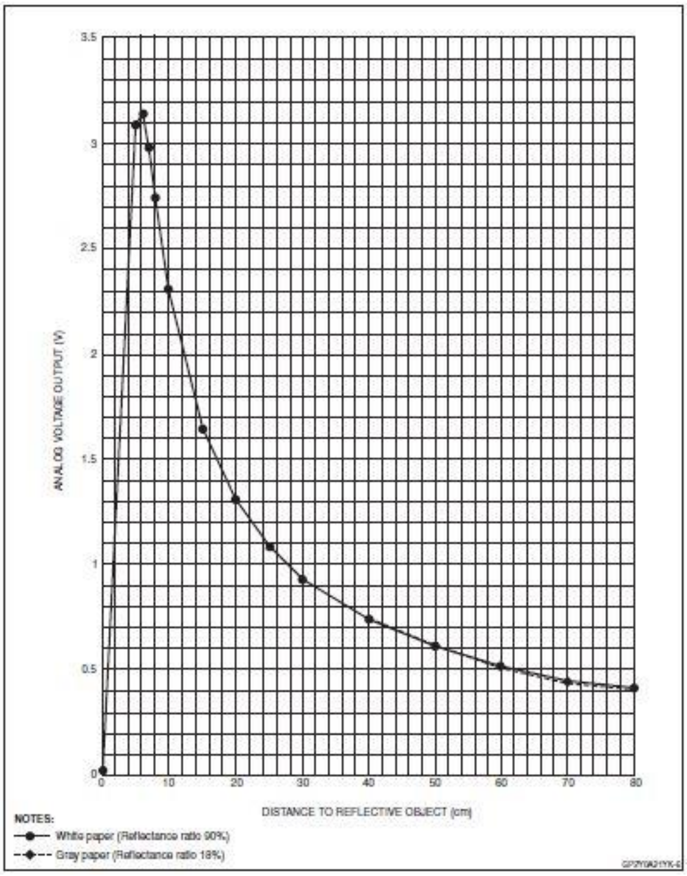


Figure 52: Output distance of Sharp GP2Y0A02YK

5.2. Force measure

Grippers interact with the work piece by the force exerted on their surface and there is a difference between grasping (prehension) and holding (retention) forces. While the grasping force is applied at the initial point of prehension (just during the grasping process), the holding force is maintained thereafter (until object is released). In the many cases the prehension force is higher than the retention force. Also when moving the grasped object, the acceleration achieves increases the prehension force needed.

Knowing the exact force needed for each of the mentioned cases requires a much deeper study. It should include an analysis of the contact areas between every object and the jaw and the exact friction coefficient with each material. It makes no sense for a gripper that is thought to be used in a wide variety of items. Also the frictions in the gears and in all the axis of the mechanism increases noticeable the torque needed in the motor. For this reasons the force study is only a brief approximation to know its order of magnitude.

An example of the torque needed for an empty beverage can in explained below. With the same procedure the torque for all the ten items of the list can be calculated.

The first step is to find the friction coefficient between plastic and metal, it can be found in Figure 53 (24).

Friction coefficient	Surfaces in contact
Wood on wood	0.25–0.50
Metal on metal	0.30–0.80
Plastic on plastic	0.10–0.30
Metal on plastic	0.10–0.20
Rubber on concrete	0.60–0.70
Rubber on tile	0.20–0.40
Rubber on wood	0.70–0.75
Bone on metal	0.10–0.20
Cartilage on cartilage	0.001–0.002

Figure 53: Aproximated friction coeficients

The second step is calculating the minimum grasping force that is a friction force (T). For that it is only necessary to pose a vertical balance of forces on the object, showed in Figure 54, with the mass of an empty can (18) that is 13 gram as follows:

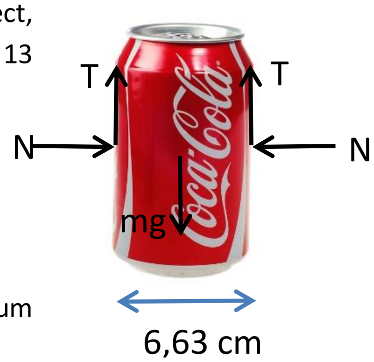


Figure 54: Force distribution on a can

$$\left.\begin{aligned} mg &= 2\cdot T = 0{,}013\ kg\cdot 9{,}81\frac{m}{s} = 0{,}128\ N \\ T &= 0{,}064N \end{aligned}\right\} \quad \text{(Eq. 5)}$$

With the condition for the stability of the prehension, the minimum force exerted with the jaws perpendicularly to the surface (N) can be found:

$$\left.\begin{aligned} T &\leq N\cdot\mu \\ N &\geq \frac{T}{\mu} = \frac{0{,}064\ N}{0{,}15} = 0{,}427N \end{aligned}\right\} \quad \text{(Eq. 6)}$$

Finally, using the force curve of the chapter 3.3, it can be found the relation between the force in the jaw and the torque in the actuator for the can diameter (18). As there is only one motor doing the forces of both jaws the real torque is double the one in the graph.

$$\left.\begin{array}{c} Minimum\ torque = N \cdot 2 \cdot \frac{torque}{force} = 0{,}427\ N \cdot 2 \cdot 3{,}38\ \frac{N \cdot cm}{N} = 2{,}88\ N \cdot cm \\ Minimum\ torque = 0{,}294\ kg \cdot cm \end{array}\right\} \quad \text{(Eq. 7)}$$

The minimum torque needed for an empty can is smaller than the recommended for the servomotor so it could be reliably grasped and be moved.

$$\left.Maximum\ stable\ torque = \frac{15{,}3}{5}\ kg \cdot cm = 5{,}1\ kg \cdot cm\ \right\} \quad \text{(Eq. 8)}$$

On the other hand, extrapolating the same calculations (Eq. 5, 6 and 7) to a full can the result is the opposite. The gripper is not stronger enough to grasp it stably.

$$\left.\begin{array}{c} mg = 2 \cdot T = 0{,}38\ kg \cdot 9{,}81 \frac{m}{s} = 3{,}7\ N \\ T = 1{,}86\ N \\ T \leq N \cdot \mu \\ N \geq \frac{T}{\mu} = \frac{1{,}86\ N}{0{,}15} = 12{,}43\ N \\ Minimum\ torque = N \cdot 2 \cdot 3{,}38\ \frac{N \cdot cm}{N} = 84{,}03\ N \cdot cm = \\ Minimum\ torque = 8{,}57\ kg \cdot cm\ > 5{,}1\ kg \cdot cm \end{array}\right\} \quad \text{(Eq. 9)}$$

With this procedure the torque needed for grasping any object can be approximately known to make sure if the gripper will be able to hold it.

The most fragile object of the list is definitely the egg. In order to know if the torque should be limited it is indispensable to know the force that needs to be applied to break an egg (25) and the diameter of a medium egg and then calculate the torque for breaking it:

$$\left.\begin{array}{c} Egg\ break\ torque = Egg\ break\ force \cdot \frac{torque}{force} (diameter\ of\ 4{,}5\ cm) \\ Egg\ break\ torque = 3{,}8\ kg \cdot 4{,}2\ \frac{N \cdot cm}{N} = 16{,}0\ kg \cdot cm \end{array}\right\} \quad \text{(Eq. 10)}$$

As the maximum torque achievable is 15,3 N an egg would most likely not suffer any damage. However, as the calculations are done with medium values and lack accuracy, to prevent the egg from break it will slightly limited, for example until its 80% of capacity.

5.3. Controller

A controller is a device which takes one or more inputs depending on their values adjusts its outputs for the purpose of a connected device functions in a controlled manner. In robotics it plays the role of the brain and it contains the programs, data, algorithms which enable it to perform.

There are many possibilities when choosing a controller. For this prototype the chosen one is CM-510 from ROBOTIS (26) (See Figure 55) due to its versatility and simplicity of programming because is particularly thought to control the Dynamixel servomotor that is being used. As the electronics are not yet inside of the shell, the size of the controller is not an important aspect but it should be changed as soon as the electronics needs to fit in the housing of the gripper. Its data sheet can be found in the annex CD. This controller includes:

Figure 55: CM 510 ROBOTIS controller

- 7 LEDs: power LED, three Status Display LED and three Mode Display LED
- 6 buttons: START, MODE and U/D/L/R and a power switch
- Buzzer
- 3 Pin Dynamixel ports and 5 Pin auxiliary devices ports (where the IR will be connected)
- PC Link (Serial Cable) and Communication Device Connection Jack
- Battery Jack and Power Jack

The ports that are used by the micro controller are summarized in the table from Figure 56.

Port Name	Function
PORTF1 ~ PORTF6	ADC
PORTD0	Start Button
PORTD1 ~ PORTD2	Tx, Rx
PORTA2 ~ PORTA7	External Output (5 Pin Port)
PORTC0 ~ PORTC6	Controller LED (Status, Power)
PORTB5	Buzzer Control Port
PORTE4 ~ PORTE6	Direction Button (U, D, L, R)
PORTD4 ~ PORTD6	Communication Control Port

Figure 56: Table with the Ports from the controller and its function

5.4. Programming

The gripper is controlled with embedded C language that is a set of language extensions for C language by the C Standards committee to address to different embedded systems.

The microcontroller that is used is ATmega2561 that is the high-performance, low-power Atmel 8-bit AVR RISC-based. It combines 256KB ISP flash memory, 8KB SRAM and 4KB EEPROM.

The different programs are created with *Amtel Studio 6* that is the new Atmel-ICE probe which provides advanced programming and debugs connectivity for Atmel ARM- and AVR-based MCUs, including the ability to capture data trace information. And it is compiled with *WinAVR* that is ATMEL's native compiler and it comes with a suite of executable, open source software development tools for the Atmel AVR series of RISC microprocessors hosted on the Windows platform. It includes the GNU GCC compiler for C and C++.

Finally the programs are transferred to CM-510 using the *RoboPlus* Terminal. RoboPlus is a software to create a customized program for every ROBOTIS product.

For controlling the Dynamixel motor (19), a specific library from ROBOTIS is being used (for reading or writing using serial there is also another library).

The Dynamixel control works with address for each parameter that can be found in the annex CD. There are a total of 49 addresses but for the gripper control there will be only used:

- Goal position (address 30, 31)

It is a position value of destination and 0 to 1023 (0x3FF) is available. As only 300^{o} are operating, the unit is 0.29 degree.

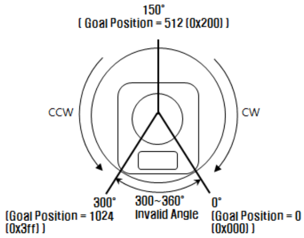


Figure 57: Scheme of the goal position

- Moving speed (address 32, 33)

It is the moving speed to Goal Position. It can go from 0 to 1023, and the unit is about 0.111rpm. If it is set to 0, it means the maximum rpm of the motor is used without controlling the speed and if it is 1023, it is about 114rpm.

In all cases the speed of the motor has been limited to the 5% of its capability to about 4.5 rpm in order to control in a better way the position of the object that is being grasped as well as the motion of the fingers.

- Torque limit (address 34, 35)

It is the value of the maximum torque limit. 0 to 1023 is available, and the unit is about 0.1%. For example, if the value is 512, it is about 50%; that means only 50% of the maximum torque will be used.

- Present position (address 36, 37)

It is the current position value of Dynamixel. The range of the value is from 0 to 1023, and the unit is 0.29 degree as for the Goal position.

Three main programs have been developed for operating with the gripper. The first one is completely manual; the user opens and closes the gripper pressing the buttons of the CM-510 without using the IR sensor. The second one is generally automated; when the sensor detects an object between the fingers it will close until the torque that it is doing achieves the limit that has been set because an object has been encountered. The third one is automated for specific items; for a particular object, the gripper will only close its fingers when the object is exactly placed in the better distance to be grasped and it will stop its closure at the appropriate point.

Manual mode

The program starts including the Dynamixel library and initializing the used parameters. Then it goes the initialization of the buttons L (left) and R (right) than will be used for closing and opening the gripper successively. At the beginning the goal position is defined as the present position of the servo. If the left button is pressed and it is not completely closed its goal position will increase 10 points and if the right button is pressed and the gripper is not completely opened its goal position will decrease also 10 points.

Generally automated mode

This mode will detect than an object is close enough to the sensor to be grasped and then the fingers will start closing until they find an object and the torque gets to the set limit. The initialization of the closure of the finger is automated but the user should manually place the object to the right place while the gripper is closing. There is also a LED alarm that shows how close the object from the sensor is. At the beginning all the LEDs are switched off and when the seventh is turned on the closure starts.

The program also starts including Dynamixel library and initializing their parameters and also including the IR sensor and the LEDs. At the beginning the goal position is completely open and while the gripper is not moving the IR will be checking how far the next object is and turning on the LEDs consequently. When the object is in the middle of the fingers the goal position will be changed to the total closure. The torque will be slightly limited (to its 80%) to make sure that none of the objects are damaged, especially the egg. The fingers will be closing until they achieve this limit and then the object will be grasped.

Particularly automated mode

In this mode every object will be grasped taking into consideration their size and shape. It has empirically been found the exact distance to the sensor for the perfect grasping as well as the final position of the motor for it. Each object has assigned a number from 0 to 9 as seen in that it will be introduced by Serial before grasping. Then the two parameters will be adjusted to this particular item with Figure 58 . The two parameters have been empirically found for each object grasping them in the manual mode and doing an average of the results. All the distances are less than 10 cm so the program will wait until the peak of the curve is registered and then compare the output value of the IR with the wanted distance.

The program also includes a LED alarm to point out when the wanted distance has been achieved and the item needs to remain in that position.

Numb	Items	Distance	Goal Pos	**Numb**	Items	Distance	Goal Pos
0	Plastic bottle	489	396	**5**	Cardboard box	451	375
1	Beverage can	618	355	**6**	Fable's brick	390	170
2	Egg	439	413	**7**	Cup	440	334
3	Shoe	602	282	**8**	Marker	639	490
4	Orange	473	358	**9**	Teddy	631	409

Figure 58: Distance and Goal position parameters for each item

6. Experiments

In order to measure up the goodness of each prototype and each mode, some tests will be passed. They will evaluate the ease of picking an object in the normal way, with some misalignment and the stability of the prehension with a rotation. Finally it will also grade the complexity of its assembly of each prototype.

As the first prototype has not IR sensor only the manual mode can be tested (test 1) whereas in the second prototype can be manually tested (test 2) but also it can be tested with the generally automated mode (test 3) and the particularly automated one (test 4). I.e. a total of four tests described as follows will be reproduced.

6.1. Test description

Each test consists of three types of grasping: normal grasping, misaligned grasping and grasping with rotation. In one test, each of the ten objects will be grasped with each of the three grasping types and it can either pass (1) or fail (0) the attempt. It will be reproduced three times as replicas to have a more reliable result, so a total of 90 results (1 or 0) will be obtained per test. To make sure that each object is always grasped in the same way it has been defined its transversal axis that is showed in Figure 59 in red.

Figure 59: Ten items with transversal axis in red

This axis (red line) always needs to be content in the green plane shown in Figure 60 that is defined as the one parallel to both jaws (orange planes) and crosses its middle point (blue circle).

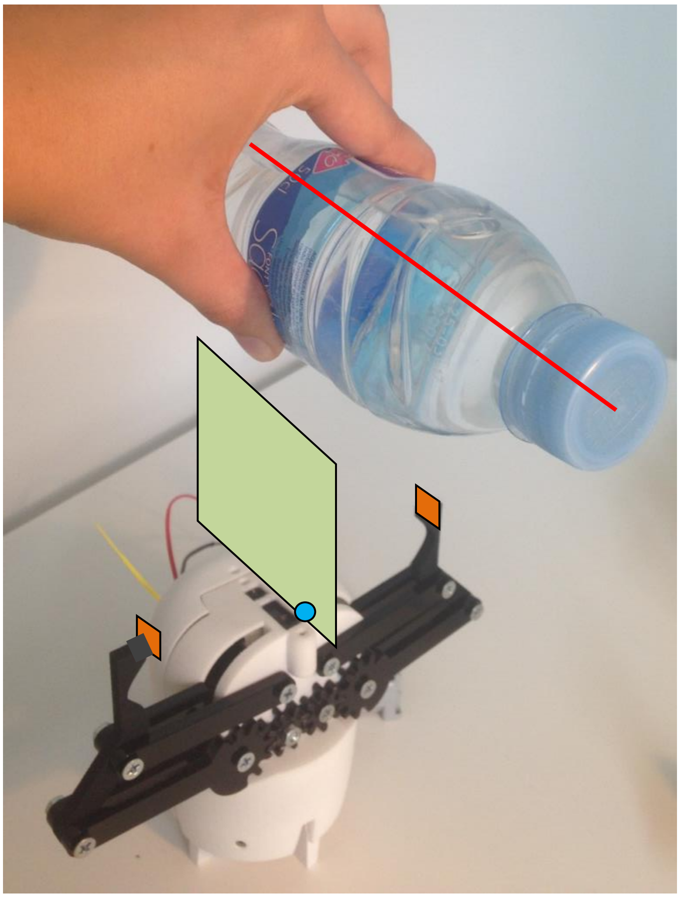


Figure 60: Positioning of the items when being grasped

- Normal grasping

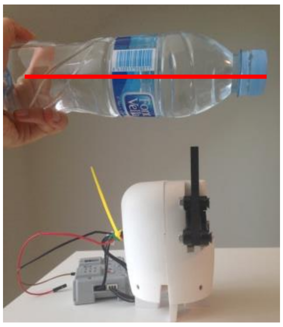


Figure 61: Normal grasping

Keeping the gripper still on the table in its open position; each item is grasped approaching the gripper from the top with the transversal axis placed parallel to the floor. Once the object has been grasped it must be held during two seconds and then open the fingers and drop the object. It will evaluate if it can grasp objects in the easiest way possible.

- Misaligned grasping

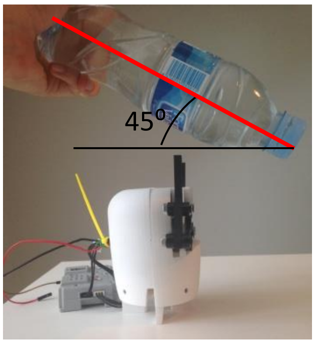


Figure 62: Missaligned grasping

It consists on the same procedure than the normal grasping but rotating the object 45 degrees when approaching the item. Keeping the gripper still on the table in its open position; each item is grasped approaching the gripper from the top with its axis contained in the middle plane but with the 45º relative to the ground mentioned. After two seconds the gripper opens dropping the object. It will evaluate the reliability of the design when misalignments occur.

- Rotation

If the object has succeed the normal grasping, the item is grasped again and then the gripper is rotated 90º to each side. It will check if it is stable enough to persist grasped when the gripper rotates.

6.2. Procedure

The experimentation will go through the four tests as follows. In the results table of each test there are the three replicas and the average of every grasping type for each object and also a last column with the total average of each object and the sum of them provides a grade from 0 to 10 of how successful the test has been.

Test 1

The first prototype is connected to the controller and to the computer and the program *1.MANUAL* that can be found on the attached CD is loaded.

The first object is manually located between the jaws as explained before and with the L button the jaws are closed until the object is subjected. If after two seconds the object is still held with the gripper, it can now be opened with the R button and the attempt is passed so the result is 1, otherwise the attempt is failed and the result is 0.

This sequence is repeated is repeated with the ten objects Then objects are grasped in their fixed order and the results are written down in the table. Then the ten objects are grasped again in normal grasping manner in the same order and then a third time. Finally the average of the three replicas is calculated.

The same procedure is done with misalignment and rotation. All the results are summarized in the table from Figure 63.

TEST 1	Normal grasping				Misaligned grasping				Rotation				TOTAL
0. Plastic bottle	1	1	1	1	1	1	1	1	1	1	1	1	1
1. Can	1	1	1	1	1	1	1	1	1	1	1	1	1
2. Egg	1	1	0	0,667	0	0	1	0,333	0	1	0	0,333	0,444
3. Shoe	1	1	1	1	1	1	1	1	1	1	0	0,667	0,889
4. Orange	1	1	1	1	1	1	1	1	1	1	1	1	1
5. Box	1	1	1	1	1	1	1	1	1	1	1	1	1
6. Fable's brick	1	1	1	1	1	1	0	0,667	1	0	1	0,667	0,778
7. Cup	1	1	1	1	1	0	1	0,667	1	1	1	1	0,889
8. Marker	1	1	1	1	1	1	1	1	1	1	1	1	1
9. Teddy	1	1	1	1	1	1	1	1	1	1	1	1	1
													9

Figure 63: Table with the results of the test 1

Test 2

The second prototype is now connected to the controller and to the computer and the same program *1.MANUAL* from the CD is used.

The procedure is exactly the same as in test 1 and the results are in the Figure 64.

TEST 2	Normal grasping				Misaligned grasping				Rotation				
0. Plastic bottle	1	1	1	1	1	1	1	1	1	1	1	1	1
1. Can	1	1	1	1	1	1	1	1	1	1	1	1	1
2. Egg	1	1	1	1	1	1	0	0,667	0	1	1	0,667	0,778
3. Shoe	1	1	1	1	1	1	1	1	1	1	1	1	1
4. Orange	1	1	1	1	1	1	1	1	1	1	1	1	1
5. Box	1	1	1	1	1	1	1	1	1	1	1	1	1
6. Fable's brick	1	1	1	1	1	0	1	0,667	1	1	1	1	0,889
7. Cup	1	1	1	1	1	1	1	1	1	1	1	1	1
8. Marker	1	1	1	1	1	1	1	1	1	1	1	1	1
9. Teddy	1	1	1	1	1	1	1	1	1	1	1	1	1
													9,667

Figure 64: Table with the results of test 2

Test 3

The second prototype is again connected to the controller and the computer and the program *2. GENERALLY AUTOMATED* is loaded.

The first object is normally approached to the griper from the top and the IR sensor is calculating the distance to it. When the object is located between the fingers they are start closing and the user has to manually place the object in the right position centered in the jaws. If it is held after two seconds the attempt is passed, the program must be reinitialized and the second object can proceed.

Again the ten objects are orderly grasped three times in each grasping mode and the results are in Figure 65.

TEST 3	Normal grasping				Misaligned grasping				Rotation				
0. Plastic bottle	1	1	1	1	1	1	1	1	1	1	1	1	1
1. Can	1	1	1	1	1	1	1	1	1	1	1	1	1
2. Egg	0	0	1	0,333	0	0	0	0	0	0	1	0,333	0,222
3. Shoe	1	1	1	1	1	1	1	1	1	1	1	1	1
4. Orange	1	1	1	1	1	1	1	1	1	1	1	1	1
5. Box	1	1	0	0,667	1	0	0	0,333	1	1	0	0,667	0,556
6. Fable's brick	0	1	1	0,667	1	0	0	0,333	0	1	1	0,667	0,556
7. Cup	0	0	1	0,333	0	1	0	0,333	0	0	0	0	0,222
8. Marker	1	1	1	1	1	1	1	1	1	1	1	1	1
9. Teddy	1	1	1	1	1	1	1	1	1	1	1	1	1
													7,556

Figure 65: Table with the results of test 3

Test 4

For the last test, the second prototype is also used. It is connected to the cm-510 and to the computer the program *3.PARTICULARLY AUTOMATED* is loaded.

When it is executed the fingers go to the open position, then one number is introduced by Serial in order to adjust the parameters of distance to the sensor and goal position of the motor to its right value for that particular item.

The object needs then to slowly approach the gripper from the top until all the LEDs are turned on to show that the distance to IR has been achieved and then remain in that position while the fingers grasp it. When any letter is introduced by Serial the gripper will opens again and it will be ready for the next attempt.

With this procedure the test is executed starting with normal grasping, misaligned and the rotation one and all the results are in Figure 66.

TEST 4	Normal grasping				Misaligned grasping				Rotation				
0. Plastic bottle	1	1	1	1	1	0	1	0,667	1	1	1	1	0,889
1. Can	1	1	1	1	1	1	1	1	1	1	1	1	1
2. Egg	0	0	1	0,333	0	0	0	0	1	1	1	1	0,444
3. Shoe	0	1	1	0,667	1	1	0	0,667	0	1	1	0,667	0,667
4. Orange	1	0	1	0,667	1	1	1	1	1	0	1	0,667	0,778
5. Box	0	1	1	0,667	1	0	0	0,333	0	0	1	0,333	0,444
6. Fable's brick	1	1	0	0,667	1	0	0	0,333	0	1	0	0,333	0,444
7. Cup	0	0	0	0	0	0	0	0	0	0	0	0	0
8. Marker	1	1	1	1	0	0	1	0,333	1	1	1	1	0,778
9. Teddy	1	1	1	1	1	1	1	1	1	1	1	1	1
													6,444

Figure 66: Table with the results of test 4

6.3. Building complexity and price

For quantifying the building difficulty, it is necessary to consider the number of pieces that are needed. On the one hand the number of plastic pieces as laser cut, 3D printed or any others; and on the other hand the number of screws and bolts that are used to fix it all together. Thirdly, the time that is required for assembly the prototype from all the separated pieces is also crucial when determining its building complexity. The results are found in Figure 67.

	Prototype 1	Prototype 2
Num. plastic pieces	18	18
Num. of screws	24	25
Time to assembly	15 min	40 min

Figure 67: Building complexity of both prototypes

The price of both prototypes is disaggregated in the Figure 68. The price of the screws and nuts has been underestimated compared with the price of the rest of the components.

	Prototype1	Prototype 2
Dynamixel AX-12A (27)	44,90 $	44,90$
12 V battery (28)	9,95$	9,95$
CM-510 controller (29)	79,90$	79,90$
Laser cut modeling	55,18$ (370,43 DKK)	27,92$ (187,41 DKK)
Bioloid frames (30)	2,98$	1,49$
SHARP (IR sensor) (31)	-	13,95$
3D printing modeling	-	75,97$
TOTAL	**192,91$**	**254,08$**

Figure 68: Disaggregated price of both prototypes

6.4. Discussion of the experiments

The results of the experiments can be evaluated separately test by test and object by object. However, the most interesting thing is to compare the different tests to see what have changed between the first and the second prototype as well as the differences between the three programs.

- Success of each test

Focusing on the general punctuation of each test it can be seen that the test with a higher punctuation is the second one with a 9.7 and it corresponds to the second prototype and manually mode. The second one with a slightly lower grade is also manual but first prototype, test 1 with a 9. Test 3 and 4 are quiet far from the others with a punctuation of 7.5 and 6.4. In any case, all of the tests have had a satisfactory result.

- Success of each object

About the objects, the most difficult to be grasped has been the egg, it has only passed 47% of attempts. The second one is the cup with passed the 53% of attempts and the third one the Fable's brick with a 67% of success. The main reason seems to be that they are completely non-deformable so the contact surface is very small. On the contrary, the teddy has been grasped the 100% of the attempts and its deformability is obvious.

- Comparison of test 1 and 2: prototypes changes.

The two prototypes have only two differences when using the manual mode. The new design of the jaws is the main change suffered in the second one but also it has been taken into consideration the loss of material when laser cutting the gears. These developments are reflected in the results but the change is only a 7% of improvement.

- Comparison of test 2, 3 and 4: programming changes

The main difference between the three programs is how much the user interferes in the control of the grasping action and how much is automated. It can clearly be seen that the best one is when everything is under the user control.

When the IR sensor acts, the results have worsened in a 15% so this is something to continue working on. Probably with the most suitable senor, the automated control would be better. Between test 3 and test 4 the difference is not that big but again it works better the one that is not totally automated and the user is responsible of part of the control.

- Building complexity

Although the two prototypes have more or less the same pieces, the assembly time is almost triple in the second one. This can be explained because inside the shield the access is more difficult and it takes more time and also in the second prototype everything is better subjected than in the first one.

- Price

The second prototype is clearly more expensive than the first one but it must be taken into consideration that it includes the IR sensor and a shield to cover the drive chain. Also this price has nothing to do with the expected for the final version because the 3D printing and laser cut are much more expensive than injection modeling when a large number of items are made.

7. General discussions

At this point, it can be said that the gripper has achieved its main purpose of grasping the ten objects with a great success, up to 97%. However, there are several improvements that need to be included in the future development, mostly to decrease the price and volume of the gripper.

After a depth study of the types of grippers that exist, the simulations of different mechanisms have been vital to choose the best design of one degree of freedom. It also leaves an open door to investigate whether the benefits of two degrees of freedom outweigh its building and controlling complexity.

Reviewing the requirements, the maximum distance between the jaws has always been the right one as well as the two points of contact to ensure the right stability. The closed housing and the incorporation of Fable's connectors system have been achieved in the second prototype. The distance to the object and force control is also included in the second prototype but without the accuracy that it should. The injection modeling, price and robustness requirements are more focused on the final version and they cannot be ensured yet but the three of them are likely to be accomplished without difficulties.

The iterative manner of designing has been really useful to first focus on the gripper mechanism design and the drive chain and only once seen that they were properly working, then think about the housing and sensors.

The next modifications that the gripper should face are in the first place changing the screws and nuts that perform as axis of the mechanism for a better option. In the second place using a more suitable IR sensor or even build it with two diodes because it would be smaller and cheaper although probably more difficult to control. And thirdly changing the servomotor to another smaller and cheaper but with the same or ever bigger torque capacity. It would be useful to choose a servomotor with force control included but this is also something that could be built separately.

As the experiments showed that the most difficult objects to grasp are the non-deformable and non-cylindrical a new jaw design could also be considered using a softer material to increase the contact area.

Finally, in order to be a real Fable system module it definitely needs to include the electronics inside the shield and also enable the wireless communication by radio. For that purpose it needs to change the CM-510 controller to a smaller board.

When all these modifications are applied the prototype will be extremely close to the final version.

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