Design Methodology & Mechatronics 1

PROJECT REPORT

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Engineering Sciences

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1 Introduction

For years, the industry has become more and more automated. From big robots transporting heavy loads to small automated devices used for a precision unachievable by a human worker, each industrial field has specific type of robots to help in various tasks. One important feature that most robots need at this time is the ability to work safely with humans in a collaborative way. This is the reason why those robots are called *cobots*.

Figure 1: Typical application of a cobot [1]

Indeed, the robots often manipulate sharp or hot tools to achieve their functions. Therefore, the cobots needs to be harmless either by a clever stopping program preventing the robot to hurt a human when it detects an abnormal resistance or by using soft robots perfectly safe.

Moreover, the food industry has become gradually automated by the use of automated sorting, washing, cutting, among others. But, in the case of small industries, the company cannot afford to buy a big expensive robot for each types of fruit or vegetable they are selling. In this context, the company needs small automation ways to reduce their cost and improve the rapidity of the industrial process between the harvesting and the selling in the market. On top of that, the devices need to be able to handle fragile things such as tomato, peach, apricot, and so on.

2 Project statement

As mentioned before, small food companies have a problem to optimise and speed up their production chain process but have a very low budget. Besides, those enterprises produce various fruits and vegetables along the year and need one production chain applicable to most types of fruit. Moreover, there is a big interest in small local companies on today's market. Therefore, the small companies need to increase their supply to counter the increasing demand.

The solution proposed to those companies is an inexpensive automated sorting process flexible enough to work with lots of fruit and vegetables and speeding up the production chain. It is very important that the product is low-cost to allow the small companies to buy several to support the workers and the process. Thus, the fruit amount produced by the companies can be increased in an inexpensive and durable way. Especially in the coronavirus context, it is vital that the companies can continue to produce food for the population without putting the workers in danger as much as possible. Using both robots and automated process is a way to ensure the production without putting lots of workers exposed to the virus.

2.1 Need Identification

To have a clear vision of the need, a first global need analysis is performed in the table below.

Utility	Sort fruit and vegetables
User	Food industry
Interference with	Workers, Conveyor belt, fruit/vegetables

Table 1: Need analysis

As explained before, the product is aimed to be a sorting process for the food industry that needs to be able to work with the humans. More precisely, the product needs to be fast to sort the fruit as his main aim is to increase the production speed. As it will probably work side by side with human workers, the product has to be human safe. It will need to move and sort the fruit without harming it and to be food safe. Finally, the product's maintainability is also a key factor in today's market. All those needs are summarised in the following table.

Needs	**Objective/Subjective**
Speed	Objective
Human safe	Objective
Food safe	Objective
Not harming the fruit	Objective
Move and sort fruit	Objective
Maintainable	Objective
Low cost	Subjective

Table 2: Needs

2.2 Functions

External principal functions	**Constraints**	**Internal Functions**
Autonomous system	Not damage the fruit	Range sensor to detect change of height on the conveyor belt
Automatic fruit detection	Cold environment	Gripper to hold firmly the vegetable without squeezing it
Pick up fruit	Adapted to conveyor belt speed	Matureness sensor to detect the maturity of the fruit
Move fruit	220V input	
Matureness detection	Gripper	
Low cost		
Reliability		

Table 3: Different functions and constraints applied to the product

The external functions are directly useful to the customer while the internal functions depend already on design choices. As mentioned before, the product needs to be autonomous and sort the fruit. It has been decided that the product is going to be focused on fruit matureness detection. Very often, the food warehouse are maintained to a cold temperature for better preservation of the food. Therefore, the product needs to be able to handle cold environment. Finally, as this project is linked to the mechatronics 1 project, it is asked from us that the design contains a gripper.

2.3 Requirements list

The requirements are taken from studied conveyor belts and concurrent sorting systems. A classical conveyor belt for fruit can have various widths but very often it is around 50cm. The product needs to cover at least 60cm in order to put the fruit on the right side next to the conveyor belt for sorting. To be able to catch all the moving fruits, the robots needs a distance of 30cm to have the time to detect and sort all the fruits. Indeed, those distances can easily be adapted to the customer's conveyor belt.

As it needs to move without hitting the fruits on the conveyor belt, the gripper must lift up to at least 10 cm which gives a global value of around 25cm height for the structure. The radius of an apple for example is around 3cm in average. Most fruits follow the same dimensions or smaller so the object radius is set to 3cm.

The global time to sort the fruits is imposed to be 10 seconds in order to have the time to take all the fruits while the conveyor belt is moving. This time is divided into the motion in X and Y directions which can be very fast as the precision is less important. It is estimated to around 2 seconds and can be lower but not higher in order to stay below the 10 seconds for the whole process. The motion in Z direction on the contrary will need precision as the gripper must hold the fruit in a good way and cannot miss it. The same applies for the time of the motion in Z, it is estimated at 2.5 seconds and cannot be higher. Also, the closing time of the gripper needs to be taken into account as it cannot be instantaneous. It is set to 0.5 seconds but can vary depending on the gripper type.

All this time for moving the gripper and taking the fruit needs to be doubled as the gripper will drop the fruit at the right location.

After research, the average weight of an apple is around 200g so the load considered in the requirements list is 250g in order to handle the variations of the fruit's weight. For obvious reasons, the gripper needs to be made in a material compatible with food.

For security matter and to protect the material and the people, the gripper must stay up when a current breakdown occurs. Besides, the robot will very likely work with other human workers. Therefore, it must be safe to work with humans.

When sorting the fruit, the gripper must not damage it. The percentage of damaged fruits must be close to zero. It is set around 0.1% but is expected to be as low as possible.

For simplicity reason, the robot needs to be able to be plugged in a commercial plug of 220V.

As the target customer is the small companies that sell different types of fruit, the robot must have a way to switch between the type of sorted fruit. This way, the robot can handle different seasonal fruit according to the production.

By looking to the concurrent robots, the precision of the fruit matureness (the percentage of error in the fruit detection) is from 95% to 99%. As the product designed is made to be cheap and target smaller companies, the robot can have a precision around 95%. This is not extremely high but as the robot is made to be cheap and to speed-up the chain process, it is sufficient in order to increase the productivity of the process.

In the food industry, the fruit and vegetables are stored and processed through a cold environment to have a better preservation of the food. The temperature for the fruit and vegetables stands usually between 5 and 10°C. The product is thought to be used at 10°C but needs to be able to handle various environments, even outside temperature up to 30°C.

The selling price is low because the customer is small companies with small budget. It will depend on some design choices but the low-cost rivals have products between 1000 and 2000€. Therefore, the product we want to sell have to place itself below the rivals. The price is then set around 700€ but can of course variate depending on the design.

By taking into account all the processing, the workers and the machines to build the robot, the material price must be around 300€ to be able to make some profit.

The working days are approximately 20 days per month, the Mean Time Between Failure is set to 1 year of working days during which the robot is sorting 8 hours per day. This gives us a MTBF of 20 days$*$12 months$*$8 hours = 1920 hours.

Due to the course requirement, the product needs to be entirely designed in 2 months maximum.

Finally, including all the requirements previously mentioned in the following table, we get a complete requirements list allowing the team to begin the design choices of the product.

Categories	Item	Value	Flexibility	Importance
Geometry	Distance covered in the belt direction	30cm	+/- 10cm	++
	Distance covered perpendicular to the belt	60cm	+/- 20cm	+
	Height dimension	25cm	+/- 5cm	++
	Object radius	3cm	+/- 2.5cm	+
Kinematics	Time to reach to the Y position of the object	2s	-1.9 ; 0	+
	Time to lift the object to the top height	2.5s	-2.4 ; 0	+
	Closing gripper time	0.5s	-0.4s ; +0.5s	+
Forces	Load	250g	-150g ; +350g	++
Materials	Food safe	V	None	+++
Safety	Not falling when current is off	V	None	++
	Safe to work with humans	V	None	+++
Quality control	% of damaged fruits	0.1%	-0.1% ; 0	++
Energy	To be plugged in commercial plug	220V	None	+
Operation	Able to change the type of sorted fruit	V	None	++
	Precision of matureness detected	95%	+/-5%	+++
	Temperature of environment	10°C	-5°C ; +20°C	+
	Speed lost in chain process	0	None	++
	Food industry	V	None	++
Cost	Selling price	700€	+/- 100€	++
	Material price	300€	+/-50€	+
Maintenance	Mean Time Between Failure	1920h	+/-10%	++
Schedules	Developing time	2 months	None	+++

Table 4: Requirements list

3 Conceptual design

3.1 Essential problems

The final product needs to detect the fruit, move it and sort it. For the matureness detection, several solutions exist. The two most used are the colour identification or the texture of the fruit (a mature fruit is softer than a non-mature one). But, the texture identification requires more expensive gripping mechanics or may damage the detected fruit. Therefore, the product will detect the matureness of the fruit by their colour for simplicity in order to provide an inexpensive solution. By deconstructing the motion of the robot, we can divide the functions into the following table:

	Essential problems
1	Finding fruits on the conveyor belt
2	Getting to the fruits on the conveyor belt
3	Grabbing the fruits on the conveyor belt
4	Identifying the matureness of the fruits based on their colour
5	Transferring the fruits to the sorting area
6	Doing the sorting autonomously

Table 5: Essential problems

Now, those problems need to be transformed into the physical means to allow us to draw all the possible solutions for each problem.

Essential Problems	**Features**
1	Means of object detection
2	Means of displacement
3	Means of grabbing the object
4	Means of colour identification
5	Means of position control
6	Means of autonomous system

Table 6: Problems and Features

Some means in the table 6 can be split up into more precise categories. The means of displacement is split into the XY axis motion features (as those are the same) and the Z motion. The motions are constituted of motors and a transmission process. Then, the grabbing is made of the gripper itself and its actuation. Finally, the robot needs to be autonomous, therefore it needs an electronic control board and it needs power in order to supply all the motors and the electronics. All the features that needs means are listed in the table below. The possible solutions are added to each feature.

Features	Means
Power	Electric, Steam, Petrol, Diesel
Displacement	Cartesian, Cylindric, Spherical, Articulated, Parallel
XY axis Transmission	Belt, Screw, Gears, Chain
Motors	Stepper, DC motor, Servomotor
Z axis transmission	Belt, Gears, Screw, Rack and pinion
Object detection	Camera, Ultrasonic distance sensor, IR distance sensor, Sharp IR distance sensor
Grabbing	Soft gripper, Mechanical gripper, Vacuum gripper, Magnetic gripper
Grabbing actuation	Pneumatic, Electric
Position control	End-course switch, Rotary encoder
Matureness identification	Camera, Colour sensor, Pheromon sensor
Operation	Manual, Automatic
Control	Arduino, Raspberry Pi, Computer

Table 7: Total features and possible means

3.2 Possible concepts

As the choices we have are numerous, we considered three concepts regrouping almost all of the possible choices to have a better vision of the concept. But, the robot will be a cartesian electric-powered robot as it is the most adapted for the conveyor belts and the easiest allowing us to make the product within two months.

The first design consists of lead screws mechanisms for the XY motions and for the Z motion. Those lead screws are driven by motors, two on the back for the X-direction and one at the end of the lead screw (not represented for clarity of the drawing) for the Y-direction. The Z-direction follows the same principle. Finally, a mechanical gripper is attached to the Z lead screw with a nut and is moving up and down as the motor rotates. The gripper in itself is moved by a servomotor.

The second design is made of belts for the XY motions. There is one motor with a power shaft for the X-direction as the two belts must move together, it is more relevant to have only one motor for both and saves money. The Y-direction is also driven by a motor close to the structure (not represented on the drawing). The Z motion is provided by a motor with a moving lead screw with a fixed nut on the YZ support. The gripper is a soft pneumatic powered gripper with three fingers.

The last concept shows a structure with chains for the XY motions driven the same way as the belts in the second design. The Z-motion is created thanks to a fixed rack with a moving pinion. Attached to this pinion is a motor for the motion and a vacuum gripper.

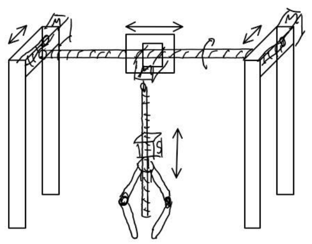

Figure 2: First concept

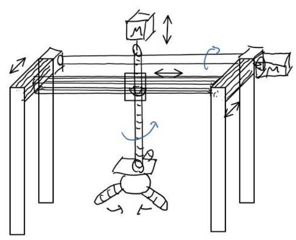

Figure 3: Second concept

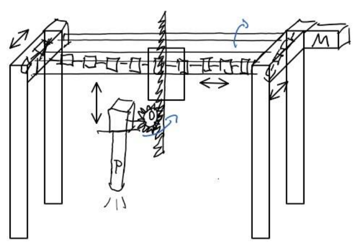

Figure 4: Third concept

To compare those concepts, the different solutions with the required characteristics are compared. Then, the most adapted design choice will be determined using points if it fulfills our requirements.

3.3 Morphological Chart

The different choices mentioned in the table 7 will now be compared. We will compare them on different criteria. The first one is the compatibility with the overall task. In our case, is it compatible with the robot being in a chain process in a company warehouse for sorting fruit. It is not directly connected to the requirement list yet. The second is: does it fulfil the demands of the requirements list. Then, is it realisable in principle (in term of performances, knowledge, and so on). Another important point is, is it doable within permission costs as we have a limited budget, it is important that the solution is not too expensive. Finally, very important factor is the safety one. Does this solution incorporate direct safety measures. In our case, it is very important that the robot is perfectly safe and cannot harm a worker under any circumstances.

Features	Means	Compatibility assured	Fulfils demands of requirements list	Realisable in principle	Within permission costs	Incorporate direct safety measures	Remarks	Decision
Power	Electric	+	+	+	+	+		+
	Steam	-	-	+	-	+	Difficult to implement	-
	Petrol	-	-	+	-	+	Too much power for what is needed	-
	Diesel	-	-	+	-	+	Too much power for what is needed	-
Displacement	Cartesian	+	+	+	+	?	Rigid	+
	Cylindric	+	+	?	?	-	Need more space around	?
	Spherical	!	+	?	-	-	Hit the fruits on the front	-
	Articulated	+	+	+	-	-	Hard to implement	-
	Parallel	+	+	?	-	-	Need special upper fixation	-
XY axis	Belts	+	+	+	+	?	Fast and cheap	+
	Screw	+	-	+	+	?	Slow	-
	Gears	?	-	-	+	?	Difficult to implement	-
	Chains	?	?	+	-	?	Heavy	-
Z axis	Belts	+	+	-	+	-	Dangerous	-
	Gears	+	?	-	+	?	Difficult to implement	-
	Screw	+	+	+	+	+	Slow but precise and safe	+
	Rack and pinion	+	+	+	-	+	Less precise and less safe	?
Motors	Stepper	+	+	+	+	+	Fast and reliable	+
	DC	+	+	+	+	-	No position control	-
	Servo	+	-	+	+	+	Limited angle, not suitable	-
Object detection	Camera	-	-	+	-	+	Too much information to process	-
	Ultrasonic distance sensor	+	-	+	+	+	Range not suitable	-
	IR distance sensor	+	-	+	+	+	Environment not suitable	-
	Sharp IR distance sensor	+	+	+	+	+		+
Grabbing	Soft Gripper	+	+	+	+	+		+
	Mechanical Gripper	-	-	+	+	-	Not compatible with fragile object	-
	Vaccuum Gripper	+	-	+	+	+	Suction might squeeze the current object	-
	Magnetic Gripper	-	-	+	?	+	Used for magnetic objects	-
Grabbing actuation	Pneumatic	+	+	+	+	+		+
	Electric	-	-	-	+	+		-
Matureness identification	Camera	-	-	+	-	+	Too much information to process	-
	Colour sensor	+	+	+	+	+	Precise enough for fruits and vegetables	+
	Pheromon sensor	-	-	?	?	?		-
Operation	Manual	+	-	+	+	-	Need human input	-
	Automatic	+	+	+	+	+		+
Control	Arduino	+	+	+	+	+		+
	Raspberry Pi	+	-	+	-	+		-
	Computer	+	-	+	-	+		-

Figure 5: Selection chart

The chosen means are highlighted in green in the table. Now, to have a better justification for the previous table, the key points will be compared next to our requirements (with [2]).

First, the XY motion is compared. We need a medium speed and medium precision as the motion needs to be fast. The load is light because the fruit and the gripper are supposed to be very light. Also, the price is a key factor so it needs to be cheap. For the rest (lifetime and lubrication), there are no requirements but for example the bigger lifetime, the better it is.

XY axis						
	Speed	**Load**	**Lifetime**	**Price**	**Precision**	**Lubrication**
Requirements	Medium	Light	/	Low	Medium	/
Belts	Medium to High	Light	Small lifetime	Low	Medium	No need
Screw	Low	Medium	Medium	Low	High	Needed
Gears	High	High	High	High	High	Needed
Chains	Low	Medium	Medium	Medium	Low	Recommended

Table 8: XY justification

From this table, the only mean that fulfils all of our requirements is the belts.

Same applies for the Z motion. Here, the speed can be low but we need a higher precision.

Z axis							
	Speed	**Load**	**Lifetime**	**Price**	**Precision**	**Lubrication**	**Safety**
Requirements	Low	Light	/	Low	High	/	High
Belts	Medium to High	Light	Small lifetime	Low	Medium	No need	Low
Screw	Low	Medium	Medium	Low	High	Needed	High
Rack and Pinion	High	High	High	High	High	Needed	Medium

Table 9: Z justification

The lead screw is then the only reasonable choice that fulfils our needs. Event though, it adds a lubrication problem.

For the motors and the gripper, we have several choices.

Motors		
	Speed	**Working Temperature**
Requirements	30 cm/S	8-30°C
Stepper	V	V
DC	V	V
Servo	X	V

Table 10: Motor justification

Actuated Gripper			
	Speed	**Cost**	**Delicacy**
Requirements	High	Low	High
Soft	High	Low	High
Mechanical	Medium	Medium	Low
Vacuum	Medium	Medium	Medium
Magnetic	High	High	Low

Table 11: Gripper justification

Both stepper motors and DC motors are sufficient for our requirements. But, in order to have an easy position controlling, we will use stepper motors. Concerning the gripper, the soft gripper is the chosen one.

We need a distance sensor for detecting the fruits on the conveyor belt.

Distance sensor			
	Material	**Range**	**Environment**
Requirements	Fruits of different colors	100-250 mm	Standard
Ultrasonic	Any color, material ok	60-800mm	Standard but echo might be a problem
IR	Refelctive surface, any color	0-150 or 150-500	No direct or indirect sunlight
Sharp IR	any surface and color	40-300	Standard

Table 12: Distance sensor justification

The sharp IR sensor is perfect for our product.

Finally, the matureness detection sensor needs to be compared.

Matureness identification		
	Sensitivity	**Signal conditioning**
Requirements	Moderate	Arduino readable
Camera	High	not arduino readable
Colour sensor	Low to moderate	Pulse width communication

Table 13: Distance sensor justification

There are a limited number of choices here, and the colour sensor is the one we will implement in our robot.

With all those comparisons, we can now estimate which of our previous concepts is the most suited for our application.

	XY axis motion	Z axis motion	Gripper	Number of motors	Safety	Easiness	Total points
Concept 1	-	+	–	-	+	++	0
Concept 2	++	++	++	+	++	-	+8
Concept 3	-	-	+	+	+	- -	-1

Table 14: Comparison of the different choices

The best concept is then the second as it regroups all the best choices. But, it adds a special difficulty in the making of the gripper as a mechanical gripper is easier but does not fit our requirements.

All the chosen means are summarised in the morphological chart below.

Features	Means			
Power	Electric	Petrol	Steam	Diesel
Displacement	Cartesian	Articulated	Cylindrical	Parallel
XY axis transmission	Chains	Gears	Belts	Screw
Motors	DC motor	Stepper motor	Servomotor	
Z axis transmission	Belt	Gears	Chains	Screw
Object detection	Camera	Laser distance sensor	Ultrasonic distance sensor	
Grabbing	Soft gripper	Mechanical gripper	Vacuum Gripper	Magnetic gripper
Grabbing actuation	Electric	Pneumatic		
Position control	End course switch	Rotary encoder		
Matureness identification	Camera	Colour sensor	Pheromone sensor	
Operation	Autonomous	Manually		
Control	Raspberry Pi	Arduino	Computer	

Table 15: Morphological chart

4 Embodiment Design

4.1 Final Design

The final design of the product is the following

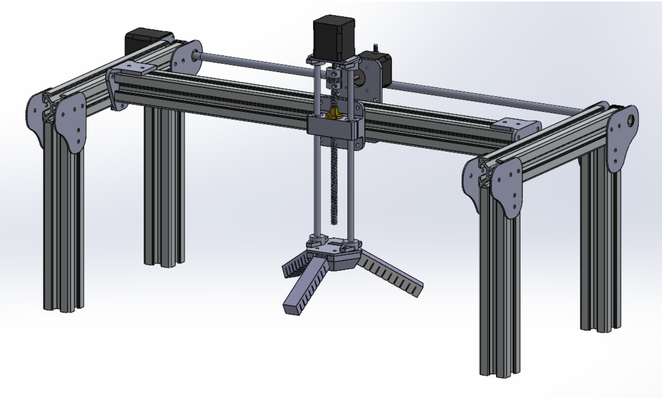

Figure 6: Full design from front

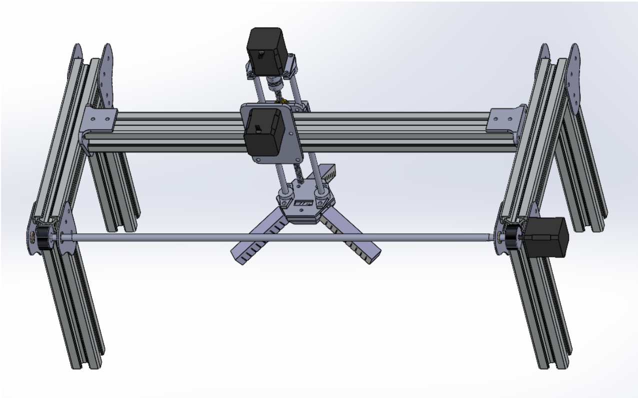

Figure 7: Full design from top

The structure in itself is made of strut profiles to allow an easy motion of the belts, to be robust, solid and light. Also, those pieces are standardised and lots of companies are making them (*custom-profiles*, *Bosch Rexroth*, and so on). This allows us to make a deal with a company making the strut profiles saving money and time. The motion in the X direction is supplied by only one motor with a power shaft that moves the two pulleys at the same time as seen on the figure 7. There are two belts for the X motion and one for the Y direction. For the motion in Y, the motor moves with the gripper. It rotates with a pulley driving a belt. The belt in itself is locked below the two bearings of the gripper fixation as seen on the figure 8.

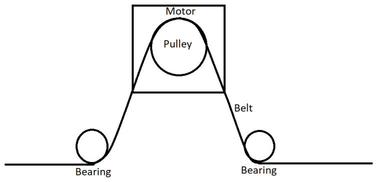

Figure 8: Pulley driven belt for the Y motion

The motion in the Z direction is provided by a lead screw with a fixed nut and two linear rods to avoid rotation. The fixed nut allows the gripper to go up and down with the lead screw. This is needed to avoid any collision of the gripper with fruits. Also, the lead screw has a protection against back-drive. Indeed, in comparison with ball screws, lead screws have lower efficiency (around 0.3) but this leads to a huge resistance to back-drive which means that even if the power shuts down, the gripper will stay up even for very high loads ([3]).

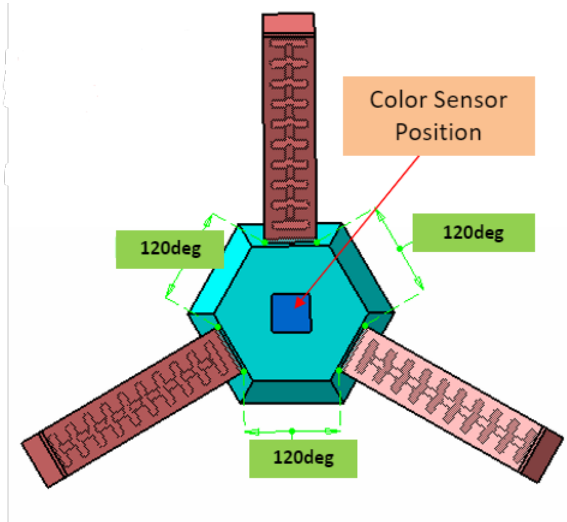

Figure 9: Gripper view from bottom

The gripper is made of a support in which 3 moulded fingers are locked. The number of three is strategical as the product needs to be able to pick the fruits but the fingers will be often replaced due to their limited lifetime. Therefore, by putting more fingers than the minimum necessary to pick the fruits, it leads to an increase of replacing cost for the customer and in the making of the product. The choice of three is also driven by biomimetism with the human hand where with thumb, index and the middle finger, we can have a good holding of the objects. The three fingers are placed with an angle of 120 degrees between each of them to surround the fruit when taking it. The fingers are likely to break after a certain time due to the soft material, they are thought to be easily replaceable.

4.2 Manufacturing processes

First, in our design, lots of pieces are easily found on the market. Those parts will be bought to save money.

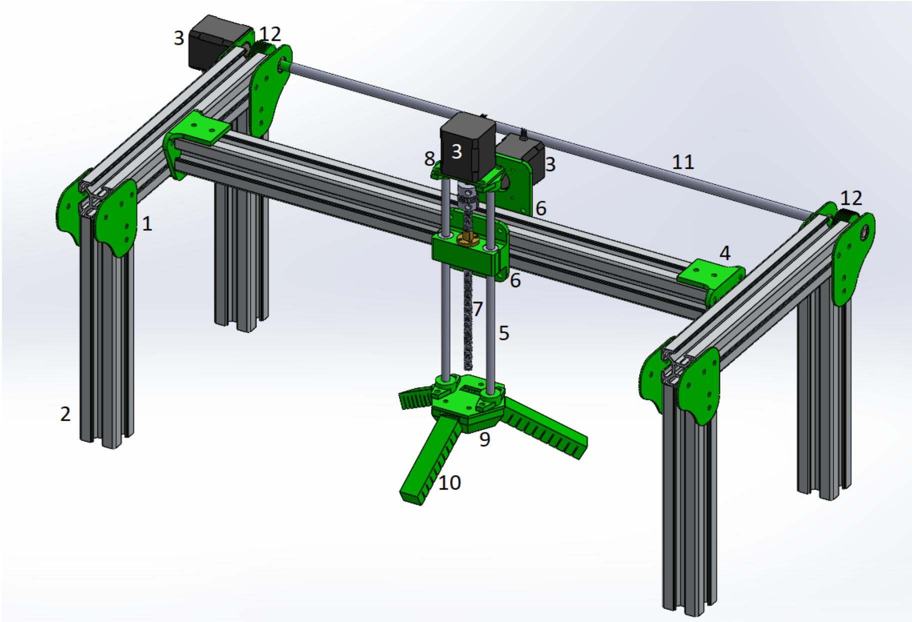

Figure 10: The pieces in green will be manufactured

Bought Parts	**Fabricated Parts**
Strut profiles (2)	Structure fixations (1)
Motors (3)	XY fixations (4)
Linear rods (5)	YZ fixations (6)
Lead screw and nut (7)	Z motor fixation (8)
bolts	Linear rods fixations
Belts	Gripper support (9)
Linear bearings and bearings	Gripper fingers (10)
Power shaft (11)	X-pulleys (12)
Y-Pulley	
Shaft coupler	
Electronics (Arduino, sensors, cables)	

Table 16: Bought and manufactured parts (Position on the figure 10)

The manufacturing processes will be divided in two categories. First, when the product will be launched into the market. For this, we consider a maximum size of 1000 of products sold. Secondly, if the customers are numerous and we need to increase the production batch, we will change the manufacturing processes in order to follow the demand and increase the batch to as high as the customers want while producing the robots in the most economic way. The processes are given in the *Design Methodology* course's slides. To find the right processes, we need to set the class of material in which the pieces will be made. The fixations will be composed of metal for solidity and the gripper fingers will be made of elastomer because of their ability to sustain reversibly very large strains.

Pieces	Small scale manufacturing process	Large scale manufacturing process
Structure and motor fixations	Conventional Machining (milling)	Sheet forming
XY fixations	Conventional machining (milling)	Sheet forming
YZ fixations	Sand casting	Low-pressure casting
Gripper support	Sand casting	Low-pressure casting
X-pulleys	Sand casting	Low-pressure casting
Gripper fingers	Polymer casting	Injection moulding

Table 17: All pieces manufacturing processes

The fixations that are flat sheets will be made by milling as it allows us to create the fixations in an economic way. If the scale becomes too big, the milling can be transformed into sheet forming, more economically adapted to large scale (around 100 000) and suited for the mass and the thickness of the fixations.

The other pieces in metal are 3D pieces and need other manufacturing processes. Therefore, they will be sand cast at small scale and for larger scale (bigger than 1000 products), the low-pressure casting will be preferred.

Finally, the gripper fingers are created by polymer casting or injection moulding depending on the batch size.

The aluminium needs a surface treatment to have a better lifetime and resist to wear. All the aluminium pieces will then anodised in order to increase their wear resistance ([4]).

4.3 Material choices

The choice of material is crucial in order to create a working structure. As the CES software is not available, we will make our comparison with this CES graph.

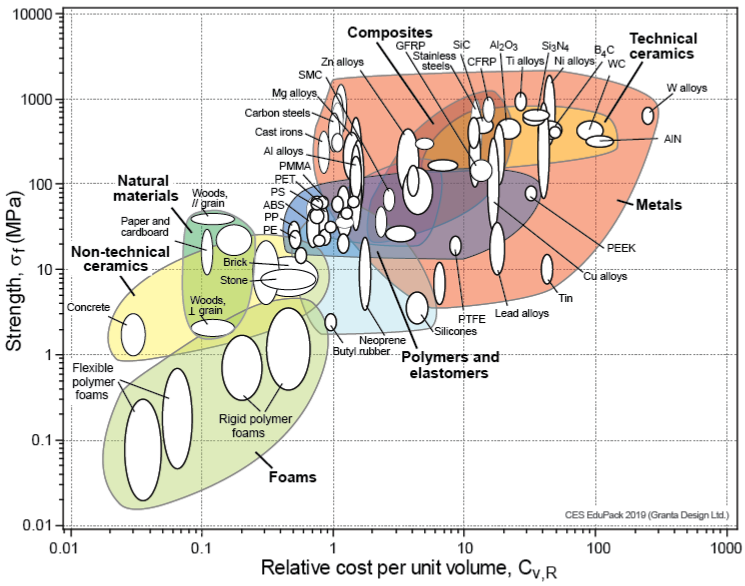

Figure 11: CES graph showing the cost per unit volume and the strength. [5]

For the creation of mechanical structures, two material are used most of the time. Those are aluminium alloy and Stainless steel. We will compare those two based on the CES graph and on some studies on the behaviour of our pieces depending on the material and choose the most suited one.

Aluminium advantages	**Stainless steel advantages**
Light weight	Strong
Cheap	Easy to weld
Strong corrosion and oxidation resistance	Strong corrosion and oxidation resistance
Good casting properties	Less reactive with food
Good performance from the surface treatment	Easy to maintain and to clean
Recyclable and rich reserves of aluminium on Earth	Recyclable
No metallic pollution, no poison, no volatile metal in the surface oxide layer	hygienic material

Table 18: Aluminium versus stainless steel based on [6], [7] and [8]

As we can make both material compatible with food and the task, the choice will be lead by the price and the needed strength in our design. As the aluminium is weaker but cheaper, all the pieces will be made of aluminium if possible. To find if the aluminium can handle the force applied on the fixations of the structure, several studies will be conducted in Solidworks.

By including a ridiculously high load to the gripper (for example if a worker is pushing his hand on the gripper) the most constrained pieces are studied with the aluminium alloy properties. If we apply a load of 150N on the XY fixation so around 15kg, a load of 200N on the gripper arm YZ fixation and a load of 100N on the YZ fixation on the motor side, we get the following results.

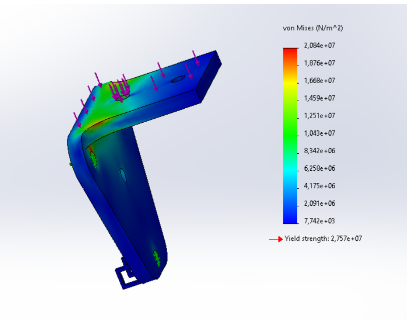

Figure 12: XY fixation study

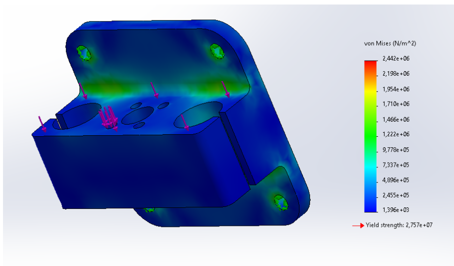

Figure 13: YZ fixation gripper arm study

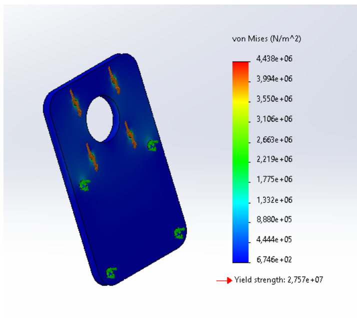

Figure 14: YZ fixation motor study

Here, the most constrained piece is the XY fixation and even with a huge load, we are at the limit with a maximal von mises stress just below the Yield strength meaning that the piece will not plastically deform. This means that all the fixations can be made of aluminium without any kind of problem.

The gripper fingers will be made of silicone as it is the most used material for soft robotics in research and in the applications as seen in [9]. It can handle the needed pressure to grasp the fruit and it is easily found and moulded.

The strut profiles will also be made of aluminium to be light and cheap. Moreover, most companies sell aluminium strut profiles. Therefore, it will be easier to have strut profiles in aluminium.

4.4 Assembly

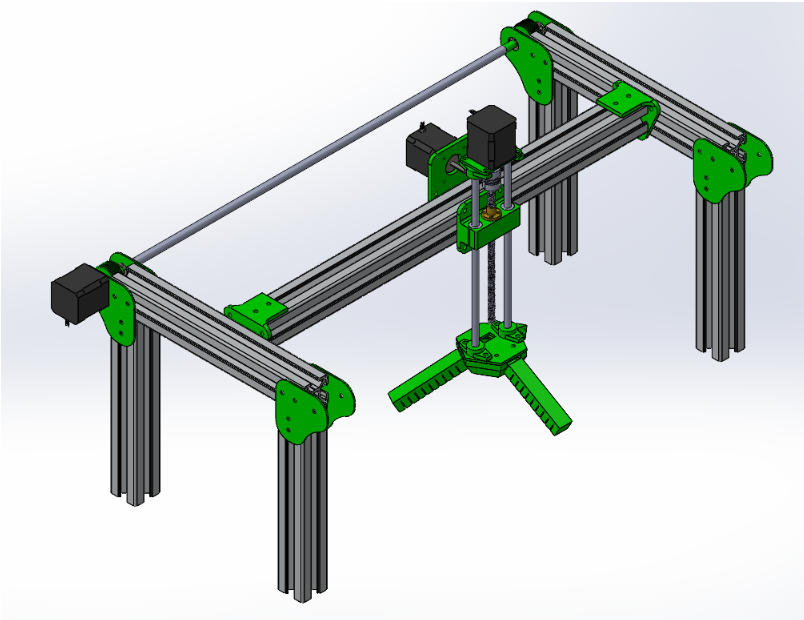

Figure 15: Full design view from the side

The assembly will follow those steps:

	Steps
1	Motors fixed to all their supports with their pulleys
2	Aluminium strut profiles fixed together to create the four legs
3	Bearings and power shaft fixed in the fixations on the X-direction
4	XY fixations attached to the Y strut profile with the belt locked
5	XY fixations attached to the global structure with their bearings in the strut profile on the belts
6	Gripper mounted together and fixed with the rods, the YZ fixation and the Z motor
7	YZ fixations fixed together and mounted on the Y strut profile with their bearings on the belt
8	Cabling

Table 19: Assembly steps

Now in order to estimate the time needed to perform the entire assembly, the list of pieces that needs to be manually hold, inserted and fixed will be linked to each step.

Steps	Pieces
1	4 bolts M3 per motor and 3 pulleys in total
2	8 times 4 bolts M6 + T-nuts
3	2 bolts M6 with 3 nuts + a bearing each and 3 bearings + 1 screw M8 for the power shaft
4	2 bolts M6 and 4 bolts M6 + T-nuts and a belt with holes to lock it in the 4 bolts
5	2 times 3 M6 bolts with bearings and nuts and the X-belts
6	4 times 2 M3 bolts with nuts for the linear rods fixations, 2 linear bearings
	Shaft coupler and 4 M3.5 bolts for the lead screw nut
7	4 M6 bolts with nuts and bearings in the strut profile on the belt
8	Arduino, sensors, cables and so on

Table 20: Fixing and assembling pieces

By using the tables given in the course, we can estimate the time needed to assemble all those pieces.

Steps	Holding time	Inserting and fixing time	Number of times	Total time
1 - M3 bolts	1.8s	2.5s + 5s	12	111.6s
1 - Pulleys	1.5s	2.5s	3	12s
2 - M6 + T-nuts	3s	5s + 5s	32	416s
3 - M6 bolts	1.5s	2.5s	2	8s
3 - bearings	1.43s	1.5s	5	14.65s
3 - nuts	1.43s	1.5s + 5s	6	47.58s
4 - bolts M6	1.5s	1.5s + 5s	2	16s
4 - bolts M6 + T-nuts and belt	3s	6.5s + 5s	4	58s
5 - bolts M6	1.5s	2.5s	6	24s
5 - bearings	1.43s	2.5s	6	23.58s
5 - nuts	1.43s	1.5s + 5s	6	47.58s
5 - belts	5s	8s + 12s	2	50s
6 - M3 bolts	1.8s	2.5s	8	34.4s
6 - nuts	1.88s	1.5s + 5s	8	67.04s
6 - linear bearings	1.13s	2.5s	2	7.26s
6 - shaft coupler	1.13s	1.5s + 10s	1	12.63s
6 - lead screw + nut	1.13s	2.5s	1	3.63s
6 - M3.5 bolts	2.25s	1.5s + 5s	4	35s
7 - M6 bolts	1.5s	5.5s	4	28s
7 - bearings	1.43s	2.5s	4	15.72s
7 - nuts	1.43s	1.5s + 5s	4	31.72s
				1064.39s

Table 21: Assembly time

The total time for the mechanical assembly is 1064.39s or 17 minutes and 44.39 seconds. To this time, the electronic assembly time needs to be added but we cannot estimate this time so we will only consider the mechanical assembly. This means that a single worker can theoretically assemble 27 robots in a normal 8h working day.

5 FMEA

The Failure Modes and Effects Analysis is a powerful tool allowing the designer to list the failure modes of each component and their effects on the global functioning of the product. It highlights the pieces that need to be optimised by classing them with a Risk Priority Number that depends on the Occurrence of the problem, the Severity of the failure if it happens and the way we can Detect it or not.

Failure Modes and Effects Analysis									Fruit/Vegetable gripper sorter Team 2 - Mechatronics			
									Re-Evaluation			
Failure item	Failure Mode	Effects	Causes	Severity	Occurrence	Detection	RPN	Recommended Action	Severity	Occurrence	Detection	RPN
Strut profiles	Fracture	Falling/Total breakdown	Unexpected heavy load	8	1	1	8	Determine the max loading and increase the safety factor	8	1	1	8
Fixations	Fracture	Falling/Total breakdown	Unexpected heavy load	6	4	4	96	Determine the max loading and increase the safety factor	6	2	4	48
Micro-controller	Burn	Total breakdown	Unexpected high current peak	8	4	6	192	Add a better protection against the current peaks	8	1	6	48
Several screws	Fracture	Total breakdown/ disassembly	Unexpected heavy load	3	5	4	60	Increase the screws diameter or change the material	3	2	4	24
Belts	Rupture	Total breakdown	Blocked belt or cutting part cut the belt	5	3	5	75	Remove the cutting part or redesign the blocking point	5	1	5	25
Gripper finger	Rupture	Total breakdown	Wear of the finger or unexpected high pressure	3	10	5	150	Change the material in order to supply higher pressure and last longer	3	5	5	75
Belts	Deformation	Imprecise motion	Wear of the belt	2	8	8	128	Change the belt	2	8	8	128
Lead screw	Lack of lubrication	Imprecise motion in Z direction	Lack of lubrication	2	5	8	80	Lubricate the lead screw	2	5	8	80
Micro-controller	Informatic bug	Task not correctly done	Informatic bug in the micro-controller	2	5	7	70	Review the code and try to resolve the bug	2	3	7	42
Motor	Burn	Partial breakdown in one direction	Unexpected high current peak	6	3	6	108	Add a better protection against the current peaks	6	1	6	36
End-switch/ sensors	Burn	Partial breakdown in positioning or sorting	Sensors broken	4	4	7	112	Change the sensors or add a protection	4	2	7	56

Figure 16: Failure Modes and Effects Analysis

The most likely failure that will certainly happen is the gripper fingers that break. As said previously, they are thought to be replaceable easily and our company will also sell replacement gripper fingers at a reasonable price.

6 Business Development

Concerning the business development of the product, several points need to be taken into consideration. First, what is actually the market and who is our competitors. Then, what will be our marketing strategy and our pricing. Finally, how can we distribute our products and reach the maximum customers.

6.1 Market analysis

In Belgium, the FEVIA (”Federation de l’industrie alimentaire belge”) states that they are 4,239 employers employing 94,631 workers ([10]). It is also a SMB-centred sector as 96% of the employers have less than 100 employees which is perfect for us, as we focused on the SMB in our design. Moreover, the sector is in big expansion as it is the first industrial investor in Belgium and the global turnover has risen of 5.9% last year. Besides, the investment in the sector has risen of 8.8% last year which means that the companies want to expand themselves. We are coming at the right moment selling them our product allowing them (especially the very small businesses) to expand easily by increasing their production.

Our competitors, on the other hand, propose either expensive robot process like the one on figure 17 that works only with specific fruit or vegetables but that can sort up to dozens of tons per hour. Or small robots parallel or articulated that work slowly and can sort or package fruit like the one on figure 18 which are cheaper (around 1000-2000 euros per robot for the cheapest). Indeed, our competitors are numerous and that force us to be more aggressive in our marketing plans and in the pricing.

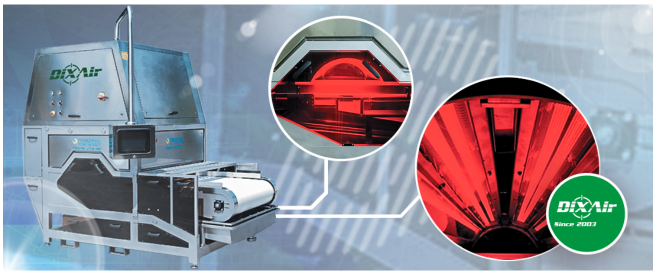

Figure 17: Protec DixAir Optical Sorter [11]

Figure 18: PROEX FOOD robot [12]

Also, due to the coronavirus crisis, there is a tremendous need for automation. Indeed, the workers cannot work normally because we need to keep them as safe as possible. A possible solution is to increase the number of autonomous robots leading to a diminution of the necessary number of workers to make the company and the processes run. Especially, the SMB suffer the most from the crisis. Therefore, they are the most likely to need our product which again is good as they are our target customers.

6.2 Marketing strategy

First, as the product needs a lot of bought pieces, we will need to make commercial agreement with other companies.To do so, we will need to make some comparisons to find the less expensive ones that can provide us the pieces on the market.

By looking at the prices of the components on the Internet, we can estimate approximately the total cost of the product. We used a price estimator ([2]) for all the manufactured pieces. Finally, by considering a rate of 100 robots made per month, we need at least 5 workers, one for the mechanical assembly, the second for the electronics and the third to handle the stock and pack the robots. The two others will be responsible of the sales department and the communication with our customers. By considering a salary of 2500€ for each workers, the cost per robots becomes 125€.

Item	Cost
Bought parts	128.22€
Sand cast pieces	2.42€/piece → 9.68€
Milled pieces	3.065€/piece → 39.845€
Injection moulded pieces	4.37€/piece → 13.11€
Employees cost	125€
Total cost	315.855€

Table 22: Total cost

Now, in order to make a coherent price for the robot including all costs, the price will be set to 500€. Indeed, as the competitor are far above this price we can allow a bigger margin without putting our company in trouble. Also, this will allow us to make a commercial move detailed in the next section.

Taking this into account, we can estimate that our incomes from the sells are theoretically 184.15€ per sell. This means that if the company can sell the 100 robots per month, it creates an income of 18,415€ per month. If we remove our three salary from this number we get 10,915€ per month that we can re-inject in the company for the advertising or the various cost that can help us grow.

6.3 Communication

As our product is launched in the market during the coronavirus crisis, we will start our sell by doing a sale on our price lowering it to 400€ to show our support to the companies hardly hit by the crisis. This allows us to attach good values to our company which will help us build stronger relations with our customers. Moreover, it is also good for us as we will also sell the replacing pieces such as the fingers that will bring us a bigger income in the beginning.

Moreover, we will try to contact as much SMB as possible in order to create some deals and some trust relations that create fidelity between our customers and our company. The market is in a deep incertitude crisis so we need to reassure our customers to help them get through this difficult time.

7 Prototype

For the *Mechatronics 1* part, it was asked to build a prototype based on the design developed. The budget is changed to 200€, and it is built using 3D-printed and laser-cut parts. In order to be able to make the whole prototype within two months, we transformed the 3 axis motions into only 2 as the motion in X and Y are similar. If the prototype is able to move along Y direction, it should be easy to add the third dimension.

7.1 Design

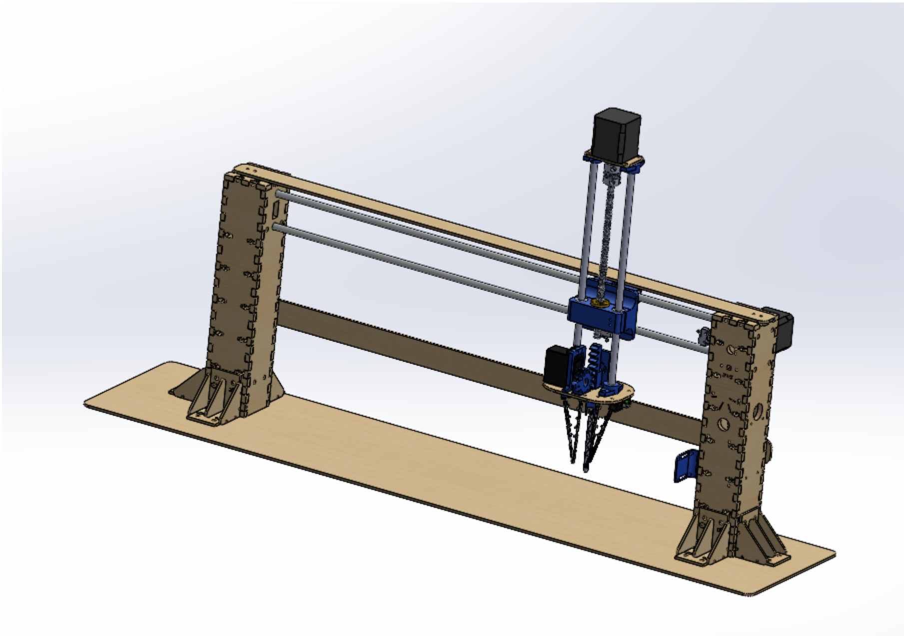

Figure 19: Full prototype design

The prototype design is shown on the figure 19. It is composed of two foot made with laser cut parts (made in birch 6mm thickness for a solid structure) and finger joints assembled together using bolts and screws. There are some small supports to increase the stability and to fix the structure to a plate or a table.

The motion in Y is ensured by two linear rods on which the junction between the axes is sliding using linear bearings. The linear rods were preferred to a strut profile because it is lighter and easier to balance. A belt is attached to the junction allowing the structure to move when the belt rotates. The belt rotation is provided by a stepper motor fixed on the right foot with a pulley driving the belt and a bearing fixed in the other foot to have a smooth rotation. This mean allows to have a fast motion with a very light structure

The motion in Z is made of a lead screw and two linear rods to have a better stability and no rotation of the gripper. The linear rods are sliding in two linear bearings as the lead screw rotates making the gripper go up or down. The lead screw is coupled with a stepper motor fixed on the top.

Finally, the gripper is made of three flexible fingers actuated by a rack and pinion driven by a servomotor. The moulded fingers designed at first could not be made due to the coronavirus leading to difficult access to the *Fablab*. A simple flexible 3D printed gripper has then been used.

7.2 Electronics

The electronics circuit contains two stepper motors with two stepper motor drivers, two end-switches, one range sensor,one servomotor, one step-down voltage module, one potentiometer for choosing the fruit to detect and a start button. All those components are connected to an arduino. The input power of the system is a 12V voltage source.

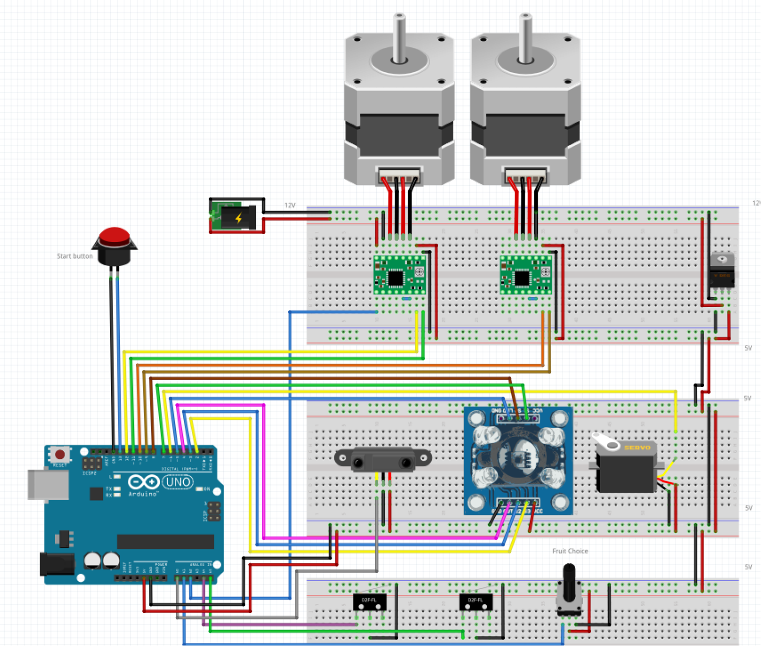

Figure 20: Complete circuit connections

7.2.1 Stepper motors

The stepper motor for the belt motion needs a torque calculated as following considering an acceleration of $2m/s^2$, a total mass of $1kg$ for the gripper and a safety factor of 2 (taking the real imperfections into account):

$$F = m * a = 1kg * 2m/s^2 = 2N \quad \Longrightarrow \quad T = 0.02 * 2 * 2 = 0.08Nm$$

The desired speed is 3 cm/s which means a motor speed in rpm of [13]:

$$v_{Belt} = \frac{\pi}{60} * D * \omega_{motor} \quad \Longrightarrow \quad \omega_{motor} = \frac{0.03 * 60}{\pi * 12.22 * 10^{-3}} = 46.89rpm$$

Where D is the pulley diameter.

As the speed of a stepper motor is inversely proportional to the torque given by the latter, we need a stepper motor capable at least to rotate at 46.89 rpm when a torque of 8Ncm is applied. By looking at datasheets, a common NEMA 17 is able to sustain that torque and speed. Moreover, as the prototype is not perfect and frictions and imperfections will increase the needed torque, it is interesting to have a stepper motor that can give more of torque while maintaining the speed.

The stepper motor for the lead screw motion needs a torque found with the following formula [14]:

$$T_{raise} = \frac{F * d_m}{2} * \left(\frac{l + \pi * \mu * d_m}{\pi * d_m - \mu * l} \right) = \frac{9.81 * 7}{2} * \left(\frac{2 + \pi * 0.2 * 7}{\pi * 7 - 0.2 * 2} \right) = 1.017Ncm$$

$$T_{Needed} = T_{raise} * SF = 2.034Ncm$$

Where SF is the safety factor and is set to 2 again.

Here, the needed speed is 1cm/s which means 5 rotation per seconds. For the same reason as before, the NEMA 17 is a good choice as it allows a high speed with the needed torque. On top of that, the Z motion will probably have a lot of friction due to the lead screw so the torque will probably rise as the motor is going up. A NEMA 17 with a sufficient max torque is then necessary to counteract those frictions.

The motor drivers are DRV8825 because they are able to give up to 1.5A per phase and can control easily a bipolar stepper motor such as the ones that we used.

7.2.2 End-switches

Figure 21: End switch

The two end-switches are fixed either on one foot for the Y-motion positioning regulation or on the YZ fixation for the Z motion positioning regulation. After setting the origin of each axis thanks to those switches, it is easy to map the position of the detected objects and control the position of both motors.

7.2.3 Range sensor

Figure 22: Range sensor GP2Y0A21

The range sensor is fixed on the gripper and allows to detect the Y coordinate of the object by scanning the distance to the ground along the Y axis

7.2.4 Colour sensor

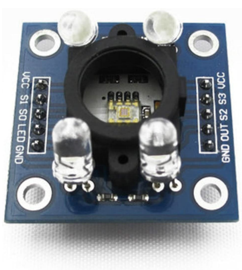

Figure 23: Colour sensor TCS3200

The colour sensor is a common cheap TCS3200 that is able to give a RGB value for the scanned object. There are also four leds that ensure the same luminosity for every measure. This sensor is fixed with a 3D printed support on the foot. After grabbing the object, the latter will be moved to the colour sensor for scanning.

7.2.5 Servomotor

Figure 24: Servomotor MG996R

In order to take the detected fruits, we need a small torque around:

$$F_r = m*g + m*a = 0.25*9.81 + 0.25*0.2 = 2.50N$$

$$T_p = F_r * r_p = 2.5 * \frac{33}{2000} = 0.04125Nm$$

As this is very small, a common servomotor as the MG996R can be used.

7.3 Cost

As said previously, we have to stay under the 200€ budget. All the prices and the total cost has been put in the following table:

Component	**Price**	**Quantity**
Birch 6mm plate	10.86€	1
Birch 3mm plate	5.98€	1
Screws and bolts M3	0.033€	75
Screws and bolt M5	0.05€	40
Belt	2.55€	1
Bearing	0.5€	1
PLA filament	18€/kg	100g
Stepper motor NEMA 17	9.5€	2
Servomotor MG996R	5.5€	1
End switch	0.5€	2
Arduino Uno	5.99€	1
Colour sensor	7.99€	1
Linear rods 8mm	13.7€	2
Stepper driver	2.4€	2
Sharp IR sensor	7.49€	1
Button	0.025€	1
Potentiometer	1.49€	1
Voltage step-down module	5.54€	1
Shaft coupler	1.39€	1
Lead screw 8mm + nut	4.5€	1
Linear bearings	0.97€	5
Cables	4.99€	Lots
Total Price	128.12€	

Table 23: Total cost of the prototype

The prototype has a final cost of 128.12€ which is way below the 200€ limitation.

7.4 Working steps

The robot will do the full task by dividing it into small tasks.

First, the robot will reset himself and setting the zero on both axes Y and Z. As explained before, this will allow to control the position of the gripper both in Y and Z.

Then, when the user presses the start button, the robot will scan the zone looking for fruits. To do so, it will measure the ground distance and move on the Y axis looking for height difference. When it detects the end of the fruit (the ground value being detected again), the gripper will place itself in the middle of the fruit. After that, it will go down to the fruit, grab it, go up again and move to the colour sensor.

After the colour scanning, the robot will determine whether the fruit has the right colour or not and putting it in the dedicated zone.

Finally, the robot will reset himself again and wait for the user to press the start button to start the same process.

A bonus feature was implemented for transport of the prototype, putting it in transport mode when detecting no object. This consists of putting the gripper low and very close to one foot in order to have less torque applied on the junction part while transporting.

7.5 Results

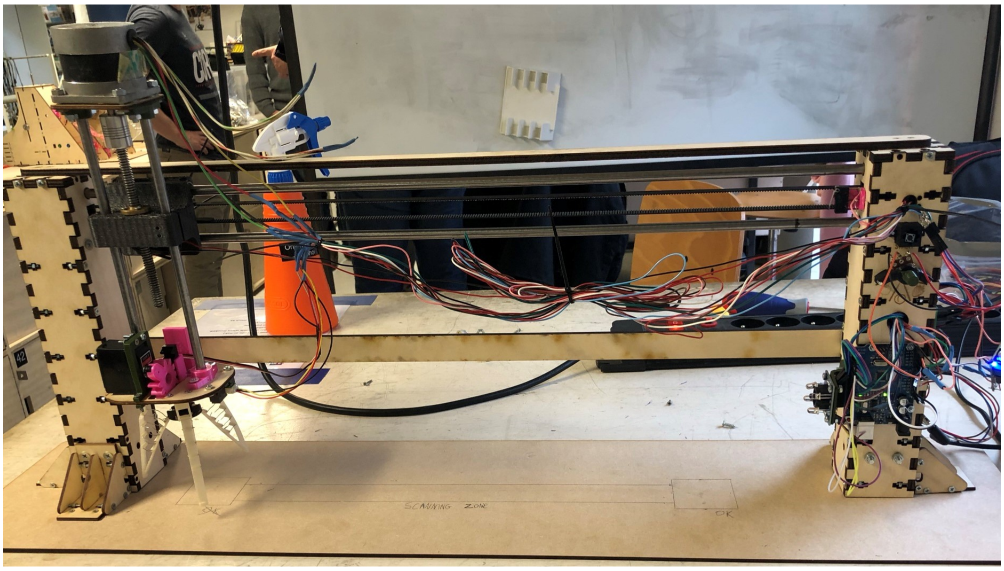

Figure 25: Full prototype design built

After building the prototype and making all the cabling, connecting, soldering and coding, we ended up with a functional prototype able to pick and sort balls of different materials and colours (representing different fruits). However, the Z motion is very slow due to the very small tooth pitch of the lead screw (2mm) and the fact that the gripper is tilted. Indeed, as the fixation has two linear bearings in the upper linear rod and only one in the lower and especially that the load is pushing forward (worsen by the heavy motor found in the fablab), the gripper becomes very tilted as it rises. This increases the frictions, increasing the needed torque and decreasing the maximum rotating speed.

8 Conclusion and Discussion

In conclusion, we have designed a fully automated robot that sorts fruit and vegetables based on their colour in order to speed up the chain process of small companies. It is rather inexpensive as we sell it for twice less than the cheapest competitor. We started from the simple idea and the requirements list and ended up by stating the full design and the manufacturing and assembly process for each piece. Then, the failure modes were analysed for each critical piece in order to improve the design as much as possible to prevent the failure from happening. Then, the business development of the company has been studied to estimate the cost of the product and the final price at which we are going to sell it. The final product will be launched at a price of 500€ on the European market. Finally, a fully functional prototype has been built in less than a month (time was restraint due to coronavirus). Some improvements such as a better Z motion can be considered in order to fulfill the functions in a better way but this prototype is sufficiently good to make the entire sorting task without any problem.

Back to the reality, this project taught us to create a product design by a strict methodology avoiding us to make mistakes at the end of the fabrication. Due to the coronavirus crisis, it was not possible for us to do meetings in physical with the assistant and the professor but thanks to the incredible patience of the assistant Mr Pétré, we were often helped even in this difficult context. Therefore, we want to thank Mr Pétré for his help during the entire project.

Concerning the practical part of the project, this project taught us to adapt (especially due to the sanitary context) and to overcome any problem that can occur in real life. Actually, it is easy to do something in simulation but the real problems happen when making it in reality. For this reason, we want to thank the assistants Mr De Beir and Mr Usman that have been really helpful to advise us in those difficult situations.

References

[1] Scott Thornton. The impacts of 5g on the future: A new era of connectivity. https://www.5gtechnologyworld.com/the-impacts-of-5g-on-the-future-a-new-era-of-connectivity/, December 2019.

[2] CustomPart. Cost estimator. https://www.custompartnet.com/estimate/.

[3] Carlicia Layosa. Lead screws vs. ball screws. https://blog.misumiusa.com/lead-screws-vs-ball-screws-differences-benefits-accuracy/, June 2014.

[4] MachineMFG. Do you really know aluminum alloy surface treatment? https://www.machinemfg.com/aluminum-alloy-surface-treatment/.

[5] ANSYS Granta. Material property charts. https://www.grantadesign.com/education/students/charts/, 2020.

[6] Alu4all. Aluminum profile advantages. https://www.alu4all.com/aluminum-profile-advantages/, January 2017.

[7] Metal Supermarkets. 10 differences between aluminum and stainless steel. https://www.metalsupermarkets.com/10-differences-aluminum-stainless-steel/, December 2014.

[8] lorecentral. Advantages of stainless steel. https://www.lorecentral.org/2017/12/advantages-stainless-steel.html, 2017.

[9] Stephen Coyle, Carmel Majidi, Philip LeDuc, and K. Jimmy Hsia. Bio-inspired soft robotics: Material selection, actuation, and design. *Extreme Mechanics Letters*, 22:51 – 59, 2018.

[10] FEVIA. Industrie alimentaire. https://www.fevia.be/fr/industrie-alimentaire, 2020.

[11] Protec. Dixair. https://www.protec-italy.com/en/equipment/dixair-optical-sorter/.

[12] PROEX FOOD. Solutions d'emballage et d'automatisation de fruits et légumes. https://proexfood.com/product/fruit-vegetable-packaging-equipment/, 2019.

[13] Kurt Heckman. Belt speed. https://www.vcalc.com/wiki/vcalc/belt+speed, May 2020.

[14] Kurt Heckman. Leadscrew torque (lift). https://www.vcalc.com/wiki/vCollections/Leadscrew+Torque+%28 2020.

Appendices

A Manufactured piece technical drawings

A.1 Strut profile fixations on the bearing side

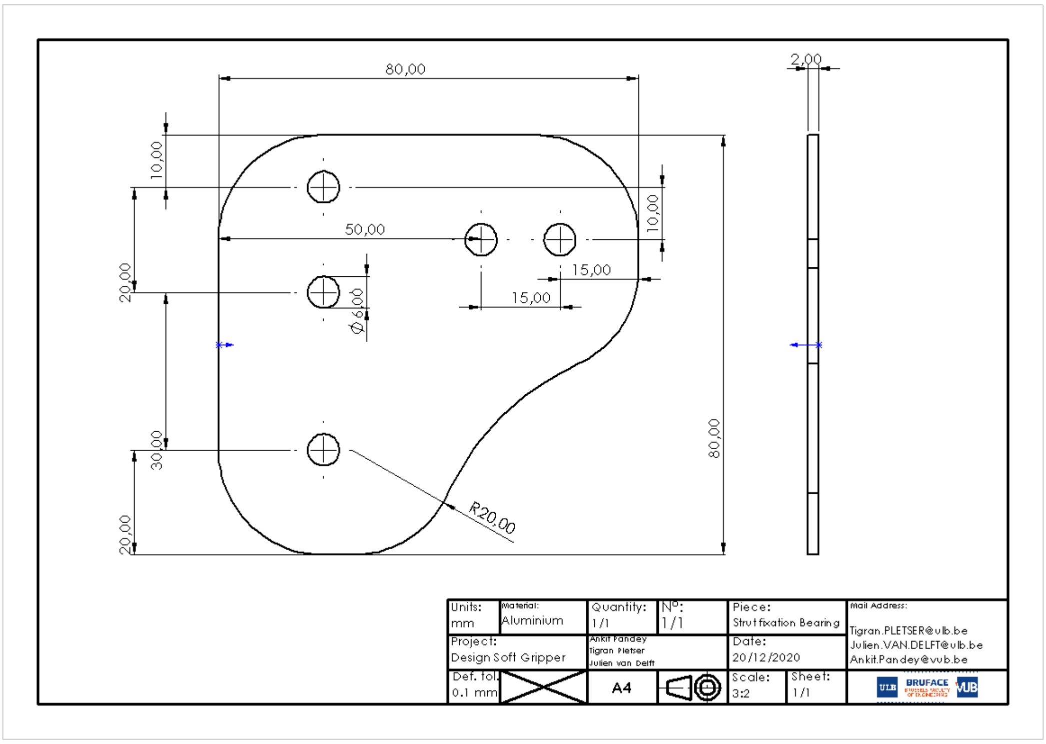

Figure 26: Strut profile fixation on the bearing side technical drawing

A.2 Strut profile fixation for the X-Motor

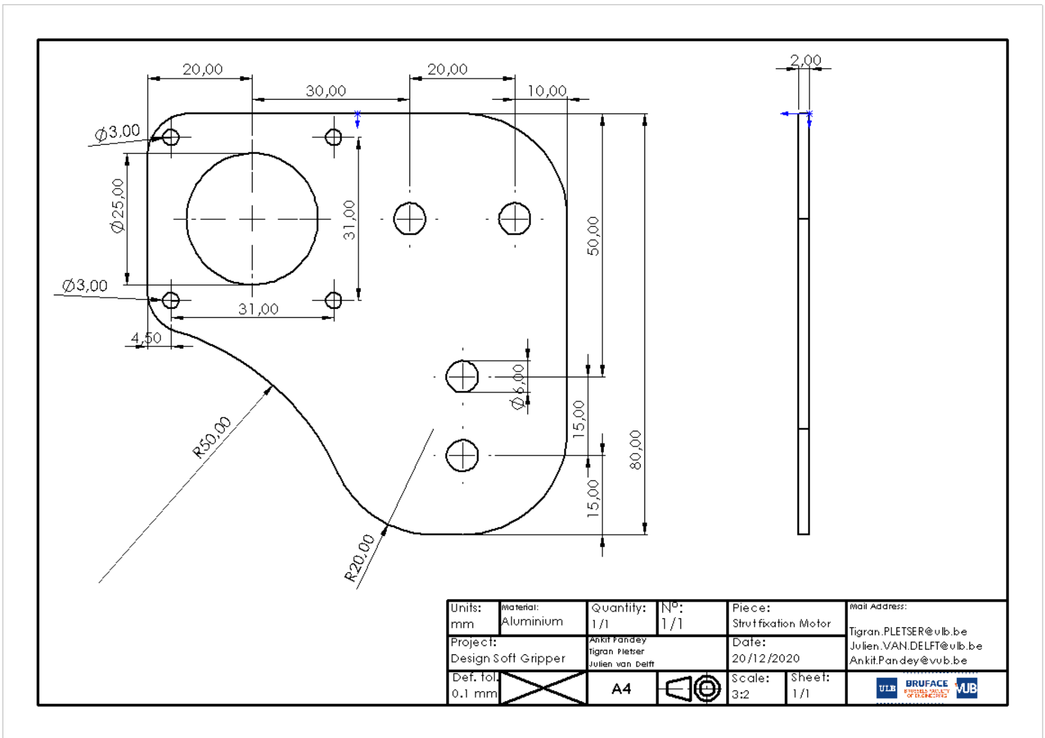

Figure 27: Strut profile fixation on the power shaft side to fix the motor technical drawing

A.3 Strut profile fixations for the power shaft side

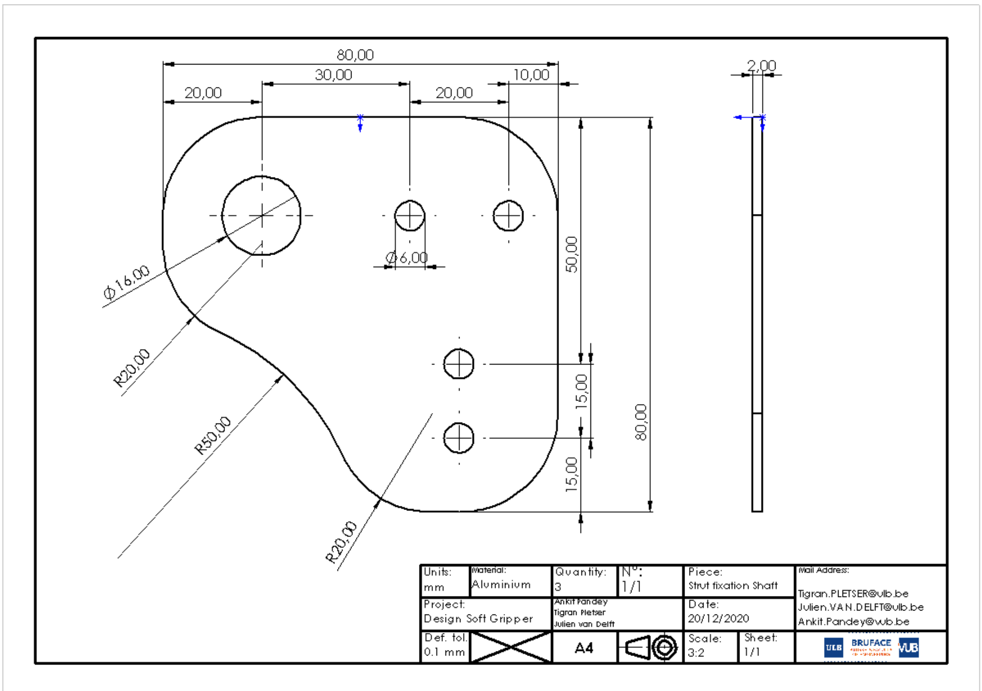

Figure 28: Strut profile fixation on the power shaft side technical drawing

A.4 Pulleys

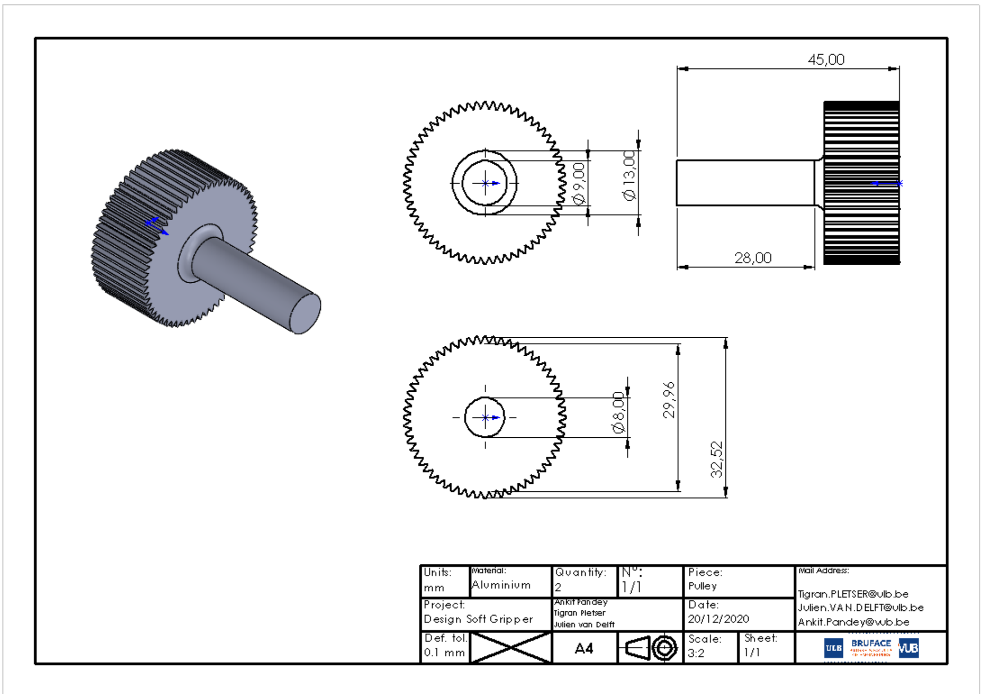

Figure 29: Pulley for the shaft technical drawing

A.5 XY fixations

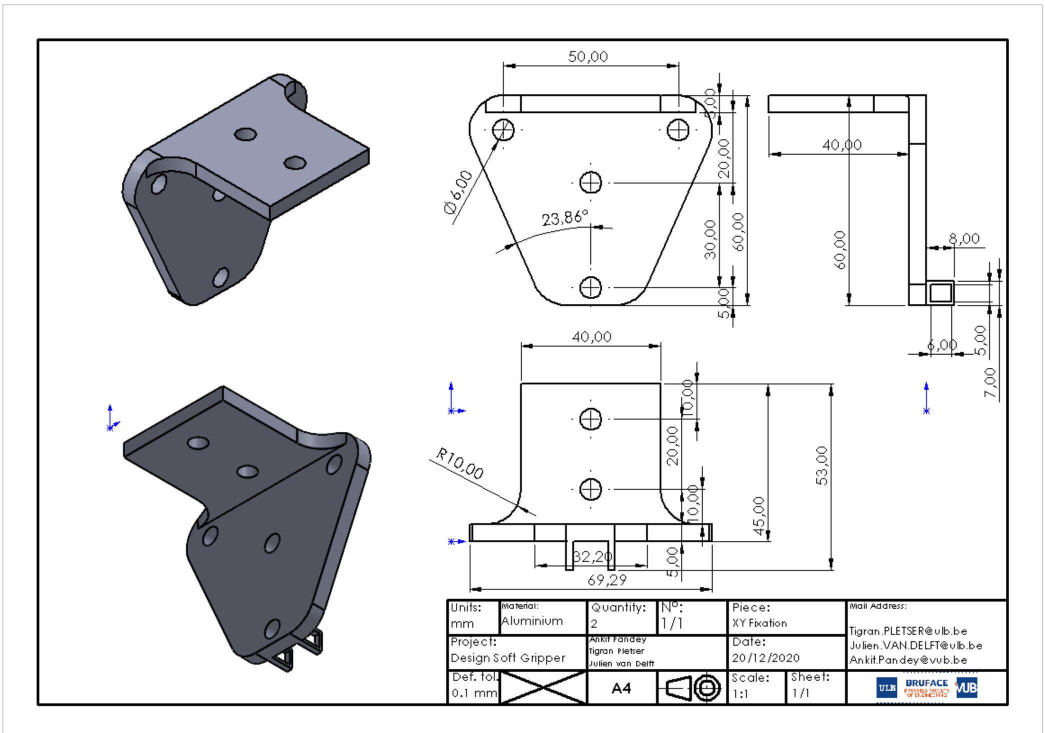

Figure 30: XY fixation technical drawing

A.6 YZ Fixation on the motor side

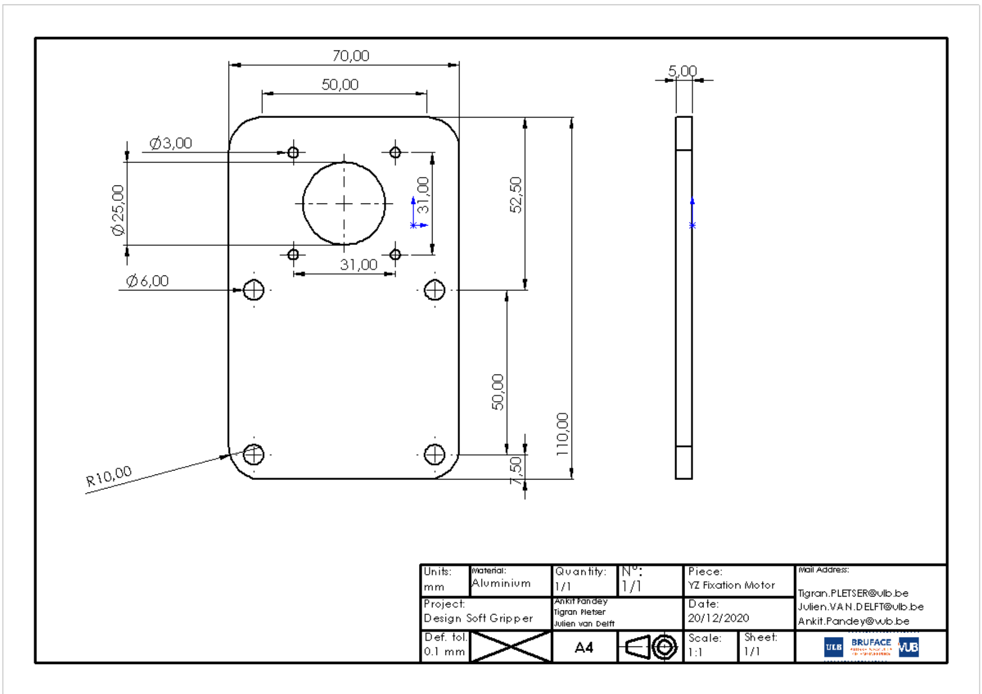

Figure 31: YZ fixation motor side technical drawing

A.7 YZ Fixation on the gripper side

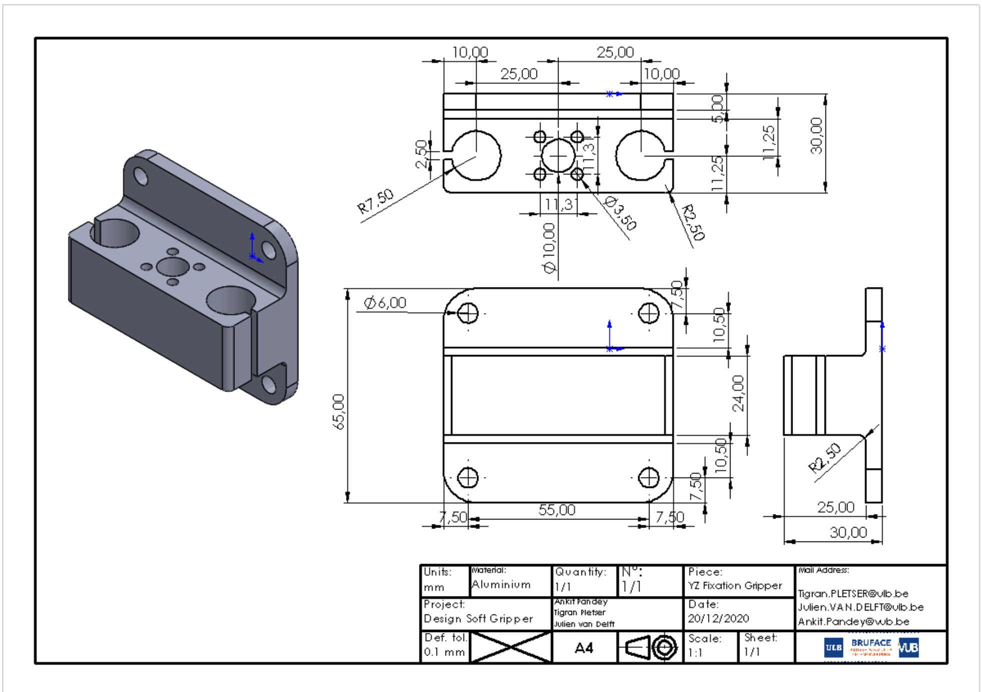

Figure 32: YZ Fixation on the gripper side technical drawing

A.8 Z Motor fixation

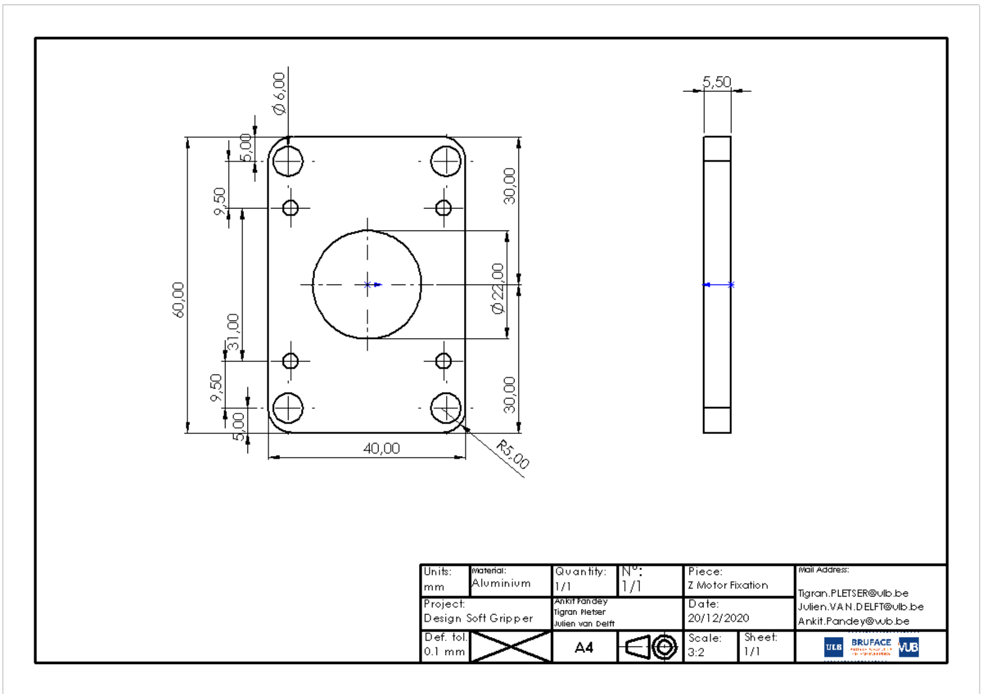

Figure 33: Z motor fixation technical drawing

A.9 Linear rods fixations

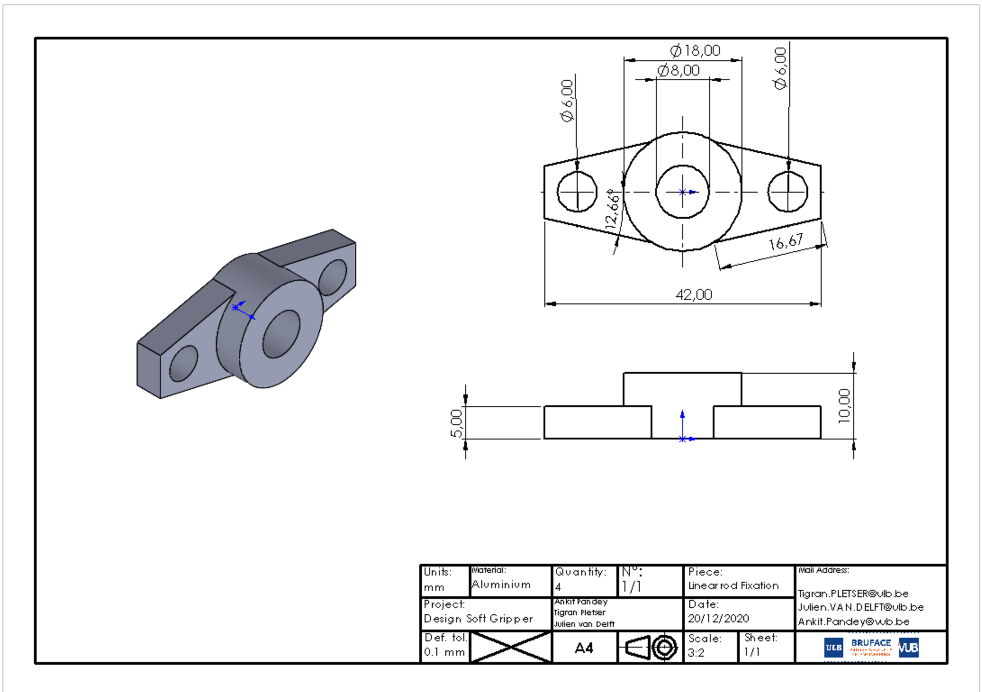

Figure 34: Linear rods fixation technical drawing

A.10 Gripper fingers holder

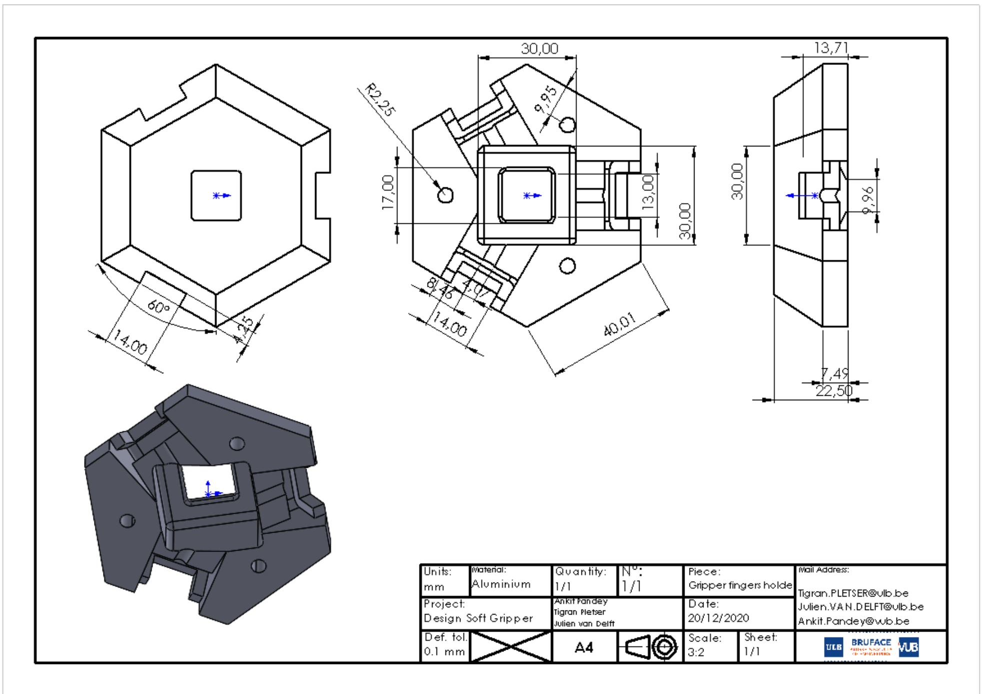

Figure 35: Gripper fingers holder technical drawing

A.11 Gripper fixation

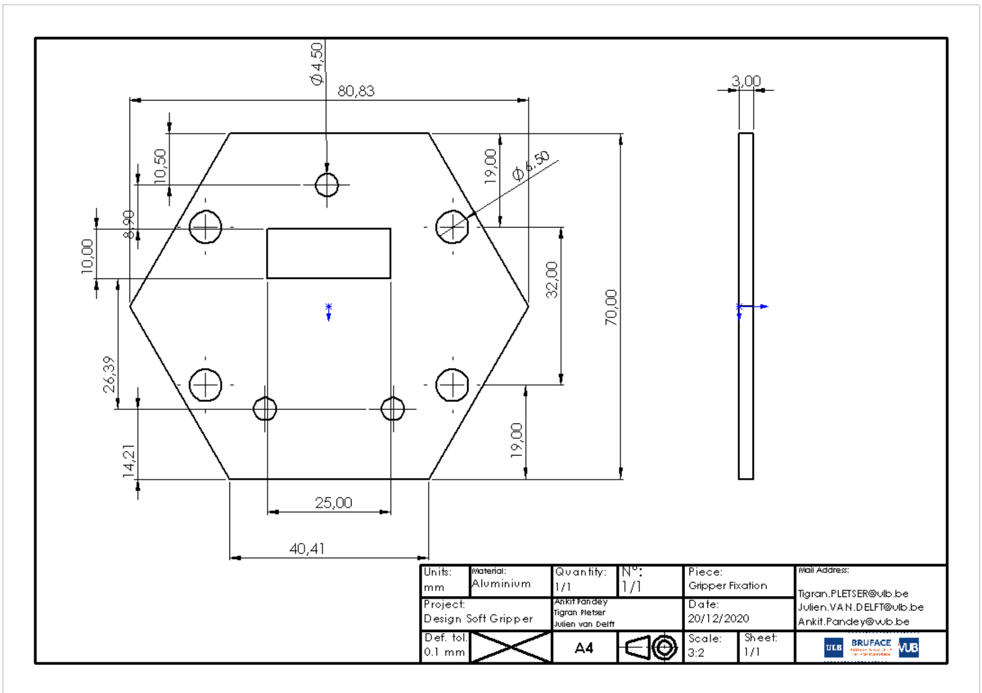

Figure 36: Gripper fixation technical drawing

A.12 Gripper fingers

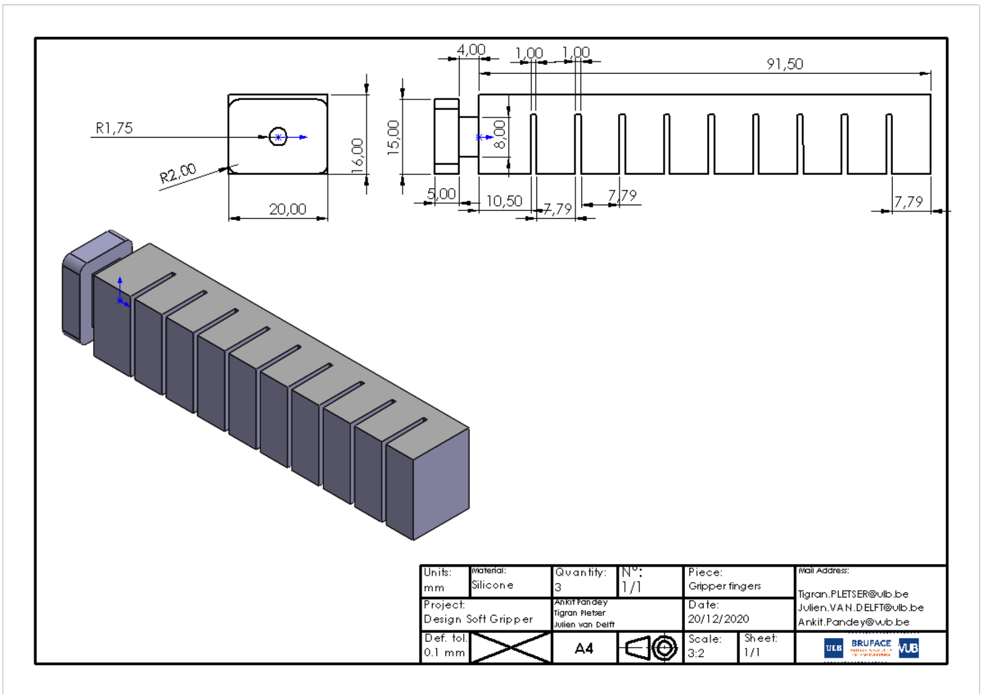

Figure 37: Gripper finger technical drawing

B List of components for the product

Component	Quantity
M3 bolts	20
M3 nuts	8
M3.5 screws	4
M6 bolts	50
M6 T-nuts/nuts	36/16
M8 screw	1
Bearings(6mm)/Linear bearings(8mm)	15/2
Pulleys	3
Belts	3
Shaft coupler	1
Lead screw(8mm) + nut	1
Linear rods(8mm)/power shaft(8mm)	2/1
Stepper motors + Stepper drivers	3
Strut profiles(4mm) x 25/30/60cm	4/2/1
XY fixations	2
YZ fixations motor side/gripper side	1/1
Z motor fixation	1
Linear rods fixations	4
Gripper support	1
Gripper fingers	3
Colour sensor	1
Sharp IR sensor	1
Arduino	1
End switches	3
Button	1
Potentiometer	1
Solenoid valve	1
Darlington transistors	2
Cables	

Table 24: List of components