FINAL REPORT

ROBOPICK

A robot for autonomous tomato harvesting

European Project Semester – Autumn 2017

Novia University of Applied Sciences, Finland

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Abstract

Despite extensive use of robots nowadays in automation factories, practical success of robots on harvesting tasks is still limited. The aim of these kind of robots is to assist farmers in the laborious harvesting work. In order to accomplish this, two main difficulties have to be faced: time, robots have to help farmers save time during the harvesting period; and quality, the plantation or fruits shall not be damaged or misplaced.

The purpose of this report is to present all the work done in order to develop an automatic robot able to recognize and harvest ripe tomatoes.

Since it is not possible to build a fully automatic harvesting robot during the time that lasts the European Project Semester, this project is divided in various stages. This report will be about the first part of the project.

First, the requirements are set up and along with it, a research about existing harvesting robots is conducted and several solutions to meet the requirements are proposed.

Following the mentioned above, a prototype is realised by designing a gripper that can be mounted on a ABB IRB1600 robot arm. The gripper is made up of three fingers and each finger has two phalanxes that closes around the tomato. The opening and closing movement is realised by a servomotor. This gripper is equipped with two mechanical switches to detect the maximum open or closed position which are all connected with an Arduino Uno processor.

The tomatoes are detected with a web camera mounted on the robot arm in combination with the SICK 3D camera placed on a fixed position. The web camera takes a picture and through different image processing the ripe tomatoes are detected. Given that a single camera is not able to determine the depth, the 3D camera is used to obtain the third missing coordinate. All three coordinates are adjusted to the robot coordinate system and finally packed together with the other tomato coordinates in a string. This information is sent to the robot controller.

The robot controller moves the arm to the given coordinates and gives the order to close the gripper. When it is closed, the robot arm moves to a fixed position and gives the order to open the gripper. The picked tomato falls in the basket and the sequence is repeated until all the tomatoes are picked.

The prototype built during this project is able to harvest ripe tomatoes but it is far from being ready for the commercial market, hence some valuable recommendations are given at the end of the report.

Keywords: Tomato harvesting, Robot, Gripper, Computer vision, 3D printing, Tomatoes

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Arto Hänninen also had an important part in our project as he install a new workstation with all the software we needed and also built a wall to hang our tomatoes. He was definitely our sixth project member.

The EPS students who helped us by giving ideas to improve the project or supporting us by cheering us up and making us viewing things differently. Also, thanks to those who distracted us from our work because sometimes focusing too much is not efficient either.

Last but not least, we are also grateful to Roger Nylund for organizing EPS and for support the students throughout the semester… it all started with you!

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1 Introduction

1.1 The European Project Semester

Today's world demands professionals that combine scientific and technological competences with soft and social skills. To cope with these new market trends, engineers must not only have a profound knowledge of engineering, be familiar with economics and management but also be prepared to work well in a multicultural environment demanding international communication teamwork skills and good command of languages. The European Project Semester (EPS) is a one semester project-based learning programme that intends to address these goals.

EPS has become a huge success and is recognized all over Europe since its start in 1995 at Copenhagen University College of Engineering. In 2017, the European Project Semester is offered by 18 European universities in 12 countries throughout Europe (Hansen, 2016).

EPS is created with primarily engineering students in mind, but other students of economics, architecture, design, management and marketing also have relevant backgrounds to contribute in the projects.

The EPS is divided into two complementary parts. One part comprises short intensive in-class workshops about topics related to team building and project management. The other part is a project-based programme that focuses on knowledge, initiative, creativity and responsibility of the students.

Students work together in international and usually interdisciplinary teams of three to six members applying their knowledge and acquiring cross-cultural communications skills.

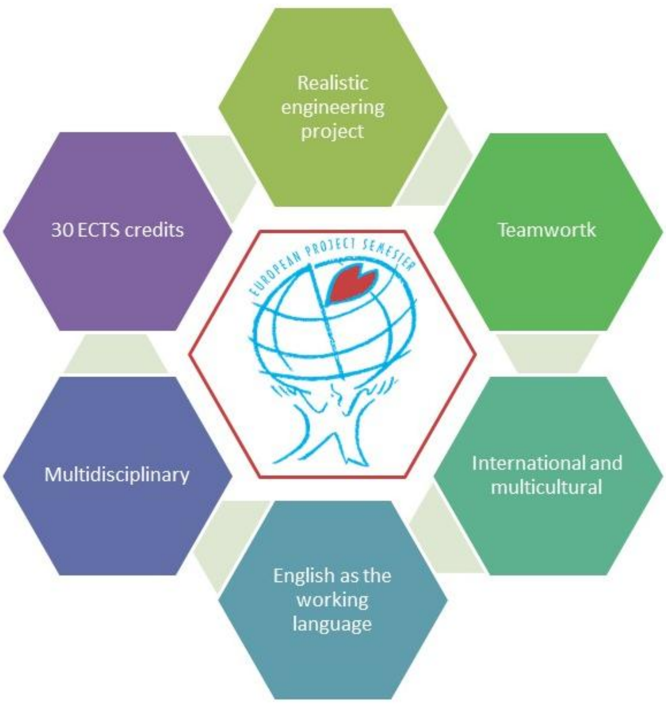


Figure 1 – EPS programme
Source: own elaboration

1.2 The project

In this paragraph, the global view about the project objectives is presented.

1.2.1 Project background

The present project aims to design a robot with the ability to recognise and harvest ripe tomatoes without human help or guidance. If successful, this pilot project could get further development in the South Ostrobothnia greenhouse industry.

The project will take part into a European competition organized by the company SICK, which has provided a sensor package and demands participants to innovate a completely new functional application using their sensors.

The idea of autonomous fruit harvesting is not new as it has already been applied to in different countries. However, in this region, the implementation of these techniques is not very common. Nonetheless, there is a huge sector in greenhouses in Finland with 334 enterprises (more than 50% of the vegetables producer companies) producing over 40.000 tons of tomatoes each year (LUKE, 2017).

Due to the large scale of this challenge, it has been divided in three steps:

The first phase is to develop the robot ability to see the ripe tomatoes and build a raw prototype to prove its functionality. In order to do so, three different grippers have to be designed and connected to the robot provided by the university. Also, some questions have to be answered such as what is the best way of identifying ripe tomatoes and how to establish communication between the vision and the gripping system.

The second phase is to realise a working prototype of the whole robot which will be tested in a greenhouse.

The third part is to introduce the product into the market and treat it as a saleable product due to its possibilities of being introduced to the greenhouse sector.

1.2.2 Mission

A mission is defined as the statement about the problem that needs to be addressed.

The mission has been defined as follows:

Our mission is to build a prototype of a harvesting robot that is able to detect and harvest ripe tomatoes and during the process to learn about automatization and robotics.

1.2.3 Vision

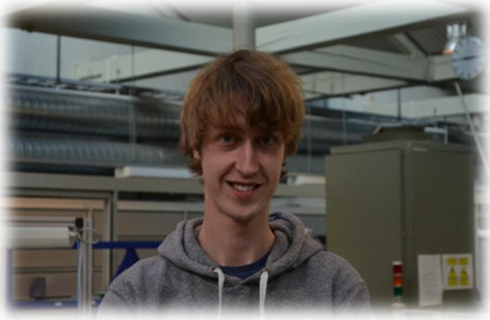
A vision defines the optimal desired future state of what is needed to achieve over time.

The vision has been defined as follows:

Our vision is to remove simple and repetitive tasks for farmers.

1.3 The team members

Hidde de Wit



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2 Requirements

The assignment is designing an autonomic-controlled and safe harvesting robot, that is able to be implemented in the greenhouses in the local environment. To fulfil this assignment, different requirements are appointed. These are listed in the tables below. In this chapter, the structure and idea behind the requirements are illustrated.

2.1 V-model

During this project, the V-model is handled as illustrated in the figure below. This model goes from a global design into detailed design to return back to a global view by using different tests.

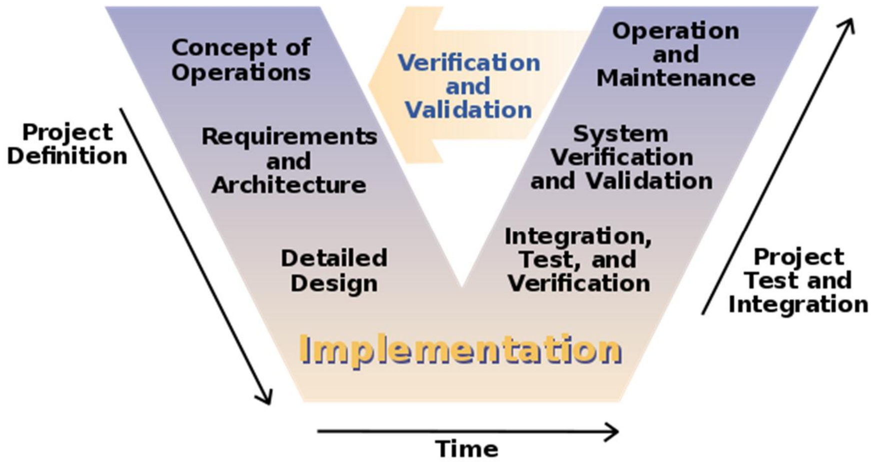


Figure 2 – V-Model
Source: https://en.wikipedia.org/wiki/V-Model_(software_development)

First of all, the requirements are set up to create a global view of the suspected functionality of the machine. Subsequently, a research phase is applied where different solutions for the demands are founded. These ideas are implemented in various concepts and tested among a theoretical pattern. The best concept will be realised in the prototype and numerous functions will be tested during the construction of the prototype. It is possible that practical test gives an undesired solution as thought in the theoretical test, in that case a different solution is resolved. With all the subparts successfully tested, the prototype has to fulfil a final verification with the requirements that are set up in this chapter.

2.2 Main requirements

The main requirements are imposed by the client and must be satisfied in the final prototype. Not every requirement is equal to a subsystem, therefore each demand has a number appointed by which references will be made.

No.	Details	Value	Comment
A	The robot is able to detect mature tomatoes automatically	-	Mature tomatoes has a bright red colour
B	The robot is able to pick mature tomatoes automatically	-	Mature tomatoes have a bright red colour

Table 1 – Main requirements
(Source: own elaboration)

2.3 Design requirements

This product must have a certain transferability between different project groups, because the amount of time is too short to realise the high level that is desired. Therefore, some design requirements are set up to improve the transferability to the next (levy?).

No.	Details	Value	Comment
C	The robot must be implemented to one of the industrial robots in Technobothnia	-	-
D	The robot must use a SICK-sensor in the implementation	-	As this robot will compete in a SICK competition

Table 2 – Design requirements
(Source: own elaboration)

2.4 Sub requirements

Next are the different subsystems with the specific requirements, the three different subsystems are detection, localisation and transport system. These requirements will be named successively.

No.	Details	Value	Comment
A1	A tomato has a minimum diameter of 60 mm	60 mm	The diameter stands perpendicular on the stem of the tomato
A2	A tomato has a maximum diameter of 80 mm	80 mm	The diameter stands perpendicular on the stem of the tomato
A3	A tomato has a bright red colour	-	At least 80% of the tomatoes must be this colour
A4	A tomato has a round shape	-	-

Table 3 – Detection requirements
(Source: own elaboration)

Next is the localisation requirements:

No.	Details	Value	Comment
A5	The X-location of the centre is determined with a uncertainty of ± 5 mm	5 mm	Relative to the robots position
A6	The Y-location of the centre is determined with a uncertainty of ± 5 mm	5 mm	Relative to the robots position
A7	The Z-location of the centre is determined with a uncertainty of ± 5 mm	5 mm	Relative to the robots position
D1	At least one coordinate must be obtained with a SICK-sensor	-	-

Table 4 – Localisation requirements
(Source: own elaboration)

Finally is the transport requirements:

No.	Details	Value	Comment
B1	The robot is able to remove the tomato from the stem	-	The tomato plant will be simulated in a lab environment
B2	The robot is able to remove the tomato without causing visual damage	-	Visual damage is optic damage for the human eye
B3	The robot is able to release the tomato in a storage box	-	-
B4	The robot is able to transport multiple tomatoes in one sequence	-	Multiple is at least 2 tomatoes
C1	The robot has a minimum reach of 650x550x400 mm (LxWxD)	650 mm, 550 mm, 400 mm	-

Table 5 – Transport requirements
(Source: own elaboration)

3 Research

3.1 Comparable harvesting robots

On this chapter, the current state of the art in automated harvesting of fruits and vegetables is presented.

3.1.1 Agrobot: Strawberry harvesting robot

AGROBOT SW 6010 is the commercial name of a strawberry harvester developed by Spanish company Agrobot.

It uses a set of cameras that can locate and identify the strawberries. When the detected fruit meets the criteria, an arm is extended to grab the berry, subsequently a blade cuts the stem with maximum precision to conserve the smoothness and delicacy of the fruit. The harvested fruits are transported by a conveyor belt to the front of the machine where two people work on a quality inspection and packaging.

This machine is not available yet (greenhousecanada, 2017; Bolda, 2017) .

Figure 3 – Agrobot: Strawberry harvesting robot
Source: http://www.agrobot.com/

3.1.2 *Octinion: Strawberry harvesting robot*

The Belgian company Octinion is also developing a robot to pick strawberries straight from the bush and place them in a basket.

Using machine vision provided by three cameras, the robot can identify ripe strawberries accurately. The gripper uses 3d printed soft clamps to remove the fruits in a gently way. Pulling with the soft clamps results in evenly divided pressure on the fruits. The risk of damaging the fruit is therefore lower than cutting or burning the stem. The picked strawberries are disposed into a basket by to the gripper.

An autonomous navigation system is implemented in this robot, therefore it can be applied to greenhouses without the need to make changes

This robot is ending the testing phase and will soon be available on the market. However, the company is working on developing new features to implement on the robot and adapting the robot in order to pick other vegetables like peppers, tomatoes, and cucumbers (Miley, 2017).

Figure 4 – Octinion: Strawberry harvesting robot
Source: http://octinion.com/products/harvesting-series/strawberry-picking-robot

3.1.3 *FFRobotics: Fresh fruit harvesting robot*

FFRobotics, an Israeli company, is also attempting to launch a mechanical picker within the next couple of years (usnews, 2017).

At this moment the robot is able to harvest apples. According to the founder of FFRobotics, due to the fruit recognition algorithm, eventually the harvester should be able to pick a variety of tree fruit after swapping the specialized grippers.

The harvesting robot uses a linear arm that goes into the tree and pick the fruit. Only the gripper proceeds into the tree, all the mechanical and the electronics are placed within the machine in order to be protected.

Applying a deep-learning algorithm in order to identify the ripe fruit, accordingly the machine improves the classification and recognition of the fruit with an ongoing learning process. By using this technique the recognition system is able to move from one kind of fruit to another type of fruit quicker (Dininny, 2017).

Figure 5 – FFRobotics: Fresh fruit harvesting robot
Source: https://www.roboticsbusinessreview.com/company/ffrobotics/

3.1.4 Swepper: Sweet pepper harvesting robot

SWEEPER is one of the applications as result of the extensive research that has been performed by CROPS on agricultural robotics. This harvesting robot will be used to pick sweet peppers.

This robot is an assembly of several subsystems such as a mobile autonomous platform, a four-degree-of-freedom robotic arm, an end-effector for fruit harvesting and post-harvest logistics that contains the sensing tools for detection mature yellow and red fruits and its surrounding obstacles.

The fruits are recognized with two different camera's using vision, removing the fruit is realized with grabbing the pepper and cut the stem.

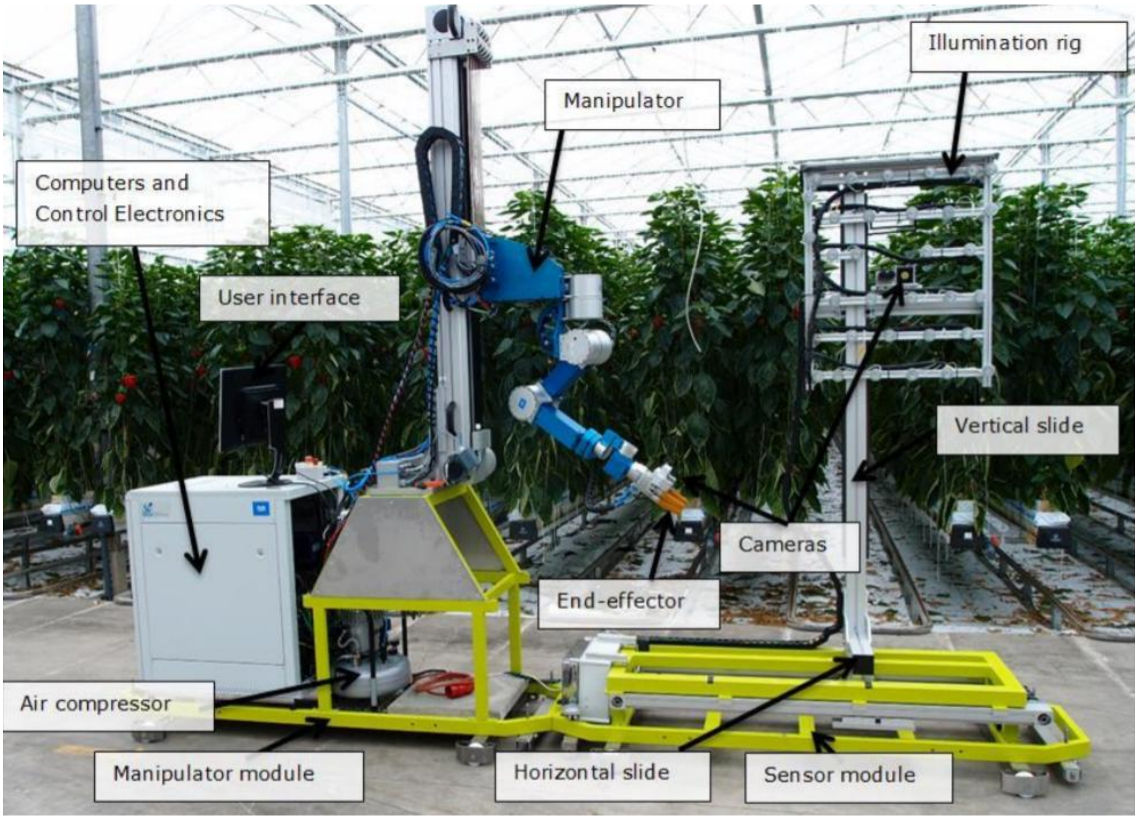


Figure 6 – Sweeper: Sweet pepper harvesting robot
Source: http://www.sweeper-robot.eu/

3.1.5 Panasonic – Tomato harvesting robot

Panasonic, the giant Japanese corporation, is also developing a tomato-picking robot.
It is unclear how this robot picks tomatoes due to the lack of information.
The company will begin selling tomato-harvesting robots on a trial basis around 2019 (Kyodo, 2017).

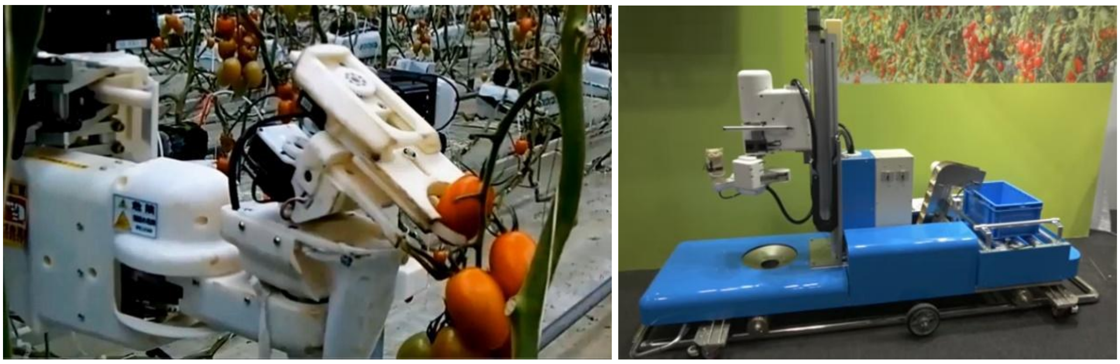


Figure 36 – Panasonic: Tomato harvesting robot
Source: https://www.youtube.com/watch?v=HWtfAIZ8sTs

3.2 Different systems

In this chapter the research in advance is explained. To create an overview the robot is divided into five subsystems.

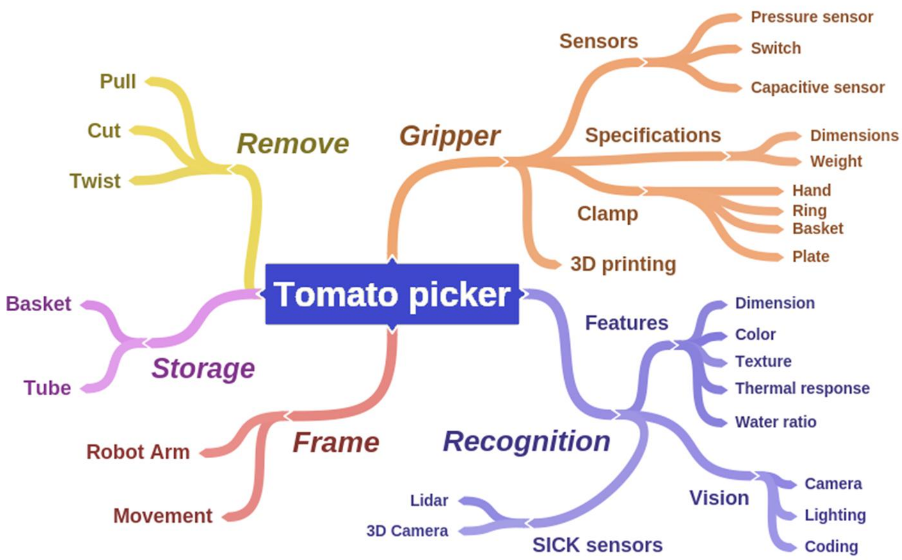


Figure 7 – Research mind map
Source: own elaboration

The main focus during this research chapter is the recognition, the gripper and the frame. With these three topic the basic principles can be fulfilled. Removing and storing will be left out of the scope of this project.

3.2.1 Recognition system

Through the recognition system the robot is able to detect and determine the position of ripe tomatoes. In this paragraph various methods of detecting are explained.

Introduction

In any production sector there is a growing need to increase the production and benefits while reducing time and costs. One of the solutions to this defiance is the development of automatic systems that replace manpower in tasks when a person performs worse than an automatic device in terms of precision, repeatability and working cycle.

Harvesting delicate fruit as tomatoes is time taking and needs large manpower, which results in high costs. Therefore, developing automatic systems capable of performing individualized collection, using selective strategies to harvest only fruit with the desired conditions, and at the same time, providing a system able to work 24 hours a day, would be a huge leap for agricultural industry.

The vision systems used in the automatic harvester aim to detect tomatoes and provide the information of the location, the size of the tomato fruits and other parameters such as its ripeness stage to the robotic controller.

The main objective of this paper is to present the research carried out in order to assess the state of the art in the development of automatic systems designed to detect, discriminate and locate ripe tomatoes fruits without human help or guidance.

Sensors

There is quite a large amount of different types of sensors and configurations employed in automatic fruit harvesting, ranging from a common camera in the simplest systems to hyperspectral cameras or chemical sensors in the most complex systems.

To set the background properly, it is considered to do a brief review of the main types and configurations that can be found focusing only in the more feasible ones for our application.

Monocular camera

One of the most employed approaches for detecting harvesting targets consists of attaching a monocular camera on the body of the robot to provide a single view on the scene being analysed (Bulanon, et al., 2001; Bulanon & Kataoka, 2010; Okamoto & Lee, 2010; Zhao, et al., 2005).

Another approach consists of attaching a monocular camera to the gripper tool. In this case, the distance between the camera and the target was estimated analytically by displacing the camera a known distance and by measuring the fruit radius before and after this displacement. In order to align the gripper tool with the fruit, the centre of the fruit and the centre of the image were matched. (Hayashi, et al., 2002; Ling, et al., 2004).

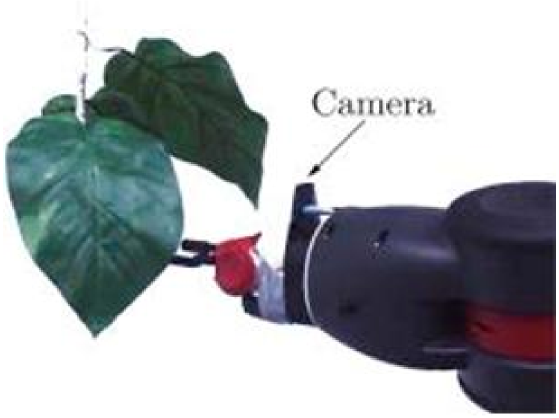


Figure 8 – Monocular camera attached to the gripper tool
Source: Barth, et al., 2016

Finally, some of the previous studies employ both types of cameras in order to have a better view of the scene and also to have a close-up view on specific targets (Edan, et al., 2000; Feng, et al., 2008; Van Henten, et al., 2002; Yuan, et al., 2010).

Stereo camera

Another alternative for detecting harvesting targets is based on the use of stereovision. In this case, two cameras are placed in the same plane at a certain distance from each other so two different views of a scene are obtained (Font, et al., 2014).

With stereovision it is possible to know where fruits are with much greater precision.

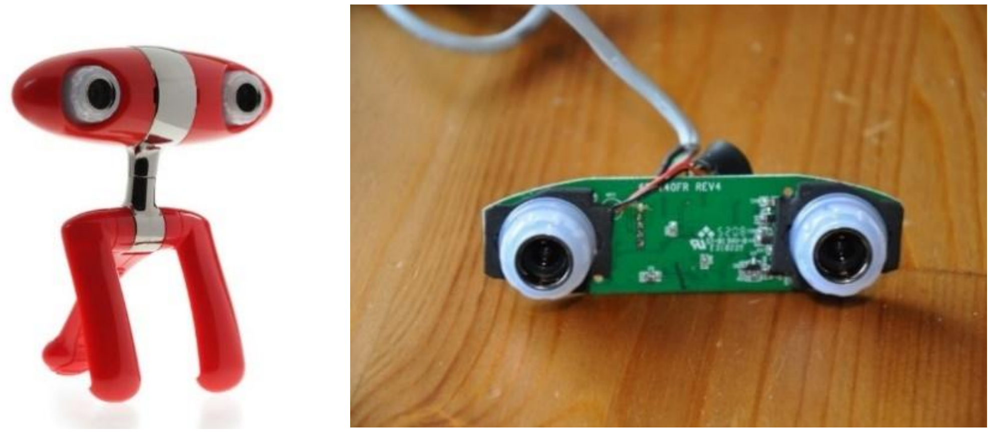


Figure 9 – Minoru 3D webcam. (a) External view; (b) Detail of stereovision cameras

Cameras on the market

In this section, all the requirements that need to be taken into account for selecting the camera will be classified and some different options that can be found into the market analyses.

In order to identify the tomatoes, some pictures will be taken of the plant to locate them. When photographing the fruit with a regular camera an input is received with information about shape, colour and (X,Y) position of the fruit. In case of taking images with a 3D camera, the depth should be also taken into consideration.

Which should be the main features for the camera?

- **Weight.** If the camera is too heavy the robot arm will not be able to move it around. The maximum weight should be 500 g.
- **Camera size.** The camera has to be added on the robot arm without blocking its movements.
- **Picture resolution.** Photos taken by the camera are processed by a computer program which cannot detect the tomatoes if the picture is too small. So at least a camera with a resolution of 2-4 megapixels is needed which is the equivalent of watching a video in 1080p.
- **Operating conditions (O.C.).** In the greenhouse there will be humidity from the watering and dust from the ground so the camera needs to be as resistant to these factors as possible.
- **Autofocus.** It should be able the detect colour and shape without blurs and by automatically focusing the objective.
- **Light.** It may be some cases where there isn't enough light to recognize the colours or the shapes so there should be some light coming from the camera.
- **Price.** Even though having a large budget, the price should not be high.

Once all the features are classified, let's search for some cameras into the market and analyse them in order to select the one which suits the best for the project.

Different kinds of cameras

- **LifeCam Cinema**

  It costs €78 and it has the following specifications:
  - Resolution of 720p at 30FPS.
  - Integrated autofocus during close-ups
  - High-precision Lens.
  - Automatically controls the exposure to colour and brightness.
  - Aluminium body.
  - Size: 55’8x23x45’9 mm.
  - Weight: 95,3 g.

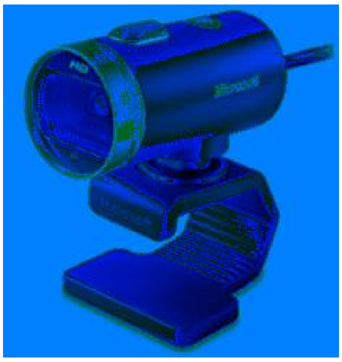


Figure 10 – LifeCam Cinema developed by Microsoft
Source: https://www.microsoft.com/accessories/

This camera has almost all the features that are demanded in the features. It is the less expensive camera that is being studied and it could be a suitable solution for the vision part.

- **SICK Inspector**

  Its price is approximately €500 and has the following features:
  Different models of the Inspector camera offered by SICK company.
  - Resolution from 384px to 600px at 45FPS.
  - It offers an IP67.
  - Manual focus.
  - Different kinds of light source.
  - Multiple inspections of patterns or details.
  - Ethernet connections.
  - Its size is 263’2x221’2x54’4 mm.
  - Weight: 350 g.

Figure 11 – SICK Inspector
Source: http://sensorstrade.com/mpn/vspm-6f2413/

This camera was made by SICK which is the company who also made the Lidar or the 3D Camera that is going to be used. An advantage of this is the possibility to combine both software easily and make the data flowing more effective. Also, this camera was specifically designed to identify objects so it would suit the project.

Besides, it offers the operating condition of working under some difficulties such as water or dust according to the IP67.

- **Robo Speciality Camera**

Its price is close to €5.000 and it has the following features:

- 3.27-megapixel resolution (720-1080p)
- You can focus manually or automatically.
- Auto White Balance
- 20x Canon zoom lens
- JPEG monitor. Remote viewing
- Working in a wide range of temperature and humidity.
- Dimensions: 63x65'6x201'2 mm
- Weight: 0'5 kg.

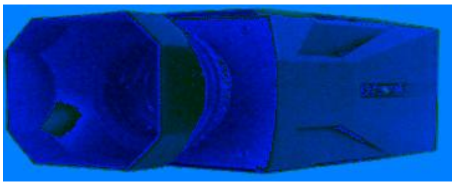


Figure 12 – Robo Speciality Camera designed by Telemetrics company

Source: http://www.telemetricsinc.com

This camera offers a lot of features that are quite interesting and which cover most of the features that are needed. Even though it is a good camera, the price is too high (almost all the budget) and there are some features which won't be used.

- **Zed (Stereo Camera)**

This camera's price is €382 and its main features are:

- 3D Stereo Camera
- 1344 x 376 resolution (4 MP per sensor).
- Depth measurement from 50cm to 20m.
- Automatic control of brightness, saturation, contrast, white balance.
- USB 3.0 connector
- Dimensions: 175x30x33 mm
- Weight: 159 g

Figure 13 – Zed, 3D camera designed by Stereo Labs

Source: https://www.stereolabs.com/zed/specs/

This camera would be useful in case of not having the Lidar or the 3D camera to measure the depth. However, it is not expensive and it covers most of the features that were demanded before.

- **Guppy PRO**

It does not have its price listed in its main page, however it has been found for €750.

Its main features are the next ones:

- 2 MP (1624 x 1234) resolution at 14 FPS.
- Colour and gamma correction
- Operating temperature from 5ºC to 45ºC
- Weight: 80 g
- Dimensions: 44'8x29x29 mm

Figure 14 – Camera Guppy PRO
Source: https://www.alliedvision.com/

Even though this camera overlays some of the pictures features, it misses some important others like the autofocus and it is possible to find better features in some of the other cameras for less money. However, it will remain as an option until making the decision.

Discriminating values

The goal of the recognition system is to locate all the tomatoes in the plant and to know which ones of them are ripe and which ones are raw in order to pick them or not. Therefore, it is rather important to know features such as the colour, shape, type of the tomato, weight and water ratio. By classifying all the characteristics, it is possible to recognize them.

Colour

The colour of the tomato is a good way to know either to harvest the tomato or not. However, when the tomato is completely ripe it has to be served within a few days. Because of that, tomatoes are gathered when the first blush of red appears at the bottom of it. If doing so, tomatoes will continue its ripening during the transport and will have less flavour that the ones who are left longer.

One of the main difficulties of using colour as a visual discrimination parameter is that can suffer from uncontrolled or changing illumination and shadows.

Figure 15 – Stages of the tomato' ripening
Source: http://www.oregonlive.com/environment/index.ssf/2012/06/the_secret_to_great-tasting_to.html

Shape

As shown in the picture below, there are many different varieties of tomatoes and also many different shapes. Therefore, the assumption is focus on the round-shape tomatoes.

Figure 16 – Most common types of tomatoes
Source: http://theseedsmaster.blogspot.fi/2016/02/top-3-heirloom-tomato-varieties-to-grow.html

Weight

Weight is also another factor to establish whether the tomato is ripe or not. As tomatoes grow, their size increases as well combined with the weight. If the volume and the density of the tomato are known, the weight can be easily defined.

3.2.2 Depth determination

In order to automatically extract the depth coordinate of the tomatoes, the team tried the different methods that are listed below:

Light detection and ranging sensors (LIDAR)

A radar technology capable to scan the environment is Light Detection And Ranging also known as LIDAR. It uses laser pulses instead of radio pulses as common with sonar scanners. With the environment scan is it possible to locate the position of the tomato.

Figure 17 – LIDAR Sensor SICK
https://www.sick.com/us/en/detection-and-ranging-solutions/3d-lidar-sensors/mrs1000/c/g387152

Method

The LiDAR instrument fires rapid pulses of laser light in the environment. Light moves at a constant and know speed. The instrument measure the travel time for each pulse to bounce back and that way calculate the distance between the instrument and the object. Combining this information creates a map of the environment. (Anon., 2017)

It is also possible to move the LiDAR during a scan, if the direction and speed of the movement is known, these can be taken in account with the calculations. The limitation is the computing power of the sensor, with present developments these boundaries are pushed.

Components

The first component is the laser, these are categorised by their wavelength. Non-scientific solutions have 600-1000nm lasers, as these can be focused and easily absorbed by the eye, the maximum power has to be limited to make them eye-safe. Lasers with higher wavelength of 1550 nm can't be focused by the eye and therefore much higher power levels can be used. Ideal for longer range and lower accuracy and common used in the military cause these pulses do not show under night-vision goggles.

The scanners and optics determine the range and resolution of the detected area. Single or multiple scanning methods are used. With the photodetector the device reads and records the signal being returned.

When the LiDAR is mounted on a vehicle, it can be used as a navigation and positioning systems. Most LiDAR's are equipped with an Inertia Measurement Unit (IMU) and combined with a Global Positioning System (GPS). That way the device can determine its precise orientation and location.

SICK Camera

The Visionary-T camera is an infrared light camera that has been provided by SICK Company alongside with the LIDAR. However, the LIDAR was not suited for the project and the 3D camera was taken into consideration.

Figure 18 – Visionary-T SICK Camera
Source: http://www.planet.co.th/en/product/brand/detail/620/3vistor-T?category=452

The camera works by sending beams of infrared lights to the environment and receiving them back. Then, the device determines the times the lights lasts to bounce back. If one of the beams takes longer to bounce back, means that the object where is bouncing is further than the others are.

When the camera has received all the beams, it shows a display on the SOPAS software (or the program that is being used) such as the next one:

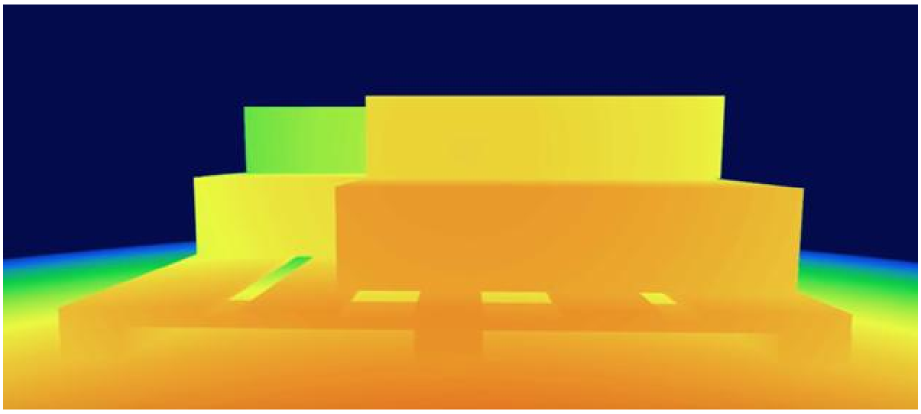


Figure 19 – 3D distance data from Visionary-T SICK Camera
Source: https://www.sick.com/fi/en/vision/3d-vision/visionary-t/c/g358152

In the picture, the closer the objects are, the warmer the colors and the other way around. Therefore, if an object is close to the camera it is more orange than the one in the back. However, this camera has some limits. It can measure up from 50 cm to 7 meters so, it cannot measure anything closer or further.

Triangulation

The triangulation method is the process of determining the distance of an object by taking bearings from two different points.

Triangulation works by measuring two angles pointing to the object, one of them being 90 degrees and a work line of 1 meter (depending on the scale). With the angles and the meter, it is easy to calculate the distance to the object, using trigonometry.

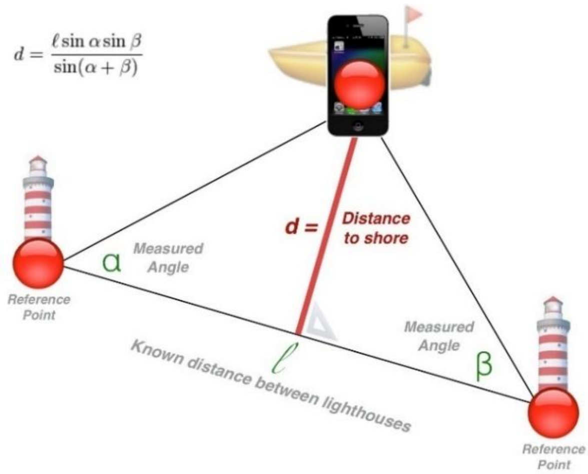


Figure 20 – Triangulation example
Source: **https://inotes4you.com/2013/04/14/location-based-services/**

This method would work the same way in the project. The robot arm holding the camera would take a picture (where the tomato is in the centre of the image) from one point, then it would move 90° to another point and it would turn the needed degrees to have the tomato again in the centre of the image. Doing so, the necessary variables (the angles and the working line distance) would be found and the distance could be calculated.

Double camera

This method would work the same way as the triangulation method works. Instead of moving the camera through the working line, another camera would be placed at some known distance in a certain known angle. This way, all the variables are known and it is possible to calculate the distance again.

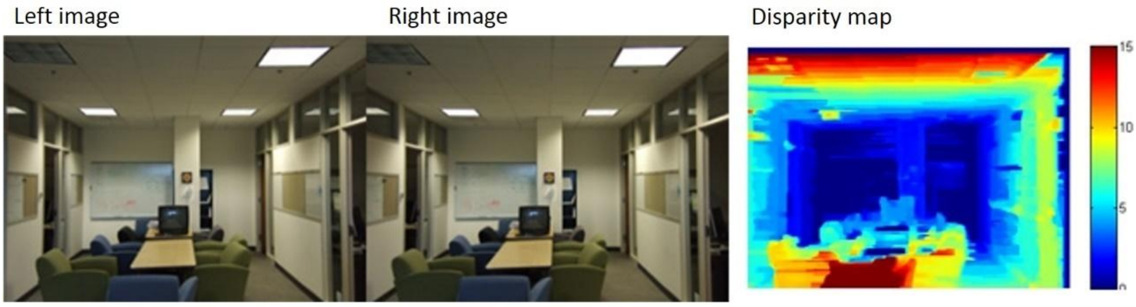


Figure 21 – Stereo vision depth estimation
Source: https://se.mathworks.com/discovery/stereo-vision.html

Diameter distance

The size measurement method is another trigonometrical system that enables to calculate the distance with some known values. In order to determine the z coordinate, the values needed are the size of the object that we want to know in two different distances, and the distance between the two measured points.

Figure 22 – Distance to objects using single vision camera
Source: https://www.youtube.com/watch?v=Qm7vunJAtKY

In the project, the team can place two different points in front of the tomato to take pictures. Then, measure how many pixels have the two tomato pictures and apply the formula to calculate the distance.

3.2.3 *Gripper tool*

The gripper tool is one of the most important parts in an autonomous robot for harvesting, because it is the link between the robot arm and the tomatoes. Therefore, the selection of the gripper in this kind of robots is highly important.

There are many different types of grippers and a wide variety of factors to consider, so to decide which type of gripper is most suitable for picking up tomatoes, a description of the different gripping techniques and a conclusion will be presented in this chapter.

The goal of the gripper looks like the following block diagram:

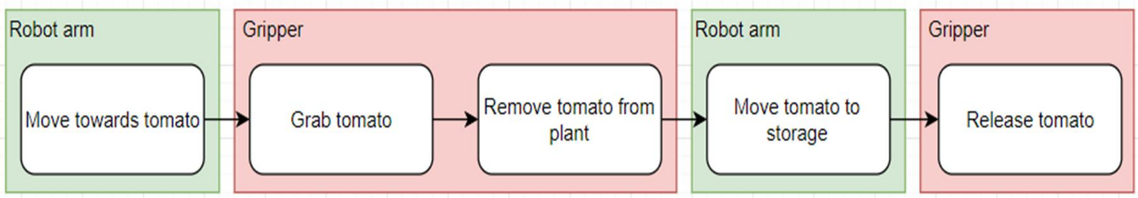


Figure 23 – Block diagram of the function of the gripper
Source: own elaboration

Design limitations of the gripper

Before designing the gripper, the requirements have to be set up. Since the gripper will be used to pick tomatoes, earlier named characteristics have to be mentioned.

Diameter

The diameter fruit classifications are:

- Extra small: 48-54 mm
- Small: 54-58
- Medium: 58-64
- Large: 64-73
- Extra-large: 73-88
- Maximum large >88 mm.

This means the gripper should have a range of at least 48mm to 88mm. A slight wider range is recommended, but it should not become excessively large.

Weight

The weight of a tomato depends on the diameter and the variety of the tomato. Most tomatoes are included in the range of 50 to 280g. Exceptions can reach 450g.

This means that the gripper should be able to carry at least 500 g. Slightly more is recommended. The maximum weight of the gripper plus tomato should not exceed 4.5 kg, as that is the limit of the robotic arm.

Shape

Depending on the variety of the tomato, shape is different. To begin with, research will be focus on spherical tomatoes which would be easier to recognize and grab.

Different kinds of grippers

Materials

According to the weight of tomatoes, plastic can certainly be used. That is why using 3D printing could be an economic way to make the gripper.

The materials should be waterproof or water resistant as tomatoes can be wet. The clamps should also be non-slippery (regardless whether the gripper is wet or dry).

The gripper should also be made of non-toxic materials.

Shape

On the following figure, different kinds of gripper are presented.

Figure 24 – Example of various gripping mechanisms

Sources: a) https://www.prlog.org/12496904-soft-robotics-inc-receives-2015-game-changer-award.html
b) https://www.festo.com/cms/es_corp/14014.htm
c) https://www.thingiverse.com/thing:193851
d) http://robotics.oregonstate.edu/reu
e) https://www.intorobotics.com/35-robots-in-agriculture/
f) https://www.cambridgeconsultants.com/media/press-releases/pick-bunch

All mechanical grippers work with two (or more) surfaces that move towards each other until it clamps the tomato.

When the clamp works with two surfaces, the mechanism often works with two gears, that pull the surfaces together. One advantage of a two-surface gripper is the easy way to manufacture it. The main downside is the two major pressure points on the tomato, which can damage the tomato when the robot is not properly calibrated.

When more clamping surfaces are used, a spiralling axis can be used that turns multiple gears and therefor can move multiple surfaces together synchronously. The good thing about this solution the more evenly spreading of the pressure on the tomato. This way the tomato is less likely to drop, because there is a supporting surface below the tomato.

The example shown on image C could be used to begin with, the 3D printing lab has already printed the parts but they are not mounted together.

Environment of the gripper

The vast majority of the grippers found use only electricity to move the gripper and to supply electronic cards and sensors.

The gripper must be attached to the robot arm. The robot is an IRB 1200-5/0.9 made by ABB. It can handle 5kg at maximum. Therefore, the maximal lifting weight is around 4.5kg

The environment would be humid so the gripper must not be sensitive to it, or at least the clamp.

Strength

The gripper is supposed to grab the tomato and remove it from the plant. During this process the tomato is not allowed to be damaged. Because we are using grabbing mechanism there are two scenarios that are unacceptable:

- Too little pressure and the tomato drops
- Too much pressure and the tomato will get squished

How much force actually is required is determined by experiments with real tomatoes.

Gripper requirements

The gripper is required to meet the following specifications:

- Grab a tomato of with a diameter of 60mm to 80mm.
- Carry a weight of 500g
- Needs to be at least water resistant.
- Should not damage the tomato in any way
- Should not be made of a toxic material.
- Should be durable
- Be able to remove the tomato from the plant
- Be able to be produced with low costs

Gripper tool sensors

To prevent the gripper from damaging the tomato it is required to limit the amount of force applied by the gripper to the tomato. This is done by placing sensors in the gripper.

There are various ways to implement the sensors in the gripper. The following methods will be researched:

- Pressure sensors
- Capacitive sensors
- Switches

The requirements of the sensor are:

- Able to mount on the fingers of the gripper without major modifications.
- Able to detect whether the tomato is in the gripper or not. Recognizing if the tomato is still hanging is a major plus. Higher accuracy is irrelevant.
- Water resistant. It should be able to resist rain wet tomato plants.
- Output of the sensor should be digital. A well-documented communication protocol like Serial Peripheral Interface (SPI) or Inter-Integrated Circuit (I^2C) is preferred.

Pressure Sensor

The idea of adding pressure sensors is that the gripper can measure how much force is applied to the tomato. This way the robot does not only know if the tomato is grabbed or not, it also knows how well the tomato is grabbed. Also, when the tomato is picked the pressure changes suddenly. This means that with pressure sensors it can be measured when the tomato is picked.

There are different kinds of pressure sensors:

- Absolute pressure sensors: these sensors measure the pressure relative to a high vacuum reference. This means that it will also measure the air pressure.
- Gauge pressure sensors: These kind of sensors measures the pressure relative to the atmospheric pressure.
- Differential pressure sensors: A differential pressure sensor measures the different level of pressure between two points. It is generally done by a membrane and applying pressure to both sides. The direction that the membrane moves in shows the difference in pressure.
- Sealed pressure sensors: This last pressure sensor has a predefined reference point that is not a vacuum or atmospheric pressure. In all other aspects it is the same as an absolute pressure sensor or a gauge pressure sensor.

All of the sensors mentioned above have different points of reference. The pressure measured with different types of sensors will give different numbers. The difference in these numbers look like the following image:

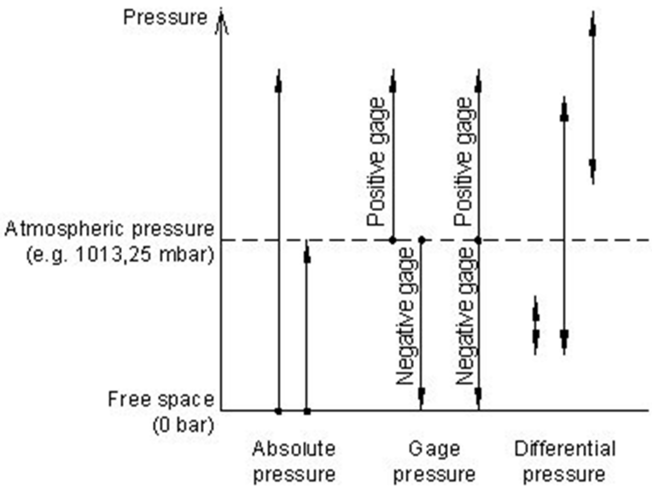


Figure 25 – Differences in data received from sensors

Source: (First-sensor, 2017)

For the tomato picker project all sensors types can be used, although the proper adjustments should be made in software.

What are the upsides and downsides of a pressure sensor?

The upsides of pressure sensors are:

- Can measure pressure and recognize when the tomato is plucked.
- All in one solution.
- Waterproof sensors are available.

The downsides are:

- Some sensors need a Printed Circuit Board (PCB).
- Mounting can be difficult depending on sensor.
- Each sensor needs a specific communication lines. This means there will be a lot of cables.
- Sensors can be expensive (up to €50 per sensor).

Capacitive Sensing

What is a capacitor?

When two conductive surfaces are close together it can create an electric field in which energy can be stored. A capacitor is an electronic component that emphasizes on this effect. The amount of energy that can be stored in the capacitor is directly related to the size of the surfaces, the distance between the surfaces and the material in between the surfaces (the dielectric material).

In a PCB made capacitor the dielectric material is the material the PCB is made of. And the material of the plates is generally copper.

What is capacitive sensing?

The idea of capacitive sensing is that you create a variable capacitor that reacts to touch. The most common way to do this is to create a capacitor on your PCB. This capacitor has a set capacitance that can be measured. The capacity lies in the pF range. When the capacitor is touched the capacitance rises drastically. This change can be measured.

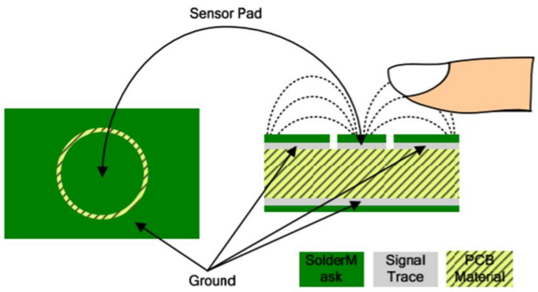


Figure 26 – Capacitor made on PCB
***Source:* (Instruments, 2017)**

The underlying ground plane is recommended for EMI reasons and to keep the set capacitance reliable.

How do we measure this change in capacity?

Capacitance is measured by sending an alternating signal through the capacitor and measure how it changes.

The capacitor behaves as a filter capacitor which removes high frequencies. Therefore, a signal that contains high frequencies is crucial. A square wave signal is often used as they are easy to create and change is easily detectable with an analog to digital converter (ADC) or an operational amplifier.

There are also many manufacturers that offer microcontrollers with capacitive sensing functionalities.

How is an accurate capacitive sensor created?

The main goal is to create a capacitor that fluctuate when touched. The capacity increases when the sensor is touched. It is unknown to what value it increases, because it depends on the material the sensor touches and how the material touches the sensor. To improve the change, it is needed to decrease the base capacitance of the sensor.

Lowering the base capacitance can be hard, because the materials are generally set and unchangeable. Besides that, when the perimeter of the sensors is larger, the base capacity improves (based on the formula). The contact area of the tomato needs to be smaller than the sensor pad. A circular shaped circle pad is the best solution as it gives the highest ratio of area to perimeter.

Another important factor is that electromagnetic compatibility should not interfere or be interfered by other nearby systems, especially since pF capacities are being used. It is highly recommended to use a ground plane around and below the sensors.

Covering the sensor to make it water resistant is necessary, but the material used to cover should have a very low dielectric constant.

What are the upsides and downsides of capacitive sensing?

The upsides are:

- Relatively cheap (only need a PCB and a microcontroller. The development kits are less than €25.
- Can sense when a tomato is picked or not.
- Easy to make water proof.
- Requires little communication lines.

The downsides are:

- Can be difficult to develop.
- Requires a microcontroller or high precision analog to digital converters.

Switch

The idea of a switch is that when the tomato is inside of the gripper it presses a momentary switch. When the tomato is not in the gripper the switch is not activated. This way the robot will know when the tomato is inside of the gripper or not.

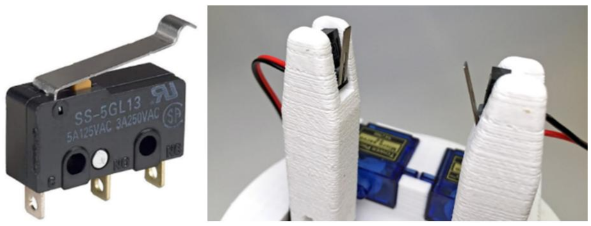


Figure 27 – Momentary switch

Sources: a) https://www.makeralot.com/ss5gl-microswitch-limit-switch-5a-125vac-p47/
b) http://danchen.work/manipulation-processes/

What are the upsides and downsides of a switch?

The positive side of this way of implementing switches instead of pressure sensors or capacitive sensing is that it is really simple and cheap. However, it is not a long-lasting solution and it can be hard to make this water proof.

The upsides of a switch are:

- Very cheap, a reed switch is less €5.
- Requires up to a maximum of one dateline per switch. Can be lowered by multiplexers.
- Very easy to develop.

The downsides of a switch are:

- Due to the mechanical working of switches they are not a long-lasting solution.
- Hard to make water proof.

Conclusion for gripper sensors

The switch method does not meet the requirements of being a good long-term solution and being waterproof. Therefore, it is not a suitable primary option.

The pressure sensors meet all the requirements however it can be quite expensive. Pressure sensors will be a good second option.

Capacitive touch sensors meet all the requirements, but it will be risky. However, it will be the best solution.

3.2.4 Robot arm

This chapter will provide key information about the robotic arm used in the project.

Information about the robot arm ABB 1600

The robot arm that will be used for this project is the IRB-1600-6/1.45 from ABB. This is a compact 6-axis industrial robot. The IRB-1600-6/1.45 model has a reach of 1450 mm and a maximum combined weight of the end effector and payload of 6 kg.

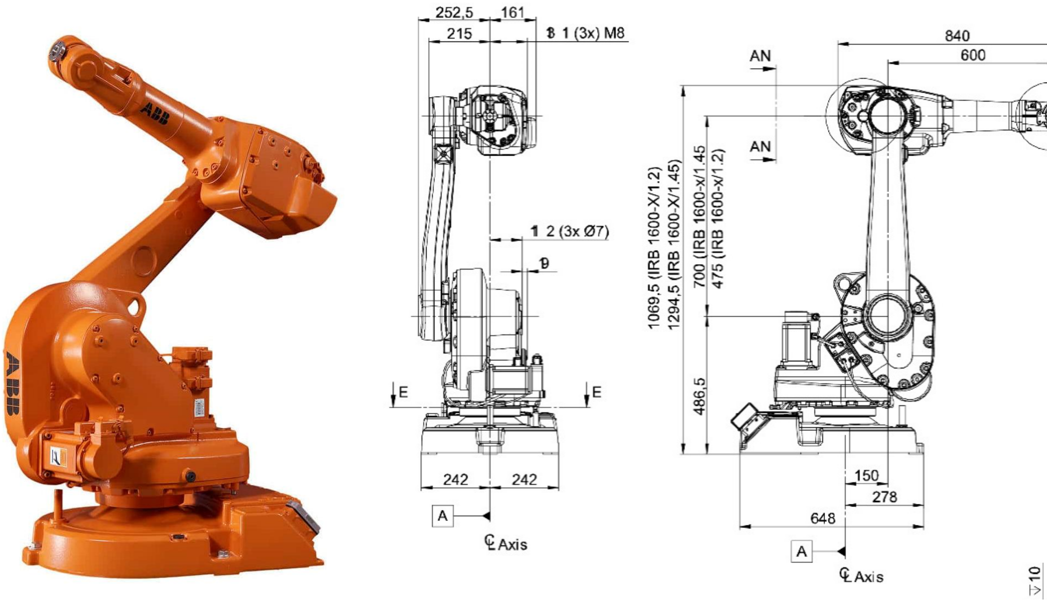


Figure 28 – Robot arm IRB-1600-6/1.45 dimensions
***Source:* https://library.e.abb.com/**

The working range of the IRB-1600 can be seen in the following figure:

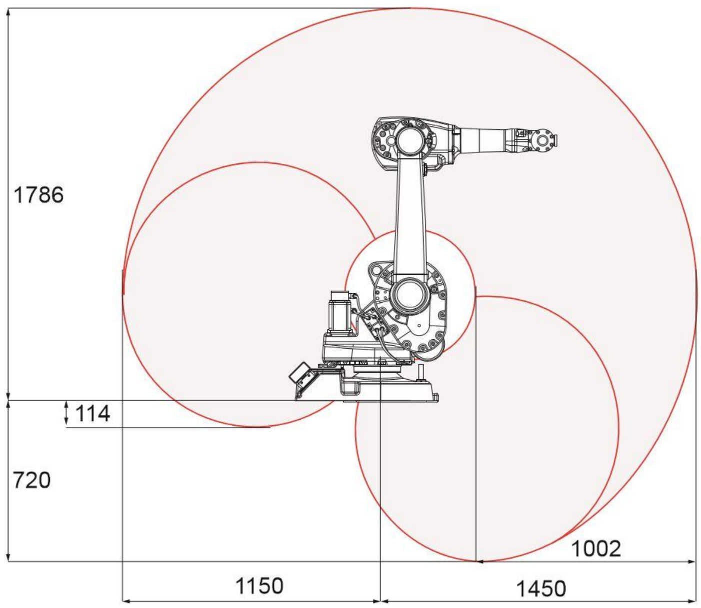


Figure 29 – Robot arm IRB-1600-6/1.45 working range
***Source:* https://library.e.abb.com/**

The 6 rotational axes are shown in the following figure:

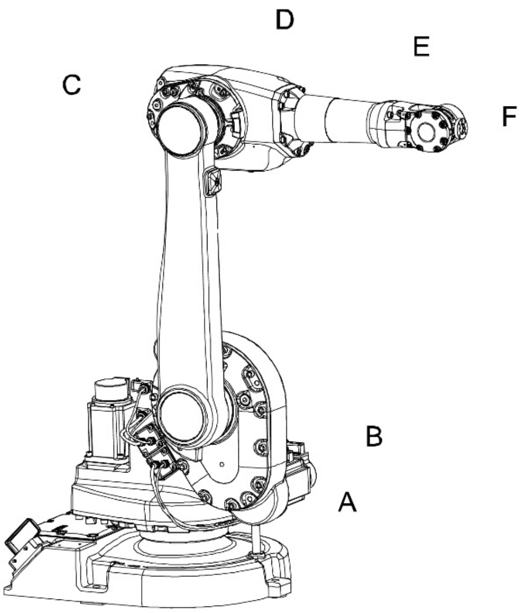


Figure 30 – Robot arm IRB-1600-6/1.45 rotational axes
Source: https://library.e.abb.com/public/.../3HAC046982-en.pdf

On the next figure, the dimensions of the tool flange are presented.

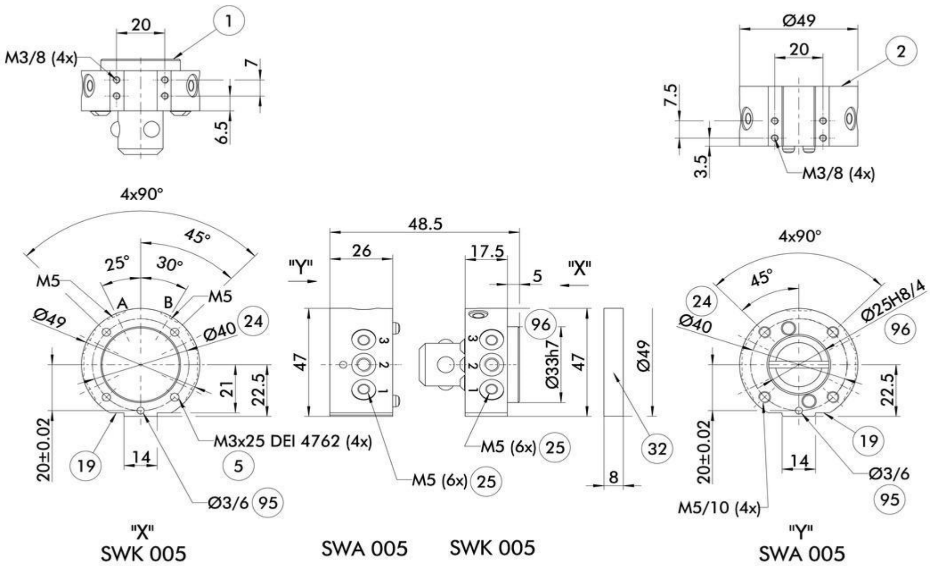


Figure 31 – Tool flange schematic
Source: https://schunk.com/fi_en/gripping-systems/product/17974-0302307-swk-005-000-000/

RobotStudio and RAPID code

RobotStudio is the software provided by ABB that allows the user to program, simulate and control the robot arm.

RAPID code is the programming language for writing the instructions that the robot will follow.

The figure below shows the working environment of RobotStudio software. In this figure, it is possible to differentiate the programming interface (on the left) and the simulate interface (on the right).

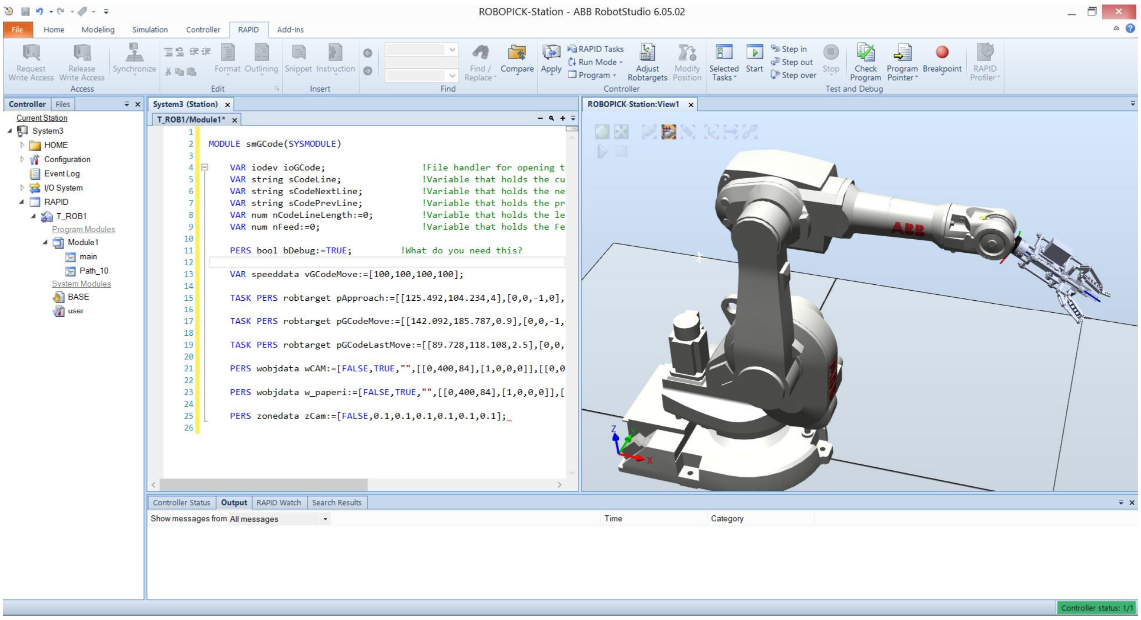


Figure 32 – Screenshot of RobotStudio interface

Source: own elaboration

4 Design

4.1 Concept generation for gripper tool

For the development of the gripper the Kesselring method is applied.

With this method, first of all, the different functions are determined. Subsequently various solutions are given to these functions. These are shown in the morphologic box, this chart combined with inspiration found in the research four different concept are developed. Finally, the best concept is determined with the Kesselring method.

4.1.1 Morphologic box

The robot fulfils various amount of functions, in this morphologic box the functions of the gripper are displayed. Because the gripper is responsible for removing the tomato from the plant and transport the tomato to a deposit box. The analyses made on this production step are shown in the next table.

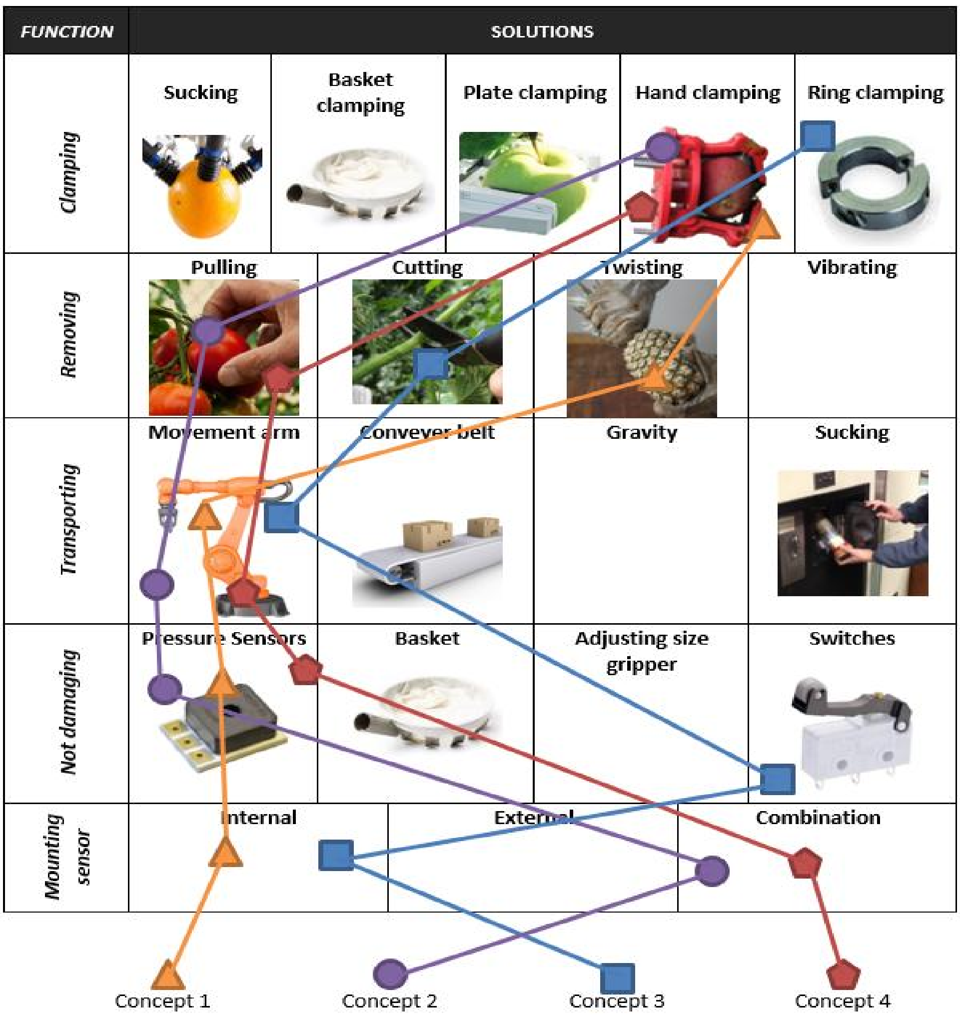


Figure 33 – Morphologic box
Source: own elaboration

Some choices need further clarification. For example, for clamping and transporting 'sucking' is not chosen. That is because the pneumatic installation that's need to be included in the robot. Also, the transporting is always done by a movement of the arm, this combine very well with the usage of the robot arm. These two choices are also made considering the amount of available time this project has to offer. The time usage rises drastically including these systems and can better be introduced as addition when this system is ready.

Furthermore concept 2 and 4 seems to be exactly the same, however all variations come to light when the concepts are described in the next paragraph.

4.1.2 Concepts

Concept 1 – Robot Arm – 4 Bar Linkage End Effector

The idea of this design is to have one rotating axis that drives the fingers together. The finger shape in the figure shown below is straight. This is not suitable for a tomato as the pressure will be applied to two points. Therefore, curly fingers are chosen for the two-finger design.

The gripper also features pressure sensors in the "fingers" of the gripper to prevent the robot from squishing the tomato.

To prevent the tomato from potentially falling the gripper has a support plate.

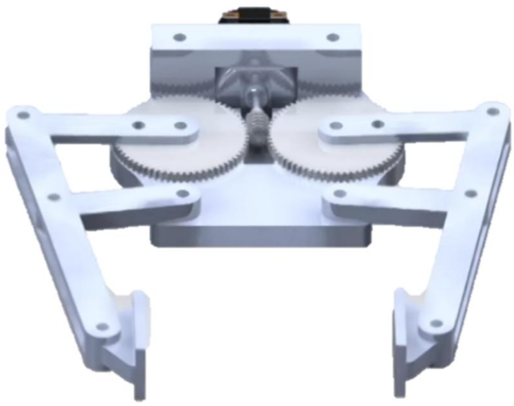


Figure 34 – Robot Arm – 4 Bar Linkage End Effector concept
Source: http://www.robotpark.com/academy/robot-arm-4-bar-linkage-end-effector-robot-gripper/

Concept 2 – Three-half-finger gripper

The design of this gripper is based on a three clamps gripper. The difference is that there is one second phalanx on only one clamp, which avoid collision between this second phalange if there was three of them. The three clamps allow the gripper to fit with the shape of different sized tomatoes. The second phalanx keep the tomato inside the gripper when the robot arm pulls on the tomato to remove it from the plant.

This gripper works with a screw and a nut which is inside the orange part. When the screw turns, the orange part move from bottom to top or vice versa, depending on the turning direction. To prevent damaging the tomato, three pressure sensors are integrated into the main fingers. So, when the pressure reaches a certain amount, the servo stops moving the screw: it means that the tomato is well grabbed.

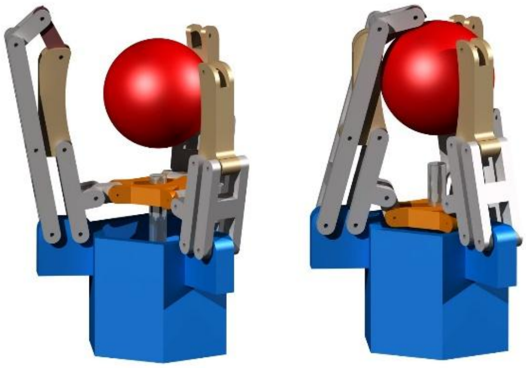


Figure 35 – Three-half-finger gripper
Source: own elaboration

Concept 3 - Basket-holder gripper

This design is based on the shape of a typical basket. However instead of putting the tomato into the basket, a basket surface is placed at the bottom of it and is held so that the tomato does not fall off.

This design grabs the fruit with two curved clamps that surrounds most of the side area of the tomato and a basket surface is placed under it, holding on the weight of the tomato. To detect how much pressure should be applied to the tomato, some switches are placed on the clamps in order to know when they are touching it and stop moving.

While the gripper is holding the fruit, a quick linear movement from an installed blade cuts the tomato off the stem and places it to the storage.

In order to not damage the fruit and to save some material, the clamps are curved and have some holes in it to prevent some potential crushing by being more elastic.

Figure 36 – Basked-holder gripper
Source: own elaboration

Concept 4 - Three-finger gripper

This concept is based on three-finger robotic gripper. The design of the gripper is open-source and ready to be 3D-printed, but the 3D model has to be adapted in order to fit the specific requirements better.

The proposed 3D-printed gripper grabs the tomato by using the first phalanges of the fingers, and ensure a complete envelope of the tomato by using the second phalanges of the fingers. Once the tomato is firmly held, the robot arm pulls and twists the tomato until it gets off the plant. Finally, the tomato is transported to a basket.

The fingers of the gripper are designed so that the surfaces are smooth and have no edges that could damage the tomatoes or the plant.

The three fingers in the gripper are attached in a circular way with 120 degrees between each other, and are actuated by a single actuator using a gear train transmission system. The servomotor is attached on the base and drives the directly connected worm gear. The worm gear transfers rotational motion to the set of worm wheels, which are connected to each finger.

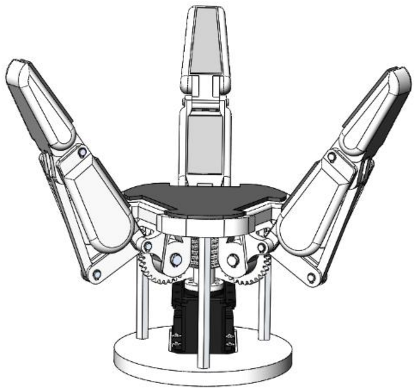


Figure 37 – Three-finger gripper
Source: (Telegenov, et al., 2015)

4.1.3 Evaluation

During this method two separated phases are named: the building phase and the user phase. This creates a better understanding of the choices that has to be made. During each phase the different requirements are judged in a certain order, which creates differences in importance. Each concept is judged at functionality or user friendliness, with the total score compared with the maximal score the Kesselring diagram is drawn. Finally, the best concept is chosen.

User phase

During this phase each concept is compared with the functional requirements. These requirements are named in the morphological box. First of all, the requirements are ranked by all team members. Clamping is rewarded with the highest importance, cause without this function the robot is unable to gather tomatoes. The least important requirement is transporting, cause this functionality can be introduced as a new assignment after concluding this robot. Next is the table of the functional requirements.

	SCORE					
	Influence	Concept 1	Concept 2	Concept 3	Concept 4	**Optimal**
Clamping	5	3	2	3	4	**4**
Removing	3	4	3	3	3	
Transporting	1	2	3	2	3	
Not damaging	4	3	3	2	4	
Mounting sensor	2	3	2	3	2	
Total		47	38	40	52	**60**
Percentage		78%	63%	67%	87%	**100%**

Table 6 – User requirements for the gripper
(Source: own elaboration)

As seen above concept 4 scores 87% of the total score. For clamping, six orientational surfaces can make contact with the tomato. Variation in form and size are not a problem for clamping. The other concepts struggle more with these variations, combined with the uncertainty of steadiness of the phalanx the second concept scores significantly lower.

On the other hand, twisting seems to be a much cleaner method the remove the tomato from the plant. No damage happens to the tomato cause of divided pressure, while pulling results in a peak of pressure on the top of the tomato. However, grippiness becomes more important because the tomato can slip during the twisting.

Building phase

In the building phase the development of the product is being central. If the concept is too complex, then the project group can't deliver a realistic prototype. Furthermore, when it is too simple, some opportunities are missed. Also, the working speed of the robot and durability are taken into account.

	SCORE					
	Influence	Concept 1	Concept 2	Concept 3	Concept 4	**Optimal**
Speed	2	2	2	2	2	**4**
Complexity	4	4	2	3	2	
Costs	3	2	2	4	3	
Reliability	5	3	3	2	4	
Durability	1	1	3	3	2	
Total		42	36	41	43	**60**
Percentage		70%	60%	68%	72%	**100%**

Table 7 – Manufacturing requirements for the gripper
(Source: own elaboration)

Reliability received the highest influence in view of a working demonstration. A safe and locked testing environment also contributes on the reliability of the demonstration. At the same time speed and durability are rated lower because it is only related to a prototype. Probably the prototype will experience further improvements after this conclusion.

The reliability of clamping and removing the tomato is higher with concept 4 than the other ideas because the six different contact plate ensures these functionalities. On the other hand, the complexity rises, controlling these six plates and make adjustment to prevent damaging the tomatoes is harder to realise. Therefore, the first concept seems to be in benefit.

Kesselring diagram

These two tables are combined in the Kesselring diagram. Were the two phases come together.

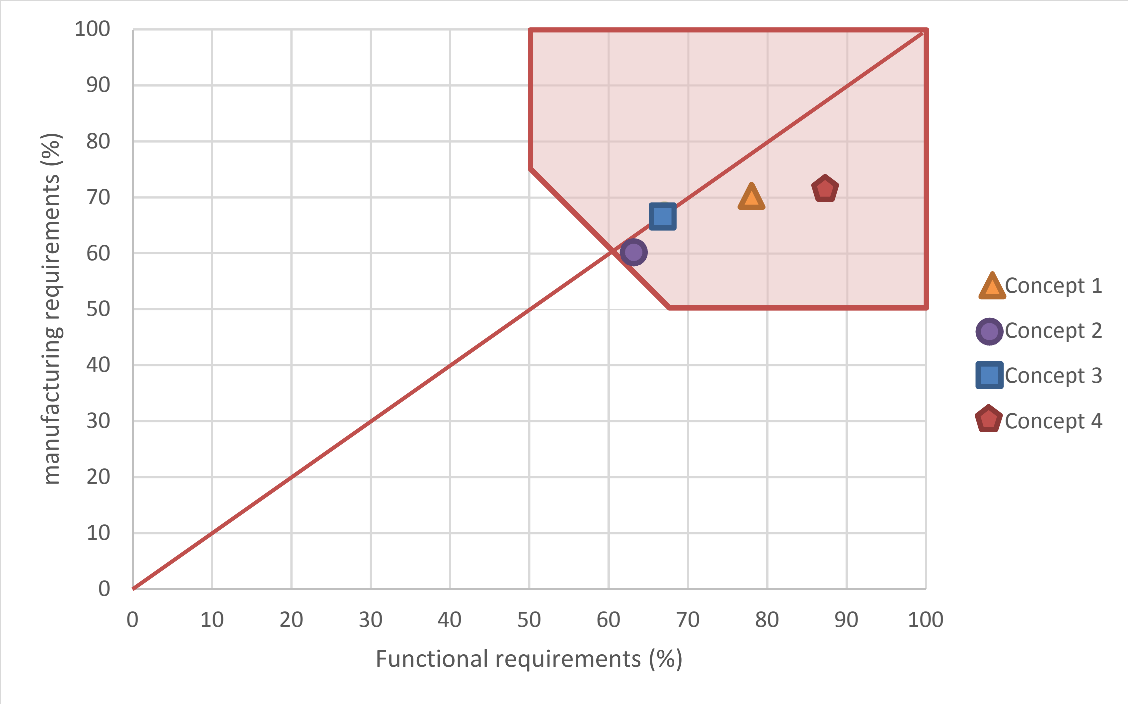


Figure 38 – Kesselring diagram
Source: own elaboration

The idea should be at least in the red area and preferable as close as possible to the red centreline. With this theory the concept number three seems to be the best. But other decisions can be made provided that these choices are explained

Over all the building phase is judged quite vacillated or the other way around, the user phase is judged quite opportunistic. The differences between the scorings are larger than predicted. Therefore, the highest scoring concept in functionality seems to be sadly balanced. With this in mind the selection is made on concept number four. Also, while this idea also scores the highest amount of point in the building phase, although less favourably compared with functional requirements.

4.2 Design process of the gripper tool

4.2.1 Testing with the existing design

Before starting the project, an open-source gripper from the website "thingiverse" has already been printed thanks to a 3D printer in Technobothnia. Therefore, it was decided to test it initially. The illustration below shows this gripper.

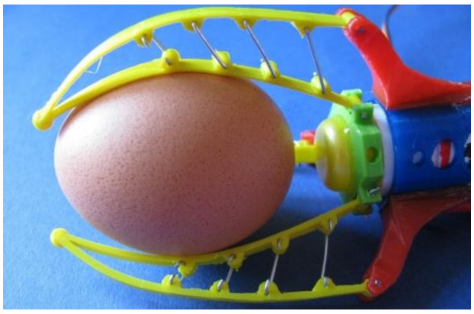


Figure 39 – Tri-Max Gripper from Gareth
Source: https://www.thingiverse.com/thing:193851

The main advantage of this gripper is its flexibility. So, it is possible to have a decent grab on a cylindrical shape. It is moved by a basic screw-nut system that uses a glue stick and a small and cheap servo which need a low amount of torque.

But this gripper was too small and it was impossible to implement any sensors. That is why a new gripper was needed.

4.2.2 Overview of the new gripper

Thanks to Kesselring method, a new concept has been chosen by all the team, taking into account all the parameters to correctly respond to the technical specifications needed to grab a tomato. The choice of the team was the "three-finger gripper".

One of the main issue is to print all these parts with a 3D printer. These limitations need to be kept in mind during the designing. Because it is very hard to print a worm gear without any manufacturing defect, the worm gear has been replaced by a circular gear and a guided toothed rack: this gives less and stronger parts which can be seen below. Moreover, the circular movement which provide the servo is converted into a linear movement.

In fact, the concept 2 and 4 has been combined together to create a better one. The printing process takes a long time, and in order to save time, it has been decided to use long screws (in grey on the picture below) instead of wide ABS parts. All the parts are made to be functional and not to looks good: that is the purpose of a very first prototype. With all these holes in the clamps, it took much less time than if it is full.

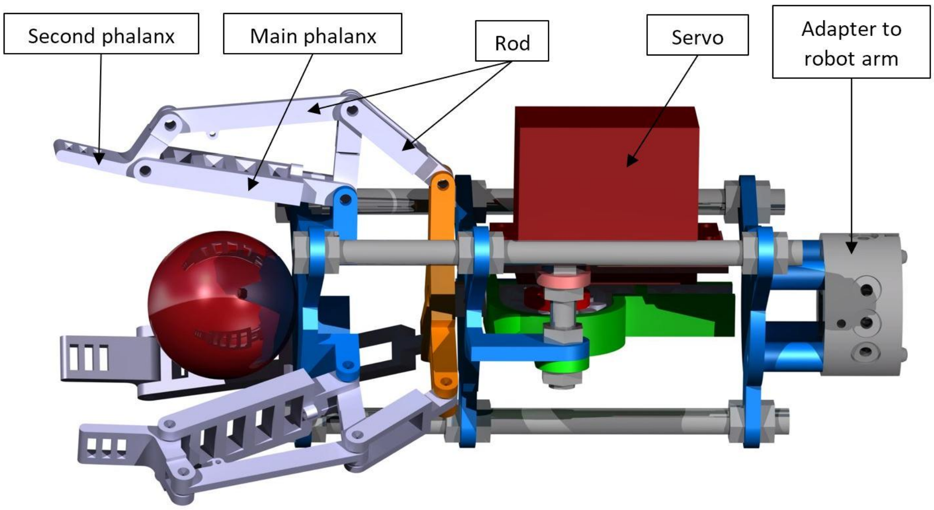


Figure 40 – First prototype of the Gripper
Source: own elaboration

4.2.3 Kinematics analysis

The special feature of this gripper is that it uses a spring (in red, below). That allows two movements in a different time. First, when the servo turns the gear anti clockwise (1), the toothed rack and the orange part moves to the left (2). The force is transmitted by the rods (3), (4) and (5), and finally the main phalanx goes in contact with the tomato (6a), rotating around the built (6b).

Secondly, when the main phalanx is stopped by the tomato, the force given by the servo and transmitted by (4) is applied on the spring (7) which extends. This allows the second phalanx to rotate around the main phalanx (8) until it touched the tomato (9).

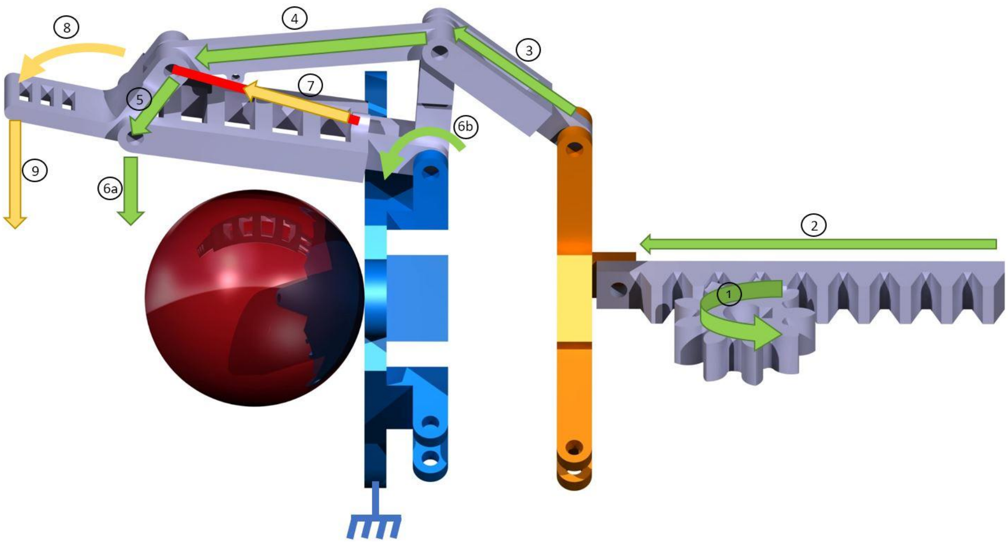


Figure 41 – Operating principle of the new design
Source: own elaboration

There are two ways to control the pressure applied on the tomato by the gripper, and both work together. Because the spring is needed to maintain the second phalanx opened during the movement of the main phalanx, it determines the force applied on the tomato by the main phalanx which allows the second phalanx to move. It is important to choose an appropriate spring stiffness to prevent damaging the tomato. Indeed, the second phalanx is not moving until the first phalanx is touching the tomato and applying a certain pressure on it. The kinematic diagram below explain how works this mechanism.

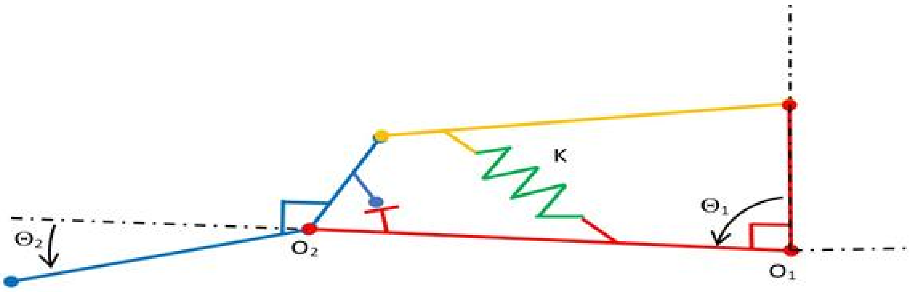


Figure 42 – Kinematic diagram of the gripper
Source: own elaboration

The easiest way to know the force applied on the tomato by phalanges depending on the stiffness of the spring, is to proceed by a static calculation. Indeed, the spring works in a range from 20mm to 50mm. By a basic calculation, it is possible to know the force created by the spring.

$$F = k \times |l - l_o|$$

F is the force in DaN, k is the stiffness in DaN/mm, l is the extended length and l_o the length without any force applied on the spring, both in millimeters.

It is now easy to calculate the force needed to move the second phalanx and the force applied on the tomato by one phalanx thanks to the diagram below.

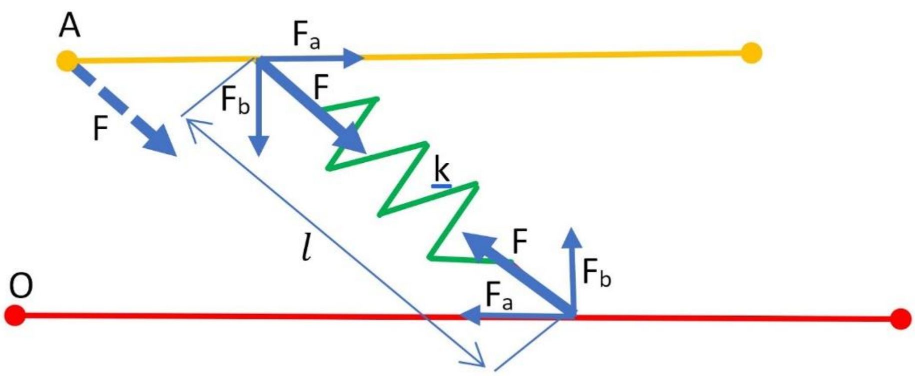


Figure 43 – Kinematic spring explanation diagram
Source: own elaboration

To simplify the calculation, it is assumed that the main phalanx (in red) and the biggest rod (in yellow) are parallel. The point A is turning around the point O, so the force F is also applied on the point A, where the second phalanx is mounted. Consequently, the force value applied on the tomato is $2F_b$ and the force needed to move the second phalanx is $2F_a$.

Because the force F keeps the second phalanx opened, this force must be higher than the weight of the second phalanx which is under 20 grams. So, this force must be at least 0.5N to be sure that the second phalanx will stay in the opened position. Furthermore, a tomato can weight around 500g so it is not damaged by a force of 5N applied on a big surface of the tomato. This means that F_b must be under 2.5N.

So, when the phalanges are opened, the force given by the spring must be at least 0.5N. And when the phalanges are on the tomato, the force given by the spring must not exceed $F=F_a+F_b=0.5+2.5=3$ N. Moreover, the length of the spring must be between 20 and 50mm.

The second point is now that the main phalanx is applying its force to the tomato, the second phalanx can move. The pressure applied by this phalanx is determined by the force given by the servo. That's why it is important to control it, thanks to pressure sensors and one of them is the minimum, because the gripper is symmetric, the same pressure should be exercised by all the second phalanges. As it is tricky to determine the exact pressure which could smash the tomato, some test need to be run to find it. So, it is now possible to know the amount of force needed to move these fingers.

About the pinion-rack system, all the calculations for the force and torque are done, the diameter of the gear can be defined depending on the amount of torque it is possible to obtain with a servo.

The calculations with the spring shows that a minimum force of 3N is required to move the second phalanx without applying a force with the second phalanx on the tomato. So, to be sure, a force of 10N is enough to move one clamp and applying a pressure on the tomato. In total, 30N are needed.

4.2.4 Parts of the gripper tool

On this section, the focus is only on some important parts, which means the main and second phalanx, the rods and finally the gear and the toothed rack.

First of all, the dimensions of the phalanges are very important because its size determines the kind of tomato which can be grabbed. The length of the phalanges has been chosen thanks to the kinematic analysis above. For the first prototype, a basic parallelepiped shape has been used to print the parts easily, because it is hard to print curved shapes, in particular spheres. But after the first test, it is obvious that a curved shape is needed to well grab the tomatoes.

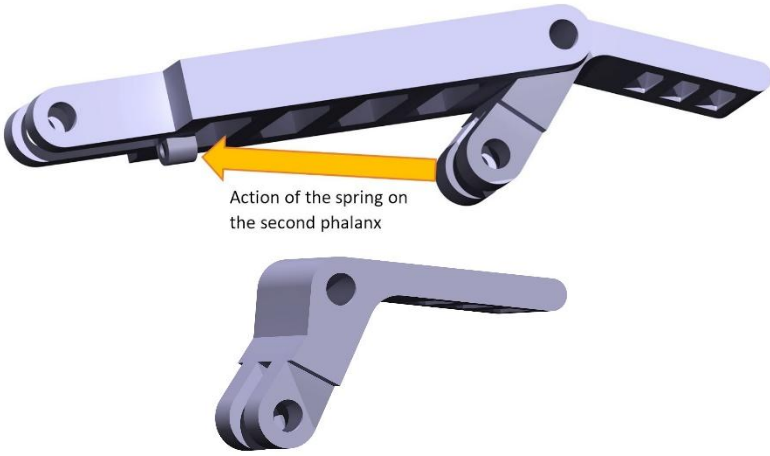


Figure 44 – Phalanges
Source: own elaboration

But another important feature of the main phalanx is to lock the second phalanx and avoid it to move too far because of the action of the spring. That is why the second phalanx has this kind of flat surface. On the diagram above, the yellow arrow shows the action of the spring on the second phalanx.

Regarding to the rods, the dimensions are also important because it can change how the clamps move. All these dimensions have been set after the kinematic calculations and some test on a 3D software. See below in the order, the rod which link the clamps to the hexagon (the orange part linked to the toothed rack), a long rod and a smaller one which link the big one, the one linked to the hexagon and the built.

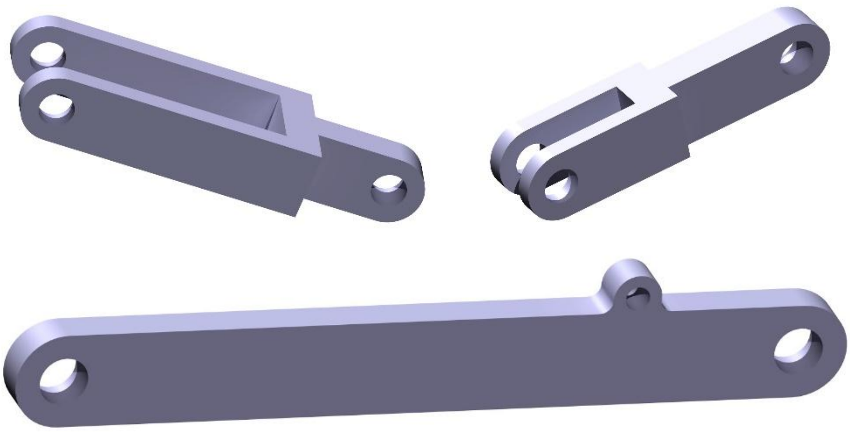


Figure 45 – Rods
Source: own elaboration

Last but not least, the design of the gear and the toothed rack is very important. Moreover, the toothed rack is linearly guided.

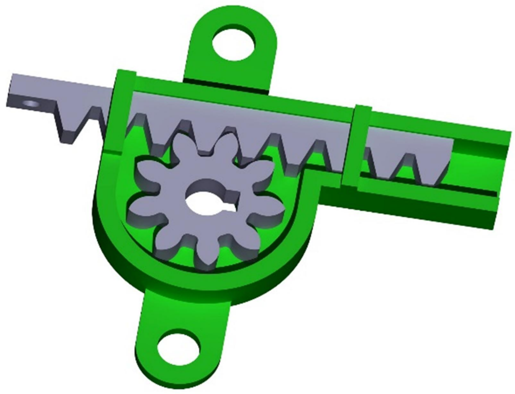


Figure 46 – Gear and guided toothed rack
Source: own elaboration

Because of the design of the clamps and the gripper, the needed linear moving distance of the toothed rack is 60mm. So, the gear must be designed to fit with the specifications of the servo. But a servo can not do more than a certain number of turns, indeed the majority of servo can not turn more than 6 turns. Moreover, a force of 30N is needed to move the gripper and grab a tomato, according to the kinematics calculations.

The spreadsheet below shows how the radius of the gear has been chosen. A radius from 1 to 13mm is impossible because it can create some interferences between the teeth of the gear and the toothed rack. So, it is possible to use a gear from 13mm radius. But it is important to precise that the bigger is the gear, the more torque is needed to move the gripper and the more space it requires for the gear. Moreover, the radius of the gear must fit with the number of tooth in the gear.

Radius (in mm)	Circumference (mm)	Number of turns needed	Torque needed (N.m)
1	6.3	9.55	0.03
12	75.4	0.80	0.36
13	81.7	0.73	0.39
13.5	84.8	0.71	0.41
14	88.0	0.68	0.42
15	94.2	0.64	0.45
16	100.5	0.60	0.48

Table 8 – Operating principle of the new design
Source: own elaboration

A gear with a radius of 13.5mm has been chosen because it is the smallest possibility. This implies a lower torque for the servo and less bulk.

4.2.5 Servomotor

The gear is now selected and the exact amount of torque and the number of turn is known. The servo must be able to do at least 1 turn and transmit 0.41Nm to the gear. Luckily, for our first prototype, a servo which fit with these specifications is available in the 3D printing room of Technobothnia and it costs around €50. The gripper can now be moved by this servo.

Here are the specifications of the servo:

- Control system: Pulse Width Control (PWM), 1500µs neutral
- Operating voltage: between 6.0V and 7.2V (DC)
- STD Direction: counter clockwise/pulse traveling 800 to 2200 µs
- Operating speed: between 0.75-0.92s/360° at no load
- Stall torque: more than 2.6N.m
- Running current: between 400 and 500mA
- Output angle: more than 6 circles
- Dead band width: 2µs (Digital PCBA)

4.2.6 Gripper mount on the robot

The robot arm has a system which allows quick changes between tools, power supply and information exchange between the robot arm and the tool thanks to the electronic connectors. Because the Robopick team is not the only team working on this robot, using this system is much flexible. The illustration below shows the mechanism. The left part is mounted on the robot arm and the right one on the gripper.

Figure 47 – Quick connection system and adapter for the gripper
Source: https://schunk.com/

It is possible to connect up to twenty wires between the robot and the gripper. Therefore, all the pressure sensors and the servo is managed by the robot or an external electronic board which manages only the servo movement and the sensors. For instance, the robot software sends to this card “close the gripper”. Once the gripper is closed, it returns to the robot “gripper is closed”.

The gripper built fits perfectly to this adapter thanks to a special design. See above the adapter built to this quick connection system and the specifications of the quick connector system.

4.3 Printing process of the gripper tool

In the following lines some key information about the 3D printing process is given.

4.3.1 What's 3D printing?

By way of introduction, 3d printing or additive manufacturing is the process of creating three dimensional solid objects from a digital file by laying down successive layers of material until the object is created.

This type of manufacturing allows the production of complex and functional shapes in a much cheaper way than traditional manufacturing methods.

The figure below shows a diagram for the 3D printing process.

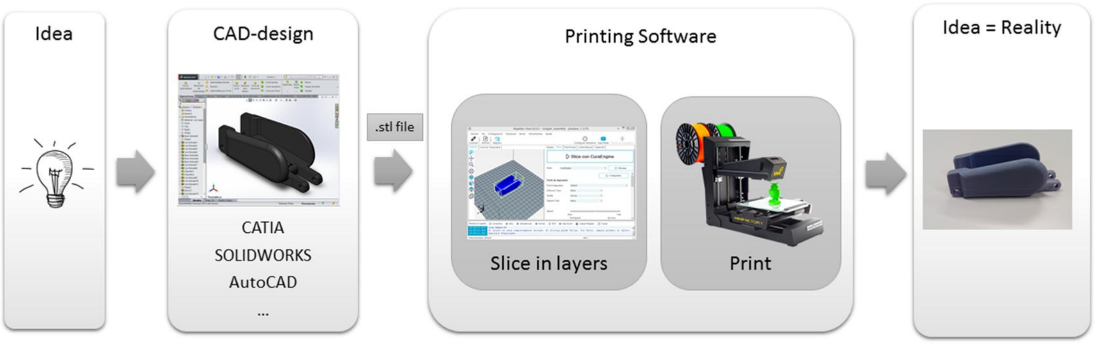


Figure 48 – Printing process diagram
Source: own elaboration

4.3.2 Printers used

Three different types of 3D printers have been used during printing phase. On the following lines a brief introduction to each printer is given.

MiniFactory 3

The first 3D printer used was the MiniFactory 3 which is, according to its manufactures, the most popular in Finland.

This 3D printer has two extrudes that enable to use support material in complex pieces, mixing different types of materials on the same piece, as well as producing pieces of two different colours. However, only one extruder is used for printing gripper's pieces.

In spite of the fact that with this 3D printer it is possible to use different kinds of materials, only ABS is used for printing gripper's pieces.

The printing software used on this 3D printer is Repetier Host. It is a quite intuitive software, but there are quite a lot of parameters that can be modified in order to obtain good results.

The MiniFactory 3 is fast, easy to use, and great for printing pieces that don't require high precision.

Figure 49 – 3d printer MiniFactory 3
(Source: http://www.minifactory.fi/en/3d-printer/minifactory-3/)

MakerBot Replicator 1

After testing with both MiniFactory 3 and MakerBot Replicator 1, it is evident that better results can be obtained with the second 3D printer. Therefore, it has been selected as the primary printer for the gripper's part.

The MakerBot Replicator 1, as well as the MiniFactory 3, is a two-extruder 3D printer with a heated build plate. This 3D printer uses mainly plastic build materials like ABS and PLA, but also other materials can be used.

The Replicator 1 is even faster and equally easy to use than the MiniFactory, and parts printed with this 3D printer are quite satisfactory.

The printing software used on this 3D printer is MakerWare.

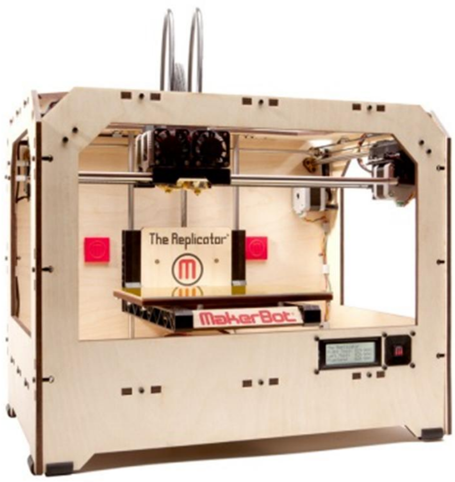


Figure 50 – 3d printer MakerBot
(source: https://www.3dhubs.com/3d-printers/replicator-original)

Wanhao Duplicator 5s

Last but not least, Wanhao Duplicator 5s is also used to print some parts of the gripper tool.

This 3D printer is really different from the ones described above. The main differences are the capability of printing bigger parts and the highest resolution. It was this last feature which was useful for printing the gripper's gear and rack.

Figure 51 – 3d printer Wanhao Duplicator 5s
Source: http://3dunique.co.za/product/dummy-text/

4.3.3 Printing materials used

During the printing process two different materials has been used: ABS and PLA. These two materials are the most commonly used in 3D printing manufacturing.

ABS, or acrylonitrile butadiene styrene, can be easily machined, polished, painted and glued. The good quality of finishing is another of strengths of ABS. In addition, it is extremely strong and has a bit of flexibility. This material has a high melting point (230-260 ºC) so it must be used only on hot-bed based printer. One of the drawback of ABS is that when it is melting it releases gases that can be harmful, so certain precautions should be taken.

ABS is the material used to print the majority of the gripper's parts.

PLA, also known as polylactic acid, is not as common as ABS. The main advantages of PLA are that it doesn't release harmful gases and it has a wide range of colours available. Besides, it can be used in all kind of printers.

Its main disadvantages are mainly two: it does not withstand high temperatures and the post processing is much more complicated (IMPRESORAS3D, 2017).

PLA was used to print the parts that needed a higher resolution, the gear and the rack.

4.3.4 Challenges found

Big challenges were found when 3D printing: problems with dimensional accuracy, gaps in top layers, overheating, layer separation, poor bridging, and so on. After a trial-and-error phase and also learning how to use printing settings all the parts of the gripper were printed satisfactory.

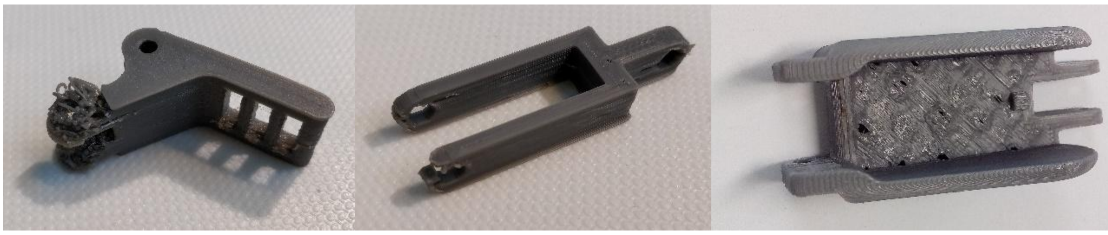


Figure 52 – Parts of the gripper with printing issues

(Source: own elaboration)

5 Implementation

5.1 Manufacturing of the gripper

This chapter will talk about the problems detected in the gripper after the design phase.

5.1.1 Weak parts

During the design process of the gripper, all the parts were designed to be quickly and easily printable with a 3D printer, but one part of the gripper was not strong enough and has been broken two times. The problem came from the 3D printing process, even if the printing parameters have been changed before printing a new one. Indeed, this process adds material layer by layer and sometimes the two layers are not well linked each other. On the picture below, the part which was not strong enough is shown in its original design and once it has been broken, the red line shows the weakest point of the part.

Figure 53 – Original design of the weak part
Source: own elaboration

In order to improve the resistance of the part on the weak points, the internal structure of the part and also its design has been changed.

Indeed, a 3D printer does not fill the entire part with material, it makes a sort of a grid inside with more empty spaces than material. This is called the infill parameter or fill density. A higher fill density means that there is more plastic on the inside of the printed part, leading to a stronger object. In the first design the infill parameter was settled on 25 %, but to improve the resistance the infill is settled at 100 % for the new part.

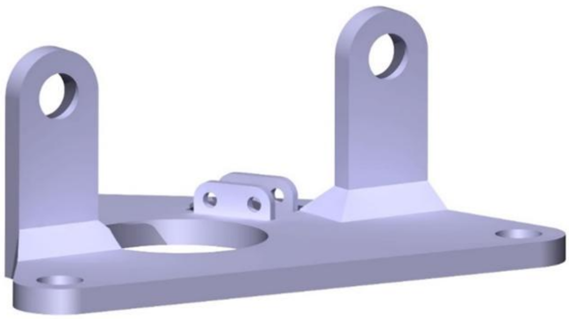


Figure 54 – New design of the part
Source: own elaboration

Moreover, this part will be printed with a different printer which is more accurate and works like a laser jet normal printer. With this printer, all the layers will be soldered and strong.

5.1.2 Sensors implementation

On the clamps

Before implementing pressure sensors, the gripper will use limit switches because they are easier to implement. Therefore, the second clamps have been redesigned to fit with this specification. The new clamp is shown in the picture below.

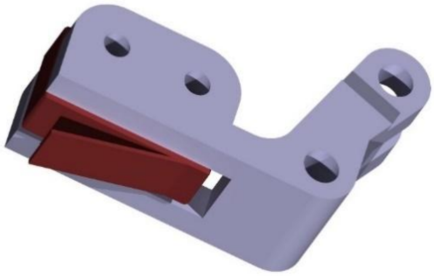


Figure 55 – Implementation of limit switches on the second clamp
Source: own elaboration

On the built

In order to define the origin of the servomotor it is important to set the limits of its movement. That is why two limit switches (in red on the picture below) have been implemented on the built: one for the maximum opened position and another one for the maximum closed position. The switch on the top will give the information to the Arduino that the orange part cannot go higher and the other way around for the switch on the bottom.

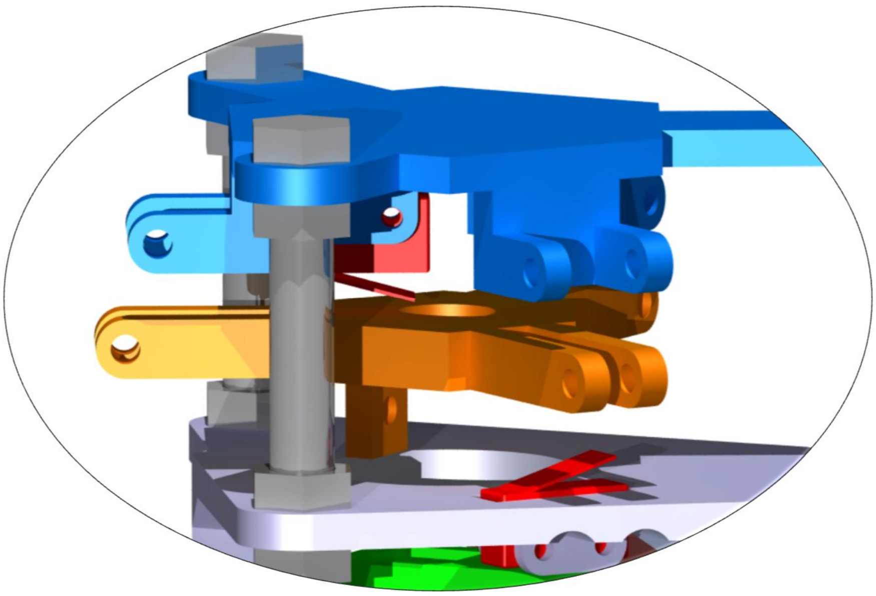


Figure 56 – Implementation of limit switches on the built
Source: own elaboration

5.1.3 Mounting supports

In order to implement the camera and the Arduino, two different supports were designed. In the figure below is presented this implantation.

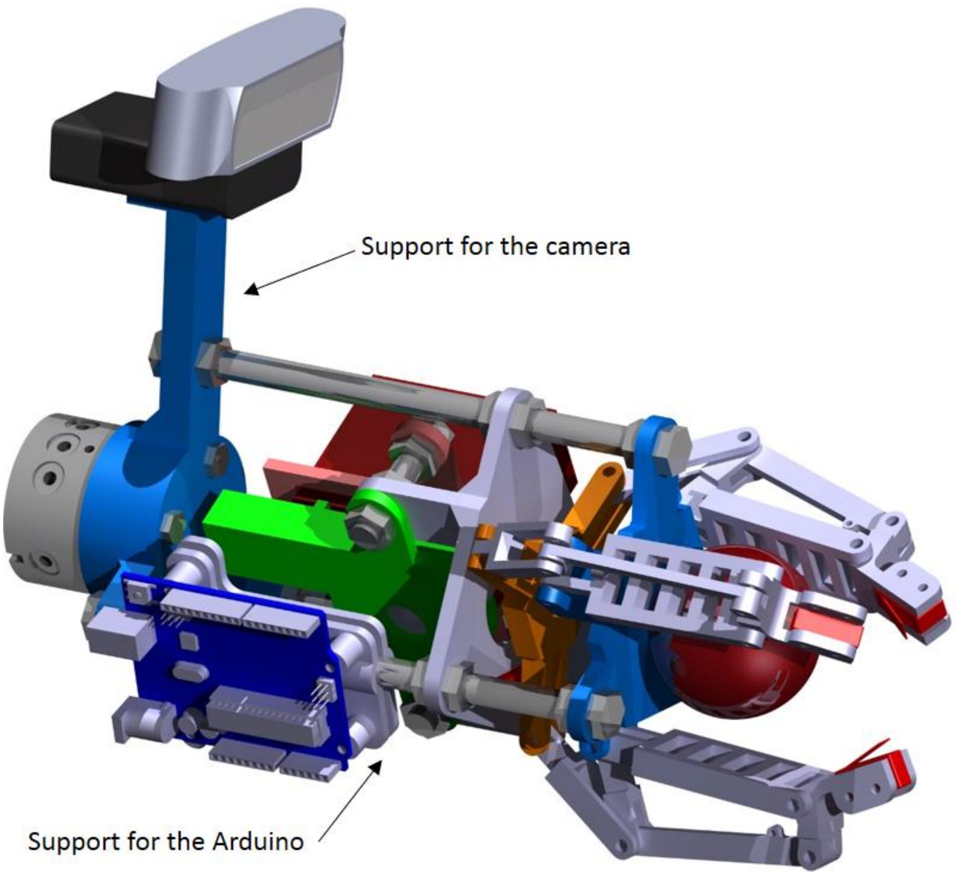


Figure 57 – Camera mounted on the gripper
Source: own elaboration

Support for the Arduino

The Arduino is mounted on the gripper to be as close as possible to the servomotor and the sensors. Moreover, thanks to the quick connection system on the robot arm, it is easier to mount and use the gripper if all the parts are in a single package. The Arduino is placed on a two-parts support which is fixed on one of the screws of the gripper. Four screws are used to fix together the Arduino and the supports which will not move on the screw due to the pressure applied by the four screws on the screw.

Support for the camera

The camera is mounted on the gripper, as close as possible to the clamps, but a certain distance between the axis of the gripper and the camera is needed to not disrupt the camera's field of vision with some parts of the gripper.

5.2 Software

In this paragraph the software will be exemplified. Three different component are controlled by different processors. The webcam and the 3D-camera is controlled by a MATLAB program running on a computer, the industrial robot is regulated by the included Robot controller and the gripper is supervised by an Arduino. The software of these three processors are illustrated with three flowcharts, but beforehand the connections between these controllers are demonstrated in a sequence diagram.

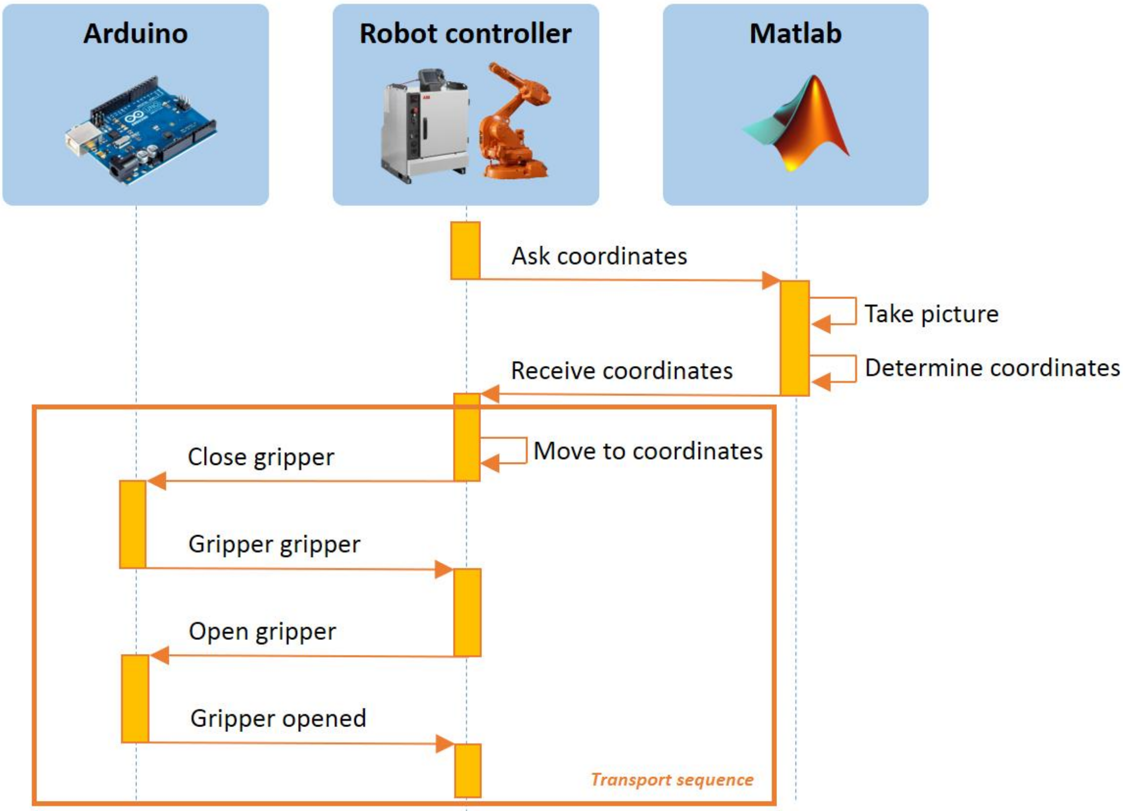


Figure 58 – Sequence diagram
Source: own elaboration

As seen in figure above the robot controller is the master controller over the other processors. The cameras and gripper will not function without the approval of the robot controller. If there is more than one tomato, the multiple coordinates will be packed together and sent to the robot controller. As soon as the coordinates are received, the robot will pick the first tomato and put it in a basket. The transport sequence is repeated until all tomatoes are picked.

5.2.1 MATLAB software

MATLAB is the software required to recognize the ripe tomatoes and determine its position. In this chapter the software of the MATLAB will be documented.

The complete source code can be found in the appendix.

Global idea of the software

In the following figure a complete flowchart of the MATLAB software is presented.

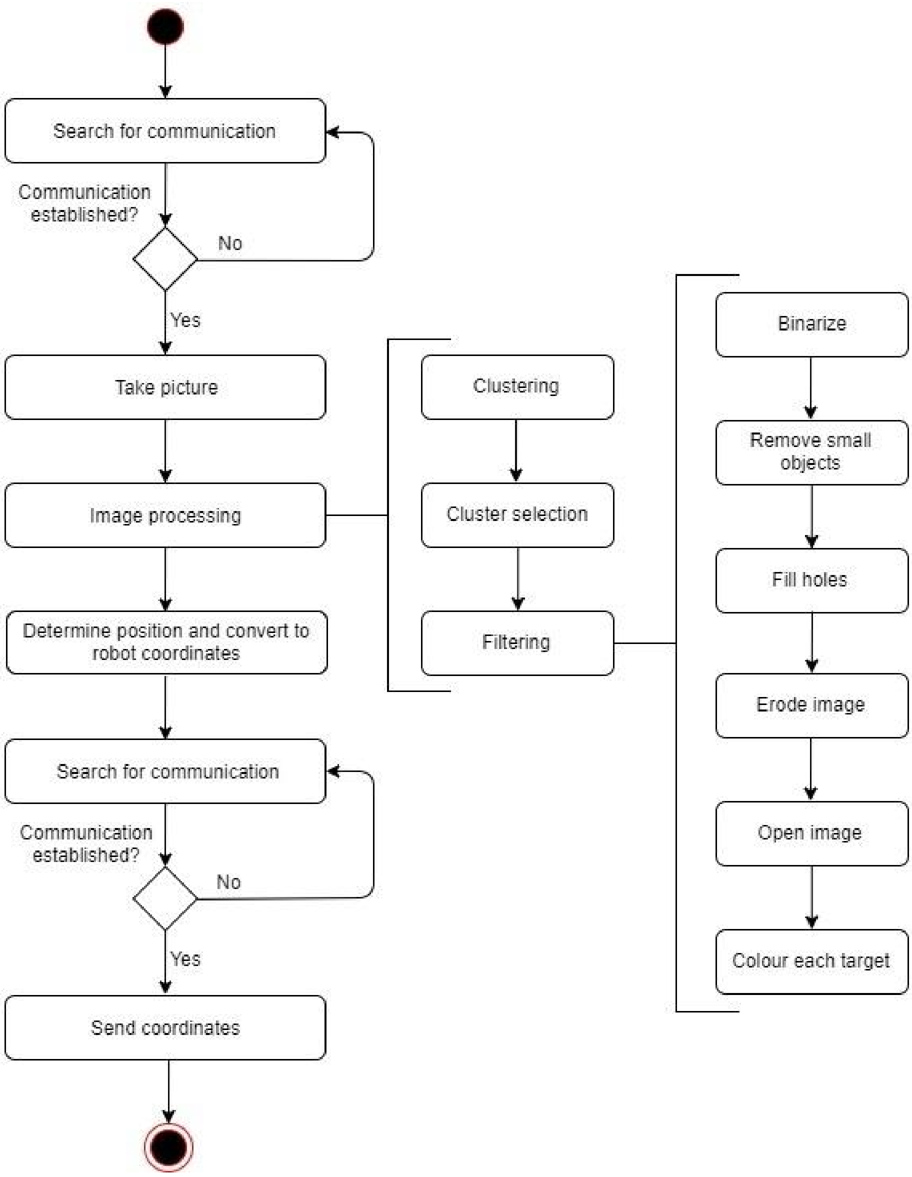


Figure 59 – MATLAB software flowchart
Source: own elaboration

Socket communication

The first step that MATLAB software needs to accomplish is the establishment of a communication connection with the robot controller. To do so, a socket communication has to be created.

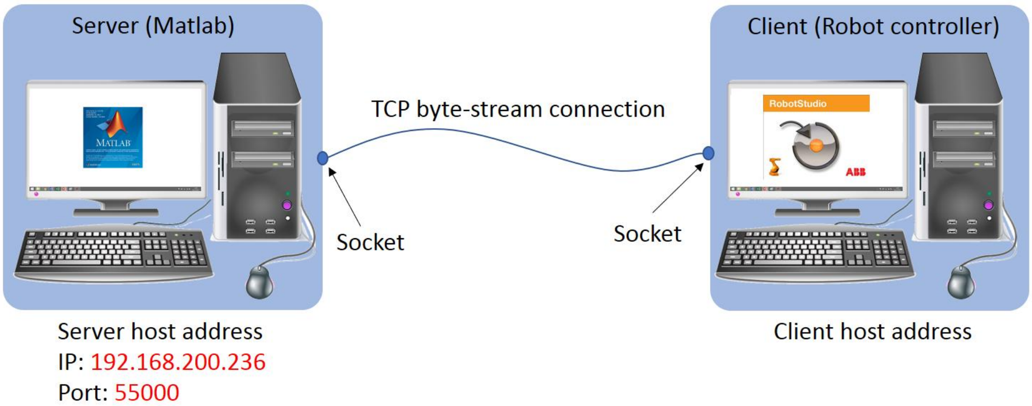


Figure 60 – Socket communication
Source: own elaboration

The communication protocol used is known as TCP (transfer control protocol). In order to achieve communication with the TCP protocol, a connection must be established between two sockets by using server's IP-address and the specific port. While the server listens for a connection request , the client asks for a connection at the known IP-address . Once two sockets are connected, they can be used to transmit data in both (or either one of the) directions. To wrap up the connection, a tear-down process shuts down the connectivity.

The chart below shows how the socket communication works.

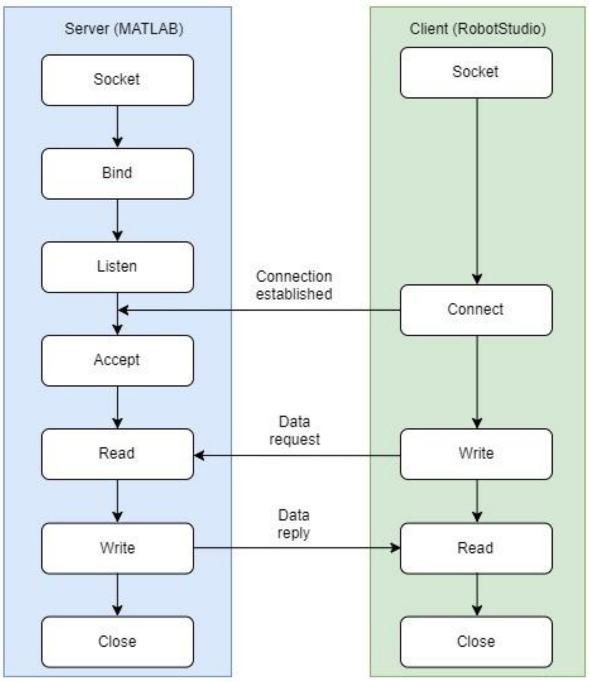


Figure 61 – Flowchart of the socket communication
Source: own elaboration

Take picture

Once the communication between MATLAB and the robot controller is established, MATLAB commands the camera installed in the gripper to take a picture.

The camera used for this project is the HD PRO WEBCAM C920 from Logitech, which is able to take pictures with a resolution of 1920x1080 pixels. However, the resolution has been reduced to 640 x 480 pixels in order to have a comparable amount of pixels and millimetres in the image. (the ratio is close to 1:1).

The pictures are taken with a white background, therefore image processing is simplified and easier executable.

Image processing

The image processing consists in three steps:

1. Clustering
2. Selection of the cluster with targets
3. Filtering

The first step, clustering, consists in dividing the image taken into n colours. In this case, n is equal to 2 since in the taken picture only green and red objects are placed, for that reason these colours will be the predominant colours.

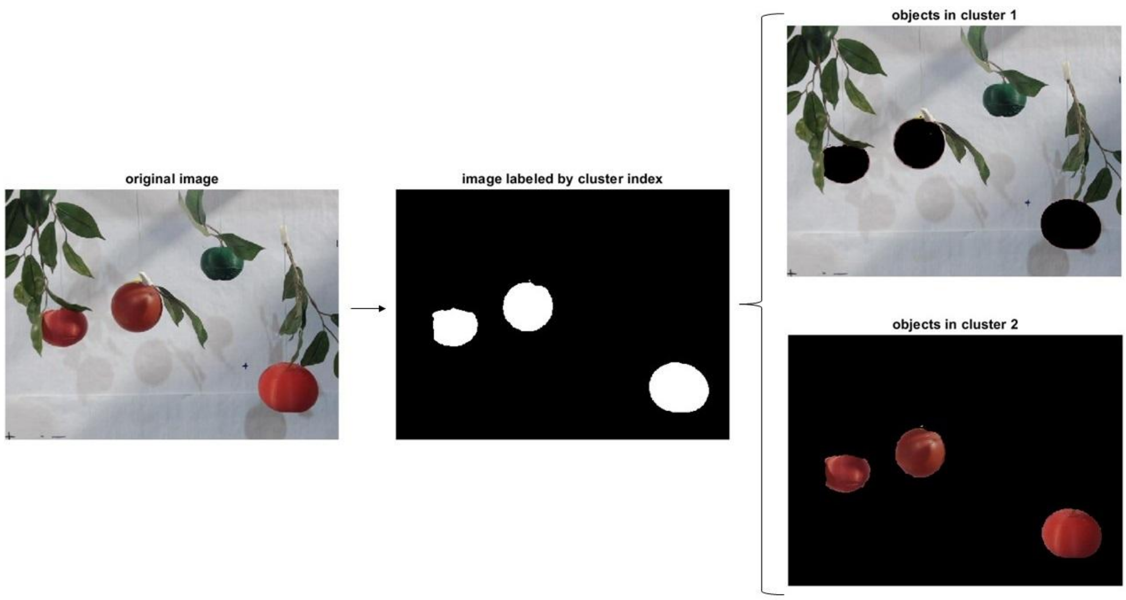


Figure 62 – Image processing: Clustering
Source: own elaboration

The two clusters obtained in the previous step are delivered randomly, hence it is impossible to know which cluster will contain the ripe tomatoes. So that, it is needed to select the cluster with targets.

To select the cluster with targets the amount of black pixels are counted. Finally, the cluster with a greater amount of black pixels is the one selected.

On the figure below the RGB histogram of both cluster are presented.

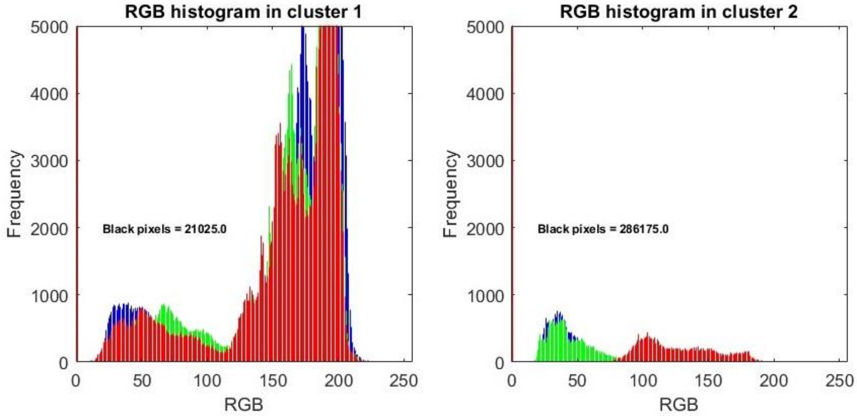


Figure 63 – Image processing: Selection the cluster with targets
Source: own elaboration

Finally, once the correct cluster is selected, the program will initiate the filtering process. This process is subdivided by the following steps:

1. Binarize: the image is converted into a binary image and a certain threshold is applied.
2. Remove small objects: all connects components (objects) that have fewer than P pixels.
3. Fil holes: the background pixels are filled.
4. Erode image: a morphological erosion is performed. To perform this step a disk-shape structuring element.
5. Open image: a morphological open is performed. This function also demands a structuring element as an argument.
6. Colour each target with a different colour

In the following figure all the steps are displayed.

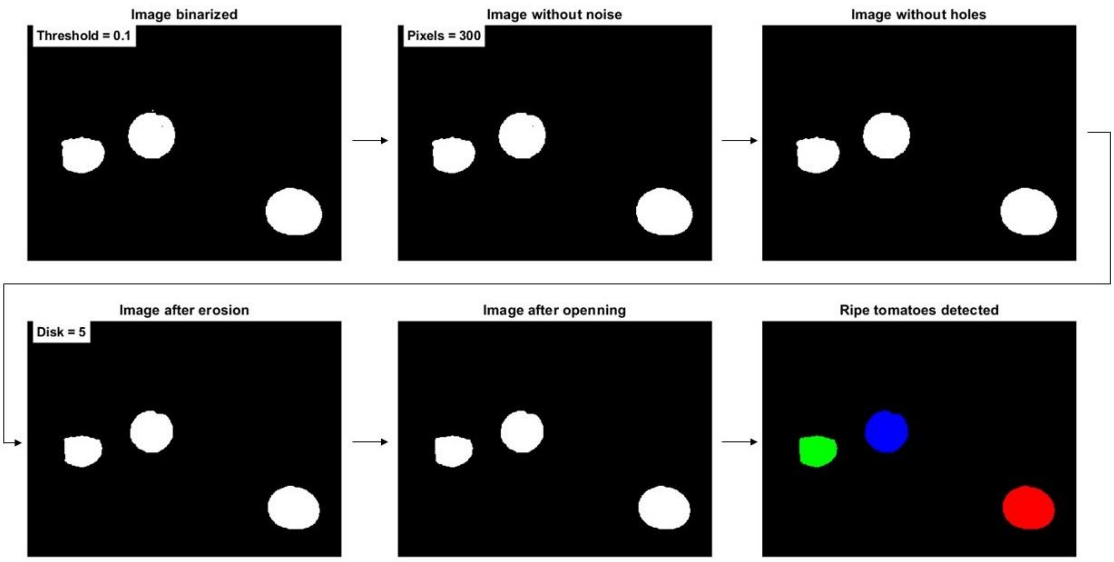


Figure 64 – Image processing: Filtering
Source: own elaboration

Determine coordinates and convert to robot coordinates

MATLAB gives the coordinates of the ripe tomatoes detected in pixels. Consequently, to use these coordinates in the robot arm it is needed to convert them into millimetres. To ease the conversion process, the picture is taken with a distance from the background which the amount of pixels and millimetres are coincident.

Also MATLAB locates the coordinate system origin in the top left of the image. Besides, the positive side of the x axis points to the right and the positive side of the y axis points to the bottom of this figure. To converge the MATLAB coordinate system to the robot's coordinate system it is necessary to change the origin to the centre of the image and also to rotate the coordinate system.

These changes are illustrated in the figure below.

Figure 65 – Coordinates conversion: pixels to mm and changes in the coordinate system

Source: own elaboration

The final obstacle found in the conversion from MATLAB coordinates to robot coordinates is the *camera projection*.

Considering that the camera is the origin (0,0,0) and a tomato is found in the coordinates (X,Y,Z), the camera project the tomato at the coordinates (a,b,c). On account of one camera being unable to see depth.

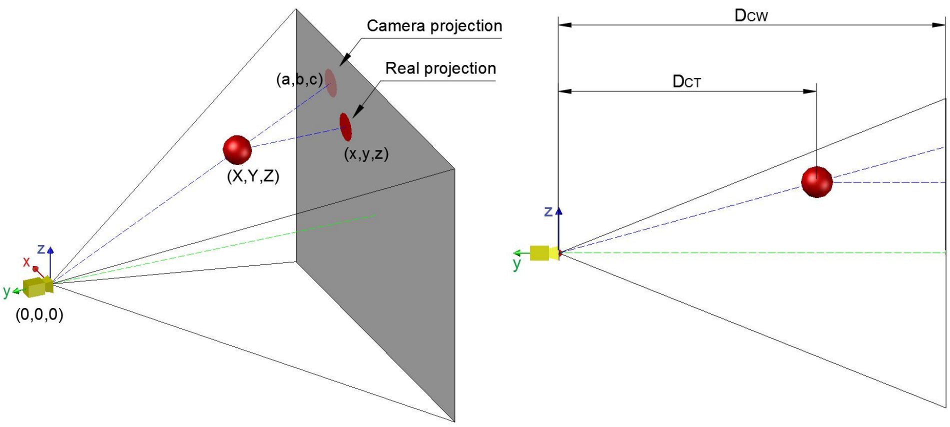


Figure 66 – Coordinates conversion

Source: own elaboration

If this effect is not corrected the gripper tries to pick a tomatoes at the wrong place. In order to correct this effect a factor must be multiplied by the fake coordinates. This factor is equal to ratio between the distance from the camera to the tomato and the distance from the camera to the wall.

The equations applied to reduce camera projection are presented below:

$$(x, z) = (a, c) \cdot F$$

$$F = \frac{dct}{dcw}$$

Send coordinates

Finally, once the coordinates of the ripe detected tomatoes are converted into robot coordinates, it is possible to send them to the Robot controller through the socket communication.

Once more the TCP communication is created and the coordinates are sent as a string, for instance, 'n3n X208 Z-28 X66 Z12 X-223 Z-145'.

5.2.2 Robot controller

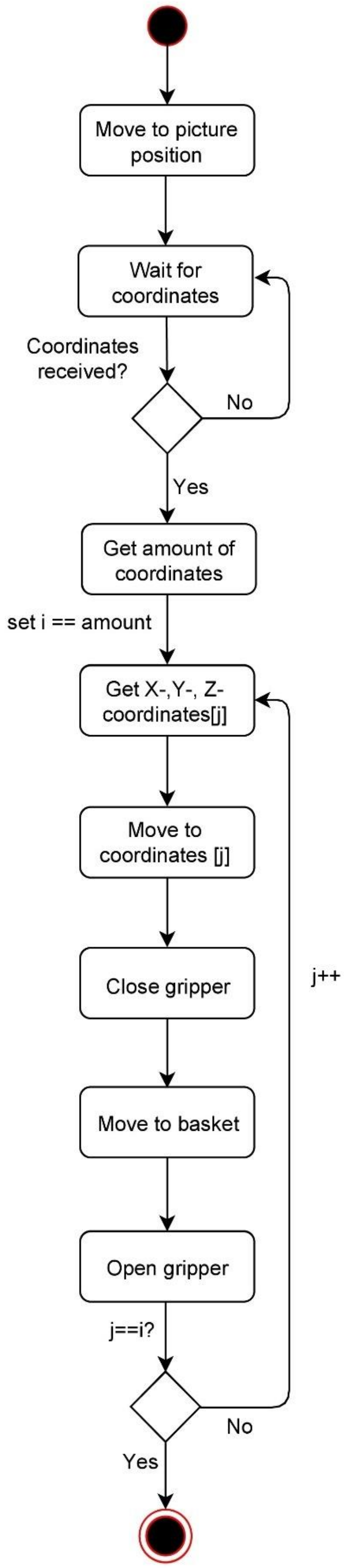


Figure 67 – Flowchart robot controller
Source: own elaboration

To help the understanding of the robot's operation, the graph on the left describes all the important steps.

Move to picture position

The first step is to move the gripper (where the camera is mounted) to the picture position. This position has been predefined and is "hard coded". It means that the coordinates of this position are not calculated or received from another device.

Wait for coordinates

Once the robot is in the picture position, a socket communication between MATLAB and the robot is created. With this accomplished, MATLAB has the confirmation that the robot is in the right position and can proceed in taking the picture and processing it. After that, the robot receives the coordinates in a specific format like: "n3n X208 Z-28 X66 Z12 X-223 Z-145".

Get amount of coordinates

To get the number of coordinates which has to reach the robot, the program in the robot searches for the position of the first "n" (in blue) and the second "n" (in red). The table below explains how the program reads the string. Each character is in one column, and a number is given to each column.

Column	1	2	3	4	5	6	7	8	9	10	…
String received	n	#	#	n		X	#	#		Y	…

Table 9 – How to get the amount of coordinates
(Source: own elaboration)

This uses the function *StrMatch* and it gives the column number of the letter "n". Once it has the column number of the second "n", the program reads the characters which are in the middle of these two positions thanks to *StrPart*. In this example, it will read the characters in the column 2 and 3 (in green). Finally, it converts these characters into a number. The program keeps running if the conversion has been completed successfully. The value found will be used in a "for" loop, to search for all of the coordinates.

Get X, Y and Z coordinates

The same protocol is used to read the coordinates into the string, but instead of looking for the character “n”, it will look for “X” and the next blank.

The program enters in a “for” loop. It will exit this loop if the robot has read all the coordinates and reached the position of all the tomatoes. This method allows to read a large number of coordinates.

In the example above, the program has read the number of coordinates which have been sent by MATLAB. So, it will search from the column 4 the next “X”, and once it has found this position, the program will search for the next blank. The same method is applied for the coordinates Y and Z. In the table below, the cells in green are the ones which contains the coordinates.

		First set of coordinates												Second set				
Column	…	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
String received	…	X	#	#		Y	#	#	#		Z	#		X	#		Y	#

Table 10 – How to get all the X, Y and Z coordinates
(Source: own elaboration)

Move to coordinates

Once the robot has the coordinates of the first tomato, it can move to its position, at 200 mm far from the tomato in the depth axis, so the robot will approach the tomato linearly without hitting the tomato.

Close the gripper

Once the robot touches the tomato a signal is sent to the Arduino to close the gripper.

Move to the basket position

As soon as the gripper is closed, the robot moves to the basket position which is also “hard coded” like the picture position

Open the gripper

Once it is in the basket position, the robot sends a signal to the Arduino to open the gripper.

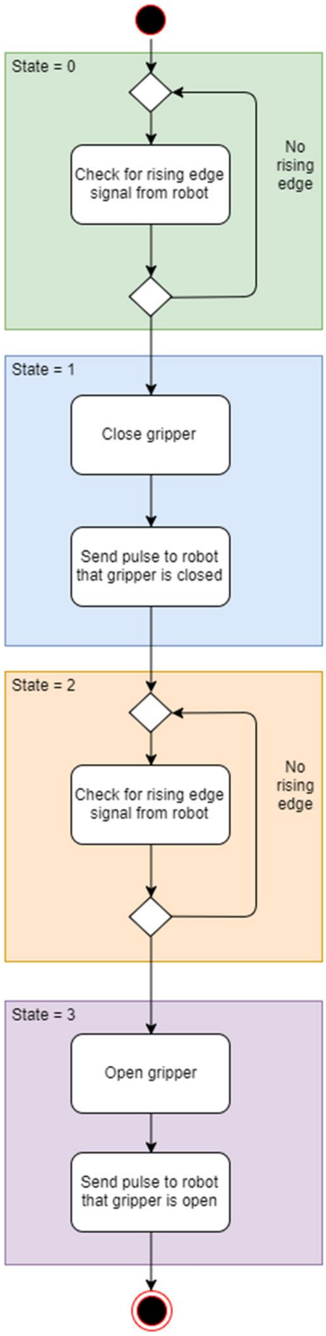
Finally, the program continues the loop and the robot arm goes to the next tomato position.

5.2.3 *Arduino software*

To control the servo and the sensors in the gripper an Arduino was required. In this chapter the software of the Arduino will be documented.

The complete source code can be found in the appendix.

Global idea of the software



On the left an activity diagram shows the main program. The main idea of the Arduino software that it waits for a pulse of the robot before it opens/closes. The states are divided in the following way:

State 0 = The Arduino waits for a pulse from the robot arm. At this moment the gripper is opened.

State 1 = The Arduino received the pulse and closes the gripper. By the end of the state the Arduino lets the robot know that the gripper is closed.

State 2 = The Arduino waits for a pulse from the robot arm. At this moment the gripper is closed.

State 3 = After receiving the pulse, the Arduino is opening the gripper. Once the gripper is completely opened the Arduino will send a pulse back to the robot.

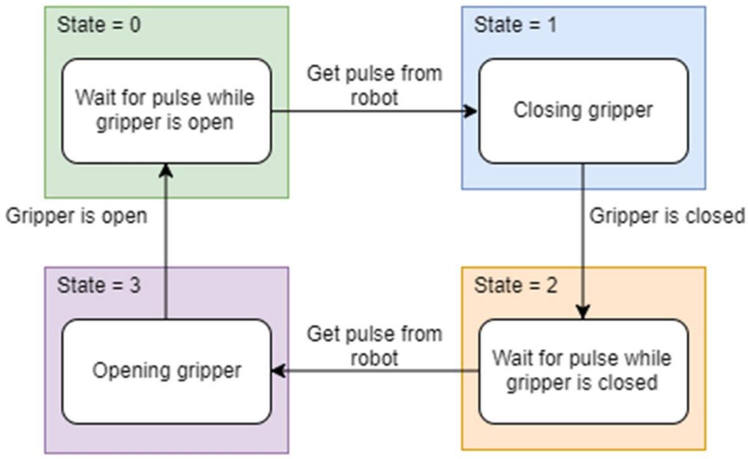
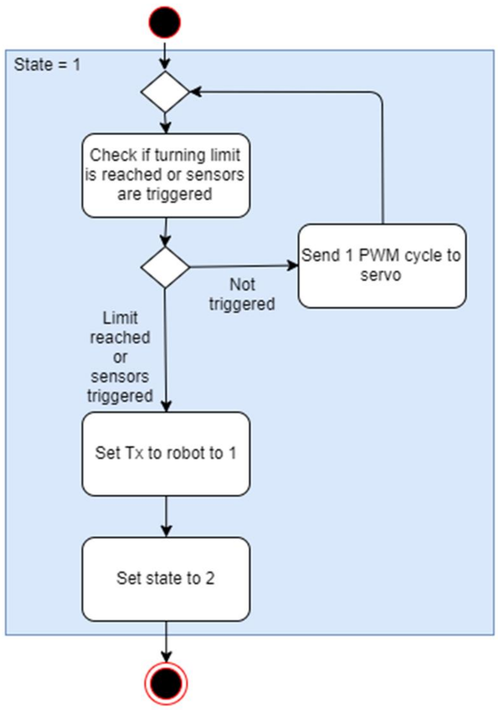


Figure 68 – State diagram of the Arduino software
Source: own elaboration

Figure 69 – Activity diagram of the Arduino software
Source: own elaboration

Closing the gripper

After receiving a signal from the robot, the gripper has to close. The Arduino closes the gripper according to the following diagram.



First the Arduino checks if the limit switch and sensors are triggered. While none of them are triggered the servo is allowed to turn.

As soon as one of the sensors is triggered or the turning limit is reached the servo has to stop. If the servo continues either the tomato will be damaged or the gripper might get destroyed.

Once the servo stopped turning (and the gripper is closed) the Arduino will send a pulse to the robot. This way the robot knows that the gripper is closed and continues its procedure.

Finally, the Arduino has to proceed to state 2.

Figure 70 – Activity diagram of the closing gripper function
Source: own elaboration

Opening the gripper

Opening the gripper works nearly the same way as closing the gripper. The only difference is that sensors inside of the fingers of the gripper are ignored.

Controlling the servo

In the project the following servo is used: Vigor precision VSD-11AYMB. To make the servo turn, a PWM (pulse width modulated) signal has to be send on the data pin.

The pulse width limits are the following:

Direction	Positive cycle time (µs)	Negative cycle time(µs)
Full speed to the left	800	2200
Neutral	1500	1500
Full speed to the right	2200	800

Table 11 – Pulse width limits
(Source: own elaboration)

If the servo should not turn on full speed, any duty cycle can be picked as long as the total pulse length does not exceed 3000µS. The dead band width of the servo is 2µs.

5.2.4 *Depth 3D camera*

The company Sick provides with its 3D camera several API (Application Programming Interface) made for MATLAB so it is possible to get the data from the 3D Camera and use it in MATLAB interface.

All the data is stored in an array, each row corresponds to 1 pixel and each column to a coordinate in space (X, Y and Z) from the coordinate system of the camera. It is known that the tomatoes are in a certain area, so a filter is applied on this array, first on the 3D camera, then in MATLAB.

The three pictures below show the view from the 3D camera. The picture on the left is the real environment, the picture in the middle is the data from the 3D camera and the last picture is filtered to the known area where the tomatoes are.

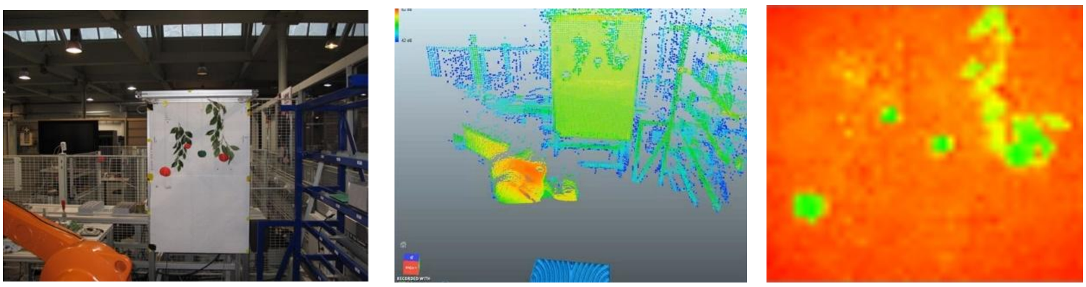
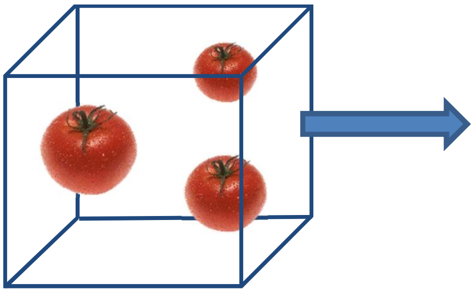


Figure 71 – View from the position of the 3D camera
Source: own elaboration

The last picture is the one that uses MATLAB to recognize the objects. But the camera still sends the data for all the pixels, even if there is no data (because it is out of the interested area). A filter is applied on the table where the data is saved to delete all the lines without data, so the new array corresponds only to the area where the tomatoes are. Then, MATLAB filters this new array again and erase all the data over a certain depth, 2200mm in this case, because the background is at 2200 mm from the 3D camera. So, only the objects between this distance and the camera are detected.

Then MATLAB selects in this array of pixels only the one which should be a tomato. So, the software looks for all the coordinates which are almost in the same depth plane (±5mm). Then, only the coordinates which are closer than 40mm together, are considered. These dimensions correspond to the minimal size of a tomato. The software proceeds on the same way for all the planes where objects are located.

Once the software has all he coordinates of the tomatoes sorted, it detects the closest point to the camera which is the middle of the tomato as this one has a round shape. Then, MATLAB creates a new matrix where the coordinates of the tomatoes are saved in order as shown in the picture below.



Coordinates			Tomato Number
X	Y	Z	
-100	0	+200	1
+100	+50	+50	2
+100	-50	+100	3

Once MATLAB has the coordinates, it sends them to the robot one by one. So, the armcan go in front of the tomato and check with the webcam if this is a ripe tomato. This last step is not yet implemented.

The flowchart below shows how works the robot with the information given by the software MATLAB.

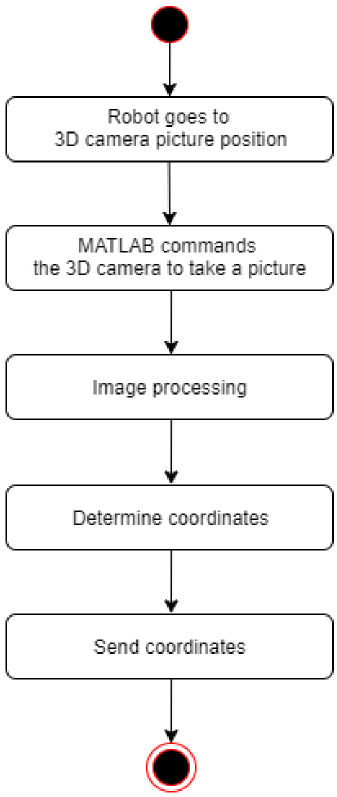


Figure 72 – Flow View from the position of the 3D camera
Source: own elaboration

Robot goes to 3D camera picture position

The first movement of the robot is made to allow the 3D camera to take a picture without the robot arm in front of it. Once it is in position, the robot sends a message to MATLAB, so the software knows when it can take a picture.

Image processing

As explained above, the 3D camera and the MATLAB program transforms the data from the camera to be understandable by the robot and in the same coordinate system.

Send coordinates to robot

Once the coordinates of each object are known, MATLAB sends the coordinates of the first tomato. Once the robot has reached the position in front of the tomatoes, grabbed and released it in the basket, MATLAB will send a new set of coordinates for the next tomato. This loop continues until all the tomato have been grabbed.

5.3 Electronics

In this chapter it is explained how the servo, the sensors, the power supply and the Arduino are linked together. This chapter also includes schematics and printed circuit board design (from now on referred to as PCB design).

5.3.1 How is everything connected

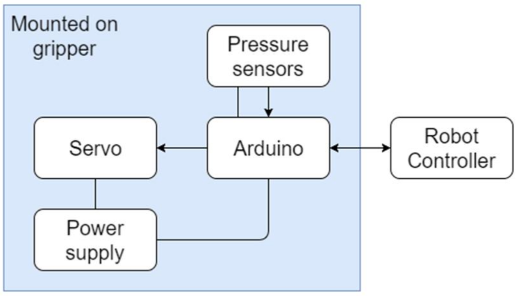


Figure 73 – Block diagram of electronics
Source: own elaboration

The block diagram above shows how all of the electronic parts are connected to each other. The arrows show the flow of data.

Example: The Arduino sends data to the servo, but the servo does not send data to the Arduino. Therefore the arrow is pointing from Arduino to the Servo.

The power supply doesn't communicate with any device, however it is a core part of the electronics. This is why it is still shown in the block diagram.

Another thing that is worth mentioning is that the Arduino acts as a power supply for the sensors. This saves on a few components.

5.3.2 The schematic requirements

Before a creating the schematic, few requirements were made. These requirements are:

- 6 to 7V, 500mA power source for the servo
- 5V, 150mA power source for the Arduino
- 3.3V power source for the Sensors
- Connection for 2x limit switches and 3x finger switches (if sensors do not work, or take too much time).
- SPI Connection for the sensors.
- 1x PWM connection to the servo.
- 1x 1X2 header to communicate with the robot arm.
- 24V input.

5.3.3 The power supply schematic

The input of the power supply is +24V and the required outputs are 6 to 7V, 5V and 3,3V.The step from 24V to 5V is too big. Due to this problem it is chosen to use 2 regulators in series in the following manner:

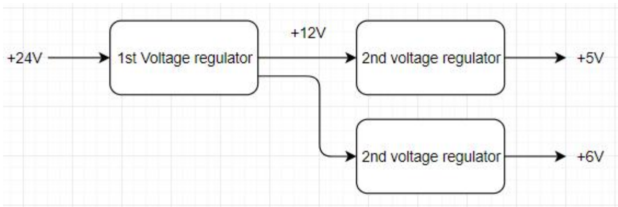


Figure 74 – Block diagram of voltage regulators
Source: own elaboration

In the requirements it was stated that besides +5V and +6V, a +3.3V source was required. However the Arduino has a +3.3V output

The exact schematic of the voltage regulators looks like this:

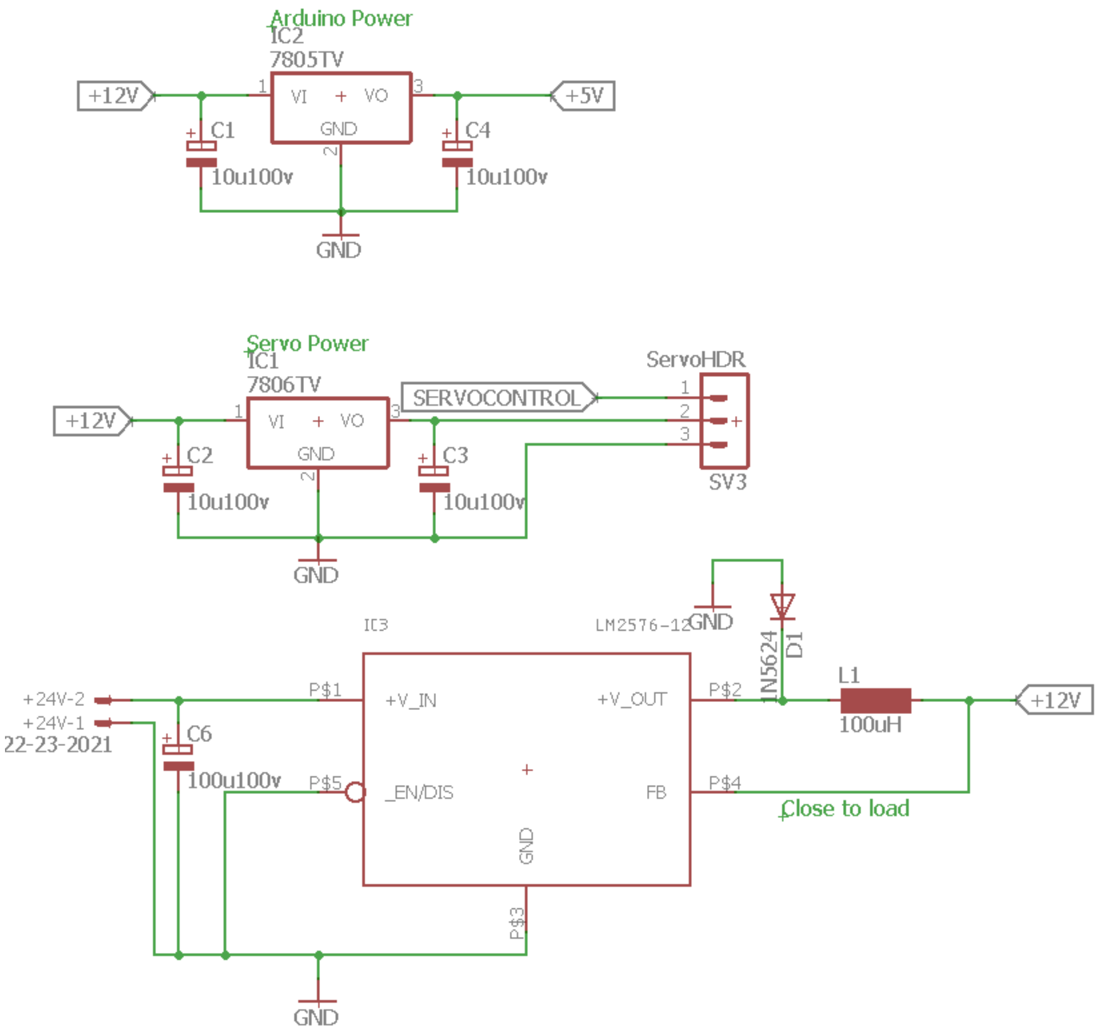


Figure 75 – Schematic of voltage regulators
Source: own elaboration

The +24V to +12V regulator is a switch-mode power supply (SMPS). These regulators are a bit more expensive, but they have a lot higher efficiency(LM2576-12 has a efficiency of 88%) than linear voltage regulators (theoretical maximum of 50%).

5.3.4 *The Arduino schematic*

The schematic of the Arduino looks like the following:

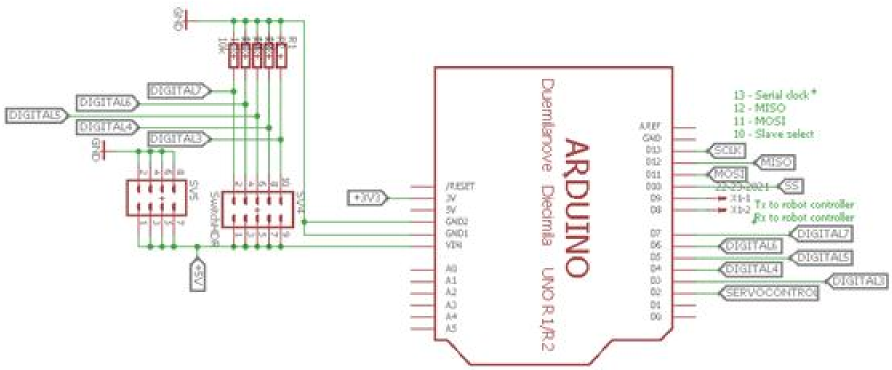


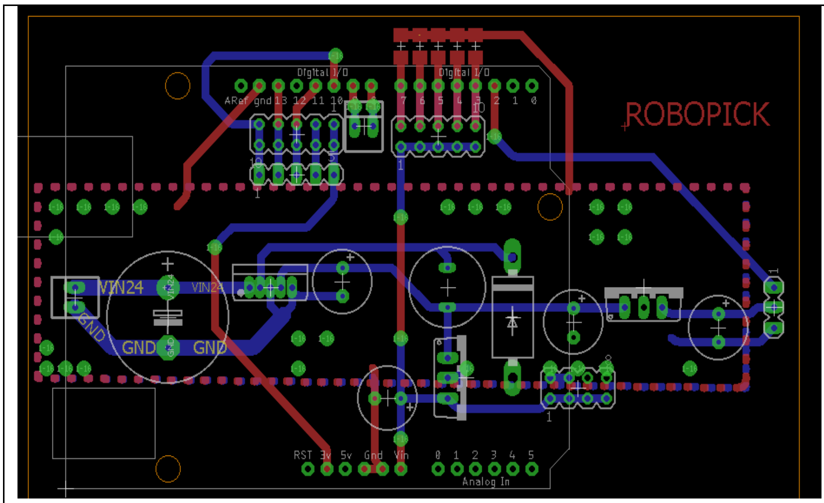
Figure 76 – Schematic of the Arduino
Source: own elaboration

As shown in the schematic, the majority of the schematic is connecting the Arduino to the switches, sensors and servo. The exact I/O list and description of the function of each I/O port can be found in the Arduino software chapter.

A few things to mention are the resistors near the Switch header. These are used as pull down resistors for the switches. This means that the switch is high-active. They are also used to prevent noise.

5.3.5 *The PCB design*

The PCB design looks like the following



Red = Copper top layer.

Blue = Copper bottom layer.

Green = Through-hole component pads and vias, these exist on both sides of the PCB.

Dotted lines = Outline of the ground plane.

Figure 77 – The PCB design of the Arduino schematic and power supply
Source: own elaboration

The goal of the PCB was to use as much surface as possible on the Arduino. This would make the PCB as small as possible.

Other requirements were that the PCB makes use of a ground plane and short traces. This is done to create higher electromagnetic interference (EMI) immunity.

5.3.6 Sensors

To prevent the gripper from squishing the tomatoes, sensors are being used.

The 3 major options were:

- Capacitive sensors
- Switches
- Pressure sensors

Kind of sensor	Price	Can sense if tomato is removed	Development risk	Delivery time
Capacitive sensors	~20 euros total	Yes	Very high	Long,
Switch	~7,50	No	Low	None
Pressure sensors	~120	Yes	Medium	Long

Table 12 – Advantages and disadvantages of the sensors
(Source: own elaboration)

During the development the group decided to try developing capacitive sensors. If the result seems hard to achieve, pressure sensors will be ordered.

Switches are already available and are very easy to implement. Therefor switches will be used as a back-up.

During the development the group also noticed that developing capacitive sensors was to risky to develop. It was mainly hard to keep the test results consistent.

Requirements of the pressure sensor

As there are various kinds of pressure sensors it was required to have specification list:

- The pressure sensors should cost less than 50 euro's a piece.
- The pressure sensors should have a digital output.
- A well-documented data communication (I2C, SPI or RS-232) protocol is highly preferred.
- Sensors should work on 3.3V, 5V, 6V, 12V or 24V.

Based on these requirements the following sensor has been chosen: TE Connectivity MS1S1-00000J-250PG.

6 Test results

To fulfil the requirements set at the beginning of this report, this test report is added. A short description of the test that will be performed combined with necessities and when it is successfully. After the different tests, also the cost will be shortly demonstrated.

6.1 Test report

The minimal diameter of the tomato

Description	Goal	Passed	Failed
The tomato picker must be able to pick a tomato with minimal diameter of 60 mm and maximal diameter of 80 mm	The gripper must be able grab the tomato and transport it to concerned coordinates		

Necessities: Tomato with 60 mm diameter, tomato with 80 mm diameter, robot mounted with gripper, measuring tool.

Execution: Measure the diameter of the tomato. Pick the tomato at certain coordinates and close the gripper. Transport the tomato to different coordinates and open the gripper.

Successfully: When the tomato is the mentioned diameter and the robot transports the tomato to entered coordinates without losing it.

The bright red colour of the tomato

Description	Goal	Passed	Failed
The vision system must be able to detect a bright red tomato.	Detecting a red tomato with the vision system, minimal visibility 80%		

Necessities: Two bright red tomatoes, a green tomato, a green leaf, web camera hooked up with the vision system.

Execution: Point the camera to the three tomatoes and apply the tomato recognition algorithm at the taken picture. One red tomato should be covered for 20 % with the leaf.

Successfully: When the algorithm recognize the two red tomato but not the green tomato.

The coordinates of the tomato

Description	Goal	Passed	Failed
The vision system must be able to determine the coordinates of a tomato.	Determine the coordinates of a tomato		

Necessities:	One tomatoes, measuring tools, web camera hooked up with the vision system.
Execution:	Point the camera on the tomato and apply the tomato recognition algorithm at the taken picture. Compare the given coordinates with the measured coordinates and repeat this five times.
Successfully:	When the average uncertainty is less than 5 mm in X-Y-Z direction and within reach of the real coordinates.

The damage of the tomato

Description	Goal	Passed	Failed
The gripper may not cause any damage on the tomato.	Determine if the gripper causes any damage.		

Necessities:	One ripe tomato, Robot mounted with gripper.
Execution:	Transport the ripe tomato from point A to point B, when released in the basket check the tomato on any visual damage
Successfully:	When the tomato did not receive any visual damage from the transportation.

The reach of the tomato picker

Description	Goal	Passed	Failed
The tomato picker must be able to pick tomatoes in a certain reach.	Determine if the gripper pick tomatoes in the area 650x550x400 (LxWxD)		

Necessities:	Four tomatoes, Robot mounted with gripper.
Execution:	Place the tomatoes in extreme point of the rang and perform a picking sequence.
Successfully:	When all tomatoes are picked successfully.

The transport of multiple tomatoes

Description	Goal	Passed	Failed
The tomato picker must be able to pick multiple tomatoes	Transport multiple tomatoes in one sequence		

Necessities: Three tomatoes, Robot mounted with gripper.

Execution: Preform one full sequence of transportations.

Successfully: All three tomatoes are transported without any human interfering

6.2 Costs

The available budget for this project is € 5000. That does not mean the whole budget can be spend without any consequence, all purchased components must be used for this project. Therefore in Appendix, the Bill of Materials is listed all components that are bought on behalf of design. In total €734,30 is spent, therefore the assignment coordinator has spent the remaining budget on a mechanical gripper. This way comparable project can be set up.

Also in Appendix, the Earn Value Analysis (EVA) results are pointed out. In the EVA, the amount of money spent is staked out against the amount of time invested in the project. During the development a few challenges showed up and therefore more time needed to be invested. Accordingly extra time was necessary than originally scheduled.

7 Conclusions

Before the conclusion is drawn the mission should be restated:

Our mission is to build a prototype of a harvesting robot that is able to detect and harvest ripe tomatoes and during the process to learn about automatization and robotics.

The prototype is able to determine ripe tomatoes in a lab environment. When the prototype uses the web camera, the vision system determines the coordinates precisely but the tomatoes have to hang on a fixed distance, because a single camera is not able to see depth. As the 3D-camera is used the resolution because a lower accurate reference point, but it is capable to determine the three coordinates. Although it is not competent to distinguish ripe and immature tomatoes. A combination between these two cameras is not yet realised.

The gripper is able to grab a tomato and transport it to the desired destination. With the pressure sensor equipped in the fingers of the gripper the robot is able to prohibit damaging the tomatoes. Although, the tomatoes have to be regular shaped.

During the development of the harvesting robot the knowledge about controlling the robot arm is greatly improved and processing techniques are developed. Also, international connections between different students, lecturers and universities are unique experiences that enriches the vision.

8 Recommendations

The purpose of this section is to present and discuss the actions that future students should take as a result of this project.

The recommendations are listed below:

- Replace the 3D-camera with a second web camera, through this the depth issue is fixed and the coordinate determination can be established with one program.
- Research materials applicable for the gripper, at this moment ABS is used in the gripper, this material is too stiff and able to damage the fruit. Other implementations of different materials will fix this problem.
- Implement this method into a realistic environment. After the prototype is further developed the prototype should be tested in a greenhouse where waterproofness and camera placement will become more important
- Set up a different project for an automatic guided vehicle. The robot needs to move between different positions without damaging itself and the environment.

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Appendices

A. Clifton StrengthsFinder

Before starting of the European Project Semester, the lecturer Peter Menger asked every member of the team to answer the 177 questions of the Clifton StrengthsFinder test. The aim of the test is to discover the top five talents (out of 34 talents) of each student and empower them to potential levels of excellence. These talents can be divided into four domains:

EXECUTING	INFLUENCING	RELATIONSHIP BUILDING	STRATEGIC THINKING
People with dominant Executing themes know how to make things happen.	People with dominant Influencing themes know how to take charge, speak up, and make sure the team is heard.	People with dominant Relationship Building themes have the ability to build strong relationships that can hold a team together and make the team greater than the sum of its parts.	People with dominant Strategic Thinking themes help teams consider what could be. They absorb and analyze information that can inform better decisions.
Achiever Arranger Belief Consistency Deliberative Discipline Focus Responsibility Restorative	Activator Command Communication Competition Maximizer Self-Assurance Significance Woo	Adaptability Connectedness Developer Empathy Harmony Includer Individualization Positivity Relator	Analytical Context Futuristic Ideation Input Intellection Learner Strategic

Figure 78 – Clifton StregthsFinder domains
Source: http://www.business-leadership-qualities.com/Strengths.html

A.1 Strengths results

In the following chart the strengths of each team member are presented.

	EXECUTING							INFLUENCING			RELATIONS		STRATEGIC THINKING					
	Achiever	Arrenger	Belief	Deliberative	Focus	Responsability	Restorative	Activator	Communication	Maximizer	Includer	Relator	Analytical	Context	Futuristic	Input	Intellection	Learner
Matthieu Courmount		1				1	1				1		1					
Xavier Botam										1		1				1	1	1
Jordi Roig			1										1	1	1			1
Hidde de Witt				1			1						1				1	1
Robbert Manak	1				1			1	1						1			
TEAM - ROBOPICK	1	1	1	1	1	1	2	1	1	1	1	1	3	1	2	1	2	3

Table 13 – Robopick's talents chart
Source: own elaboration

At first glance the results reveal an unbalanced graph as most of the talents are on strategic thinking and executing groups while on influencing and relationship building there are only few themes. Also, the team top 5 strengths such as Analytical and Learner with three people on it and Intellection and Restorative with two people having them as their top talents. Even though the talent Futuristic is shared by two persons in the team the meaning is different for both of them.

From the table, it can be deduced that the team has two strong points (with 20 talents out of the 25 possible) in accomplishing goals and analysing the situations and information to achieve these goals. However, the possibility of getting stuck at some point and collisions between members is high due to the lack of talents (just 5 of 25) in the influencing and relationships building team.

A.2 Ofman's Model

After having the top 5 talents in the team, Peter Menger proposed another exercise called the Ofman's Model. The objective of this exercise was to discover how far the top five talents are able to work before turning into a pitfall and which challenge should be taken in order to solve the core quality.

Figure 79 – Ofman's Core Quadrant

Source: https://www.toolshero.com/communication-skills/core-quadrant-ofman/

With the core qualities as the team top five strengths, the pitfalls and challenges have to be defined in order to know what the team should try to avoid and what should try to get accomplished.

- **Analytical**

  People who are especially talented in the Analytical theme search for reasons and causes. They have the ability to think about all the factors that might affect a situation.

  Pitfall: Noticing too many little details.

  Challenge: Only focusing into the necessary details.

- **Learner**
  People who are especially talented in the Learner theme have a great desire to learn and want to continuously improve. In particular, the process of learning, rather than the outcome, excites them.

  Pitfall: Learning without a goal in sight.

  Challenge: Applying the learning towards a goal.

- **Intellection**
  People who are especially talented in the Intellection theme are characterized by their intellectual activity. These people are introspective and appreciate intellectual discussions.

  Pitfall: Not willing to change unless it is a superior reasoning.

  Challenge: Being open for changes.

- **Restorative**
  People who are especially talented in the Restorative theme are adept at dealing with problems. Restorative people are good at figuring out what it is wrong and resolving it.

  Pitfall: Getting stuck fixing a mistake and bounded to the idea of fixing it.

  Challenge: Approaching the idea from a different perspective.

B. Belbin test

At the beginning of this project every team member was asked to take the Belbin test. This test aims to identify the different clusters of behaviour that are displayed in the workplace. These are called Belbin Team Roles.

Coordinator	Needed to focus on the team's objectives, draw out team members and delegate work appropriately.
Shaper	Provides the necessary drive to ensure that the team keeps moving and does not lose focus or momentum.
Plant	Tends to be highly creative and good at solving problems in unconventional ways.
Monitor	Provides a logical eye, making impartial judgements where required and weighs up the team's options in a dispassionate way.
Implementer	Needed to plan a workable strategy and carry it out as efficiently as possible.
Resource investigator	Uses their inquisitive nature to find ideas to bring back to the team.
Team worker	Helps the team to work together smoothly, using their versatility to identify the work required and complete it on behalf of the team.
Finisher	Most effectively used at the end of tasks to polish and scrutinise the work for errors, subjecting it to the highest standards of quality control.

Table 14 – Belbin Team Roles
(Source: http://www.belbin.com/about/belbin-team-roles)

The results of the Belbin test for each team member are shown below.

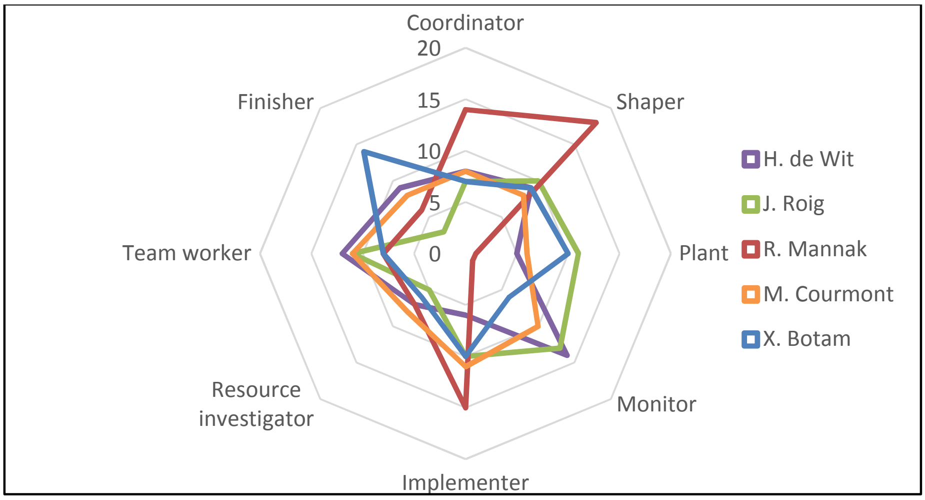


Figure 80 – Results of the Belbin test of all the team member
Source: own elaboration

On the following figure it is shown the results of Belbin test for the team as one.

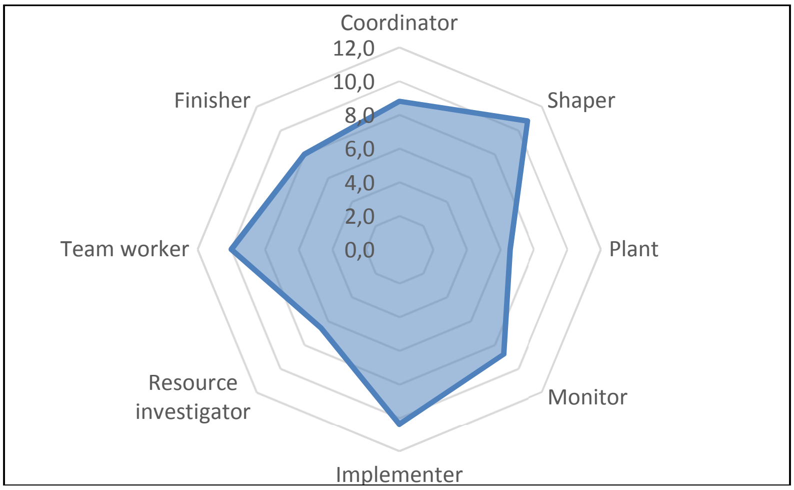


Figure 81 – Results of the Belbin test of the team

Source: own elaboration

B.1 Conclusions about the Belbin test

- **General comment**

As a general impression, Belbin test results suggests that there is a considerable spread of roles within the team since all roles are represented.

- **Values of each member**

Looking at the strengths of each team member it can be said that Robbert, as a coordinator, has a firm grasp of objectives: an ability to drive both himself and others, and a readiness to maximize the resources of the team. He is also able move the team forward, overcome obstacles and handle conflicts easily.

Xavier and Jordi, since both of them has Plant as a prominent role, will be valuable for their creativity and ability to solve problems. Xavier, according to his strength as Finisher, will be also helpful at the end of tasks to polish and check out the work for errors in order to achieve a high level of quality.

Hidde, as well as Jordi, has a prominent role as a Monitor. It means that they could be helpful to analyse all possible options and judge accurately in a logical way.

Matthieu has neither a particular strength nor a particular weakness. However, his main strength is his ability to work in team.

- **Other potential values apart from Belbin**

Although Belbin test could be really helpful to check if each team member is performing to his full potential, also the personal contribution to the project is highly related to their personal interests and field of studies.

C. Team identity

C.1 Name of the team

The name chosen for our project is ROBOPICK. This word, ROBOPICK, combines the words robot and picker, which are the main features of the project.

The team adopted this name and used it throughout the rest of the project.

C.2 Logotype

The main purpose of the logo created is to promote the project and to build a visual identity. The logo is used on every presentation material to allow people to easily recognize the project and its meaning.

Some of the requirements that were taken into consideration when designing the logo were: to have a unique, highly impacting, and eye-catching logo.

With the purpose of having a professional looking logo, it has been created with the software Adobe Illustrator and using the low-poly technique.

The logo contains the name chosen for the project, ROBOPICK, but the first vowel has been changed for a low-poly picture of a tomato.

The picture below shows how the logo looks like.

Figure 82 – Logotype
Source: own elaboration

C.3 Business card

A business card is used to provide team member's contact information to potential customers and colleagues and also serves as a way to remember the team member after a first meeting.

It has to portray Robopick project's values. Since every customer receive several business cards from competitors, a smartly designed business card helps the project stand out among the crowd.

The main priority taken into account when designing front part of the business cards was including only the important information (logo, name, role, phone number, email and website).

On the back of the business cards a QR code was included, so when this QR code is scanned, the visitor is redirected to the Robopick website.

The picture below shows the final design of the business cards.

Figure 83 – Business card: front and back
Source: own elaboration

C.4 Website

In order to promote the project and show the progress of the work, a website has been created. The website also contains information about the team members and enable visitors to contact them.

The website is developed using a WordPress free domain due to it is easy to use and great aesthetics.

The picture below shows how the website looks like.

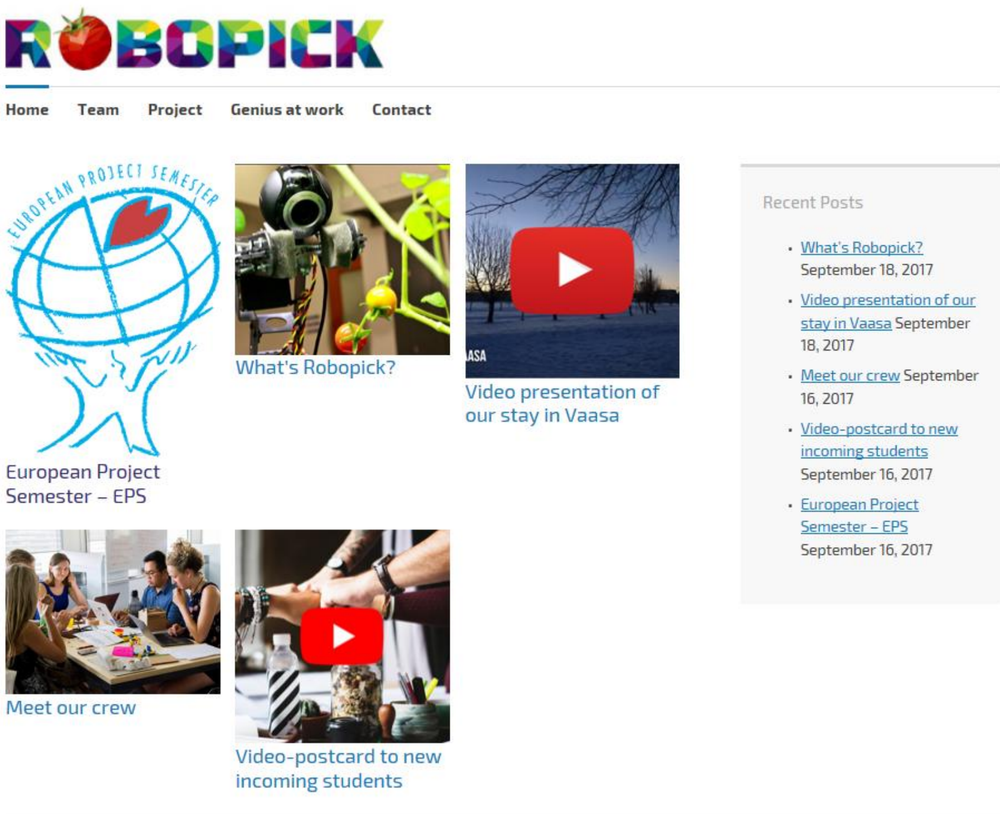


Figure 84 – Main page of the website (robopick.wordpress.com)
Source: own elaboration

The website contains the following information:

- Home
  This is the main page where there are all the posts published.
- Team
  The aim of this section is to describe briefly the members of the team
- Project
  On this section there is a description of the project and some other details. The deliverables of the project will be uploaded on this section.
- Genius at work
  On this page some of the pictures taken during the project are uploaded.
- Contact
  This section provides a contact form to enable the visitor to contact the team.

The whole website is kept up to date during the project.

C.5 Video of our staying in Vaasa

A video of our staying in Vaasa was created with the aim of learning how to present something in a good way as marketing and also to show to potential new students.

The video can be found on Robopick's Youtube channel as well as on the website.

Video presentation of our stay in Vaasa

C.6 Video of our project

Also another video about the project was produced. The purpose of this second video is to show the challenges found during the project as well as the lessons learned.

This video can be found on Robopick's Youtube channel as well as on the website.

Video-postcard to new incoming students

D. Project Management

What is Project Management?

Project management is the application of processes, methods, knowledge, skills and experience to manage a project from conception through completion (PMI, 2008) .

What are the knowledge Project Management?

According to *The PMBOK Guide – 4th*, the nine knowledge areas of project management are:

1. Project Integration Management
2. Project Scope Management
3. Project Schedule Management
4. Project Cost Management
5. Project Quality Management
6. Project Resources Management
7. Project Communications Management
8. Project Risk Management
9. Project Procurement Management

Project Management in this project

The present project is focus only on the first eight knowledge areas of project management.

In this chapter all the tools and techniques used for project activities to meet the project requirements are presented.

D.1 Project Integration Management

D.1.1 Smart Objectives

Once the project is planned, the goals should be defined in order to be successful (Haughey, 2017).

The acronym SMART gives the project some criteria to set the goals and stands for:

- **Specific**, well defined objectives clear to anyone with a basic knowledge of the project
- **Measurable**, have measurable goals to track the progress
- **Achievable**, the goals can extend the team abilities but still be realistic
- **Relevant**, the project has to matter to the team and to match with the stakeholders' goals
- **Time-based**, enough time to achieve the goal.

Our SMART objective would be:

Designing an automatic tomato harvesting robot and three gripping tools by using the given facilities and SICK sensors within three months.

This goal is:

- Specific because it states what the team wants to design
- Measurable due to the countable parts that have to be designed
- Achievable thanks to the technologies from Novia and SICK
- Relevant because it matches with the stakeholder goals
- Time-based because the project has a deadline for the project to be finished.

D.1.2 Milestones

The milestones are used in a project to establish some dates to be taken into consideration such as the final or the midterm report and to track if the project is progressing as it should. The following dates are some of the milestones for the project:

- 7/9 - Project initiation
- 19/10 - Midterm project documentation delivery
- 24/10 - Midterm project presentation.
- 13/12 - Final project documentation delivery.
- 15/12 - Last day to present the project documentation to SICK company.
- 18/12 - Final project presentation.

D.1.3 Deliverables

The main deliverables for this project are listed below:

- Midterm report
- Midterm presentation
- Final report
- Final presentation

In the following, other deliverables of the project are listed.

- Professional website for our project
- Video presentation about our stay in Vaasa to market Novia-EPS
- Video-postcard to new incoming students about lessons learned during the project

D.1.4 Stakeholders

According to the Project Management Institute (PMI), the term **project stakeholder** refers to, "an individual, group, or organization, who may affect, be affected by, or perceive itself to be affected by a decision, activity, or outcome of a project"

The stakeholders in this project are the ones listed below:

- **Team members.** Each of the five team members is eager to get the best result as possible and have interest in completing this work successfully before the SICK deadline.
- **Project supervisor.** Mika Billing is the supervisor of the tomato picker project who aids and guides the team through the whole project. If the team need any equipment in order to get the project done, Mika is the responsible of purchasing it.
- **EPS coordinator.** As a supervisor for all the EPS projects, Roger Nylund gives lectures about project management and helps the students through the duration of the project.
- **Novia University.** The University provides the budged to complete the project and also all the machines that the team will be using for creating the prototype.
- **SICK company.** It is one of the most important stakeholders. This company organizes the competition involving the project and it will judge the project in the end.
- **Greenhouse' farmers.** If the project is successful, farmers will take benefit from it and the harvesting robot could be applied in their greenhouses.
- **EPS students.** Students of other teams may give some suggestions or opinions about the project.
- **EPS lectures.** For instance, Rayko Toshev and Peter Menger are also stakeholders of the project because their suggestions can also have some effect on it.

D.2 Project Scope Management

Project Scope Management refers to the set of processes that ensure a project's scope is accurately defined and mapped.

D.2.5 Scope of the project

The scope of this project is to design a functional prototype of a robot able to recognize the tomatoes using a sensor provided by SICK and remove them from the plant in a greenhouse without being damaged. Also, developing and testing three different gripping tools.

Out of scope: The project does not involve moving the robot through the greenhouses nor introducing the product to commercial partner by organizing marketing event.

D.2.6 Work Breakdown Structure

The Project Management Body of Knowledge (PMBOK 5) defines the work breakdown structure as a "A hierarchical decomposition of the total scope of work to be carried out by the project team to accomplish the project objectives and create the required deliverables."

The WBS for this project can be viewed below.

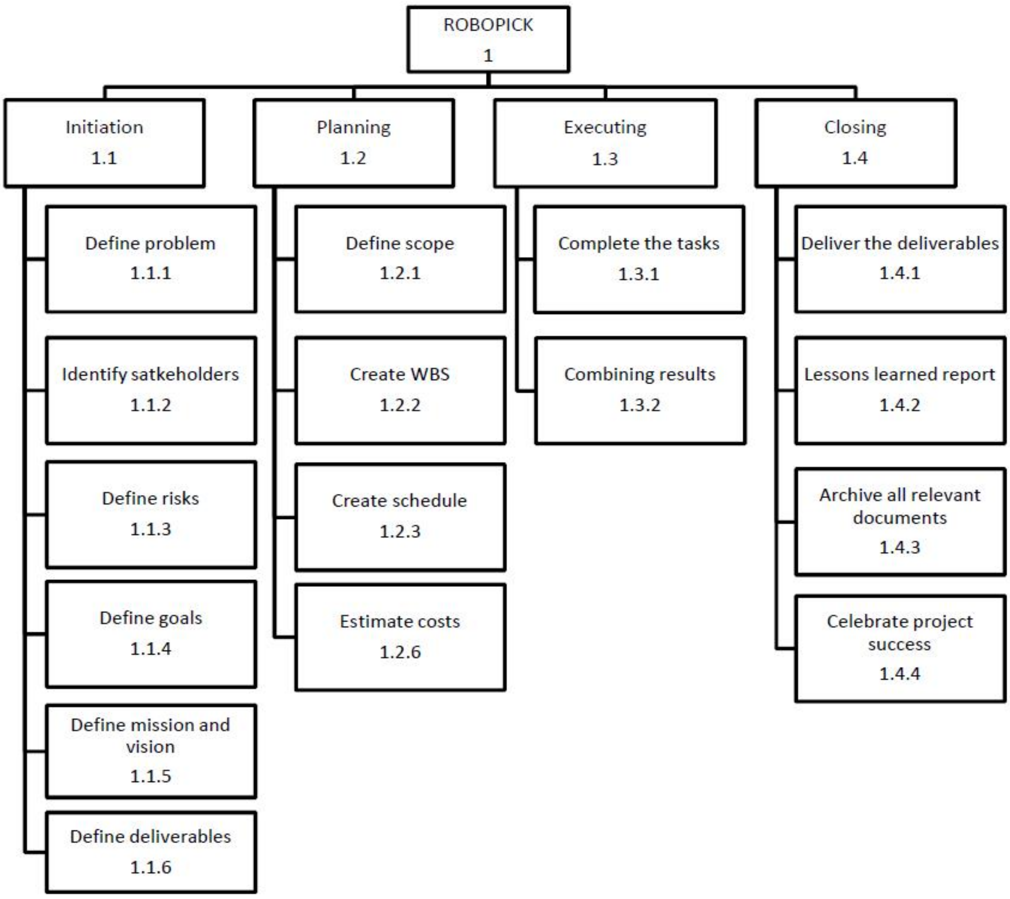


Figure 85 – Work Breakdown Structure
Source: own elaboration

D.3 Project Time Management

In this paragraph the general planning will be discussed, starting with the planning before the research and after that the adjustment that where made concerning the clarification of the project.

D.3.7 First global planning

The first planning was made in the beginning of the project, that way not all things were clarified. The deadline for the mid-terms is planned on the 17th of October. The work is divided in four parts. The vision for detecting the tomato, the gripper for picking the tomatoes, robot including the LiDAR-sensor and finally the documentation about the project. In the end, these components will be integrated in the tomato picker. These subjects can be unpacked into smaller targets, that way the work is divided in smaller segments.

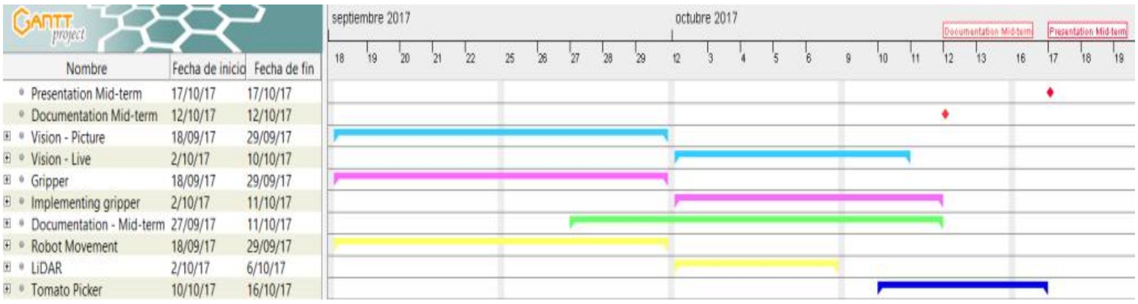


Figure 86 – First global planning
Source: own elaboration

D.3.8 Improved Gantt diagram

After the first weeks some major changes have occurred, the planning had to be adjusted to that. Maybe the most important adjustment is the shifting of the mid-term deadline. It shifted up one week and that way there was still five instead of four working weeks. Also, the marketing tasks including the project management was not included, this task was a big chunk of the mid-term deadline. The marketing goes about this planning till the risk management but also include the website and the business card for example. The vision-part was finished earlier than calculated but the LiDAR arrived later predicted.

Figure 87 – Gantt diagram mid-term
Source: own elaboration

D.3.9 *Gantt diagram for the second term*

In the following figure the planning for the second term is presented.

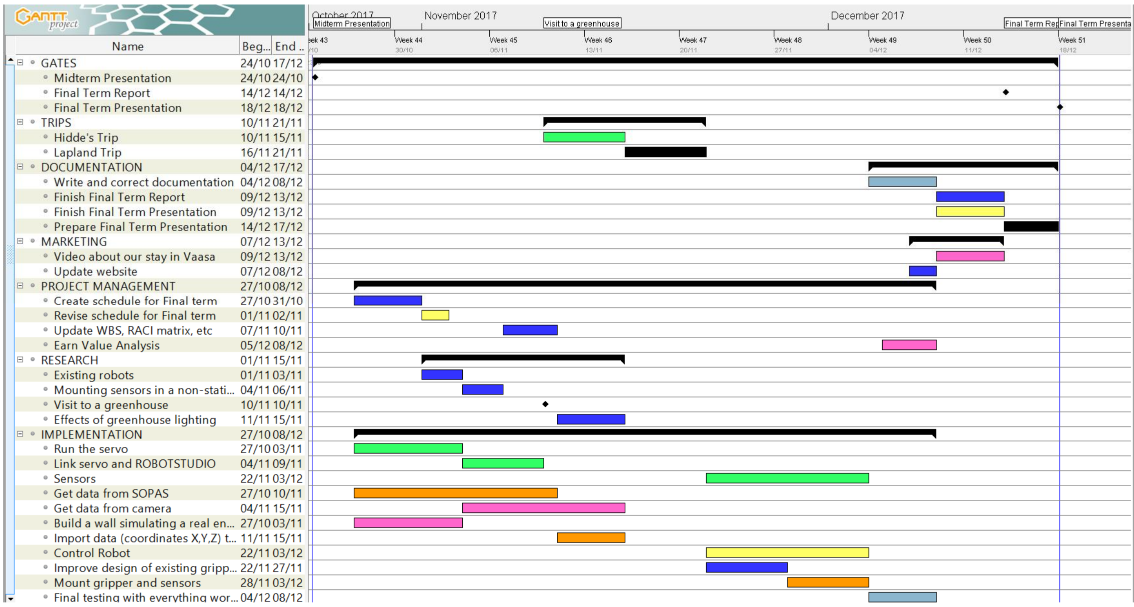


Figure 88 – Second term planning

Source: own elaboration

D.4 Project Cost Management

D.4.10 Earn Value Analysis

The EVA (Earn Value Analysis) is a graphic to display the progress of the project against the plan. It considers the planned costs and milestones of the project and compares it to the actual ones. This method can be used to show the past and the current performance of the progress and try to predict the future of the project by using statistical techniques. In order to analyse the progress, the schedule, the scope, the costs of the project and the number of hours that the team has been working in the project are needed (Varsani, 2017).

In the graphic, there are four main keys indicators:

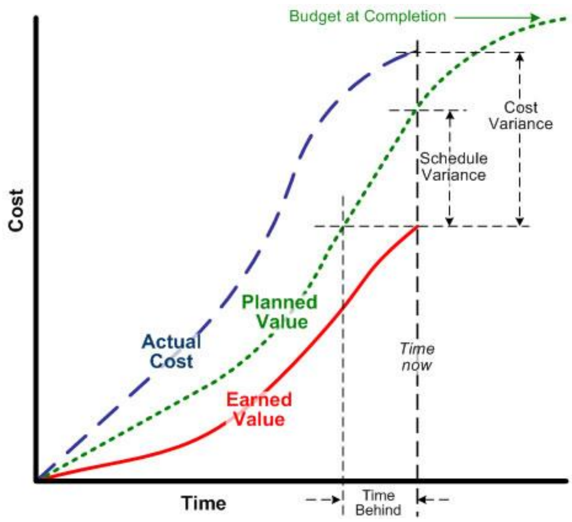


Figure 89 – Earn Value Metrics

Source: http://www.chambers.com.au/glossary/earned_value_management.php

- Budget at Completion (BAC). It represents the total budget cost for the project.
- Actual Costs (AC or ACWP). It is described as the expenses incurred in the project till the time of measurement
- Planned Value (PV or BCWS). It represents the planned work that should be completed until the time of measurement.
- Earned Value (EV or BCWP). The actual work that has been completed until the time of measurement.

The first step to get the EVA done is to obtain your Planned Value by setting a price per hour to all the tasks on the schedule and multiply them by the amount of time you are planning to take on the task. The team Planned Value for the 1st of December below:

Planned Value

TASK	€/h	Week 8		Week 9		Week 10		Week 11		Week 12		Week 13		Week 14		Week 15	
Project management	40	22,5 h	€ 900	22,5 h	€ 900	30,0 h	€ 1.200		€ 0		€ 0		€ 0	30,0 h	€ 1.200		€ 0
Servo	25	7,5 h	€ 188	37,5 h	€ 938		€ 0		€ 0		€ 0		€ 0		€ 0		€ 0
Sensors	30		€ 0		€ 0		€ 0		€ 0	22,5 h	€ 675	37,5 h	€ 1.125		€ 0		€ 0
3D camera data	30	7,5 h	€ 225	37,5 h	€ 1.125	37,5 h	€ 1.125		€ 0		€ 0		€ 0		€ 0		€ 0
Camera data	20		€ 0	37,5 h	€ 750	22,5 h	€ 450		€ 0		€ 0		€ 0		€ 0		€ 0
Robotstudio	35		€ 0		€ 0	30,0 h	€ 1.050	37,5 h	€ 1.313	22,5 h	€ 788	37,5 h	€ 1.313		€ 0		€ 0
Build a wall	20	7,5 h	€ 150	37,5 h	€ 750		€ 0		€ 0		€ 0		€ 0		€ 0		€ 0
Marketing	25		€ 0		€ 0		€ 0		€ 0		€ 0		€ 0	22,5 h	€ 563	22,5 h	€ 563
Research	20		€ 0	37,5 h	€ 750	22,5 h	€ 450	15,0 h	€ 300		€ 0		€ 0		€ 0		€ 0
Documentation	35		€ 0		€ 0		€ 0		€ 0		€ 0		€ 0	37,5 h	€ 1.313	37,5 h	€ 1.313
Mounting and testing	15		€ 0		€ 0		€ 0		€ 0		€ 0	30,0 h	€ 450	30,0 h	€ 450		
Gripper design improvement	30		€ 0		€ 0		€ 0		€ 0	22,5 h	€ 675	7,5 h	€ 225		€ 0		€ 0
Total		45 h	€ 1.463	210 h	€ 5.213	143 h	€ 4.275	53 h	€ 1.613	68 h	€ 2.138	113 h	€ 3.113	120 h	€ 3.525	60 h	€ 1.875

Table 15 – Planned Value

Source: own elaboration

Even though that at the planned chart there are only eight weeks, the previous weeks before the midterm report are also taken into account. If the table is analysed, most of the money is spent in working hours of the team members into programming of the robot and the different devices.

The following step is to achieve the Actual Value by including the real time that each student has put into each task as the next table shows:

Actual Value

TASK	€/h	Week 8		Week 9		Week 10		Week 11		Week 12		Week 13		Week 14		Week 15	
Project management	40	30,0 h	€ 1.200	10,0 h	€ 400	15,0 h	€ 600		€ 0		€ 0	10,0 h	€ 400		€ 0		€ 0
Servo	25	5,0 h	€ 125	20,0 h	€ 500	20,0 h	€ 500		€ 0		€ 0	35,0 h	€ 875		€ 0		€ 0
Sensors	30		€ 0	30,0 h	€ 900	10,0 h	€ 300		€ 0		€ 0		€ 0		€ 0		€ 0
3D camera data	30	10,0 h	€ 300	5,0 h	€ 150	20,0 h	€ 600		€ 0		€ 0	40,0 h	€ 1.200		€ 0		€ 0
Camera data	20	5,0 h	€ 100	40,0 h	€ 800	15,0 h	€ 300	15,0 h	€ 300		€ 0		€ 0		€ 0		€ 0
Robotstudio	35	10,0 h	€ 350	40,0 h	€ 1.400	40,0 h	€ 1.400	30,0 h	€ 1.050	30,0 h	€ 1.050	30,0 h	€ 1.050		€ 0		€ 0
Build a wall	20	5,0 h	€ 100	15,0 h	€ 300		€ 0		€ 0		€ 0		€ 0		€ 0		€ 0
Marketing	25	5,0 h	€ 125	5,0 h	€ 125	5,0 h	€ 125	5,0 h	€ 125	10,0 h	€ 250	30,0 h	€ 750		€ 0		€ 0
Research	20		€ 0	20,0 h	€ 400		€ 0		€ 0		€ 0		€ 0		€ 0		€ 0
Documentation	35		€ 0		€ 0		€ 0	5,0 h	€ 175		€ 0	40,0 h	€ 1.400		€ 0		€ 0
Mounting and testing	15		€ 0	5,0 h	€ 75	5,0 h	€ 75	5,0 h	€ 75	5,0 h	€ 75	20,0 h	€ 300		€ 0		
Gripper design improvement	30		€ 0		€ 0		€ 0		€ 0	20,0 h	€ 600	20,0 h	€ 600		€ 0		€ 0
Total		70 h	€ 2.300	190 h	€ 5.050	130 h	€ 3.900	60 h	€ 1.725	65 h	€ 1.975	225 h	€ 6.575	0	€ 0	0	€ 0

Table 16 – Actual Value

Source: own elaboration

If the Actual Value and the Planned Value are compared, there are some weeks when the group had to work harder because sudden complications came up. In the graph, some of the hours exceed the normal timetable hours someone should do and it means that more than one person was doing that task.

The last task is to rate the progress of each of the planned tasks and multiply that progress for the task total value over the weeks into the Planned Value table as in the team chart below:

TASK	Planned Value	Actual Value	% Progress	Earned Value
Project management	€ 4.200,00	€ 2.600,00	95%	€ 3.990,00
Servo	€ 1.125,00	€ 2.000,00	60%	€ 675,00
Sensors	€ 1.800,00	€ 1.200,00	50%	€ 900,00
3D camera data	€ 2.475,00	€ 2.250,00	30%	€ 742,50
Camera data	€ 1.200,00	€ 1.500,00	100%	€ 1.200,00
RobotStudio	€ 4.462,50	€ 6.300,00	95%	€ 4.239,38
Build a wall	€ 900,00	€ 400,00	100%	€ 900,00
Marketing	€ 1.125,00	€ 1.500,00	80%	€ 900,00
Research	€ 1.500,00	€ 400,00	100%	€ 1.500,00
Documentation	€ 2.625,00	€ 1.575,00	90%	€ 2.362,50
Mounting and testing	€ 900,00	€ 600,00	100%	€ 900,00
Gripper design improvement	€ 900,00	€ 1.200,00	90%	€ 810,00
Total	€ 23.212,50	€ 21.525,00	83%	€ 19.119,38

Table 17 – Comparison between Planned Value and Actual Value
Source: own elaboration

In this chart, it is possible to realize the total amount of the actual progress of the project compared to the schedule. The project is currently at its 83% progress of achieving its final goals. A visual way to identify the performance of the team is in the following graph:

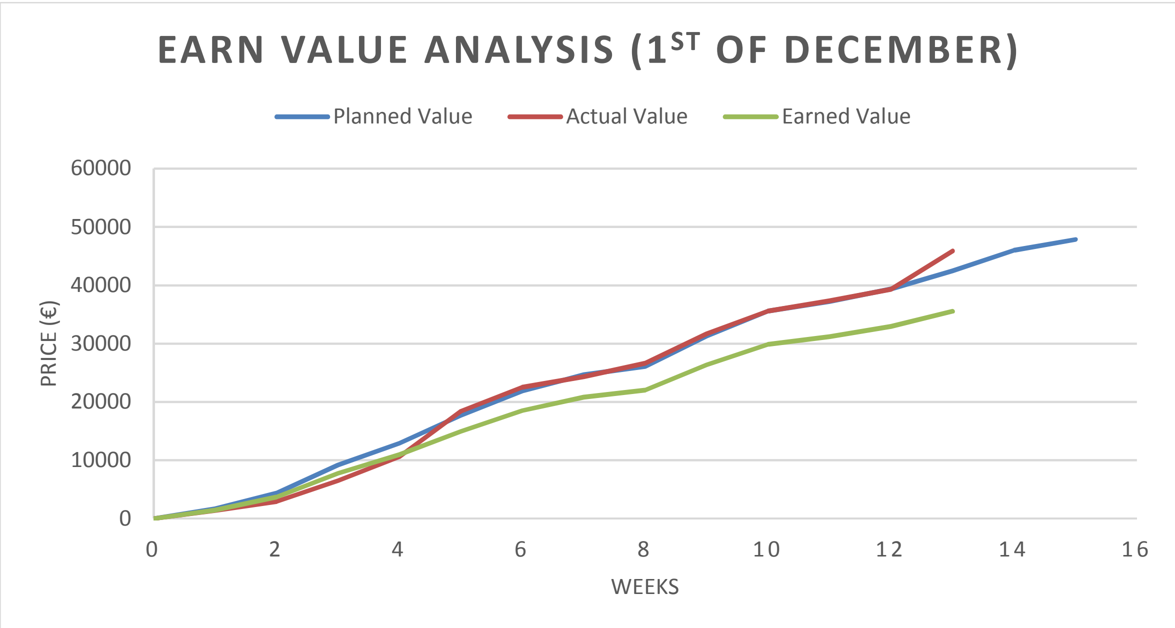


Figure 90 – Earn Value Chart
Source: own elaboration

In the figure above, the Earn Value is below both Actual and Planned Value, which means that the project is running behind schedule and the money is being overspent. The reason behind this is the difficulties with the devices which are not working until date because they are not enabling the team advance and the members are spending more hours than planned on them.

D.4.11 Bill of Materials

In this chapter, all the parts that the team members used for the project will be listed out with the price and why did the team used them.

Item #	Part Name	Description	Field	Quantity	Unit Cost	Cost
1	Arduino UNO	Microcontroller used to control the servo.	Electronic	1	€ 19,00	€ 19,00
2	Servomotor	Electronic motor to move the gripper.	Electronic	1	€ 25,00	€ 25,00
3	Camera	Logitech C-920 HD Pro Webcam.	Electronic	1	€ 110,00	€ 110,00
4	M2 Screw	Assembly parts	Mechanical	16	€ 0,05	€ 0,80
5	M5 Screw	Assembly parts	Mechanical	5	€ 0,10	€ 0,50
6	M8 Screw	Assembly parts	Mechanical	2	€ 0,15	€ 0,30
7	Long M8 Screw	Assembly parts	Mechanical	3	€ 0,30	€ 0,90
8	Nuts M2	Hold the screws	Mechanical	16	€ 0,05	€ 0,80
9	Nuts M5	Hold the screws	Mechanical	5	€ 0,15	€ 0,75
10	Nuts M8	Hold the screws	Mechanical	21	€ 0,20	€ 4,20
11	Cable tie	These were used to hold some parts during the tests.	Mechanical	4	€ 0,20	€ 0,80
12	Wires	Connects the electronic devices and building the tomato structure	Electronic - Mechanical	1	€ 11,00	€ 11,00
13	USB connector	It connects the camera to the main computer	Electronic	1	€ 10,00	€ 10,00
14	3D printing filament	It was used to 3d printing the different parts of the gripper	Mechanical	4	€ 30,00	€ 120,00
15	BuildTak 8" x 10"	3D Printing Build Surface	Mechanical	3	€ 10,27	€ 30,81
16	Pressure sensors	Knowing the force applied to the tomatoes by the gripper	Electronic	5	€ 39,00	€ 195,00

17	Capactive sensors	Build to detect if the tomatoes are still connected to the stem	Electronic	2	€ 0,50	€ 1,00
18	Switches	To prevent damages to the gripper	Electronic	5	€ 1,40	€ 7,00
19	Resistors	Enabble enough current in the circuits	Electronic	5	€ 0,20	€ 1,00
20	LEDS	Used to try the circuits	Electronic	3	€ 0,33	€ 1,00
21	Capacitors 100uF	Used for the electronic circuits	Electronic	8	€ 0,48	€ 3,81
22	Capacitors 10uF	Used for the electronic circuits	Electronic	2	€ 0,93	€ 1,85
23	Robot connector	It connects the gripper with the robot	Mechanical	1	€ 176,00	€ 176,00
24	Fixed Inductors	Used for the electronic circuits	Electronic	2	€ 0,95	€ 1,90
25	Thick film resistors	Used for the electronic circuits	Electronic	15	€ 0,02	€ 0,30
26	Wire housing 2x20P	Used for the electronic circuits	Electronic	1	€ 1,95	€ 1,95
27	8P DR	Used for the electronic circuits	Electronic	2	€ 0,39	€ 0,78
28	Diodes	Used for the electronic circuits	Electronic	2	€ 0,52	€ 1,04
29	Switches	Stabilizing the power supply	Electronic	2	€ 2,36	€ 4,72
30	Linear Volts reg.	Stabilizing the power supply	Electronic	2	€ 1,04	€ 2,08
					Total	**€ 734,30**

In total, 141 pieces are used for building the tomato picker with a cost of €734,30. After analysing the cost, it is possible to divide them in 2 major groups as shown in the pie chart below.

Figure 91 – Bill of Materials
Source: own elaboration

Most of the money, almost €400, was spent with electronic devices such as the pressure sensors or the camera to recognize the tomatoes. The other parts are the small electronic devices that the team is using for electronic circuits.

The mechanical parts are the other big group, with a total cost of roughly €335. These costs mainly come from the 3D printed parts and the connector that connects the gripper and the robot controller.

D.5 Project Quality Management

The quality of this project can be measured on three different ways. It can be measured on the project itself, on the prototype but also the documentation. Each subject will be taken in consideration separately, first identifying the quality requirements, followed by the quality assurance and ending with the quality control

D.5.12 Project quality

The project should be a learning experience for all the team members, despite their background, nationality or education. Furthermore, internationalising is one of the main focus point of this project. The internationalisation will happen automatically through the composition of the team and the several different people that needs to collaborate. Also, the opportunity for members to plan trips through Finland will further develop these skills, all within certain reasonability.

The team has a diversity of skill and therefore time is scheduled for transferring knowledge. This will mean, not always the most experienced team member will fulfil the assignment, but will act more as a coach for a different team member. Another example is the comments that need to be inserted between the code, so other people will understand the functionality of the code.

Everybody is responsible for fulfilling their personal goals mentioned above. During weekly meetings participant can occur their preferences. Halfway the project, a special meeting will be planned. During this meeting the progress and efficiency will be discussed and also personal point can be expressed.

D.5.13 Prototype quality

The prototype should function according to the requirements made beforehand. Different environments should not interfere with the functionality. Therefore, the project will be subdivided into various subsystems which can be tested individually. These will be integrated into the robot, only if the test gives a positive result.

Furthermore, the team will visit a tomato farmhouse to get inspired by the environment and that way involve this into the project. By following a test protocol on the different systems, the quality of the prototype can be controlled. This test protocol will follow the requirements mentioned before.

D.5.14 Documentation quality

There is a possibility this project will be followed up by another group of students, therefore the quality of the documentation is rather important. Not only that, also the supervisor must be able to see the progress of the project. Next to the weekly meetings with the supervisor, documentation is a proper way to fulfil this task.

To assure the quality of the documents, a special function is assigned to a member. The function of the ‘editor’ is to ensure the layout of the document and oversee the progress in the different articles. The documentation report must to be delivered at least one week before the deadline. The editor makes sure all articles are implemented in the report. All team members read the report and write down the comments and during a special meeting these comments will be processed. That way the quality of the documentation is checked.

D.6 Project Human Resources Management

According to the Project Management Institute, human resource management (HRM) consists of all the processes that assist a project manager in organizing, managing and leading the project team.

D.6.15 Organisation chart

In the following figure the organisation chart is presented.

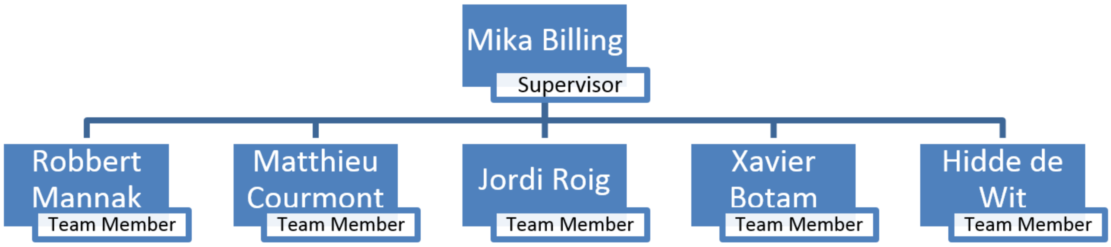


Figure 92 – Organisation chart
Source: own elaboration

D.6.16 RACI matrix

In the following figure the RACI matrix is presented.

Responsible	Person(s) assigned to do the task
Accountable	Person accountable for signing off the work
Consulted	Person(s) consulted before and during the task
Informed	Person(s) informed of work progress/completion

Work Area	Task Description	Project Team Members: Robbert	Hidde	Xavier	Jordi	Matthieu	Key Stakeholders: Supervisor (Mika Billing)	EPS Coordinate (Roger Nylund)
Project Management	Project Statement				A R			I C
	Define scope				A R			I C
	Objectives and milestones	C			A R			I C
	Planning	A R	I	R	I	I		I C
	Earn Value Analysis				A R			I C
	Project Quality Management	A R						I C
	Communication Management			A R				I C
	Risks Management			A R	R			I C
Marketing	Name and logotype	R	R	A R	R	R	I	
	Website			A			I	
	Business cards			R		A R	I	
Research and Implementation	Design of the gripper		I R	R		A R	I C	
	Electronics and sensors	C	A R			I	I C	
	Fruit recognition	A R		R			I C	
	Robot arm	R	R		A R	R	I C	
Documentation	Midterm report	I	I	A	I	I	I	
	Midterm presentation	A					I	

Figure 93 – RACI Matrix
Source: own elaboration

D.6.17 Resources calendar

On the following figure the resources calendar is presented.

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Aug 2017	28	29	30	31	1	2	3
Sep 2017	4	5	6	7	8	9	10
	11	12	13	14	15	16	17
	18	19	20	21	22	23	24
	25	26	27	28	29	30	1
Oct 2017	2	3	4	5	6	7	8
	9	10	11	12	13	14	15
	16	17	18	19	20	21	22
	23	24 Midterm	25	26	27	28	29
	30	31	1	2	3	4	5
Nov 2017	6	7	8	9	10	11	12
	13	14	15	16	17	18	19
	20	21	22	23	24	25	26
	27	28	29	30	1	2	3
Dec 2017	4	5	6	7	8	9	10
	11	12	13	14	15	16	17
	18 Final term	19	20	21	22	23	24
	25	26	27	28	29	30	31

Absences
All
Matthieu
Hidde
Robbert and Matthieu
Robbert

Presentation

Figure 94 – Resources calendar

Source: own elaboration

D.7 Project Communications Management

In this section are included some of the processes required to ensure a good communication between team members and also other project stakeholders.

D.7.18 Communication plan

The following table contains the information about how the team is going to communicate with the stakeholders.

Target audience	Contact	Deliverable information	Deliverable method	Deliverable frequency
Mika Billing (Project supervisor)	Email: mika.billing@vamk.fi Phone: +358 40 591 2854	Project status	Meeting, email or phone	Weekly
Roger Nylund (EPS coordinator)	Email: roger.nylund@novia.fi	Project management tasks status	Email or phone	As needed
Juha Liinamaa (Sales engineer SICK)	Email: juha.liinamaa@sick.fi Phone: +358 (0)9 2515 800	Information about SICK sensor's usage	Email or phone	As needed
Hanna Latva (English teacher)	Email: hanna.latva@novia.fi	Written documentation status	Email	As needed

Table 18 – Communication plan

Source: own elaboration

D.7.19 Stakeholder management plan

The Stakeholder management plan is the process of developing appropriate management strategies to effectively engage stakeholders throughout the project life cycle.

Stakeholder	Power	Interest	Expectations	Actions	Strategy
Mika Billing (Project supervisor)	High	High	Having a successful tomato picker	Manage Closely	Endorse decisions made by the team
Roger Nylund (EPS coordinator)	Medium	Medium	Having a successful EPS project and proving tools to apply project management	Keep Informed	Deliver project following project management procedures
Juha Liinamaa (SICK Company)	Low	Low	Having an innovative application for their sensors	Keep Informed	Deliver project before SICK competition deadline
Hanna Latva (English teacher)	Low	Medium	Providing effective tools to improve our performance in terms of academic writing	Keep Informed	Keep informed about written documents status
Other EPS students	Low	Low	Learning something interesting about the project	Monitor	Presenting project in an engaging way and keeping website updated

Table 19 – Stakeholder management plan

Source: own elaboration

Another way to classify stakeholder by their power over the project and by their interest is presented in the following figure.

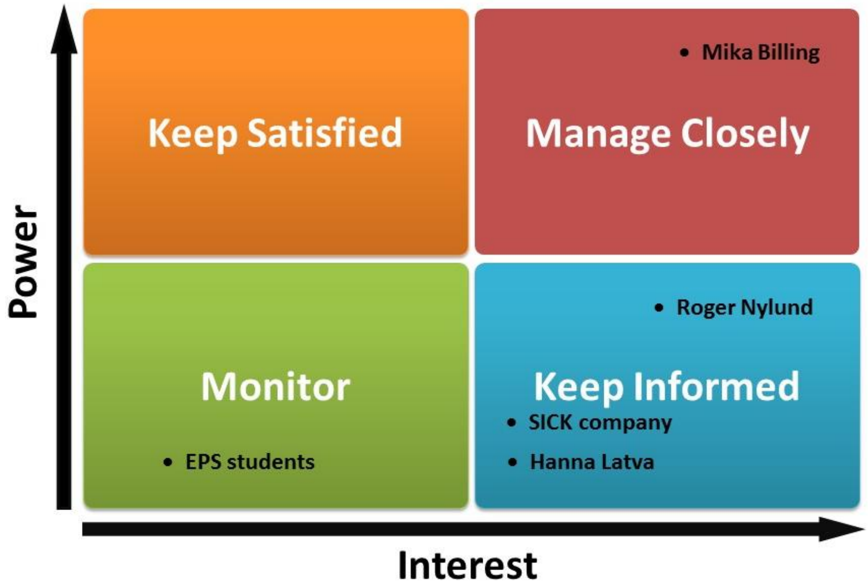


Figure 95 – Power/Interest Grid for Stakeholder Prioritization

Source: own elaboration

D.8 Project Risk Management

There are many risks that can arise over the life cycle of a project. In order to help the project remain on track and meet its goal, in this section risks are identified, their likelihood and the impact they can have on the project are analysed, and finally, actions or preventive measures to minimize them are proposed (Calleam, 2017); (Projectkickstart, 2017).

D.8.20 Definition of possible risks

Scope ▪ Unclear objectives ▪ Not identify all the deliverables
Planning ▪ Bad work distribution ▪ Poor scheduling ▪ Unclear tasks ▪ Lack of time ▪ Team member on a trip
Unplanned events ▪ Sickness or injuries ▪ Loss of information and/or damaged files
Project issues ▪ Denied access to certain resources ▪ Lack of support and guidance from the supervisor ▪ Lack of leadership ▪ Lack of motivation or laziness ▪ Lack of knowledge
Communication issues ▪ Lack of coordination ▪ Communications problems ▪ Language barriers ▪ Conflicts between team members

Figure 96 – Risk Register
Source: own elaboration

D.8.21 Risk assessment matrix

With the purpose of obtaining a quick view of the probable risks evaluated in terms of the likelihood or probability of the risk and the severity of the consequences we have employed a risk assessment matrix.

		IMPACT			
		ACCEPTABLE LITTLE TO NO EFFECT ON THE PROJECT	**TOLERABLE** EFFECTS ARE FELT, BUT NOT CRITICAL	**UNDESIREABLE** SERIOUS IMPACT TO THE COURSE OF THE PROJECT	**INTOLERABLE** COULD RESULT IN DISASTER
LIKELIHOOD	**PROBABLE** RISK WILL OCCUR	Team member on a trip	Communications problems Language barriers	-	-
	POSSIBLE RISK WILL LIKELY OCCUR	Sickness or injuries	Lack of knowledge Unclear tasks	Bad work distribution Lack of coordination Poor scheduling Lack of motivation Lack of leadership Lack of time	Unclear objectives Loss of information
	IMPROBABLE RISK IS UNLIKELY TO OCCUR	-	-	Not identify all the deliverables	Conflicts between team members Lack of support and guidance from the supervisor

RISK LEVEL	**LOW**	**MEDIUM**	**HIGH**	**EXTREME**
	0 - ACCEPTABLE OK TO PROCEED	1 - AS LOW AS REASONABLY PRACTICABLE TAKE MITIGATION EFFORTS	2 - GENERALLY UNACCEPTABLE SEEK SUPPORT	3 - INTOLERABLE IMMEDIATE MESURES HAVE TO BE TAKEN HOLD

Figure 97 – Risk Assessment Matrix
Source: own elaboration

D.8.22 Definitions of actions and/or preventive measures

Based on the evaluation of the risks with the combination of likelihood and the impact on the project, we have studied the causes, effects and solutions for the ones which have a high or extreme risk level.

Risk	Unclear objectives	**Risk level**	Extreme
Causes	Misunderstanding of the subject between the members of the group, lack of information about the project.		
Solutions	Write down all the objectives at the beginning of the project, discuss them with all the stakeholder and reach an agreement. Establish clear deadlines and roles.		

Risk	Loss of information and/or damaged files	**Risk level**	Extreme
Causes	Undefined way of working may lead to documentation loss. Human errors.		
Solutions	Establish a methodology of working at the beginning of the project and make copies of the work done.		

Risk	Conflicts between team members	**Risk level**	High
Causes	Different points of views or unequal amount of work.		
Solutions	Create strong compromises on some choices and engage discussion inside the team.		

Risk	Lack of support and guidance from the supervisor	**Risk level**	High
Causes	Supervisor not engaged with the project or too busy.		
Solutions	Setting meetings with the supervisor in his free hours. Ask for another supervisor if it’s impossible to meet with him.		

Risk	Bad working distribution	Risk level	High
Causes	Lack of knowledge, team cohesion and communication. Bad responsibility matrix and WBS.		
Solutions	Knowing the background of each member and communicate with each other in case of mistakes. Being attached to the project and willing to learn and apply different subjects. Ask for a review of the WBS to the supervisor.		

Risk	Lack of coordination	Risk level	High
Causes	Bad planning and communication between members. Goals not defined or unclear.		
Solutions	Make a good planning which every team member understands and knows how to proceed with it. Asking before proceeding.		

Risk	Poor scheduling	Risk level	High
Causes	Inaccurate understanding of the project and its scope, goals and objectives not clear.		
Solutions	Write down all the deliverables of the project. Create a detailed WBS and Gantt chart.		

Risk	Lack of motivation	Risk level	High
Causes	Cultural shock, depression, bad field of work, uncomfortable within the group, lack of short term goals, too much big tasks, not enough meetings. Unappropriated team rules, bad work conditions.		
Solutions	Breaking down the big tasks into smaller pieces, learning and trying to share/dialog with others, giving specific work in a coherent field of background, and giving responsibilities.		

Risk	Lack of leadership	Risk level	High
Causes	Project leader that does not see the opportunity and does not listening to the team members.		
Solutions	To get the diverse background, education and experiences of project team members performing at maximal effectiveness.		

Risk	Lack of time	Risk level	High
Causes	Can happen due to many factors added together		
Solutions	Create a good scheduling of our project and anticipate the possible problems in the future as much as we can.		

Risk	Communications problems	Risk level	High
Causes	Team members have uncommon set of expectations in terms of what is to be delivered and when, are not kept informed about what is going on or do not know what the state of the project is.		
Solutions	Set expectations in a Project Charter document. Write down all the deliverables of the project. Create a status report, put in all the information necessary to understand the true status of the project, including accomplishments, issues, risks, scope changes, etc.		

Risk	Language barriers	Risk level	High
Causes	Bad communication skills from team members.		
Solutions	Ensure that the communication is delivered in a simple language to avoid the misunderstanding.		

Risk	Lack of knowledge	Risk level	Medium
Causes	Lack of information and experience on the subject.		
Solutions	Search for information and try to learn from it. Ask for help to the supervisor or other team members.		

Risk	Unclear tasks	Risk level	Medium
Causes	Big tasks, undefined goals, misunderstanding of the task.		
Solutions	Understand the tasks clearly and ask members for clarification.		

Risk	Denied access to certain resources	Risk level	Medium
Causes	Not given permissions or licenses from the supervisor.		
Solutions	Ask for permissions or licenses to the supervisor.		

E. Fruit recognition

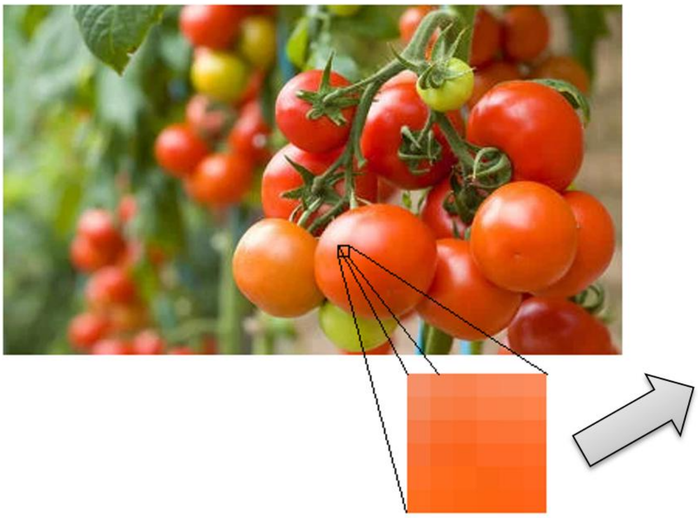
In this paragraph the vision recognition is illustrated, starting with an overview picture. Then, step by step each handling is described shortly. But before that, a short introduction about digital information.

E.1 Digital information

For this explanation it is important to understand how pictures are constructed.

E.1.23 Pixels

Depending on the resolution a picture consists of a matrix of pixels, each pixel representing a number. For example, with a resolution of 800x600 is 600 rows of 800 numbers after each other. When the image is in grayscale, the value of the number is between 0 (black) and 255 (white). For a red green blue also RGB-picture the pixel is a socket of three values: [30,170,0] such as the red-value is 30, green-value is 170 and the blue-value is 0. The pixel appears in the colour which combination of numbers symbolizes.



[247,144,105]	[240,128,75]	[245,138,75]	[247,164,95]
[247,125,68	[224,102,58]	[219,125,68]	[227,155,32]
[255,107,30	[240,112,25]	[255,107,30]	[235,87,24]
[250,108,20	[249,98,15]	[253,109,35]	[240,108,20]

Figure 98 – Image with a portion greatly enlarged where pixels can be seen

(Source: own elaboration)

E.1.24 Byte

The computer communicates with 0's and 1's, also open or closed in electrical circuits. They are called bits. A group of 8 bits are often called a byte, this creates a number between 0 to 255. For instance, the computer sees the byte of 10110011 as $2^7+2^5+2^4+2^1+2^0 = 179$, when there are only ones than makes it 255 and with only zeros it is 0. This way digital information is stored and can be read by the processor. Depending on the decoding device the computer translates the number to a colour or a letter in a writing program.

E.2 Python program structure

In the next figure four different steps are shown, which will be used during the explanation of the vision program. For the first program python language is used.

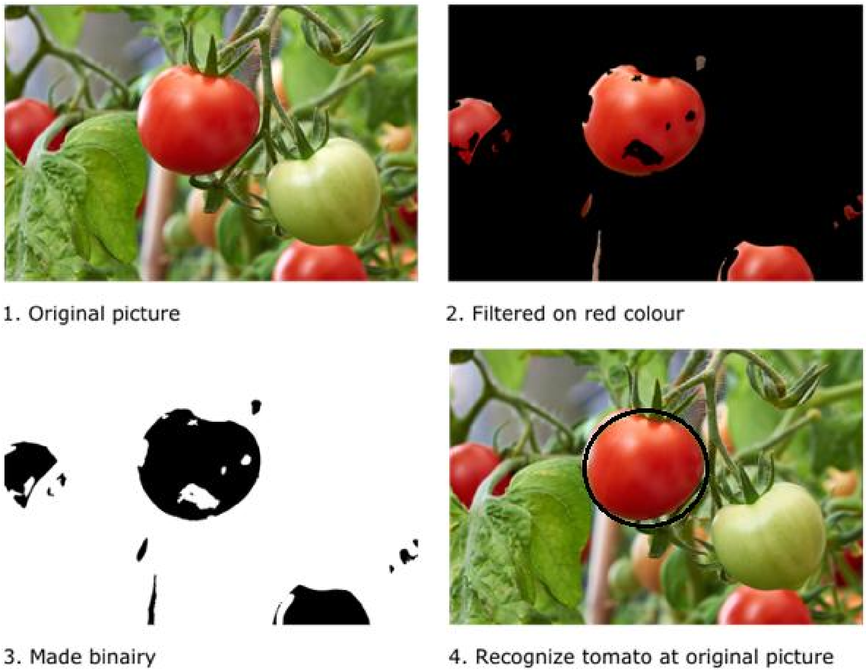


Figure 99 – Different picture about the tomato recognition
(Source: own elaboration)

E.2.25 Image operations

At number one the original picture is shown, while uploaded into the program the image is resized to a standard size from 800x600 pixels. Following up are different image operations.

Starting with blurring, blurring makes an image vaguer and leaves out many details. With less sharp differences between the pixels, colours and shapes can be detected more smoothly, because the amount of noise is reduced.

Following up is the saturation. Tomatoes often have a glance on them what is observed as a white colour by the camera. The picture is turned into grayscale and all the pixels above 230 (so bright white) is selected and filled with a value of the surrounding pixel.

Masking

Setting up the mask is the most important part of the program, which pixels is the camera detecting and which not. Masking is creating a copy from the picture but only with ones and zeros on the different pixel locations. Different conditions determine different masks, which is clarified later on.

First the image is changed to Hue-Saturation-Value (HSV) colour model.

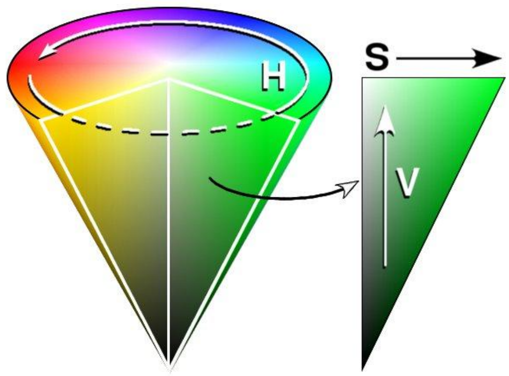


Figure 100 – HSV-colour model
(source: https://nl.wikipedia.org/wiki/HSV_(kleurruimte))

Once the boundaries are set, in this program the bottom boundary is [0,50,100] and the upper boundary is [9,255,255]. Therefore, the red colour has a Hue-rate between 0 and 9. If the Hue-rate is between 10 and 255, so off the limits as set before, the program makes that position a zero and the same goes for the saturation- and value-rate. The program checks each pixel for these conditions and that way ends up with a picture of the same size only with ones and zeroes.

Masking will combine both pictures into a new image, during which the pixel associated with a zero will be deleted and leaving it unharmed when reading a one. Resulting in the second picture in figure 1.

Binary

The red colour which is detected in the image is still hard to process for most regular functions. Therefore, it is converted to binary, this is done by converting the picture to grayscale. A black pixel stays 0 and all the other pixels are converted to 1. To prepare the picture for the next phase, the picture is inverted, so a 0 becomes a 1 and vice versa. Now the third picture of figure 1 is reached.

Erosion is the next image operation applied to this picture. When a 1 is bordered by a 0 it is turned into a 0. That way the areas of one's will become smaller but also little islands of ones disappears.

Blob detection

Blob detection is a function that can do different things with a binary picture. It can detect areas of one's on shape or number of pixels. In this case the minimal number of pixels is set, cause the round shape of the tomato is not a certainty. Leaves or branches can stand between the tomato and the camera.

With Blob detection the centre of the tomato is determined as a coordinate in x- and y-direction. Comparing the middle position of the camera with the location of the tomato delivers a path. In the final picture a green circle is added to prove the principle.

E.3 MATLAB program structure

The basic structure of this program is similar to the python program described above. Therefore, the two major differences between the two programs are illustrated and finally the contrast between the two visuals are analysed.

The inequality

As the python program works with the HSV colour-model, this program functions with the RGB colour-model. Accordingly, the boundaries are adjusted when the masking happens. The different colour-model gives some interesting contrast in the processed images.

The second major difference is the shape recognition. The blob detection searches for circles on the binary image. In the next picture the result of the MATLAB-program is shown.

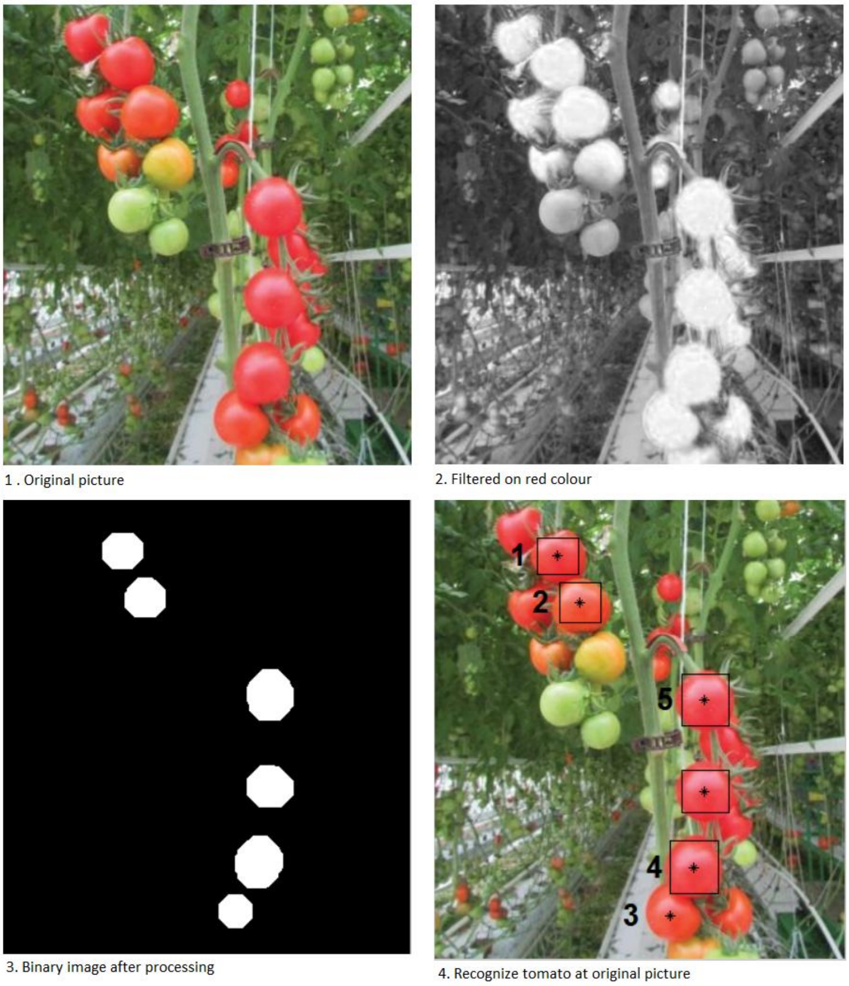


Figure 101 – Tomato recognition with MATLAB

(Source: own elaboration)

Contrast

The colour-model delivers different visual results. Where HSV struggles with the light red tones, the RGB struggles with the darker red tones. For instance, the centre of the second tomato detected with the MATLAB code is moved upwards because the darker red tones at the bottom side of the tomato. The similar happens in Python code but then vice versa.

The development of these programs did not take much effort and is enough for a proof of principle. Depending the environment and the necessary input, the choice is made which program will be implemented.

F. Code of Conduct

During the project a few work-related rules were made. These rules are made so that everything is clear for everyone.

Meetings

- Meetings will take place twice a week, on Mondays and Thursdays.
- The aim of these meetings is to overlook the status of the project, setting new weekly goals, adjust the schedule and discuss the problems within the team.
- Meetings will be, preferably, in Tritonia's meeting rooms and booked by Jordi.
- If someone can't attend a meeting has to give reasonable explanations.
- Absences at meetings must be notified in advance.
- Agenda will be uploaded onto Google Drive the day before a meeting so that every team member can keep up with the order of business. Meeting minutes will be written by the secretary and will be uploaded onto Google Drive one day after the meeting as a maximum.
- Agenda and minutes have also to be uploaded to Dropbox so that the EPS coordinator, Rogger Nylung, will be able to read them.

Working methodology

- Documentation is done in Google Drive and so is file-sharing.
- Project working will be done in the EPS room, the 3D printing room or the LIDAR room.
- All work will be checked by other team members. The creator should notify the others when he is finished and it is ready for checking.

Disagreements

- If someone feels uneasy with some situation or behaviour, the disagreement has to be expressed.

Making decisions

- All team members have to agree before a decision is made. A unanimous decision is required to proceed.
- Team leader is responsible for making sure that everyone's opinion is taken into consideration and that everyone is cooperating.

G. I/O ports

G.1 Robot arm I/O ports

In the following table, the input and output ports of the robot arm are listed.

I/O Port Name	Description
Blue light	Turns on the blue light (H1) on the panel.
Red light	Turns on the green light (H2) on the panel.
Green light	Turns on the red light (H3) on the panel.
DOGripServo	Used for open and close the gripper. PIN number 4 in the robot panel.
DO 10_2_toolchange	Enables to change the tool on the robot.

Table 20 – I/O ports robot arm

G.2 Arduino I/O ports

In the following table, the input and output ports of the Arduino are listed.

Pin number	Name	Function
0	Rx	Receiving line for programming the Arduino externally. Not used for current project.
1	Tx	Transmitting line for programming the Arduino externally. Not used for current project.
2	Servo control	This is the pin that sends the PWM signal to the servo.
3	Closing limit switch	This is the switch that limits the gripper from closing.
4	Opening limit switch	This is the switch that prevents the gripper from opening too far.
5	Switch finger 1	This is the switch that is located in finger 1. It is there to recognize tomatoes inside of the gripper.
6	Switch finger 2	This is the switch that is located in finger 2. It is there to recognize tomatoes inside of the gripper.
7	Switch finger 3	This is the switch that is located in finger 3. It is there to recognize tomatoes inside of the gripper.
8	Tx to robot	This is the data line where the Arduino sends pulses from to the robot.
9	Rx from robot	This is the data line where the Arduino receives pulses from the robot.
10	SPI-Slave Select	This is the slave select pin that is used for the SPI protocol. It is required to select the sensor the Arduino needs to read data from.

Table 21 – I/O ports
(Source: own elaboration)

H. Source code

The MATLAB's, RobotStudio's and Arduino's code can be downloaded from the Robopick's website.

https://robopick.wordpress.com/downloads/

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