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Specialised Hook Gripper For Robotic Grasping of Vine Tomato Trusses

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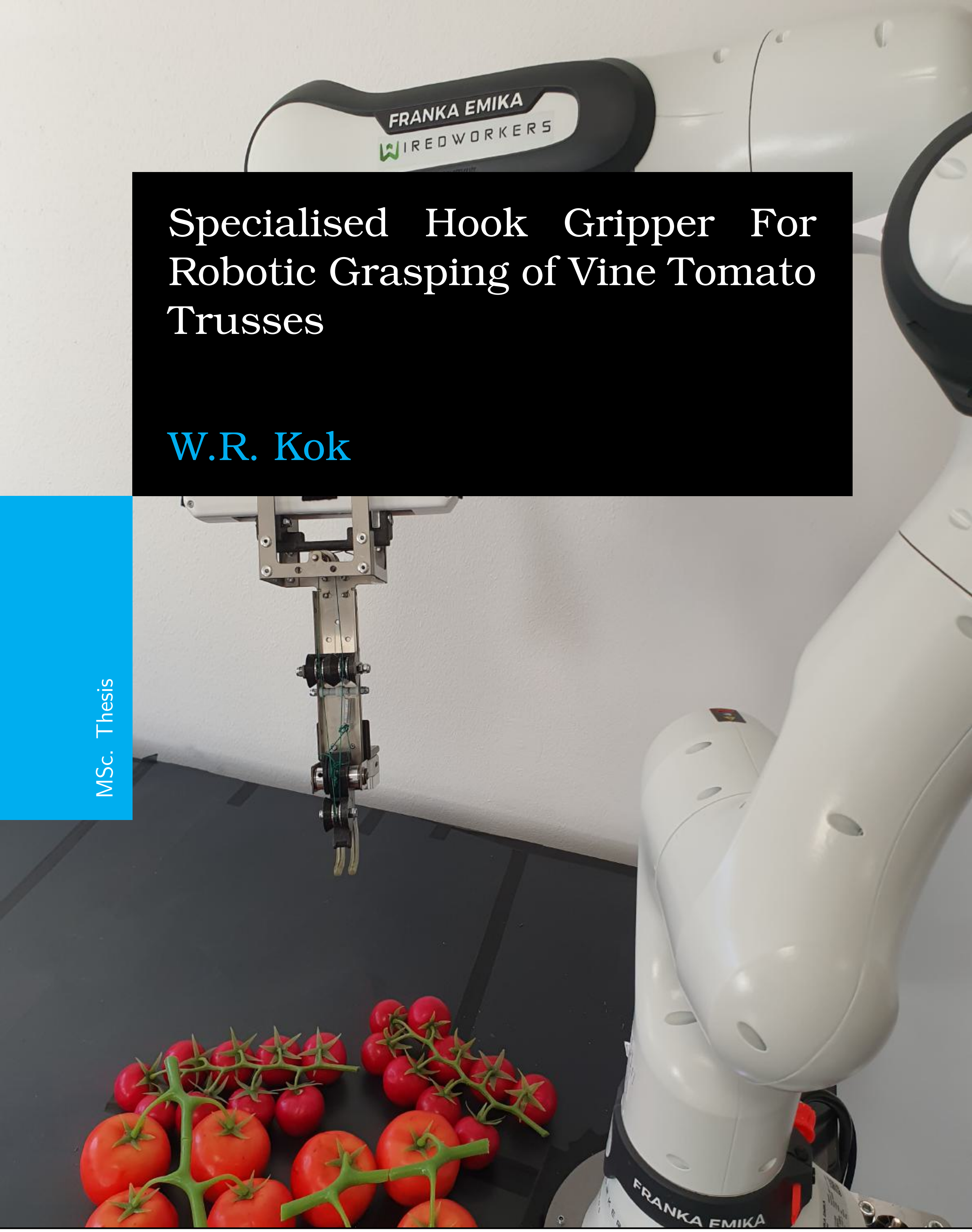

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MSc. Thesis

MSc. Mechanical Engineering and MSc. Robotics

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Master of Sciences, Thesis

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Summary

In this master thesis, I present the development of an innovative gripper designed specifically for grasping the delicate peduncles of vine tomato trusses. This research addresses a critical challenge in agricultural automation: efficiently and safely manipulating high-value crops without causing damage. The thesis begins with a comprehensive review of the current state of agricultural automation, particularly focusing on the post-harvest handling of vine tomatoes, from harvesting to packaging. Building on the limitations, identified in existing robotic grippers and automated systems, I propose a novel gripper design. This design is unique in its approach to grasping the peduncle of vine tomato trusses.

Tomato trusses are difficult to grasp by a mechanical gripper, as the fruits are easily damaged, the peduncle is small and can easily be damaged by mechanical impact or friction.

In former research, the most researched method is picking up the truss using the tomato fruits and enclosing it. Trusses have traditionally been grasped by the peduncle with standard pinching grippers for pick and place operations.

The gripper proposed in this paper grasps the truss with a hook around the peduncle often optimally at the centre of mass, and increases the success rate of grasping, the stability, and avoids damaging the truss. Furthermore, it has a higher tolerance for the detection errors, as it permits for inaccurate positioning of the robotic system. A hook-gripper can successfully grasp a wider range of tomato varieties than a pinch gripper.

The hook, which consists of two fingers empowers for a more stable lifting of the truss, additionally it can handle peduncles in hard to grasp positions as in a crate filled with tomatoes. In addition to increased reach capabilities, the hook-gripper also has the ability for manipulations, such as dragging and pushing.

The study involved an iterative design process, prototyping, and testing of the gripper. Key features of the design include a hook mechanism for secure grasping, enhanced mobility for reaching into cramped spaces like packed crates, and a delicate touch to prevent bruising or damaging the fruit. The research also integrates the gripper with advanced detection systems, ensuring precise and effective operation within automated setups.

Results from extensive testing demonstrate that the newly designed gripper not only improves the success rate of grasping and manipulating vine tomato trusses, but also significantly reduces the risk of damage compared to conventional pinch grippers.

Testing for the different positions showed an increased range of grasping position that resulted in a successful grip. In practical experiments, the gripper performed well, lifting trusses with ease. Other test results show that the position of the peduncle is of great importance for the success rate. Test results indicated an 80In practical experiments, the gripper performed well and was able to lift trusses with ease.

The specialized hook-gripper offers insight into a practical solution for picking and placing the vine tomatoes using the peduncle. This thesis not only contributes to the field of agricultural robotics but also facilitates a step in the stage for future innovations in the automation of high-value crop handling.

This study looks into hook-gripper design and actuation, because this is crucial in achieving optima

l performance in robotic manipulation systems.

Table of Contents

Acknowledgements

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Chapter 1

Introduction

The rising demand for agricultural products at competitive prices increases the demand for automation. The challenge of handling high-value crops is an essential component of the overall solution for the automation of farming. For the production process of packaged vine tomatoes, multiple steps are researched for automation purposes. Generally, the first steps are to grow the crops (in a greenhouse [50]), harvest, transport, and process the harvested product. The vine tomatoes are sorted by weight and food class before being packaged for (retail) resale.

Figure 1-1: Workers, processing tomatoes from a crate to a conveyor belt. Weighing, sorting, inspecting and sometimes cutting the trusses before they are put on the conveyor belt.(33,34,45)

These steps are labour-intensive when done manually. As a result of an ageing working population and long hours of manual labour, farmers in the USA are unable to attract enough workers [6]. This is also true for the ageing manual labour force within the European Union [10]. Creating automation for each step of the process, from the tomato vine to the final product, would significantly impact the need for manual labour. A forecast of the highly automated machinery market development by 2045, shown in Table 1 by Solovyev et al. (2022) indicates high worldwide market needs.

The main body of previous research on handling tomatoes is focused on harvesting. In this study, the focus is on picking the vine tomatoes up from a crate and placing them outside the crate on a conveyor belt. Illustrated in Figure A-1 with the yellow box. Any mentioned picking and placing in this study will refer to this study's aforementioned focus. In this introductory chapter, the following sections will outline the research further. The previous research that focuses on a similar use-case is briefly outlined in section 1-1.After

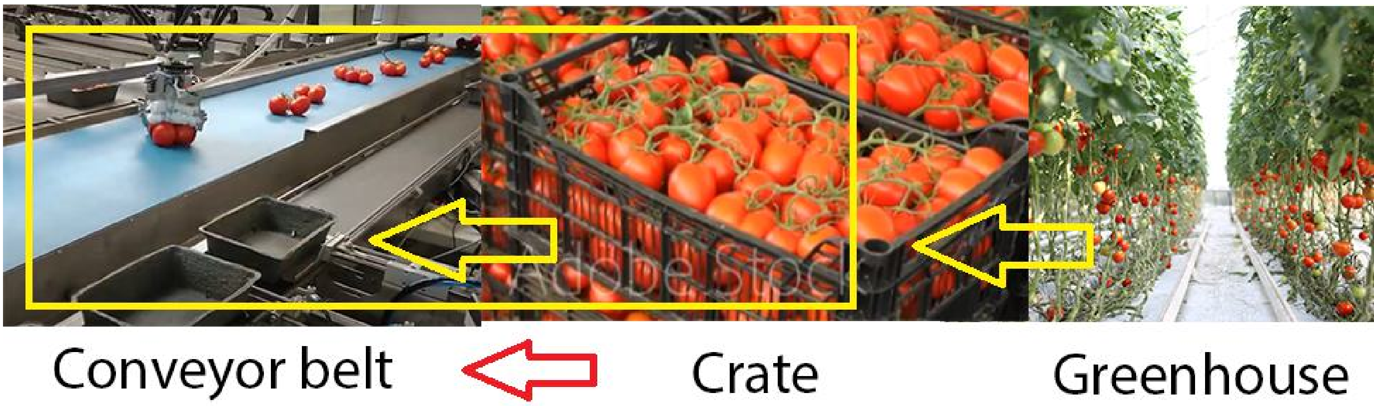


Figure 1-2: Steps in the vine tomato production process [24,1].

which additional background information (1-2) is introduced, the explanation of the industrial setting (1-2-2), the terminology used for the tomato truss (1-2-3) and the different physical values related to the different tomato cultivars (1-2-4).

The thesis explores the development of a hook gripper for vine tomato trusses, and the prototyping towards the tested design. The report is organized as follows: This document is structured into eight distinct chapters, each with a specific focus and purpose. In Chapter 1, we lay the foundation with an introduction to the challenges faced in previous research, the background of agricultural automation, and essential terminology. Chapter 2 delves into related work, examining various gripper mechanisms and innovations in the field. Chapter 3 explores the crucial step of gathering tomato data. Moving forward, Chapter 4 defines the problem and presents design specifications, including the integration of the Franka Emika Robot Arm. Chapter 5 is a critical section, where we discuss the selection of prototypes and their initial development, highlighting key features and testing procedures. In Chapter 6, we present the results of our experiments, while Chapter 7 provides a detailed analysis and discussion of these findings. Finally, Chapter 8 draws conclusions from the research and outlines potential avenues for future work. Together, these chapters aim to provide an overview on creating and testing of the specialized hook gripper for robotic grasping of vine tomato trusses for a pick and place task.

1-1 Challenges from Previous Research

There is still a lot of work to be done to automate the process of moving tomato trusses out of a box so that it can be applied accurately in industry. Previous research by Zuurbier (2022) and de Haan et al. (2021) has laid the groundwork for the execution of the picking and placing of stacked vine tomatoes, for which the success rate needs to be improved. The previous work was able to detect stacked tomato trusses in most of the experimental cases, using a Deep Neural Networks (DNN) called RetinaNet Lin et al. (2017) to predict bounding boxes for the trusses. A geometry-based gripping method [7] was then used to detect the gripping point. The vision pipeline was complete and working, but the success rate can still be improved for the case where tomatoes are fully stacked in a box. van den Bent et al. (2023) proposed a three-stage vision method which involves utilizing an object detection model to identify unobstructed trusses, extending the YOLOv7 and YOLO-Pose algorithms (52, 32) to identify candidate grasping poses, and employing an autoencoder network with a k-Nearest Neighbor (KNN) classifier to select the most promising grasp pose.

Different cultivars, challenging peduncle shapes, and obstructed trusses complicated the execution of a successful grasp, especially when the grasp position is not accurate due to the “result of inadequate predictions from the grasp pose identification network”van den Bent et al. (2023). Additionally, the requirement for tomatoes to be perfectly upright presents a restriction. These issues might be addressed by employing a specialized gripper. The following challenges arise based on previous research, which this gripper aims to improve upon.

1. Avoiding a collision with the crate during manipulation of the truss using a combination of mechanical and vision components.
    (a) The motion of the gripper to the pre-grasp position must be adjusted to reach places near the crate walls.
    (b) A different gripper can help adjust for the limited space near the edges of the crate.
2. Improving the success rate for the pick-and-place tasks for vine tomatoes from a filled crate. Considering the following challenges:
    (a) Improve the gripper design.
        i. A robust grasp on the peduncle.
        ii. The truss does not tilt during manipulation.
        iii. The truss does not get dropped during the lift.
        iv. A closer grasping distance to an optimal grasping point.
        v. Being able to deal with inaccurate grasping positions.
        vi. Less grasping attempts for a successful grasp, which means a wider range of acceptable grasping points.
    (b) Not damaging the tomatoes or the peduncle.
    (c) Able to handle increased manipulation speed.
    (d) Partially obstructed trusses, which can also be obstructed by the crate itself.
    (e) Handling trusses that are not orientated perfectly upward.


(a) Tomatoes in a crate [47].


(b) Robot arm in the lab.


(c) Grab the truss by the peduncle.

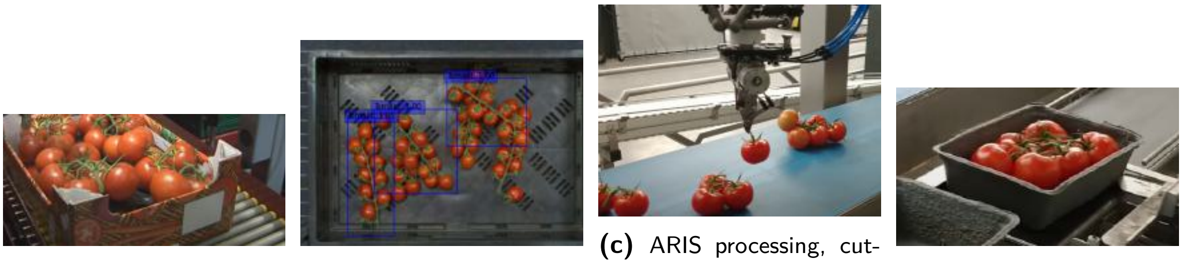

(d) Default gripper.

(a) The FARO harvest robot in a greenhouse.

(b) Harvester by Denso in action.

(c) Harvest robot with fingers [20].

Figure 1-4: Harvest robots selection.



(a) Crate with layers in-between.

(b) Black crate for processing.

(c) ARIS processing, cutting the trusses for recombination.

(d) Trayes after conveyor belt.

Figure 1-5: ARIS packaging line together with possible crates and the final product.

1-2 Background

1-2-1 Agricultural Automation for Harvesting Vine Tomatoes

This thesis will focus on handling vine tomatoes from a crate (subsection 1-2-2). Before we have a crate with tomatoes, harvesting must be completed. Some of the current methods for harvesting are discussed below. These harvesting methods show that harvesting trusses into crates, not individual tomatoes, is not only time effective but will be the most likely outcome for the robotic harvesting of vine tomatoes. Given the current development in automation, it will increase harvesting efficiency. The harvesting process could give some indication of how to improve the process of automating vine tomato production downstream, and techniques that can also be utilized in the pick-and-place step used for handling vine tomatoes from a crate. Additionally, it illustrates that the researched gap is the step in the automated process to get the tomatoes from a crate after harvest to the conveyor belt, with a possible inspection step in between (e.g. as shown by Gastélum et al. (2011)).

There are multiple harvest robots mentioned in the literature, of which some are in active development. The system by Denso [9, 8] called FARO (Figure 1-4a), is reported to be tested on a large scale in Certhon facilities. The collaboration for automated harvesting is well underway between Denso and Certhon [46, 51]. This system, which works on cherry tomatoes used to be "highly costly on labour and time" [11]. Some cherry tomato harvesters approach it by plucking a single cherry tomato [56], making the process very time-consuming still. The harvesting of trusses is an important aspect that speeds up the system as a whole and the processing steps after it. The harvesting robot by Yaguchi et al. (2016) harvests single tomatoes with a rotational gripper. A pneumatic finger design [20] grabs a single cherry tomato at a time and twists it off the truss (Figure 1-6).

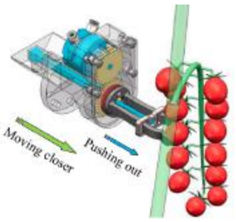


Figure 1-6: Cherry tomato harvester by Gao et al. (2022b).

After the harvesting step in the process, there is a system to fill crates. One such system is made by Zu et al. (2022), a post-harvest processor [60] to put tomatoes in crates. It can also be done directly by the robot arm itself, which is the approach the machines by Denso [9] seem to take. In the absence of robots, workers manually stack trusses of tomatoes into crates. Companies such as Aris B.V. [2], and their partners, created systems to process the tomatoes as vines on a conveyor belt to be recombined in trays of a specific weight for reselling. The researched gap is the step in the automated process to get the tomatoes from a crate after harvest to the conveyor belt, with a possible inspection step in between (e.g. shown by Gastélum et al. (2011)).

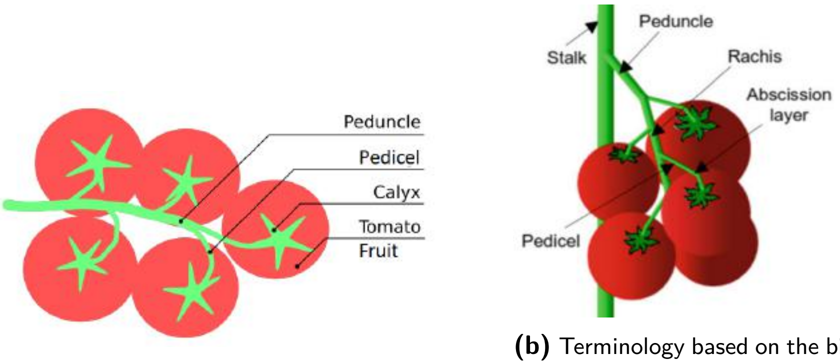
1-2-2 Industrial Setting

The tomatoes are harvested and stacked in a crate, with an optional sheet of paper between each layer of tomatoes. The tomatoes from the crate need to be transferred to a conveyor belt located next to the crate. A separate process redistributes the tomatoes for retail into baskets of 1kg via this conveyor belt.

The lighting in the processing area is held constant and consistent. The tomatoes might have some dust on them which can transfer onto the machines. The tomatoes are grown on fibreglass, which is a reasonably clean working space. The machines might get dirty from handling the vine tomatoes, which is assumed to be mostly the juices from small damages to tomatoes, of which there should not be a high amount. The trusses are rid of leafs and consist of only ripe (not partially green) tomatoes, which are only allowed to have minor damages. When handling tomatoes, plant materials and tomato juices will get on the equipment (or traditionally the worker's hands/gloves). The plant material consists mostly of the small 'tomato hairs' called trichomes [31,15] and the outer layer of the peduncle. These trichomes also excrete "essential oils" [36] which create what farmers sometimes call "tomato tar" [57] as it is quite sticky and hard to clean with soap.

1-2-3 Terminology of a Single Tomato Truss

The end of the peduncle is cut from the stalk of the tomato plant. The part that we are looking to grip is from a biology naming standpoint, called the rachis (1-7b). A large research base looks into cutting and detecting the peduncle, which is very similar in structure and size to that of the rachis. The main difference between a peduncle and a rachis is the thickness, the rachis itself has a changing cross-section similar to how tomatoes further down the truss are smaller, which is related to nutrient delivery and throughput. As many papers refer to it as peduncle or stem instead of rachis and given that the difference in structure is minimal, the term “peduncle” will be leading. Throughout the literature review, the terminology shown in Figure 1-7a will be used to refer to the tomato’s vine and individual parts.



(a) Illustration of a single truss tomato, edited image of de Haan et al. (2021).

(b) Terminology based on the biological naming convention [35], image from the book by Liu et al. (2021a) ("Fig. 3.43 Cluster structure of tomato").

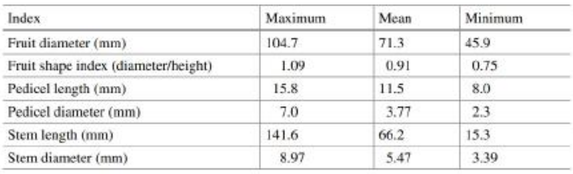
Figure 1-7: Terminology of a single tomato truss. This cluster of tomatoes consists of the stem and the tomatoes. The stem has a peduncle (leading to a rachis) with multiple pedicels that attach with a calyx to the tomato.

1-2-4 Types of Tomatoes

Many sorts of tomatoes exist [54, 53]; these cultivars have different properties, e.g. space between the peduncle and the tomato. The most common varieties sold in supermarkets are medium- to small-sized vine tomatoes. A supermarket tomato is considered a high-value crop with a high-ranking food class label. The higher the class, the nicer the crop looks, considering shape, colour and cosmetic damage. It is quite a challenge to automatically process the tomatoes without damaging the fruit to be able to get the high food class label assigned to it. This is an important distinction, as there are also "canned tomatoes" with a lower food class label. Often, these tomatoes are harvested from cultivars other than vine tomatoes, so it is possible to harvest them using the machine shown in Figure 1-8, since processing will not be affected if the fruits are damaged.

The different types share common characteristics, which would allow for the generalizability of applied methods. Within a particular cultivar, some physical properties are shown in figures 1-9a and 1-9b. The geometric differences will mainly be a factor to be considered for the

Figure 1-8: Harvesting done for bush tomatoes [14].



Index	Maximum	Mean	Minimum
Fruit diameter (mm)	104.7	71.3	45.9
Fruit shape index (diameter/height)	1.09	0.91	0.75
Pedicel length (mm)	15.8	11.5	8.0
Pedicel diameter (mm)	7.0	3.77	2.3
Stem length (mm)	141.6	66.2	15.3
Stem diameter (mm)	8.97	5.47	3.39

(a) The sizes and weights were measured of 50 tomatoes from different farms and cultivars after the "Breakers" stage.[29]

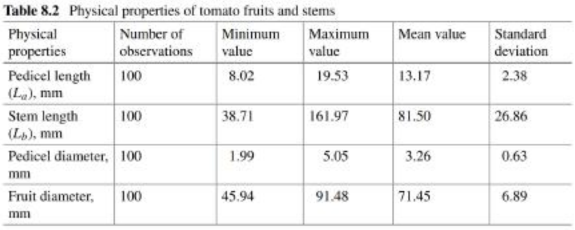
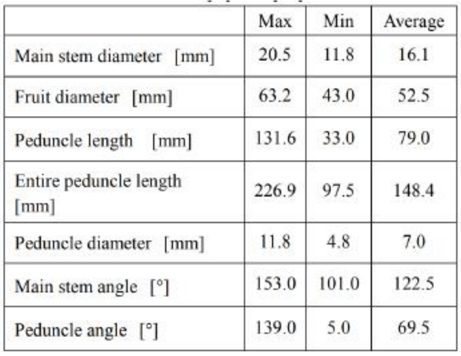


Table 8.2 Physical properties of tomato fruits and stems

Physical properties	Number of observations	Minimum value	Maximum value	Mean value	Standard deviation
Pedicel length (L_a), mm	100	8.02	19.53	13.17	2.38
Stem length (L_b), mm	100	38.71	161.97	81.50	26.86
Pedicel diameter, mm	100	1.99	5.05	3.26	0.63
Fruit diameter, mm	100	45.94	91.48	71.45	6.89

(b) Observations made from 100 samples of "Jinpeng 5" tomatoes, measured with a micrometre calliper with a sensitivity of 0.01 mm.[29]



	Max	Min	Average
Main stem diameter [mm]	20.5	11.8	16.1
Fruit diameter [mm]	63.2	43.0	52.5
Peduncle length [mm]	131.6	33.0	79.0
Entire peduncle length [mm]	226.9	97.5	148.4
Peduncle diameter [mm]	11.8	4.8	7.0
Main stem angle [°]	153.0	101.0	122.5
Peduncle angle [°]	139.0	5.0	69.5

(c) Physical properties of unknown cultivar, peduncle measured for 20 tomato clusters. [27]

Own empirical data	mean [mm]	min	max
Fruit diameter	79.6	65	82
Height	53		
Circumference	250		
Peduncle length	115		
Index (diameter/height)	1.5		
Pedicle length	35	25	40
Pedicle distance to Peduncle	25		
Peduncle Diameter	6	4	8
Pedicle diameter	4		
Space around	10	4	18

(d) Measurement of a single dutch store-bought tomato truss.

Figure 1-9: Physical properties of vine tomatoes.

component detection and gripper design. The general ability for these methods will be on the smallest possible re-design of the gripper or training of the learning method.

From the tables in Figure 1-9 can be seen that the physical properties differ between cultivars, although the clusters of tomatoes are very similar in appearance. The section about laser cutting peduncles (based on the tomato subset shown in 1-9b) by Liu et al. (2021b) shows in the paper's figures 8.20 and 8.18 that the minimum peduncle size measured was about 2.4 mm, with a median of 3.7 mm and a maximum value of 5.2 mm. This minimum value could be an outlier, most clusters are between 3.0 and 4.5 millimetre. The minimum peduncle diameter listed in Figure 1-9c is 4.8 mm, with an average of 7.0 mm. The authors for the section of Table 1-9a do sometimes use the word stem for sections of the plant of which the peduncle is a part, making stem diameter almost the same as the diameter of the peduncle. It seems safe to assume the minimum peduncle diameter to be 3 mm until measurements have been done for the specific cultivar used in a setup. Based on the range of values listed before, and the values listed in Figure 1-9 and Table 1-1. Given the smaller fruit diameter described in Kondo et al. (2010) the peduncle should be at the lower end of the distribution (for the peduncle diameters found). As a peduncle is throughput for the nutrition of the plant's fruit and directly relates to fruit growth and therefore also size.

	Min	Mean/Median	Max	Citation
Peduncle Diameter [mm]	3.39	5.47	8.97	[29] Table 3.2
	2.4	3.7	5.2	[29] Figures 8.20 and 8.18
	4.8	7.0	11.8	[27]
	4	6	8	Dutch supermarket
Pedicle length [mm]	8.0	11.5	15.8	[29] Table 3.2
	8.02	13.17	19.53	[29] Table 8.2
	25	35	40	Dutch supermarket

Table 1-1: Important physical tomato cluster values for design tabulated.

1-3 Summary

In conclusion, this thesis addresses the escalating demand for competitively priced agricultural products, underscoring the critical need for increased automation in farming. It delves deeply into the various stages of vine tomato production, from cultivation to packaging, a journey integral to the agricultural industry's future. This exploration is particularly aimed at addressing the labour shortages and enhancing overall efficiency in these processes. Previous research shows the lack of a specialized gripper for vine tomato trusses specifically engineered to optimize the pick-and-place operations from crate to conveyor belt in automated tomato handling.

Several challenges are identified in previous research and form the base for this thesis builds upon the foundation laid by earlier studies. The thesis is comprehensively structured into eight distinct chapters, leading to development of a specialized gripper, that has the potential to revolutionize tomato handling in a specialized part of the process.

Chapter 2

Related work

In this chapter, we examine two primary gripping methods used in agricultural robotics: force-closed and form-closed grips, with a focus on handling tomato trusses. The force-closed grip, particularly the pinch grip, is explored for its reliance on friction and its impact on the delicate peduncle of tomatoes (section 2-1). We also discuss form-closed grips, which secure objects by their shape, offering more consistency but posing challenges in terms of space and potential damage to the produce (subsection 2-1-1).

The chapter further reviews commercial grippers, contrasting traditional rigid designs with innovative soft robotics and flexible solutions, assessing their effectiveness in delicate agricultural tasks (Sections 2-1-2, 2-1-3). Special attention is given to the Finray gripper, known for its adaptability and potential in handling fragile agricultural items (subsection 2-1-4).

Finally, we conclude by identifying the limitations of current technologies and the necessity for specialized grippers that can handle delicate produce like tomato trusses efficiently and without causing damage (section 2-2).

Force-closed Gripping

A force-closed grip involves applying force to hold an object in place and is dependent on friction to maintain stability, but can be impacted by environmental and object factors. During a pinch grip, the two fingers will grasp the object by applying force from the sides and utilising friction to counteract gravity (Figure 2-2).

The peduncle is flexible and cannot handle excessive stress for increased friction. The damage to the peduncle should be kept at a minimum because further handling would benefit from a non-damaged peduncle.

The benefits of the pinch grip would be the following. A pinch grip, which involves holding an object between two fingers or parallel jaws, presents several advantages in robotic grasping. This type of grip provides the ability to manipulate objects with greater precision, as the fingers can control the object with a high degree of accuracy. Furthermore, a pinch grip is versatile and can be utilized to handle a wide variety of objects, as long as they have a sufficient surface for the fingers to grip onto. The fingers are also capable of adapting to the shape of the object, making it easier to grasp irregularly shaped items. Additionally, using a pinch grip minimizes the surface area in contact with the object, reducing the chance of causing damage to delicate or sensitive items. Finally, the pinch grip enables greater dexterity, allowing for a wider range of motion and finer control, making it easier to manipulate objects in tight spaces or challenging environments.

Form-closed Gripping

A form-closed grip holds an object in place through its shape, the stability is ensured through the object's shape rather than friction, making it more consistent and predictable. Enclosing the object by the end-effector is caging; depending on the gripper and its flexibility, this can enclose the shape completely or adapt (using joints in) the gripper and create a partial form-closed grip (as "shape adaptive grippers" do). The cage binds the object, and a force can still be applied to clamp the peduncle to avoid sideways movement and improved stability during transportation. The play between the object and the cage determines how much the truss can move while constrained. When the fingers of the gripper are partially closed around the object, there is still an opening left, but the object is not allowed to slip, making it a kind of cage grip, often referred to as wrapping.

The downside of a caging grip is the limited space around the peduncle. This increases the risk of damaging the tomatoes.

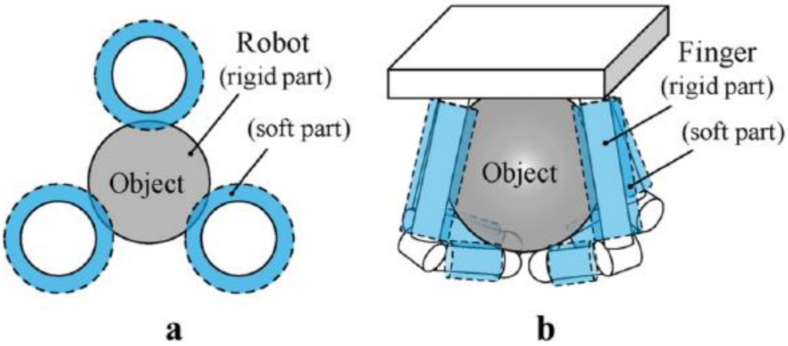


Figure 2-1: Illustration for a caging grip, using a gripper with fingers that have a soft outer part. [26]

2-1 Commercial Grippers

The overview of commercial grippers, as discussed in subsection 1-2-2, highlights the prevalence of rigid grippers. While there is a broader range of products available for handling individual tomatoes, many of these are still under development and have not yet reached a stage of widespread adoption.

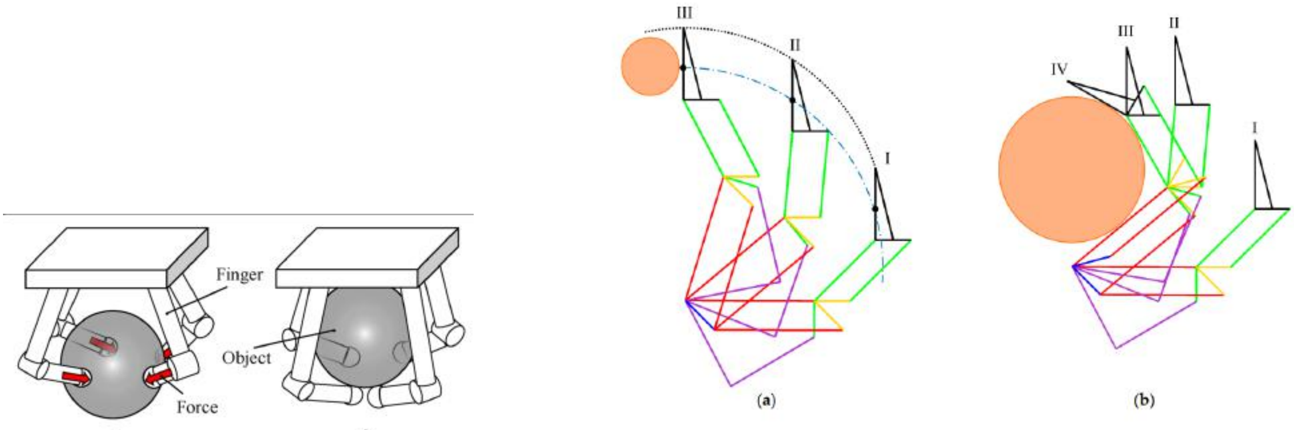


Illustration of grasping using pinch grip (a) or caging (b). [26]

Schematic of an underactuated finger that performs a parallel pinch grip (a) and a shape-adaptive caging grip (b) [25].

Figure 2-2: Caging and pinch grip visualized.

2-1-1 Current Grasping methods

Grasping the Complete Truss
Attempts to grasp the entire tomato truss have resulted in damage to the tomatoes. This underscores the challenges in handling delicate agricultural produce and the need for more refined and specialized gripping mechanisms.

Grasping Individual Tomatoes
The grasping of individual tomatoes requires a different harvesting process. For which different grippers are developed Friederich (2022).

Grasping the Peduncle
Methods for gripping the peduncle have been limited by the gripper, which limits the grasping positions and require multiple attempts, impacting the overall success rate of grasping vine tomatoes (van den Bent et al. (2023), Zuurbier (2022),de Haan et al. (2021)).

2-1-2 Rigid Grippers

Commercial grippers are sold as gripping modules with customisable fingers and tips. The drive stage that moves the fingers is the critical factor for speed and accuracy. Although the fingers are not considered the most important component, customised tips are required for a better gripping performance and delicate handling. Grasping a peduncle is challenging due to the limited space, and the parallel gripper may not be the optimal solution. Longer fingers appear advantageous for this application to provide sufficient reach into the corners of the box. Further research is needed to evaluate the performance of these grippers for the use-case. The specifications of the commercial grippers are often higher than necessary, which may unnecessarily increase the cost of the components. A specialised gripper could be a more cost-effective solution for pick and place systems. A selection of commercial grippers that are parallel grippers with longer end effectors are presented in Figure 2-3.

(a) Schunk PGN-Plus [40,41]. **(b)** Zimmer GP400 [59]. **(c)** 2F-140/2F-85

Figure 2-3: Commercial grippers, which can be outfitted with longer end-effectors.

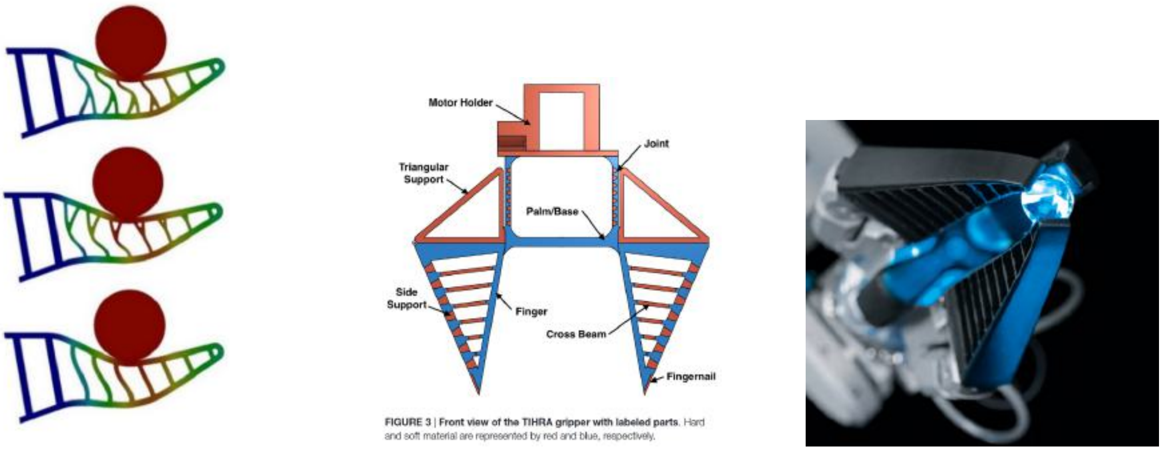
2-1-3 Soft Grippers

The commercial market for pneumatically driven soft robotics and flexible fingers is not large. The company Soft Robotics Inc. seems to be the current market leader with the best specification for this type of gripper. They have a variation of grippers, with the only difference being the length and number of fingers attached, in combination with an 'AI' system behind it. Below is the "Mgripper" shown (Figure 2-4) in the two-finger parallel configuration. Besides the hefty cost, the gripper in its smallest configuration is still quite large. The smallest width is 20 mm in its resting position, and the ribs can collide due to the limited working space around the peduncle.

Figure 2-4: Mgripper by Soft Robotics inc. [48,42].

2-1-4 Finray

Through the Fin Ray effect, Finray grippers are flexible and adjust based on the point of contact. The Finray patent [3] shows the initial design, a current Finray gripper design is called TIHRA (2-5b) by Crooks et al. (2016) which is used in an application for production [38]. The Finray finger is analysed with structural optimisation by Suder et al. (2021) to gain insight into different patterns of the internal structure of Finray fingers by mathematically evaluating how the finger wraps around the object (Figure 2-5a).



(a) Finray finger deformed under a load [44].

(b) Schematic of the Finray TIHRA gripper [5].

(c) Festo's Finray multigripper attachment [12].

Figure 2-5: Finray gripper illustrated.

Festo

Festo's adaptive gripper DHAS [13], the Fin Ray effect-inspired gripper, is a commercialised gripper which is able to grasp many objects. The concept of Finn Ray grippers was inspired by the natural biomechanics of the Fin Ray effect, presents an intriguing alternative. Of particular interest is Festo's adaptive gripper DHAS, utilizing the Fin Ray effect as well. Its ability to grip a wide range of objects with different shapes and textures hints at its potential for delicate handling of tomato trusses, especially if customized to match the size and fragility of the product. We can note that the specifications, shown in Figure 2-6, illustrate that for the "size 60", the gripper has enough lifting force to hold a truss of tomatoes. The gripper should be able to fit with these dimensions around the peduncle for a pinch grip (/wrapping). The design can be scaled down, as a typical truss weighs around 500 grams and requires less retention force.

2-2 Conclusion

Nor rigid or soft grippers fulfill the need of delicate handling of tomato trusses utilizing the peduncle. Although rigid grippers dominate the market for handling in general, they are not

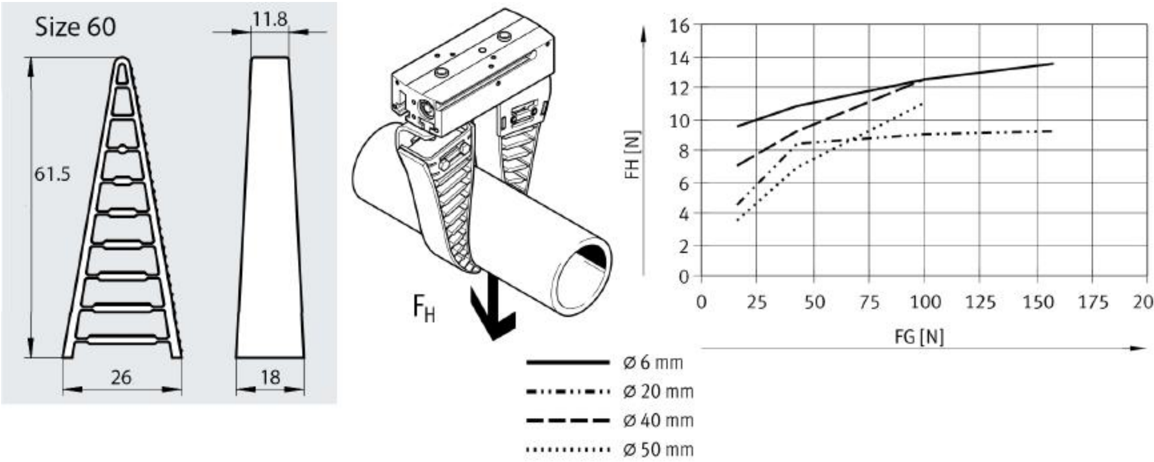


Figure 2-6: Specifications of DHAS, Fin Ray finger[13]. Max. retention force FH as a function of gripping force FG (of two gripper fingers).

suitable for specifically delicate agricultural products such as tomato trusses. Only the idea of using elongated fingers for better access, gripping the fragile tomato truss peduncle, deserves thoughtful consideration.

Regarding soft grippers, Soft Robotics Inc. stands out as a notable example. Their inherent flexibility is commendable, yet their relatively larger size and higher cost might limit their suitability for specific agricultural applications.

The concept of Finray grippers, with their capability to conform and adapt to contact surfaces, implies potential in handling delicate agricultural items. Combined with the reasonable size, which seems appropriate for peduncle grasping.

Chapter 3

Gathering Tomato Data

In this section, we delve deeper into additional research conducted on various trusses from different cultivars(section 3-1). This builds upon the initial research (Figure 1-9) and literature review (Section 1-2-4) that shaped the expectations for the design criteria employed in developing the gripper prototype. For which an analysis is provided in section 3-2. The effect of loading during a pinch grip to determine the extent of damage on the peduncle(section 3-3). The supplementary measurements on the tomato trusses aim to enhance our understanding of the variations between cultivars.

3-1 Cultivars

Supermarkets offer a diverse range of cultivars for sale, particularly focusing on vine tomatoes of medium size. Supermarket tomatoes are selected on similarity when used in the experiments. The availability of tomatoes, cultivars in the winter period, can vary widely, leading to a more diverse selection with less uniformity and freshness in supermarkets. Which can be noticed in the peduncle diameter and strength, as tomatoes easily fall off supermarket tomato trusses (Figure 3-5 and Figure 3-4).

Greenhouses cultivate different varieties, and one such example is the "Maxcise" cultivar (Figure 3-1). These tomatoes weigh approximately 136 grams each, with 4 to 5 on a truss. The trusses are coarse, with slightly more spacing, similar to what some supermarkets may offer.

Another greenhouse cultivar is the "Provine van Nunhums", (Figure 3-3) known for its high variability in the number of tomatoes, their weight and colour due to ripening. This cultivar is a robust grower, making it suitable for winter. The peduncle is either laid on the tomatoes, or very close to them, this is the case for many trusses. This cultivar combined with supermarket tomatoes is what is used in my experiments. The batch looks like the harvest towards the end of the harvesting season.

The "Capricia van Rijk Zwaan" cultivar, used in the paper of van den Bent et al. (2023), (Figure 3-2) is a summer cultivar with uniformly red and ripe tomatoes. It features a large vine, thick peduncle, and the widest spacing around the peduncle. The trusses are somewhat heavier than the average tomato truss, carrying 5 tomato fruits each. This particular cultivar is utilized for adapting design criteria.

Figure 3-1: Vine tomato cultivar: Maxcise.

Figure 3-2: Vine tomato cultivar: Capricia van Rijk Zwaan

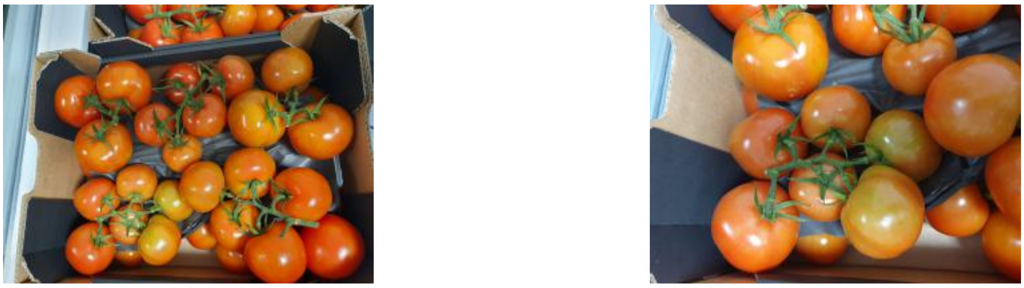


Figure 3-3: Vine tomato cultivar: Provine van Nunhums

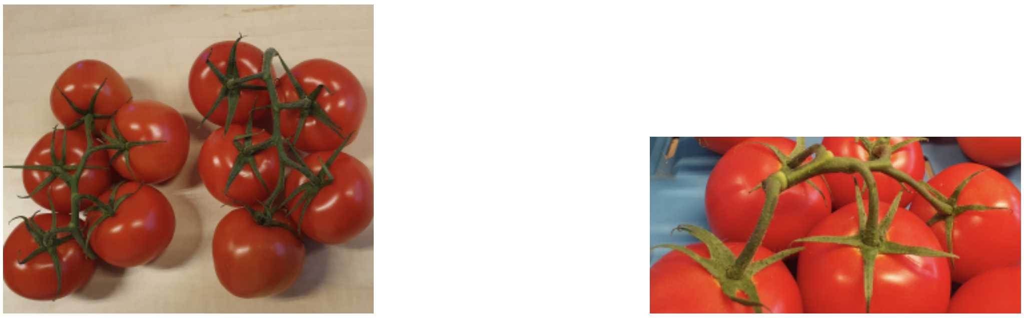


Figure 3-4: Supermarket tomatoes, from different batches.

Figure 3-5: Supermarket tomatoes, from different batches.

3-2 Analysis of the Trusses

The following section provides an analysis, based on the generated statistics, for properties which seems relevant for grasping. The statistics detailing key attributes and average of vine tomatoes can be found in section A-7. The accompanying images highlight variances among cultivars, with weight being relatively consistent, while differences in spread are noticeable. Of particular significance are the spacing around the peduncle and the overall width for gripper placement, which determines the distance between pedicles (Figure 1-7) and is crucial for ensuring a successful grip due to the in general limited space for gripper positioning.

Moreover, the thickness of the peduncle serves as an indicator of truss strength, providing a larger point for connecting the gripper to the truss. Supermarket trusses pose particular difficulties for grasping, due to their slender peduncles, despite having a greater amount of space around the peduncle.

The Provine van Nunhums cultivar displays a notable variability in its attributes. In contrast, the Capricia van Rijk Zwaan cultivar exhibits remarkable consistency.

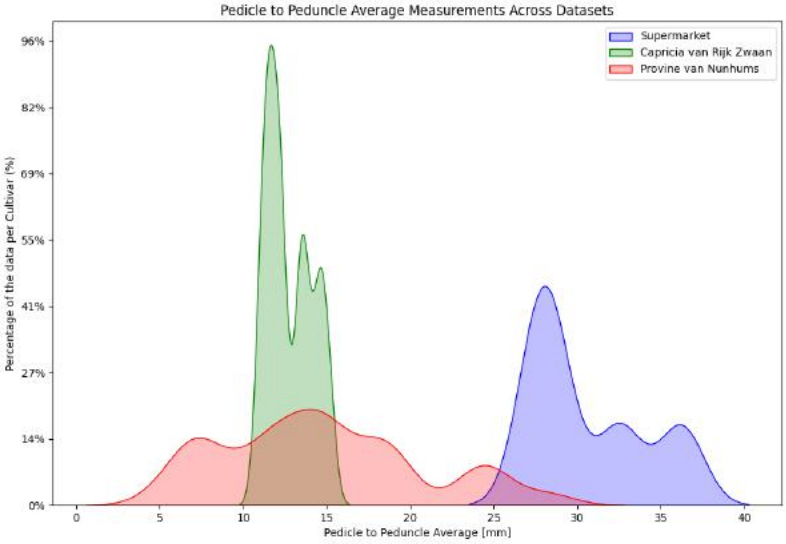


Figure 3-6: Distribution spacing around the peduncle.

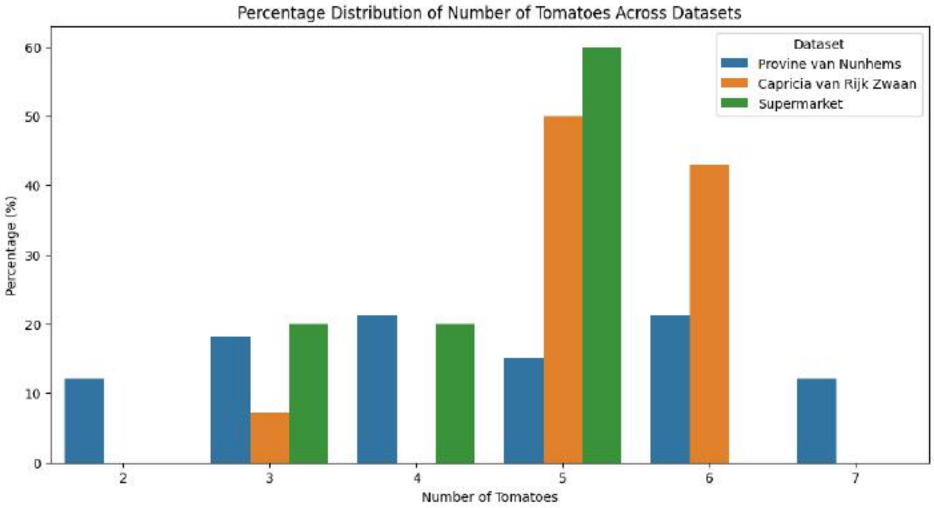


Figure 3-7: Number of tomatoes on a truss.

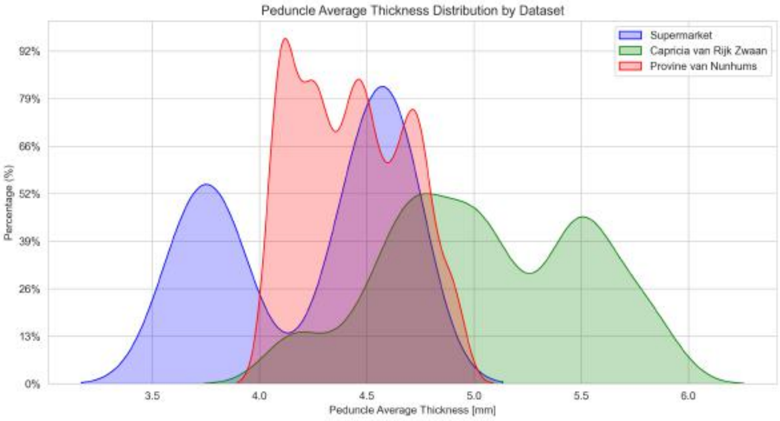


Figure 3-8: Peduncle thickness in diameters [mm].

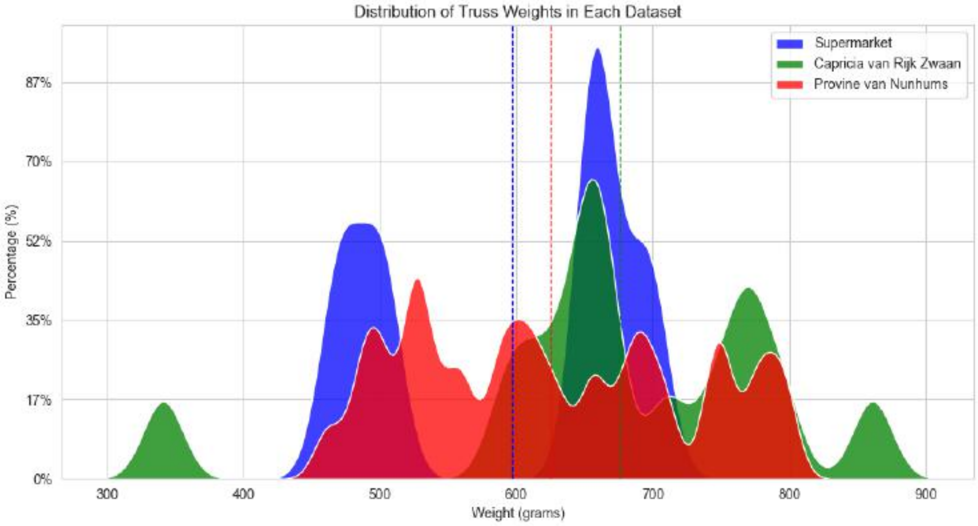


Figure 3-9: Weight average of tomato trusses.

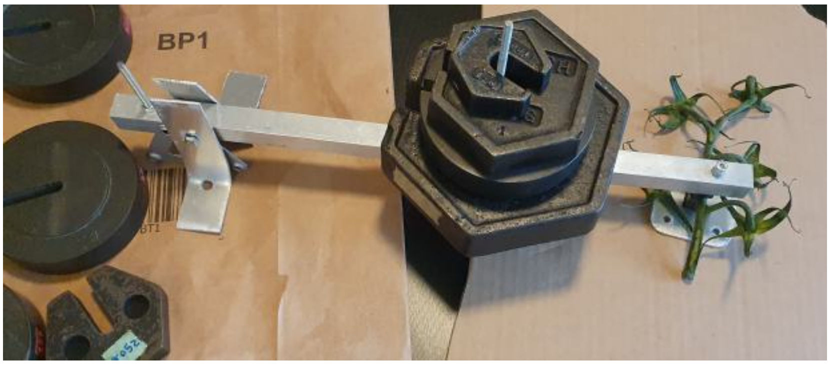


Figure 3-10: Lever setup

3-3 Tomato Pinch Test

In evaluating the types of damage to peduncles, friction, internal damage, and impact on tomatoes were considered. To determine the permissible pinching force, peduncles are subjected to pinch grasping using a testing setup. This setup involves a lever (3-10) and a set of blocks (3-11) that load the peduncle in a manner similar to a pinch grasp. The applied loads range from 200 grams to 6 kilograms, with a 30-second timer for the force applied without impact. Since the work of van den Bent et al. (2023) applies a force of 40 N, it was intriguing to explore if there exists an optimal point for the applied force on the peduncle of a truss.

Given the force required to maintain grip on the peduncle, lower weights would not be viable options with a standard pinch gripper. For any other gripper, it is still important to know at what loading bruising of the peduncle occurs, as this influences freshness and shelf life of the complete truss. The experiments revealed that any applied weight resulted in bruising or even surface damage (Figure 3-12), highlighting that pinch gripping with rigid grippers would not contribute positively to the quality of the truss. The extent of damage was reduced for lower loads and in areas where the peduncle exhibited greater thickness.

While incorporating padding on the gripper's surface and adopting rounded edges may alleviate certain effects (Figure 3-13), pinch gripping still imposes a greater force on the peduncle compared to alternative methods, as it aims to counteract gravity through friction. These heightened forces often result in bruising, and the frictional forces can lead to surface damage.

3-4 Conclusion

Investigating various tomato cultivars, including greenhouse types and supermarket varieties, reveals key differences in peduncle strength, fruit weight, and truss spacing, which are crucial for designing effective, gentle robotic grippers. Cultivars like "Maxcise," "Provine van Nunhums," and "Capricia van Rijk Zwaan" demonstrate unique challenges that significantly influence the success of different grasping methods in agricultural automation. Factors such as the spacing around the peduncle and the weight of the truss are critical, as seen in experiments (chapter 9), highlighting the need for tailored design criteria in response to cultivar variation.

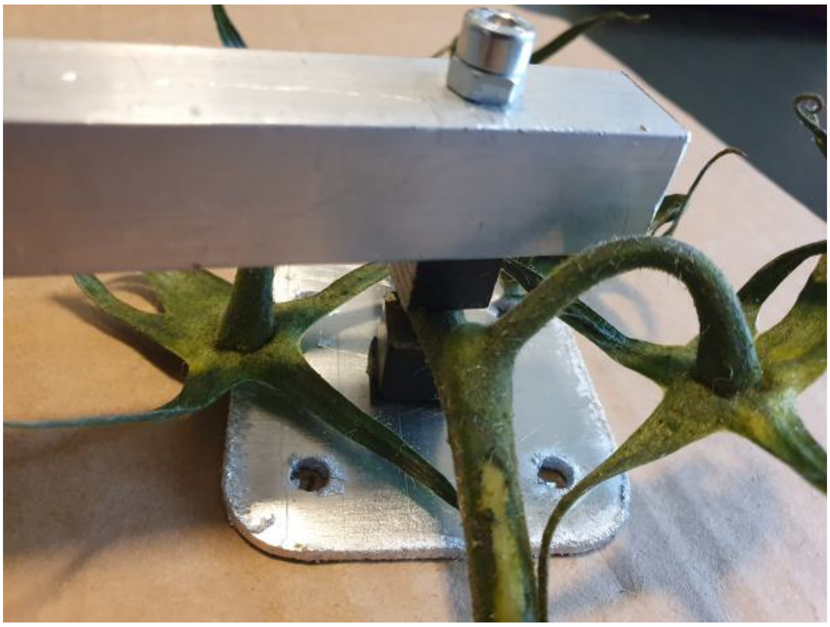


Figure 3-11: Example of point of contact.

Figure 3-12: Overview of pinching damage or bruising on the peduncle.

Figure 3-13: Pinch gripped truss with parallel gripper with padding for multiple grasping attempts.van den Bent et al. (2023)

Chapter 4

Design and problem definition

4-1 Introduction

This chapter describes the design methodology, beginning with an examination of the use case, which is used to establish the grippers functions. These functions, in turn, serve as guiding criteria during the design phase. The design process comprises two stages. Initially, multiple prototypes are developed based on three distinct grasping principles. From these prototypes, one is chosen to advance in the research. Subsequently, the most promising prototype is iterated upon to improve its functionality. Subsequently, from these prototypes the most promising prototype is chosen to develop further in this research, aiming to improve its functionality. This thesis will focus on handling vine tomatoes from a crate (section 1-2-2).

I reviewed related work on grippers for whole tomato trusses and current industry standards. Previous students who used default grippers encountered issues with maintaining grip, damaging peduncles, or only succeeding with easy varieties.

4-2 Design Criteria

Here's a very short version of the design criteria for the robot arm end-effector:

1. **Robust Grip**: The gripper must reliably hold the peduncle of vine tomatoes, maintaining stability during various actions, and prevent tilting or dropping of the truss. It must provide a strong, secure grip, and be capable of operating at increased speeds without sacrificing accuracy or reliability.

2. **Cleanability**: The gripper should be able to operate in a clean environment, withstand small amounts of dirt, and should function in moist or wet conditions.

2.1 **Friction**: The gripper should be able to operate without relying solely on friction. Which is impaired by the lack of cleanliness.

3. **Power Requirements**: The gripper must have sufficient force to firmly hold the truss without damage, and be strong enough to lift it from a grip on the peduncle. A supermarket truss has an average of 500g, given the range of weights over different cultivars the prototype should be able to carry 950g.

4. **Cost-Effectiveness**: The system should be reasonably priced, efficient, and precise. It should rarely require reattempting grips, and maintenance like cleaning should not significantly impact operational time. The gripper's open and close cycle time should be quick, aligning with industry standards.

5. **Working Space and Dimensions**: The gripper must accommodate variability in peduncle and pedicle dimensions, and the space between them. It should be precise enough for small peduncles. The smallest grasping spaces are 5 mm where a suitable option is any size below 10 mm due to the ability to pick different grasping positions for suitability. Additionally, it should utilize the (small) space around the peduncle to avoid damage to the fruit. To accommodate for grasping from a crate, the reach of the gripper should be sufficient to gain access to the trusses.

6. **Speed and Accuracy**: The gripper needs to be quick and precise, capable of consistently performing grasping and releasing tasks without slippage or misalignment. It should adapt to less precise starting positions and be effective even with initial detection inaccuracies.

7. **Durability and Reliability**: The gripper should withstand multiple operations over time without failure or performance degradation, maintaining a consistent success rate.

4-3 Franka Emika Robot Arm

In various industries, especially in food packaging, robot arms with multiple degrees of freedom, like Delta-robots, are commonly employed. Alternatively, SCARA-type serial robotic arms with 6 degrees of freedom are utilized. This research specifically employs the Franka Emika FR3 robot arm, renowned for its seven degrees of freedom, offering flexibility and dexterity for intricate tasks. Recognized for its user-friendly interface, adaptability, and safety features, this robot is ideal for collaborative efforts with humans. The Franka Emika FR3's lightweight and compact design make it well-suited for precision-driven applications in manufacturing, research, and development, where both precision and collaboration between humans and robots are crucial. The design should work in combination with the FR3 robot arm and optionally the hand attachment.

Figure 4-1: Default E-hand of the Franka Emika arm.

Table 4-1: Franka Emika Panda/FR3 Specifications

Category	Specification
Arm	7 Degrees of Freedom Payload: 3 kg
Motion	Cartesian Velocity Limits: Up to 2 m/s Pose Repeatability: < ± 0.1 mm (ISO 9283) Path Deviation: < ± 1.25 mm
Gripper	E-Hand: Parallel Gripper with Exchangeable Fingers Grasping Force: Continuous Force: 70 N Maximum Force: 140 N Travel Span: 80 mm Travel Speed (per finger): 50 mm/s Weight: 0.73 kg

(a) Steel truss for testing.

(b) FR3 robot arm.*Franka Research 3* (n.d.)

4-4 Test Objects

A steel truss was created to test grip capabilities, simulating the real weight of truss tomatoes. This steel truss consisted of removable blocks to alter its total weight en dynamics, to imitate the balance and inertia effects of real trusses. The peduncle diameter is 8 mm, and the truss weight is 552 g. Initial prototypes were tested with this steel truss or real tomatoes.

4-5 Design Specifications

In conclusion, the design specification summary table provides an overview of the essential criteria guiding the development of the gripper for truss tomatoes. The identified design criteria, ranging from robust grip and cleanability to power requirements and specific operational considerations, outline the multifaceted nature of the gripper's intended functionality. By adhering to these criteria, we aim to achieve a balance between efficiency, precision, and adaptability in addressing the challenges posed by the delicate nature of vine tomato trusses.

Table 4-2: Design Specification Summary

Design Criteria	
1. Robust Grip	Reliable peduncle holding, preventing tilting or dropping.
2. Cleanability	Operate in clean, moist conditions.
3. Power Requirements	Sufficient force for a 950g truss, quick open/close cycle.
4. Cost-Effectiveness	Reasonably priced, efficient, and precise.
5. Working Space	Accommodate peduncle variability, precise for small peduncles.
6. Speed and Accuracy	Quick and precise, adaptable to less precise starting positions.
7. Durability and Reliability	Withstand multiple operations without degradation.
8. Specific Requirements	Operate in moist conditions (IP54), precise positioning (1mm), Cycle time $<$ 10 seconds, small form factor for different gripping methods.

Chapter 5

Prototype selection and initial prototypes

In this chapter, we will be discussion the initial prototypes. The first prototype, is a rigid gripper, and will investigate the capabilities of a customized rigid gripper. The second, prototype is a Finray-based flexible gripper. The third prototype is a hook based gripper that is the selected prototype for development which is improved in chapter 6, about prototype 2.

5-1 Prototype 1.1: Rigid Gripper

In the section on Commercial Grippers (section 2-1), we provide an overview of the capabilities of rigid grippers. In this prototype, our goal is to enhance the end-effector for effectively grasping the peduncle. One of the challenges discussed in section 1-1 pertains to the limited effectiveness of rigid grippers due to their short finger length. To address this issue, we aim to extend the reach to prevent collisions with the truss and ensure access to the peduncle, especially when the truss is situated deeper in the crate or near its sides. The integration of longer fingers is intended to extend the reach within crates and avoid clashes with the linear actuator of the e-hand (section 4-2). It's important to note that the rigid grippers still utilize the e-hand for actuation (Figure 4-1), and the orientation and overall accessibility are influenced in part by the dimensions of the e-hand. Despite these advancements, the grasp is still constrained by the e-hand, depending on the required orientation.

5-1-1 Pinch Gripping

Rigid grippers commonly employ a pinch gripping mechanism, as observed in commercial models (see section 2-1). Exploration was undertaken to adapt the gripper to accommodate the average curvature and diameter range of peduncles. This exploration, combined with variations in enclosure and approach, led to the creation of the prototypes presented in Figure 5-1. The grippers are fabricated using either PLA or PETg, with PLA being more rigid.

Figure 5-1: Overview of rigid pinch gripper prototypes.

Prototype Testing

An assessment conducted a day later revealed that trusses gripped by these prototypes did not meet supermarket standards due to the incurred damage on the peduncles. Testing involved grasping forces ranging from 500 g to 4 kg and peduncle diameters from 3.3 to 6.1 mm. Additional tests with lower weights for shorter durations consistently resulted in damage.

Immediate post-testing observations indicated surface bruising or perforation, with the peduncle's condition worsening significantly the next day. These grippers, although capable of gripping, often inflicted damage and struggled to maintain a secure hold. The required force to sustain a grip was often excessive.

Prototype Evaluation

The inherent rigidity of these grippers, while enabling access to the peduncle, frequently resulted in tomato damage when the peduncle was inaccessible. The open-close movement required additional space, which was not always available. However, if the peduncle was positioned between the fingers, it could eventually be pinched.

The stiffness of these grippers could be enhanced, as they exhibited some flex when loaded. This issue was addressed by incorporating a bent shape in the end-effector. Nevertheless, the design criteria for a robust grip were not met, as tomato trusses tended to swing and wobble during pick-and-place actions.

Maintaining a grasp on higher-weight trusses often led to slipping out of the end-effector or dirtying of the gripper by the tomatoes (refer to subsection 1-2-2), reducing the effectiveness of the grip. Regular cleaning could mitigate this issue.

Despite the gripper's rounded shape conforming to the peduncle's shape and allowing for an additional sleeve, undesired peduncle damage still occurred.

The reach of the gripper is still limited by e-hand as shown below.

Figure 5-2: The gripper reaching in the corner.

5-1-2 Cage Gripping

This rigid gripper employs a caging technique on the peduncle. The testing involved enclosing the peduncle within a cage-like structure. However, this approach often led to trusses twisting out or required stiffer materials, resulting in increased damage to the peduncle. Furthermore, precise positioning is essential for effectively enclosing the peduncle. Given the restricted space, there are limited options for suitable caging due to size constraints.

5-2 Prototype 1.2: Deformable Gripper for Pinch Gripping

In the related work, briefly summarized in subsection 2-1-3, various deformable grippers were highlighted. The optimization of parameters for finray grippers and insights from relevant papers played a crucial role in shaping the designs.

Pneumatic options were excluded due to their large size, softness, and slow operation. Additionally, I delved into different internal structures, analyzing their impact on overall performance.

Deformable grippers offer the advantage of successful grasping even in imprecise positioning, accommodating larger positional errors. Furthermore, they contribute to more evenly distributing the load on the peduncle.

The exploration of rigid gripper options aimed not only to identify a viable solution but also to underscore that a customized end-effector may not effectively address the underlying problem.

(a) Caging rigid end-effector. (b) Example of a grasping action.

Figure 5-3: Caging gripper variations.

Property	**Value**	**Units**
Elastic Modulus	9.3 ± 0.3	MPa
Poisson's Ratio	∼0.495 (estimated)	Dimensionless
Shear Modulus	∼3.11 (estimated)	MPa
Mass Density	1.19 – 1.24	g/cm^3
Tensile Strength	29.1 ± 2.8	MPa

Table 5-1: Properties of OVERTURE TPU 95A Filament

5-2-1 Finray end-effector and Variations

5-2-2 Prototype Variations

The flexible grippers offer a spectrum of parameters to fine-tune. The angles of approach to the peduncle exhibited considerable variation. Through intermediate tests and simulations, diverse structures were formulated and subsequently evaluated for their suitability.

1. Crossbeam count and rib count
2. Rib slope
3. Slope of the outer wall
4. Outer wall thickness
5. Finger width

6. Thickness of front and rear beams
7. Filling pattern structure
    - Straight ribs
    - No internal filling
    - Branched ribs with branching in the middle
    - Branched ribs with branching shifted to the left or right

A redesign of the official Finray product revealed that it was excessively bulky and rigid for our intended purposes. Most of the configurations resulted in the gripper dropping items, as maintaining a grip required excessive force. Or the fingers would become too large for effective grasping.

A downscale of the Festo Finray gripper, which might offer better accessibility than the original size, but showed that similar issues persisted. Modifying the orientation hindered performance, as the point of contact was too close to the tip of the end-effector, making it less effective. Additionally, the Festo gripper was too stiff, requiring excessive force to deform and applying more force than desired on the peduncle.

To assess some of the design options, I favoured quick prototyping over simulation, enabling a swifter evaluation and decision-making process regarding the feasibility of each design.

While a smaller fin might seem like a plausible solution, potentially used in combination with a rigid gripper, experimentation with different types and asymmetric placements yielded no improved results.

For this experimental setup, I employed extended fingers similar to those of the rigid designs. However, I adapted them for seamless interchangeability with diverse end-effectors. These fingers were crafted from 95A (Shore hardness) TPU, a notably flexible material. Some fingers were crafted from PETG, allowing for some deformation, albeit plastic deformation, which proved sufficient for short-duration testing.

I conducted tests with various configurations, exploring different angles of approach to the peduncle. This was pivotal because having the gripper's surface flat against the peduncle did not consistently ensure adequate force application. Moreover, there was a potential risk of the flexible fingers folding under certain conditions.

Although employing a smaller fin may initially appear as a viable solution, perhaps in conjunction with a rigid gripper, experimenting with various types and asymmetric placements failed to yield any noteworthy improvements.

The Finray and other deformable designs were examined for their ability to adapt to different angles of approach. The primary goal was to increase strength and prevent buckling, the main failure mode, rather than slipping. A textured surface on the tips was tested to address this.

5-2-3 Prototype Testing

In my initial tests, a steel truss weighing 500g proved too heavy for the prototype, exceeding its maximum weight capacity of 294.1 grams. The prototype frequently failed to maintain

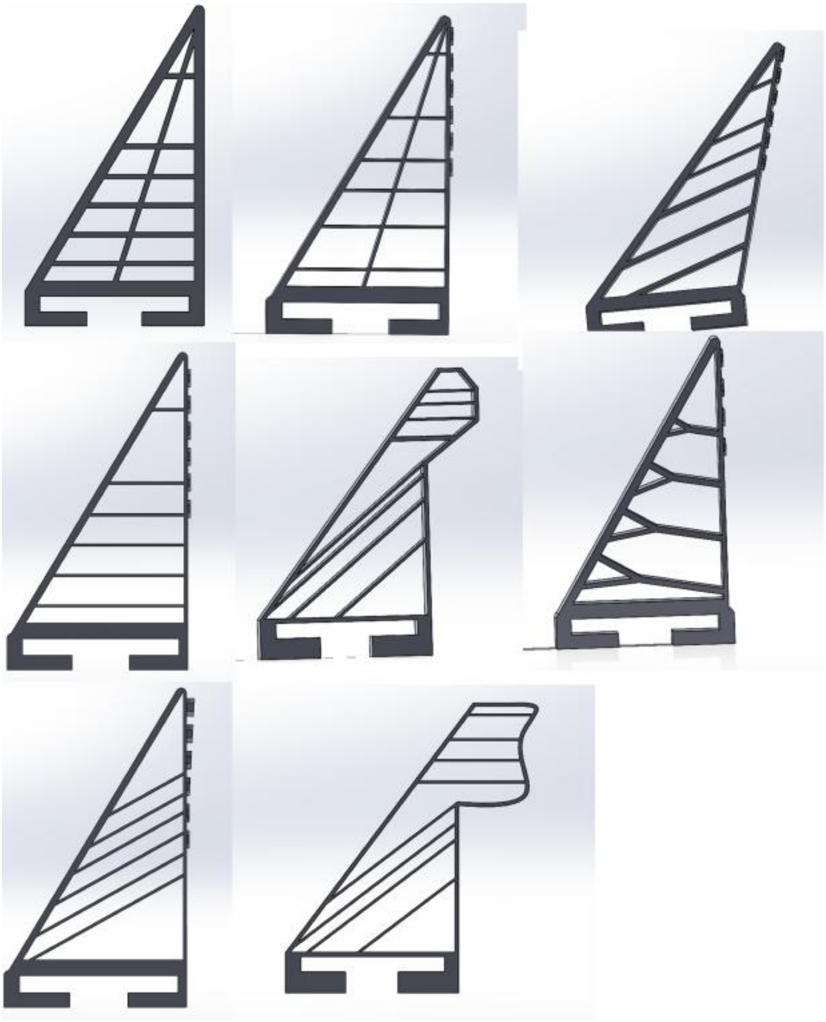


Figure 5-4: Overview of some made flexible end-effectors.

a grip on various weights, and when the robot was in motion, it often resulted in dropping the held weight. I tested multiple different loading cases with small increments to get these results. The internal structures buckles when the load is too high causing the gripper to fail. The tips of the end-effector are not a stable configuration. A slight tilting or motion of the truss and the tips might miss align, causing the truss to fall out. The maximum weight carried was 294.1grams, but this was not a successful pick and place, nor a stable grip.

This design falls short of meeting the design criteria for accuracy, durability, and reliability. Additionally, it fails to meet the power requirement, as the prototypes prove incapable of lifting an average truss.

Simulation

The various simulations conducted for different configurations of the flexible grippers provided insights into their deformation and loading behaviour. It is noticeable that the red areas in the simulations align with the points of failure observed in the real tests, leading to the flexible

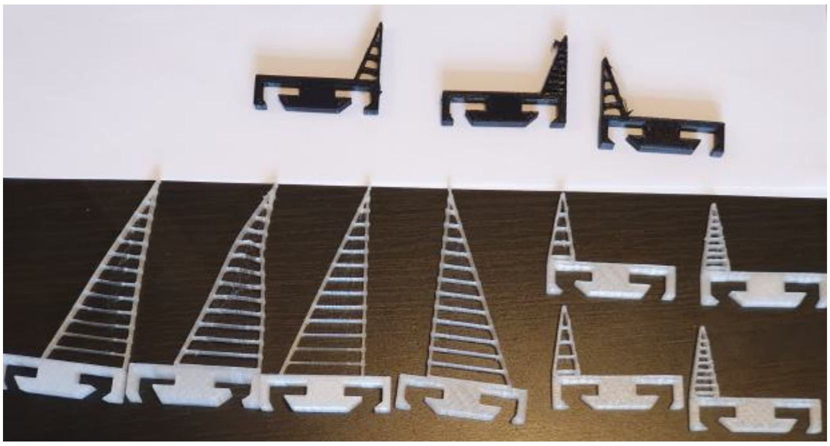
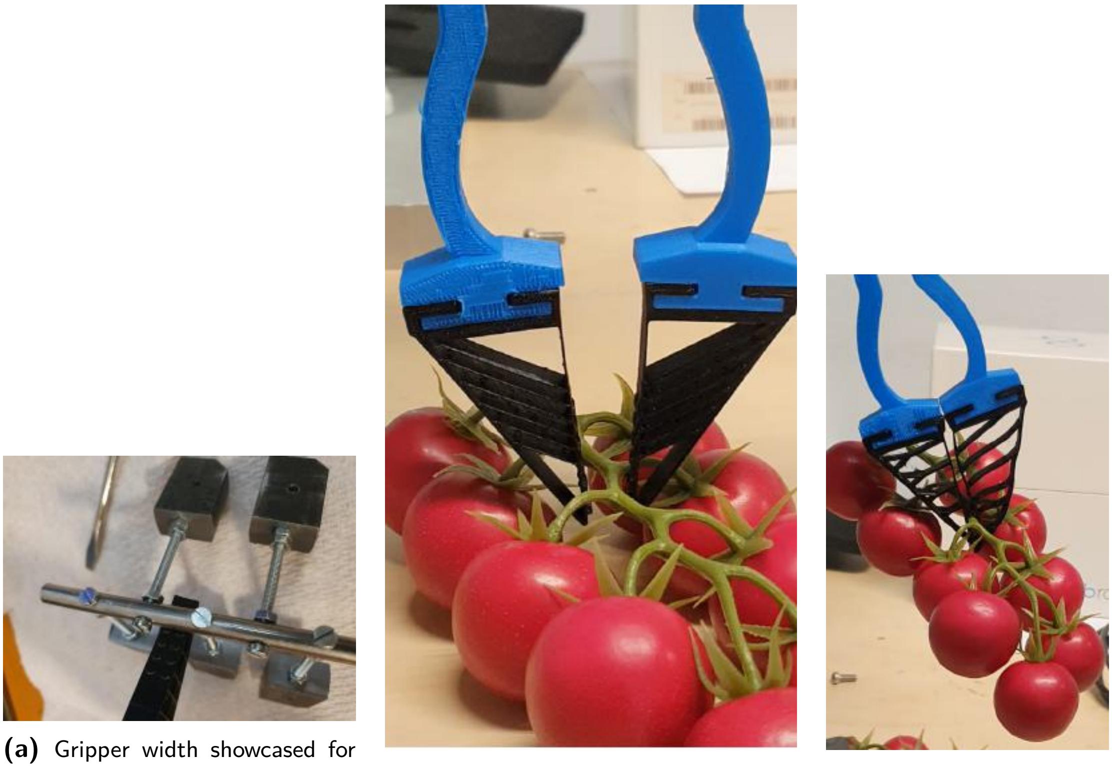


Figure 5-5: Small and PETg Finray variations.

gripper's failure, akin to buckling of the outer shell structure.

Navigating the trade-off between maintaining a flexible gripper that keeps the end-effector closed during lifting without exerting excessive pressure or collapsing, resembling the buckling of the outer shell, appeared to be a challenging aspect of the design.



(a) Gripper width showcased for steel tomato truss.

(b) Finray gripper neutral poistion.

(c) Finray gripper active position.

Figure 5-6: Prototype 1.2; Finray gripper.

Figure 5-7: The best performing Finray variation.

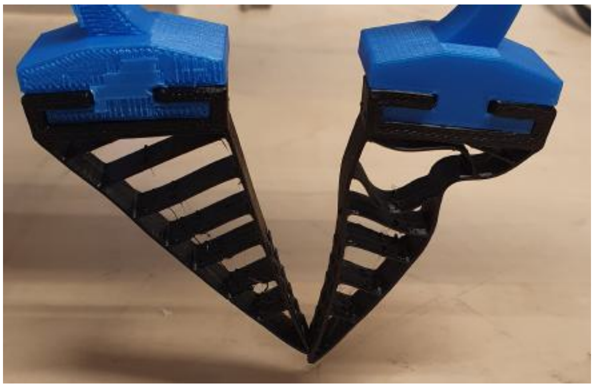
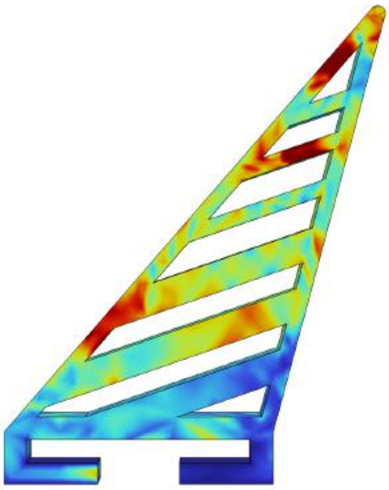
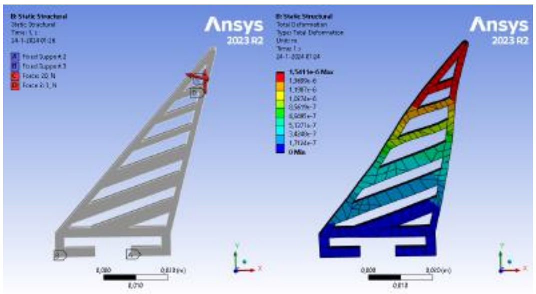


Figure 5-8: An illustration of the structural failure of the Finray end-effector.



(a) Displacement of the Finray gripper simulated in Comsol.



(b) Ansys was employed to conduct a static structural analysis with applied forces. A ramped force of $20\,\text{N}$ was utilized to simulate pinching, while an additional force of $3\,\text{N}$ in the direction of gravity was applied to represent the weight of the tomato.

Figure 5-9: Simulation results for Finray gripper.

5-3 Prototype 1.3: Hook gripper

The prototype features an end-effector with a distinctive hook shape. Due to challenges encountered with the laser cutter, the gripper's body is crafted from stainless steel sheet metal instead of aluminium. This material selection aligns with the operational capabilities of the Franka Emika robot arms. The design is intentionally upright, ensuring compatibility with various robot arms, including those with fewer than 7 degrees of freedom, such as SCARA or delta robot arms.

The prototype's length enables effective reach into crates. Although a tilting mechanism for the entire arm could offer additional grasping options, the current weight of the arm surpasses the capacities of the FR3 and Panda, leading to error messages when tilted.

The bearing is secured by a slot tightened with bolts, and internal springs pre-tension the gripper.

Originally designed for independent finger movement, the e-hand's fingers are not initially linked. The wires and pre-tensioning springs operate separately. Subsequently, for certain prototype tests, they are connected using bolts.

The fingers, resembling hooks, are crafted from PLA and manipulated by a wire, tensioned with a spring. In their default position, the fingers point downwards, facilitating insertion under the peduncle. The motor pulls the wire to close the fingers, and upon release, a weaker spring tension ensures the wire stays taut, keeping the fingers open.

The wire is powered by the linear actuator of the Franka Emika E-Hand and is guided to the fingers through v-groove bearings.

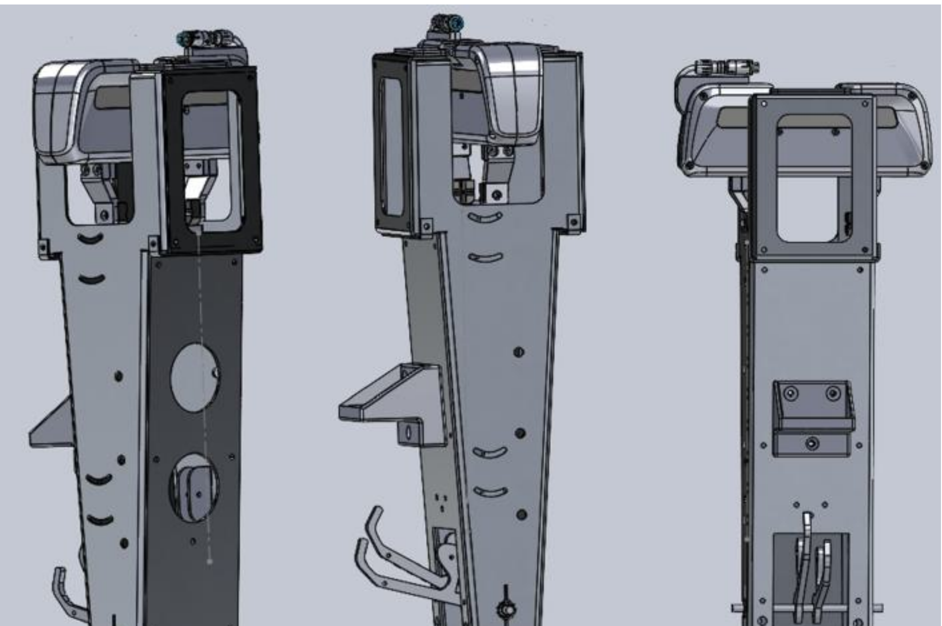


Figure 5-10: Prototype 1, hook gripper.

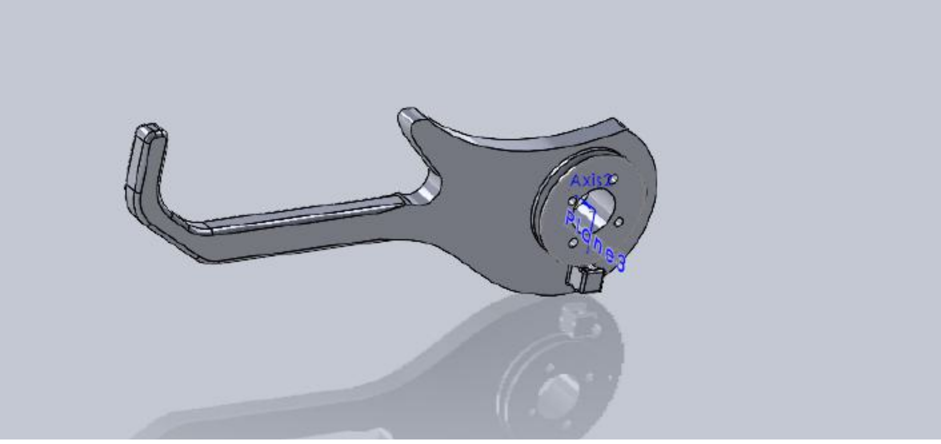


Figure 5-11: Finger hook

Prototype Testing

The prototype has too much friction for the e-hand to properly actuate a grasp of the 500 g steel truss, Which is in part the problem with the e-hand discussed down below (5-3).

Prototype Evaluation

The hook design appears promising for grasping the peduncle. However, the primary challenge lies in the limitations imposed by the robot arm and e-hand, necessitating a redesign. This redesign entails incorporating weaker springs, adopting a lighter design that can be scaled down, and leveraging tilting instead of maintaining an upright position.

Additionally, the end-effector hooks are linked as one unit, eliminating separate actuation. To enhance efficiency, the force transfer between components connected by the wire should be smoother and in line with the applied forces. This adjustment aims to minimize power loss due to friction or forces pulling components askew. Implementing machine parts with better compatibility is crucial, as it should allow for less play in the overall mechanism and reduce internal friction.

A critical step in this redesign is linking the wires together to optimize coordination and performance in the revamped system.

The prototype showed potential to be feasible and meet the design requirements.

E-hand Loading Tested

The e-hand undergoes testing to assess its force capabilities, aiming for a continuous force of 70 N and a peak force of 140 N (section 4-3). The test results, detailed in section A-5, indicate that the e-hand consistently fails after encountering loads exceeding 2.4 kg. Instances of time-outs occur intermittently when issuing LibFranka commands to open or close the e-hand.

It's noteworthy that there are distinctions in movement commands utilized with the LibFranka library for controlling the FR3. The "grasp" command allows for additional parameters, such

Figure 5-12: Internal structure prototype 1.3

as force, speed, and grasp success, while the "move" command will try to reach a specified position with maximum motor effort.

Although a load of 3.5 kg appears to be the upper limit, numerous time-outs occur, necessitating a reboot of the hand and the restart of all ROS-dependent software. The e-hand demonstrated overall unreliability in operation, establishing 2.4 kg as a suitable maximum input load for actuating the gripper.

Chapter 6

Prototype 2

The design of Prototype 2 features a hook as the end-effector, which enhances the robustness of the grasp. This hook is strategically positioned underneath the peduncle, effectively encaging it to prevent slippage. This design ensures a stable grip even during the robot arm's movement, facilitating faster operational speeds. Unlike a pinch grip which requires overcoming both the weight and friction between the peduncle and fingers, the hook's design only needs to counteract the weight of the peduncle and truss. Additionally, the hook's ability to reach beneath the peduncle and encage it from below offers more versatility in manipulating the trusses, especially for tasks like emptying a crate.

The hook grip offers an advantage in accurately positioning trusses at a desired location, unlike the pinch grip, which requires precise pre-positioning of the tomato to avoid accidental dropping upon release. Unlike the pinch grasp, where releasing the grip results in dropping the truss, the hook grip's motion of opening the gripper facilitates placing the truss down, if it has not been placed already.

6-1 Design Considerations

The initial design encountered issues with smooth movement. The use of a flange (flench) inadvertently caused misalignment of the finger. To counter this, a sprocket was mounted on an axle instead.

The sprocket was secured with a press fit, and axle set screws were utilized to firmly attach it to the axis. This adjustment provided better stability and alignment for the moving parts.

Additionally, the fingers were redesigned to have a more pronounced bend. This modification improved their ability to hook under the peduncle, leading to a higher success rate in grasping.

To enhance cleanliness and efficiency, additional grip and friction were incorporated. This feature aids in the manipulation of the trusses and requires only the fingertip to make contact. In situations where the tomatoes are accidentally bumped, the softer shell of the fingers helps in minimizing damage.

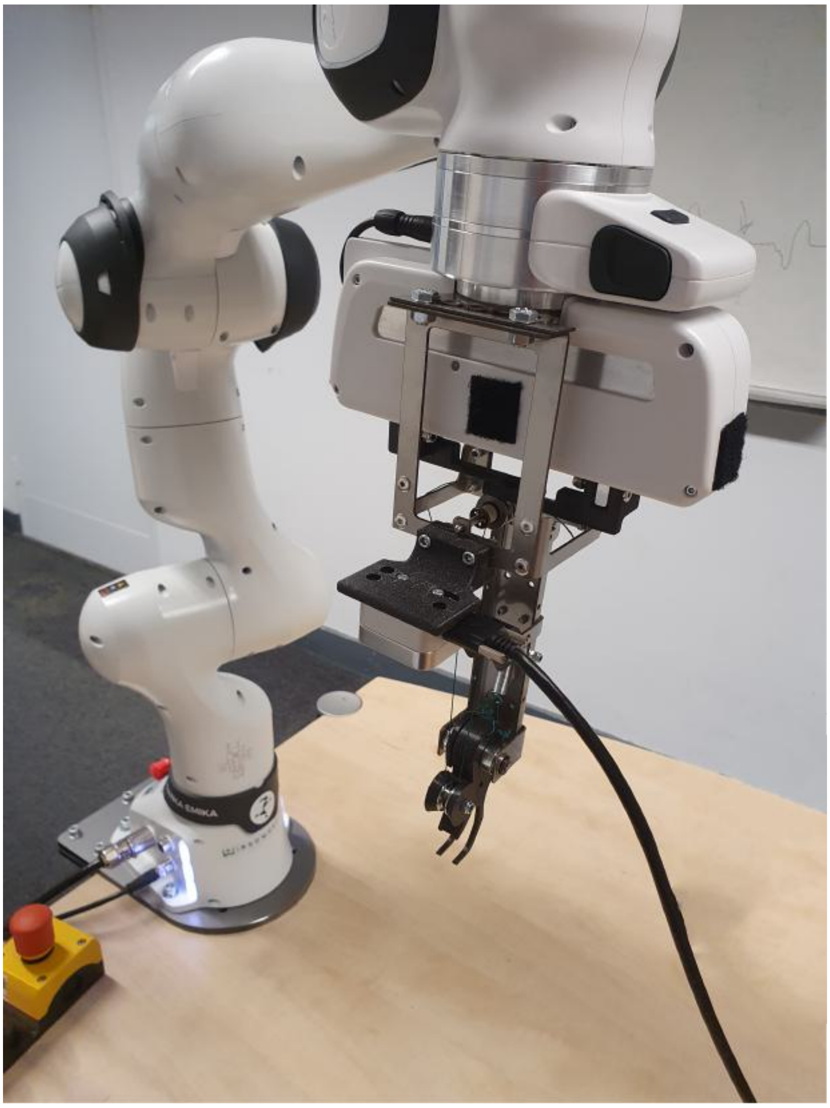


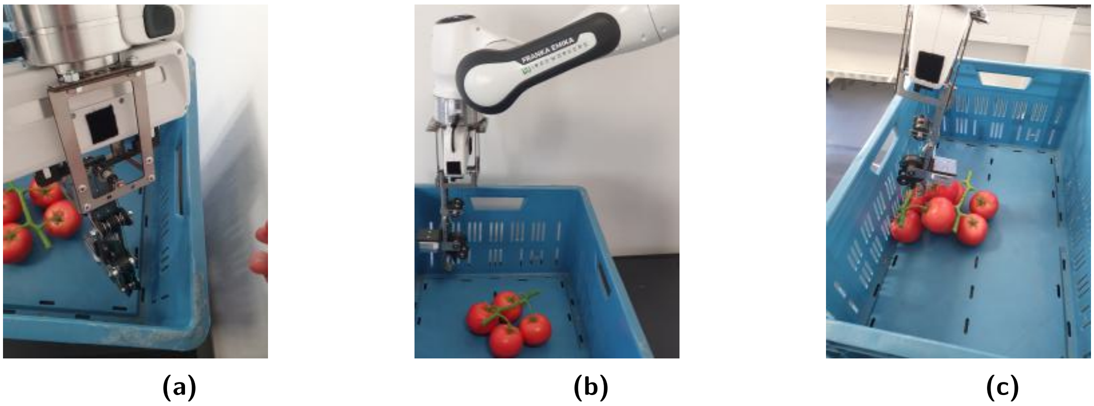
Figure 6-1: Prototype 2

The prototype can tension the wire by adjusting the positioning of the middle v-groove bearing. Moving the position backwards tensions the wire, when the initial wire is attached with some tension when the bearing is in the front.

I observed that the peduncle sustained slight surface damage after several pickup attempts, even under its own weight. This issue was significantly mitigated by replacing the hard PLA contact surface with a softer shell.

6-2 The End-Effector Design

Numerous design iterations were undertaken to enhance the end-effector, refining its shape until the optimal configuration for manoeuvring beneath the pendulum was achieved. In the pursuit of crafting a robust yet slender hook, a combination of clear PETg filament



(a) (b) (c)

Figure 6-2: Prototype 2 in relation to the different positions in the crate.

(allows for resin like qualities) and a metal rod was employed. The outcome was a prototype featuring a transparent filament encasing an internal metal rod, ensuring requisite strength while minimizing its overall profile. This was prone to breaking out of the plastic shell. The bend and the attachment points for springs and the axle has been improved. The bend of the end-effector allowed for less bending than the previous designs.

The end-effector used in Prototype 2 is updated compared to Prototype 1.3. The hook is made shorter with two distinct points where the peduncle can take place. When the gripper closes, the peduncle moves from the tip inwards, making the prototype able to lift more weight. The highest loading occurs when the gripper is nearly closed.

Thinner sleeves were explored for better cleaning and increased grip. These adjustments allowed for fine-tuning of thickness and bending radius to match various tomato sizes. As long as the design fits beneath the peduncle, it proved to be effective.

Figure 6-3: End-effector for prototype 2, the main body connected to the axle in blue. The v-groove bearing's housing on top in green, which is connected to the wire that drives actuation.

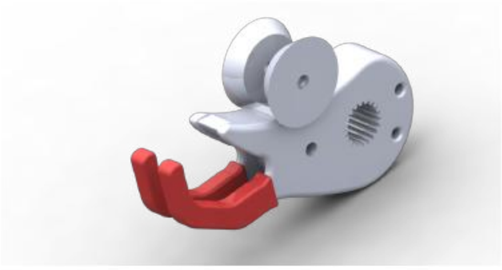


Figure 6-4: End-effector with the added sleeves shown in red.

6-3 Force Analysis

The gripper ascends as the wire pulls on the top v-groove bearing situated at the apex of the end-effector. The Dyneema wire, a brand name for synthetic ultra-high molecular weight polyethylene (UHMWPE) wire, has a diameter of 0.5mm and a load capacity of up to 33 kg. This wire does not elongate under strain, this mitigates any spring like effects from the wire and allows for direct force transfer.

The v-groove bearings operate smoothly with negligible resistance. The disparity between output force and input force primarily arises from the difference in the moment arm of the end-effector. The end-effector offers two grasping positions, initially placing the peduncle at the gripper's tip. As the gripper closes, the peduncle moves inward, resulting in a shorter moment arm.

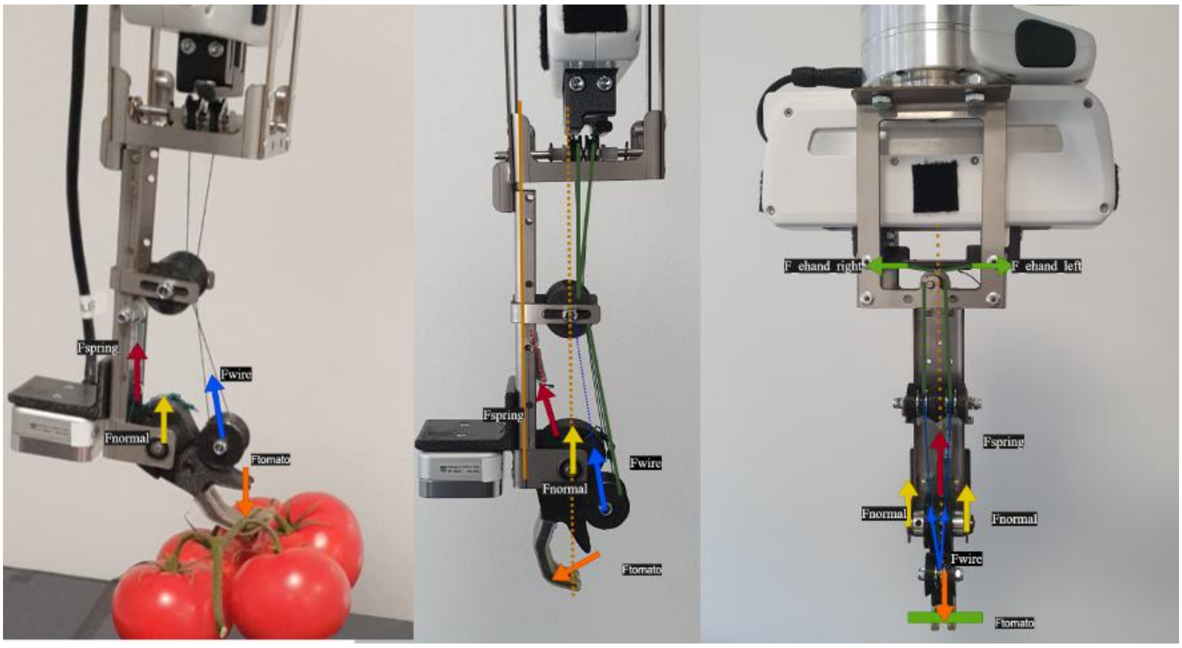


Figure 6-5: Hook gripper forces overview.

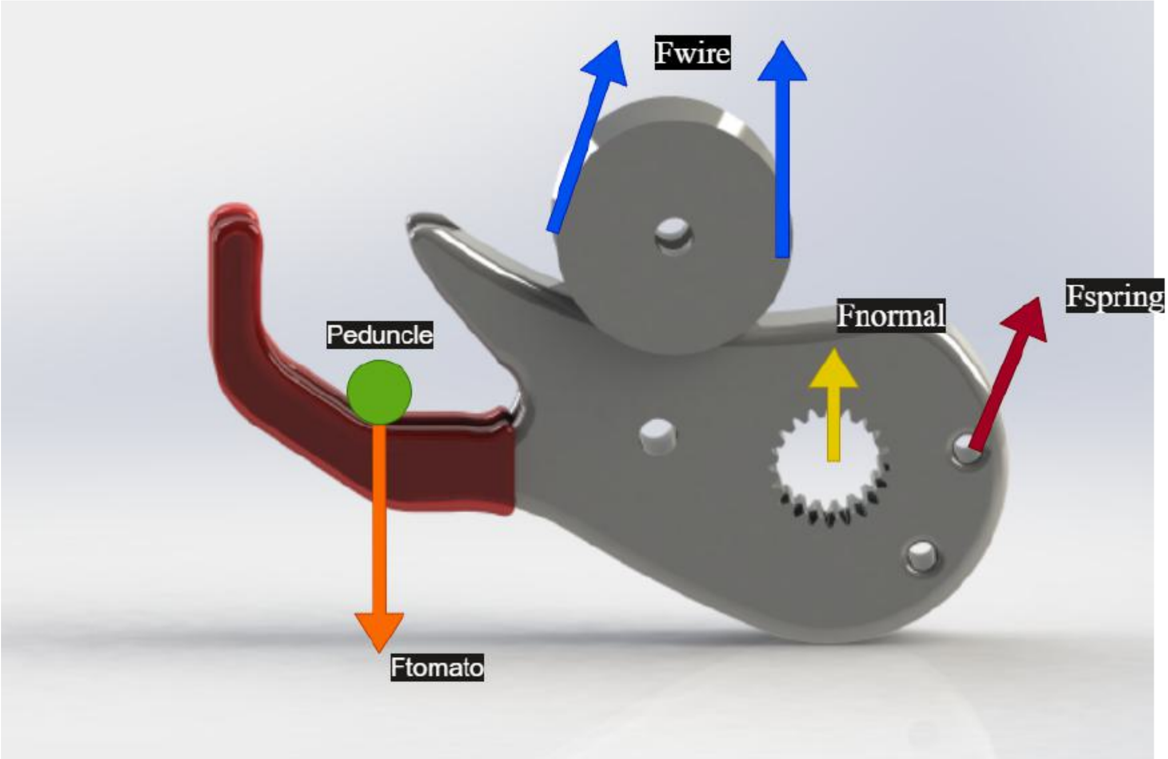


Figure 6-6: Forces overview end-effector.

6-4 Simulations

Loading the body with a higher load then the actual design specifications of 20 N the displacement of the bottom part is 0.301 mm. When the loading of the body occurs is after the grip is successful, meaning that the displacement does not cause any issues.

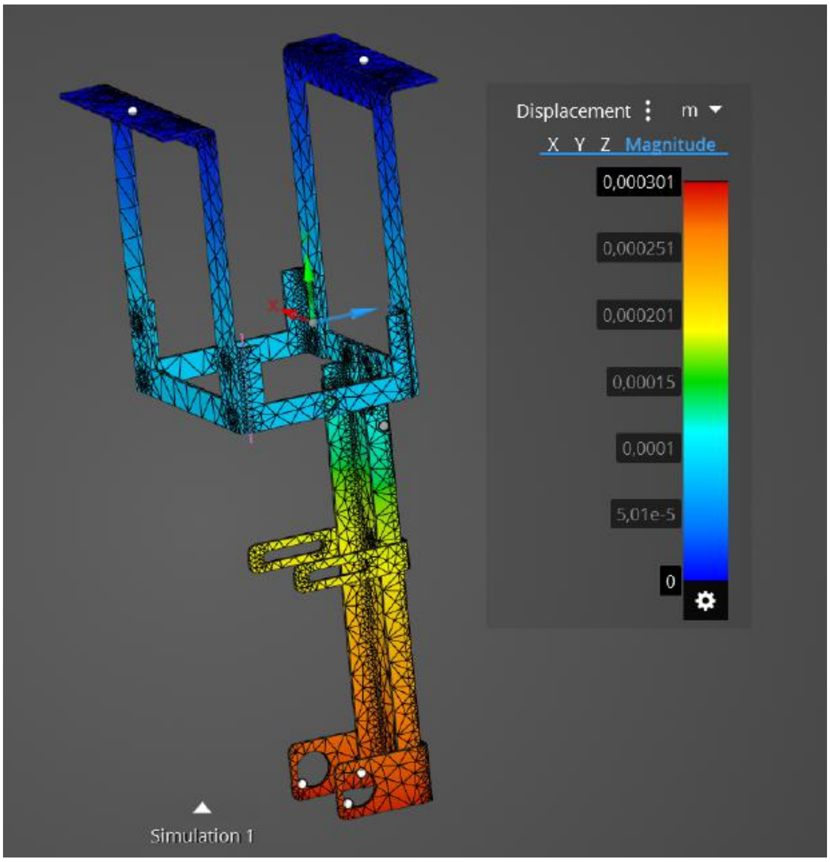


Figure 6-7: Loaded sheet metal body simulation in Ansys, static loading conditions.

The durability of the stainless body is great, with a high fatigue life and the ability to allow for impact caused by errors during testing (section A-8). The estimated fatigue due to cyclic loading of the body is negligible.

Aluminium, specifically of grade 5754 (AW-5754-H12 or AlMg3/ 5754-H111), could be a viable material choice. Alternatively, stainless steel grade AISI 304 has been utilized. The chosen thickness for the sheet metal is 1.5 mm, aligning with the minimum thickness requirement of the laser cutter. Additionally, this thickness is constrained by the bending radius that the sheet metal can accommodate.

For the connection mechanism, a flange is employed to attach to the fingers. The fingers have been designed to be straighter, thereby extending their operational range. This modification enhances the overall functionality and reach of the device.

6-5 Testing the prototype

The prototype is tested with an unster, of 2 kg maximal and increments of 10g, for different variations of loading the prototype. The unster is used as input force on the right side, while the left side of the input is fixed. The end-effector is linked to a pulley that has a 1 kg weight hanging straight down.

The end-effector has two positions, one for initial contact with the peduncle and when the gripper closes the peduncle is close to the point of rotation of the end-effector. The force test however keeps the wire that loads the end-effector on the same position, which is near the tip of the end-effector.

When the prototype is driven by the e-hand, the maximal output force is measured using the unster. The e-hand always fails at 1300 g and up, it is reliable at 900 g, but it should be able to lift a couple of times around 1100 g before timeout errors occur (testing of the e-hand is done in Section 5-3).

The analysis shows that the prototype is able to meet the power requirements to lift all the different cultivars.

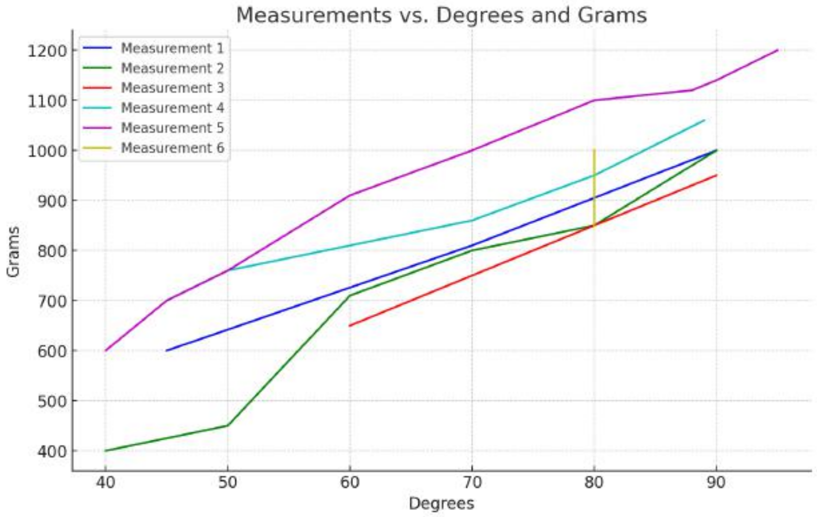


Figure 6-8: Forces measured on prototype 2.

Figure 6-9: Prototype 2 - Loading Configuration 1

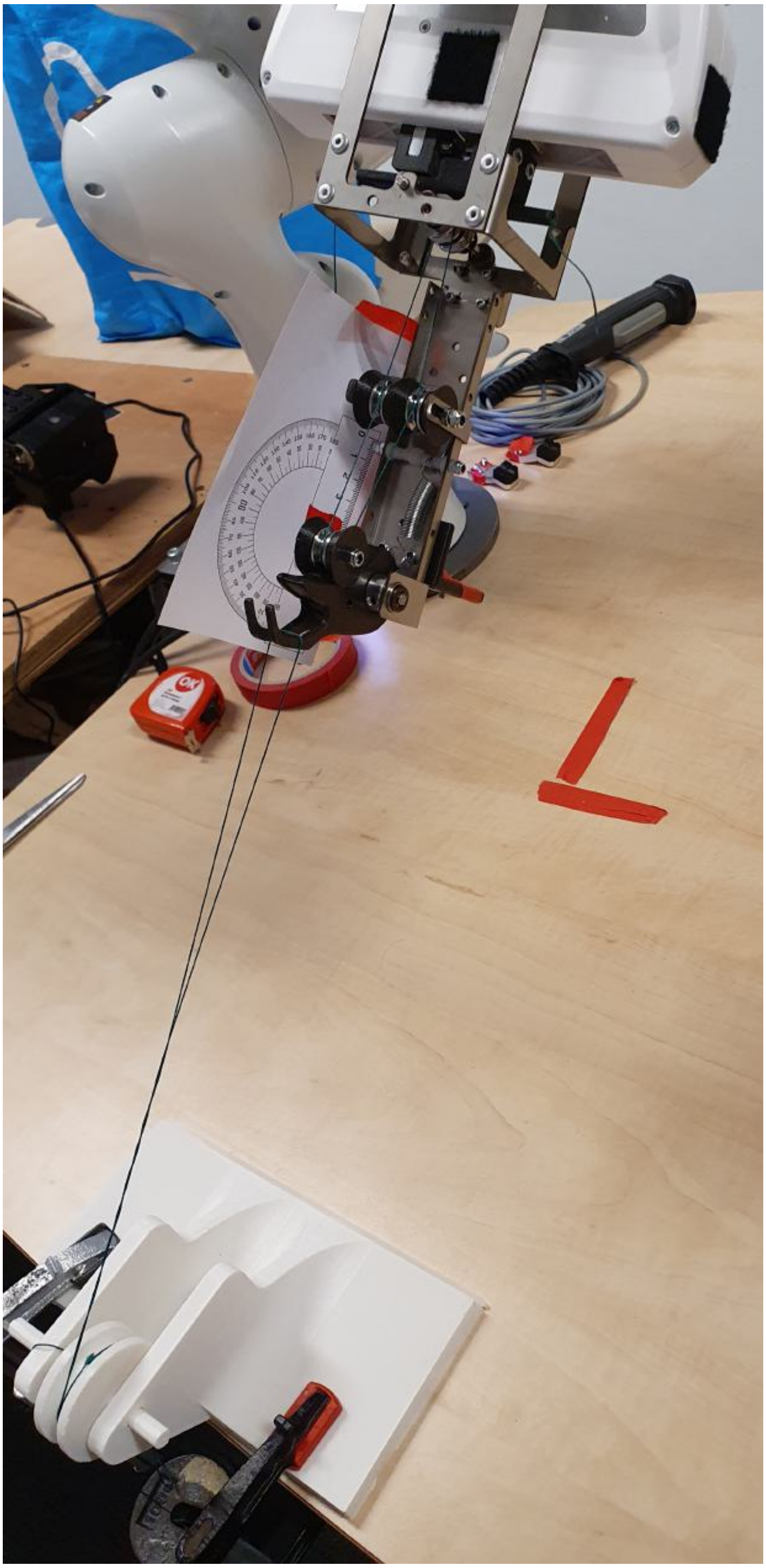


Figure 6-10: Prototype 2 - Loading Configuration 2

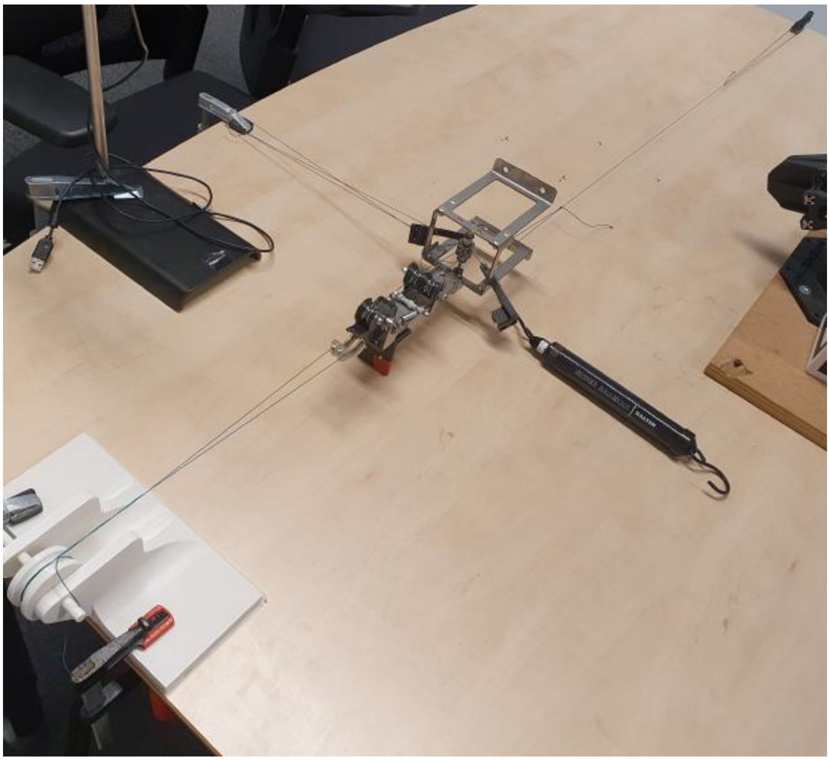


Figure 6-11: Prototype 2 - Loading Configuration 3

Chapter 7

Prototype 3

The third prototype seeks to address two challenges identified in the second iteration. The goal is to enhance the functionality of an underactuated cable-driven flexible finger, enabling it to effortlessly reach beneath any peduncle for effective grasping without the need for additional motions. The substitution of servos for the existing e-hand not only resolves issues associated with the e-hand but also significantly enhances the lifting power and speed of the gripper.

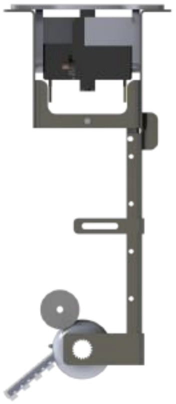


Figure 7-1: Prototype 3

7-1 Design Considerations

Rigid Hook End-effector
The end-effector of Prototype 2 can be improved the following way. This prototype allows for swapping the end-effector, making it possible to test different end-effectors on the same prototype more easily. Enhancements can be made to the hook gripper of prototype 2 by

adopting a different fabrication method, specifically utilizing SLA (Stereolithography) instead of FDM (Fused Deposition Modelling). The transition to Tough 1500 resin in SLA printing brings about notable improvements.

Tough 1500 resin is characterized by its toughness and durability, creating stiff and pliable parts with the ability to bend and quickly spring back. This simulates the strength and stiffness akin to polypropylene (PP). In contrast to materials like PLA commonly used in FDM printing, Tough 1500 is designed to exhibit greater resilience, making it particularly suitable for parts requiring flexibility and high impact resistance.

When compared to materials such as PETG or PETG Plus, Tough 1500 may be less rigid, but it excels in terms of impact resistance and the ability to return to its original shape after deformation. While PETG is recognized for its combination of toughness, clarity, and stiffness, the selection of Tough 1500 over PETG is advantageous when a more flexible and less brittle material is needed. This is especially pertinent for prototypes subject to wear and tear or for connectors and assemblies demanding a certain level of flexibility.

The printing accuracy achieved through SLA enables the creation of a smaller hook, and the utilization of Tough 1500 ensures that despite its reduced size, the hook remains sufficiently robust.

7-2 Development of Underactuated Cable-Driven Flexible Fingers

The Design Improvements
One significant advantage of utilizing flexible fingers in robotic systems is their ability to adapt to various positions. Similar to the rigid hook end-effectors, these fingers require minimal space, conforming to the surrounding area of a peduncle. The flexible fingers have as added benefit that they require less information for optimal execution of the grasping task. This feature allows them to be positioned in tight spaces, simplifying the positioning process. In contrast, a hook gripper, even in the smallest spaces, necessitates a degree of tilting during the grasping action. However, a flexible gripper can be inserted into a gap and naturally wraps around the peduncle.

Over the course of 15 iterations, I identified key findings and refined the designs, as depicted in Figure 7-4. The initial concepts included: a foldable structure with a central wire, a second design is a variation on that with rounded tips and mechanical stops in between, and the third is a chain design that rolls up due to moments around pin connections, with a wire attached to the front causing to roll up due to the sequential forces by the mechanical stop.

These designs, however, revealed certain limitations. For instance, the first prototype faced issues with wires colliding with the truss structure. If the finger did not fold adequately around the peduncle, it could lead to entrapment within the joints.

Considerable focus was dedicated to enhancing the third design. A protective sleeve was deemed necessary to shield the peduncle from wires, prompting a relocation of the wires to the sides. Despite concerns about the potential reopening of the chain due to sleeve thickness and gravity, I addressed this by introducing an extra wire to facilitate the opening mechanism. The chain should open when the tension of the wire is released.

I also implemented mechanical stops to prevent collisions and ensure the finger remains at a 45-degree angle when in a resting or open position. The manufacturing process presented challenges, particularly with the print-in-place pin connections, which were eventually replaced by metal pins. Perfecting the support and curing of the sleeves also proved difficult.

Adjustments to the sleeve design, aimed at altering overall stiffness, were not successful. The more durable TPU with a shore hardness of 50A, featuring sloped and open sides, was selected for its durability. However, the high compression of the sleeve still impeded proper folding of the chain, or required excessive force.

Subsequent iterations involved testing the chain mechanism without the sleeve. The final iteration involved removing the sleeve entirely and applying glue tips to the chain's top, although the spacing proved suboptimal. This prototype highlighted the need for further research and, in its current form, is unsuitable for practical application.

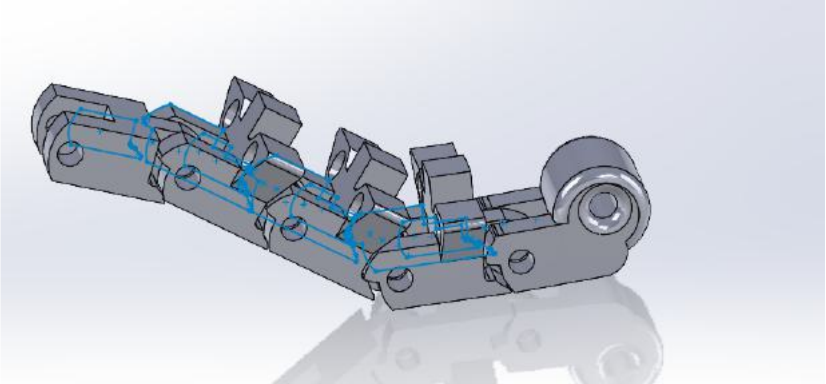
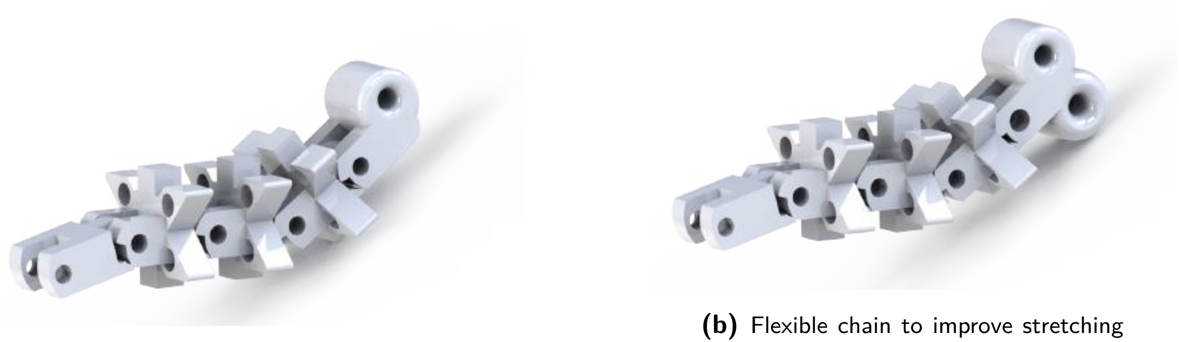


Figure 7-2: Underactuated end-effector, consisting of links.



(a) Flexible chain

(b) Flexible chain to improve stretching of the finger with a wire.

Figure 7-3: Underactuated Cable-Driven Flexible Fingers.

Engineering Application, SLA	Values
Flexural Strength	39.0 MPa
Flexural Modulus	1.4 GPa
Notched Izod (PP-Like)	67.0 J/m

Table 7-1: Engineering Material Properties

Servo Selection

Considering different servo options:

1. A 180-degree servo, known for its cost-effectiveness, provides a practical rotation range of approximately 120 degrees.
2. Opting for a 270-degree servo represents a slightly more expensive choice. This servo type offers an extended range of motion, accommodating smaller parts while maintaining the required stroke length for gripper closure. The use of smaller parts allows for the utilization of a less powerful servo.
3. The continuous rotation servo ensures consistent force output, with its speed defined per degree. This characteristic facilitates timed rotations. Additionally, the continuous servo streamlines the wire tensioning process and eliminates slack. Since the precision of the end-effector's angle is not critical, minor deviations of a few degrees are negligible, making this servo an efficient and practical choice.

Manufacturing Prototype

The SLA process posed a challenge in separating the pin connections. To overcome this, metal pins were integrated to facilitate the linking of components. Dyneema wire was employed to actuate the finger. Mechanical stops were incorporated to enhance the functionality of the wire.

To accommodate fabrication feasibility, the design was scaled up. This adjustment ensured that the components could be realistically produced and assembled. Fine-tuning of tolerances was necessary to make the realistic size functional.

The gripper opens due to gravity, and the mechanical stops are placed to maintain its stretched position. This design allows the end-effector to be angled as needed for precise operations.

Regarding sleeve variations, I experimented with different material types specifically 50A and 85A (Shore Hardness) TPU. These variations were tested to identify the optimal balance of flexibility and rigidity for the application.

Figure 7-4: The overview of different fabricated iterations on the flexible chain.

Chapter 8

Integration with Robotics

In this section, we delve into the intricate details of optimizing robotic grasping motions with a focus on strategic positioning. We briefly touch upon the additional features of the gripper and discuss various controllers. The integration of human-friendly control, calibration processes, camera mounting, and collision avoidance techniques is thoroughly explored for overall system efficiency. The calibration methodology and diverse positioning strategies are highlighted.

The implementation of MoveIt ensures dynamic path planning and obstacle avoidance, facilitating seamless robotic arm navigation around crates. The detection pipeline employed for automated grasping is also outlined.

The conclusion points to areas for future exploration, including 3D scanning, improved motion planning, and ongoing efforts to enhance segmentation algorithms for faster processing.

8-1 Grasping Motion

In the initial phase, I meticulously positioned the robotic device directly above the targeted area. This deliberate placement was crucial for obtaining a comprehensive overview and ensuring precise alignment for subsequent maneuvers.

In the second step, the device approaches the target for a closer inspection. This proximity is essential for detailed detection and precise identification, facilitating effective interaction with the trusses.

During the pre-grasp phase, the prototype tilts to improve the grasping motion and enhance hook fitting under the peduncle. This tilt is chosen strategically to optimize both the viewing angle and interaction with the truss, improving overall operational effectiveness.

This tilt is particularly valuable for hooking tomatoes, especially when a straight-on approach is impractical due to limited space around the peduncle. This added flexibility proves crucial for navigating potential obstacles and achieving the desired positioning and orientation for effective operation.

Subsequently, the gripper closes, and the prototype orients upward, completing the grasping motion.

8-2 Additional Motions, Features

Dragging the Tomato Truss
The gripper can hook the peduncle, not fulling lifting the truss. After which the truss can be dragged for better positioning to complete the grasp.

Pushing the Tomato Truss
The sleeves on the end-effectors of the gripper, the hooks, allow to also push a tomato. This would be utilized if one truss is obstructing another truss, and should be moved out of the way first to avoid damage to either one.

8-3 Controllers

8-3-1 Human Friendly Control

The Human-Friendly Controller (18) is an impedance controller that facilitates Cartesian planning by accepting waypoints as goals. The stiffness can be configured to suit the prototype, with higher stiffness providing acceptable precision. This code integrates functions from the "learning from demonstration" code, enabling the recording and playback of waypoints.

8-3-2 MoveIt

The MoveIt controller employs linear Cartesian planning to ensure lab safety and predictability. This approach builds upon the detection pipeline presented in van den Bent et al. (2023), which leverages both MoveIt and the PILZ industrial motion planner (39).

8-4 Calibration

For arm positioning calibration, the methodology from Franzese (2023a) is implemented.

This codebase utilizes the Impedance controller, referenced in Section 8-3-1 by Franzese (2023b), along with the April tag library. Additionally, it incorporates the automated easy hand-eye calibration technique from IFL-CAMP (23). This combination proves effective in determining the camera's calibration.

The calibration process involves manoeuvring the robot arm around an April tag at various positions. This step is crucial as the camera is fixed to the robot arm, requiring calibration in relation to the arm's movements. The calibration movements can be saved, enabling recalibration later with a different camera module or to a different mounting position of the camera.

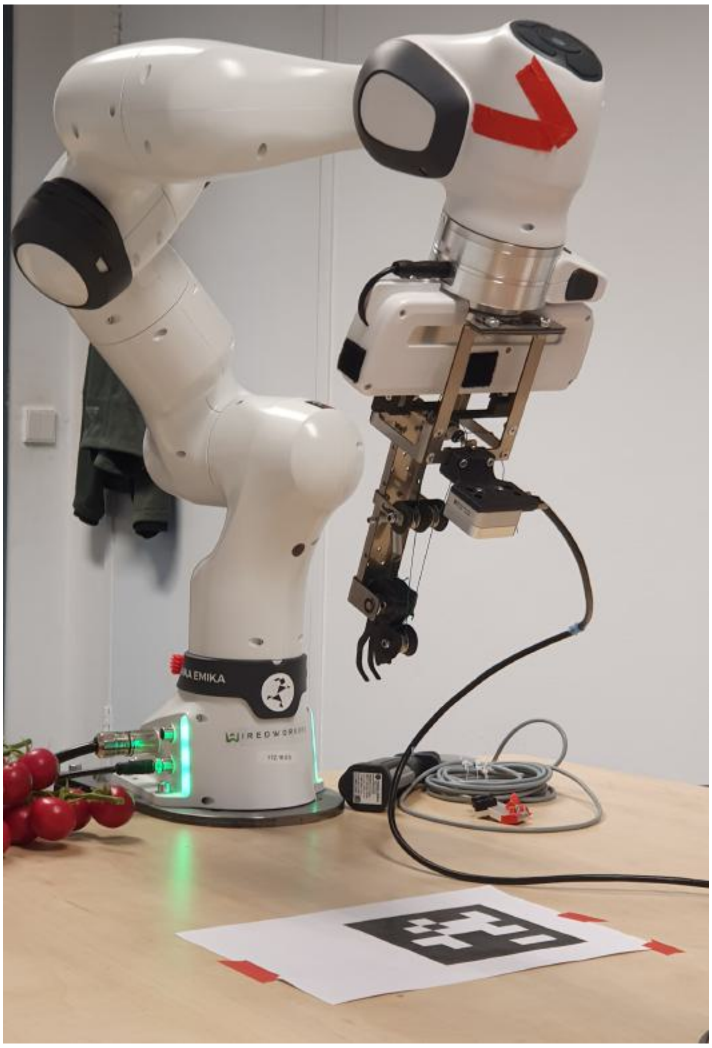


Figure 8-1: Calibration setup.

8-4-1 Camera Mounts

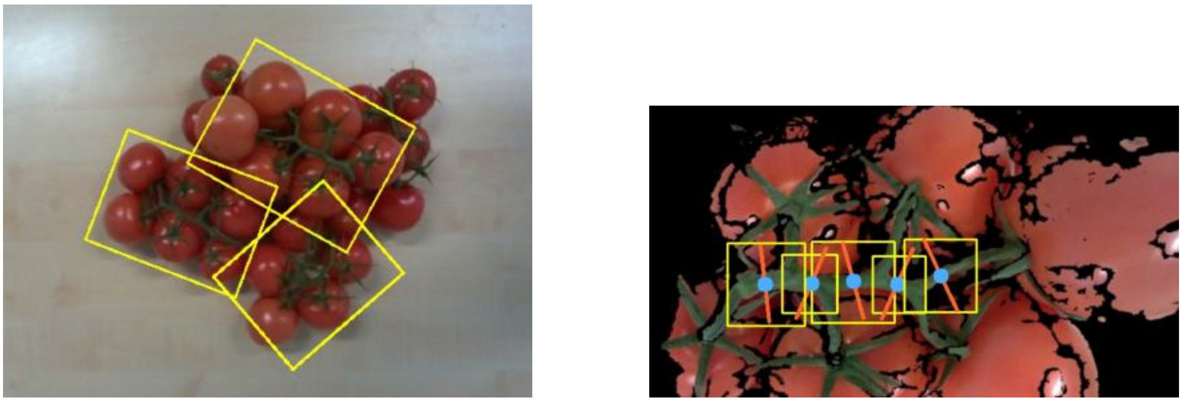
The camera mount is depicted in Figure 8-2. Various mounting positions provide different viewing angles. A downward-facing camera offers the best view of the tomato trusses. Adding a forward-facing camera might be advantageous for certain scenarios. The mounts can be angled, although in this setup, they are positioned to look straight down. The configuration supports the installation of multiple cameras, but in this particular setup, only one camera is utilized.

8-5 Detection

In this thesis, when detection is used, the detection pipeline by van den Bent et al. (2023) is used (reviewed in section 1-1). We utilize the bounding boxes for the trusses to localize the trusses, which is done by YOLOv5. Moving in for the close-up of these trusses gives possible

Figure 8-2: Optional mounting position.

grasping points and a pose for pinch grasping. This pose is utilized by approaching from one side after this pose is rotated to fit our prototypes' orientation, which is a 90 degrees rotation compared to what is used for a pinch grip with the e-hand.



(a) Bounding box for trusses.

(b) Grasping pose detection.

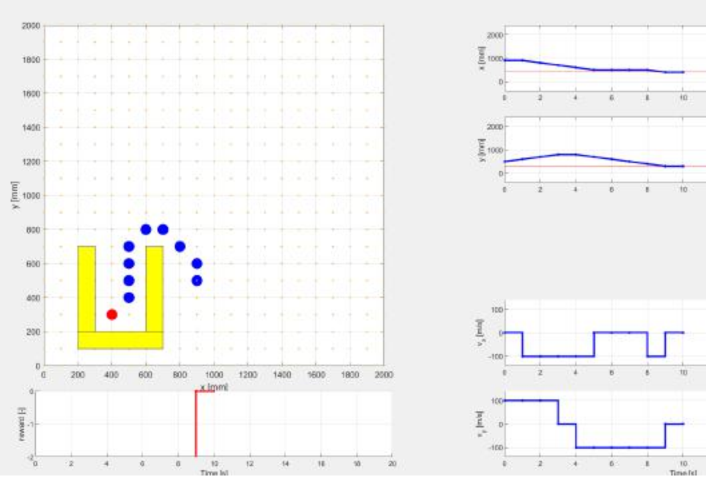
Figure 8-3: The detection pipeline utilized by van den Bent et al. (2023).

8-6 Collision Avoidance for the Crate

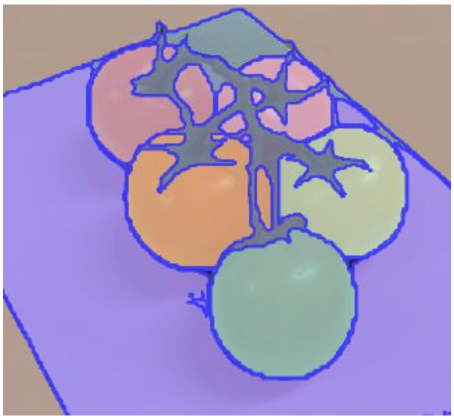
MoveIt handles motion planning for the robot arm by specifying the final goal, generating intermediate movement steps between the starting position and the goal. Collision avoidance with MoveIt involves adding an extra collision object for the prototype. Since the e-hand and the attached link (link 8) each have their own collision object, the prototype is designated as link 9. The collision object defines the size, collision properties, and spacing around the object. MoveIt considers these specifications to prevent collisions with itself or predefined obstacles.

The robot arm's workspace is delimited by imperceptible barriers designed to prevent collisions, ensuring user safety. Similarly, a similar approach is employed for the crate, where the dimensions of the crate are utilized to create virtual barriers, inducing collisions in the robot's planning process.

An alternative strategy to avoid collisions and plan for the goal is explained under future work below.



(a) Reinforcement Learning and Dynamic Programming Using Function Approximators for a crate Busoniu et al. (2017).



(b) Segmentation that can be utilized for peduncle segmentation or peduncle separation. (Zhao et al. (2023))

8-7 Future Work and Improvements

8-7-1 Motion by Waypoint in HFC

Utilizing an alternative solver for waypoint setting offers a distinct approach. These waypoints can be seamlessly integrated into the impedance controller (HFC), introducing additional constraints for maintaining a straight trajectory and preventing collisions with other robotic arm joints.

The application of the value iteration method, as detailed in Busoniu et al. (2017) in "Reinforcement Learning and Dynamic Programming Using Function Approximators", not only facilitates avoiding the crate but also optimally selects the shortest path to the target.

This solver, when applied in a discretized space tailored to real-world scenarios, provides a 2D representation of the 3D environment. While introducing additional collision objects to avoid contact with other tomatoes may be considered, it is deemed unnecessary given the robotic arm's top-picking design, minimizing the risk of disturbing surrounding tomatoes. This strategic approach to path planning and collision avoidance is pivotal for the effective implementation of the robotic system in handling vine tomato trusses.

8-7-2 Fast Segmentation

The current metadata-based segmentation algorithm proves overly intricate and computationally demanding. A preference leans toward a faster algorithm, exhibiting decent out-of-the-box performance and room for further optimization.

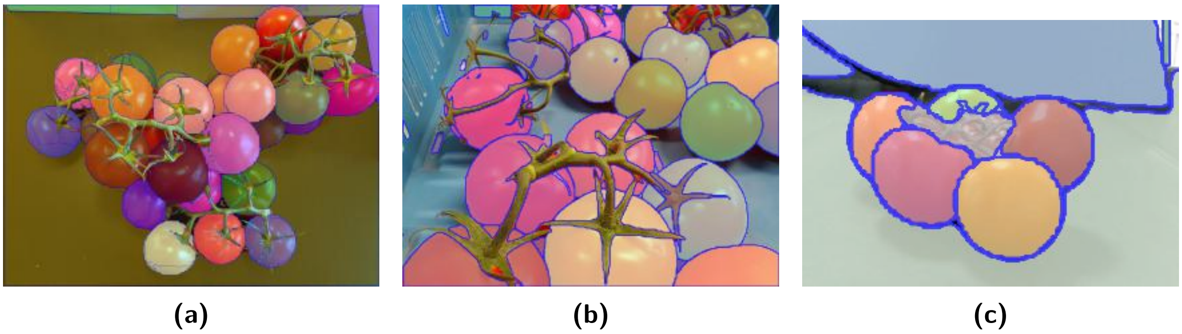
Contour fitting emerges as a viable alternative (Figure 8-4b), surpassing the existing bounding box method. It not only delivers a more accurate representation of the object's shape but also aids in precisely estimating the center of mass, an essential aspect when handling vine tomato trusses.

This method aligns with the geometric approach by de Haan et al. (2021). The anticipated enhancement in contour fitting is poised to significantly improve truss separation, potentially revisiting the centre of mass-based method. This approach could isolate the entire truss, estimating its weight based on factors such as the number of colours in the tomato fruit.

Fast segmentation by Zhao et al. (2023), coupled with de Haan's geometric method, holds promise for improved results by separating the peduncle and understanding the layout of the truss.

Creating space around the peduncle for enhanced grasping without damaging surrounding tomatoes is a crucial consideration.

Improper orientation upward could lead to detection errors, with inaccuracies in bounding box, grasping points, and depth estimation, rendering the system unusable.



(a) **(b)** **(c)**

Figure 8-5: Various representations of the FAST-SAM algorithm output.(58)

8-7-3 3D Objects

Incorporating 3D scanning of tomatoes could potentially enhance the robustness of detection by providing multiple viewing angles. However, in my research, I encountered challenges with this approach. Combining different point clouds often resulted in inaccurate representations and prolonged processing times, rendering this method not very successful. Additionally, the software intended for aligning point clouds either failed to perform this task effectively or was complex to operate.

Processing just the images yielded similar outcomes, suggesting that the issue was not solely with the 3D scanning process but also with the subsequent data processing and integration.

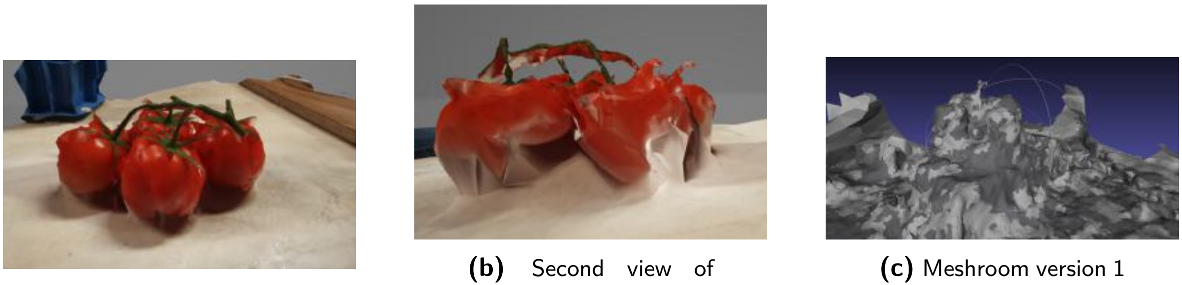
Despite these setbacks, I explored other scanning and processing methods, but they too produced low-quality images with artifacts and inaccuracies. Such images were unlikely to improve the overall performance of the detection system.

To potentially overcome these challenges, I implemented a rotating platform. This platform, which is inexpensive to produce via FDM 3D printing, is designed to rotate an object, such as a tomato truss. The platform operates on a ball bearing and is rotated using a string. By setting the camera at different azimuth angles, a complete 360-degree scan of the object is achievable.

The rotating platform's design is sufficiently large to accommodate a tomato truss, making it a practical tool for this purpose. However, the software attempted for processing the scans, including CloudCompare, Meshmixer, MaxtoA for 3ds Max 2024, Maya, Autodesk 3ds Max 2024, Recap, Recap Photo, Rhino8, Meshlab, and Meshroom, faced limitations in delivering the desired quality and accuracy of 3D models.

These experiences highlight the complexities involved in integrating 3D scanning technology into the detection process and underscore the need for further research and development in this area.

Figure 8-6: Rotating platform for 3d scans



(a) First view of Kirin

(b) Second view of Kirin

(c) Meshroom version 1 of tomatoes

Figure 8-7: Various subfigures

Chapter 9

Experiments

9-1 Test 1: Gripper Positioning

To assess the gripper's performance without the influence of motion planning and detection, a grid search test is conducted. This involves multiple grasping attempts at various positions on the peduncle, considering both the direction of approach and the specific position on the peduncle. The gripper's capability to pick up from different positions on the peduncle, not necessarily the optimally ranked position, is evaluated.

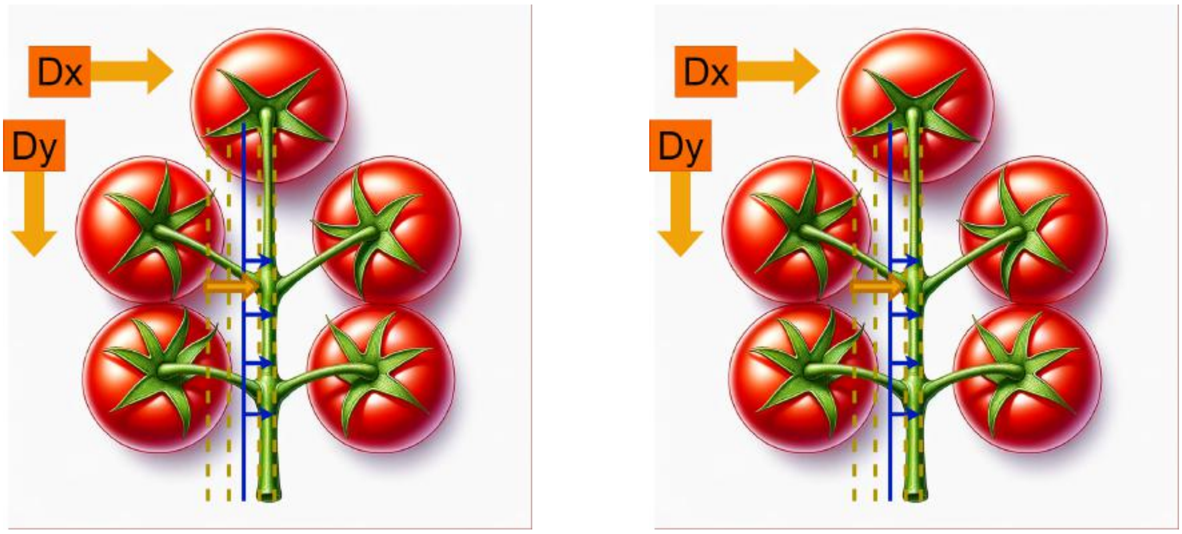
This initial test, without detection, reveals successful grasping locations and does establish a baseline for comparison. So that when integrated with detection, the gripper demonstrates resilience in achieving successful grasps despite detection inaccuracies.

The gripper maps a truss, and the analysis of grasping positions is illustrated in Figure 9-1a. The blue arrows represent grasping attempts with variations in dy (Figure 9-1b), with the number of grasps determined by the peduncle length. Pedicles are not utilized as grasping points due to their fragility and thinner structure, although some grasps may occur around a pedicle, particularly when close to the fifth tomato pedicle is an option for grasping.

The orange lines indicate different x positions corresponding to the blue grasping attempts. The approach is from one side, assuming the truss's consistent symmetry allows testing from a single side. A placeholder ensures alignment of the same truss after each attempt and facilitates comparison between different trusses. Alignment is assumed to be similar in the x-direction, allowing for variations in y-direction during grasping attempts.

The height (z-direction) is adjusted based on each truss's characteristics. Trusses are selected based on their suitability for grasping, excluding cases where the peduncle lies on the tomato, as seen in the "Provine van Nunhums" cultivar.

The variation in approach, as shown in Figure 9-2, aims to demonstrate that even if the orientation of the grasping point is inaccurate, the gripper can still successfully grasp the truss.



(a) The grid for which grasping attempts are made, showing discretization in the x and y directions.(Tomato truss generated by OpenAI (2024)

(b) Grasping test in the y-direction, along the blue line at each blue arrow, an attempt is made. The dx-steps are indicated by the dotted yellow lines.

Figure 9-1: Gripper grasping test configurations.

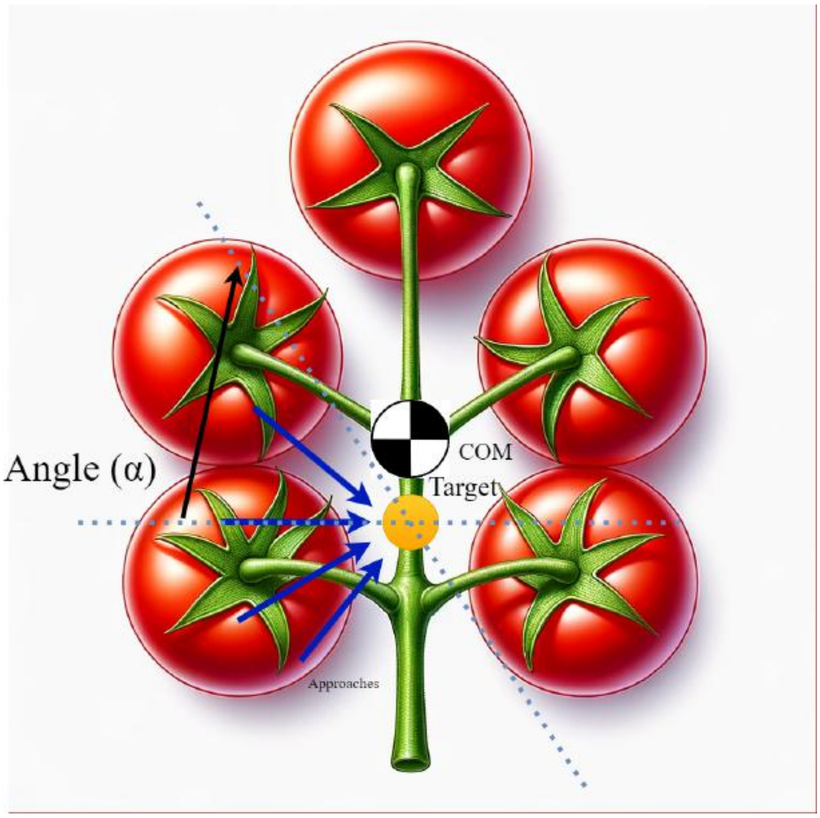


Figure 9-2: Grasping test with varying the approach angle.

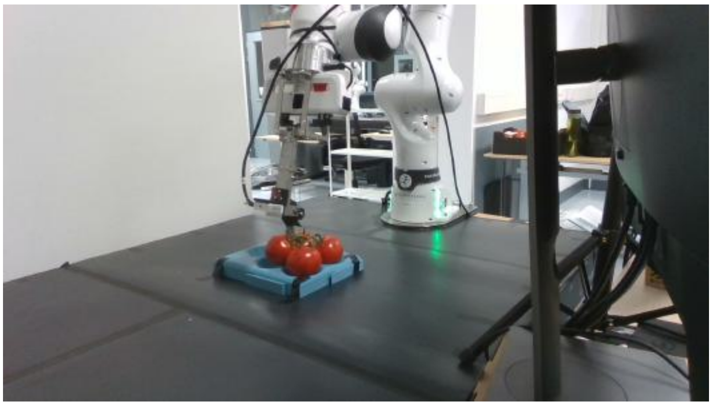


Figure 9-3: Showing the placeholder for tomatoes.

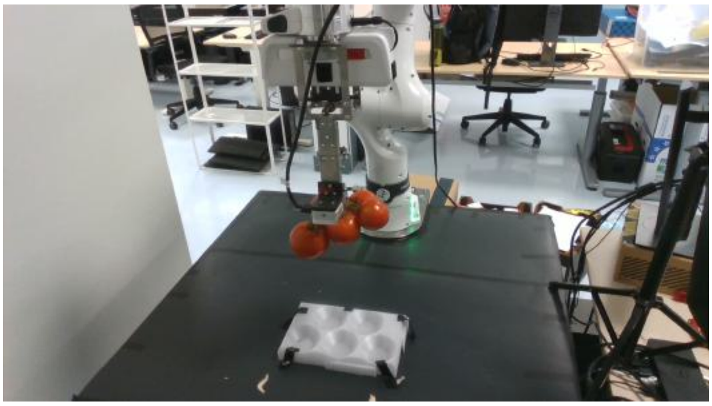


Figure 9-4: Top view, for the variations of the placeholder.

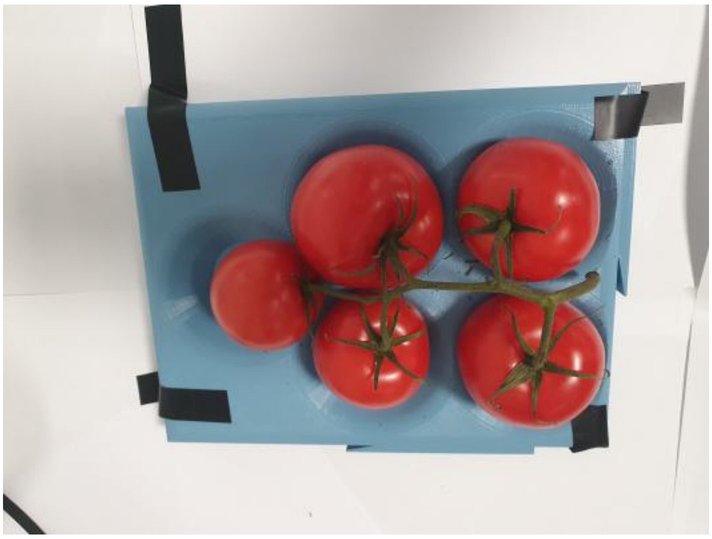


Figure 9-5: Tray to keep tomatoes in a measurable place.

9-2 Test 2: Edges of the Crate

During the investigation, I assessed how the gripper's placement within the crate impacts its performance, especially when dealing with trusses in challenging orientations. The evaluation consisted of trials where the gripper's movements were guided by either pre-recorded hard-coded motions, or by replaying waypoints created with "the learning from demonstration" code using "the human-friendly controller" [18]. The waypoints are Cartesian positions of the arm and the state of the gripper. The gripper consistently moved from the middle of the crate outward to the edges during motion planning. The primary constraints for reaching the crate's sides, considering possible collisions, were the mounted camera and the sheet metal frame. To address this limitation, alternative mounting options for the camera were explored, as detailed in Section 8-4-1. As the gripper can rotate around the z-axis, different approaches were considered for reaching the tomato, such as moving from the top with the gripper oriented towards the middle of the crate instead of outward. For illustrative purposes, trusses were dispersed around the crate, and each configuration was separately tested in the experiment. The selected tomatoes for this test were chosen for their accessibility from above, ensuring a fair comparison when evaluating the gripper's effectiveness in varied positions.

The arrangement of tomato trusses in the crate comprised of three trusses positioned in the corners (2, 7, 8), four located near the sides (1, 3, 9, 10), with two of them (9, 10) being skewed, posing a challenge due to their angled and sideways placement. Additionally, three trusses were situated close to the edges (4, 5, 6), leaving some space.

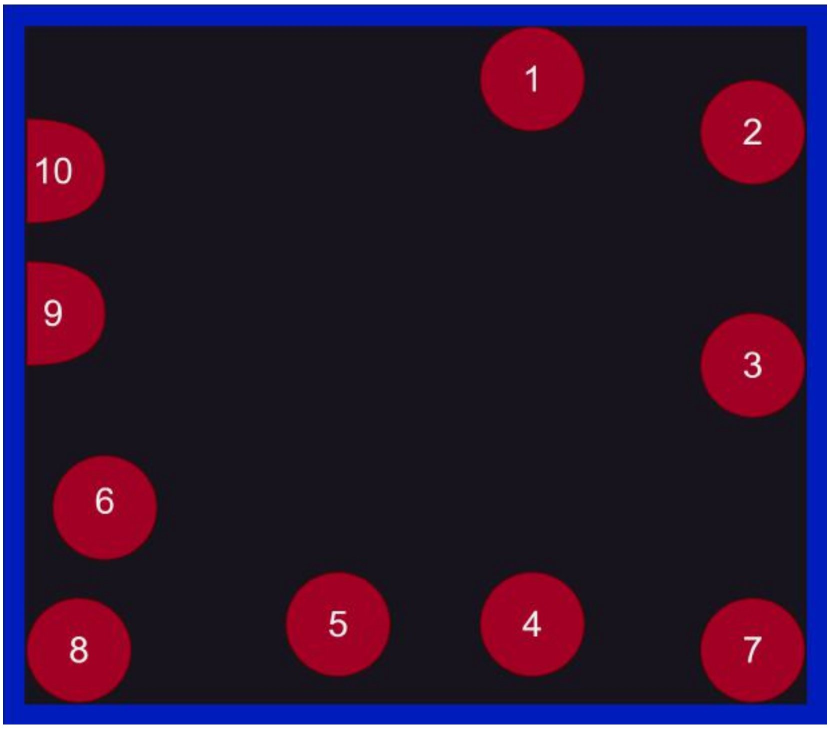


Figure 9-6: Tomato truss positions for test 2, trusses indicated in red.

9-3 Test 3: Tomato Pile

Grasping from a pile placed directly on the table, without the use of a crate.

The process involves directly interacting with a pile of trusses placed on a table, eliminating the need for a crate. This approach simplifies the grasping steps, as it removes the complexities and spatial constraints associated with a crate. By doing so, the robotic arm can freely access the trusses from multiple angles, enhancing its efficiency and effectiveness in picking up items from the pile. This setup also potentially reduces the risk of collision and allows for a more straightforward path planning for the robotic arm, focusing solely on the trusses' positions and orientations on the table.

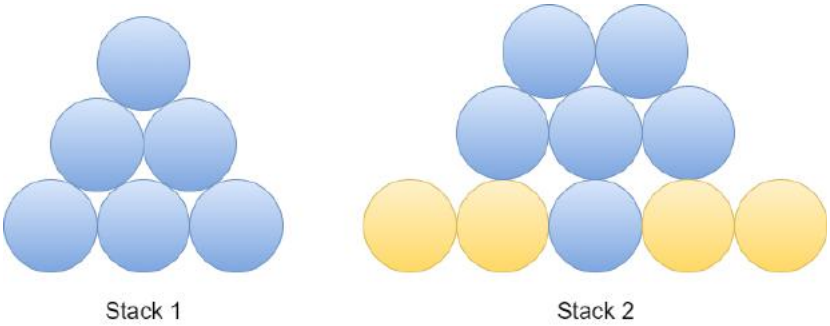


Figure 9-7: Positions of the tomato truss placement for test 3. In blue are the real trusses. In yellow the plastic ones.

9-4 Test 4: Tomatoes in a Crate

This test aims to demonstrate the pick-and-place operation from a crate, where the trusses are organized in a manner resembling how a human would arrange them in the crate.

In my approach to retrieving items from a stacked configuration within the crate, I tackled challenges related to collision avoidance by utilizing MoveIt, a motion planning framework (refer to section 8-6). MoveIt is employed for path planning, ensuring the robot navigates around the crate during grasping operations within the confined space.

The crate contains a stack comprising five real tomato trusses from the supermarket, along with additional fake plastic tomatoes. The objective of the test is to evaluate whether the prototype can successfully pick the tomato vines from the stack and relocate them to the designated drop-off point. In cases of detection errors, users have the option to override and restart the picking sequence. If a correct bounding box is not detected or the pick point is inaccurately identified, manual intervention is possible. This involves manually drawing the bounding box and selecting the pick point from the detected options.

9-5 Summary

In this chapter, various experiments were conducted to evaluate the gripper's performance in diverse scenarios. Test 1 involved assessing the gripper's capability without motion planning and detection, showcasing its ability to pick up from different positions on the peduncle. Test 2 explored the impact of gripper placement within the crate, considering alternative camera mounting options. Test 3 simplified the setup by grasping directly from a pile on the table, eliminating the need for a crate. Test 4 addressed collision avoidance challenges when retrieving items from a stack within a crate. These experiments provided valuable insights into the gripper's capabilities, thereby facilitating the refinement of the robotic system for improved tomato harvesting.

Chapter 10

Results

10-1 Test 1: Gripper Positioning

Performing z-variation proved challenging due to the limited space around the peduncle and the overall height variability. Consequently, this variation was excluded from the study after observing consistent failures when introducing it.

The variability in x-orientation (dx), stemming from different peduncle positions, yields insignificant results in the x-variation. Accessibility is binary – either reachable or not – influenced by peduncle spacing. Aligning different peduncles to map the impact of various x-orientations proves unfeasible. An invalid dx indicates collisions with tomatoes or the peduncle without successfully grasping the truss.

The application of the impedance controller proves beneficial in situations with restricted peduncle space. When collisions occur, the controller gradually manoeuvres into the designated position, salvaging some grasps that would otherwise fail.

Given the lack of valid contributions from dx variations, the optimal x-position is chosen for comparing the effects of different grasping positions on the peduncle, as depicted in Figure 10-2. The bar plot distinctly portrays the expected outcome, revealing challenges with the "Provine van Nunhums" cultivar, resulting in failed grasps even in proximity to the centre of mass. Challenges are particularly evident at the beginning and end of the peduncle, where the end often slopes downward, and the beginning may involve pedicles that collide.

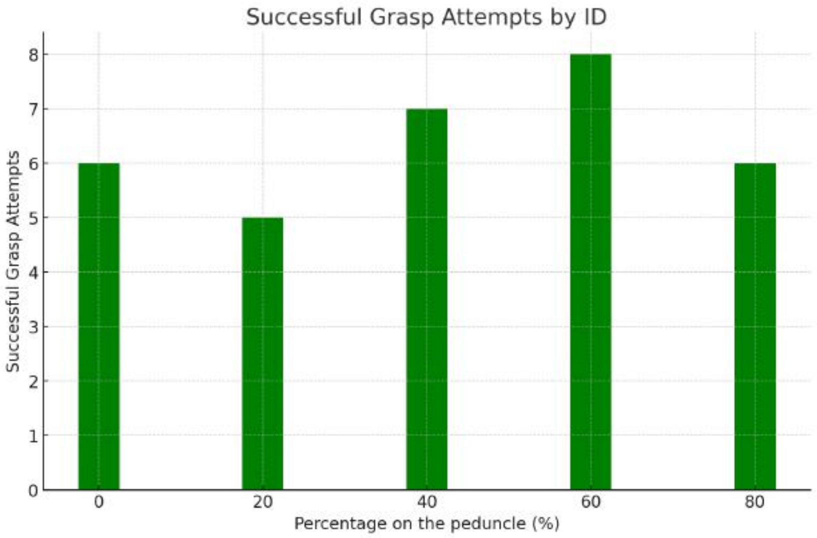


Figure 10-1: Successful attempts plotted for the five normalized positions on the peduncle, out of the 10 trusses in total. Where 100% is the peduncle ending to the vine (where it was cut-off), and 0% is the other end of the peduncle.

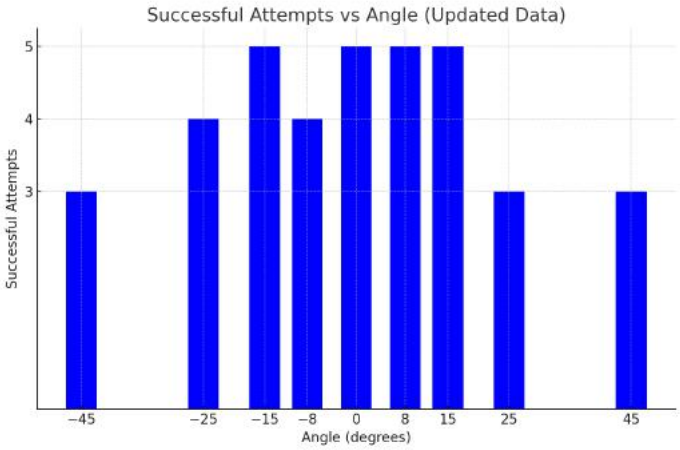


Figure 10-2: Successful attempts plotted for the angle of approach.

10-2 Test 2: Edges of the Crate

Truss number 2 (Figure 9-6) experienced scraping against the crate side during lifting, posing a notable issue. Despite the technically successful grasp, I categorize it as a failure due to the undesired contact. Truss number 9 (Figure 9-6), was a challenge as it was too tilted, and the gripper could not get into position to lift the truss by the peduncle. The peduncle's orientation toward the side of the crate reflects a realistic scenario, compared to a slope towards the crate's interior. Nevertheless, the gripper's reach was adequate for various positions, resulting in the successful grasping of 8 out of the 10 trusses.

10-3 Test 3: Tomato Truss Pile

10-3-1 Manual Execution

Due to technical challenges in both software and hardware aspects, tests 3 and 4 could not be executed as originally planned. The intended purpose was to assess the entire system in a real-life scenario, aligning with related research parameters. However, a scaled-down version of the test was conducted due to these constraints, and the obtained results will be presented.

The chosen grasping points, located near the centre of mass of the tomato trusses, were selected. Only feasible grasping points were considered, and the movements were recorded and directly replayed using the "learning from demonstration" method. Specifically, two stacks of six trusses of the "Provine van Nunhums" cultivar were tested. Despite the challenges, the test yielded success, with all six trusses being successfully grasped.

10-3-2 Detection Execution

Previous tests, utilizing the detection pipeline with smaller batches consisting of supermarket tomatoes, offer insights into automated operations.

The detection performance for the realistic-looking tomatoes was suboptimal, requiring manual bounding box selection. Both stacks are tested twice with a different configuration.

The pile of tomatoes did not pose significant challenges. However, one supermarket truss failed as it lost a tomato, causing instability and slipping out of the gripper. Plastic tomatoes, being light and consistently spaced, generally did not present challenges during the testing process.

Attempt	Stack	Success Rate
1	1	6 of 6
2	1	6 of 6
3	2	11 of 11
4	2	10 of 11

Table 10-1: Grasping Attempts and Success Rates for Different Stacks

10-4 Test 4: Tomatoes in a Crate

The gripper demonstrates its capability to lift and relocate objects accurately. Utilizing additional collision objects (section 8-6), the gripper efficiently manoeuvres around the crate, mitigating the need for direct crate interaction. Occasionally, MoveIt faces challenges in resolving specific configurations, but adjusting the initial gripper position or orientation often resolves this issue. Due to spatial constraints at the edges of the crate, the robot arm sometimes needs to start at the centre of the crate to achieve the optimal starting position, to make the pick and place action, which is solvable with MoveIt.

Three stacks of five trusses were attempted, revealing varying outcomes. The first stack encountered challenges with path planning to the two bottom trusses, as MoveIt consistently identified collisions, causing operational interruptions. In contrast, the middle stack proceeded without issues. The last stack presented errors related to the top truss, but adjusting the initial position resolved the problem. However, the last truss at the bottom faced issues due to a detected collision during movement, which was not solved. The mixed results highlight the prototype's sensitivity to specific configurations, and potential improvements are needed for robust performance across diverse scenarios.

Stack	Initial Attempt	Adjusted Attempt
1	2 of 5	2 of 5
2	0 of 5	3 of 5
3	3 of 5	3 of 5

Table 10-2: Results of Gripper Testing on Different Stacks

10-5 Summary

In the results chapter, Test 1 evaluated gripper positioning and the approach angle. Test 2 addressed challenges at the edges of the crate, with specific instances of scraping and tilting, resulting in 8 out of 10 successful truss grasps. Test 3, designed for real-life scenario assessment, faced technical constraints, leading to a scaled-down version. Manual execution yielded successful grasps for all 6 trusses tested. Detection execution using supermarket tomatoes and realistic-looking plastic tomatoes showcased the performance with detection included, with one truss failed to grasp successfully due to instability. Test 4 demonstrated the gripper's ability to lift and relocate trusses from a crate, navigating around the crate with collision objects. MoveIt occasionally faced configuration challenges, resolved by adjusting the arm's position, highlighting limitations near crate edges. Overall, the gripper showed promising performances for a filled crate with tomato trusses and moderately successful.

Chapter 11

Discussion

11-1 Test 1: Gripper Positioning

11-1-1 Grasp Positions in a Grid

Challenges arise for the adjustments in the z-direction by the confined spacing of the "Provine van Nunhums" cultivar. However, alterations in the x-direction encounter a sharp limitation, leading to collisions with tomatoes beyond a specific point. This limitation is expected to be less problematic when dealing with tomatoes that offer more space around the peduncle, particularly when the peduncle is positioned higher above the tomatoes. In such instances, the maximum reach is constrained by the length of the end-effector.

The variability in the y-directions does not take into account the presence of pedicles, representing a limitation in this test. A more effective approach would involve testing the detected grasping positions for success rates, allowing for a comparison with the rankings learned by van den Bent et al. (2023) for the several grasping positions. Despite this limitation, the test demonstrates a decent success rate on a challenging cultivar when compared to prior research, particularly in contrast to random grasping positions and the centre of mass.

11-1-2 Angle of Approach

This test had some collision with the tomato fruits, which left a bruising or a dent. A bigger angle compared to a straight on approach means that for the higher angles not both fingers are under the peduncle or the gripper should move in further during the pre-grasping motion. The reason it failed was due to either pushing the truss away due to collision with a tomato, or collision with a pedicle. Additionally, an attempt is considered a failure, when the peduncle and a pedicle were hooked instead. This leads to an unstable grasp on the truss, causing the lifting attempt to be considered a failure.

11-2 Test 2: Edges of the Crate

Although there are many small variations in which the tomatoes can be positioned near the crates edges combined with the many cultivars and truss topologies that are available the test gives insight in the grippers performance for the difficult positions in a crate. The trusses are used from the cultivar "Provine van Nunhums", which is given the statistics shown in chapter 3 a hard to grasp truss due to the limited spacing and variation in truss shapes. As a realistic crate is stacked quite orderly, with only a few trusses ending up with difficult positions due to transportation or moving of other trusses, this example case is harder than what would be found in the use-case scenario. As the difficulty was not in grasping the tomatoes in these positions, I think the batch size is adequate.

The test is influenced by bias as the user stacks and selects the trusses. The user positions the gripper on an optimal location and is able to assess depth for grasping locations to a greater degree than the current detection could. I tried to execute each moment as close to the automated grasping as possible, using the same steps the pre-programmed grasping motion would.

The truss number 2 during lifting scraped the side of the crate, which is an issue. This grasp was successful, but I consider it failure. This can be avoided using the feature of the gripper that drags the truss first, to improve accessibility and does not need to be a problem.

The truss number 9, can be avoided with having the camera mounted in a different position, which is not the case for the current prototype.

11-3 Test 3: Tomato Truss Pile

Due to technical difficulties software and hardware wise, this test 3 was not performed with the tomato batch from the greenhouse ("Provine van Nunhums"), using the detection software. Instead, a stack was manually executed without detection. Manually guiding the gripper with playing back the waypoints from demonstration. The bottom layer is never an issue, as they can be considered the same as individual trusses.

The second segment of Test 3, specifically focused on Stack 2, highlighted challenges in the detection system's handling of plastic tomatoes, with manual selection introducing bias to the results. Similar to real tomatoes that deviate from the training set, they face detection issues, as the bounding boxes may not always be wide enough, causing the center of the bounding box to misalign with the center of the tomato truss.

Picking up plastic tomatoes posed no significant challenges, primarily due to their consistent weight and fixed spacing. Hence, for the experiment, real tomatoes were positioned atop the plastic ones. While mixing different cultivars typically faces hurdles due to variations in spacing around the peduncle, the supermarket tomatoes exhibited acceptable spacing. Additionally, the gripper's grasp height proved effective for both plastic and real tomatoes.

11-4 Test 4: Tomatoes in a Crate

The current approach, attempting to grasp from the top, might not be the optimal solution according to MoveIt, as it leads to collisions. An alternative technique, discussed in the Future Work section (section 8-7), could potentially address this issue entirely.

MoveIt occasionally struggles with certain configurations, and adjusting the initial gripper position or orientation can resolve these challenges. The detection pipeline is highly sensitive to camera positioning, requiring a fixed distance for each step in the process to maintain accuracy. The code assumes the gripper always faces the crate, and the camera is consistently angled perpendicular to the crate. Additional tuning may be needed for the acceleration and velocity during the lifting of tomatoes after grasping.

The detection process, involving initial crate overview and subsequent closer inspection of trusses, is hindered by the pipeline's sensitivity to camera position. Deviations from the training set's camera distance can lead to detection issues or reduced accuracy. Hovering over a truss for grasping point detection sometimes poses a challenge, potentially resulting in collisions with the crate. The current pipeline does not support angled viewing, as the coordinates are not transformed to the camera frame for such scenarios.

Supermarket tomatoes, lacking the freshness of greenhouse tomatoes, exhibited fruit detachment during the experiment. This observation suggests the need for further tuning in the acceleration and velocity parameters for lifting tomatoes after grasping.

11-5 Summary

The peduncle can be held stable and grasped as long as the hook can manoeuvre under the peduncle successfully. The tomato cultivar influences the overall success rate. Stacked supermarket trusses can competently be picked and placed

The more difficult configurations are possible but require improved locating of the grasping point. Overall, the gripper can successfully grasp on different positions with a wider range of orientations on the peduncle.

The Discussion explores insights and challenges from the various tests. In Test 1, gripper positioning adjustments in the z-direction were effective in addressing spacing challenges, while limitations in the x-direction led to collisions. Test 2 examined gripper performance at crate edges, revealing challenges with trusses scraping against the crate and tilting. Test 3, focusing on a tomato truss pile, faced technical issues, prompting a manual execution. Detection challenges were noted with plastic tomatoes, and real tomatoes were successfully handled. In Test 4, attempts to grasp from the top encountered issues, suggesting the need for alternative techniques. MoveIt and the detection pipeline exhibited sensitivity to configurations of the robot arm and camera positioning, necessitating further tuning for optimal performance. The Discussion emphasizes the need for addressing challenges and refining the system for robust, automated handling of various scenarios.

Chapter 12

Future Work and recommendations

For future research and exploration, several aspects merit further investigation.

The section on future work (discussed in section 8-7) delves into additional enhancements related to robotic integration and addresses specific challenges in motion planning. The exploration of alternative solvers, coupled with an impedance controller, presents an avenue for refining motion planning. The consideration of faster segmentation algorithms is proposed to enhance the handling of vine tomato trusses. The chapter also acknowledges the complexities and future opportunities in advancing 3D scanning techniques for more robust object detection. It recommends further research to address the intricate integration of advanced path planning and object recognition in robotic systems.

In future comparisons for standardized tests involving similar cultivars, it is suggested that reliable experiments with batches of similar sizes could provide results to systematically compare methods.

The gripper's current maximum weight capacity presents an opportunity for investigation, exploring its performance across different cultivars. Introducing flexibility or adaptability to the hook could enhance its utilization. While the exploration of foldable or origami grippers is beyond the scope of this research, it is acknowledged as a potentially promising avenue for improving the hooking mechanism.

Consideration is given to the detection system's ability to identify potential grasping positions in scenarios such as sloppily loaded crates resulting from e.g. transportation. This capability could extend to the autonomous emptying of such crates by a robotic arm.

In conclusion, the hook, as a gripper, demonstrates effective functionality; however, there is room for improvement, possibly through shape modifications to enhance its grip.

Chapter 13

Conclusion

The study comprehensively evaluates concepts for robotic gripping systems, particularly in the context of handling delicate agricultural products like tomato trusses. It highlights the challenges and practical issues encountered in testing prototypes, including unexpected complications. The study underscores that neither rigid nor soft grippers fully meet the requirements for delicately handling tomato trusses by the peduncle. Rigid grippers, despite their market dominance, lack suitability for such specific agricultural tasks due to their inability to handle fragile components like the tomato truss peduncle gently. The potential of elongated fingers for better access and grip on the fragile peduncle is noted as a promising concept.

Soft grippers, exemplified by Soft Robotics Inc., offer commendable flexibility but are limited by their larger size and higher cost, making them less ideal for certain agricultural applications. The study introduces the concept of Finray grippers, which show promise due to their ability to conform and adapt to contact surfaces, combined with a reasonable size for peduncle grasping.

The research also identifies significant differences between cultivars, which greatly affect the success rate of various grasping methods. Factors such as the spacing around the peduncle, the distance between the pedicles, and the overall weight are crucial in influencing design criteria. The study reveals that pinch gripping, tested using a loaded lever, tends to damage the peduncle.

However, the study finds that the peduncle can be stably grasped and held, provided the hook can manoeuvre effectively under it, with the tomato cultivar playing a key role in the success rate. Stacked supermarket trusses can be efficiently picked and placed by the gripper. While more complex configurations are achievable, they require enhanced precision in locating the grasping point. In conclusion, the study demonstrates the gripper's ability to successfully grasp at different positions and orientations on the peduncle, offering insights for further development in robotic handling of delicate agricultural products.

Appendix A

Appendix

A-1 Inertia Tensor Calculation

The following MATLAB code calculates the inertia tensor and other relevant properties of the design:

```
% Define the offsets in millimeters
dx = 48.54;
dy = 66.00;
dz = 5.59;

% Define the center of mass in millimeters
COM_X = 5.28;
COM_Y = -119.69;
COM_Z = -30.00;

% Calculate the center of mass relative to the flange
X_com_flange = dx + COM_X;
Y_com_flange = dy + COM_Y;
Z_com_flange = dz + COM_Z;

% Convert center of mass position to meters
meterX_com_flange = X_com_flange * 1E-3;
meterY_com_flange = Y_com_flange * 1E-3;
meterZ_com_flange = Z_com_flange * 1E-3;

% Define the inertia tensor in gram * square millimeters
I = [91919204.60, -137213.47, -448825.80;
    -137213.47, 11678626.87, 10289877.91;
    -448825.80, 10289877.91, 90470127.35];
```

```
% Convert inertia tensor to kg * square meters
nI = I * 1E-3 * 1E-6;
```

This code first defines the offsets and the center of mass of the system in millimeters. Then, it calculates the center of mass relative to the flange and converts these measurements into meters. Finally, the inertia tensor, initially given in grams and square millimeters, is converted into kilograms and square meters for further use in calculations.

The calculation of the inertia tensor and other relevant properties of the design is presented as follows:

Offsets and Center of Mass

Given the offsets (dx, dy, dz) and the center of mass (COM_X, COM_Y, COM_Z) in millimeters:

$$\begin{aligned}
\mathrm{dx} &= 48.54\,\mathrm{mm},\\
\mathrm{dy} &= 66.00\,\mathrm{mm},\\
\mathrm{dz} &= 5.59\,\mathrm{mm},\\
\mathrm{COM\_X} &= 5.28\,\mathrm{mm},\\
\mathrm{COM\_Y} &= -119.69\,\mathrm{mm},\\
\mathrm{COM\_Z} &= -30.00\,\mathrm{mm}.
\end{aligned}$$

Center of Mass Relative to the Flange

The center of mass relative to the flange is calculated as:

$$\begin{aligned}
\mathrm{X\_com\_flange} &= \mathrm{dx} + \mathrm{COM\_X},\\
\mathrm{Y\_com\_flange} &= \mathrm{dy} + \mathrm{COM\_Y},\\
\mathrm{Z\_com\_flange} &= \mathrm{dz} + \mathrm{COM\_Z}.
\end{aligned}$$

Conversion to Meters

The center of mass position in meters is obtained by:

$$\begin{aligned}
\mathrm{meterX\_com\_flange} &= \mathrm{X\_com\_flange} \times 10^{-3},\\
\mathrm{meterY\_com\_flange} &= \mathrm{Y\_com\_flange} \times 10^{-3},\\
\mathrm{meterZ\_com\_flange} &= \mathrm{Z\_com\_flange} \times 10^{-3}.
\end{aligned}$$

Inertia Tensor

The inertia tensor I in gram-square millimeters is given by:

$$I = \begin{pmatrix} 91919204.60 & -137213.47 & -448825.80 \\ -137213.47 & 11678626.87 & 10289877.91 \\ -448825.80 & 10289877.91 & 90470127.35 \end{pmatrix}$$

Conversion to Kilograms and Square Meters

The inertia tensor in kilograms and square meters nI is calculated as:

$$nI = I \times 10^{-3} \times 10^{-6}$$

A-2 Calculation of the Steel Truss Weight

Material Properties: Density of S235 steel, $\rho_{\text{S235}} = 7.85 \times 10^{-3}$ g/mm^3.

Base Truss Element: Diameter, $D_{\text{staf}} = 8$ mm, Length, $L_{\text{staf}} = 120$ mm. Calculated volume and mass of the truss element are given by

$$\text{Vol}_{\text{staf}} = \pi \left(\frac{D_{\text{staf}}}{2}\right)^2 L_{\text{staf}}$$

$$m_{\text{staf}} = \rho_{\text{S235}} \times \text{Vol}_{\text{staf}}$$

Hole in Truss Element: Hole diameter, $D_{\text{hole}} = 4$ mm, Angle, $\theta = 45°$. Adjusted length and volume of the hole are calculated as

$$L_{\text{hole2}} = \frac{8}{\tan(\theta)}$$

$$\text{Vol}_{\text{hole}} = \pi \left(\frac{D_{\text{hole}}}{2}\right)^2 L_{\text{hole2}}$$

$$m_{\text{hole}} = \rho_{\text{S235}} \times \text{Vol}_{\text{hole}}$$

Tomaat Shape Block: Dimensions: Width, $b_{\text{block}} = 25$ mm, Height, $h_{\text{block}} = 15$ mm, Depth, $d_{\text{block}} = 35$ mm. Volume and mass of the block are given by

$$\text{vol}_{\text{block}} = b_{\text{block}} \times h_{\text{block}} \times d_{\text{block}}$$

$$m_{\text{tomaat}} = \rho_{\text{S235}} \times \text{vol}_{\text{block}}$$

Removed Corner Calculation: Corner dimensions and volume are

$$\text{corner\_vol} = d_{\text{block}} \times h_{\text{corner}} \times b_{\text{corner}}$$

$$m_{\text{corner}} = \rho_{\text{S235}} \times \text{corner\_vol}$$

Fasteners: M4 Screw and Nut calculations are based on their respective geometries and material density.

Total Weight: The total weight of the assembly is computed as

$$m_{\text{total}} = m_{\text{effective}} + 5 \times (m_{\text{tomaat}} + M4 + \text{moer} - m_{\text{corner}})$$

Drill Depth and Purchase List: Drill depth, h_{depth} and required material length, rechthoek are calculated for the assembly process.

A-3 Springs Tested

Available springs with dimensions that could be appropriate tested.

Spring ID	Average Spring Constant (N/m)
1	1.460096
2	1.345067
3	0.950900
4	1.013700
5	0.329062
6	0.213573

A-4 Spring Elongation Test

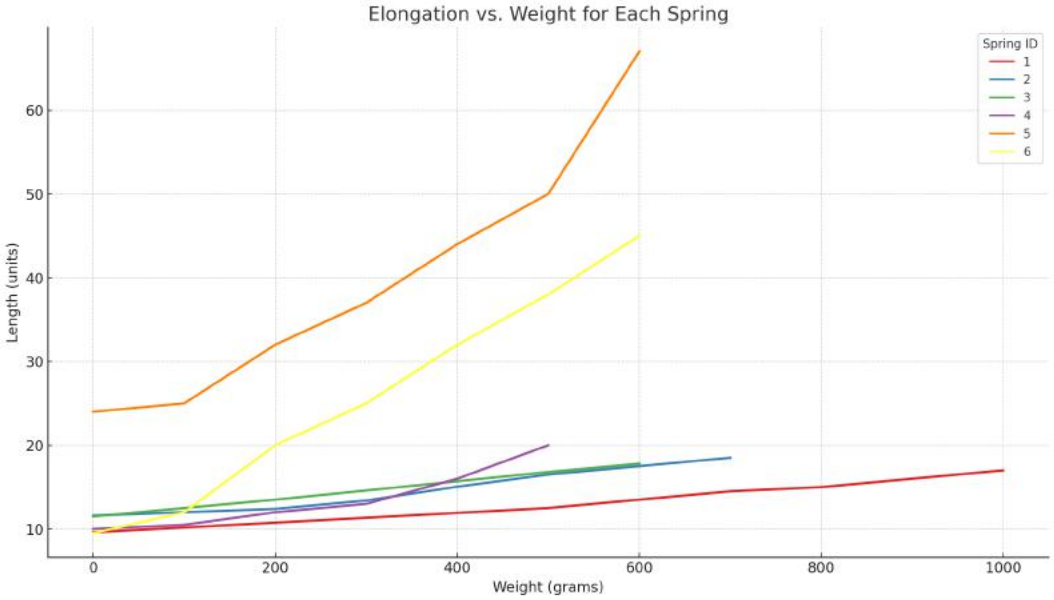


Figure A-1: Springs options for pre-tensioning of the end-effector.

A-5 E-hand Test Data

Attempt	Left	Right	Total	Time	Command: Move/Grasp	Holding position	ROS OK
1	1	1	2	780	m	v	v
1	1	1	2	1080	g	v	v
1	1.5	1	2.5	1050	m	v	v
1	1.5	1.5	3	1200	m	v	v
2	1.5	1.5	3	1520	g	v	v
1	2	1.5	3.5	1760	m	v	v
2	2	1.5	3.5	1930	g	x	v
1	1	1	2	780	m	v	x
2	1	1	2	580	m	v	x
3	1	1	2	760	m	v	x
4	1	1	2	810	m	v	x
1	1	1	2	1130	g	v	v
2	1	1	2	1100	g	v	v
3	1	1	2	1200	g	v	v
1	1.2	1.2	2.4	1150	m	v	x
2	1.2	1.2	2.4	460	m	v	x
3	1.2	1.2	2.4	760	m	v	x
1	1.2	1.2	2.4	1200	g	v	v
2	1.2	1.2	2.4	840	g	v	v
3	1.2	1.2	2.4	1110	g	v	v

Table A-1: E-hand loading test.

A-6 TPU Shear Modulus

Given that the elastic modulus E is 9.3 MPa and the Poisson's ratio ν is approximately 0.495, the shear modulus G can be estimated using the formula:

$$G = \frac{E}{2(1+\nu)} \tag{A-1}$$

Substituting the given values:

$$G = \frac{9.3\,\text{MPa}}{2(1+0.495)} \tag{A-2}$$

$$G \approx 3.11\,\text{MPa} \tag{A-3}$$

Therefore, the estimated shear modulus for the OVERTURE TPU 95A filament is about 3.11 MPa.

A-7 Vine Tomato Cultivar Statistics

	min	mean	max
Weight (g)	341.2	675.792857	861.2
Number of tomatoes	3.0	5.285714	6.0
Pedicle to P COM [mm] 1	7.0	11.107143	16.0
Pedicle to P COM [mm] 2	8.0	12.392857	17.0
Pedicle to P COM [mm] 3	7.5	11.785714	18.5
Pedicle to P COM [mm] 4	12.0	15.714286	22.0
Peduncle thickness min	3.5	4.187143	5.5
Peduncle thickness mid	4.0	5.314286	6.5
Peduncle thickness max	5.0	5.675000	6.5

Table A-2: Capricia van Rijk Zwaan, Juli

Attribute	Minimum	Average	Maximum
Weight (g)	471.20	597.04	696.20
Fruit	3.00	4.40	5.00
Peduncle 1	4.10	4.654	5.21
Peduncle 2	3.33	4.014	4.80
Peduncle 3	3.21	3.665	4.12
Pedicle 1	2.63	3.014	3.53
Pedicle 2	2.70	3.084	3.59
Pedicle 3	2.63	3.082	3.75
Fruit max	0.00	51.09	68.45
Fruit min	0.00	36.318	66.990

Table A-3: Supermarket trusses

	min	mean	max
Weight (g)	462.00	624.969697	798.00
length	10.00	17.445455	25.00
height	6.00	20.514000	82.79
fruits	2.00	4.515152	7.00
Peduncle length	3.04	53.510303	100.00
space COM	4.00	20.971212	49.00
Space Left	0.00	9.576970	20.00
Space Right	0.00	13.458788	30.00

Table A-4: Provine van Nunhums

A-8 Fatigue Life for Sheet Metal Prototype 2

The fatigue life of the stainless steel body is high and allows for some errors causing impact during testing of the prototype.

$$
\begin{aligned}
&\text{Calculate Area (A):} \\
&\text{Width} = 1.5 \text{ mm} \\
&\text{Length} = 4\pi \text{ mm} \\
&A = \text{Width} \times \text{Length} \\
&A = 1.5 \times 4\pi \text{ mm}^2 \\
&A = 1.5 \times 4\pi \times 10^{-6} \text{ m}^2 \\
&\text{Calculate Stress } \sigma\text{:} \\
&\text{Force (F)} = 10 \text{ N} \\
&\sigma = \frac{F}{A} \\
&\sigma = \frac{10}{1.5 \times 4\pi \times 10^{-6}} \text{ Pa}
\end{aligned}
$$

$$
\begin{aligned}
\text{Given: } & \sigma_a = 0.53 \text{ MPa}, S'_f = 1000 \text{ MPa}, b = -0.09 \\
\text{Basquin's Equation: } & \sigma_a = S'_f \cdot Nf^b \\
\text{Rearranging for } Nf: & Nf = \left(\frac{\sigma_a}{S'_f}\right)^{\frac{1}{b}} \\
\text{Substituting Values: } & Nf = \left(\frac{0.53}{1000}\right)^{\frac{1}{-0.09}} \\
\text{Calculating } Nf: & Nf \approx 2.49 \times 10^{36} \text{ cycles}
\end{aligned}
$$

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