Novel Twisting-Tube Gripper: Design and Evaluation for Blackberries

For the degree of Master of Science in Mechanical Engineering at Delft University of Technology

To be defended on 19th of July 2022

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Abstract:

Fruit and vegetable production is increasing worldwide, and farmers currently face a tough challenge in finding enough agricultural workers. Automation of the labour-intensive task of crop harvesting could help fill in this gap between supply and demand. However, picking soft fruits is challenging, as they can be easily damaged if not carefully handled. This paper focuses on designing and evaluating a novel robotic gripper for gently harvesting blackberries, which is nicknamed the Twisting-Tube gripper. The gripper consists of a fabric tube which closes in an enveloping manner due to a motorized twisting action of the ends of the tube. A custom tensile-testing bench was used to test blackberry detachment, release, and damage rates for three types of tubes: radially elastic, fully elastic, and compressible. These tubes were manufactured out of different combinations of foam padding, spandex and food-safe cotton cheesecloth and compared to a handpicked control. The results showed that compressible, thicker cheesecloth outperformed radially elastic or fully elastic or extremely compressible tubes with 82% successful detachment and 95% successful release rates. Furthermore, the Twisting-Tube gripper with thick cheesecloth discoloured at least one drupelet of 19% of the blackberries after 48 hours, which is less than the 33% measured in the handpicked control group, but still more than the 10% of the unhandled berries with discolouration. Moreover, the gripper with thick cheesecloth caused leakage to at least one drupelet for 29% of the successfully harvested blackberries compared to 13% of the hand-harvested control. It can be concluded that the presented Twisting-Tube gripper prototype shows promising results for harvesting small soft fruits.

Keywords: soft grippers; end-effectors; soft robotics; blackberry; fruits; vegetables; harvesting; handling;

1 Introduction

The majority of countries around the world have dietary recommendations that include daily intake of different fruits and vegetables. The vitamins and minerals they provide to the diet help protective mechanisms in the human body and the fibre intake is linked to a lower occurrence of obesity and cardiovascular disease (Slavin & Lloyd, 2012). Individuals around the world adjusted their diet, as the mean global fruit intake grew by 5.3 grams/day per person between 1990 and 2010 (Micha et al., 2015). Subsequently, according to the Food and Agriculture Organization of the United Nations, global production of fresh fruit grew every year for the past 30 years, from 402 million metric tons in 1990 to 887 million metric tons in 2020 (*World Production Fruit in Tonnes*, 2022).

Currently, producers across the world have a hard time hiring agricultural workers to supply the required healthy food (Lowenberg-DeBoer et al., 2020). Mentioned causes of the shortage in the workforce are the relatively low wages, many health problems that arise due to high humidity, heat, and repetitive movements whilst working in uncomfortable postures (Van Henten, 2006). A possible solution would be to automate the labour-intensive task of fruit and vegetable harvesting to limit the number of workers needed and/or decrease the strain of the task. Mechanization is already implemented for many crops such as potatoes, wheat, and corn, which are often mass harvested by a human-operated machine. Other so-called high-value crops ripen heterogeneously, i.e., not all at the same time, and therefore need to be selectively harvested (Kootstra et al., 2021). Furthermore, fresh crops are known to be susceptible to mechanical damage during harvesting, which can considerably reduce their quality (Li & Thomas, 2014). Consequently, these crops require a more gentle and precise approach, one that robots with specialised grippers could provide.

This paper focuses on robotically harvesting a species of high-value crop, namely the blackberry. Blackberries are so-called aggregate fruits, where each berry is made up of individual drupelets which are all connected to a central receptacle (Edgley et al., 2020). At the top, the receptacle is attached to the sepal which is connected to a thin stem called the pedicel, which via the branches is joined to the rest of the blackberry plant. An important type of damage to the blackberry is Red Drupelet Reversion (RDR), also called red drupelet disorder. This type of damage is visible through the reddening of individual drupelets of the berry after harvesting (Edgley et al., 2020). In a survey study conducted in the US, Dunteman (2019) reported that participants preferred blackberries without RDR because of associating RDR with unripe fruit. Most discolouration occurs within 24 hours of the fruit entering cool storage (Edgley, Close, Measham, et al., 2019). Furthermore, mechanical injury due to handling of the fruit during harvest is a probable major cause of RDR as in a recent study 85% of handled fruit developed RDR compared to 6% of not handled fruit (Edgley et al., 2020; Edgley, Close, & Measham, 2019). We therefore consider robotizing harvesting blackberries as a worth-investigating solution against unfavourable discoloration.

Within the framework of a harvesting robot, it is important to note that this work does not aim to design and experiment with a full robotic platform but focuses on the robotic gripper only. We thus assume that the control software has correctly defined the location and that the robotic manipulator has positioned our gripper around a blackberry. Additionally, since we are not focussing on perception or path planning, we choose to assess the system in a controlled lab environment instead of a field or greenhouse. Furthermore, to limit the number of variables and to focus on the pull and twist behaviour of the Twisting-Tube gripper, it was decided to use a tensile bench as a measurement setup.

In literature, only one gripper was found that was tested on blackberries, which was a tendon-driven gripper with force feedback. The authors of this soft gripper noticed that the hard support needed for the force sensor was a source of damage to the berry, but without the force feedback, the reliability of their gripper suffered (Gunderman et al., 2022).

In section 2, we present the Twisting-Tube gripper, where we briefly describe the concept selection and what components were used to manufacture it. During the design of the gripper, we identified three promising types of tubes: compressible, elastic, and radially elastic. In the methods section, we describe these terms and how we use a custom tensile bench to assess the prototype gripper. In the results section, the detachment rates, release rates, forces upon removal, and damage in terms of leaking drupelets and RDR drupelets are presented with respect to the seven different types of tubes manufactured. Furthermore, the versatility of the gripper is briefly evaluated on cherry tomatoes and three different kinds of grapes. We then discuss the results, draw the conclusions, and give directions for future work for this gripper and for the field in general.

2 Prototype design

In this section, the various steps taken to conceptualize and design the robotic blackberry gripper are laid out. First, the design requirements are listed, whereafter the problem is analysed. From that problem, several different concepts were considered and subsequently, the principle which was most likely to succeed according to the requirements was selected. Within this concept, the actuating principle was chosen and followed up with suitable choices for actuators, sensors, and their control. In the last section, the detailed design of the Twisting-Tube prototype is presented.

2.1 Design requirements

The design of a robotic gripper for picking and handling soft fruit is a complex task, so in this section, we dissect it into its different requirements. These requirements are split up into two categories: functional requirements and fruit parameters which can be seen in Table 1. The functional requirements stem from the investigated use case, in which a single fruit must be detached from a plant and placed at a different location, without imposing damage. For eventual industrial applications, the gripper should be food-safe and able to pick and release the fruit in the order of ten seconds to allow the gripping platform to keep up with production. The fruit parameters are those of blackberries. The range of size and weight are based on the extremes of a sample of 36 blackberries picked by the author. The other fruit parameters are in regard to the tapered cylindrical shape with protruding drupelets blackberries have and the fact that they are relatively soft objects suspended from a pedicel.

Table 1: Functional requirements and fruit parameters for robotic gripping of blackberries

Functional requirements:
- Detach the fruit from the plant
- Release the fruit from the gripper at a different location
- The fruit must not be damaged due to high overall or localised pressures or slippage during the whole procedure
- Food safe, following EU regulation No 178/2002
- Cycle time below 10 seconds
- Gripper space claim should be small enough to fit the dense canopy of most plants

Fruit parameters:
- Length between 15 and 40 mm
- Diameter between 15 and 35 mm
- Weight between 4 and 16 grams
- Overall spherical or cylindrical (tapered) shapes
- Surface variations at a millimetre scale
- Suspended from pedicel
- Soft & deformable object

2.2 Problem analysis

Following the requirements, the gripper should grab the crop and initiate a procedure to harvest the fruit. To detach the fruit from the pedicel, torques and/or forces are needed which are applied by possible detaching movements which are usually called twisting, flicking, bending or pulling, or a combination of those four (as often seen in manual harvesting) (Elfferich et al., 2022). In order to bend the fruit with respect to the plant and consequently impose a torque on the pedicel, at least two opposing forces are needed, as can be seen in Figure 1. So, for bending the fruit, the gripper needs contact area at two opposing sides of the berry to transmit the forces. For a twist around the major axis of the berry, there are tangential forces needed to give an overall torque with respect to the pedicel. These tangential forces can be friction forces produced by the normal forces at the top of protruding drupelets. Furthermore, these tangential forces can also stem from normal forces that act on the side of protruding drupelets. Finally, to pull on the irregular fruit, normal forces at the top of the berry and friction forces at the sides of the berry produced by normal forces there can be used. These forces also act on the berry surface and are pointed away from the pedicel, along the major axis of the fruit.

To limit damage, the above described required harvesting forces should be spread out across the surface of the berry. This will allow the gripper to utilize a larger surface area, which will lower the local pressure on the blackberry, which is thought to induce damage to the fruit. The gripper should thus conform its shape to the surface of the berry, uniformly spreading the detachment forces across the protruding drupelets.

In the blackberry use case, however, we do not target the entire surface area but aim to prevent interaction with the top of the berry. The top of the berry houses the pedicel and its tiny leaves, which should be left free to detach from the fruit during the removal procedure. The alternative would be a gripper that separately also finds and grasps the pedicel and would pull on that in the other direction whilst holding the berry. The only advantage would be that the robotic arm would have to pull less far because the pedicel, peduncle, and the stem of the plant are quite compliant and will move in the direction of the pull. But, grabbing the pedicel is another task in which the robotic gripper could fail. In addition it complicates the design and increases the weight of the gripper, therefore making it probably not worth the small advantage.

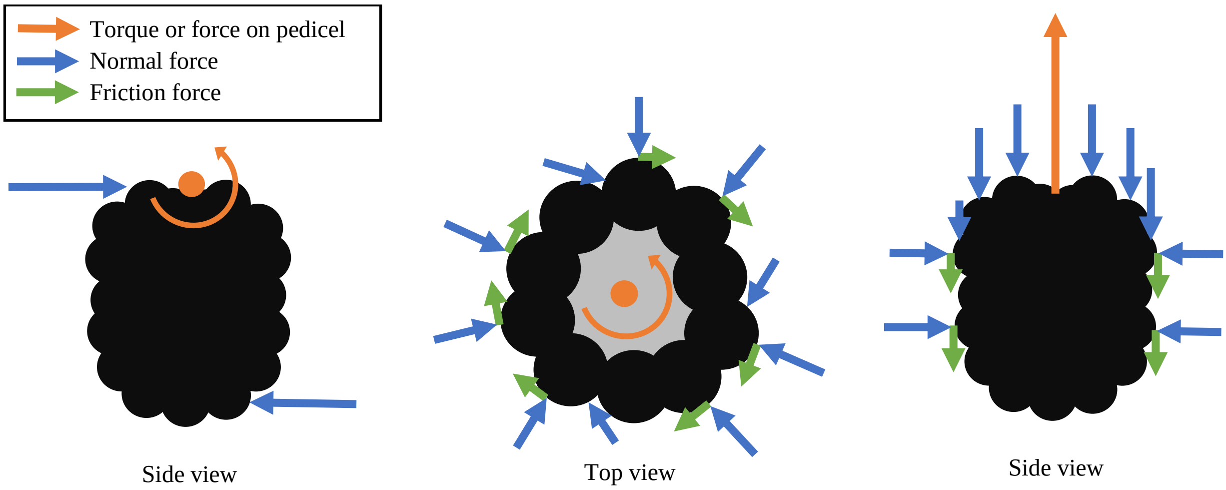

Figure 1: Free body diagrams of a blackberry during pedicel detachment movements. On the left a bending movement that imposes a torque around the pedicel (orange), in the middle a top view with a torque (orange) around the major axis of the berry, and on the right a pull force on the pedicel in orange. Exemplary normal forces are shown in blue and exemplary friction forces in green. Depending on the contact points the gripper is able to make, these forces can differ in size, and where they act.

2.3 Concept expansion and selection

The gripper should impose a homogenous and low-stress distribution across irregular, size-varying, soft objects to maintain grip whilst multidirectional forces are applied. A shape grip which maximises the surface area at the sides and bottom whilst also keeping the top free follows from section 2.2. For the diverse blackberry use case, this requires a concept with the ability for shape and size adaptation and optionally local deformability.

For instance, imagine a surface approaching a blackberry; the most protruding drupelet at that side will contact the surface first, at which point the surface has to continue to move inwards to contact the rest of the berry without imposing large local stresses on this first drupelet. This can be achieved by applying a deformable layer on the interacting surface of the gripper, see Figure 2a, or by (also) decoupling parts of this surface to move independently, see Figure 2b. A disadvantage of the first approach is that at the outer ends of this surface the contact is initiated at an angle as opposed to pointed towards the centre of the berry. This limits the amount of contact area that the gripper could use. A disadvantage of the second method is that independently moving surfaces require some sort of complicated mechanism to allow them to follow the irregular shape of the berry whilst keeping a constant contact force. In Figure 2b we see six interacting surfaces, and if we continue to add more joints and surfaces we reach concept Figure 2c. Here, no stiff components are necessary but rather the soft layer will decrease in diameter around the entire berry. A disadvantage of this approach is that control is harder due to its virtually infinite degrees of freedom.

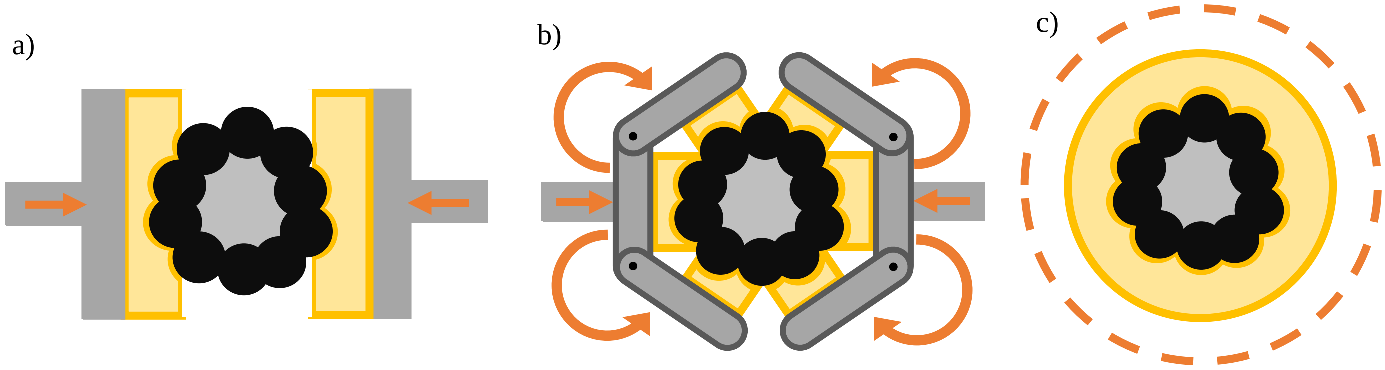

Figure 2: Top view of three different approaches to the soft berry in the middle. a) shows two hard surfaces (grey) that approach the berry with a deformable layer (yellow). b) shows six hard surfaces (grey) that pivot and approach the berry from more sides with deformable layers (yellow). c) shows only deformable components (yellow) which interact with the berry by decreasing in diameter and closing in around all sides of the berry.

To approach the approximate shape of the deformable concept in Figure 2c, the closed state of the gripper was first considered, namely, the outer irregular surface of a blackberry, which looks somewhat like an elongated tapered sphere with relatively large surface variations. Following the requirements, this space should range in size and shape to accommodate a range of blackberry exemplars. The open state of the gripper should be able to let the largest exemplars of blackberries enter and leave easily, so this state should look like a tube. This tube can either have one or both ends open, depending if the berries should be able to leave the gripper through the other end of the tube.

Three concepts were considered with a tube-like shape that deforms to embrace the elongated tapered sphere shape of the blackberries: an inflating tube, a lasso tube, and a twisting tube concept, see also Figure 3.

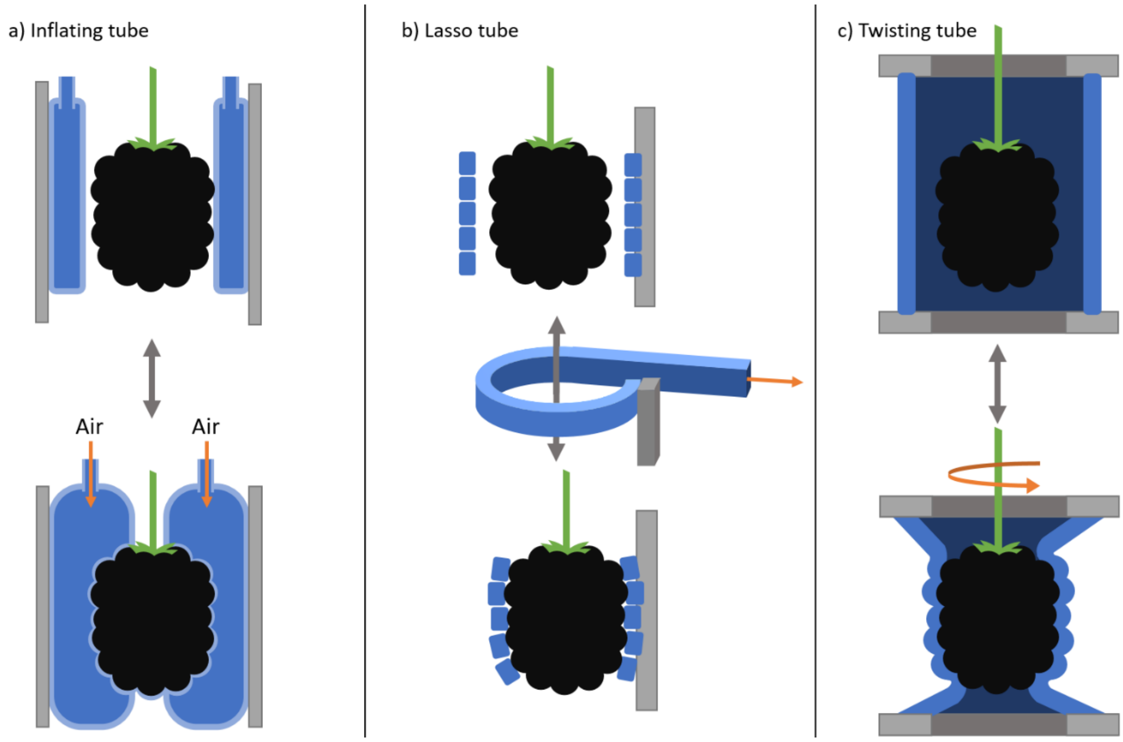

Figure 3: Six cross-sections of the main concepts considered to grab and detach a blackberry, in an open configuration in the top row and a closed configuration in the bottom row. The deformable concept is in blue, the stiff frame in grey and the actuation is represented as an orange arrow. a) inflating tube, positive air pressure inflates the tube from all sides. b) lasso tube, here five strips are shown that are pulled at one end to tighten around the berry. c) twisting tube, a tube gets twisted by turning the ring(s) on one or both ends so that the flexible material in between gets wrapped around the blackberry.

The inflating tube concept is an elastomeric actuator in the shape of a tube with walls which can increase in thickness. A disadvantage of this concept is that it would need relatively thin walls or built-in sensors to be able to adapt to and/or detect an interaction with the soft and squishy blackberry. In the rather harsh operating environment, this could pose an issue if this would decrease its lifetime or reliability, especially for the blackberry use case in which some varieties of plants have sharp thorns along their stems.

The lasso tube concept operates by decreasing the radius of the tube by pulling on one or both ends of the tube. The tube material should be at least somewhat elastic to follow the 3D curvature of the berry, and the whole mechanism should pull the cloth back to its starting position when the open configuration is required. Probably the hardest part to design is an actuator that can pull various parts of the cloth in a manner that the top, middle, and bottom section of the berry is covered in cloth with sufficient, yet not too high, normal force.

The twisting tube concept grabs a berry by twisting one end of a flexible tube and fixating the other or by twisting both ends in opposite directions. This twisting motion decreases the diameter of the tube whilst also shortening it. An important advantage of this concept is that one part of the tube touches the side of the berry, while the rest of the tube can still continue to deform and starts wrapping around the top and bottom of the berry. When the entire berry is grasped, it gets compressed from all sides, and subsequently the resistance to turning increases. So, measuring when the grip is secure can simply be achieved by measuring the torque on one or both rings or by having a torque coupling detach when a certain threshold is reached. Furthermore, the twisting tube concept has inherent twisting and pulling motions, aiding the detachment of berries. Lastly, when empty, the gripper's closing mechanism can also be initiated to decrease the diameter and length, making it smaller and therefore easier to manoeuvre in the dense canopy of blackberries. These advantages and its straightforward design made the twisting tube concept the most promising out of the three to manufacture and test. Additionally, we could not find a similar twisting tube gripper concept in current academic literature, industry, or patent databases, making this gripping mode worth investigating.

2.4 Actuating principle

To close the Twisting Tube gripper, one end of the tube must be twisted with respect to the other end. This could be achieved with just a single actuator which turns both rings or it could just turn one ring whilst the other ring would be fixated. In our prototype, it was decided to independently actuate both rings with separate actuators. This allows us to separately turn and measure how far each end needs to rotate to obtain a secure grasp.

Whilst the two actuators turn both rings, the tube in between gets twisted around the object, thereby making it contract in length, see also Figure 3c. Vice versa, to open the gripper the rings would turn to their original position, the tube would become straight and, as a result, the distance between the rings would enlarge. So, for correct operation of the gripping principle, it is important to ensure that the distance between the rings is not fixed. This distance could be either coupled with the rotation of the gripper, controlled by another actuator, force-controlled, or left to translate freely.

An example of coupling of rotation and translation could be a spindle/helix-like mechanism which contracts the tube whilst it turns with a certain rate determined by the pitch of the helix. A disadvantage of this mechanism is that differently shaped and sized objects require different amounts of translation with respect to the amount of rotation of the rings to ensure that the cloth wraps around the maximum area of the object. For example, an object that is much wider than it is tall would require a lot of translation for a secure grasp whilst a tall object would benefit from little translation given the same rotation. Therefore, coupling the rotation with the translation with a certain pitch limits the scope and performance of the gripper to a small subset of shapes of target objects.

The second option, to control the distance between the rings with a dedicated actuator, gives more freedom to exactly grab and possibly manipulate objects with the gripper. Besides the addition of another (relatively heavy) actuator, a large disadvantage is that this concept makes the gripper overactuated. For example, when the tube is twisted around a berry and the extra actuator tries to push the rings apart, this will increase the tension in the cloth and will squeeze and damage the berry. Careful control is therefore required to keep the rings an appropriate distance apart. This could be vision-based to determine how far the rings should be apart during the twisting procedure in order to not damage the size-varying berries whilst still generating sufficient grip.

The last example illustrates that position control would be hard to realise and that perhaps a force-controlled actuator would be the best option to ensure that the cloth is taut, but not so tight that it damages the object inside the gripper. As both rings are independently turned until a secure grasp is obtained, the force between the two rings could also come from a passive component as control and sensing of this force are not necessarily required. In the end, it was therefore decided to implement a pre-tensioned compression spring in between the rings. So, in the prototype, the relatively small force the spring generates makes sure that the length of the tube follows the stronger twisting motion, whilst making sure the tube is always taut. Furthermore, if the gripper is opened, this force also pulls the flexible tube straight, eliminating big wrinkles and folds that would impede the object from easily entering and being released from the gripper.

2.5 Actuators, sensors and control

To rotate the two ends of the twisting tube, brushed and brushless DC motors, servos, torque motors, and stepper motors were considered. Nonelectric motors were considered inconvenient in the highly likely electric use case with an electric platform and robotic arm in future agriculture. Commercial torque motors were seemingly not available at the low speeds and relatively low torques this use case requires. Stepper motors were also discarded, because they are not well equipped to give a constant high holding torque after the gripper has closed. Stepper motors by themselves can only provide a sufficiently high torque when stationary by constantly drawing current, which is energy inefficient and eventually overheats the motor. Brushless DC motors do not generate constant torque during their operation and operate efficiently at relatively high speeds, which both do not suit the gripper characteristics. Eventually, it was decided to use a brushed DC motor with gearbox and encoder, also commonly known as a servo. This configuration reaches the desired high torques at low speeds whilst also keeping track of the position of the motor. The high gear ratio also made the outgoing axle non-backdrivable, which meant that after turning, the power to the motor could be cut off to lock the position and save energy. For the presented prototype two servos were selected that match the low speeds and have ample torque to operate the gripper. The servos (Cytron, n.d.) have a 120:1 gear ratio which after our own transmission of 55:20 give desired characteristics at each end of the tube of a stall torque of 6.14 Nm, rated torque of 1.62 Nm, and rated rpm of 10.2 (assuming no losses). To control the two 12v motors with stall currents of 1.8 amperes a suitable motor shield was selected (DFRobot, n.d.).

At a certain point, the servos should stop twisting the tube because otherwise the berry might be crushed inside. The control could be feedforward using a vision system to determine the size and the shape of the berry and then use a model to determine how far the top and bottom ring should turn for a secure grasp. This approach has some difficulties, however, as the vision system must be very accurate, and should possibly even determine the shape of the berry in three dimensions. Furthermore, the model could be hard to program as the tube on berry interaction is soft and there are quite some uncertainties in the hardness of the berry and the way the tube folds and wrinkles. Therefore, a second approach was pursued, in which the forces felt during gripping were used to determine when a successful grasp is obtained.

Commercially available torque limiting couplings were considered to limit the torque during gripping by only transferring a certain amount of torque towards the ends of the tube from the motor. This option was not chosen because the possible setpoint of the torque is relatively large, and it cannot be precisely controlled. Furthermore, most torque limiting couplings are prone to wear and are often relatively large and heavy. A second option would be to measure the torque and stop at a certain setpoint. A dedicated torque sensor could do this, but it was decided to measure the amperage that the motor draws as an indication of the torque necessary on the outgoing axle. This is both a cheaper option, as well as allowing the sensor to not be on the gripper itself (but via cables on the stationary control module), making the gripper smaller and more lightweight. To enable this measurement, a high side DC current sensor was placed in series between the motor controller and the DC motor. The INA219 chip from Adafruit was selected to measure the amperage as it houses a precision amplifier to measure the voltage across a 0.1 ohm (1% tolerance) resistor and a 12-bit ACD to convert it to a digital signal with a resolution of 0.8 mA (Adafruit, 2021).

To open the gripper to its exact original position a hall-effect encoder placed on the axle of the motor was used. After the transmission ratio of 330:1, the encoder gives a resolution of 0.16 degrees on the rotation of the ring. This value was constantly monitored and when the gripper was sent a signal to be opened, a PID loop steered both rings to their initial position.

The entire control was handled with an Arduino Mega 2560 Rev3 (Arduino, n.d.), this prototyping platform allows for easy programming and control of both DC motors via the motor shield and communication of the current chips via I2C and the encoders. Furthermore, the stepper motor of the measuring set-up and the values of the load cell (see section 3.3) could also be handled by the Arduino, centralizing both the control of the gripper and the measurement thereof onto one board. The recorded values of the measurement set-up were not stored onto the relatively small memory of the Arduino but sent via USB connection and serial communication to a laptop.

2.6 Final design of Twisting-Tube prototype

In section 2.4, it was decided to use a spring as a passive component that determines the distance between the ends of the tube. To keep the design simple and the spring easy to install, just one single large pre-tensioned spring was housed along the outside of the tube. This spring was stable if the tube was straight and taut, which means that there was no need for linear guidance between the ends of the tube. Of course, this also means that external forces could deflect the spring to bend sideways, but this actually is a welcome compliant feature, as this compliancy helps to move the gripper in a dense canopy with less risk to harm nearby crops. The compliancy furthermore allows the soft gripper to reposition itself around the target fruit if it did not enter the centre of the tube correctly.

The placement of the two servo motors could be at either side of the tube, but it was decided to have them both at the fixed end of the tube. This allows the other “free” end to be as lightweight as possible, which makes positioning the gripper easier as the free end is smaller and more compliant. The lighter free end also allows the spring to be weaker, as it needs to offset less weight with respect to gravity, which makes the spring more compliant in other directions. A disadvantage is that there should be some form of compliant transmission between the motor at the fixed end and the free end of the tube. This could be achieved by gears, pullies, tendons, etc., but it was decided to use the already present spring as a compliant rotation transmitter. So, one motor in the base powers the bottom end of the tube directly, whilst the other motor rotates the bottom end of the spring which then turns the top end of the spring attached to the rotating top end of the tube. Noteworthy is that this second coupling has some play, as the spring is not infinitely stiff in the rotational direction.

A consequence of this configuration is that during tightening of the gripper, both ends rotate and contract the tube from the free end toward the fixed end. So, during the closing of the gripper, not only can the tube twist the fruit with respect to its major axis, but it also pulls the fruit away from the pedicel, which are two important modes of pedicel detachment as seen in section 2.2. Important to note is that during preliminary testing, it was observed that the direction of twisting the tube is of importance, as the spring is not symmetrical; it bends and enlarges when unwound and performs as intended only when wound tighter.

The fixation of the tube to the top and bottom of the gripper is achieved via a custom hose clamp that could be tightened around the tube. This allowed us to fit the tube over the gripper and quickly clamp it down to secure it without having to customise the tube.

The dimensions of the gripper are based on the requirements of section 2.1 and on the limitations of the rapid manufacturing method, which was a consumer level 3D printer. For example, the inner diameter of the tube is 40 mm, so the biggest blackberry could enter the top of the tube with some room to spare, and the diameter of the tube is left constant, so the berry could leave at the bottom of the tube. The length of the tube is 70 mm, as in preliminary testing it was found that, around this length, there was some room for vertical misalignment whilst still being able to grab sufficient area of the blackberry without grabbing the pedicel at the top. The smallest feature size was 0.4 mm, as that was the diameter of the nozzle of the 3D printer. The other dimensions were sized such that the prototype was stiff enough to operate the twisting tube but kept as small as possible to impose a small space claim in the future use case of harvesting in a dense canopy of plants. For exact measurements see section 11.11.

To manufacture this prototype, it was decided to 3D print all structural components (so excluding the tube, spring, electronics and the fasteners). This allowed for rapid manufacturing and custom-sized components. For stationary components, PLA+ (brand: eSun) filament was used, and for components that came in contact with food or slid over other components iglidur® filament (brand: IGUS, I151-PF) was used. It was considered to use regular ball, roller, or plain bearings for components that needed to rotate with respect to one another, but at the required inner diameter of at least 40 mm, these were unnecessarily large and heavy so custom components were necessary to elegantly fit the gripper. The food-safe, low friction, and high abrasion resistant iglidur® filament was chosen instead.

The tubes were manufactured out of cloth and sewn into a tube shape using a regular sewing machine, see section 3.2 for materials used. The spring needed a relatively large diameter to fit around the tube whilst the forces it had to produce were relatively small. This combination was not present on the commercial market, nor could it be custom made by local manufacturers. So, using the input from manufacturers, we wound the spring ourselves, using a mandrel of 27 mm in diameter and 1 mm thick piano wire. After releasing its tension, this gave the required spring with an inner diameter of 68 mm diameter spring with a free length of 140 mm. The spring is slid in a U-shaped channel at either end of the gripper and held in place with setscrews spaced 90 degrees apart. The rest of the gripper is assembled using regular fasteners and the result can be seen in Figure 4 and Figure 5.

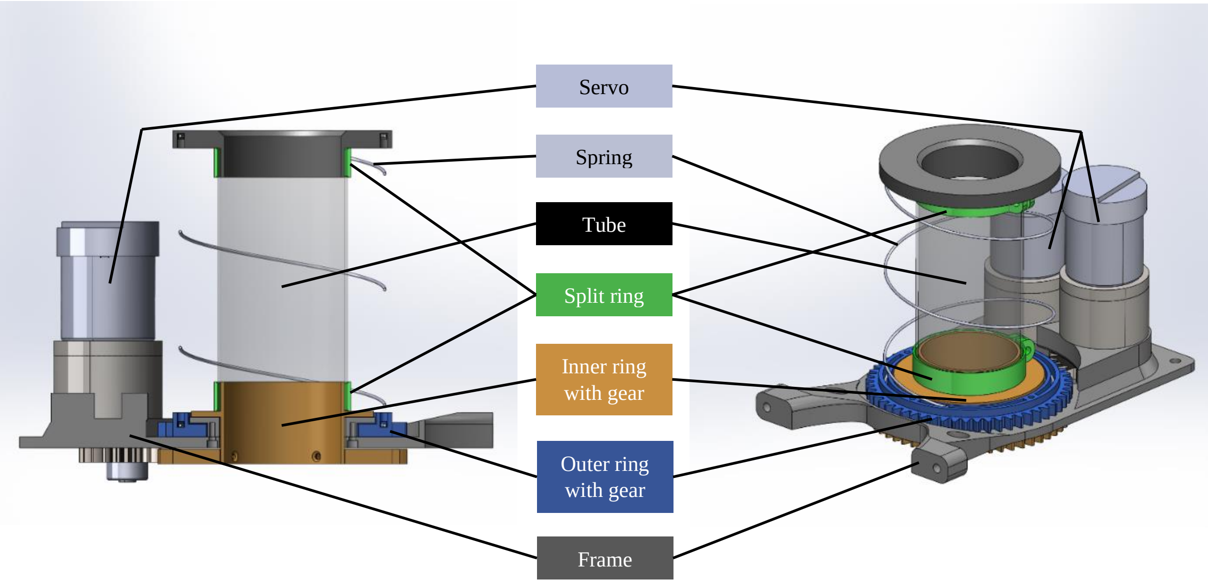

Figure 4: CAD drawings made in SOLIDWORKS, on the left a cross section of the model and on the right an 3D view. Fasteners are removed and the tube is made partly transparent in this drawing to better see the mechanism.

Figure 5: Picture of the Twisting-Tube gripper prototype.

3 Methods

In this section, the testing procedure is described. This includes the testing specimen, being blackberries of the Sweet Royalla variety and the different kinds of tube materials which were used for testing. This is followed up with a description of the measurement setup and the measured variables: detachment and removal rates, force, vertical stage translation, rotation of the tube and damage rates.

3.1 Blackberry testing specimen metrics

In all tests, blackberries were used as testing specimens except for the versatility tests in section 4.5, where the performance of other fruits is reported. Furthermore, it was decided to evaluate the berries in a measurement setup in a lab and not in the field or in the greenhouse itself, in order to limit confounding variables such as nearby leaves, other berries, stems and also the angle and length of the pedicel.

The blackberries were harvested by the author at a local greenhouse (De Berkelse Braam, Bosch Fruit B.V.), which is located about 52.0 N 4.5 E. These berries were picked on 29th of March 2022 from 10:00 until 10:45 at 19.5°C at a relative humidity between 70 and 80 % and then moved towards cold storage at 5°C. In total, 18 punnets were filled with 12 blackberries each; 16 of those punnets were filled with blackberries of which the stem was cut about 1 cm above the sepal and the remaining two punnets were filled with handpicked berries as a control. A second control group was made by taking two punnets of the 16 punnets with blackberries with stem, these were subsequently never handled. The remaining 14 punnets with stem, to be tested on the gripper, were divided into two groups of seven for the first and second testing day. On each testing day, each of the seven different kinds of tubes, see section 3.2, was evaluated in random order using blackberries from a single randomly chosen punnet.

During harvesting, care was taken to handle the blackberries gently. During the entire harvesting process, no purple stains due to leakage of the berry on the hands of the author were observed. Blackberries were always placed and kept in punnets and were never stacked on top of each other. Furthermore, just like in industry, only ripe blackberries were picked, i.e. completely black berries (Perkins-Veazie et al., 1996). All blackberries were from the Sweet Royalla variety and had a length of 30.8 (SD = 2.8) mm, diameter at the widest point of 23.4 (SD = 1.9) mm and weight of 7.8 (SD = 1.6) grams (measured with a digital calliper on 36 randomly chosen blackberries). Research on four different blackberry cultivars showed similar averages and ranges in size and weight (Myers et al., 2022).

3.2 Different tube materials

The proposed gripping principle twists the tube and therefore shortens the tube axially and decreases its radial distance to the object, see also section 2.3. Using these principles, three types of tubes were defined, tubes with compressibility, full elasticity, and radial elasticity, see also Figure 6. With the term tube compressibility, we intend to convey that in all major directions, the tube has a low stiffness inward, so it is compressible in radial, axial, and circumferential directions, whilst in the outwards direction, the tube is relatively stiffer, e.g., because of the pre-tensioning of the mechanism and the material properties of the tube. A fully elastic tube is defined as having the same properties in the inwards direction, i.e., it is compressible, but in all of the outwards directions, the tube is elastic instead of stiff. A radially elastic tube is defined as being compressible in the inwards directions but being elastic only in the radial direction and thus stiff in the outwardly pointed axial and circumferential directions.

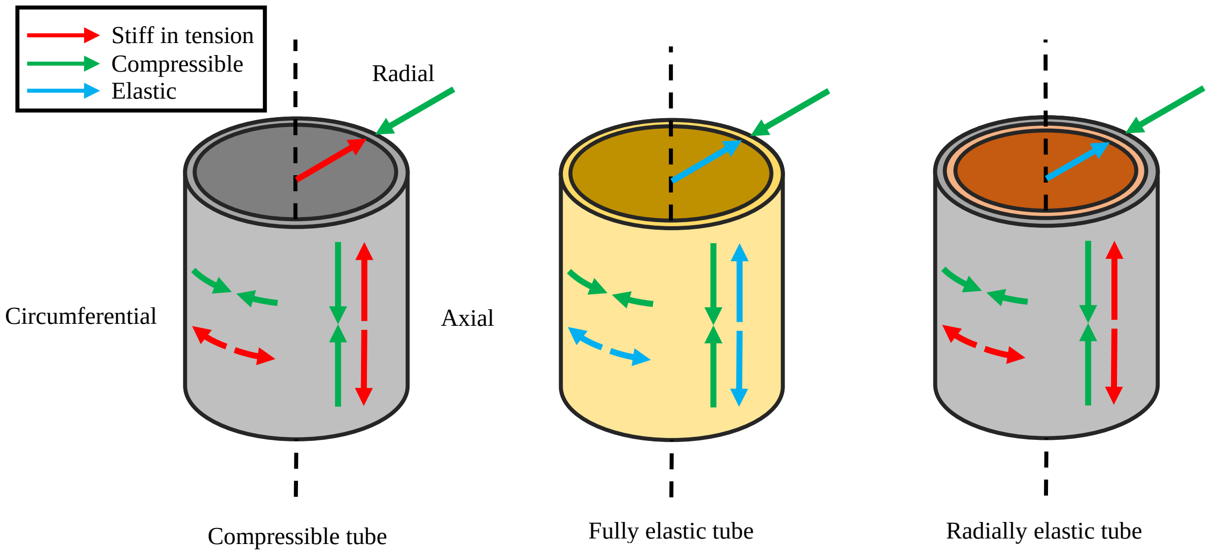

Figure 6: Three types of tubes considered: compressible, elastic in all directions, and radially elastic. In red arrows, the directions in which the tube is stiff due to tension in the material and pretension of the mechanism. In green arrows, the directions in which the tube is compressible, and in blue arrows, the directions in which the tube is elastic. The grey material is compressible (e.g., cloth), the yellow material is elastic in all directions, and the orange material is compressible (e.g., foam).

To gain insight into the influence the different types of tubes on the performance of the gripper, it was decided to manufacture seven different tubes, see Table 2. As the main material (seen in grey in Figure 6), cheesecloth was chosen as it is a food-safe version of non-elastic, woven, cotton cloth. To test if extra compressibility of the cloth would impact performance, a second cheesecloth was used which was exceptionally thin and lightweight. To determine if full elasticity would alter performance, spandex with a so-called four-way stretch (stretch is along sewing direction as well as perpendicular) was chosen (seen in yellow in Figure 6). This spandex had different surface properties, so two more tubes were necessary, where the thick cheesecloth was sewn to the outside and the inside of the spandex, in order to be able to investigate whether any difference in performance between the tubes was due to the surface properties or due to their compressibility or elasticity instead. Lastly, a cheesecloth tube with padding on the inside was manufactured that could be flipped inside out to give padding on the outside (padding seen in orange in Figure 6). It was expected that this radial elasticity could deform locally to better adapt to the local surface variations seen in blackberries, whilst using the stiffness of the cheesecloth to transfer forces. The radial elasticity was added in six strips of 18 mm wide foam and sewn in place to fixate. The strips ran vertically along the folds seen during the twisting of the tube to lessen impediments to the twisting motion. The flipped inside out tube with padding on the outside was used to investigate whether the extra thickness of the tube, which made it stiffer, or its radial elasticity was the source of the differences in gripping performance, see also Figure 7.

Table 2: Overview of the seven different tubes and the materials used in manufacturing them.

Tube description	**Material**
Thin cheesecloth	100% cotton unbleached, 65 grams/m^2
Thick cheesecloth	100% cotton unbleached, twill weave, 230 grams/m^2
Spandex	82% Polyamide & 18% Elastane, 4-way stretch, 200 – 225 grams/m^2
Thick cheesecloth inside, spandex outside	See above
Spandex inside, thick cheesecloth outside	See above
Thick cheesecloth, padding inside	Cheesecloth, see above Padding: 5mm thick polyether foam SG25
Thick cheesecloth, padding outside	See above

Figure 7: The seven tubes used in testing the blackberries. From left to right, the presentation order is the same as in Table 2. The cheesecloth is white, and the spandex is blue. Tube 7 seen in the picture on the right is the same tube as number six seen on the left but turned inside out.

3.3 Measurement setup

The purpose of the measurement setup was to determine the gripper success and damage rates whilst also being able to measure vertical detachment force with respect to the pedicel. To enable this, a custom tensile bench with sufficient vertical range of motion and a loadcell to measure the forces was used, see Figure 8. The Twisting-Tube gripper was situated at the bottom of the setup and fixed with respect to the frame. The short pedicel of the berry was lengthened by attaching a piece of string to the end of the pedicel with a piece of high strength tape. This allowed the berry to enter the gripper to any desired height, without being hampered by the length of each individual pedicel. The string was then clamped to a custom clamp which was placed exactly above the gripper. The vertical placement of the berry was kept constant with a custom spacer arm which was pivoted down each time a berry was placed into the clamp. This arm could be pivoted away during testing to not hamper the gripping procedure.

The submodule of the blackberry suspended by its pedicel in the clamp was only vertically attached to one end of a loadcell. The other end of the loadcell was attached to a vertical stage. So, this loadcell could measure the vertical forces that were present on the submodule with respect to the vertical stage. These were the weight of the submodule and the detachment force of the gripper once it has grabbed the berry. The vertical stage was powered by a stepper motor that moves the vertical stage via a threaded rod. Counting the pulses sent to the stepper motor and converting via the pitch of the threaded rod, one can calculate the relative location of the vertical stage.

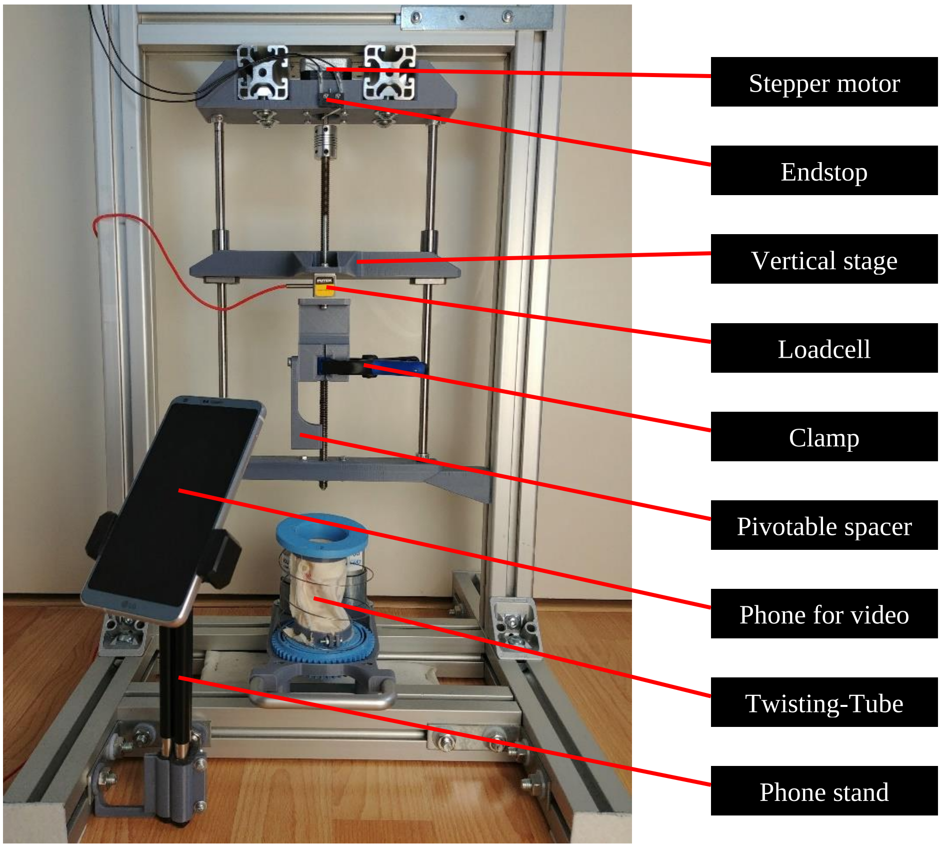

Figure 8: Measurement setup. A stepper motor powers a vertical stage that connects to a clamp for holding the blackberries via a loadcell. The phone shoots a video of the closing procedure of the Twisting-Tube gripper at the bottom.

3.4 Detachment and removal measurement

During the measurement procedure, the berry was placed in the clamping setup seen in Figure 8. After a press of the start button, the automated process commences. It started by lowering the berry with a speed of 3.5 mm/s to the pre-determined height of 50 mm between the top of the berry and the bottom of the tube. This height was determined by trial and error to have the berry roughly in the centre of the tube when grasped. The gripper then shook the tube by rotating the bottom ring two times for 110 degrees clockwise and counter clockwise to aid the berry entering the tube. The tube then continued to tighten until the DC motors (each attached to a single end of the tube) reached a current draw just above their free-spinning current draw. This indicated that the motors encountered more resistance to be turned, therefore the tube had contacted an object. At this point, the berry could already have been detached due to the shortening of the tube whilst closing. The setup then continued to move the vertical stage upwards by 10 mm at 0.4 mm/s. This manoeuvre pulled on the string, thus also on the stem and, if not already detached, it likely detached the berry from the pedicel at this stage. The twisting tube then rotated the top ring clockwise and counter clockwise two times for 110 degrees to aid with releasing the berry, see also Figure 9. During this whole process the researcher watched the detachment procedure and wrote down at which stage the berry was detached (closing, vertical pull, or opening), and if and at which stage it was released (when the gripper opened, when it tried to shake it loose or if there was no release). The build-in pauses between each stage of the process allowed the researcher to clearly separate when an event occurred. The researcher also wrote down the modes of failure of the gripper (no detachment, wedging out from the top or bottom, stem breakage, berry ripped into pieces) or failure of the setup (clamp failure or stem slipped from tape). If the researcher doubted what exactly occurred, a camera recording of the whole process could be advised to see what happened from a different angle. The recording with timestamp could also be used in the data analysis as an aid to rewatch the procedure.

a) b) c) d) e) f)

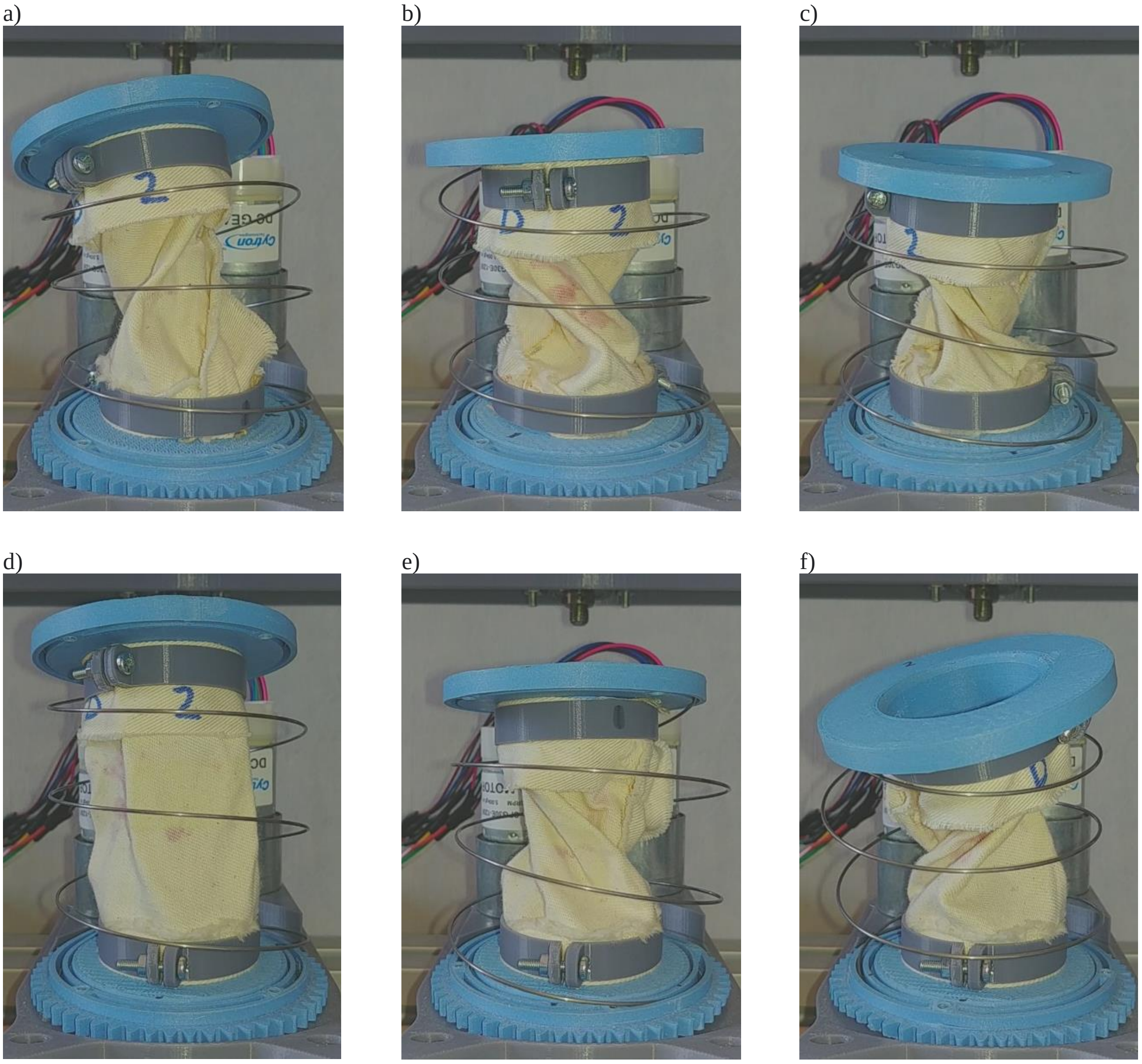

Figure 9: Stills of gripping procedure without an object inside. a,b) Tube rotates bottom ring 110 degrees clockwise and counter clockwise to aid an object in entering the tube. c) Tube twists close. d) Tube returns to initial open position. e,f) Tube rotates top ring 110 degrees clockwise and counter clockwise to aid an object leaving the tube.

3.5 Force, rotation and position measurement

After the berry was clamped to the setup its weight got measured by the loadcell, the loadcell also recorded the force during gripping and the vertical pull procedure. In this manner, the detachment force of the berry with respect to the pedicel was measured by subtracting the weight of the clamp plus the berry of the measured force during detachment. The loadcell used in this setup was the miniature S-Beam Jr. Load Cell (Futek, n.d.) which after a strain gauge conditioner (Scaime, n.d.) and 10 bit ADC on an Arduino Mega gave a resolution of 0.04 N. The position of the vertical stage was calculated by the pulses sent to the stepper which drove this stage via a threaded rod to give a vertical resolution of 6.25 µm. The rotation of the ends of the tube was tracked by the gripper itself using hall effect encoders on the DC motors and had a resolution of 0.16 degrees, see section 2.5. These four different values were sent to a nearby laptop via USB cable to be recorded.

3.6 Damage measurement

One hour before testing, the blackberries were retrieved from cold storage to acclimate back to room temperature. Furthermore, just before entering the gripper, leaking, bruised or discoloured exemplars were trashed, with the same treatment for the control group, to exclude berries which were harmed during harvesting at the greenhouse or during transport or storage. This lead to a total amount of berries per punnet of ten or eleven.

After the berry was handled by the gripper, the researcher placed it on a paper towel, to see if a drupelet was leaking juice and where that drupelet was located. Three zones on the blackberry were identified for this purpose, the top two rows of drupelets, the bottom two rows of drupelets or any drupelets in between, see also Figure 10. Under a bright light, the researcher inspected how many drupelets had their membrane cut and were thus leaking and wrote down this data for each zone.

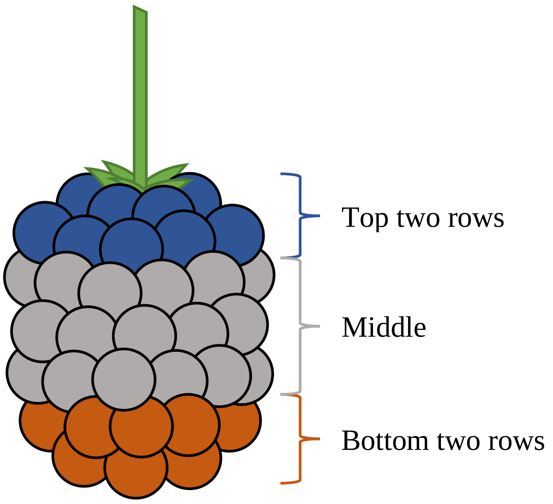

Figure 10: Schematic image of blackberry with the three zones highlighted in blue, grey and orange.

Almost all berries were inspected for Red Drupelet Reversion (RDR) 24 and 48 hours after testing. First, the berries were left outside the fridge for one hour to acclimate them to room temperature. Then, each berry was held under a bright light and visually inspected by the author to see if individual drupelets were discoloured and where they were located. Again, here we define three zones, top two rows, bottom two rows of drupelets or in between in the middle. Discolouration is defined in terms of a shift in colour with respect to unaltered black drupelets on that same berry. In this manner, discoloured drupelets can be quickly identified next to unaffected black neighbouring drupelets. The shift in colour can be slight from black to black/red or fully evolved and thus completely red. Separately recorded were drupelets that have part of their surface discoloured to red and part still black. Also, at this stage, the researcher took pictures of the punnet for later reference. This specific type of measurement allows for the calculation of the Red Drupelet Index (RDI) for each of the three zones. Following the following formula:

RDI = number of PR drupelets + (2 * number of FR drupelets)

The above formula is from the work by Edgley et al., where they account for the greater visual impact for a consumer of fully red (FR) drupelets with respect to partially red (PR) drupelets (Edgley et al., 2020).

3.7 Versatility tests

A second test was also performed on four other fruits to determine the versatility of the Twisting-Tube gripper, see Figure 11. These four types of fruit were bought at a store instead of directly harvested at a farm and were all the locally available options that would fit within the tube of the current prototype and had a pedicel available to attach it to the test set-up. Furthermore, keep in mind that these four fruits serve as examples, and that usually these specific fruits are not individually picked. It was decided to use the thick cheesecloth as the tube as this cloth had the overall best performance in the blackberry tests. All other settings and procedures were kept the same as in the blackberry tests except for the height of the fruit with respect to the gripper, these fruits had differing lengths and thus were vertically moved to be at the centre of the gripper when it closed. Moreover, it was decided to do ten tests with each of the fruits, as the aim is to see the versatility of the gripper and not to see differences between any specific settings or conditions. Finally, the three kinds of grapes were stored at 5°C, the same as the blackberry tests, but the cherry tomatoes were stored, as recommended, at room temperature.

Figure 11: Test specimen of the versatility tests. From left to right: a Sweet Sapphire™ grape, a Thompson white seedless grape, a Timco™/ Sheegene 13 red seedless grape and a cherry tomato.

4 Results

This section presents the results of the above-described tests with seven different tubes. We begin with the detachment and release rates, then pedicel removal forces and rotations of both rings, and conclude with the damage rates in terms of leaking and RDR drupelets. We then compare the different materials of the tubes, to see what influences the performance of the Twisting-Tube gripper. The last section shows the results of the versatility tests in which cherry tomatoes and three different kinds of grapes are detached by the gripper.

4.1 Berry detachment and release rates

The different modes of detachment of the blackberry from the pedicel are set out in Table 3 across the seven different tubes, see also Figure 12 for an example. Noteworthy is that in some cases the pedicel slipped from the tape. We decided to leave out these cases because they are neither a failure nor a success of the gripper. Thus, the sample size is different for each condition. Furthermore, some possible modes of detachment and failure were not seen in any of the tests, namely, detachment during opening of the gripper or wedging the fruit out of the bottom of the gripper.

The bottom row of Table 3 shows the percentage of successful detachments with respect to the total sample size for each of the seven different conditions. The results show that the thick cheesecloth, spandex and combinations thereof performed better than other materials, with more than 75% of the berries successfully detached. The other material options thus performed poorly, e.g., the thin cheesecloth often wedged the berry out at the top whilst tightening and only successfully gripped 24% of the berries. In most cases, both of the padded tubes also failed to detach the berry, with around 50% of the berries detached. Also noticeable from Table 3 is that in most cases the twist and inherent slight pull during the gripping procedure alone was sufficient to detach the berry and that only in some cases the subsequent vertical pull of the vertical stage was necessary to detach the berry successfully.

Table 3: Different kinds of successful or unsuccessful detachments of the blackberry from the pedicel.

		Thin cheese-cloth (n = 21)	Thick cheese-cloth (n = 17)	Spandex (n = 16)	Thick cheesecloth inside, spandex outside (n = 17)	Spandex inside, thick cheesecloth outside (n = 16)	Thick cheese-cloth, padding inside (n = 17)	Thick cheese-cloth, padding outside (n = 21)
Successful detachment at pedicel	During gripping	5	12	14	12	9	2	8
	During vertical pull	0	2	1	1	4	6	3
Unsuccessful detachment	No detachment	2	0	0	0	0	7	10
	Wedging out at top	14	2	1	3	3	2	0
	Berry ripped apart	0	0	0	1	0	0	0
	Stem breakage	0	1	0	0	0	0	0
Gripper successes w.r.t. total successful measurements (%)		24	82	94	76	81	47	52

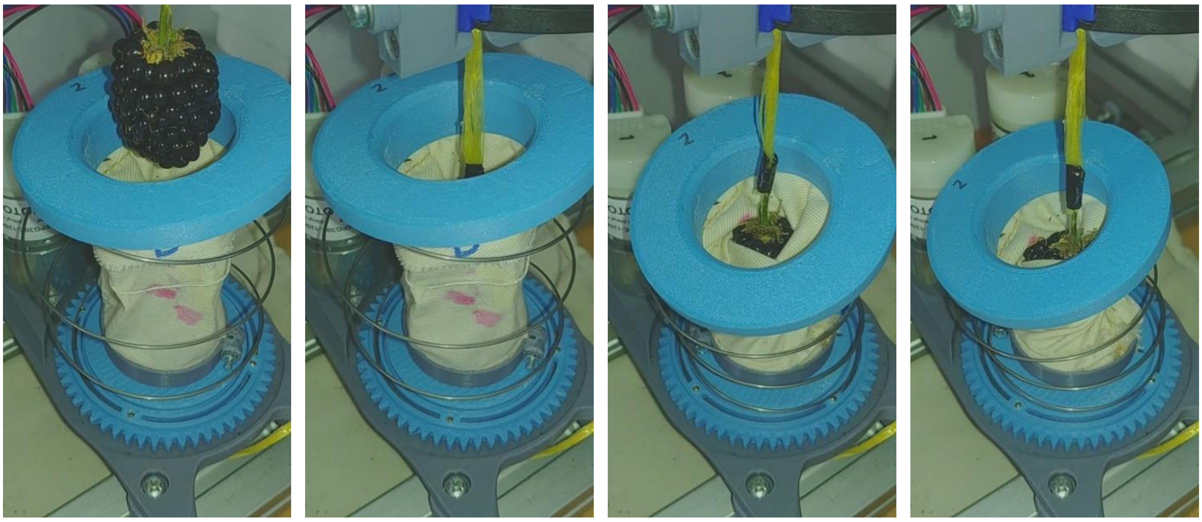

Figure 12: From left to right, pictures of a single pedicel removal procedure can be seen for the Twisting-Tube gripper equipped with thick cheesecloth. The blackberry enters, the tube twists and tightens around the berry, and in the final picture the pedicel is detached from the berry.

All berries that were present in the gripper after the detachment procedure were observed to see how often and when the berry left the gripper, see Figure 13. The sample sizes consequently differ as some berries slipped or wedged out of the gripper in the previous stage and were therefore not present in the gripper for it to release. Again, noticeable is the high success rates of the thick cheesecloth, 95%, and of the spandex, 85%. The tube with thick cheesecloth on the inside with spandex on the outside performed also rather well with 72%, whilst the inverted version performed poorly with 18% of the berries being able to leave successfully. The thin cheesecloth had very few samples as often the fruit was wedged out during gripping, see also Figure 13. Furthermore, the padded tubes had limited samples but the test with padding on the inside performed worst with no releasement of berries. Also noteworthy in Figure 13 is the rather high number of berries that needed a shake of the tube at the end of the gripping procedure. This shake rotated the top end of the tube back and forth two times for 110 degrees after the gripper was opened and allowed the relatively lightweight berry to be shaken loose from the grip of the gripper, see also Figure 9.

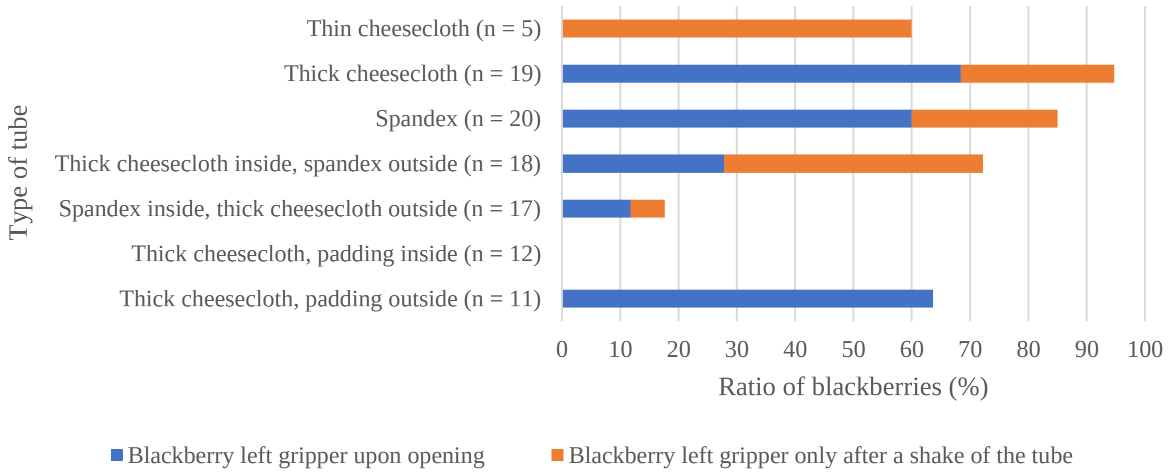

Figure 13: Ratio of tested upon blackberries that left the gripper successfully after being detached from the pedicel during opening or the subsequent shake of the tube.

4.2 Pedicel removal forces, rotations and vertical displacement

In Table 4, the average and standard deviation of the pedicel removal force can be seen per condition for the berries that were detached during the gripping phase. Most tubes needed on average around two Newtons to detach the berry from the pedicel, the thick cheesecloth was a bit of an outlier and needed an average of 3.4 N. Figure 14 further shows that for different types of tubes, the forces could be anywhere between one to five Newtons. Moreover, in Table 4 reports the amount of rotation of both ends of the tube after grasping the blackberry. Here it is noticeable that the compressible thin cheesecloth and the elastic spandex turned on average at least 100 degrees further than the other tubes, indicating that their material twisted and wrinkled around the object more before the setpoint was surpassed by the current sensor. Table 4 furthermore shows that in most cases the bottom end of the tube twisted further than the top end except for the padded versions and the tube with thick cheesecloth on the inside and spandex on the outside.

Table 4: For successfully detached blackberries gripping: mean (SD) force of pedicel removal and mean (SD) position of the tube ends per condition. The ends of the tube were counter-rotated to enable the twist motion, hence the minus sign for the top end of the tube.

		Vertical force to detach pedicel (N)	Rotation top end of the tube (deg)	Rotation bottom end of the tube (deg)
Type of tube	Thin cheesecloth (n = 5)	2.29 (1.26)	-370 (66)	442 (121)
	Thick cheesecloth (n = 12)	3.42 (1.11)	-272 (162)	311 (109)
	Spandex (n = 14)	2.23 (1.07)	-455 (272)	527 (166)
	Thick cheesecloth inside, spandex outside (n = 12)	2.59 (0.62)	-276 (105)	244 (86)
	Spandex inside, thick cheesecloth outside (n = 9)	2.00 (0.72)	-254 (183)	307 (118)
	Thick cheesecloth, padding inside (n = 2)	2.13 (0.53)	-239 (9)	173 (38)
	Thick cheesecloth, padding outside (n = 8)	2.02 (1.14)	-295 (127)	191 (79)

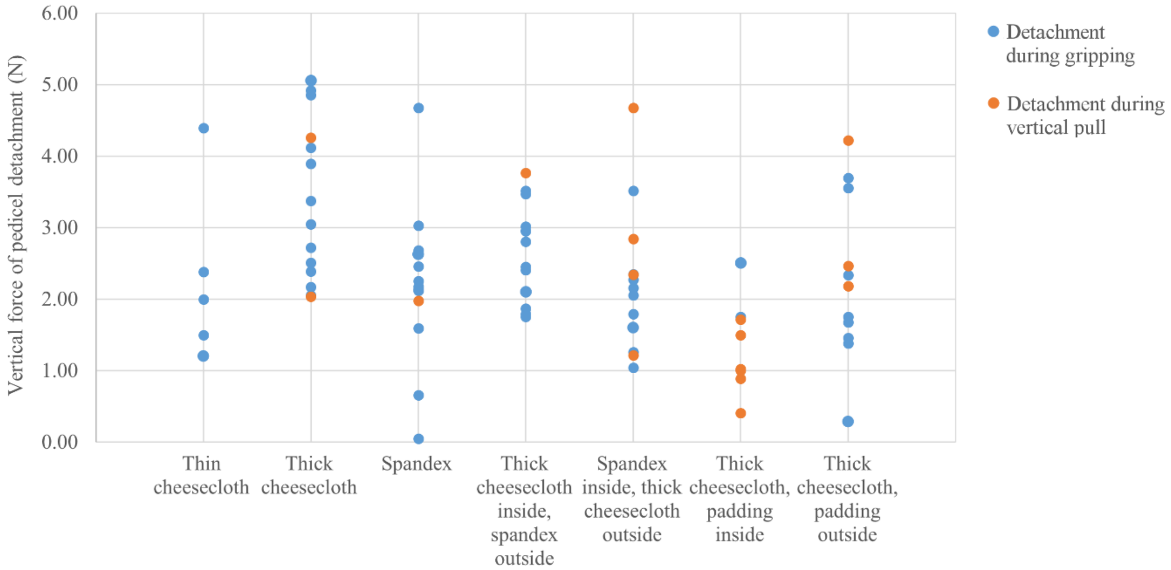

Figure 14: Vertical force necessary for successful detachment of the blackberry during gripping (blue) and during the subsequent vertical pull (orange), each dot represents a test on a single blackberry.

4.3 Blackberry damage in terms of RDR and leaking drupelets

We investigate two metrics to determine the gripper performance in terms of damage to the blackberry. The amount of cut damage on each drupelet which causes its fluids to leak out and the amount of Red Drupelet Reversion (RDR), see also Figure 15.

In Table 5 one can see the percentage of the blackberries that had more than one or three drupelets leaking for each different zone. Only successfully detached berries during gripping or the subsequent vertical movement are compared here, as they all transferred the detachment forces from the gripper to the pedicel successfully. Immediately noticeable is that the compressible thin cheesecloth and the elastic spandex inflicted the most damage with 100% and 53.3% of the berries having at least one drupelet leaking, respectively. The other tubes performed well with damage rates comparable to the control cases, with the tube with padding on the outside as an outlier with no damage to any of the berries. Furthermore notable are the two control groups, handpicked or cut at the stem, which both have nonzero damage rates, indicating that handling the berries during harvesting and/or transport induced some damage. Finally apparent in Table 5 is that most often berries had leaking drupelets in the larger, middle zone of the berry followed by the bottom and then the top of the berry.

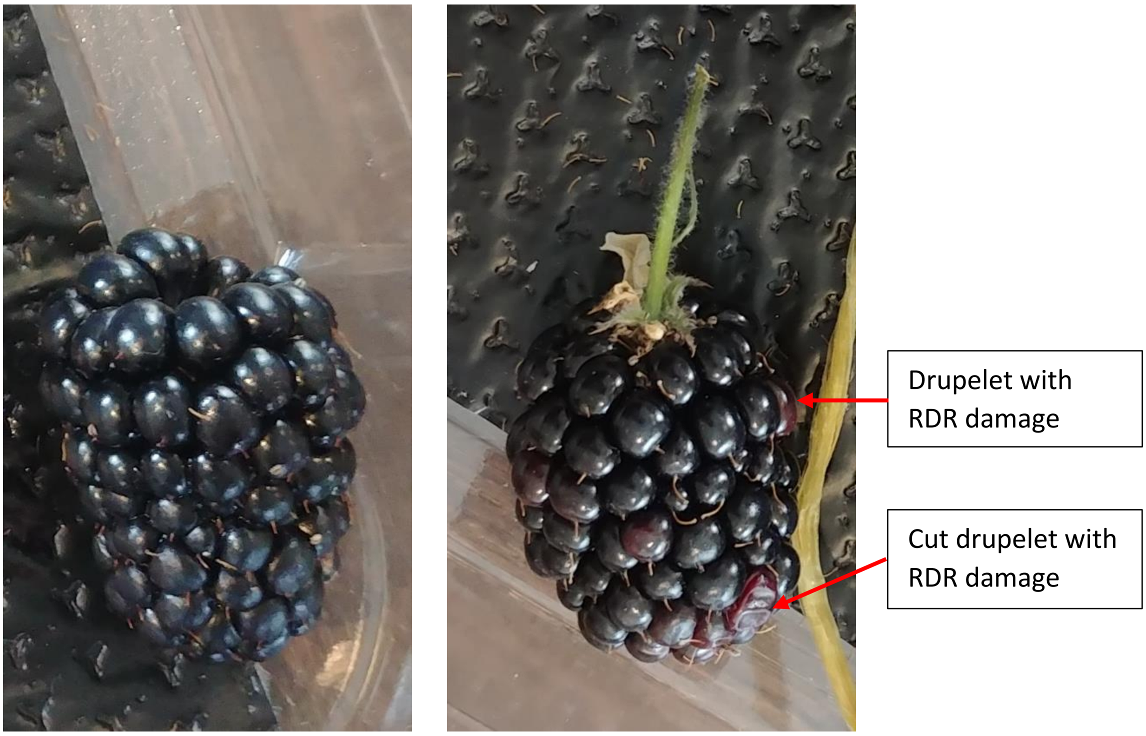

Figure 15: On the left a blackberry without damage after 48 hours. And on the right a blackberry with multiple drupelets having RDR damage and one drupelet with cut damage.

Table 5: Percentage of successfully detached blackberries that had at least one or three drupelets leaking, counted for each specific zone (see Figure 10), per different type of tube.

	Zone of drupelet leaking	**Total three zones**		**Top**		**Middle**		**Bottom**	
	Number of drupelets leaking	**1+**	**3+**	**1+**	**3+**	**1+**	**3+**	**1+**	**3+**
Type of tube	Thin cheesecloth (n = 5)	100.0	80.0	0.0	0.0	100.0	40.0	100.0	60.0
	Thick cheesecloth (n = 14)	28.6	14.3	21.4	7.1	21.4	7.1	7.1	0.0
	Spandex (n = 15)	53.3	20.0	13.3	0.0	40.0	6.7	20.0	13.3
	Thick cheesecloth inside, spandex outside (n = 13)	7.7	7.7	0.0	0.0	7.7	7.7	0.0	0.0
	Spandex inside, thick cheesecloth outside (n = 13)	15.4	15.4	7.7	7.7	7.7	0.0	7.7	0.0
	Thick cheesecloth, padding inside (n = 8)	25.0	0.0	12.5	0.0	25.0	0.0	0.0	0.0
	Thick cheesecloth, padding outside (n = 11)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Average of all types of tubes	32.9	19.6	7.9	2.1	28.8	8.8	19.3	10.5
	Control, handpicked (n = 24)	12.5	4.2	8.3	4.2	4.2	0.0	0.0	0.0
	Control with stem (n = 20)	20.0	10.0	5.0	0.0	20.0	10.0	0.0	0.0

The damage in terms of Red Drupelet Reversion (RDR) was divided into three zones and converted into the Red Drupelet Index (RDI), see section 3.6. Interestingly, only one berry out of all samples had a fully converted drupelet (in the top rows, tested with the thin cheesecloth). So, the RDI index can in all other cases presented here be interpreted as the number of drupelets which were partially discoloured red. The sample size used for determining the RDI is based on all berries gripped by the gripper, successfully detached or not. Berries with too much damage for reliably observing the RDR rates were not considered for inspection. Consequently, some sample sizes differ slightly, and therefore the totals are given in terms of percentages of their total sample size for easy comparison.

In Table 6, noticeable is the high RDI indexes 24 hours after testing of spandex and the tube with padding on the inside, with 33.3 and 35% of the blackberries having an RDI larger than zero. In Table 7, 48 hours after testing most RDI increased, and only the thick cheesecloth had below 28% of its berries with RDR damage. This thick cheesecloth therefore performed best in terms of having the least RDR damage and could even slightly outperform the handpicked control group in most zones across the berry. Furthermore apparent between the two control groups is that the handpicked exemplars did sustain some RDR damage due to the detachment procedure with the human hand, whilst the control group with its stem cut off had no RDR after 24 hours and only 10% of the berries with one drupelet in the middle discoloured after 48 hours. Finally, Table 6 and Table 7 also show that averaged across all types of tubes, for both after 24 and 48 hours, the larger middle section more often sustained RDR damage followed by the top and bottom.

Table 6: Percentage of berries with an RDI index of one or more or of three or more, for each zone of the blackberry, compared between different tube types. RDR was measured 24 hours after testing.

	Zone of drupelet RDR	**Total three zones**		**Top**		**Middle**		**Bottom**	
	RDI-index	**1+**	**3+**	**1+**	**3+**	**1+**	**3+**	**1+**	**3+**
Type of tube	Thin cheesecloth (n = 21)	19.0	9.5	4.8	0.0	9.5	4.8	14.3	0.0
	Thick cheesecloth (n = 21)	9.5	0.0	4.8	0.0	4.8	0.0	0.0	0.0
	Spandex (n = 21)	33.3	4.8	19.0	0.0	19.0	4.8	0.0	0.0
	Thick cheesecloth inside, spandex outside (n = 20)	15.0	5.0	5.0	5.0	10.0	5.0	10.0	5.0
	Spandex inside, thick cheesecloth outside (n = 20)	15.0	0.0	5.0	0.0	10.0	0.0	0.0	0.0
	Thick cheesecloth, padding inside (n = 20)	35.0	10.0	5.0	0.0	30.0	10.0	0.0	0.0
	Thick cheesecloth, padding outside (n = 21)	9.5	0.0	0.0	0.0	9.5	0.0	0.0	0.0
	Average of all types of tubes	19.5	4.2	6.2	0.7	13.3	3.5	3.5	0.7
	Control, handpicked (n = 24)	16.7	4.2	8.3	0.0	12.5	4.2	0.0	0.0
	Control with stem (n = 20)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7: Percentage of berries with an RDI index of one or more or of three or more, for each zone of the blackberry, compared between different tube types. RDR was measured 48 hours after testing.

	Zone of drupelet RDR	**Total three zones**		**Top**		**Middle**		**Bottom**	
	RDI-index	**1+**	**3+**	**1+**	**3+**	**1+**	**3+**	**1+**	**3+**
Type of tube	Thin cheesecloth (n = 20)	35.0	10.0	25.0	0.0	30.0	5.0	15.0	10.0
	Thick cheesecloth (n = 21)	19.0	9.5	9.5	4.8	19.0	4.8	9.5	0.0
	Spandex (n = 21)	38.1	19.0	19.0	0.0	23.8	14.3	19.0	0.0
	Thick cheesecloth inside, spandex outside (n = 19)	31.6	5.3	10.5	0.0	31.6	5.3	10.5	0.0
	Spandex inside, thick cheesecloth outside (n = 20)	30.0	10.0	5.0	0.0	25.0	10.0	5.0	0.0
	Thick cheesecloth, padding inside (n = 20)	40.0	25.0	25.0	15.0	25.0	25.0	10.0	5.0
	Thick cheesecloth, padding outside (n = 21)	28.6	0.0	0.0	0.0	19.0	0.0	9.5	0.0
	Average of all types of tubes	31.8	11.3	13.4	2.8	24.8	9.2	11.2	2.1
	Control, handpicked (n = 24)	33.3	8.3	8.3	0.0	29.2	8.3	0.0	0.0
	Control with stem (n = 20)	10.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0

4.4 Overall Twisting-Tube gripper performance

To give an indication of the overall performance of each of the different tube materials in the twisting gripper Figure 16 was created. This figure shows in blue first the number of berries that were successfully detached. In yellow, it shows the number of berries that were also successfully released from the gripper. Finally, in green it is shown how many blackberries were successfully grasped and released and also had no damage that caused leakage in any one of the drupelets. Ultimately, we consider this latter index as the metric for evaluating the immediate, overall performance of the gripper in our use case.

From Figure 16 it can be seen that the thick cheesecloth performed best by picking and releasing 43% of the presented berries without imposing immediate damage. The tube with the same thick cheesecloth on the inside and spandex on the outside performed a bit worse with 33% of successfully handled berries, whilst the inverted case only achieved 5%. Spandex alone was able to detach 67% of the berries and detached and released 57% of the tested upon berries but imposed so much damage that only 29% was successfully handled. The thin cheesecloth and the tube with padding on the inside performed exceptionally poorly with no successfully handled berries. The tube with padding on the outside was able to detach and release 19% of the berries of which none had leaking drupelets. Finally, at the bottom in Figure 16, the control handpicked batch is shown for comparison. These carefully picked blackberries with a sensitive and dexterous human hand still received damage and only 88% were without leaking drupelets.

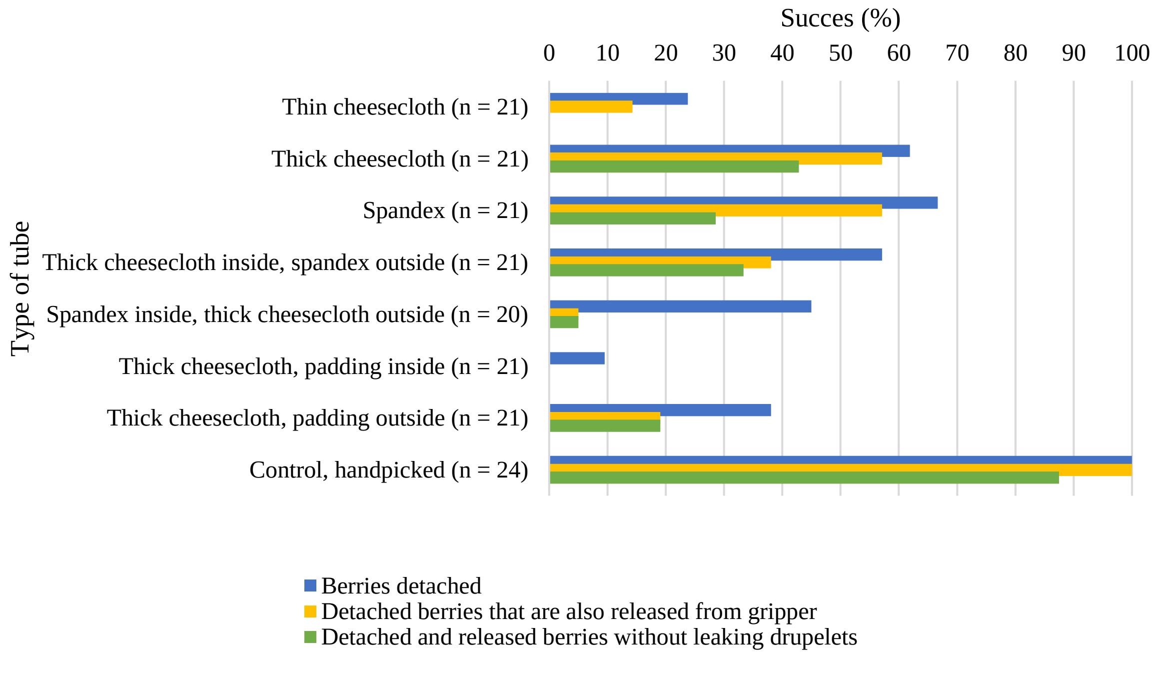

Figure 16: The number of berries after each of the performance checks: detachment, releasement and no leaking drupelets.

4.5 Versatility testing results

Besides the blackberry tests and results, a secondary test was also performed on four other fruits to determine the versatility of the Twisting-Tube gripper, see Figure 11. The elongated grapes of the Sweet Sapphire™ variety were detached three times during closing of the gripper and six times during the subsequent vertical pull. The white grapes were detached eight times during gripper closing and the red grapes seven times. In the other tests, the pedicel of the grapes slipped in the tape attachment making the test invalid. The cherry tomatoes were four times successfully detached during the gripping procedure and the other six times the pedicel broke before detachment took place. Indicatively, some stems broke at forces as low as 2.0 and 2.5 N whilst the pedicel used detachment forces starting at 3.2 N in other tests.

After gripping, all four types of fruit left the gripper immediately after opening, no shaking of the tube was necessary for the fruit to leave the gripper. Furthermore, for all four types of fruit no relevant damage was observed, neither for the ten gripped fruit nor the ten controls with stem or the ten control fruits that were handpicked. Namely, none of the fruit were leaking and after 24 and 48 hours no bruising damage or discolouration was observed, see also Figure 17. The only damage that could be seen in both the handpicked control and the robotically gripped grapes was about a one mm long cut near the opening on the top of some grapes. This was due to the nature of the fruit, as the detachment of the pedicel also pulled along some fibres and seeds through the small opening at the top, which sometimes enlarged it.

The Twisting-Tube gripper, although designed for blackberries, could thus detach and release similarly sized fruit successfully without imposing damage. Table 8, shows that the gripper could at least handle weights varying between 3 and 15 grams and lengths between 19 and 54.4 mm. Diameters at the widest point could be between 14.4 and 24.6 mm. Furthermore, Figure 11, shows that the Twisting-Tube gripper could handle different shapes, from the spherical cherry tomato to the prolate spheroid of the Sweet Sapphire™ grapes.

Table 8: Overview of the versatility tests of the Twisting-Tube gripper. A range of fruits with different lengths, diameters, weights and pedicel removal forces could be handled by the gripper.

Type of fruit	**Variety**	**Origin**	**Length range (mm)**	**Diameter at widest point range (mm)**	**Weight range (grams)**
Grapes (n = 10)	Sweet Sapphire™	*Unknown*	29.2 - 54.4	14.5 - 23.3	4 - 14
White seedless grapes (n = 10)	Thompson	India	19 - 22.9	16.6 - 19.3	3 - 5
Red seedless grapes (n = 10)	Timco™/ Sheegene 13	South-Africa	22.5 - 27.8	20.7 - 24.6	7 - 10
Cherry tomato (n = 10)	*Unknown*	Spain	24.2 – 27.9	25.0 - 29.3	9 - 15

Figure 17: Ten exemplars of each of the four versatility-tests fruits is shown here 48 hours after detaching them from their pedicel with the Twisting-Tube gripper. No relevant cuts or bruising was observed and no discolorations were present. Note that on some fruits spots and marks can be seen, these were not caused by the gripper as they were already observed before testing.

5 Discussion

The discussion is divided into six sections. First, the differences between the fruits are analysed. Then the shortcomings of the RDR observation method are discussed. The third section delves into the detachment mechanics of blackberries. The fourth section discusses the influence of compressibility, overall elasticity and radial elasticity on the performance of the gripper. The fifth section discusses the principles of the gripper and provides some more insights gained during this work. The last section hence also introduces possible improvements for some shortcomings of the current prototype gripper.

5.1 Fruit evaluation

Comparing the results of the versatility tests in section 4.5 with the results of the same thick cheesecloth tube on the blackberry tests, it is clear that the Twisting-Tube gripper has more successful detachments with less damage on the cherry tomatoes and the different kinds of grapes than it does on blackberries. This was expected from the onset of this research, as we hoped that focussing on the hard to handle blackberry would inform a gentle gripper design that then would more easily pick tougher types of fruit. Their relative toughness also can be seen from the control groups, where even careful detachment with a human hand results into leakage as well as RDR to the drupelets and no noticeable damage to the other kinds of fruits. Therefore, we argue that the difference in results stems from the fact that blackberries are more fragile and get damaged more easily than cherry tomatoes and the different kinds of grapes we tested upon. Hence, the choice of fragile blackberries to do the majority of testing upon was a sound decision as it exposes the limits of the careful grasping principle more clearly.

5.2 Damage observation

In hindsight, a shortcoming of this study is the method of RDR observation of the blackberries. First of all, it was recorded for each punnet and not tracked per individual blackberry. This was an oversight as in the analysis phase no comparison could be made between the RDR damage of detached blackberries of different conditions. Instead, the RDR data was mixed with blackberries that were for example wedged out and therefore probably sustained less RDR damage as a result. A second improvement in the RDR observation could be made by using image analysis instead of counting the damage by a human observer. If done correctly, this will likely be a more detailed and fair method for discolouration comparison. In this study, it was decided to rely on the work by Edgley et al. (Edgley et al., 2020) and append its manual method of RDR observation by adding three separate zones to separate the damage. Image analysis such as performed by Worthington et al. could be used as a starting point for more objective analysis (Worthington et al., n.d.), but for our current research it was considered out-of-scope to implement as it is in an early stage. We deem that in this field consensus is first necessary about the specifics of the measurement setup, lighting conditions, camera settings, viewing angles on the 3D object, et cetera. But also in terms of how to analyse the data, e.g., handle gloss of the berry and determine at what values the blackberry is considered discoloured.

Furthermore, we introduce in this work three zones (top, middle and bottom) for more accurately tracking damage on the blackberry, see section 3.6. Due to natural variability, blackberries differ in size and number of drupelets, making the three zones not constant in size in a relative or absolute sense. For example, for a small blackberry, the middle section could be about two rows high all around the berry, but for larger exemplars, it could be twice as large. The results from Table 5, Table 6, and Table 7, where most often the middle zone of the berries sustained RDR or leakage on the drupelets, could thus be caused by the fact that this zone is often the largest and thus had the most drupelets that could be harmed. The choice for this specific division in these three unequal zones was rather to zoom in on the damage to the top and bottom of the berry. Initially, it was thought that because the shape grip pulls the berry with respect to the pedicel downwards, the top of the berry would sustain the most damage. This is seemingly not the case as most berries had the least amount of leaking drupelets at the top, and about equal amounts of RDR damage on the top and the bottom. Looking at all the damage inflicted by the Twisting-Tube gripper, keeping the larger middle section in mind, the damage results seem to indicate that the gripper had quite an uniform grip across the berry, using the top, middle, and bottom for transferring the required harvesting forces.

5.3 Blackberry detachment mechanics

In Figure 14, each vertical pedicel removal force can be seen as individual data points, separated into the cases in which the berry was detached during gripping and those detached during the subsequent vertical pull. There were only limited cases in which the detachment took place during the vertical pull, but these results seem to indicate that neither mode of detachment consistently required more or less force than the other. This result was unexpected, as our initial supposition was that if the pulling force during gripping was not sufficient, the subsequent increasing vertical pull would impose more force for successful detachment. But apparently, the detachment mechanics of blackberries with our Twisting-Tube gripper are more complicated, and our current reasoning is that during the gripping phase the amount of contraction of the tube could also have been the limiting factor. Evidence for this reasoning can be seen in the data, as in the 17 experiments where the blackberry detached during the vertical translation, seven tests were present were the detachment force was lower than the force measured during the during the gripping phase. Furthermore, present in the raw data of every single test is the force on the pedicel alongside the increasing displacement. It was observed that this force increases up to a certain point and then decreases somewhat until suddenly it drops to zero upon detachment. This behaviour can be compared to a textbook stress-strain curve, where fracture often happens at a lower stress than the ultimate stress but at a higher strain.

5.4 Tube properties

First of all, noticeable from the results is that the extra compressibility of thin cheesecloth decreased performance compared to the thick cheesecloth. Only 24% of the berries were successfully detached w.r.t. 82% and it imposed leakage on drupelets on all specimens whilst the gripper equipped with the thick cheesecloth only had 28.6% of the berries with leaking drupelets. During testing, it was observed that the increased compressibility seemed to allow the tube to grasp the sides and bottom of the berry only slightly. It subsequently prefers to knot itself under the berry and thus wedging the berry out of the top 14 out of 21 times. The damage due to this slippage of the thin cheesecloth can also be seen in Table 5, where the middle and bottom sections of all berries had leaking drupelets whilst the top section was completely free of damage. Furthermore, during testing it was observed that the thin cheesecloth tended to stay wrinkled after it became wet due to leakage of cut berries, even if the tube was opened, see also Figure 18. This limited performance as the wrinkles stopped the berry from entering and leaving the tube easily. The spandex and thicker cheesecloth of which the other tubes were made did not show this permanent wrinkle behaviour in any significant way and it thus seems a negative side effect of the compressible thin cheesecloth.

Figure 18: The thin cheesecloth tube after testing, noticeable are the many stains in the middle of the tube due to leaking drupelets. This type of tube stayed wrinkled during and after testing, probably due to the dried up blackberry fluid and the thinness of the material.

To test the influence of overall elasticity, the performance of spandex is compared to that of the thick cheesecloth, but as also the surface of spandex is significantly smoother, two extra tubes were tested that had the same elasticity and stiffness but different smoothness on the interacting surfaces (spandex on the inside of the thick cheesecloth and vice versa). In terms of detachment, the elastic spandex seemed to had a slightly better grip with 94% successful detachments compared to 82% of the thick cheesecloth tube, see Table 3.

The release rates were quite similar across all spandex and thick cheesecloth material combinations except for the case in which spandex was on the inside of thick cheesecloth, here only 18% of the berries were successfully released, see Figure 13. It was observed during testing that the two-layer approach could stop the inner layer of the tube from becoming nicely straight once opened. I.e., the elastic spandex often got wrinkled inside the outer cheesecloth tube and below the lightweight blackberry thereby impeding its exit due to gravity. In hindsight, the two layers of the tube perhaps should have been secured to each other across the entire surface. We decided not to do this because we did not want to measure the influence of e.g., a glue used for this purpose. But possibly a different method of attaching the two layers without changing the material properties too greatly would allow for a multi-layer tube without wrinkling effects.

Table 4 shows that the elasticity of the tube with only spandex allowed it to turn the furthest before the setpoint is reached. During testing the cloth could be seen stretching around the object whilst covering it. Unfortunately, this stretch around the object probably caused too much pressure on the local high points of the berry which gave rise to high damage rates in terms of leaking and RDR drupelets, see Table 5, Table 6, and Table 7. This damage is likely not caused by the different surface properties because the two-surface comparison type of tubes had both less damage in terms of leaking and RDR drupelets. Furthermore, these two tubes had roughly the same detachment performances, so the influence of the surface properties is rather small, which makes sense as the gripper is designed to be mainly a shape grip and not a friction grip.

The padded tube was expected to increase grip and decrease damage rates as the tube could better locally deform to the irregular shape of the berry whilst not imposing high localised pressures. To eliminate the influence of the increased stiffness of the tube with padding to the thick cheesecloth tube, tests were also performed whilst the tube was flipped inside out with the padding on the outside. However, the results show that the radial elasticity does not seem to improve but in fact decreases the performance of the gripper. Both padded tubes detached around 50% of the berries, and the tube with padding on the outside released 64% successfully whilst the other padded tube released none of the berries. During testing, it was noticed that the local deformability allowed the berry to slip in the grip of the tube after tightening. I.e., the berry was present in the tightened tube but the gripper failed to transmit the vertical forces to detach the berry. The radial elasticity allowed for the berry to push the sides of the tube away whilst slowly leaving the tube towards the top. Furthermore, we think that the increased thickness and stiffness of the tube with padding made it conform less to the overall prolate spheroid shape of the berry. This was observed in the tests and can also be seen in Table 4 where the top end but especially the bottom end of the tube rotated less far compared to the other types of tubes. In terms of leaking drupelets, both tubes perform quite well with very limited damage to their handled berries, see Table 5. But in terms of RDR damage, perhaps surprisingly, the tube with padding on the outside performs slightly better than the handpicked exemplars, whilst the tube with padding on the inside performs worse, see Table 6 and Table 7. This difference in performance could have been caused by the smaller inner diameter of the tube with added padding on the inside, which after about the same amount of rotation caused higher pressures than the tube with a bigger opening and its padding on the outside. This smaller opening is also thought to be the cause of the poor releasement rates of the tube with padding on the inside, as only a slight (residual) grip of the padding was enough to hold the lightweight berry in the gripper, even after the extra shake of the tube to aid releasement. Moreover, it was noticed during testing that the slightly smaller opening made it harder for the berry to enter correctly, and often the entry shake of the tube was necessary for it to fully enter the tube.

Overall, a compressible tube is probably more likely to push a berry out. Furthermore, a stiff tube is harder to deform and therefore it is also harder to conform to the shape of the object. The higher stiffness also makes it more difficult to measure the small increase in torque when it correctly deformed around a blackberry. Additionally, an elastic tube seems to have a firmer grip on the blackberry but also imposes too much damage in the process. Besides, a smoother surface does not seem to impact the performance of the gripper in these tests. Moreover, a tube with radial elasticity can limit damage but also allows for the object to slip out of the grip. Lastly, the tube must be as thin as possible to impose a small space claim in the dense canopy but still have a large opening with some play for a berry to enter and leave easily. All learnings and results taken together, the thick cheesecloth, without elasticity and with some compressibility, has the best overall performance.

The performance of our Twisting-Tube gripper with thick cheesecloth can only be compared to one other gripper tested on blackberries known to the author, which is the tendon-driven gripper with force feedback of Gunderman et al. The harvesting success rate of their most successful setup is 95% where our gripper is currently less reliable with 82%. The gripper from Gunderman et al. is also faster with a harvest time per berry of 4.8 seconds whilst ours presently takes a minimum of 12 seconds. The damage rates cannot be fairly compared as Gunderman et al. did not report leaking drupelets and observed RDR rates after storing at 2°C for 21 days (Gunderman et al., 2022).

5.5 Gripping principle

There were also some practical lessons learned and insights gained by manufacturing and testing the twisting tube prototype. For example, in some initial testing, the motors were steered to rotate far further than needed to see if they would crush a blackberry. This was not exactly the case because after the cloth wraps around the object, the weakest link in the system becomes the compression spring which then starts to deform if torque is supplied to it. Consequently, the gripper in its entirety has an inherent safety feature that stops the object inside from being crushed if too much torque is applied.

Another example from some initial testing is the flexibility of the gripper to adapt to the position of the object in vertical and horizontal directions. The compression spring allows the upper end of the tube to be pushed away horizontally and vertically. Furthermore, the horizontal location of the berry inside the gripper does not seem to change the performance of the grip. I.e., the berry could be located at the sides inside the gripper instead of directly in the centre, and still the gripper would close and grab the berry successfully by pushing it into the centre. The vertical location of the berry is important though, the same initial tests showed that the berry needed to be around the centre of the gripper when closed around the object. Which for the blackberry tests presented here meant that they would have to enter the tube for about two-thirds in length from its free end for a successful grip.

During testing, the Twisting-Tube gripper not once wedged a fruit out of the bottom. We think this is due to the fact that the fruit is vertically suspended from the pedicel at the top, and if the tube gripper tried to wedge it down, the gripper would detach the fruit successfully as it pulled on the pedicel. In the other direction, the stem does not have much strength in compression so the fruit can be easily wedged and pushed to the top of the gripper without much force. Therefore, a possible improvement of the gripper could be to lower the fruit a bit lower on average with respect to the middle of the gripper. In this manner, it would less likely be pushed upwards and more likely be pulled downwards with possibly a partial grip in some cases.

Finally, section 2.1 posed some requirements that the gripper prototype had to fulfil, most of which are proven in the results section by detaching and releasing a range of blackberries and other fruit without imposing damage. Other requirements are fulfilled by the design of the gripper, such as food safety by using food-safe material, such as the 3D printer filament and the cheesecloth. Furthermore, the tube is easy to remove and can be washed by hand or by a laundry machine after a period of use, so it can be relatively easily cleaned. Moreover, the measured (unoptimised) cycle time of the gripping procedure (tube shake + grip + releasement) is about 38 seconds, which is above the proposed cycle time of 10 seconds. This can be improved by tightening the tube faster or by speeding up or removing the entry and release shake (without the shake movement, grip and releasement currently takes 12 seconds).

5.6 Possible gripper improvements

The current prototype gripper proves that the concept is viable but leaves room for upgrades for a possible industrial version. Firstly, the DC motors operated in the low end of their possible range, needing only up to 20% of their max current draw. So, the next iteration could use lower power servos to decrease the volume and weight of the gripping tool. Secondly, the dimensions of the prototype design were sized around the characteristics of a blackberry, and to house the mechanism and the motors whilst being able to be 3D printed. If other manufacturing techniques, other motors, or other fruits would be used, the design could be altered. In a later stage, the design could then also be optimised to make it as lightweight and efficient as possible. For the current prototype, optimisation of the dimensions through analysis or simulations was considered. But in this use case, with the different soft tubes on soft fruits interactions, there are currently simply too many unknown variables. A simple improvement, however, would be to decrease the diameter of the spring to make a smaller space claim with the entire mechanism in the dense canopy. The presented prototype was purposely fitted with a large diameter spring to limit its influence on the tube if the spring were to buckle or decrease significantly in diameter, but this was not observed during testing.

Furthermore, Table 4 shows that both rings turned about equally far on average to close the gripper around the object. In practice, however, it has also been observed that sometimes one or the other end of the tube stops turning quite a bit sooner with respect to the opposite end. This thus indicates that the choice of two independent actuators was not only insightful for measuring its behaviour, but probably also allowed for a more secure grip in some cases. Future work can still investigate if just turning one gripper would impact performance, as the mechanism can be simplified, and the overall weight can be significantly lower if just one end of the tube is actuated.

6 Conclusion

This research had set out to find a robotic gripper for the delicate use case of detaching blackberries from pedicels. The problem was analysed, a twisting tube concept was selected, and a prototype was subsequently manufactured. A custom measurement set-up has also been made to test the pedicel removal force, vertical displacement of the berry and rotation of the tube. Seven different tubes were tested and showed that food-safe cheesecloth (100% cotton) performed best in most metrics. The other tubes with extra compressibility, overall elasticity and radial elasticity performed worse by having less success removing blackberries and/or by imposing more damage to them. The gripper with a cotton cheesecloth tube could grab, detach from the pedicel and release 43% of the blackberries without cutting the drupelets, whilst the handpicked condition scored 88%. Furthermore, only 19% of the robotically grasped berries showed Red Drupelet Reversion (RDR) after 48 hours whilst the handpicked control blackberries showed 33% damage. The same cloth was also tested on cherry tomatoes and three different kinds of grapes in which the differently shaped and sized fruits were almost always successfully grasped without imposing damage. The presented Twisting-Tube gripper prototype therefore showed some initial promise for grasping soft fruit, and future work can expand its scope and increase its performance.

7 Future work

Before this gripper can be deployed in the agricultural field, more design work and thorough testing and iterations are necessary. First of all, the gripper must be attached to a robotic manipulator with at least five degrees of freedom to position the gripper along the required approach direction. The use case of fruits attached to pedicels in different directions require positioning in three dimensions, and rotation of two axis to align the tube with the major axis of the crop. To enable this positioning in the often dense canopy of most crops the gripper must make as small as possible space claim. With respect to the presented prototype, the tube could be, for example, shorter and the spring around the tube could be smaller or even integrated into the tube. Tests can then be performed to see what the vertical workspace is of the Twisting-Tube gripper and how it can be enlarged without lengthening the tube. This would allow for more robust gripping of different lengths of fruit and less precise positioning of the manipulator and supporting vision system.

Another way to make this prototype smaller is by implementing lower powered actuators, considering that the eventual necessary torque and power are significantly lower than that what the chosen motors were capable of providing. Future work can furthermore optimise the design in terms of the size of the mechanism and the frame and subsequently test on different crops, their varieties and cultivation methods. This test should show if the gripper is able to safely approach the target fruit between the surrounding leaves, branches, wires and other fruit.

Future work can test the cycle time of the entire harvesting procedure or just the gripping procedure and optimise its speed to make the robot more economically viable. When this new first viable product is produced, durability tests would then also be necessary to see if the lifetime of the gripper is satisfactory. These tests should gather data about the influence of the environmental factors and cloth material in terms of long-term performance of the gripper.

The presented research only produced seven different kinds of tubes and subsequently saw quite a large impact on performance. More exotic types of tubes might increase the performance of the gripper. For example, the tube can be non-uniform, with a gradient in thickness or different materials. The tube could also have folding lines that would force the tube to twist around a certain path which could increase performance. There could also be layers of materials seen in other grippers, such as anisotropic surfaces, lattice structures, column buckling, (hydro-)gels, granular jamming chambers, etc. See, for example, the fruit gripper of Lee et al., which utilises a honeycomb supporting layer for local deformability and a mesh with granular material for a stiffness transition after conforming to the object (Lee et al., 2021). Or the small untethered hydrogel gripper by Kim et al. which can open and close due to an electric field and move by applying a magnetic field (Kim et al., 2020).

Identifying different kinds of crops and their varieties could be quite a challenge, especially when only ripe crops should be picked. For most crops, some localisation and mapping in 3D space is necessary that shows possible occlusions and obstacles to plan a path safely and quickly towards the crop. This path can either avoid obstacles, or actively try to separate the target fruit from surrounding obstacles for more dense canopies (Xiong et al., 2020). When arrived at the crop, the gripper could use mechanical methods to verify if the crop is ripe and therefore is allowed to be picked. For example, the gripper could measure the force necessary for a certain displacement on the pedicel or the surface of the fruit and possibly abort detachment of the fruit if it is deemed unripe. A gripper by Blanes et al. already does something similar, in which they use non-destructive impact measurements with accelerometers to predict the firmness of eggplants (Blanes et al., 2015).

When the fruit is classified to be harvested, different detachment movements can be investigated for each type of crop. In our previous work, common methods include horizontal and vertical flicks, pulls, bends and twists of the fruit (Elfferich et al., 2022). As manual harvesting by human hands usually uses a (combination of) specific method(s) to increase speed and decrease damage, it is expected that the same would be true for robotic grippers. For example, for the gripper presented in this paper, a bending of the tube with respect to the pedicel could be interesting to investigate. Furthermore, turning both motors in the same direction to turn the entire tube could also increase performance, as this twist was observed to be done by human harvesters as well. All these detachment translations and rotations impose forces and torques on the fruit and on its pedicel which result in detachment of the fruit. Meanwhile, Figure 14 shows that these forces can vary significantly even among a single variety of fruit. It could thus also be interesting to map out the different forces and torque (combinations) needed for each direction, per type of crop, to better inform the design of future grippers. The work by Liu et al. could serve here as a good starting point, as they provide an analytical foundation for the complex mechanics of robotic fruit harvesting patterns (Liu et al., 2020).

The Twisting-Tube gripper presented in this paper is from the onset a specialised gripper that is designed and tested on blackberries and similar fruit. A possible parallel direction for future research in to the gripper could be to consider other use cases. This will probably lead to a redesign if differently sized or shaped objects are supposed to be grasped. For example, the material, length or diameter of the tube could be altered, or its cross-section could be changed to follow target objects' shape more closely.

8 Acknowledgements

I would like to thank Wouter van den Bosch and Jaap de Schipper from the company Bosch growers for giving me insight into their growing and harvesting process of blackberries, and for allowing me to buy and harvest their blackberries myself with and without the stem.

I further declare no conflict of interest.

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10 Supplementary material

The raw data and its subsequent analysis can be found in the supplementary excel files.

11 Appendices

These appendices consist of extra material that provides further background information to the main text. In the first section, more background is given to the concept expansion phase. The second section delves into a first prototype of the Twisting-Tube gripper and its learnings. In the third section an overview is given of the bought components to allow other researchers to replicate this gripper exactly. In the fourth section a diagram is given of the electrical components and their connections. In the fifth section the used code is given to control the gripper and read values of the sensors using the Arduino and connected laptop. In the sixth section the lessons learned from the initial pilot test with the finished gripper are laid out. In the seventh section it is explained why measuring internal discolouration of blackberries was considered but subsequently not used for the systematic tests. The eighth section presents further data: average number of drupelets counted, drupelets leaking for all blackberries and the results of every single test. The nineth section expands the future work section of the main text with some more ideas. The tenth section explains the printer settings and the correct order of assembly of the gripper. The eleventh and last section gives CAD drawings of the 3D printed components, highlighting their material and dimensions.

11.1 Concept expansion process

Using the results of the literature review and the above objectives, multiple systematic brainstorming sessions were held that resulted in a solution space which spanned dozens of concepts which all in principle would fulfil the requirements. This, for example, included grippers with fingers that used soft pads to limit damage whilst grasping in an enveloping manner. Other concepts included 3D-Bernoulli or vacuum systems which used differences in local air pressures to gain a gentle grasp. Furthermore, granular jamming, anisotropic surfaces, fluidic elastomeric actuators and combinations of these technologies were considered. These concepts could be narrowed down to the three most promising concepts by looking at maximizing the surface area in the range of objects considered, which as stated in the main text, would limit damage whilst transferring the required harvesting forces. This excluded concepts that approached the berry from the sides are could not utilise the top and bottom of the berry to transfer forces. Other concepts would have to be designed around a set curvature of the berry and could thus securely grasp the entire area of averaged sized berries but would leave parts of the surface of bigger berries unused and would have problems closing around smaller berries.

11.2 Initial prototype

In Figure 19 a CAD screenshot and picture can be seen of the exploratory, 3D printed, simplified prototype of the Twisting-Tube gripper concept. This first prototype was operated by hand to allow the researchers to feel the forces and see the operation of the gripper most clearly. The most insightful observation was made by gently grasping a single extended finger of a researcher. The researcher felt uniform forces all around her/his finger, and thus knows that this gripper can impose a uniform grip on an object inside of the tube. The length of the tube and the custom-wound spring could be altered by re-tightening the screw of the split ring and the vertical screws respectively, see Figure 19. This adjustability showed that a tube of 70mm had enough but not too much length for grasping a berry-sized object. Allowing it to grasp the entire berry surface except for the pedicel at the top. The split rings also allowed us to change the cloth and both cheesecloth and see-through plastic were tested. The cheesecloth worked well, but the plastic was probably too smooth as it wedged the object out often during the tightening of the tube. The plastic tube did allow the researchers to see the action inside the gripper more clearly during tightening, not only from above and below but also from the sides.

This first prototype thus showed that the concept could uniformly grasp objects securely by twisting the tube. The custom spring showed that it had enough restoring force to return the gripper after its twist to the original open position. Furthermore, this prototype gave insight into the optimal position for a berry-sized object to be grasped, which was about halfway down the collapsed tube.

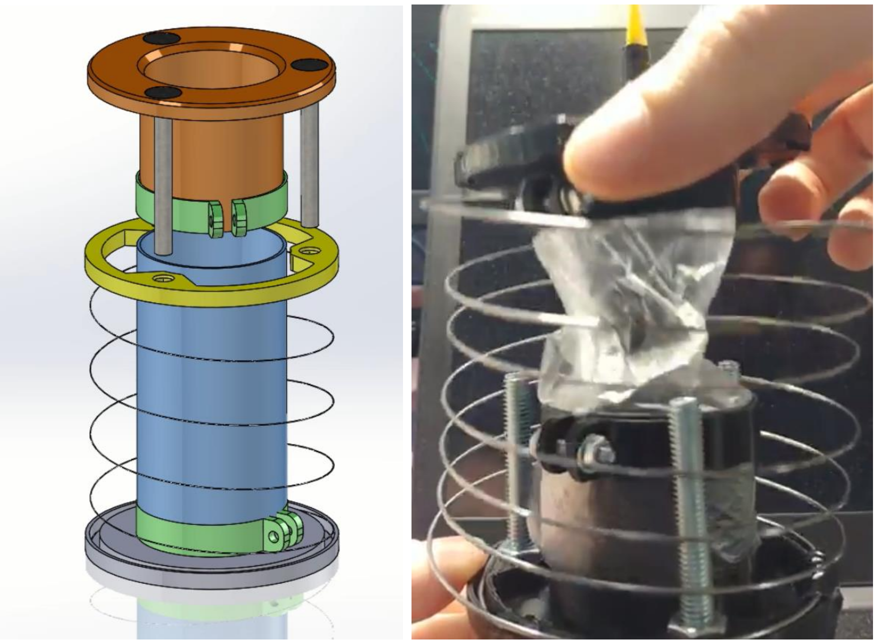


Figure 19: On the left is a screenshot of the CAD design of the first prototype Twisting-Tube gripper, with in green split rings which clamp the blue tube in place and in yellow an adjustable stage to tension the spring. On the right is a still of a video in which the gripper gets tightened using a plastic, see-through tube.

11.3 Overview bought components

In Table 9 an overview of the bought and used components for the gripper can be found. In the last column, the name of the webshop can be found and in the supplementary material, a clickable link is present that directly opens the product on the webshop page.

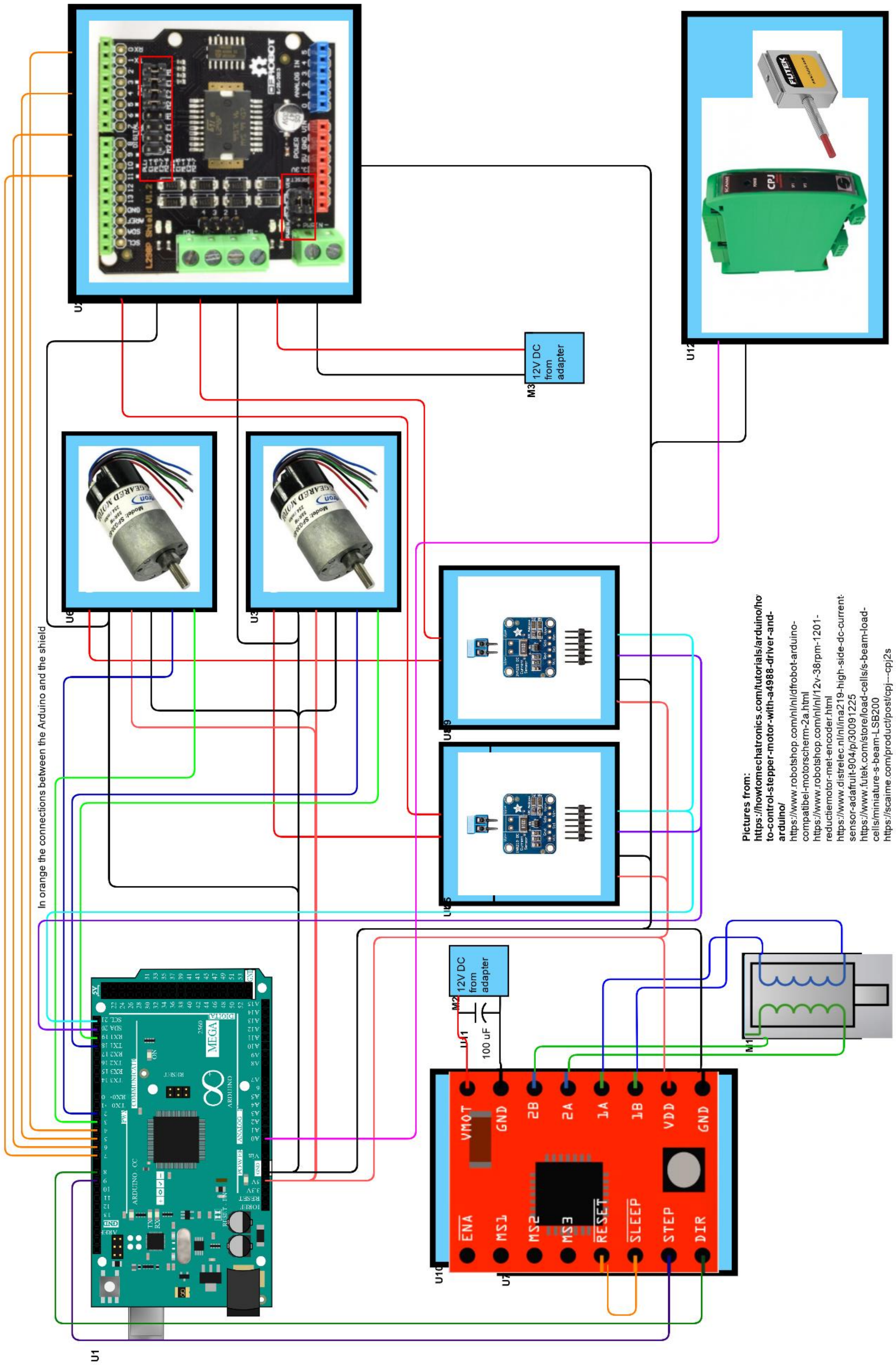
Table 9: Overview of bought components used in the Twisting-Tube gripper.

Component name	**Amount**	**Price per piece (€)**	**Price total (€)**	**Webshop**
Cheesecloth (A) 160 cm wide 65g/m^2	1	2.95	2.95	Stoffenshop
Cheesecloth (D) 150 cm wide 230g/m^2	1	5.95	5.95	Stoffenshop
1 mm thick piano wire	1	7.75	7.75	amazon.de
12V, 38RPM 120:1 DC motor with Encoder	2	19.99	39.98	robotshop
iglidur® I151-PF, filament for 3D printing	1	91.31	91.31	igus
Arduino MEGA R3	1	19.99	19.99	amazon.de
12V 5A power adapter	1	12.99	12.99	amazon.nl
INA219 High side dc current sensor breakout - 26V ±3.2A MAX	2	11.99	23.98	Kiwi-electronics
Prototyping board - 4X6 cm - 2.54 mm pitch	1	1.95	1.95	Kiwi-electronics
Polyether SG25 foam	1	9.45	9.45	schuimwinkel.nl
Lycra: Dark petrol basic	1	14.94	14.94	Royallook
DFRobot Arduino compatible Motorshield (2A)	1	17.12	17.12	robotshop
80 Pcs neodymium magnets	1	9.00	9.00	amazon.nl

11.4 Electronics diagram

The below electronics diagram is made with the scheme-it tool of Digi-Key[1]. It shows the electrical connections between the different components of the gripper and the measurement setup. In the top left the Arduino Mega is shown, in the bottom left the stepper with its stepper driver is visible. In the middle, the two DC motors with encoders can be seen along with the two accompanying current sensors of Adafruit. In the top right, the DC motor shield is shown and in the bottom right, the loadcell with signal amplifier is visible. This circuit was first tested on a breadboard and afterwards soldered in place with connectors to ensure secure connections during testing and operation of the gripper.

[1] https://www.digikey.com/schemeit/



In orange the connections between the Arduino and the shield
12V DC from adapter
12V DC from adapter
100 uF
VMOT
GND
2B
2A
1A
1B
VDD
GND
ENA
MS1
MS2
MS3
RESET
SLEEP
STEP
DIR
Pictures from:
https://howtomechatronics.com/tutorials/arduino/how-to-control-stepper-motor-with-a4988-driver-and-arduino/
https://www.robotshop.com/nl/nl/dfrobot-arduino-compatibel-motorscherm-2a.html
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https://www.distrelec.nl/nl/ina219-high-side-dc-current-sensor-adafruit-904/p/30091225
https://www.futek.com/store/load-cells/s-beam-load-cells/miniature-s-beam-LSB200
https://scaime.com/product/post/cpj---cpj2s

11.5 Arduino code for control of Twisting-Tube gripper and measurement setup

Below code for the Arduino Mega is developed to control both the gripper and measurement setup and records the values of the sensors via USB cable in Excel via the Data Streamer Add-In.

```
//Thesis final script, soft gripper project
//Twisting-Tube gripper

//Student name: Rick Elfferich
//Student number: 4565339

/*
This script is in control of the gripper and the measurement setup at the
same time, so it can both control the gripper and the measurement setup as
it measures their properties via sensors

 *  It can home and control the stepper motor which translates the vertical
stage
 *  It can move both DC motors (that each turn an end of the tube) via a
PID control loop to a certain desired position or via smoothed current
sensors to a desired level
 *  It measures the position of the vertical stage, the rotation of both
ends of the tube, and the force of the loadcell. It sends those values in
real-time to a connected laptop via USB cable to be recorded in Microsoft's
Excel
 */

//Sources used for below code:
//https://www.arduino.cc/en/Tutorial/BuiltInExamples/Button
//https://www.arduino.cc/en/Tutorial/BuiltInExamples/Smoothing
//Example code from the Adafruit_INA219 library

//--- libraries: ---
#include <util/atomic.h> // For the ATOMIC_BLOCK macro
#include <Wire.h>
#include <Adafruit_INA219.h>

//Current measuring chip INA219 use pins SDA and SCL
Adafruit_INA219 ina219_1;
Adafruit_INA219 ina219_2(0x44); //second chip is bridged using solder on
the back, so it uses a different address.
//0x40 (left) and 0x44 (right)

//--- pin allocation: ---
//Arduino PWM Speed Control via motor shield:
const int E1 = 5;
const int M1 = 4;
const int E2 = 6;
const int M2 = 14; //bridged because pin 7 stopped working properly

//Encoder pins for both DC motors
#define EN1A 2
#define EN1B 3
#define EN2A 18
#define EN2B 19

//stepper pins
const int steppin = 11;
```

```
const int dirpin = 10;
const int enable_stepper_pin = 9;

//Button pins
const int Button1 = 41;
const int Button2 = 45;
const int Button3 = 49;
const int Button4 = 8;
const int Button5 = 15; //long wire extra button, does same as button 4
const int endstop_pin = 12; //endstop can be seen as a simple button

// sensor pin futek load cell:
int sensorPin_futek = A0;

//--- variables: ---
float desired_location = 0; //adjustable variable to steer dc motors to

const float one_step_in_mm_stepper = 1.25/(8*200); //thread pitch M8 is
1.25 mm and this stepper has 200 steps per revolution & is set to 1/8
microstepping
float vertical_displacement_berry = 0; //w.r.t. start of displacing the
berry
float current_stepper_position = 0; //the current position of the stepper
motor


//for reading the button state
int Button1_state = 0;
int Button2_state = 0;
int Button3_state = 0;
int Button4_state = 0;
int Button5_state = 0;


volatile int posi1 = 0; // specify posi1 as volatile:
https://www.arduino.cc/reference/en/language/variables/variable-scope-
qualifiers/volatile/
volatile int posi2 = 0; // specify posi2 as volatile:
https://www.arduino.cc/reference/en/language/variables/variable-scope-
qualifiers/volatile/

//variables used for PID steering via values of encoder
long prevT = 0;
float eprev1 = 0;
float eintegral1 = 0;
float eprev2 = 0;
float eintegral2 = 0;
// PID constants encoder
float kp = 2;     //good value: 2
float kd = 0.1;   //good value: 0.1
float ki = 0;     //good value: 0

//smoothing current reading sensor 1 and 2
//current sensors give values at a high rate but fluctuating
//sizes are found via testing and trial and error
const int numReadings_c1 = 300;     // size of the smoothing window of
first sensor
const int numReadings_c2 = 100;     // size of the smoothing window of the
second sensor

// variables for force logging
```

```
float force_newton; //loadcell value converted to newtons
float sensorValue_futek; //value directly from futek loadcell

void setup()
{
  Serial.begin(9600);
  while (!Serial) {
      // will pause Arduino until serial console opens
      delay(1);
  }

  // Initialize the INA219.
  if (! ina219_1.begin()) {
    Serial.println("Failed to find INA219_1 chip");
    while (1) { delay(10); }
  }
  if (! ina219_2.begin()) {
    Serial.println("Failed to find INA219_2 chip");
    while (1) { delay(10); }
  }

    //defines pinmodes of pins
    pinMode(M1, OUTPUT);
    pinMode(M2, OUTPUT);

    pinMode(EN1A,INPUT);
    pinMode(EN1B,INPUT);
    pinMode(EN1A,INPUT);
    pinMode(EN1B,INPUT);
    attachInterrupt(digitalPinToInterrupt(EN1A),readEncoder1,RISING);
    attachInterrupt(digitalPinToInterrupt(EN2A),readEncoder2,RISING);

    pinMode(Button1, INPUT);
    pinMode(Button2, INPUT);
    pinMode(Button3, INPUT);
    pinMode(Button4, INPUT);
    pinMode(Button5, INPUT_PULLUP); //does NOT have own resistor, needs
internal resistor
    pinMode(endstop_pin, INPUT_PULLUP);

    pinMode(steppin, OUTPUT);
    pinMode(dirpin, OUTPUT);
    pinMode(enable_stepper_pin, OUTPUT);
    digitalWrite(enable_stepper_pin, HIGH); //disables stepper


    //when starting up, the position of the vertical stage is unknown, so
it gets homed to the top until it hits the end stop
    homestepper(95);    //home the stepper to the top with a relatively low
speed of 95%
    current_stepper_position = 0;

}

void loop()
{

  // ------- Start measuring sequence -------
  // read the state of the pushbutton value:
  Button4_state = digitalRead(Button4);
  Button5_state = digitalRead(Button5);
```

```
  // check if the pushbutton is pressed. If it is, the buttonState is HIGH:
  if (Button4_state == HIGH || Button5_state == LOW) {

        // speed with force measurement is about  0.4 mm/s of the vertical
stage (90%)
        // speed without force measurement is about 3.5 mm/s of the
vertical stage (95%)

        // 2235 counts are one full turn of the ring, moves at about 74
deg/s when up to speed


        //starting position
        runstepperto(95, 95); //110 - 15 = 95 mm of stage position w.r.t.
endstop; 0-100, 95 motor speed

        //take measurement to determine weight of berry
        berry_Forcelogging();
        delay(100);


        //run stepper certain amount down into gripper
        runstepperto(173, 95); //173mm for 50mm between top of berry and
bottom of tube (for blackberries and long grapes), 200 - 15 = 185 mm of
stage position w.r.t. endstop, 0-100 motor speed
        //runstepperto(185, 95); //185mm for 38mm between top of berry and
bottom of tube (for shorter cherry tomatoes and grapes), 200 - 15 = 185 mm
of stage position w.r.t. endstop, 0-100 motor speed
        delay(1000);


        //little shake of bottom ring to force berry in
        movemotorencoderPID(true, 700, true, 0);
        movemotorencoderPID(true, -700, true, 0);
        movemotorencoderPID(true, 700, true, 0);
        movemotorencoderPID(true, -700, true, 0);
        movemotorencoderPID(true, 0, true, 0);

        delay(2000);

        movemotorcurrent(true, 75, 10, true, -95, 10); //FINAL values: 75,
-95, bool move motor 1, move up to which current in mA (negative gives
counter clockwise on outputshaft motor), cap power/speed between 0-100,
bool move motor 2, move up to which current in mA, cap power/speed between
0-100
        //Serial.println("done thightening the motor");
        delay(1000);

        runstepper_withForcelogging(10, 0, 90); //move vertical stage
upwards whilst measuring the force for 10 mm, 0 is clockwise (up), 1 is
anticlockwise, 0-100 motor speed
        delay(1000);
        movemotorencoderPID(true, 0, true, 0); //open gripper to resting
position
        delay(1000);


        runstepperto(95, 95); //110 - 15 = 95 mm of stage position w.r.t.
endstop; 0-100, 95 motor speed
```

```
        //little shake of top ring to let go of berry
        movemotorencoderPID(false, 0, true, 700);
        movemotorencoderPID(false, 0, true, 0);
        movemotorencoderPID(false, 0, true, -700);
        movemotorencoderPID(false, 0, true, 0);
        movemotorencoderPID(false, 0, true, 700);
        movemotorencoderPID(false, 0, true, 0);
        movemotorencoderPID(false, 0, true, -700);
        movemotorencoderPID(false, 0, true, 0);

  }


  //button to home stepper
  Button3_state = digitalRead(Button3);
  // check if the pushbutton is pressed. If it is, the buttonState is HIGH:
  if (Button3_state == HIGH) {

        homestepper(90);   //home the stepper to the top with low speed
        delay(1000);

  }


  // --- alter bottom ring position stepwise to easily align rings after a
possible error ---
  Button1_state = digitalRead(Button1);

  if (Button1_state == HIGH) {
      desired_location = desired_location + 50;
      movemotorencoderPID(true, desired_location, false, 0);
      delay(50);
  }

  Button2_state = digitalRead(Button2);
  if (Button2_state == HIGH) {
      desired_location = desired_location - 50;
      movemotorencoderPID(true, desired_location, false, 0);
      delay(50);
  }

}

//log weight of berry for 100 measurements via loadcell and send via serial
to laptop
void berry_Forcelogging(){
    for (int x = 0; x < 100; x++){
      sensorValue_futek = analogRead(sensorPin_futek);
      force_newton = 0.0418 * (sensorValue_futek - 3); //mapping from
meetshop from 10 bit to newton

      //print the values in a format excel understands "N" stands for No
value
      Serial.print(force_newton);
      Serial.print(",");
      Serial.print("N");
      Serial.print(",");
      Serial.print("N");
      Serial.print(",");
      Serial.print("N");
      Serial.print(",");
```

```
      Serial.print("N");
      Serial.print(",");
      Serial.print("N");
      Serial.print(",");
      Serial.println();
    }
}

//move the vertical stage, thus stepper motor to certain position w.r.t.
the home position at a certain speed
void runstepperto(float mm_position, int motspeed){

   //first check if entered value is within reachable range of vertical
stage, as values outside this range would make the stage collide with the
frame
   if (0.0 < mm_position && mm_position < 225.0){
     float diff_position = mm_position - current_stepper_position; //checks
distance to go to w.r.t. the current position of the vertical stage
     current_stepper_position = mm_position;
     //Serial.println(diff_position);
     //depending if the stepper has to go down or up adjust runstepper
function
     if (diff_position < 0){
        runstepper(abs(diff_position), 0, motspeed);
     }
     if (diff_position > 0){
        runstepper(diff_position, 1, motspeed);
     }
   }
   else{
      //Serial.println("position outside of reachable range");
   }
}

//at a certain speed move stage upwards until it hits the endstop
void homestepper(int motspeed){
  int motspeed_mapped = map(motspeed, 0, 100, 1000, 50); //motorspeed
between 0-100% is tested to be the reachable range of this specific setup
translating to delays between 1s and 50ms in the pulse
  digitalWrite(enable_stepper_pin, LOW); //enables stepper

  //send pulse until enstop is touched
  while(digitalRead(endstop_pin) == LOW){
    digitalWrite(steppin, HIGH);
    delayMicroseconds(motspeed_mapped);
    digitalWrite(steppin, LOW);
    delayMicroseconds(motspeed_mapped);
  }

  digitalWrite(enable_stepper_pin, HIGH); //disables stepper
}

//moves stepper motor for certain distance in (anti-)clockwise direction at
certain speed
void runstepper(float mm_distance, int dir, int motspeed){
  int motspeed_mapped = map(motspeed, 0, 100, 1000, 50); //motorspeed
between 0-100% is tested to be the reachable range of this specific setup
translating to delays between 1s and 50ms in the pulse
  digitalWrite(enable_stepper_pin, LOW); //enables stepper
  delay(10);
  digitalWrite(dirpin, dir);
```

```
  delay(50);

  float distance_in_steps = mm_distance / one_step_in_mm_stepper;
//calculates steps to take given the amount to travel in millimetre

  //sends pulses with delay until enough have been taken
  for(float x = 0; x < distance_in_steps; x++){
    digitalWrite(steppin, HIGH);
    delayMicroseconds(motspeed_mapped);
    digitalWrite(steppin, LOW);
    delayMicroseconds(motspeed_mapped);

  }

  digitalWrite(enable_stepper_pin, HIGH); //disables stepper

}

//moves stepper motor for certain distance in (anti-)clockwise direction at
certain speed whilst also measuring the force on the loadcell and logging
it
void runstepper_withForcelogging(float mm_distance, int dir, int motspeed){
  if (dir == 0){
    current_stepper_position = current_stepper_position - mm_distance;
  }
  if (dir == 1){
    current_stepper_position = current_stepper_position + mm_distance;
  }


  int motspeed_mapped = map(motspeed, 0, 100, 1000, 50); //motorspeed
between 0-100% is tested to be the reachable range of this specific setup
translating to delays between 1s and 50ms in the pulse
  digitalWrite(enable_stepper_pin, LOW); //enables stepper
  delay(10);
  digitalWrite(dirpin, dir);

  force_newton = 0;
  sensorValue_futek = 0;
  vertical_displacement_berry = 0; //w.r.t. start of displacing the berry

  float distance_in_steps = mm_distance / one_step_in_mm_stepper;
  int print_counter = 0; //to not communicate the force during every pulse
of the stepper but every 10 pulses, this allows the stepper to run at
moderate speeds instead of extremely slow speeds
  for(float x = 0; x <= distance_in_steps; x++){

    print_counter = print_counter + 1;
    if (print_counter > 10){
    sensorValue_futek = analogRead(sensorPin_futek);
    force_newton = 0.0418 * (sensorValue_futek - 3); //mapping from
meetshop from 10 bit to newton
    vertical_displacement_berry = x * one_step_in_mm_stepper; //translates
the steps to vertical translation in mm

    //print the values in a format excel understands
    Serial.print("N");
    Serial.print(",");
    Serial.print("N");
    Serial.print(",");
    Serial.print("N");
```

```
    Serial.print(",");
    Serial.print("N");
    Serial.print(",");
    Serial.print(vertical_displacement_berry);
    Serial.print(",");
    Serial.print(force_newton);
    Serial.print(",");
    Serial.println();
    print_counter = 0;
    }

    //take the step
    digitalWrite(steppin, HIGH);
    delayMicroseconds(motspeed_mapped);
    digitalWrite(steppin, LOW);
    delayMicroseconds(motspeed_mapped);
  }
  digitalWrite(enable_stepper_pin, HIGH); //disables stepper

}

//reads the encoder of motor 1, and determines direction to add it to the
current position
void readEncoder1(){
  //gets attached to interrupt of A, and depending if B is triggered at
that point or not adds or substracts one pulse from the posi counter
  int b = digitalRead(EN1B);
  if(b > 0){
    posi1++;
  }
  else{
    posi1--;
  }
}

//reads the encoder of motor 2, and determines direction to add it to the
current position
void readEncoder2(){
  //gets attached to interrupt of A, and depending if B is triggered at
that point or not adds or substracts one pulse from the posi counter
  int b = digitalRead(EN2B);
  if(b > 0){
    posi2++;
  }
  else{
    posi2--;
  }
}

//moves the DC motors which twists the tube at certain mapped speed in a
certain direction
void movemotor(int M1orM2, int percspeed, int dir){
//which motor (1 or 2), at which percentage (0-100) of speed in which
direction (1 = clockwise, -1 = anti-clockwise)
int mapped_speed = map(percspeed, 0, 100, 100, 255); //(100-255) PWM Speed
Control between 100 and 255 for lowest speed and highest speed from
standstill

  //Checks if motor 1 or 2 needs to be moved
  if (M1orM2 == 1){
    //Checks in which direction the motor needs to be moved
```

```
    if(dir == 1){
      digitalWrite(M1, HIGH);   //HIGH is clockwise (and low anti-
clockwise) on the outgoing axle
      analogWrite(E1, mapped_speed);   //(100-255) PWM Speed Control
between 100 and 255 for lowest speed and highest speed from standstill
    }
    else if (dir == -1){
      digitalWrite(M1, LOW);   //HIGH is clockwise (and low anti-clockwise)
on the outgoing axle
      analogWrite(E1, mapped_speed);   //(100-255) PWM Speed Control
between 100 and 255 for lowest speed and highest speed from standstill
    }else{
      analogWrite(E1, 0); //if direction is unequal to 1 or -1, then stop
the motor
    }

  }
  if (M1orM2 == 2){
    if(dir == 1){
      digitalWrite(M2, HIGH);   //HIGH is clockwise (and low anti-
clockwise) on the outgoing axle
      analogWrite(E2, mapped_speed);   //(100-255) PWM Speed Control
between 100 and 255 for lowest speed and highest speed from standstill
    }
    else if (dir == -1){
      digitalWrite(M2, LOW);   //HIGH is clockwise (and low anti-clockwise)
on the outgoing axle
      analogWrite(E2, mapped_speed);   //(100-255) PWM Speed Control
between 100 and 255 for lowest speed and highest speed from standstill
    }else{
      analogWrite(E2, 0); //if direction is unequal to 1 or -1, then stop
the motor
    }
  }
}

//move one (or both  motors at the same time) towards a certain position
counted in pulses of the encoder (relative to start-up), using a PID loop
void movemotorencoderPID(bool move1, int target1, bool move2, int target2){

  //keep track if target is reached by PID loop to eventually leave both
loops
  bool reached_target = false;
  bool reached_target1 = false;
  bool reached_target2 = false;

  while (reached_target == false){
    // time difference
    long currT = micros();
    float deltaT = ((float) (currT - prevT))/( 1.0e6 );
    prevT = currT;

    //move first motor via PID
    if (move1 == true){
    // Read the position in an atomic block to avoid a potential
    // misread if the interrupt coincides with this code running
    // see:
https://www.arduino.cc/reference/en/language/variables/variable-scope-qualifiers/volatile/
    int pos1 = 0;
    ATOMIC_BLOCK(ATOMIC_RESTORESTATE) {
```

```
      pos1 = posi1;
    }

    //PID values were set by trial and error for this use case, adding the
integral decreased performance as it increased oscillations

    // error
    int e1 = target1 - pos1;

    // derivative
    float dedt1 = (e1-eprev1)/(deltaT);

    // integral
    //eintegral1 = eintegral1 + e1*deltaT;

    // control signal
    //    float u1 = kp*e1 + kd*dedt1 + ki*eintegral1;
    float u1 = kp*e1 + kd*dedt1;
    // motor power
    float pwr1 = fabs(u1);
    //cap motor power to 100
    if( pwr1 > 100 ){
      pwr1 = 100;
    }

    // motor direction
    int dir1 = 1;
    if(u1<0){
      dir1 = -1;
    }

    // signal the motor
    movemotor(1, pwr1, dir1); //moves motor 1 or 2 at speed (0-100), in
direction 1 or -1

    //if both the previous error and the current error is equal to zero,
then the position is considered to be steadily reached and the motor can
stop turning
    if (eprev1 == 0 && e1 == 0){
      reached_target1 = true;
      movemotor(1, 0, 0); //stop the motor
    }

    // store previous error
    eprev1 = e1;

    }
    else{
      reached_target1 = true;
    }

    //move second motor via PID
    if (move2 == true){
    // Read the position in an atomic block to avoid a potential
    // misread if the interrupt coincides with this code running
    // see:
https://www.arduino.cc/reference/en/language/variables/variable-scope-
qualifiers/volatile/
    int pos2 = 0;
    ATOMIC_BLOCK(ATOMIC_RESTORESTATE) {
      pos2 = posi2;
```

```
    }

    //PID values were set by trial and error for this use case, adding the
integral decreased performance as it increased oscillations

    // error
    int e2 = target2 - pos2;

    // derivative
    float dedt2 = (e2-eprev2)/(deltaT);

    // integral
    //eintegral2 = eintegral2 + e2*deltaT;

    // control signal
    //float u2 = kp*e2 + kd*dedt2 + ki*eintegral2;
    float u2 = kp*e2 + kd*dedt2;
    // motor power
    float pwr2 = fabs(u2);
    //cap motor power to 100
    if( pwr2 > 100 ){
      pwr2 = 100;
    }

    // motor direction
    int dir2 = 1;
    if(u2<0){
      dir2 = -1;
    }

    // signal the motor
    movemotor(2, pwr2, dir2); //moves motor 1 or 2 at speed (0-100), in
direction 1 or -1

    //if both the previous error and the current error is equal to zero,
then the position is considered to be steadily reached and the motor can
stop turning
    if (eprev2 == 0 && e2 == 0){
      reached_target2 = true;
      movemotor(2, 0, 0); //stop the motor
      //Serial.println("motor 2 stopped because it reached its target");
      //return;
    }

    // store previous error
    eprev2 = e2;

    }
    else{
      reached_target2 = true;
    }

    //if both targets are reached this function is complete and the motors
can stop turning
    if (reached_target1 == true && reached_target2 == true){
      reached_target = true;
    }

  }
}
```

```
//move one (or both  motors at the same time) until the current going to
the motor has reached a certain threshold
void movemotorcurrent(bool move1, int targetcurrent1, int cappower1, bool
move2, int targetcurrent2, int cappower2){
  bool reached_target = false;
  bool reached_target1 = false;
  bool reached_target2 = false;


  int print_counter = 0;


  //to avoid measuring current spikes in start-up, make a first motor
command outside of measuring the current
  if (move1 == true && reached_target1 == false){
    if (targetcurrent1 > 0){
      movemotor(1, cappower1, 1);
      delay(100); //need 100ms to know for sure that the initial spike is
over
    }else{
      movemotor(1, cappower1, -1);
      delay(100);
    }
  }


  if (move2 == true && reached_target2 == false){
    if (targetcurrent2 > 0){
      movemotor(2, cappower2, 1);
      delay(100); //need 100ms to know for sure that the initial spike is
over
    }else{
      movemotor(2, cappower2, -1);
      delay(100);
    }
  }

  //values needed for smoothing the current measurement
  int readings_c1[numReadings_c1];    // the readings from the analog input
  int readIndex_c1 = 0;               // the index of the current reading
  int total_c1 = 0;                   // the running total
  int average_c1 = 0;                 // the average
  int e1_c = 0;

  int readings_c2[numReadings_c2];    // the readings from the analog input
  int readIndex_c2 = 0;               // the index of the current reading
  int total_c2 = 0;                   // the running total
  int average_c2 = 0;                 // the average
  int e2_c = 0;

  // initialize all the readings to 0:
  for (int thisReading_c1 = 0; thisReading_c1 < numReadings_c1;
thisReading_c1++) {
    readings_c1[thisReading_c1] = 0;
  }

  // initialize all the readings to 0:
  for (int thisReading_c2 = 0; thisReading_c2 < numReadings_c2;
thisReading_c2++) {
    readings_c2[thisReading_c2] = 0;
```

```
  }

  while (reached_target == false){
    if (move1 == true && reached_target1 == false){

    //smoothing the signal (low PWM values increase the fluctuations the
current sensor reads)
    // subtract the last reading from total:
    total_c1 = total_c1 - readings_c1[readIndex_c1];
    // read from the sensor:
    readings_c1[readIndex_c1] = ina219_1.getCurrent_mA();
    // add the reading to the total:
    total_c1 = total_c1 + readings_c1[readIndex_c1];
    // advance to the next position in the array:
    readIndex_c1 = readIndex_c1 + 1;

    // if we're at the end of the array...
    if (readIndex_c1 >= numReadings_c1) {
      // ...wrap around to the beginning:
      readIndex_c1 = 0;
    }

    // calculate the average:
    average_c1 = total_c1 / numReadings_c1;

    // error
    int e1_c = targetcurrent1 - average_c1;

    // motor direction
    int dir1 = 1;
    if(e1_c < 0){
      dir1 = -1;
    }

    // signal the motor
    movemotor(1, cappower1, dir1);

    if (abs(e1_c) < 1){
      reached_target1 = true;
      movemotor(1, 0, 0); //stop the motor
    }

    }
    else{
      reached_target1 = true;
    }

    if (move2 == true && reached_target2 == false){

    //smoothing the signal (low PWM values increase the fluctuations the
current sensor reads)
    // subtract the last reading from total:
    total_c2 = total_c2 - readings_c2[readIndex_c2];
    // read from the sensor:
    readings_c2[readIndex_c2] = ina219_2.getCurrent_mA();
    // add the reading to the total:
    total_c2 = total_c2 + readings_c2[readIndex_c2];
    // advance to the next position in the array:
    readIndex_c2 = readIndex_c2 + 1;

    // if we're at the end of the array...
```

```
    if (readIndex_c2 >= numReadings_c2) {
      // ...wrap around to the beginning:
      readIndex_c2 = 0;
    }

    // calculate the average:
    average_c2 = total_c2 / numReadings_c2;

    // error
    int e2_c = targetcurrent2 - average_c2;

    // motor direction
    int dir2 = 1;
    if(e2_c<0){
      dir2 = -1;
    }

    // signal the motor
    movemotor(2, cappower2, dir2);

    if (abs(e2_c) < 1){
      reached_target2 = true;
      movemotor(2, 0, 0); //stop the motor
    }

    }
    else{
      reached_target2 = true;
    }

    if (reached_target1 == true && reached_target2 == true){
      reached_target = true; //escape the while loop
      movemotor(1, 0, 0); //stop the motor just to be sure
      movemotor(2, 0, 0); //stop the motor just to be sure
    }

    //stop if button is pressed (sort of emergency stop)
    // read the state of the pushbutton value:
    Button2_state = digitalRead(Button2);
    if (Button2_state == HIGH) {
      reached_target = true;
      movemotor(1, 0, 0); //stop the motor
      movemotor(2, 0, 0); //stop the motor
      delay(1000); //to stop further input of button for 1 s
    }


    //print sensor values once every 10 times
    print_counter = print_counter + 1;
    if (print_counter > 10){
    sensorValue_futek = analogRead(sensorPin_futek);
    force_newton = 0.0418 * (sensorValue_futek - 3); //mapping from
meetshop from 10 bit to newton

    //print the values in a format excel understands
    Serial.print("N");
    Serial.print(",");
    Serial.print(posi1);
    Serial.print(",");
    Serial.print(posi2);
    Serial.print(",");
```

```
    Serial.print(force_newton);
    Serial.print(",");
    Serial.print("N");
    Serial.print(",");
    Serial.print("N");
    Serial.print(",");
    Serial.println();

    print_counter = 0;
    }

  }
}
```

11.6 Pilot test learnings

Before the systematic tests were done, of which the results are used in the main text, a pilot test was conducted to test and subsequently optimize the gripper and testing procedure. This pilot test was shortly done before the systematic tests and used the same finished gripper with thick cheesecloth and used blackberries from the same farm.

The first purpose of the pilot tests was to set the parameters of the gripping procedure to allow secure but gentle grasping of blackberries. So, e.g., the height to which the berry should be lowered in the gripper was determined in order to have most averaged sized berries in the middle of the closed gripper. Furthermore, the current at which the berry is grasped securely without excessively twisting the tube was determined via trial and error.

The second purpose of the pilot testing was to see if the test setup and procedure were optimized. To limit the influence of decay of the blackberries, the tests should be done within a short timeframe (2 days after harvesting). To allow as many individual blackberries to be tested, each test should last as short as possible. First of all, the height of the blackberry with respect to the measurement setup was easy to set with the spacer arm that determined the placement of the berry. So, no ruler or measurement by the researcher was needed to place the berry in the setup. Secondly, with a single press of the button, the connected Arduino was programmed to perform each step of the measurement by itself. It lowered the berry, closed the gripper, started pulling on the berry, and released and reset the entire setup for another berry to be placed. Lastly, the data gathering via the Data Streamer Add-In in Excel was simple to operate with a simple click, but correctly storing the data took the researcher about two minutes with multiple steps in excel. So, a custom macro was written to perform all those steps with a single shortcut. This allowed the researcher to place a berry, click on two buttons and let the Arduino and Excel do the rest. Subsequently, the researcher could observe the testing procedure and the damage to the berry whilst the test setup performed the experiment mostly by itself, which immensely increased the speed of the process. In the end, on average, each test took about 3 minutes per blackberry. And about 5 minutes were needed to exchange the cloths of the tubes between tests.

During the pilot test with blackberries, multiple lessons were learned that were implemented in the systematic tests. First of all, the entry and release of some berries were not smooth, they did not enter correctly, or they did not leave after successfully detaching from the pedicel. It was noticed that the slightest extra movement of the gripper did allow enough room for it to enter or leave the gripper. So, an entry and release “wiggle” was programmed to slightly twist the tube backwards and forwards upon entry and releasement which increased both those rates. Secondly, it was observed during the pilot testing that the closing procedure was also able to detach the berry. As during gripping the tube decreased in length, it slightly pulled on the berry, which in some cases was enough to detach the blackberry from its pedicel. To record this phenomenon, the script was altered to also log the loadcell data during gripping and not only the subsequent pull.

11.7 Internal blackberry discolouration due to external forces

It had come to the author's attention that the Hague University of Applied Sciences was performing research in which blackberries were squished between two plates and afterwards cut in half to see correlating discolouration on the inside of the blackberry (unpublished work as of writing). During the pilot testing of the Twisting-Tube gripper, successfully harvested berries and control berries were also compared on the inside, but no difference in terms of discolouration nor reflectiveness could be observed by the author, see also Figure 20. The internal discolouration observed by the researchers of the Hague University was probably due to the higher forces they subjected to the berry by compressing it between two hard plates, whilst the Twisting-Tube gripper has a quite gentle and uniform approach which seemingly does not leave behind internal marks. So, for the systematic tests, the berries were not cut in half, and their damage was only observed from the outside in terms of cut membranes and RDR damage.

Figure 20: Some of the cut-in-half blackberries from the pilot test. In person nor in this photo differences in internal discolouration could be seen in either the control handpicked blackberries or the robotically harvested blackberries.

11.8 Other data from tests

The number of drupelets per berry was also counted for 21 berries. These berries were taken in groups of three, randomly, from punnets of batches 8 through 14. The mean number of drupelets for this sample was about 90 with a standard deviation of 17.

Further interesting data is shown in Table 10, which presents the same type of data as Table 5 in the main text, but instead of analysing the data only for successfully detached berries, here, the leakage of drupelets can be seen for all blackberries. The biggest difference is the seemingly, relatively better performance of the thin cheesecloth here, as it imposes cut damage on 38% of all berries instead of the 100% leakage damage on successfully handled berries. As also can be seen in the results table of the types of detachment, see Table 3, this cloth often wedged the berry out at the top, and the table below indicates that this does not impose cut damage that results in leakage of drupelets.

Table 10: Percentage of all blackberries that had at least one or three drupelets leaking, counted for each specific zone (see Figure 10), per different type of tube.

	Zone of drupelet leaking	Total three zones		Top		Middle		Bottom	
	Number of drupelets leaking	**1+**	**3+**	**1+**	**3+**	**1+**	**3+**	**1+**	**3+**
Type of tube	Thin cheesecloth (n = 21)	38.1	28.6	4.8	4.8	23.8	9.5	38.1	23.8
	Thick cheesecloth (n = 21)	23.8	9.5	19.0	4.8	19.0	4.8	4.8	0.0
	Spandex (n = 21)	52.4	19.0	9.5	0.0	33.3	4.8	28.6	14.3
	Thick cheesecloth inside, spandex outside (n = 21)	9.5	4.8	4.8	0.0	4.8	4.8	0.0	0.0
	Spandex inside, thick cheesecloth outside (n = 20)	10.0	10.0	5.0	5.0	5.0	0.0	5.0	0.0
	Thick cheesecloth, padding inside (n = 21)	14.3	4.8	4.8	0.0	14.3	4.8	0.0	0.0
	Thick cheesecloth, padding outside (n = 21)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Average of all types of tubes	21.2	11.0	6.8	2.1	14.3	4.1	10.9	5.4
	Control, handpicked (n = 24)	12.5	4.2	8.3	4.2	4.2	0.0	0.0	0.0
	Control with stem (n = 20)	20.0	10.0	5.0	0.0	20.0	10.0	0.0	0.0

Furthermore, an overview of interesting metrics on the level of individual tests is given below. These tables were too big for the main text but were instead used for further data analysis to provide the tables and figures that are present in the main text. For the raw data, see the supplementary files.

Table 11 below shows the weight of the blackberry including the clamp of the setup, the rotation of both ends of the tube when finished tightening along with the max force during this phase. For the vertical pull phase, the max force can also be seen along with the vertical displacement at the moment of this max force. In Table 12, the same metrics can be seen but then for the versatility tests on cherry tomatoes and the different kinds of grapes.

With batch ID:

A = Thin cheesecloth

B = Thick cheesecloth

C = Spandex

D = Thick cheesecloth inside, spandex outside

E = Spandex inside, thick cheesecloth outside

F = Thick cheesecloth, padding inside

G = Thick cheesecloth, padding outside

Table 11: Metrics of the Twisting-Tube gripper measured per individual blackberry test.

Test ID	Batch ID	Berry detachment?	Max force during vertical movement (N)	Vertical displacement at max force during movement phase (mm)	Max force on pedicel during twisting/grabbing phase (N)	Average force of clamp and berry weight (N)	Max rotation top end (deg)	Max rotation bottom end (deg)
0	Empty gripper		0.33	1.79	0.33	0.32	-330	607
1	C	Stem ripped from duct tape	0.33	1.56	2.3	0.38	-573	301
2	C	Detachment at pedicel during gripping	0.33	0.76	3.01	0.38	-578	421
3	C	Detachment at pedicel during gripping	0.33	8.34	5.06	0.38	-833	321
4	C	Detachment at pedicel during gripping	0.33	7.79	2.51	0.39	-14	687
5	C	Detachment at pedicel during gripping	0.29	0.02	3.01	0.38	-581	487
6	C	Stem ripped from duct tape	0.29	0.02	0.92	0.38	-15	613
7	C	Detachment at pedicel during gripping	0.9	3.77	2.51	0.37	-606	503
8	C	Detachment at pedicel during gripping	0.33	7.85	2.63	0.38	-607	482
9	C	Detachment at pedicel during gripping	0.29	0.02	3.05	0.37	-582	524
10	C	Wedging out at top	0.46	3	0.42	0.38	-709	623
11	C	Detachment at pedicel during gripping	0.33	1.42	1.04	0.38	-596	510
12	A	No detachment	1.04	1.35	1.09	0.37	-335	449
13	A	No detachment	0.46	4.83	1.84	0.41	-16	956
14	A	Wedging out at top	0.38	0.02	1.88	0.39	-593	544
15	A	Wedging out at top	0.38	0.33	0.42	0.38	-592	569
16	A	Wedging out at top	0.42	1.6	0.46	0.39	-596	553
17	A	Wedging out at top	0.38	0.03	2.17	0.37	-603	555

18	A	Detachment at pedicel during gripping	0.29	0.02	1.59	0.39	-348	628
19	A	Wedging out at top	0.38	0.57	2.17	0.38	-609	578
20	A	Wedging out at top	0.8	7.42	0.92	0.38	-600	609
21	A	Wedging out at top	0.38	0.01	4.05	0.38	-599	579
22	A	Wedging out at top	0.38	0.15	1.34	0.36	-607	602
23	D	Detachment at pedicel during gripping	0.29	0.02	2.51	0.41	-226	213
24	D	Detachment at pedicel during gripping	0.29	0.03	3.97	0.45	-354	197
25	D	Stem ripped from duct tape	0.29	0.01	2.68	0.38	-346	214
26	D	Detachment at pedicel during gripping	0.33	0.26	2.26	0.39	-353	214
27	D	Wedging out at top	3.3	2.8	2.26	0.37	-354	212
28	D	Detachment at pedicel during gripping	3.76	1.73	3.39	0.38	-241	213
29	D	Detachment at pedicel during gripping	0.29	0.02	2.8	0.39	-355	212
30	D	Stem ripped from duct tape	0.29	0.03	4.18	0.37	-355	213
31	D	Detachment at pedicel during gripping	0.33	8.15	3.85	0.38	-356	217
32	D	Detachment at pedicel during gripping	0.38	0.06	3.18	0.38	-15	501
33	D	Detachment at pedicel during gripping	0.29	0.02	2.13	0.38	-353	227
34	B	Detachment at pedicel during vertical movement	2.42	2.05	2.05	0.38	-364	247
35	B	Detachment at pedicel during gripping	0.29	0.02	5.43	0.37	-364	251
36	B	Wedging out at top	0.42	1.85	0.75	0.38	-14	643
37	B	Detachment at pedicel during gripping	0.33	7.66	2.88	0.37	-352	273

38	B	Stem ripped from duct tape	0.33	3.7	2.88	0.38	-350	269
39	B	Stem ripped from duct tape	0.29	0.02	4.1	0.38	-364	257
40	B	Detachment at pedicel during gripping	0.33	9.72	3.72	0.34	-369	273
41	B	Detachment at pedicel during gripping	0.29	0.02	2.47	0.42	-360	258
42	B	Detachment at pedicel during gripping	0.33	7.7	2.55	0.38	-354	277
43	B	Detachment at pedicel during gripping	0.29	0.03	2.76	0.38	-385	241
44	B	Detachment at pedicel during gripping	0.33	1.92	4.31	0.42	-242	259
45	F	Wedging out at top	0.79	4.2	0.63	0.38	-232	219
46	F	Wedging out at top	0.67	5.4	0.5	0.38	-241	221
47	F	Detachment at pedicel during gripping	3.14	0.3	2.88	0.37	-245	146
48	F	Stem ripped from duct tape	3.76	3.07	1.8	0.38	-248	108
49	F	Stem ripped from duct tape	3.3	1.37	2.59	0.38	-97	276
50	F	Detachment at pedicel during vertical movement	1.25	4.07	0.79	0.36	-14	428
51	F	Detachment at pedicel during gripping	0.33	0.11	2.13	0.38	-232	200
52	F	Stem ripped from duct tape	0.46	0.01	1.71	0.38	-230	214
53	F	Stem ripped from duct tape	0.29	0.03	1.04	0.36	-353	168
54	F	Detachment at pedicel during vertical movement	1.38	0.91	1.17	0.38	-231	236
55	F	Detachment at pedicel during vertical movement	0.79	2.98	0.33	0.38	-15	285
56	G	No detachment	1.71	3.94	1.17	0.38	-226	110
57	G	No detachment	2.93	4.05	1.84	0.38	-225	177
58	G	No detachment	1.34	0.31	1.17	0.36	-16	282
59	G	No detachment	2.34	2.82	1.59	0.38	-18	286

60	G	Detachment at pedicel during gripping	0.29	0.02	0.67	0.38	-360	121
61	G	Detachment at pedicel during gripping	0.33	3.33	1.76	0.38	-347	176
62	G	No detachment	2.63	2.53	1.8	0.38	-224	146
63	G	Detachment at pedicel during gripping	1.5	0.03	2.13	0.38	-232	161
64	G	No detachment	2.13	0.8	1.67	0.36	-240	170
65	G	No detachment	1.88	2.31	1.55	0.38	-16	293
66	G	Detachment at pedicel during gripping	0.29	0.02	1.84	0.38	-365	114
67	E	Wedging out at top	3.51	7.66	1.88	0.37	-15	580
68	E	Detachment at pedicel during gripping	0.29	0.02	1.96	0.36	-382	288
69	E	Stem ripped from duct tape	0.25	0.02	3.76	0.33	-485	198
70	E	Detachment at pedicel during gripping	0.46	0.15	2.42	0.37	-380	238
71	E	Detachment at pedicel during gripping	0.29	0.03	2.63	0.36	-15	568
72	E	Detachment at pedicel during gripping	0.29	0.04	1.63	0.37	-379	290
73	E	Detachment at pedicel during vertical movement	3.22	5.46	2.01	0.38	-15	574
74	E	Stem ripped from duct tape	0.29	0.03	4.47	0.38	-379	273
75	E	Detachment at pedicel during gripping	0.29	0.03	2.68	0.33	-379	289
76	E	Detachment at pedicel during vertical movement	1.63	0.51	1.59	0.41	-373	296
77	E	Stem ripped from duct tape	0.29	0.03	3.93	0.35	-385	194
78	G	Detachment at pedicel during gripping	0.33	0.7	2.72	0.39	-387	183
79	G	No detachment	1.55	6.29	0.88	0.38	-13	193
80	G	No detachment	0.42	6.26	0.42	0.39	-13	33
81	G	No detachment	0.92	9.08	0.96	0.38	-12	290

82	G	Detachment at pedicel during vertical movement	2.88	1.63	2.01	0.42	-13	277
83	G	Detachment at pedicel during vertical movement	2.59	0.34	2.38	0.41	-12	314
84	G	Detachment at pedicel during gripping	0.33	8.14	4.1	0.40	-386	185
85	G	Detachment at pedicel during vertical movement	4.6	3.96	2.8	0.38	-12	352
86	G	Detachment at pedicel during gripping	2.93	0.01	3.93	0.38	-270	222
87	G	Detachment at pedicel during gripping	0.33	3.57	2.09	0.41	-13	367
88	B	Detachment at pedicel during gripping	0.9	4.25	3.14	0.42	-12	489
89	B	Detachment at pedicel during gripping	0.29	0.03	4.51	0.39	-394	276
90	B	Detachment at pedicel during gripping	0.33	4.79	5.23	0.38	-410	171
91	B	Stem ripped from duct tape	4.18	0.54	3.97	0.38	-11	365
92	B	Stem ripped from duct tape	0.29	0.01	3.93	0.37	-11	552
93	B	Detachment at pedicel during gripping	0.33	3.53	3.43	0.38	-14	505
94	B	Detachment at pedicel during gripping	0.33	6.3	5.31	0.39	-12	457
95	B	Stem breakage	0.29	0.02	3.34	0.38	-11	569
96	B	Wedging out at top	0.38	2.8	1.96	0.34	-12	682
97	B	Detachment at pedicel during vertical movement	4.6	2.48	4.05	0.34	-12	361
98	F	Detachment at pedicel during vertical movement	2.09	1.94	1.25	0.38	-400	237
99	F	No detachment	0.29	0.35	0.29	0.40	-11	38
100	F	No detachment	2.42	5.19	1.38	0.37	-12	460

101	F	Detachment at pedicel during vertical movement	1.42	4.17	0.33	0.40	-286	208
102	F	No detachment	1.21	3.83	0.46	0.38	-173	267
103	F	Detachment at pedicel during vertical movement	1.88	6.72	0.71	0.38	-12	494
104	F	No detachment	0.29	0.89	0.25	0.38	-11	38
105	F	No detachment	1.09	7.17	0.33	0.42	-11	467
106	F	No detachment	3.05	6.56	1.13	0.37	-11	509
107	F	No detachment	2.13	7.66	1.5	0.38	-12	490
108	E	Detachment at pedicel during gripping	0.33	7.05	2.55	0.40	-301	212
109	E	Stem ripped from duct tape	4.31	4.96	3.43	0.38	-166	195
110	E	Detachment at pedicel during vertical movement	5.06	1.73	4.14	0.38	-292	221
111	E	Detachment at pedicel during gripping	0.33	4.75	3.89	0.38	-425	205
112	E	Detachment at pedicel during gripping	0.33	5.48	1.42	0.38	-13	427
113	E	Detachment at pedicel during gripping	0.33	8.97	2.17	0.38	-14	247
114	E	Wedging out at top	1.67	2.55	1.21	0.41	-397	230
115	E	Wedging out at top	3.39	1.35	3.18	0.38	-297	215
116	E	Detachment at pedicel during vertical movement	2.76	0.02	3.39	0.42	-14	403
118	C	Stem ripped from duct tape	0.33	9.13	1.92	0.38	-581	277
119	C	Detachment at pedicel during vertical movement	2.38	2.92	1.34	0.40	-456	633
120	C	Detachment at pedicel during gripping	0.33	7.86	2.01	0.42	-14	835
121	C	Detachment at pedicel during gripping	0.33	4.16	2.84	0.38	-15	831

122	C	Detachment at pedicel during gripping	0.29	0.02	2.93	0.76	-711	408
123	C	Detachment at pedicel during gripping	0.33	2.87	3.43	0.40	-325	629
124	C	Stem ripped from duct tape	0.33	1.39	2.47	0.38	-585	437
125	C	Detachment at pedicel during gripping	0.29	0.02	2.51	0.39	-591	459
126	C	Detachment at pedicel during gripping	0.29	0.02	0.46	0.41	-316	285
127	C	Stem ripped from duct tape	0.33	5.75	2.01	0.38	-445	463
128	D	Other failure	2.72	0.48	2.63	0.36	-209	294
129	D	Detachment at pedicel during gripping	0.33	4.51	2.17	0.38	-332	212
130	D	Detachment at pedicel during gripping	0.29	0.02	3.34	0.39	-329	197
131	D	Detachment at pedicel during gripping	0.33	1.99	2.84	0.39	-191	215
132	D	Wedging out at top	0.71	1.25	0.67	0.37	-15	513
133	D	Stem ripped from duct tape	1.92	1.45	1.59	0.37	-14	501
134	D	Detachment at pedicel during vertical movement	4.14	1.55	3.64	0.38	-196	294
135	D	Stem ripped from duct tape	0.46	0.51	3.39	0.38	-326	212
136	D	Detachment at pedicel during gripping	0.29	0.03	3.34	0.38	-203	312
137	D	Wedging out at top	0.5	7.73	1	0.36	-328	306
138	A	Detachment at pedicel during gripping	0.33	2.09	2.38	0.38	-339	365
139	A	Wedging out at top	0.38	0.02	0.42	0.38	-15	1113
140	A	Wedging out at top	0.42	4.75	2.97	0.38	-495	597
141	A	Wedging out at top	0.38	0.03	1.96	0.38	-490	580
142	A	Detachment at pedicel during gripping	0.33	0.84	1.88	0.38	-339	338

143	A	Wedging out at top	0.38	0.94	2.22	0.37	-491	617
144	A	Detachment at pedicel during gripping	0.29	0.02	4.77	0.38	-486	434
145	A	Detachment at pedicel during gripping	0.29	0.03	2.84	0.46	-336	345
146	A	Wedging out at top	0.38	0.06	2.3	0.75	-15	997
147	A	Wedging out at top	0.38	0.16	1.38	0.37	-740	600

Abbreviations used in the table below:

T = cherry Tomato

GL = Grape Long

GW = Grape White

GR = Grape Red

Table 12: Metrics of the Twisting-Tube gripper measured per individual grape or cherry tomato.

Test ID	**Batch ID**	**Fruit detachment?**	**Max force during vertical movement (N)**	**Vertical displacement at max force during movement phase (mm)**	**Max force on pedicel during twisting/grabbing phase (N)**	**Average force clamp and berry weight (N)**	**Max rotation top end (deg)**	**Max rotation bottom end (deg)**
0	Empty gripper		0.29	0.02	0.33	0.29	-348	345
1	T	Stem breakage	0.29	0.02	3.59	0.43	-14	585
2	T	Detachment at pedicel during gripping	0.29	0.02	4.6	0.46	-373	253
3	T	Stem breakage	0.33	6.63	3.01	0.44	-368	279
4	T	Stem breakage	0.5	0.01	3.09	0.46	-14	585
5	T	Detachment at pedicel during gripping	0.29	0.01	3.22	0.42	-380	257
6	T	Stem breakage	0.29	0.02	4.14	0.42	-15	594
7	T	Stem breakage	0.29	0.02	2.47	0.42	-375	246
8	T	Detachment at pedicel during gripping	0.33	7.64	4.1	0.42	-15	554
9	T	Detachment at pedicel during gripping	0.29	0.02	3.47	0.39	-382	243
10	T	Stem breakage	0.29	0.02	2.01	0.43	-15	549

11	GL	Detachment at pedicel during gripping	0.29	0.02	3.51	0.36	-13	527
12	GL	Detachment at pedicel during vertical movement	3.93	0.38	4.18	0.33	-13	538
13	GL	Stem ripped from duct tape	5.35	1.29	4.81	0.43	-12	524
14	GL	Detachment at pedicel during vertical movement	7.02	3.97	4.93	0.44	-391	195
15	GL	Detachment at pedicel during vertical movement	4.93	1.19	4.31	0.41	-13	500
16	GL	Detachment at pedicel during vertical movement	3.72	0.05	4.1	0.40	-14	509
17	GL	Detachment at pedicel during vertical movement	6.4	3.02	4.93	0.45	-282	286
18	GL	Detachment at pedicel during vertical movement	6.44	2.97	4.85	0.42	-13	537
19	GL	Detachment at pedicel during gripping	0.29	0.03	3.59	0.42	-268	309
20	GL	Detachment at pedicel during gripping	0.29	0.02	2.59	0.34	-13	691
21	G W	Detachment at pedicel during gripping	0.29	0.04	3.26	0.33	-12	545
22	G W	Detachment at pedicel during gripping	0.29	0.03	3.14	0.33	-10	550
23	G W	Detachment at pedicel during gripping	0.29	0.04	3.76	0.33	-400	333
24	G W	Detachment at pedicel during gripping	0.29	0.02	3.59	0.33	-11	562
25	G W	Stem ripped from duct tape	0.38	0.62	2.63	0.33	-293	305
26	G W	Detachment at pedicel during gripping	0.29	0.02	4.47	0.34	-296	311

27	G W	Detachment at pedicel during gripping	0.29	0.02	3.85	0.33	-13	948
28	G W	Detachment at pedicel during gripping	0.29	0.04	2.97	0.34	-295	306
29	G W	Detachment at pedicel during gripping	0.29	0.02	3.59	0.33	-295	320
30	G W	Stem ripped from duct tape	0.54	2.04	3.3	0.33	-298	316
31	GR	Detachment at pedicel during gripping	0.33	6.37	2.97	0.38	-394	256
32	GR	Stem ripped from duct tape	0.29	0.25	4.05	0.40	-14	506
33	GR	Detachment at pedicel during gripping	0.29	0.02	5.39	0.38	-13	484
34	GR	Stem ripped from duct tape	0.29	0.03	3.93	0.39	-13	497
35	GR	Detachment at pedicel during gripping	0.33	9.07	3.05	0.38	-298	306
36	GR	Stem ripped from duct tape	0.29	0.57	4.64	0.38	-422	236
37	GR	Detachment at pedicel during gripping	0.29	0.08	4.1	0.38	-14	489
38	GR	Detachment at pedicel during gripping	0.29	0.02	4.26	0.41	-13	501
39	GR	Detachment at pedicel during gripping	0.29	0.03	5.31	0.38	-15	488
40	GR	Detachment at pedicel during gripping	0.29	0.03	6.06	0.38	-296	285

11.9 More ideas for future work

This section will briefly expand the future work section of the main text with some more ideas and possibilities for new research directions for the Twisting-Tube gripper.

Currently, the control system of the gripper measures the current which the DC motors use to tighten the tube around the object. If the tube faces resistance to be twisted due to the object, the motors start using more current and at a certain threshold, the motors can then be stopped. Future research can investigate if other types of sensors could assist or replace the current sensors to improve performance. For example, directly measuring the torque on the outgoing axle of the motor or even on the ring itself could provide a more accurate and direct way of measuring the twist behaviour of the tube. One could also think of strain and/or sensors embedded in the cloth of the tube itself to directly measure the wrapping of the tube and the interaction with the object. A possible disadvantage of these new methods is that the sensor could impede the performance of the gripper, by making it heavier and larger, and perhaps decrease the flexibility of the tube.

Since the current prototype can independently actuate both ends of the tube, another idea could be to loosen and tighten the ends in a certain order to produce a kind of peristaltic motion of the tube. This movement could then help the tube grab and gently pull and transport a harvested fruit along the tube in a similar way as intestines do. The simplest way imaginable is that after grabbing the crop the bottom end loosens and the top end tightens so that the object inside moves towards the bottom end. Research is needed though if the rubbing against the outer edge of the tube will damage fragile objects inside, such as delicate fruits and vegetables.

Using the above-described peristaltic motion, or as in the current prototype by simply opening, the fruit leaves the gripper through the bottom. The robotic manipulator can thus pick a fruit from the plant, move above a punnet and then release the fruit. This extra movement will take some precious time though, and another possibility could be to have a punnet/container underneath the gripper, so after it detaches the fruit, it can immediately drop it and move towards the nearest next fruit. This will require some kind of actuated punnet clamp to be added to the bottom of the gripper, as full punnets must be able to be replaced with empty ones. Another idea could thus be to attach a flexible, tube system to the bottom of the gripper to transport the fruits to their storage location. For fragile fruits such as blackberries, this will probably be hard to design to not get damaged by colliding with the sides of the tube during its fall. It is furthermore questionable for both ideas if the added weight of the punnet and clamp or the tube system will not slow down accelerations of the manipulator so much that it is just quicker to move individual fruits to their containers located on the moving platform.

As mentioned in the main text, it can also be considered to actuate one or both ends of the tube with a single actuator to cut down on costs, control complexity, and weight. In this case, it might also be interesting to consider closing one end of the tube, so it is shaped more like a cup. This idea can be seen as permanently having one end of the tube closed without needing an actuator to do so. A disadvantage could be that the gripper cannot open the bottom to let go of the fruit and it thus needs to rely on the manipulator to hold the cup upside down to have gravity release the fruit into a container. An advantage can be that the cup can approach a fruit and keep moving upwards until it senses that the fruit touches the bottom of the cup. So, the initial localization can be slightly less accurate and the grip can be more robust as the fruit would always be at the bottom of the cup when grasped.

A different idea would be to mount and utilize the gripper upside down. So, the positioned ring by the manipulator would be the top ring instead of the bottom ring. An advantage would be that this top ring can be exactly positioned to the right height with respect to the pedicel, the bottom ring would then contract up to contact the fruit. This would allow for more precise control about where the tube will contact the top of the fruit, and it would thus be less likely to mistakenly grab the pedicel. A second advantage would be that the free end would be pulled downwards with respect to gravity, so a weaker spring, or no spring at all, would be necessary for the gripper to return to its open state. A disadvantage would be that the distal end of the tube, which approaches the fruit first, is not anymore compliant. So, the advantage of the current gripper being able to gently collide with the plant and the fruit in case of imperfect approaches is gone.

Furthermore, this report focussed on the problem of detaching fruits from the point of view of adjusting the robot to fit the requirements. But it also can be considered to (at the same time) selectively breed plants that facilitate the limitations of robots, see Figure 21 for the current conditions of for example blackberries. E.g., it can be a beneficial plant trait to produce the majority of its fruits at the very ends of its branches, so the robot does not have to find its way too deep into the plant. Moreover, it can also be beneficial if the fruits are more uniformly spaced, as it is likely easier for most robotics manipulators to approach a single fruit compared to multiple fruits next to each other in a cluster. Lastly, for robotic harvesting, it would also be beneficial if leaves did not grow close to the target fruits. As for the gripper, leaves could get stuck in the mechanism or get grasped along with the fruit, and for the vision software, leaves can obstruct viewing and recognising ripe fruits.

Figure 21: Picture of the blackberry plants of the Sweet Royalla variety at De Berkelse Braam, Bosch Fruit B.V. Notice how some fruits are relatively close together and how some are further inside the plant and possibly behind leaves.

Lastly, a whole new range of objects could be considered to be grasped with the Twisting-Tube gripper. For example, grabbing objects with sharp corners or edges could be interesting, it can be for example investigated if the cylindrical tube could adapt to these kinds of shapes and utilise the entire surface area whilst imposing uniform pressure. Furthermore, it can be investigated if issues arise with objects small in size with respect to the tube. Probably, their vertical placement must be exactly at the right location for the Twisting-Tube to contact it, or otherwise, it will twist and knot either above or below the object and subsequently wedge it out.

11.10 Manufacturing and assembly

In section 11.11 the eight CAD drawings can be found that were 3D printed on a Creality™ CR10S Pro V2 with a nozzle of 0.4 mm, see Table 13 for the printer settings used in the slicer (Ultimaker Cura™). The other components that made up the gripper, such as fasteners, electronics and motors were bought. The assembly order is only of importance for the innermost parts as they enclose one another, see the correct numbered order in Figure 22. All connections are done with fasteners to allow easy assembly and disassembly of the prototype.

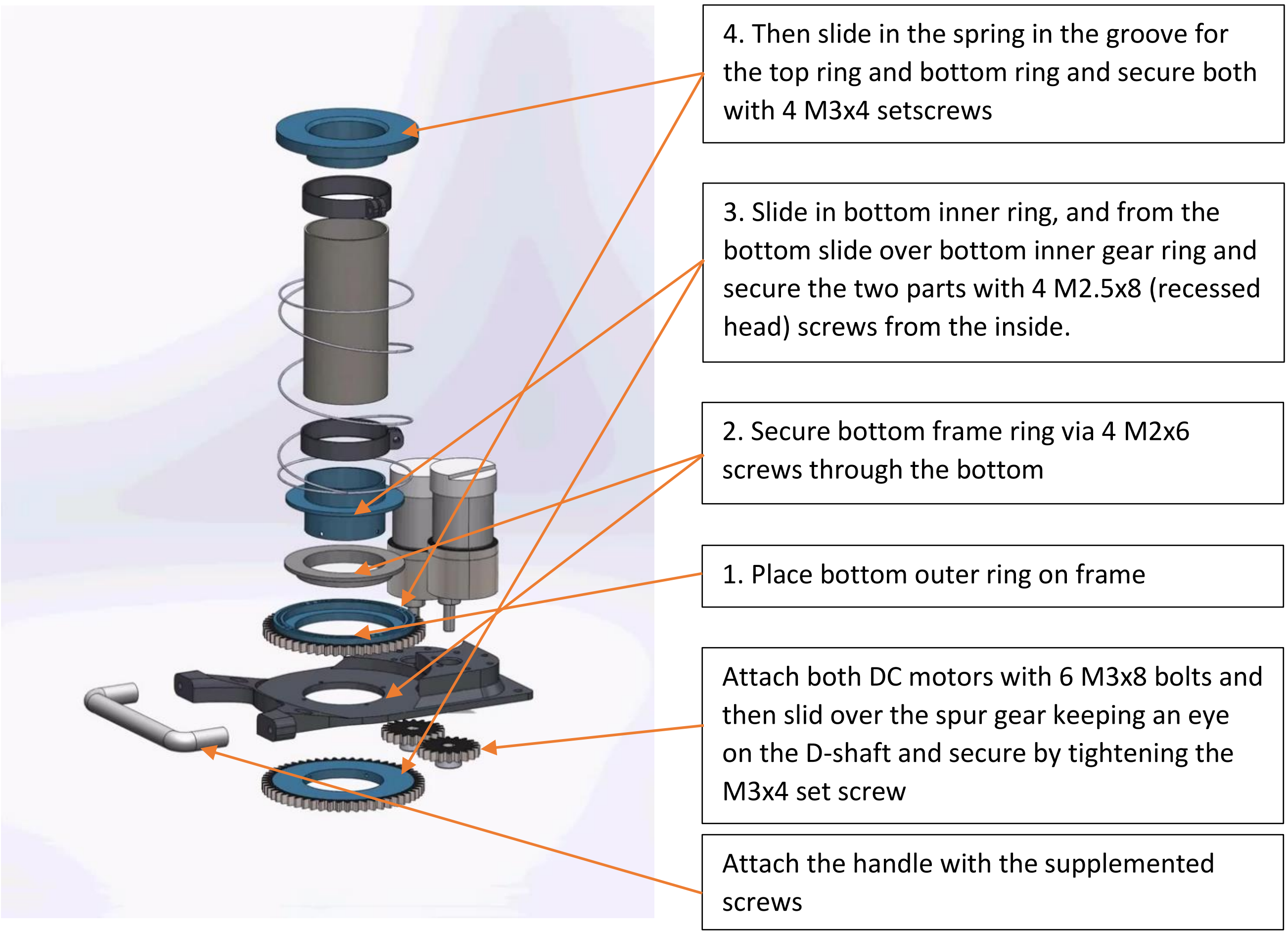


Figure 22: Exploded view of the Twisting-Tube gripper. On the right, the correct numbered order can be seen to assemble the gripper. The handle, motors and cloth can be installed and removed without needing to disassemble the entire gripper. Replacing the cloth is made especially easy by untightening the split rings that hold it in place at either end, this allowed for relatively quick replacement during testing of the gripper.

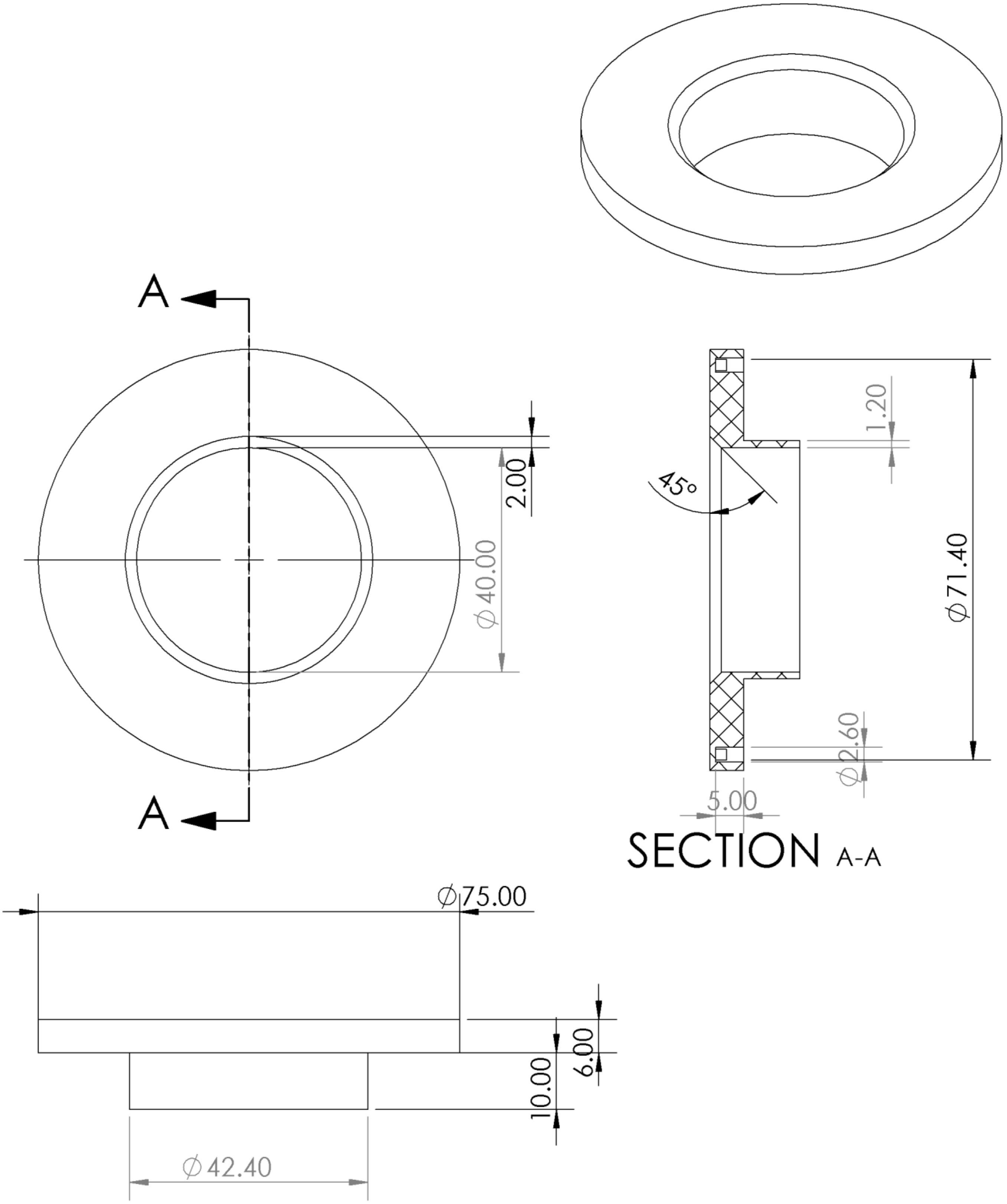
Table 13: Slicer settings on Ultimaker Cura™ slicer, to be used on the 3D printer: Creality™ CR10S Pro V2. These settings were informed by the manufacturer and then tweaked after some trial and error on test pieces.

Material:	eSun™ PLA+	Igus™ I151-PF
Setting on slicer:		
Layer height (mm)	0.15	0.15
Wall thickness (mm)	1.0	1.0
Top/bottom thickness (mm)	0.6	0.6
Infill pattern	Triangles	Triangles
Infill density (%)	30	30
Printing temperature (°C)	215	240
Build plate temperature (°C)	50	70
Infill speed (mm/s)	60	70
Wall speed (mm/s)	40	40
Top/bottom speed (mm/s)	25	25
Support	Depending on part	Depending on part

11.11 CAD drawings

Below, Computer-Aided Design (CAD) drawings can be seen of the eight 3D printed components that make up the Twisting-Tube gripper prototype. These parts were designed in SOLIDWORKS™ and then exported to .stl files so they could be imported into the slicer. The slicer then converted the 3D object into instructions for the 3D printer (.gcode) and subsequently uploaded them to a local server hosted on a Raspberry PI™ (OctoPrint™ software) which controlled the 3D printer. This allowed me to upload the files all to the server and print them out one by one whilst observing the progress of the print online, from a distance, via a connected webcam.

Note that these parts were designed with the limitations and advantages of 3D printing in mind. These parts could be manufactured with conventional methods, but would probably require a redesign to limit complexity and allow more space for tooling to produce the part.



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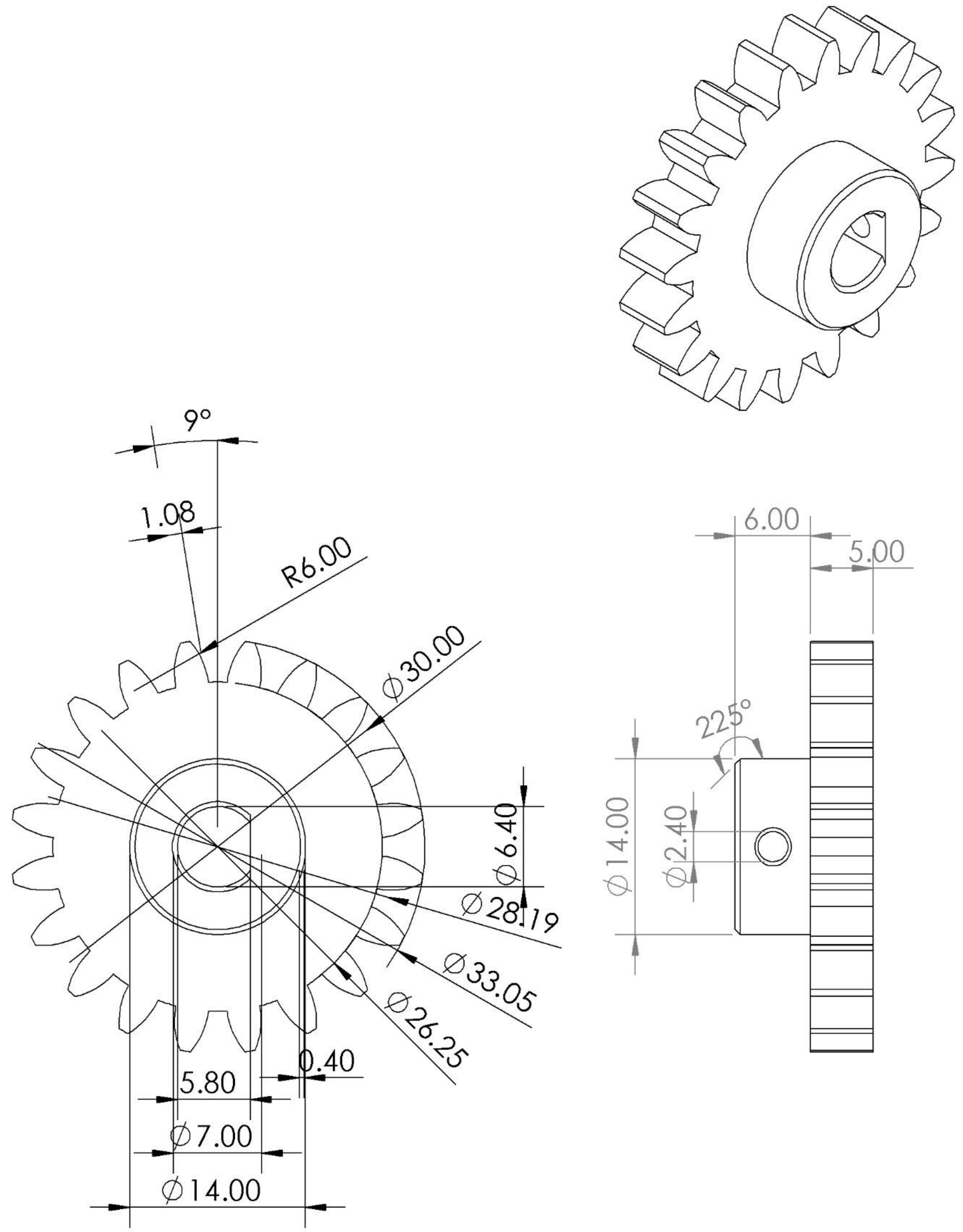
			3D printed	

	NAME	SIGNATURE	DATE		
DRAWN					TITLE: Twisting-Tube gripper project
CHK'D					
APPV'D					
MFG					
Q.A				MATERIAL: Igus I151-PF	DWG NO. V2_top_ring — A4
				WEIGHT:	SCALE:1:1 — SHEET 1 OF 1



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			3D printed

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE:

Twisting-Tube gripper project

MATERIAL: Igus I151-PF

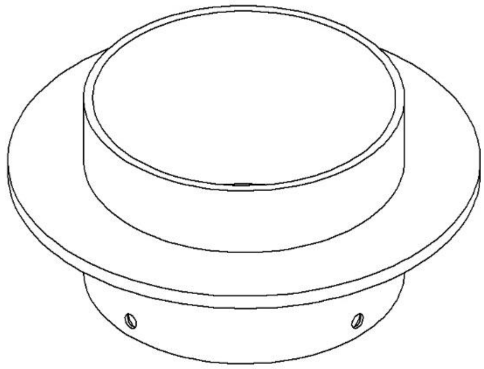
DWG NO. Spur gear iso with collar

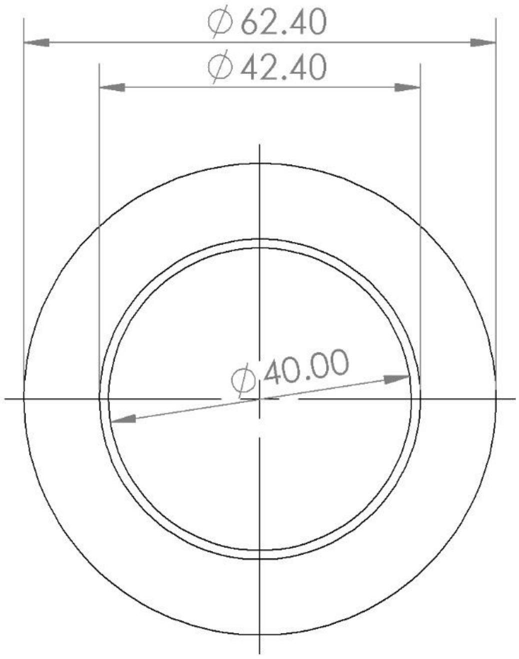
A4

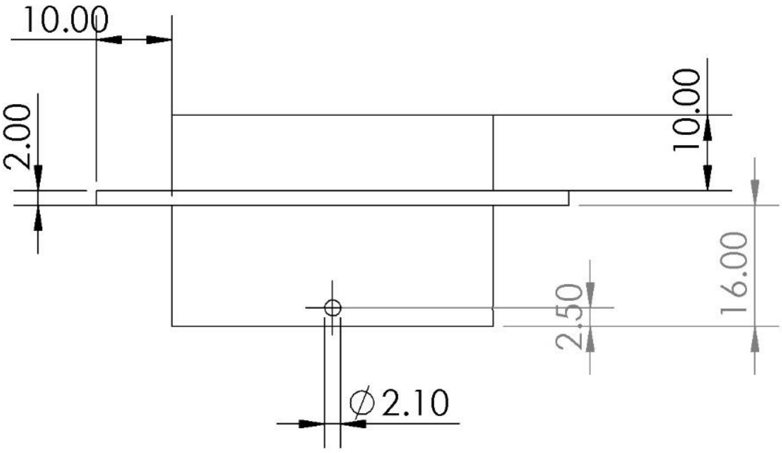
WEIGHT:

SCALE:2:1

SHEET 1 OF 1







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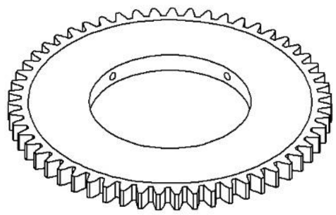
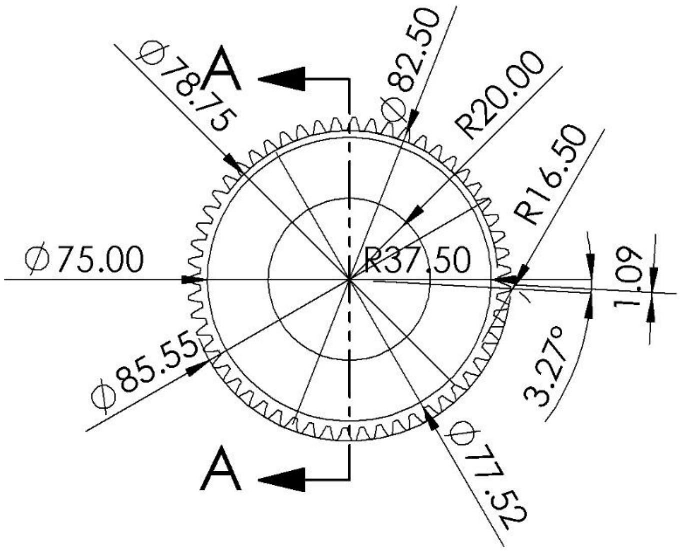
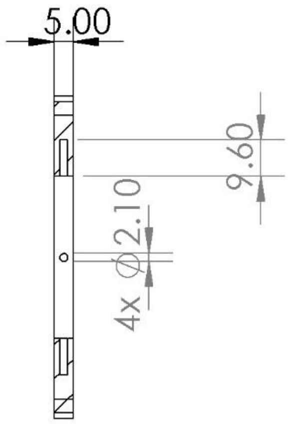
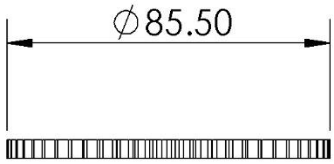
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: Igus I151-PF	DWG NO. Bottom_inner_ring	A4
			WEIGHT:	SCALE:1:1	SHEET 1 OF 1



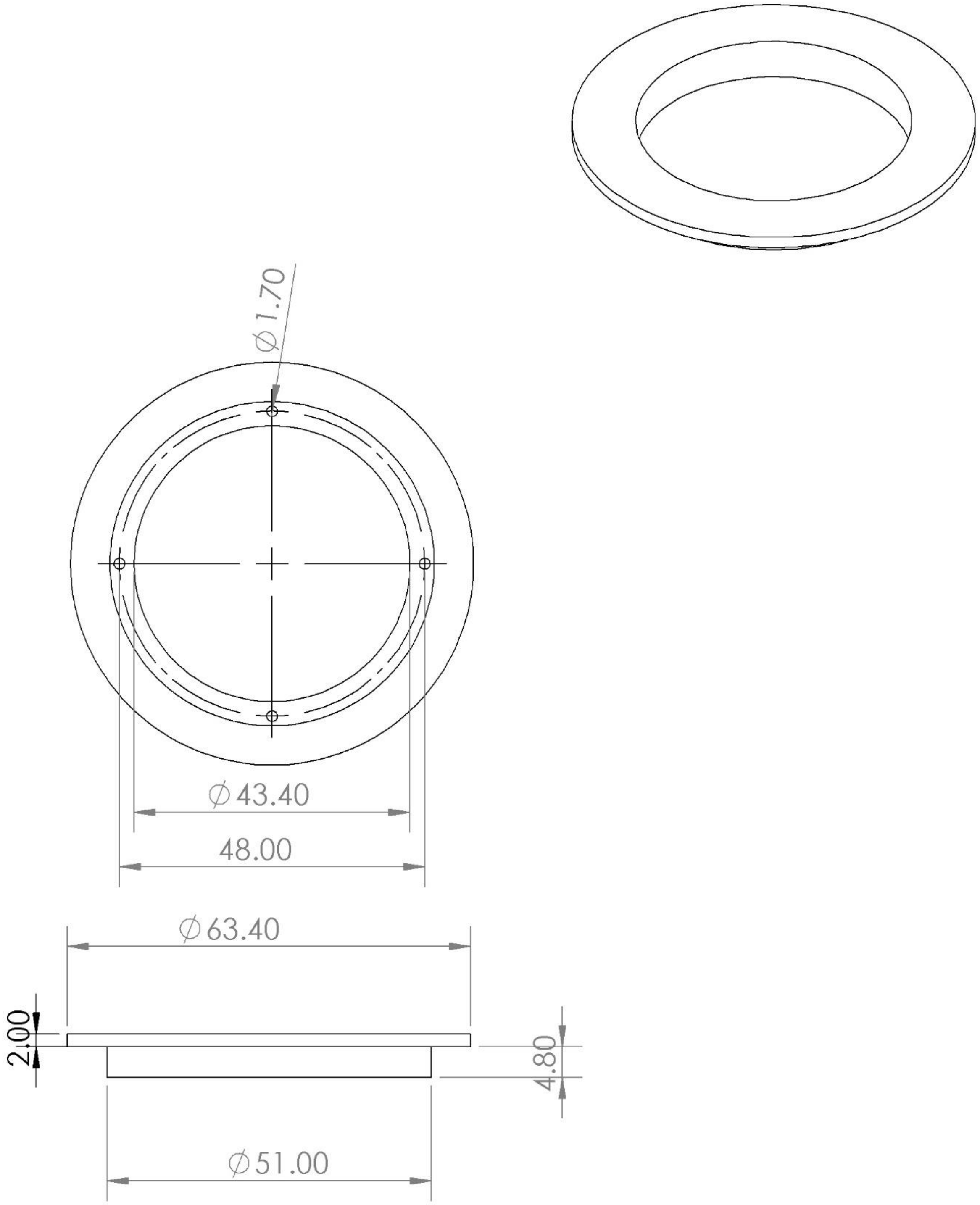




SECTION A-A



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
			3D printed		
NAME	SIGNATURE	DATE	TITLE: Twisting-Tube gripper project		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: Igus I151-PF	DWG NO. Bottom_inner_gear_ring	A4
			WEIGHT:	SCALE:1:2	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

3D printed

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Twisting-Tube gripper project

MATERIAL:

Igus I151-PF

DWG NO.

Bottom_frame_ring_cap

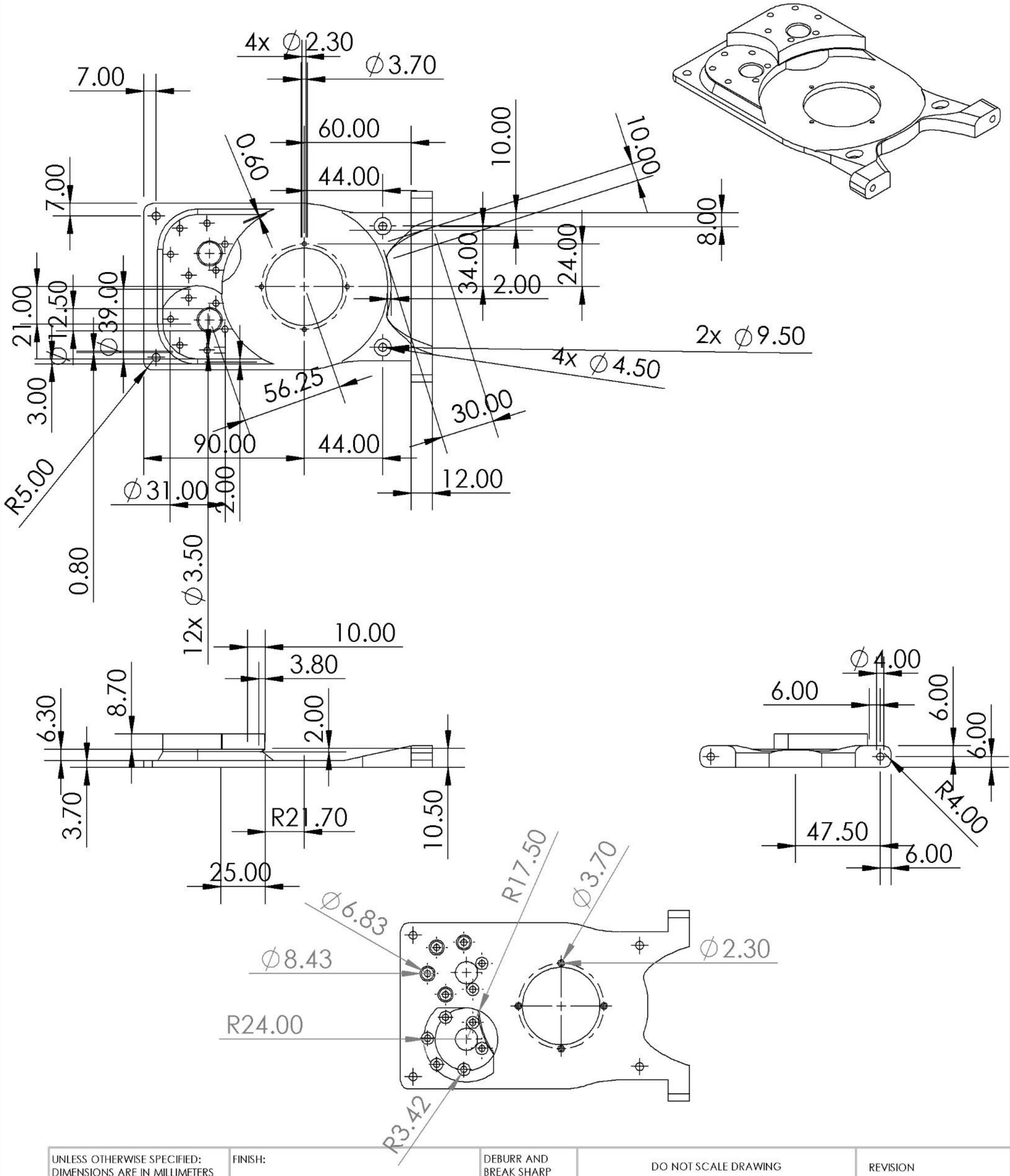
A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1

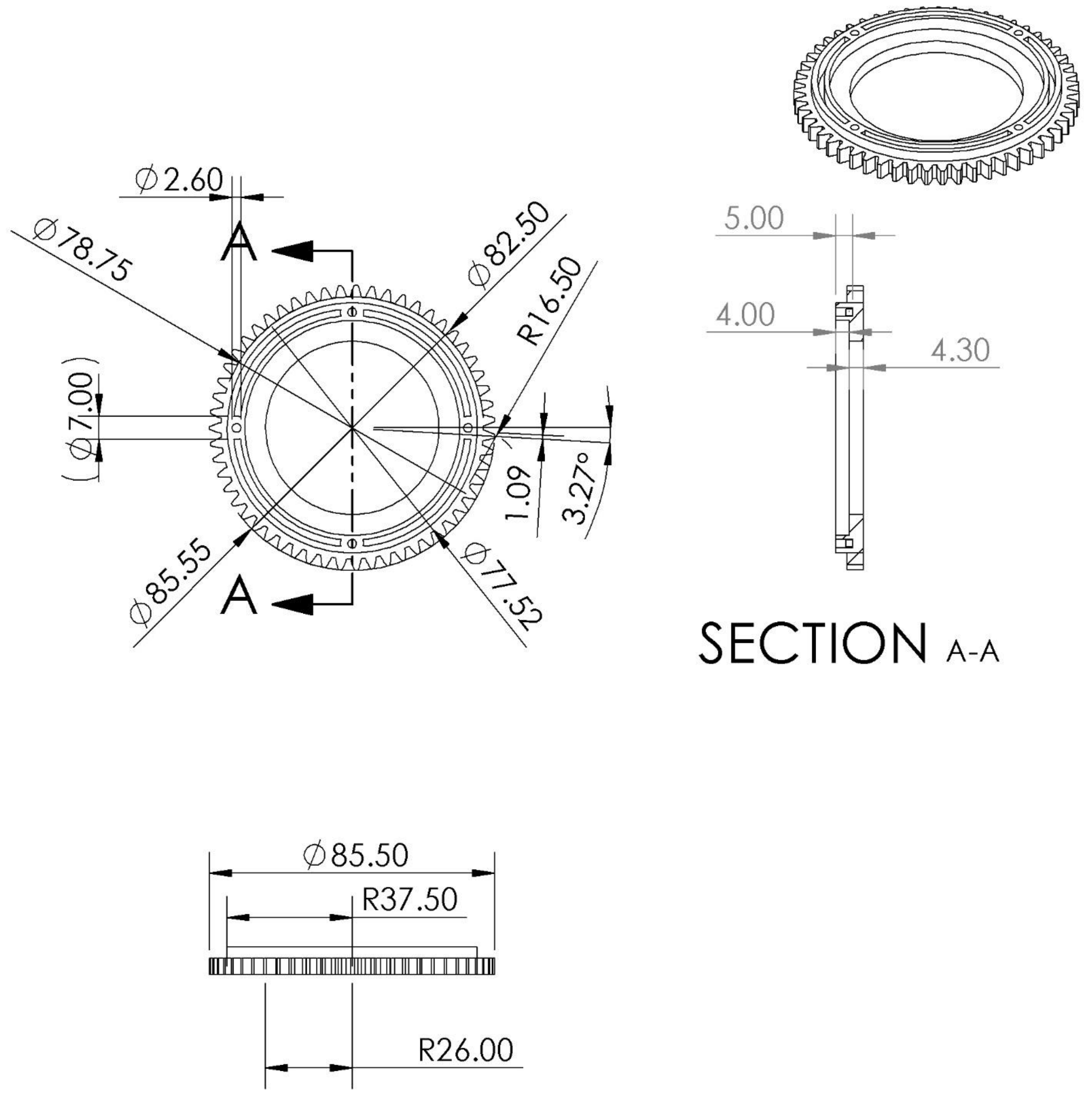
4 3 2 1



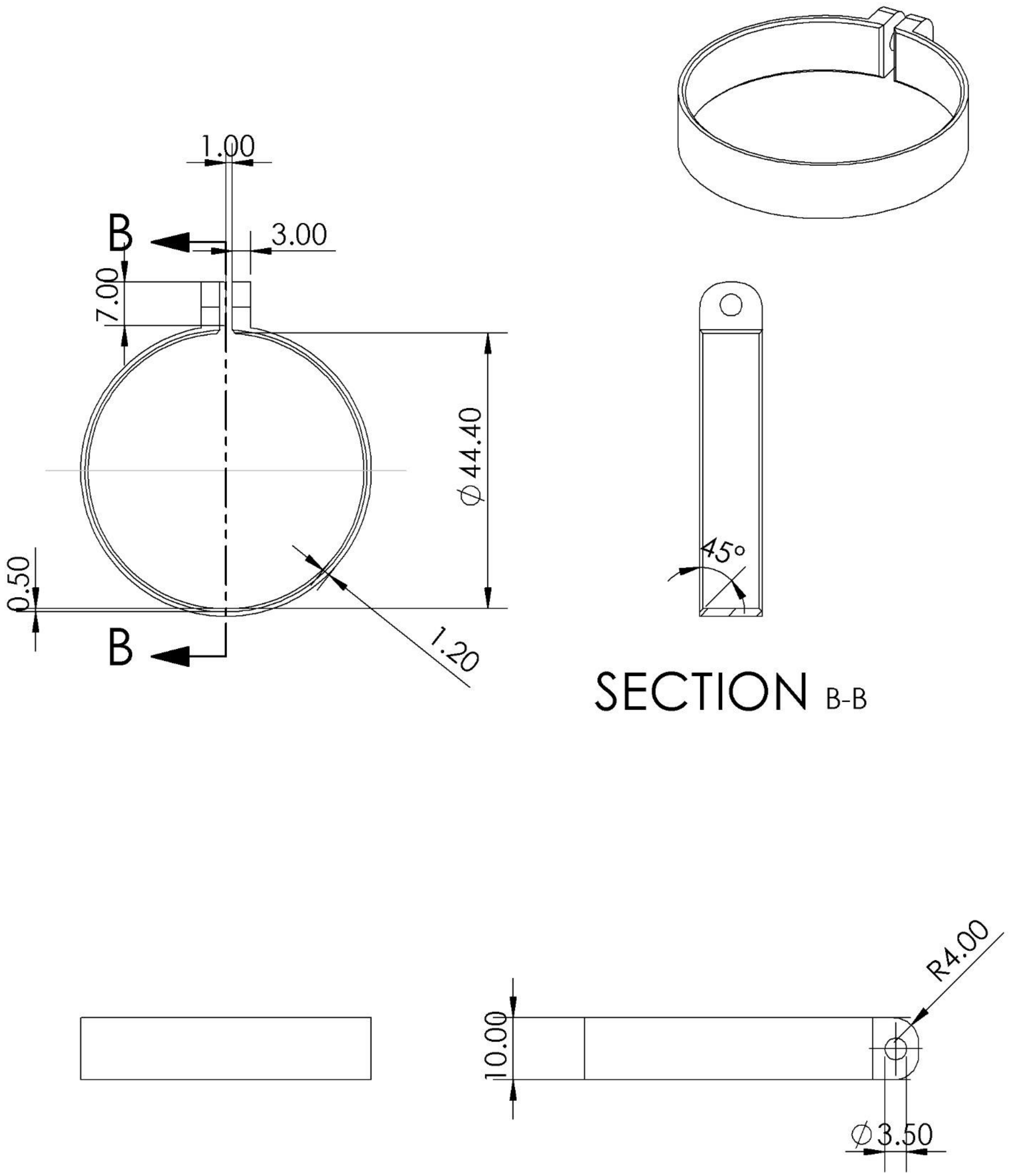
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
			3D printed		

	NAME	SIGNATURE	DATE		TITLE:
DRAWN					Twisting-Tube gripper project
CHK'D					
APPV'D					
MFG					
Q.A				MATERIAL: eSun PLA+	DWG NO. Bottom_frame_ring A4
				WEIGHT:	SCALE:1:3 SHEET 1 OF 1

4 3 2 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING 3D printed	REVISION
	NAME	SIGNATURE	DATE		TITLE: Twisting-Tube gripper project	
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: Igus I151-PF		DWG NO. Bottom_outer_ring	A4
			WEIGHT:		SCALE:1:2	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING 3D printed	REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Twisting-Tube gripper project

MATERIAL: eSun PLA+

DWG NO. V2_split_ring_1

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1