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BerryTwist: A Twisting-Tube Soft Robotic Gripper for Blackberry Harvesting

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Abstract*—Asglobal demand for fruits and vegetables continues to rise, the agricultural industry faces significant challenges in securing adequate labor. Robotic harvesting devices offer a promising solution to address this issue. Harvesting delicate fruits, such as blackberries, presents unique open challenges due to their fragility. This letter introduces BerryTwist, a prototype robotic gripper specifically designed for blackberry harvesting. The gripper features a fabric tube mechanism that uses motorized twisting action to gently envelop the fruit, ensuring uniform pressure application and minimizing damage. The twisting motion is transferred to the tube through a compliant mechanism, thus maintaining the overall softness of the structure. We thoroughly tested BerryTwist, paying particular attention to the effect of varying tube properties. We developed three types of tubes varying in elasticity and compressibility, using foam padding, spandex, and food-safe cotton cheesecloth. Performance testing focused on assessing each gripper's ability to detach and release blackberries, with an emphasis on quantifying damage rates. The results indicate that the proposed gripper achieved an 82% success rate in detaching blackberries and a 95% success rate in releasing them, demonstrating its promising potential for robotic harvesting applications. Finally, we will demonstrate the robotic harvesting operation by establishing a simple farm setup and integrating the gripper with Franka Emika's robot manipulator.

***Index Terms*—Agricultural automation, agriculture harvesting, blackberry harvesting, grippers and other end-effectors, soft robot applications.**

I. Introduction

The agricultural industry is facing significant challenges in hiring enough workers to meet the global food demand, primarily due to low wages and the negative health effects associated with agricultural labor [1], [2]. Automation, particularly in the harvesting of fruits and vegetables, is being explored as a viable solution to address these issues. However, several obstacles remain, particularly in the selective harvesting of crops with uneven ripening patterns and the potential for mechanical damage during harvesting, which can compromise crop quality [3], [4].

Harvesting of blackberries is especially challenging. One major concern in blackberry harvesting is Red Drupelet Reversion (RDR), where individual drupelets turn reddish after harvesting [5]. According to a 2019 survey by Dunteman, consumers prefer blackberries without RDR, associating the discoloration with unripe fruit [6]. This discoloration typically occurs within 24 hours of the fruit entering cool storage [7]. Mechanical injuries sustained during harvesting are a major cause of RDR, with a recent study indicating that 85% of handled fruit developed RDR compared to just 6% of unhandled fruit [5], [8].

Current general-purpose robotic harvesting technologies primarily use standard rigid grippers [9], [10]. However, these grippers are limited by their limited adaptability to varying shapes and delicate textures when it comes to handling soft fruits. They apply forces unevenly, posing risks such as bruising, crushing, or deforming the delicate crop [11]. Moreover, rigid grippers often require precise positioning and alignment, making them less practical in the complex environment of a greenhouse. In contrast, soft grippers [12], [13], [14], [15], [16], [17] have gained significant attention for fruit harvesting in recent years due to their ability to handle delicate and easily damaged fruits [18], [19], [20]. Using compliant materials and designs, soft grippers offer gentle handling and better conformity to the fruit's shape [21], [22], [23], [24].

Given the issue of RDR, blackberry harvesting demands careful force distribution, thus making soft grippers a natural solution to the challenge. In response to this pressing need, a few works in literature have investigated the topic of blackberry harvesting[1]. Gunderman et al. [26], and Qiu et al. [27] have introduced a tendon-driven gripper for blackberry harvesting with force feedback; however, they found that the rigid support required for the force sensor caused damage to the berries. More recently, Johnson et al. [28] proposed and thoroughly tested a novel soft gripper design aimed at enhancing the shelf life of harvested blackberries.

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[1]Note: the design we propose in this letter is the output of the first author's master's thesis [25]. The associated report first appeared online as a pre-print in 2022, thus positioning this design prior to the ones reviewed here.

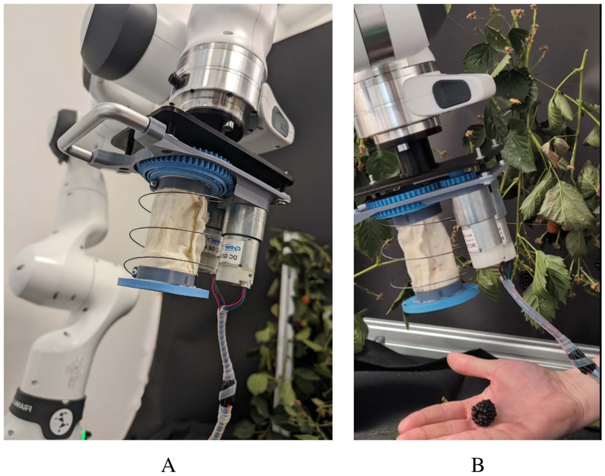

Fig. 1. BerryTwist gripper mounted on a robotic arm, demonstrating its application in a real-world setting. (A) shows a close-up of the gripper's design and attachment to the arm. (B) demonstrates the gripper delicately grasping and detaching a blackberry, highlighting its effectiveness in real-world harvesting.

Fig. 2. General view of the BerryTwist gripper mechanism. The fabric tube is visible in the center of the picture, enclosed between the two blue rings. The upper ring is free to move as it is connected to the base only via the spring used for transferring the twisting motion. The two motors actuating the system are on the back.

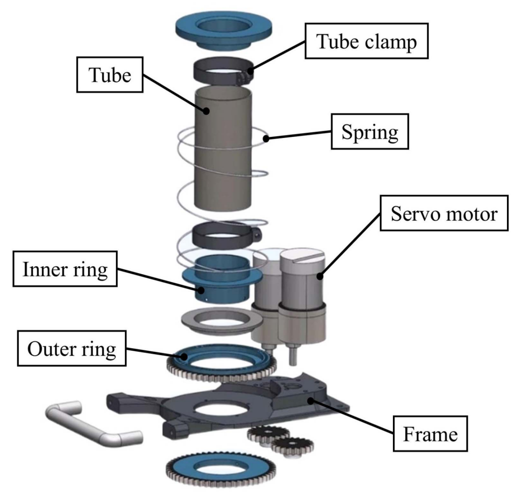

Fig. 3. Exploded view of the BerryTwist gripper. The gripper consists of a fabric tube that is manipulated by two servo motors. The split ring and inner ring, in conjunction with the spring, generate a twisting motion to gently envelop the fruit. The outer ring and frame provide structural support.

In this work, we introduce the BerryTwist, a new gripper specifically designed for blackberry harvesting applications (as showcased in Fig. 1). Two motors twist the fabric from both sides, generating a twisting motion that gently but firmly envelops the fruit. Compared to other non-fingered soft grippers [29], [30], this grasping solution has the advantage of being inherently food-safe as the cloth could be selected among the ones usually employed in the agri-food sector. Additionally, the part that comes into contact with the fruit can be replaced if damaged or contaminated.

We evaluated BerryTwist, assessing its performance based on detachment rates, release rates, removal forces, and damage indicators such as leaking drupelets and RDR. Addressing the challenge of blackberry harvesting presents an opportunity to develop grippers capable of reliably handling various small and delicate crops.

The remainder of the letter is organized as follows: Section II outlines the design and manufacturing process of the mechanism and tubes, along with an explanation of their working principle. Section III presents the quantitative results of blackberry grasping, including the percentage of accuracy for grasping and releasing the blackberry. Finally, Section IV concludes the letter and discusses avenues for future research.

II. Materials and Methods

This study focuses on blackberry harvesting, aiming to safely detach a single fruit from the plant and relocate it without causing any damage. The gripper must comply with the food safety standards specified in EU Regulation No 178/2002. Additionally, our goal is to achieve pick-and-place cycles within minimum time to allow efficient integration with the production process. Furthermore, the gripper's design should be adaptable to the dense canopy typically found in most plants for successful operation across various agricultural environments.

A. Design and Fabrication

In view of the prototype (Fig. 2), the relatively modest force applied by the spring ensures that the tube's length adjusts stronger twisting motions while maintaining proper tension. The single pre-tensioned spring was positioned externally along the tube's frame, eliminating the need for additional linear guidance. This design keeps the gripper's flexibility, improving its maneuverability within the dense crop canopies and minimizing the risk of crop damage.

Additionally, this spring allows the gripper to adapt its position around the target fruit, even if it does not align precisely with the tube's center. Clamps were used at both ends of the gripper to attach the tube to the rotating rings. These clamps were designed for the specific diameter and thickness of the cloths while minimizing the weight of the part. The tube has an inner diameter of 40 mm, providing enough space for even the largest blackberries to enter with clearance. The tube length is set at 70 mm (see Fig. 3).

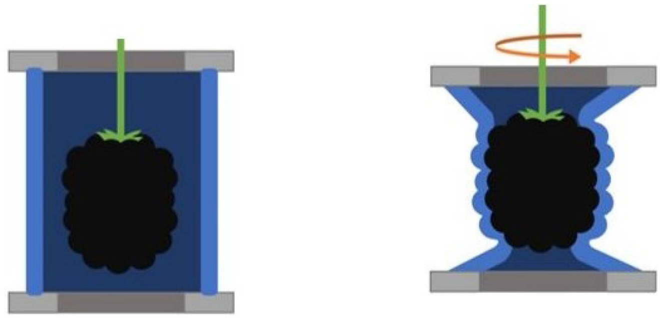

Fig. 4. Cross-section demonstrating the twisting tube concept in action, depicting the open configuration (left) and closed configuration (right) during the grasping and detaching of a blackberry. Deformable components are highlighted in blue, the stiff frame in grey, and an orange arrow represents the actuation.

For fabrication, all structural components were 3D printed using iglidur filament (IGUS, I151-PF). This filament was chosen due to its compliance with food safety standards and its low friction properties. The tube itself was custom-made from food-safe cloth and sewn into a cylindrical shape using a sewing machine for hygienic handling of the fruit.

The spring was custom-made by winding a 1 mm thick piano wire around a 27 mm diameter mandrel. This process resulted in a spring with an inner diameter of 68 mm and a free length of 140 mm. These springs were then inserted into U-shaped channels at each end of the gripper and secured in place with setscrews spaced at 90-degree intervals. This configuration eliminates the need for linear guidance systems, which could compromise the gripper's flexibility and adaptability. The even distribution of the securing points allows for uniform tension around the target object and preserves the flexibility required for maneuvering through dense canopies and handling delicate fruits.

As seen in Fig. 4, the twisting mechanism in the presented gripper design rotates a tube's two ends in opposing directions to hold berries. The twisting movement causes the tube's diameter and length to decrease, encasing the fruit in the cloth. During the harvesting process, the tube stays in touch with the edges of the fruit and wraps around its top. Tugging and twisting motions help break off the blackberry from its pedicel. This spacing between the rings can be adjusted through free translation, allowing for force-based modifications, controlling with an additional actuator, or coupling it with the gripper's rotation. To maintain lightweight and compliant characteristics at the opposite end of the tube, we strategically positioned both servomotors at one end. In this arrangement, the base motor directly propels the bottom end of the tube, while the other motor rotates the bottom end of the spring. Subsequently, the upper end of the tube receives this rotational force via the windings of the spring.

As the gripper tightens, both ends of the tube undergo simultaneous rotation and contraction, commencing from the free end and progressing towards the fixed end. Thus, during gripper closure, the tube twists around the fruit's main axis and exerts a pulling force to detach the fruit from the pedicel. To implement this system, two servos (Cytron, SPG30E-120K) with a 120:1 gear ratio were used, allowing rotation of the two ends of the twisting tube. Through a modified 55:20 gearbox combination, a rated torque of 1.62 Nm and a stall torque of 6.14 Nm were achieved at the tube's ends. Assuming no losses, the servos operate at a rate of 10.2 RPM. To effectively manage the 12V motors, which have a stall current of 1.8 amperes, an appropriate motor shield from DFRobot (DRI0009) was selected.

Fig. 5. Seven tubes utilized for testing blackberries. Cheesecloth tubes are depicted in white, while spandex tubes are shown in blue. Tube 7, shown on the right, is identical to Tube 6 on the left but reversed inside out.

B. *Tube Materials*

The selection of tube material greatly impacts the overall performance of the gripper. To thoroughly investigate this aspect, we conducted tests using tubes with varying compressibility, elasticity, and radial elasticity. Seven distinct tubes were manufactured and tested, as illustrated in Fig. 5, with detailed characteristics provided in Table I. Our selection process involved opting for cheesecloth as the primary material due to its food-safe properties and non-elastic, woven cotton composition.

Additionally, to evaluate the impact of cloth compressibility on performance, we utilized a second cheesecloth variant of thin and lightweight nature. Moreover, we introduced spandex with a four-way stretch to assess the effects of full elasticity. Considering the distinct surface properties of spandex compared to cheesecloth, we custom-made two additional tubes by sewing thick cheesecloth to the exterior and interior of the spandex. This allowed us to investigate performance differences attributable to surface properties, compressibility, or elasticity. Furthermore, a cheesecloth tube with internal padding, reversible to provide external padding, was manufactured to introduce radial elasticity. This feature was meant for better adaptation to surface irregularities observed in blackberries while still having the stiffness of cheesecloth to transmit forces. Radial elasticity was achieved by sewing six strips of 18 mm wide foam along the twisting folds of the tube to facilitate twisting motion. By using the flipped

TABLE I
OVERVIEW OF SEVEN DISTINCT TUBES USED IN THE STUDY

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 gram/m^2
Thick cheesecloth inside, spandex outside	Cheesecloth, 100% cotton unbleached, twill weave, 230 grams/m^2. Spandex, 82% polyamide, 18% elastane, 4-way stretch, 200-225 gram/m^2
Spandex inside, thick cheesecloth outside	Cheesecloth, 100% cotton unbleached, twill weave, 230 grams/m^2. Spandex, 82% polyamide, 18% elastane, 4-way stretch, 200-225 gram/m^2
Thick cheesecloth, padding inside	Cheesecloth, 100% cotton unbleached, twill weave, 230 grams/m^2. Padding, 5mm thick polyether foam SG25
Thick cheesecloth, padding outside	Cheesecloth, 100% cotton unbleached, twill weave, 230 grams/m^2. Padding, 5mm thick polyether foam SG25

inside-out tube with external padding, we investigated whether differences in gripping performance stemmed from the tube's increased thickness, rendering it stiffer, or its radial elasticity.

III. RESULTS AND DISCUSSION

We performed a series of experiments to first characterize the BerryTwist gripper and then validate its integration into the robotic system. All experiments were carried out in laboratory settings and designed to replicate similar farm configurations.

A. Experimental Setup

The objective of the measurement setup was to evaluate the gripper's success rate and the extent of damage incurred and to measure the vertical detachment force relative to the pedicel. A custom tensile bench was used to achieve this. This bench was equipped with a high-precision load cell (Futek, FSH00104). The BerryTwist gripper was positioned at the base of the setup and securely fixed to the frame (see Fig. 6).

To accommodate blackberries with varying pedicel lengths, a piece of high-strength string was attached to the end of each pedicel using industrial-grade tape. This modification allowed the blackberries to be introduced into the gripper at any desired height, regardless of the pedicel length. The string extension allowed for the vertical positioning of the blackberry to be precisely controlled for consistent testing conditions. The string was then fastened to a custom clamp positioned directly above the gripper, which held the blackberry in place during the detachment tests (see Fig. 7). Considering blackberries' varying sizes and shapes, we monitored the servomotor's current to control its rotation, ensuring accurate grasping. This approach enabled us to verify that the rotation was sufficient to securely and fully grasp the blackberry.

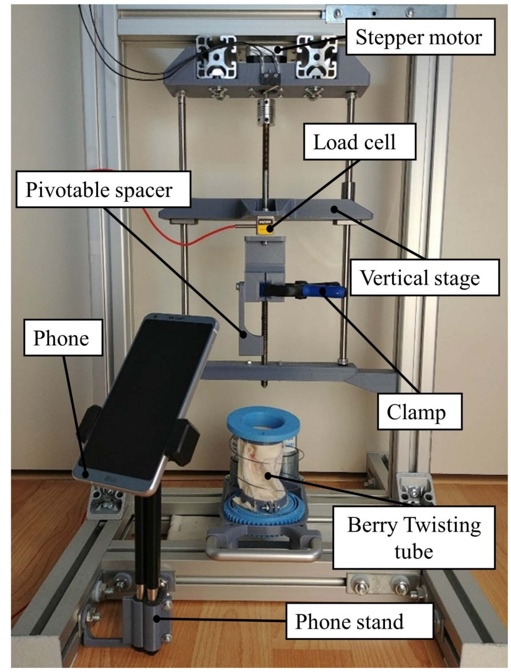

Fig. 6. Custom tensile bench setup is used to evaluate the BerryTwist gripper's performance. Key components include the stepper motor, load cell, vertical stage, and pivotable spacer for consistent blackberry positioning. The BerryTwist gripper is securely mounted at the base. A phone on a stand records the detachment process.

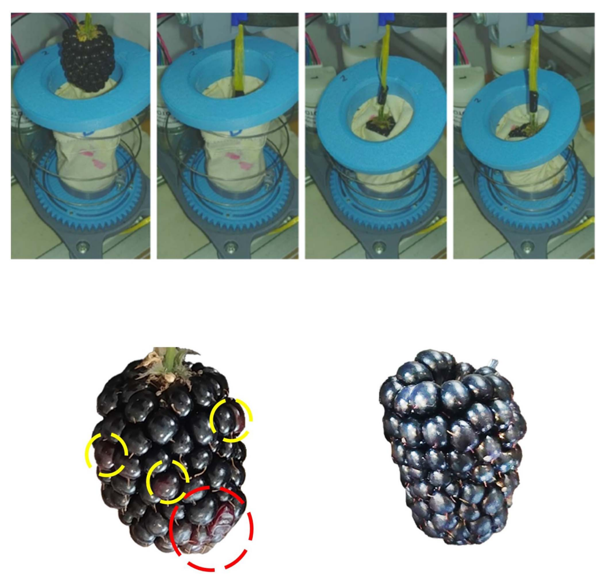

Fig. 7. Sequential steps of the pedicel removal process using the BerryTwist gripper with thick cheesecloth (top). The bottom section highlights the effects of post-harvest handling, comparing two blackberries: one without Red Drupelet Reversion (RDR) on the right, and one with RDR on the left. The red circle indicates leaking drupelets and severe RDR, while the yellow circles highlight areas with RDR but no leaking.

The tensile bench setup was designed to replicate the vertical detachment forces encountered in a real-world harvesting scenario. By measuring the forces required to detach the blackberry from the pedicel, the effectiveness and gentleness of the BerryTwist gripper could be quantitatively assessed. Additionally,

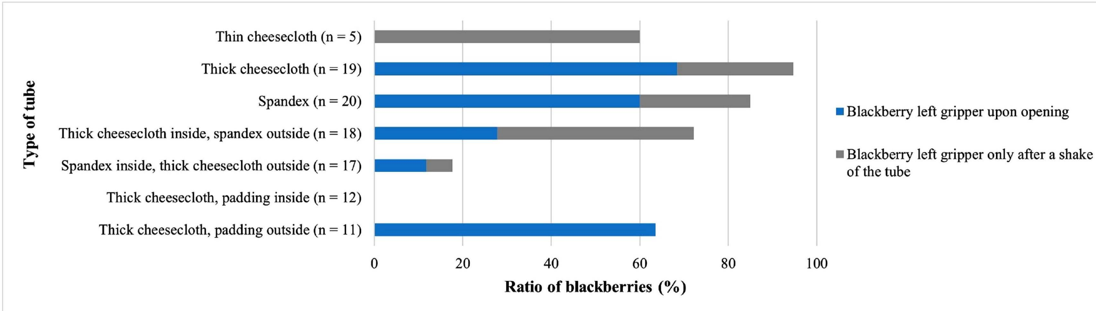

Fig. 8. Overall results on the release rates of blackberries from various tube configurations. We differentiate the cases in which the crop leaves the gripper upon opening from the ones that would require a shaking motion from the robotic gripper. Thick cheesecloth and spandex tubes showed high release rates (95% and 85%, respectively).

this setup allowed for the evaluation of damage incurred by the blackberry during the detachment process, providing data on the gripper's performance and its potential impact on fruit quality. The blackberry submodule, suspended by its pedicel in the clamp, was vertically connected to one end of a load cell, with the other end linked to a vertical stage. This setup allowed measurement of vertical forces acting on the submodule in relation to the vertical stage, including the weight of the submodule and the detachment force exerted by the gripper once it had secured the blackberry. The vertical stage was powered by a stepper motor, which moved it via a threaded rod. By tracking the pulses sent to the stepper motor and converting them using the pitch of the threaded rod, the relative position of the vertical stage could be calculated. We examined detachment and release rates, pedicel removal forces, and rotations of both rings, concluding with an analysis of damage rates in terms of leaking and RDR drupelets. Additionally, we compared the performance of the BerryTwist gripper with different tube materials to understand their impact on effectiveness. The blackberries used in this study were harvested from De Berkelse Braam, Bosch Fruit B.V., at a temperature of 19.5°C and a relative humidity between 70% and 80%. After harvesting, they were stored at 5°C. We filled 18 punnets, each containing 12 blackberries. Sixteen punnets contained blackberries with stems cut approximately 1 cm above the sepal, and two punnets contained handpicked blackberries as a control group.

Additionally, two punnets from the 16 with stems were left unhandled as another control group. The remaining 14 punnets were divided into two groups of seven for testing on the first and second day, respectively. On each testing day, we evaluated the seven different types of tubes in random order, using blackberries from a single randomly chosen punnet.

1) Detachment and Release Rate: Throughout the harvesting and handling process, we treated blackberries gently to avoid any purple stains or signs of leakage. The blackberries were consistently placed and stored in punnets and never stacked atop one another. Only fully ripe blackberries of the Sweet Royalla variety were used, with an average length of 30.8 mm (standard deviation (SD) = 2.8 mm), a diameter of 23.4 mm (SD = 1.9 mm), and a weight of 7.8 grams (SD = 1.6 g), measured using a digital scale and caliper on 36 randomly selected blackberries. Research on four different blackberry cultivars showed similar average sizes and weight ranges [31]. We observed various modes of detachment of the blackberry from the pedicel across the seven different tubes. The gripper was tested on a sample of 21 blackberries for each type of cloth. However, the sample size shown (n-value in Fig. 8) for the release measurements is smaller, as it only includes the blackberries that were successfully harvested by the gripper. Thin cheesecloth had a 24% success rate, with 5 successful detachments during gripping and none during the vertical pull. Thick cheesecloth showed an 82% success rate, with 12 successful detachments during gripping and 2 during vertical pull. Spandex had the highest success rate at 94%, with 14 successful detachments during gripping and 1 during vertical pull. Thick cheesecloth inside with spandex outside had a 76% success rate, with 12 successful detachments during gripping and 1 during vertical pull. Spandex inside with thick cheesecloth outside showed an 81% success rate, with 9 successful detachments during gripping and 4 during vertical pull. Thick cheesecloth with padding inside had a 47% success rate, with 2 successful detachments during gripping and 6 during vertical pull. Lastly, thick cheesecloth with padding outside had a 5% success rate, with 8 and 3 successful detachments during gripping and vertical pull, respectively. The findings reveal that thick cheesecloth, spandex, and their combinations performed better than other materials, achieving successful detachment in over 75% of the cases. Conversely, thin cheesecloth often wedged the blackberry out at the top whilst tightening, resulting in a successful grip for only 24% of the blackberries. Padded tubes also generally failed to detach the blackberry, with around a 50% detachment rate.

In most cases, the twist and inherent slight pull of the contracting tube during the gripping procedure alone were sufficient to detach the blackberry, and only occasionally was a subsequent vertical pull necessary for successful detachment. We visually observed all the blackberries that remained in the gripper after the detachment procedure to determine the frequency and timing of blackberry release (Fig. 8). It is important to note that the sample sizes varied, as some blackberries slipped or wedged out of the gripper during the previous stage and were, therefore, not present in the gripper for release.

Nevertheless, we observed high success rates with the thick cheesecloth, achieving a 95% release rate, and with the spandex, achieving an 85% release rate. The tube featuring thick

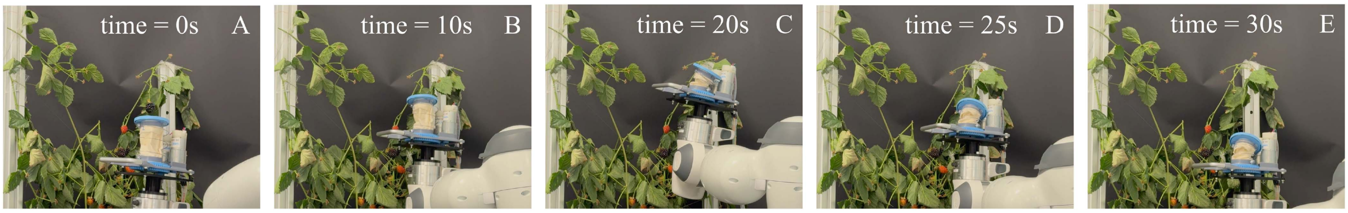

Fig. 9. Sequence of stills showcasing one example of the tested robotic application. (a) Positioning of the BerryTwist gripper under the blackberry; (b) Upward movement of the robotic arm to align the gripper with the fruit; (c) Manual activation of the gripper to secure the blackberry; (d) Retraction of the robotic arm, detaching the fruit; (e) The gripper holding the detached blackberry.

cheesecloth on the inside and spandex on the outside also performed relatively well, with a 72% release rate. Conversely, the inverted configuration exhibited poor performance, with only 18% of the blackberries successfully released.

B. Evaluation of the BerryTwist in Real World

To accurately assess the gripper's performance in a real-world setting, we simulated a scenario where a blackberry plant is situated in a small schematic farm setup (see Fig. 9). The BerryTwist gripper was attached to a Franka Emika Panda robotic arm, a highly versatile 7-degree-of-freedom (DOF) arm with an 855 mm reach and a maximum payload of 3 kg. The robotic arm was mounted on a mobile platform and positioned 60 cm away from the plants. This specific distance was chosen so that the gripper could reach the target without encountering complex configurations that might introduce kinematic singularities, which could impede smooth operation and control. In this simulation, The robot was programmed with a predetermined motion path based on the known position of the blackberries using an imitation learning algorithm. Initially, the BerryTwist gripper was positioned directly beneath the blackberry. The Franka Emika Panda robotic arm was then moved upward, aligning the gripper with the fruit to initiate the picking process (see Fig. 9(a), (b)). Once the blackberry was fully enclosed within the gripper's tube, the gripper was manually activated to secure the fruit firmly (Fig. 9(c)). Following the secure grip, the Franka arm was retracted to its initial position, detaching the blackberry from its stem (see Fig. 9(d), (e)). After detachment, the Franka arm executed a rotational movement to position the gripper for the release phase. The gripper then gently released the blackberry into a designated collection area.

Throughout the process, some shaking was intentionally introduced during both the grasping and releasing phases. This shaking was necessary so that the gripper could fully engage with the blackberry, overcoming any residual adhesion between the fruit. The detailed steps and outcomes of this procedure are comprehensively documented in Video 1 in the Supplementary material.

C. Versatility Assessment

Given the constraints of conducting tests in a controlled greenhouse environment and the complexity of evaluating blackberries across all size and shape variations, we employed substitute fruits with differing dimensions to evaluate the versatility of the BerryTwist gripper. The selected fruits–elongated Sweet Sapphire¢grapes, white and red grapes, and cherry tomatoes–were specifically chosen for their comparable size, shape, and fragility to blackberries, providing a reliable assessment (Fig. 10).

Fig. 10. Test specimens for the versatility tests, shown from left to right: a Sweet Sapphire$^{\text{TM}}$ grape, a Thompson white seedless grape, a Timco$^{\text{TM}}$/Sheegene 13 red seedless grape, and a cherry tomato.

The results indicated that the gripper effectively handled fruits within a weight range of 3 to 15 g, with lengths between 19 and 54.4 mm and diameters between 14.4 and 24.6 mm. These parameters captured a broad spectrum of shapes and sizes, replicating the variability found in blackberries. Throughout the tests, the BerryTwist gripper demonstrated its ability to securely grip the fruits without inducing any damage, as none of the specimens showed bruising, deformation, or structural compromise either during or after handling.

IV. Conclusion

In this work, we introduced BerryTwist, a new type of gripper designed specifically for blackberry harvesting. The gripper demonstrated high success rates in grasping and releasing blackberries. By setting up a simple farm setup and attaching the gripper to a robot, we verified its ability to function effectively in real-world scenarios.

To further enhance BerryTwist for industrial harvesting, some optimizations are needed. Reducing the gripper's size would allow the flexible tube to move more easily through dense canopies. This could be achieved by modifying the rotating rings or integrating the spring mechanism into the BerryTwist tube. Additionally, developing software to detect the position and orientation of blackberries and surrounding obstacles would enable a robotic manipulator to autonomously perform the entire process. Implementing specialized systems at the farm, like rotating trellises, could also improve the accessibility of fruit for robotic pickers.

Future efforts will focus on enhancing the gripper's performance by integrating sensor technology, including deformation sensors in the fabric and a camera at the tube's base. Additionally, a sensor to accurately detect blackberry positions will be crucial for developing a fully automated harvesting system.

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