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Compliant Robotic Gripper with Integrated Ripeness Sensing for Blackberry Harvesting

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***Abstract*— Global blackberry demand has been surging due to their antioxidant and nutritional value in a traditional diet. However, blackberries have extreme fragility (resulting in up to 85% of harvest batches sustaining damage) and near-ripe and ripe blackberries are difficult to distinguish in normal lighting conditions. These challenges in maintaining the blackberry supply motivate the development of an autonomous robotic solution to harvest fully ripe blackberries with minimal damage. The present paper details the mechanical design, methodology, analysis, and experimental results of a compliant robotic gripper created for this purpose. The gripper has a compact form factor and retractable fingers with specialized TPU finger pads for gentle picks, a near-infrared (NIR) reflectance-based probe for detecting full ripeness and a standardized harvesting sequence for effectively picking berries. In an outdoor harvesting experiment, the gripper attempted picking 26 berries without ripeness sensing, with 65.4% (17) being successfully picked and 38.5% (10) sustaining damage. The movements of the robot arm in the harvesting sequence were accordingly adjusted and finalized for following in-lab experiments, in which the gripper was also outfitted with ripeness sensing. Out of 40 berries, 62.5% (25) were successfully picked, with 0% of them sustaining damage. The ripeness probe classified 56 ripe and 11 near-ripe berries, with 89% (50) of the ripe and 64% (7) of the near-ripe berries being correctly classified. In a second in-lab experiment, 16 of 20 berries were successfully picked, with 2 sustaining damage.**

I. Introduction

Blackberries are a delicate fruit that currently require labor-intensive manual harvesting to minimize damage to their drupelets [1]. A handful of soft robotics solutions have been studied to address both the labor and fragile handling challenges of automated harvesting applications (e.g., [2] (recent survey), [3], [4]), including specifically for blackberries ([5], [6], [7], [8]). This present paper describes work in developing a compliant gripper (Fig. 1) that considers two challenges arising in real world blackberry harvesting that have not been fully addressed in the literature thus far: (1) the ability to handle “clusters” of berries spaced closely together on canes in the farm and (2) the ability to distinguish between ripe and near-ripe berries that may not appear visibly distinct on an image detection system. While the literature suggests a correlation of luminance, chroma and hue with ripeness progression [9], there is a lack of a definition for near-ripe berry optical properties.

Existing reported blackberry grippers have a three-finger morphology (e.g., [6] and [8]), relatively large form factor [8], and/or rely primarily on encapsulating the berry [6]. Taken together, they preclude harvesting of tightly spaced clusters of blackberries. The gripper described in this paper has been designed with a compact, two-finger configuration with compliant fingertips to better enable harvesting within clusters.

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Fig. 1: Compliant gripper *in situ* in a blackberry farm, shown without integrated ripeness sensor for clarity. The three-berry cluster in foreground contains representative ripe (right-most two) and near-ripe (on the left) blackberries.

Object detection algorithms based on visible RGB images often have difficulty distinguishing among slight color variations, especially in outdoor settings. For example, recent work by Zhang et al. [10] implemented machine learning-based blackberry detection, though focusing on distinguishing between ripe (dark) and unripe (reddish) fruit. Near infrared-based reflectance measurements have been shown to discern subtle ripeness variations in fruits such as blueberries (see, e.g., [11] and [12]). This paper studies NIR reflectance for blackberries and develops an operable ripeness sensor based on its principles. The sensor has been fabricated using low-cost LEDs and photodiodes and has been fully integrated into the developed compliant, two-finger gripper. The sensor is able to distinguish between ripe and near-ripe blackberries (an example of which is illustrated in Fig. 1).

II. Method

A. Compact Gripper Mechanism Motivation and Design

One of the main objectives for the developed mechanical gripper is the ability to successfully pick berries regardless of growing conditions, focusing especially on those that have grown in tightly packed clusters. This has motivated the need

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for a highly compact mechanical design. For the scope of this work, a cluster is defined as a group of berries within close proximity to each other originating from the same central stem (see Fig. 2).

In order to meet the design constraints of achieving a compact form factor, the proposed gripper design takes inspiration from the work by the Brigham Young University Compliant Mechanisms Research Group on developable mechanisms (see, e.g., [13], [14], and [15]). A developable mechanism is a mechanism that conforms to the surface (developable surface) it is on during a certain configuration state [16]. Developable mechanisms allow for complex functionality while staying hyper-compact in certain configurations.

The mechanical gripper described in this paper is a two-fingered end-effector that utilizes a four-bar linkage for deploying the fingers as well as allowing for them to fold back into the main body. Although it is not technically a developable mechanism due to the absence of a true developable surface, it borrows the concept of utilizing multiple positional configurations in order to achieve the retracted and deployed states. The four-bar linkage system includes a ground linkage which fixes the mechanism to the gripper body, while two dynamic linkages attached to the static base move the fourth linkage (the finger) – see Fig. 3. The driven crank linkage features a pinion gear that interfaces with a rack in a rack-and-pinion system. The rack runs along the length of the gripper body and interfaces with another pinion gear driven by a servo motor. Actuation provided by the servo motor enables the fingers to exhibit a range of motion between fully retracted and fully deployed states, making it capable of gripping berries of different sizes and folding up into its long and narrow form factor.

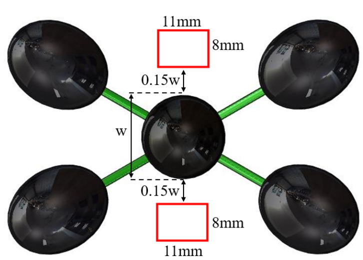
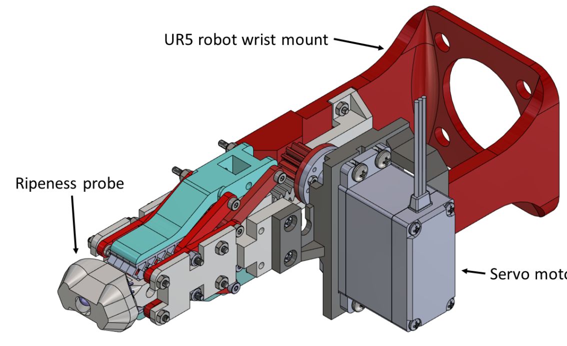


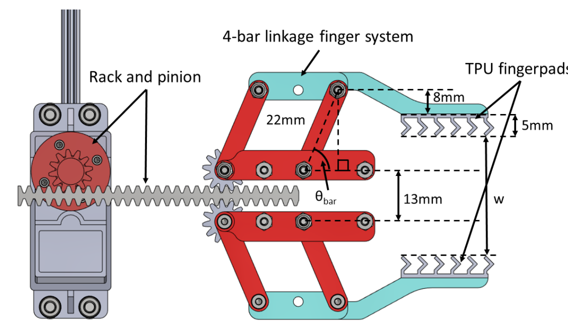
Fig. 2: Schematic of a blackberry cluster that can be accommodated by the developed gripper. The center berry (of dimension w) is the target. Gripper finger cross-section is 8 mm × 11 mm.

The angle of the front linkage bar θ_{bar} with respect to the horizontal fixed linkage can be related to the width w of the berry, i.e., the spacing between the fingers. The gripper mechanism's dimensions and symmetrical nature with respect to the rack and pinion axis, shown in Fig. 3(b), yield the equation $w = 2\,(22\sin(\theta_{bar}) - 13) + 13$. Rearranging for the angle in degrees yields $\theta_{bar} = (180/\pi)\arcsin((w+13)/44)$.

Due to physical limitations of the four-bar linkage system in its fully retracted position, the angle of the motor θ_{servo} is 40° greater than the angle the linkage bar makes with the body θ_{bar}. The motor rotates from 180° (fingers fully retracted) to the angle required to match the width of the berry. The minimum value of θ_{servo} is 57° (fingers fully extended), which prevents interference with the ripeness probe (described later in this paper).



(a) Isometric view of gripper



(b) 4-bar linkage cross-sectional view

Fig. 3: Isometric view and cross-sectional view of the developed gripper with dimensions labeled.

B. Compliant Fingertip Bristles

The developed gripper's fingertips are 3D-printed from flexible thermoplastic polyurethane (TPU), designed to compress and conform to the shape of the blackberry to achieve the desired compliance (Fig. 4). The angled bristles were designed to engage with the space between drupelets and prevent the blackberry from slipping out as the gripper is retracted during robotic harvesting motions.

Bristle angles of 110°, 135°, and 150° were tested. The angle of 135° was chosen because it was the most successful in preventing the berries from sliding out of the fingertips. The bristles are able to harvest the berry best when they make contact between the blackberry's drupelets. A bristle thickness of 0.75 mm was used because smaller bristles would result in poor quality 3D prints, and the thickness was minimized to maximize compliance, as higher rigidity would result in drupelets being pierced on contact.

Each bristle extends 4mm from the base of the fingertip pad, with a total of 30 on a single pad. A cumulative force of 0.5 N over all bristles in contact with a berry is required to successfully grip it without damage [8]. If all 30 bristles on a pad are engaged, a theoretical maximum force of 2.1 N can be achieved. Designing the bristles such that their maximum force stays below the accepted threshold ensures minimum likelihood of damaging the berries.

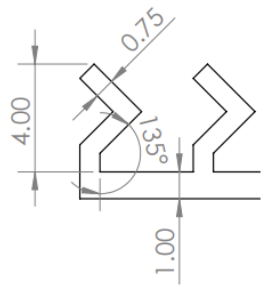


Fig. 4: Dimensions of a single TPU fingertip bristle (mm).

Calipers were used to measure the vertical compression of the bristles when engaged with blackberries. Only the bristles on the side of the fingertips were accessible, so multiple blackberries were placed within the fingers to collect 45 data points. The average vertical compression of a single bristle was 0.26 mm, with most readings within the range of 0.20-0.30 mm; these readings exclude uncompressed bristles. Finite element analysis reveals that a vertical force of 0.07 N (2.1 N / 30 bristles) on a single bristle produces this compression range (Fig. 5).

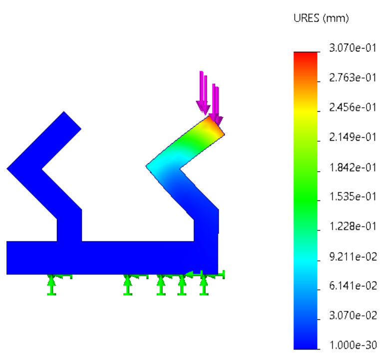


Fig. 5: FEA of a TPU bristle with a 0.07 N vertical force.

C. NIR Reflectance-Based Ripeness Sensing

The motivation for a near-infrared (NIR) reflectance-based ripeness detector stems from the difficulty of distinguishing near-ripe from fully ripe berries based on a traditional RGB camera system alone. Near-ripe berries can exhibit large variability in color distribution across its drupelets, allowing them to appear fully ripe from one vantage point (Fig. 6(a)) while their lack of ripeness is apparent from a different vantage point (Fig. 6(b)). Compact cameras that fit within the small form factor of the developed gripper are low-resolution, and lack a robust lighting system to distinguish noise in the camera feed (caused by shadows) from near-ripe and ripe berries. An integrated NIR reflectance-based ripeness sensor provides an additional non-invasive perception modality to make a final decision regarding whether to harvest a candidate blackberry.

To develop an integrated NIR ripeness detector, the reflectance spectra of near-ripe and fully ripe berries were

(a) Ambiguous near-ripe (b) Clearly near-ripe

Fig. 6: Unripe (top), near-ripe (middle-left), and fully ripe (bottom) berries taken from two vantage points, (a) and (b), that are approximately $90°$ apart.

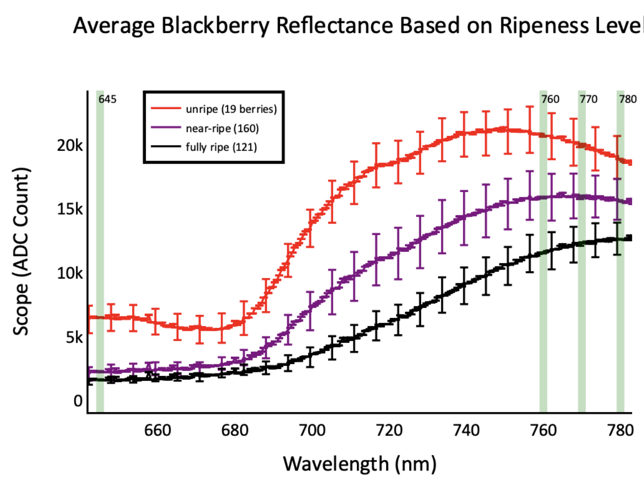


Fig. 7: Reflectance spectra collected using an *Avantes UV-Vis Spectrophotometer*, excerpted to show region with maximum separation between unripe, near-ripe and fully ripe blaberries. Error bars denote standard deviation.

collected to determine if it is possible to distinguish the two groups based on reflectance. Satisfactory separation between the groups was observed (described below) and specific wavelengths were selected to be used in an integrated ripeness probe. Once the probe was fabricated, reflectance spectra for near-ripe and ripe berries were collected again using the probe to calibrate its readings. Finally, criteria were chosen to classify readings from the probe as near-ripe, fully ripe or out-of-range, with priority given to minimize false positive ripeness readings.

The *Avantes UV-Vis Spectrophotometer* was used to collect the reflectance spectra of 19 unripe, 160 near-ripe, and 121 fully ripe berries between the wavelengths of 176.04 nm and 1100.13 nm for 1611 wavelengths (Fig. 7). A sample of 19 unripe berries was used to provide context to the separation between near-ripe and fully ripe berries, since unripe berries were expected to be significantly different. Fig. 7 was

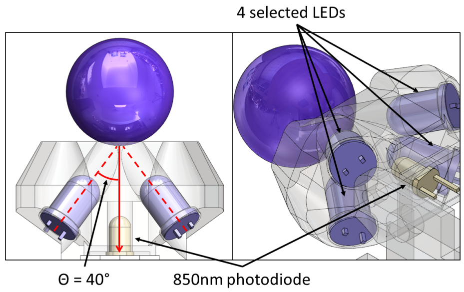


Fig. 8: Side (left) and bottom (right) views of gripper's ripeness sensing probe tip. A 40° incident angle yielded maximum reflectance from blackberry surface.

excerpted to the region with the most separation between the three ripeness categories. The standard deviation of the average reflectance reading at every 25 wavelengths is shown to indicate a statistically significant difference between the ripeness levels for this region of the spectra. Based on this spectra and LED availability, four wavelengths (highlighted in green) were selected for the integrated ripeness sensor: 645 nm, 760 nm, 770 nm, and 780 nm.

The integrated ripeness probe head (Fig. 8) was designed to utilize NIR LEDs from *Thorlabs, Inc.* To measure reflectance, light from an LED is emitted towards the surface of a berry, which then reflects it into an INL-3APD80 photodiode from *DigiKey* with maximum sensitivity near 850 nm. This photodiode has a total range of $40-1100$ nm with 80% of its spectral sensitivity between $790-920$ nm. The key identified parameters that impact the reflectance readings were the angle between the LEDs and photodiode, photodiode placement depth, and ambient lighting conditions. After experimenting with different angles between the LEDs and photodiode keeping while keeping ambient conditions and the depth of the photodiode constant, it was determined that a 40 degree angle was optimal.

Reflectance readings were seen to drop significantly if the photodiode was not near the surface of the berry; thus, the reflectance probe was designed to allow the photodiode to be as close to the fore of the probe without intersecting the illumination path from the LEDs. Finally, ambient light entering the probe was prevented as much as possible by making the probe opening as small as possible.

The LEDs and photodiode were controlled using an *Arduino Uno* using four digital output pins for the LEDs and an analog input pin for the photodiode. Each LED was connected in series with a 150 Ω resistor to prevent burnout over time (Fig. 9) since they were rated for 1.5 V, and the *Arduino* provided an output of 5 V. The 850 nm photodiode was connected to an OPA2132PA *DigiKey* operational amplifier via a non-inverting circuit with a 1e6 Ω external resistor to produce sufficient gain to amplify the signal.

To obtain a reading, each of the four LEDs were turned on for 2.5 milliseconds, during which the average of 250 values from the analog input is recorded with a 10 microsecond delay between each measured value. The delay ensures that each LED is turned on for a sufficient amount of time so that the result from a prior LED does not affect current readings due to latency in the *Arduino*.

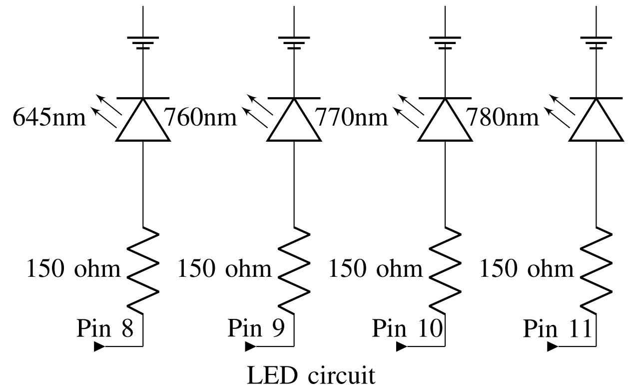


Fig. 9: Circuit diagram of NIR ripeness sensing probe.

The ripeness probe was used to instantiate a reflectance spectra graph (similar to Fig. 7) to calibrate the readings of the probe (Fig. 10). Calibration was performed at a local blackberry farm in Atlanta, GA on 100 near-ripe and 100 fully ripe berries to generate the graph in Fig. 10. There was no overlap between error bars, indicating that the ripeness probe was able to distinguish between near-ripe and fully ripe berries. After a few hours, another set of 100 near-ripe and 100 ripe berries were measured with the probe and plotted on the calibration average plots to validate the calibration set. The validation set readings follow the same spread as the original calibration set and also exhibited separation for the first standard deviation at each of the four wavelengths. Specifically, 67%, 75%, 68%, and 64% of the validation data falls within the first standard deviation of the plotted calibration set at the wavelengths 645 nm, 760 nm, 770 nm, and 780 nm, respectively.

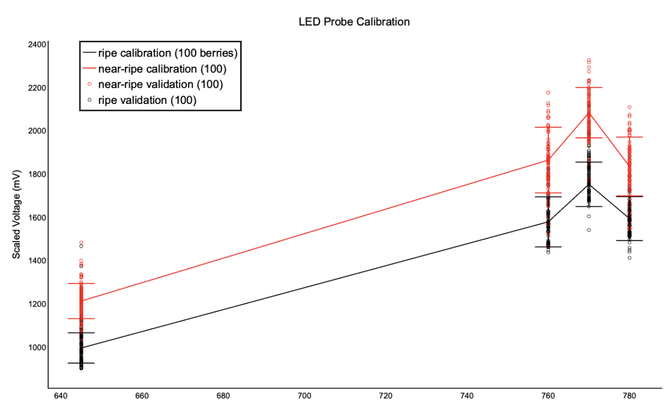


Fig. 10: *In vitro* LED ripeness detector photodiode voltage readings converted from *Arduino* ADC for near-ripe and fully ripe blackberries.

Classification of the ripeness level of a blackberry used the criterion that at least 3 wavelength reflectance readings fell within 1.25 standard deviations of the calibrated average for those wavelengths for a ripeness level.

D. Automated Blackberry Harvesting Operational Sequence

Blackberries are often difficult to pick due to the compliance of the branches on which they grow. Pulling the berry in a direction perpendicular to the main branch results in the whole branch being pulled along with it. To address this, a robotic harvesting sequence was developed to perform picking motions along multiple axes (Fig. 11 and Fig. 12). (Note that a "stem" connects the berry to the main branch on its other end.) The sequence is performed as follows:

1) Gripper is initially positioned 25 mm away from the end of the blackberry opposite its stem and oriented along the stem axis. The width of the berry w is known from measurement by caliper beforehand.
2) Move gripper 25 mm forward to touch berry with ripeness probe and take reading.
3) Pre-closing (to accommodate clusters):
    a) Retract gripper 25 mm.
    b) Close the fingers until they are spaced apart $1.3w$ (refer to Fig. 2).
4) Closing:
    a) Re-advance gripper forward 25 mm.
    b) Close the fingers to grip the berry.
    c) Pitch the gripper by 80° (direction depends on available robot workspace).
    d) Roll the gripper by 45° clockwise.
    e) Jog backwards 125 mm to pick the berry off the stem.

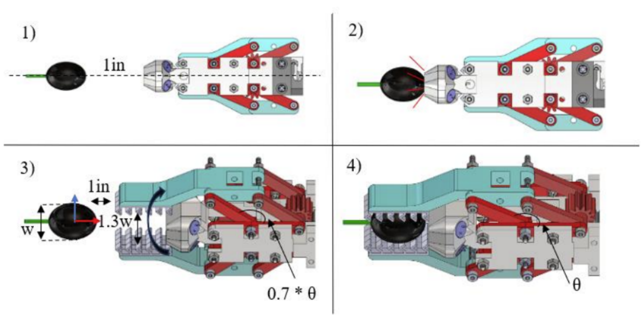


Fig. 11: Illustration of four-step harvesting sequence.

Each pick attempt was evaluated according to 3 criteria:

1) Was the grip of the fingertips satisfactory?
2) Was the berry removed from the stem?
3) Was the berry damaged after the pick?

A grip is satisfactory if the berry is gripped in the center of the fingertips such that the majority of the bristles are engaged and the berry does not slide out (refer to Fig. 13). Once picked, the berries were left in an open, room-temperature environment overnight. If there was any red drupelet reversion [17], the berry was classified as damaged.

Ideally, a satisfactory grip should result in a compression of bristles such that they conform to the shape of the berry. The ideal deflection is approximated via FEA by assuming the greatest force of 0.5 N occurs at the region of widest diameter and decreases linearly in both directions going away from it (Fig. 14). The physical prototype was not observed to match the ideal deflection, as not all bristles are engaged sufficiently despite a satisfactory grip due to irregularities on the surface of the blackberry.

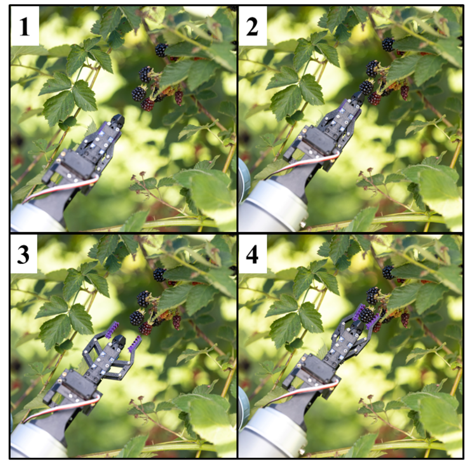


Fig. 12: Four-step harvesting sequence *in situ*.

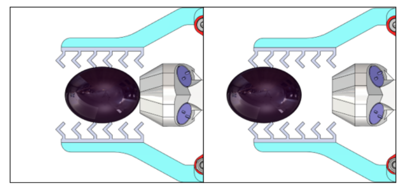


Fig. 13: Satisfactory grip (left) vs. unsatisfactory grip (right).

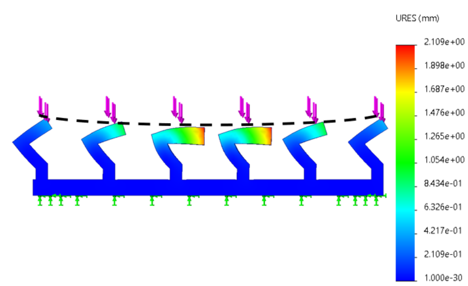


Fig. 14: Ideal deflection of bristles assuming the central region of widest diameter experiences a 0.5 N force.

III. Results

Three sets of blackberry harvesting experiments were conducted to test the gripper: one outdoors at the local blackberry farm (without ripeness sensing) and two in-lab experiments (the first of the two with integrated ripeness sensing).

In the outdoor experiment, the mechanical gripper alone was used to attempt picks of a total of 26 berries, with a variety of motions tested out to determine the best ones that would yield the most successful picks. 65.4% (17) berries were successfully removed from their stems. 96.1% (25) of the runs yielded satisfactory grips. However, 38.5% (10) of the picked berries sustained damage during picks (TABLE I). Based on these results, the robot motions in the harvesting sequence were adjusted for the two in-lab sets of experiments.

Criterion	Percentage (%)
Satisfactory Grip	96.1
Picked Off Stem	65.4
Sustained Damage	38.5

Grip	Successful Pick (%)	Unsuccessful Pick (%)
Satisfactory	58.3	41.7
Unsatisfactory	68.8	31.2

TABLE I: Evaluation criteria results for outdoor harvesting experiment.

Grip	Successful Pick (%)	Unsuccessful Pick (%)
Satisfactory	58.3	41.7
Unsatisfactory	68.8	31.2

Criterion	Percentage (%)
Satisfactory Grip	60
Picked Off Stem	62.5
Sustained Damage	0

TABLE II: Evaluation criteria results for first in-lab harvesting experiment.

For the in-lab experiments, branches with stems and berries attached were transported back from the farm and attached to an artificial tree with compliant branches. The four-step harvesting sequence (with integrated ripeness sensing) was first run on a total of 40 blackberries. Evaluation criteria were recorded for each pick. 62.5% (25) of the berries were successfully removed from their stems (TABLE II). 60% (24) of the attempts had satisfactory grips. Most failed picks occurred due to the compliance of the branches (allowing them to be pulled and twisted along with the berry), even in cases with satisfactory grips. It was observed that unsatisfactory grips resulted in a higher pick success rate. An unsatisfactory grip allows the berry to slide within the fingertips. The pitch, roll and retraction of the gripper could hence twist the berry relative to stem, allowing it to be picked without stretching the stem. In all of the picks, 0% of the berries had sustained any damage, showing that the gripper is capable of non-destructive harvesting.

The ripeness probe was used to classify 56 ripe and 11 near-ripe berries in this first in-lab experiment. 89% (50) of the ripe berries were correctly classified as ripe and 64% (7) of the near-ripe berries were correctly classified as near-ripe (TABLE III). These results demonstrate the probe's efficacy in distinguishing between near-ripe and ripe blackberries.

A second in-lab experiment was performed late in the harvest season (latter half of July 2023). A new TPU fingertip bristle (see Fig. 15) was designed and fabricated for use in this second experiment. This revised bristle has a more acute 30 degree flexure angle (compared to 45 degrees), which theoretically results in 1 mm additional compliance. The "cap" on the tip better distributes the contact pressure from the blackberry.

The second in-lab experiment was performed with 20 berries (fewer berries were available from the farm), with

Ripeness Level Detected	Count	Unsuccessfully Picked (%)
Ripe	50	89
Near-ripe	2	4
Out-of-range	4	7

Ripeness Level Detected	Count	Unsuccessfully Picked (%)
Ripe	1	9
Near-ripe	7	64
Out-of-range	3	27

TABLE III: Ripeness detection probe results for ripe (top) and near-ripe (bottom) berries for in-lab setting. Out-of-range classification given to readings outside of calibration values.

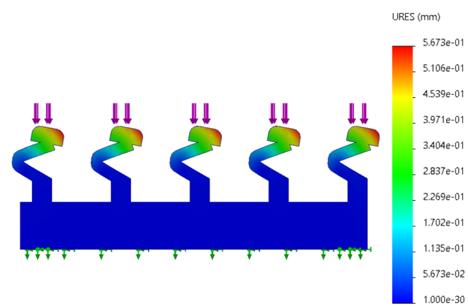


Fig. 15: FEA of revised TPU bristle.

a successful pick rate of 80% (16 berries). Of the four failed picks, three were observed to have the berry's stem orthogonal to the main supporting branch, which resulted in compliant bending in the direction of manipulator retraction. Nearly axial stem angle resulted in reliable picks. Two berries were observed to exhibit discoloration due to damage.

IV. Conclusions and Future Work

The development, fabrication, testing and evaluation of a novel gripper for robotic harvesting of blackberries has been described. Preliminary results of its integrated NIR-based ripeness sensing and berry grasping capability based on compliant fingertips, integrated within a robot harvesting sequence, have been reported to yield successful pick rates as high as 80% and as low as a 0% damage rate.

A significant problem encountered during the described outdoor harvesting experiment at the blackberry farm was the interference of sunlight with the ripeness probe readings. This will be addressed in the future with a method of calibrating the ripeness readings to allow the photodiode to distinguish between interfering sunlight and wavelengths of reflected infrared light from the LEDs. The mechanical design of the probe opening will also be enhanced to attempt to reduce ambient illumination.

The compliant finger bristle design will be improved upon in order to increase compliance and reduce the risk of post-harvest damage. Additionally, the current four-bar linkage finger deployment system yields a simple circular fingertip motion that tends to squeeze and push the berry away during the gripping process. Therefore, the kinematics of the deployment system will be re-examined to eliminate unintended berry motion.

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