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Dynamic evaluation of a suction based gripper for fruit picking using a physical twin

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***Abstract*— We present and evaluate a novel suction-based gripper designed for fruit picking. This work is motivated by common problems observed in field trials of robotic harvesting: Calibration/perception errors, workspace obstacles, fruit swinging/moving when contacted, and varying stem and branch stiffnesses. The gripper consists of three suction-cups located on the palm, along with in-hand perception. To evaluate the gripper, we developed a physical proxy that approximates a realistic apple-stem-branch dynamic system. We performed 756 apple picks on the proxy with varying branch stiffness, stem strength and gripper pose (*yaw*, *roll* and offset w.r.t. the apple). Our results show that grasping performance improves when the gripper *yaw* w.r.t. the apple has two suction cups on the bottom of the apple and one suction cup on top. Even with $\pm 15mm$ offset, at least two suction cups engaged with the apple 80% of the time, regardless of branch stiffness. Moreover, the gripper withstands $\pm 20mm$ offset when it approaches the apple near its equator.**

I. INTRODUCTION

Fresh-market apple harvesting with robots remains a difficult task. Fruits are delicate and — if not handled properly — they can be easily bruised or damaged [1]–[3]. Although modern orchard architectures are designed to make picking easier — consisting of narrow, planar canopies [4] — there are still challenges with reaching fruit. They can be at any orientation, have different sizes and shapes, be close to/clustered with other objects (branches/trunks, fruit, wires) and occluded by leaves [4], [5]. A less-obvious challenge is the variable mechanics of the fruit-branch attachment (Fig. 1-*bottom right*). Fruit on long, thin compliant branches "swing" out of the way when pushed, while fruit attached with a short stem to a thick branch tied to a trellis wire may not move at all. These dynamics also mean that fruit can *move*, either because of wind or because of vibrations from previous picks. All this, while also needing to provide high throughput (i.e. low cycle time per pick) and handle inaccurate perception/localization of the fruit in challenging outdoor conditions.

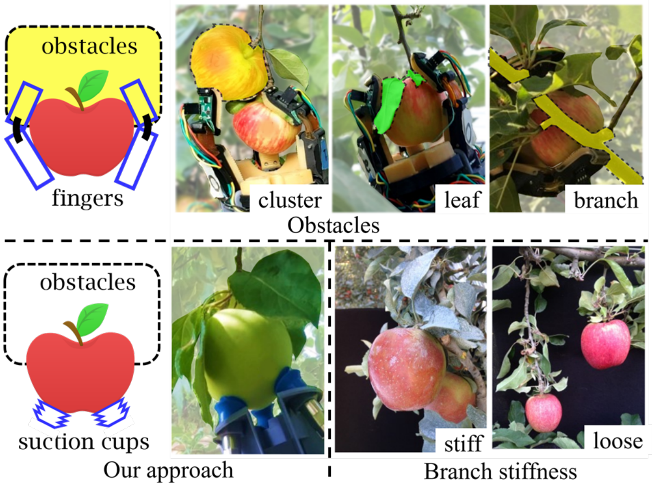

Fig. 1. *Top*: Grippers with large approach volumes, such as designs with spanning fingers, can become obstructed during the grasp due to collisions with neighboring fruit, leaves, and branches. One potential benefit of suction-based grippers (*bottom left*) is a smaller approach volume less likely to cause unwanted collisions. *Bottom right*: Apples attached to a 'stiff' branch behave differently when contacted compared to apples attached to 'compliant' branches.

The recent literature has converged on using elements of soft robotics for grasping delicate objects [6], [7], but this still leaves a wide range of possibilities. Some approaches use compliant mechanisms [8]–[10] while others leverage fluid actuation, such as positive pressure (Fluidic Elastomeric Actuators (FEA) [11]), vacuum (Universal Vacuum Gripper [12]), or suction cups [13]–[15]. Based on their publicly available media, most commercial ventures working on robotic soft fruit harvesting appear to use suction cups in their designs. Our own experience [16] has shown that finger-based grippers struggle because they require a much wider approach volume, which is problematic in highly cluttered spaces like fruit trees (Fig. 1-*top*). Even within the space of suction-cup based designs, however, there are still many open questions — how many suction cups and what size? How should they be oriented? Underneath this is a fundamental question: How do you *evaluate* a proposed design?

In this work we propose a novel, rigorous method for evaluating a gripper design that takes into account i) the dynamics of the apple-stem-branch connections, and ii) the robustness of the design to uncertainty in fruit pose. Our evaluation uses a physical apple proxy that supports different poses, branch stiffnesses, pick forces, and known pose relative to the gripper. We use this proxy — plus structured approach-vector sampling — to evaluate our novel 3-suction-cup based design.

Contributions: i) We demonstrate a suction-based robotic gripper that integrates three suction cups with in-hand perception sensors (In-Hand-Camera (IHC), Time-of-Flight (ToF) and pressure transducers). This work builds on our

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previous work [17] in which we characterize the optimal suction-cup pose. ii) We present an upgraded version of our apple proxy [16] that has a compliant stem attachment that mimics observed forces and stiffnesses. This proxy supports testing under different conditions, including branch stiffness, stem strengths, gripper pose (*yaw*, *roll* and offset). iii) We evaluate the novel gripper with the proxy to determine ideal configurations and behavior under perception noise and different branch mechanics (756 apple picks). This evaluation showed that our gripper was highly effective even when mis-aligned and using only an open-loop, naive controller. Specifically, if the gripper is aligned in a Δ-*yaw* configuration (Fig. 4), at least two suction cups engage 80% of the time even if the gripper is offset from the apple center by $\pm 15mm$.

II. Related Work

We focus on suction-based grippers that have been used for grasping and picking fruit. Some methods use cutting to detach the fruit (e.g. peppers, tomatoes), while other fruit picking techniques keep the stem intact, and instead "peel" the fruit free at the stem-branch abscission layer (e.g. apples, pears). Variations include the number of suction cups as well as different actuation methods. There is very little work in the area of fruit picking proxies.

A. Suction grippers in agriculture

Prior work has used suction-based grippers to pick different types of fruit. Vu et al. [18] designed a gripper to pick tomatoes based on four fingers and a single cup located on the palm that extends to bring targets close to the fingers. In another work, Jun et al. [7] developed a kirigami-patterned suction module to pick tomatoes. In some cases (peppers, tomatoes) the fruit detachment is achieved through cutting [19]; this requires less gripping force but more precision in fruit localization. In contrast, in other fruits (apples, pears) the stem needs to be kept intact or is too short to reach with a cutter. This requires applying sufficient mechanical stress (shear, tensile, etc.) [20] to the abscission layer to separate the stem from the branch (without damaging or removing the stem).

B. Suction cup designs and arrangements

Grippers with different numbers and sizes of suction cups can be found in the literature. Huh et al. [14] used a single suction cup with four pressure transducers located at four inner chambers which help detect partial cup disengagement. Jiang et al. [21] used multiple cups in order to bin-pick different sized objects. Other suction cup-based gripper designs are largely influenced by the objects' geometry. In one work, Tanaka et al. [22] used two surface grippers for cardboard boxes in order to grab them from the corners. However, these more general designs tend to require large approach volumes which is cumbersome when approaching fruits in trees.

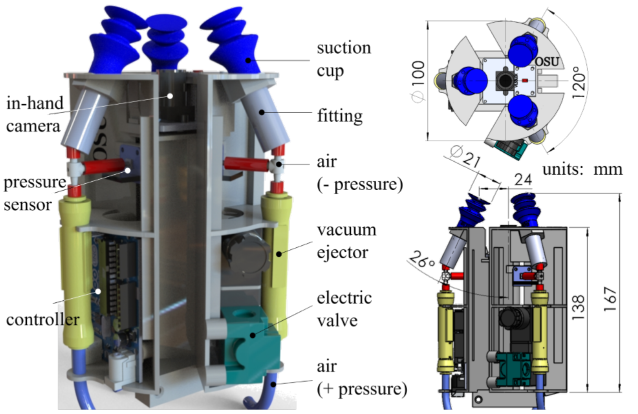

Fig. 2. Suction-based gripper. Left: 3D render of the assembly and its main components. Right: gripper general dimensions and ideal placement of suction cups according to previous work [17].

C. Suction cup combined with other actuation modes

An interesting trend is to use suction cups in combination with other actuation principles (e.g. fingers). In one work, Bryan et al. [6] developed an octopus-inspired gripper, where they placed suction cups on the gripper's cable-driven fingers. Zhou et al. [23] combined one suction cup centered on the palm and four fin-ray fingers. They used pressure sensors on each of the fingers' pads to detect collisions and avoid bruising the fruit. Sandoval et al. [24] adopted a similar arrangement but used FEA fingers instead of fin-rays.

D. Performance measurements and testing environments

In the study closest to our work [25], the authors thoroughly analyze the effect of four independent variables (number of suction cups, diameter of suction cups, angle of suction cup and apple *roll*) in the performance of a suction-based gripper for apple picking. They achieved the best performance with four suction cups, a cup diameter of $25mm$, an angle of 27° and apple growth posture A (main axis angle between 60° and 90°). This performance may be biased because they primarily grasped from the side (which is relatively "flat" compared to the bottom/top). Their choice of suction cup angles and diameters is similar to the ones we arrived at. In another work focused on bin picking [15], the authors tested their gripper by varying the distance and angle of the target, achieving tilt angles up to 60°.

Physical twins are one solution for dealing with the seasonal constraints of fruit harvesting. However, to our knowledge most of the fruit testing environments just deal with fruit detection and localization [26]. We only found one work that replicates the dynamics of grasping and picking fruit, in this case raspberries [27]. The authors measure the pressure and pulling force applied by the gripper on the fake raspberry in order to evaluate quality of picks and fruit damage, and to optimize the robotic gripper controllers.

III. Methodology

Our suction cup based robotic gripper for apple picking was motivated by i) minimizing the overall form-factor to

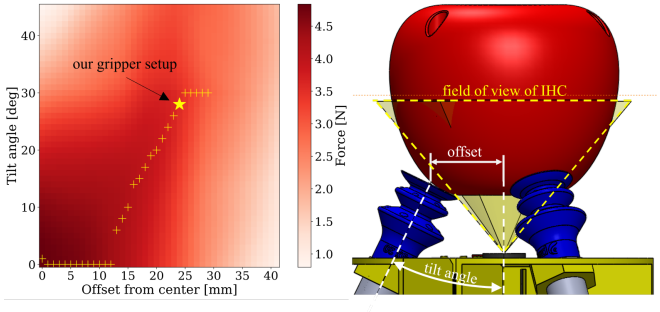

Fig. 3. Left: Optimal tilt angle for a suction cup offset from the center of an spherical object (star points at our gripper setup). Results obtained after 640 characterization experiments performed in a previous work [17]. Right: Details of suction cup positioning used to prevent interference with the IHC's FOV.

avoid collisions during approach, ii) maximizing the range of poses where the apple is successfully grasped, and iii) using in-hand sensing to support closed-loop grasping. Our solution has a small cross-section (slightly wider than an apple) and leverages the suction cups' abilities to (i) engage when in contact with a portion of the fruit and (ii) provide a pulling force without needing to embrace the fruit.

Our gripper has multiple in-hand sensors (Fig. 2). There is a pressure sensor attached to each suction cup. While not a focus of this paper, these sensors could eventually be used to help measure grasp quality and pick success (in combination with the force/torque sensor in the UR5e wrist). The second set of sensors consists of an IHC and ToF sensor located at the center of gripper's palm, which are used for visual servoing during the approach to the fruit's location.

To test the performance of the gripper we used an upgraded version of our apple proxy [16] which mimics the mechanics of the apple-stem-branch using a combination of magnets and springs. We selected magnets and springs that match stem strengths and branch stiffnesses observed in real apple picks (3 variations each, for 9 combinations in total). To evaluate sensitivity to pose alignment, we varied the gripper *yaw*, *roll* and offset w.r.t. the apple's center. Altogether, we performed 756 apple picks on the proxy.

A. Gripper Design

We chose suction cups due to their ability to seize objects without needing to embrace them. This was an important factor due to the cluttered/occluded environments of fruit trees. We also chose suction cups due to the apple's smooth skin ($Ra < 2um$ [28]). Moreover, we chose multi-bellow suction cups (PIAB F-BX20) to comply with fruit variability (e.g. symmetry, shape, size). We selected the suction cup diameter based on the space outside of the IHC's Field of View (FOV) and within the apple's diameter ($80mm$). Finally, we decided to use three suction cups equidistant from each other, offset from the palm center, in order to provide a stable grasp and simultaneously to avoid wobbling from a higher number of suction cups (similar to a four-legged table) which simplified the design.

TABLE I

BRANCH STIFFNESS AND STEM STRENGTH FROM REAL APPLE PICKS [16], AND THEIR APPLE PROXY RESPECTIVE COUNTERPARTS REPRESENTED BY SPRING CONSTANT AND MAGNET FORCE.

Domain	Parameter	Low	Medium	High
Real apple tree	Stem strength [N]	8.1	15.8	26.6
	Branch stiffness [N/m]	182	414	711
Apple proxy	Magnet force [N]	9.8	16.4	26.6
	Spring constant [N/m]	210	455	736

TABLE II

TRIALS FOR EACH COMBINATION OF SPRING CONSTANT AND MAGNET FORCE.

Spring constant	Magnet force			
	Low	Medium	High	Total
Low ($210N/m$)	108 [a]	108	36[b]	252
Medium ($455N/m$)	108	108	36	252
High ($736N/m$)	108	108	36	252
Total	324	324	108	**756**

[a] $(2yaw * 9roll * 1offset * 2rep) + (2yaw * 9roll * 4offset * 1rep)$
[b] $(2yaw * 9roll * 1offset * 2rep)$

In our previous work [17], we characterized the suction cups at different angles and offsets w.r.t. the center of a spherical target (Fig. 3). As a result, we placed each suction cup $24mm$ offset from the palm center and tilted to 26°, and spaced by 120° from the other two suction cups (Fig. 2). For vacuum generation we used vacuum ejectors near each suction cup with a $65PSI$ feed-in pressure; there are in-line pressure sensors (Adafruit MPRLS) along the path to each suction cup (Fig. 2).

B. Apple Proxy

To test our gripper, we used our apple proxy developed in previous work [16] with three upgrades (different stiffnesses, improved branch-apple linkage, and a more realistic apple).

Upgrade 1: The revised apple proxy supports i) different branch stiffnesses by changing the strength of the springs attaching the stem to the "branch", and ii) different stem detachment forces by changing the strengths of the magnets. To choose the springs/magnets we began with data collected from real apple picks performed with linear pulling patterns [16]. From the UR5e manipulator we collected both wrist Force/Torque measurements and robot kinematics relative to the apple's estimated pose. We performed linear regression of the magnitude of the linear force vs. end-effector displacement to estimate a stiffness. We also took the maximum force magnitude from successful picks (i.e. the measurement just prior to separation of the fruit from the tree) as the stem strength. We used k-means to obtain three clusters (low, medium and high) for branch stiffnesses and three clusters for stem strengths. For each cluster we identified off-the-shelf components that matched closely (within 100% and 120%) with the parameters from the real apple tree in order to mimic the behavior in our proxy (Table I).

Upgrade 2 modified the branch-apple linkage to better mimic how rotating the apple reduces the force required to detach the stem. As shown in Fig. 4-*left* the upgraded linkage

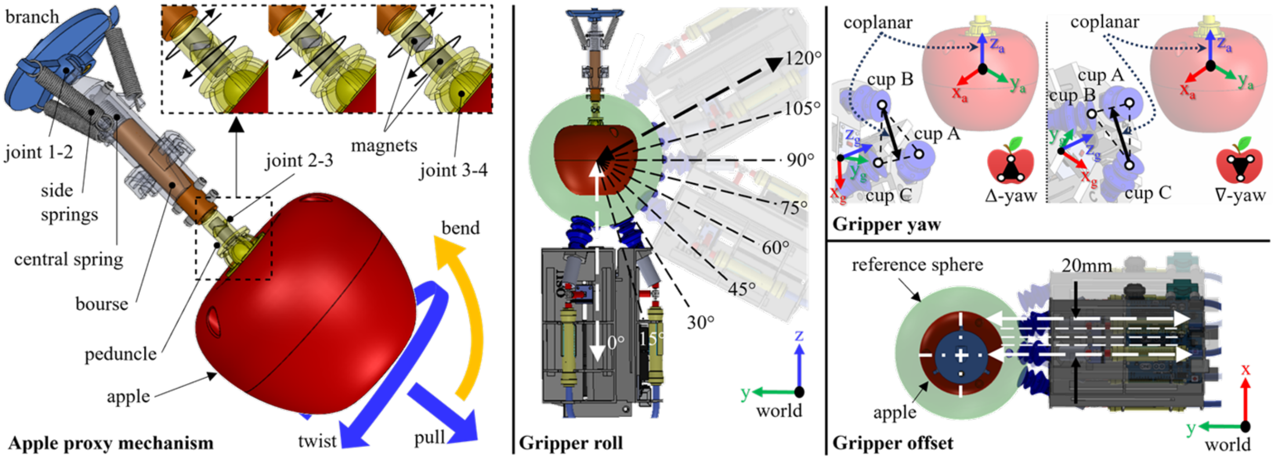

Fig. 4. (Apple proxy and test set-up. From left to right) Apple proxy mechanism: dashed area shows wedge-magnetic *joint 2-3* that creates an air-gap between magnets when twisted. Gripper *roll*: rotation of gripper w.r.t. apple center from 0° to 120° with steps of 15°. Gripper *yaw*: the gripper pose with ∇-*yaw* has one cup (C) on the bottom and two cups (A and B) on the top, whereas with Δ-*yaw* it has two cups (A and C) on the bottom and one cup (B) on the top. Gripper offset: five offsets of the gripper center w.r.t. apple center from $0mm$ to $20mm$ with steps of $5mm$.

consists of: *link 1* (branch), *joint 1-2* (ball socket + side springs + central spring), *link 2* (bourse), *joint 2-3* (magnets + twist wedge), *link 3* (peduncle), *joint 3-4* (ball socket) and *link 4* (apple). *Joint 2-3* has a wedge feature that mimics the weakening of the stem abscission layer when torsion is applied during a real apple pick. In the proxy, when torsion is applied, the wedge displaces the magnets from each other and creates an airgap, which weakens the magnetic force (*joint 2-3*).

Upgrade 3 replaced the 3D printed apple from our first version with an off-the-shelf styrofoam decorative apple with diameter $80mm$ and height $70mm$. We placed a 3D printed core with a spherical interface (Fig. 4-*left*, *joint 3-4*) and a steel cylinder in its center to increase the apple's weight to $100gr$.

C. Apple Proxy Experiments

The goal of the experiments was to determine i) the best *yaw* of the gripper — Δ or ∇ (Fig. 4-*top right*) and ii) how much "noise" in the estimated position of the apple the gripper can tolerate. We break noise into two components: The angle of approach relative to the apple stem (Fig. 4-*middle*) and offset relative to the center of the apple (Fig. 4-*bottom right*).

We used a 6DOF robotic manipulator UR5e (Universal Robots, Odense, Denmark) and our suction-based gripper as the End Effector (EEF); we used an air compressor (2HP dual piston) near the base of the robot to supply the vacuum ejectors. We configured the apple proxy with each spring-magnet combination (Table I) and kept the apple in the same pose (with its main axis aligned with the world's z-axis). We arranged the three suction cups in an equilateral triangle, and picked two yaws rotated 60° apart. Both yaws keep one of the medians of the triangle coplanar with the apple z-axis (Fig. 4-*top right*). With Δ-*yaw* the gripper pose has two cups ($cupA$-$cupC$) on the bottom and one ($cupB$) on top, while with ∇-*yaw* the gripper pose has two cups ($cupA$-$cupB$) on the top and one ($cupC$) on the bottom. Furthermore, at each *yaw* we varied the gripper *roll* w.r.t. apple center (Fig. 4-*middle*) from 0° (pointing at apple calyx) to 120° (on the stem side) with 15° steps. Finally, at each *roll* we offset the gripper w.r.t. the apple center from $0mm$ to $20mm$ with $5mm$ steps to see how much offset the gripper could withstand (Fig. 4-*bottom right*). The $20mm$ threshold was chosen from the suction cup characterization that we performed in [17]. In total we performed 756 trials as explained in Table II.

During each trial we recorded the gripper sensor measurements (e.g. three pressure sensors, ToF and IHC), the robot sensor measurements (e.g. wrench sensor located on the wrist and joint angles), and a fixed camera located on the proxy. For each trial we (i) placed the gripper at the desired *roll* and with the face of the suction cups tangential to a reference sphere with diameter $120mm$ (Fig. 4-*middle and bottom right*), (ii) adjusted the gripper *yaw*, and (iii) offset the gripper from the apple center along the world's x-axis. Then, we performed a pull-back pick as shown in Fig. 5. We labeled each attempt with the number of suction cups that engaged with the apple, and assessed the pick result.

IV. RESULTS AND DISCUSSION

Results showed that when two or three suction cups engaged with the apple, the pick was very likely to be successful. Hence, here we evaluate gripper performance with the likelihood of two or three suction cups engaged. With this metric we found that performance was highly influenced by *yaw*. The majority of the trials performed while varying the proxy setup (spring constant and magnet force) and the gripper pose (*roll* and offset) showed that gripper success was higher when it had a Δ-*yaw*.

A. Suction cup engagement versus pick result

The likelihood of a successful pick was strongly correlated with the number of suction cups engaged (Fig. 6-*left*). There

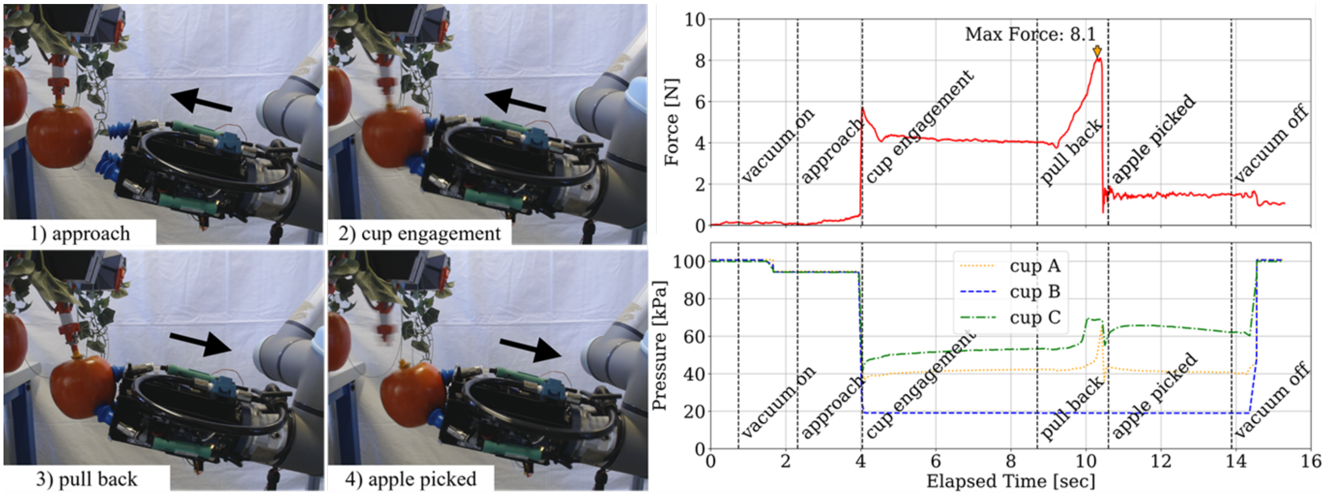

Fig. 5. Left: Sequence of an apple-pick using the proxy (Gripper pose: 75° *roll*, Δ-*yaw*, offset $= 0mm$). Right: (top) wrist net force and (bottom) suction cup pressure plots for the apple pick shown left. Note that only one suction cup (cup B) achieved 20kPa air pressure.

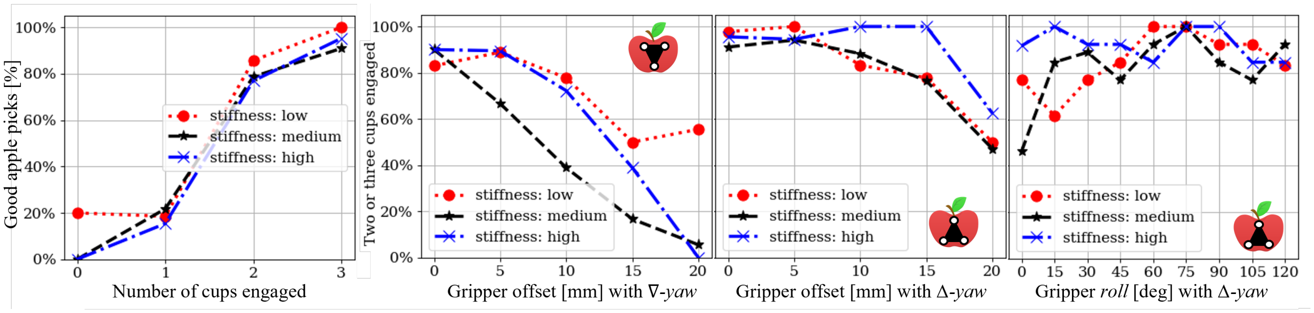

Fig. 6. Left: Correlation between the number of cups engaged and apple pick success when a *Low* magnet force was used. Middle-Left: Influence of stiffness and offset when gripper had ∇-*yaw*. Middle-Right: Influence of stiffness and offset when gripper had Δ-*yaw*. Right: Influence of stiffness and *roll* when gripper had Δ-*yaw*.

is a significant difference between one and two cups, with the percentage of successful picks increasing from 18% (one cup) to nearly 80% (two cups). This is encouraging because implementing a control scheme to engage the third cup is potentially achievable with pressure feedback. The 20% result with zero cups is not an error; as the gripper was moved away the branch dynamics (springs) pushed the apple towards the gripper, which eventually engaged and picked it. Based on these findings, the remaining discussion presents results using the number of grasps with two or three cups engaged, rather than pick success.

B. Branch stiffness

We studied the influence of stiffness as we varied the gripper offset with each *yaw* (Fig. 6-*middle left*). The gripper with ∇-*yaw* performed similarly when *low* or *medium* spring constants were used, and had the worst performance with the *medium* spring constant. In contrast, with Δ-*yaw* (Fig. 6-*middle right*) the gripper performed similarly with low or medium spring constants, and had the best performance with the *high* spring constant. With Δ-*yaw* success remains over 80% for offsets within $\pm 15mm$. We also observed the influence of stiffness at each *roll* for Δ-*yaw*. As seen in Fig. 6-*right*, the best results are obtained under *high* spring constant in most of the rolls. Low and middle stiffness hinder the gripper's performance for rolls between 0° and 15°. These observations are shown from another perspective in Fig. 7-left. In general, ∇-*yaw* (55%-73%) performed poorer compared to Δ-*yaw* (82%-93%).

C. Gripper pose w.r.t. apple

We evaluated gripper orientations (*roll* and *yaw*) and gripper positions (*x-offset*). We assumed a symmetric spherical apple, and while *pitch* and *y-offset* were not studied in this paper, we expect that they would have similar influence as *roll* and *x-offset*, respectively. *Yaw* highly influenced the stability of the attachment and the chance of a suction cup touching the apple calyx (bottom) where the surface is complex.

1) Offset from center: As expected, the gripper's performance decreases when it is misaligned with the apple's center (Fig. 7-*middle left*). Here Δ-*yaw* clearly outperforms ∇-*yaw*, and even at $15mm$ the success rate is still over 84%.

2) Roll: As seen in Fig. 7-*middle right*, Δ-*yaw* outperformed ∇-*yaw* again for all rolls, except 0°. This was expected because at 0° – regardless of the *yaw* – the three

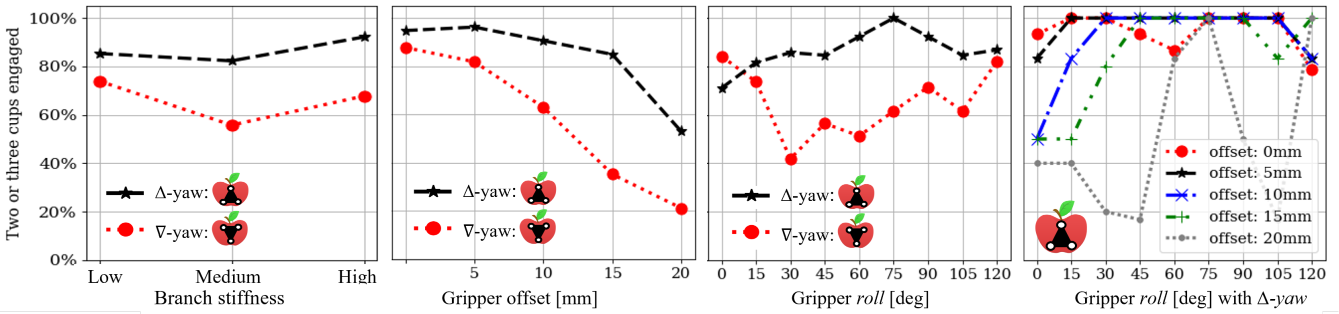

Fig. 7. Cup engagement while varying independent variables. Overall, Δ-*yaw* out-performs ∇-*yaw* in nearly all cases. From left to right: Branch stiffness: cup engagement for low, medium and high stiffnesses for both Δ and ∇ gripper yaws. Gripper offset: cup engagement while varying the offset from $0mm$ to $20mm$ with steps of $5mm$. Gripper *roll*: cup engagement at each of the gripper-stem rolls from 0° to 120° with steps of 15°. Gripper *roll* with Δ-*yaw*: influence of the offset at each of the gripper-stem rolls, for the best observed *yaw*.

suction cups are exposed to a similar convex relief around the calyx. For most of the rolls the gripper's performance with Δ-*yaw* ranged between 82% and 100%; in contrast, with ∇-*yaw* the gripper's performance dropped below 65%. We hypothesize this occurs because in the latter arrangement suction cup C faces the apple calyx, which has more cusps and is harder to engage with.

3) Offset and roll with Δ-yaw: Fig. 7-*right* shows how the offset affected gripper performance for different rolls, specifically for Δ-*yaw*. We observed that between 0° and 15° *roll*, with $\pm 15mm$ offsets the gripper fails more often. In contrast, for rolls between 30° and 105° gripper performance remained over 84% (within $\pm 15mm$ offsets). The performance drops with an offset of $20mm$ (as expected from our previous work [17]). However, at 60° and 75° rolls, even with an offset of $20mm$ the gripper performance was over 84%. We hypothesize that suction cups engage easier near the equatorial region of the apple.

D. Real apple tree trials

We performed 14 picking trials with Honeycrisp apples on a real tree to conduct a preliminary evaluation of our setup in the real world (Fig. 8). However, we only had access to apples with an average equatorial diameter of $63.2 \pm 3mm$, which was smaller than our target ($75mm - 85mm$). This affected the gripper performance, and only one suction cup engaged in most of the trials which ended in failed picks. In the future we will explore a modular design where the position/angle of the cups can be adjusted according to apple size.

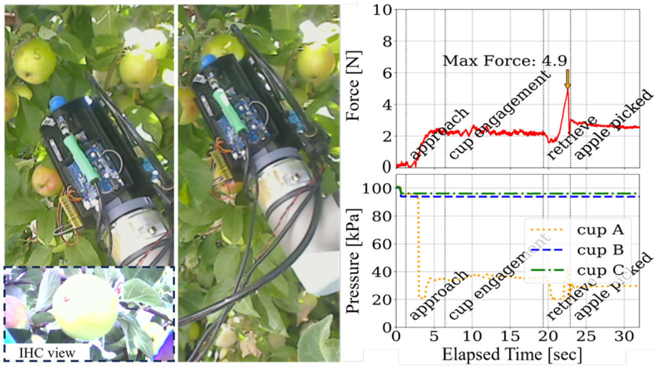

Fig. 8. Real apple pick trials. Left: UR5e approaching apple. Bottom left: perspective of IHC. Right: Force and Pressure plots. Note that in this trial only one suction cup (A) engaged with the apple, which was likely caused by the small apple size.

V. CONCLUSION

We present a suction cup-based gripper with a small form factor designed for apple picking. The gripper has IHC and ToF sensing capabilities and three suction cups — with vacuum generation and pressure sensors — in an arrangement optimized for grasping apples. We show that a physical proxy is useful for creating a detailed analysis of grasp and pick behavior in a controlled environment. The proxy enabled 756 apple picks at a rate of one pick per minute. In contrast, in previous work collecting grasp sensor data from a real tree [16], we were limited to a small number of approach vectors and were only able to collect 70 trials with unknown branch dynamics (with over 10 minutes per grasp trial). Moreover, we performed a thorough analysis of gripper performance by combining nine different rolls (from 0° to 120° w.r.t. apple center), two yaws, and five different offsets (from $0mm$ to $20mm$ w.r.t. apple center). When placed within $\pm 15mm$ w.r.t. the apple center and with Δ-*yaw*, at least two suction cups engage 80% of the time. This greatly reduces the need for highly accurate estimation of the fruit's location.

This study used a simple open-loop controller in order to analyze the passive mechanical behavior of the suction cups' interaction with the proxy. Because we can sense when a suction cup is engaged, an obvious extension is to use a smarter control strategy that "rolls" the remaining suction cups into contact. This, along with extensive field trials in a commercial orchard, we leave for future work.

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