Development of an adaptable vacuum based orange picking end effector

Kyusuk You[1], Thomas F. Burks[1*], John K. Schueller[2]

(1. *Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL 32611, USA;*
2. *Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL 32611, USA*)

Abstract: A prototypical end effector was designed to validate its fruit picking performance focusing on picking success rate and crop quality. The end effector model composed of a central vacuum gripper and four articulate vacuum fingers to enable firm and secure grasping for citrus fruit. Slider-crank mechanism finger structures achieved solid contact between vacuum pad and fruit surface. Instead of stem severing, the fruit was removed by the combined geometrical motion of rotation and pulling. The developed end effector model fulfilled its fruit picking performance with 90.8% of removal rate at 90 degrees (±5°) of the initial approaching angle producing 6~31.5 N and 0.04~1.03 Nm of the detachment force and torque during field assessments.

Keywords: robotic harvesting, vacuum gripper, orange harvesting

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1 Introduction

Typically, an end effector is a critical component in any fruit picking robot which could mimic the human hand to grip and pick the fruit. One challenging task in the development of fruit picking end effectors is the ability to maintain a firm and safe grip on the fruit throughout the harvesting cycle, because it influences the market value of the product (Monta et al., 1998). Therefore, various technologies in the end effector were proposed in this study to enhance fruit gripping capability.

For industrial robot grippers, vacuum pads were commonly used to minimize contact damage to target objects by regulating to a safe pressure. This approach is especially useful for fragile objects that require careful handlings such as glass objects and semiconductor components. The vacuum grippers also can often adapt to variations in object dimensions and shapes. Due to their adaptive functionality and reliable performance, vacuum grippers were proposed for fruit harvesting by Bullock (1956), Gerber (1987), Ceres et al. (1998), and Koselka and Wallach (2006). Although the fruit was grasped by a suction gripper in these cases, the fruit was picked using a cutting device, such as scissors or a cutting blade, to prevent damage to the fruit peel or bruising during detachment.

In other research, manipulator arm and wrist motions were utilized to harvest the fruit from the stem similar to human harvesting approaches. Glover (1975) developed a rotating auger which was integrated in the center of a cylindrical tube. Pool and Harrell (1991) developed a fruit harvesting end effector with a rotating lip and a collection sock. Ling et al. (2004) developed a robotic tomato harvester with a linearly actuated movable suction cup which extended to grasp the fruit and then retracted to separate the selected fruit from other nearby fruits. Four articulated gripping fingers then grasped the separated fruit and the fruit was harvested through a pulling action executed by the manipulator. In most cases, machine vision was used to locate the fruit position and

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*** Corresponding author: Thomas F. Burks,** Professor in Agricultural and Biological Engineering Department, University of Florida, Gainesville, FL 32611, USA. Email: tburks@ufl.edu, Tel: 1 352 392-1864.

servo-control the manipulator to the target fruit position. Flood (2006) designed a three-finger robotic orange harvesting end effector which relied on developing sufficient gripping forces between the fruit and end effector to accommodate the detachment forces. This gripper incorporated a machine vision camera in the palm of the hand. The validation tests were performed using a 7-DOF commercial ready manipulator which employed a snap-twist-pull harvesting technique. The results showed very low damage rates. The result of the articulated harvesting motions was measured using a 6-DOF sensor which measured the forces and torques imparted to the fruit during harvest.

To maintain an acceptable grasp on the fruit during picking by articulated motion, a vacuum-based gripper must be improved over earlier works. Mantriota proposed a mathematical gripping model for a set of multiple square shaped suction cups (2007a), for a single square shaped suction pad (2007b), and for a single circular suction pad (2011). In those studies, he defined the axial and tangential forces of contact between suction pad and object, and its static friction coefficient. Bahr et al. (1996), Nishi and Miyagi (1995), Liu et al. (2006), Novotny and Horak (2009) simulated and analyzed the deformation of suction pads under shear force, pulling force and moment as an elastic model, which were used in a wall climbing robot. Based on the definition of suction force, multiplying the vacuum pressure by the active area of vacuum pad, a variation of physical properties of vacuum pad was studied.

One of the common challenges faced in prior research using vacuum-based grippers was to maintain the grip on fruit during the entire picking cycle. In natural crop settings, other fruit located nearby (fruit often is located in clusters), leaves, and adjacent branches can create obstructions, which makes it difficult for the gripper to separate and grasp an individual fruit. In addition, forces and torques induced on the fruit during the harvesting motions can tend to pry the fruit off the suction cup which can break the vacuum seal and causes harvest failure. You (2015) designed an orange picking vacuum gripper using a central linearly actuated vacuum plunger, the initial fruit separator, and a static configuration of four small circumferential vacuum pads, the multi-directional gripper. During field assessments, the developed model carried out up to 90% of removal rate for successfully separated oranges (Washington Navel) within 120~150 degree of end effector's initial approaching angel to fruit. However, the end effector approached to the fruit and separated it from its cluster successfully for only 55% of fruits. And it was also over served that the position fixed multi-directional grippers loosed their vacuum during fruit picking because of various fruit size and shape.

Therefore, the objective of this study was to design a more robust end effector that can not only remove the fruit in higher removal rate, but also be able to pick up without damage. Instead of the finger-based end effector model, a vacuum-based gripper was developed in this study to achieve the proposed goal, along with its pneumatic control system. The new end effector concept was designed, 3D modeled, fabricated, and tested under laboratory and field conditions.

2 Materials and methods

2.1 Design study of end effector

2.1.1 End effector structures

To improve fruit grasping performance, slider-crank mechanism linkages were utilized as the gripping finger of the end effector model, each gripping finger's structure were clenched and released by 50 mm stoke of a single Pancake® cylinder (I121-XV, Fabco Air Inc. Gainesville, FL). It was found from the previous developed model (You, 2015) that longer retracting distance (125 mm) caused to fail fruit retrieval. A center vacuum socket and a manifold integrated end effector base were custom designed to simplify the air hose lines (Figure 3). Considering the dimensional properties of Washington Navels, described in the experimental method and results, the four fingers were designed to be expanded up to 120 mm of outer circumferential diameter by 50 mm of linear movement of the central cylinder. Vacuum passages and ports integrated into the gripping fingers provided vacuum pressure to the end fingers. And polychloroprene foam was padded at each end finger to prevent the vacuum leak during grasping fruit. Each structural element was manufactured by 3D printing techniques due to the elements' complexity and the time that would be required to machine each component by conventional manufacturing methods. The central vacuum bellows had an outer diameter of 14.5 mm and 1.5 folds (Model: FSGA 14 M5-AG, Schmalz Vacuum Technology Ltd., Germany).

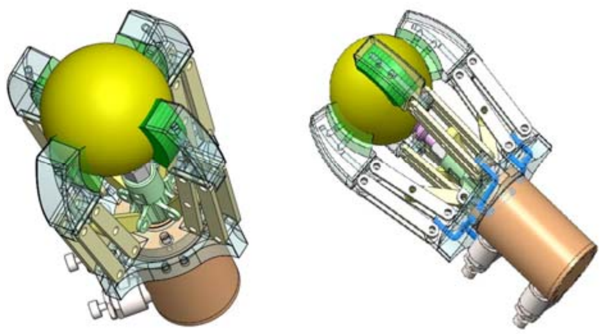


Figure 1 Design of the second prototype model

2.1.2 Vacuum system

Six ejector modules (Model, SMC Pneumatics Co. Japan) generated the vacuum pressure for each vacuum pad. Each of the four fingers used a single ejector module, while a double ejector module was used for the central vacuum bellows to create a higher pulling force. Each ejector module consisted of a vacuum valve unit (ZX1-VJ114-Y-6LZB), an ejector assembly unit (ZX1-W071), and a vacuum pressure switch unit (ZSE3-0X-21CL-Q). The ejector module could generate –84 kPa of maximum vacuum pressure, with a minimum of 10 L min^{-1} suction flow, using a maximum of 0.7 MPa of primary air pressure.

Considering the diameter of vacuum pads, four electrical pressure regulators (Model: ITV1030s, 200 L min^{-1} of max flow rate, SMC Pneumatics Inc. Japan) were adopted in vacuum unit of individual gripping finger and one regulator (Model: ITV 3030, 5000 L min^{-1} of max flow rate, SMC Pneumatics Inc. Japan) was equipped to the central vacuum unit. Both regulators could adjust output air pressure up to 0.5 MPa, with 1 MPa input air by analogue signal. Output air pressure from each regulator was controlled by Labview Virtual Interface (NI Inc. Austin TX) and two data acquisition devices (Model: MyDAQ ECEN 2250, NI Inc, Austin TX) and a PCI slot I/O board (NI Inc. Austin, TX). DAQ devices received twelve analog inputs within 0~5 V from air pressure vacuum sensors (Model: ZSE40-01-22L, SMC Pneumatics Inc. Japan) to record current pressures. Vacuum pressure of each vacuum unit was maintained within –65 kPa ±10% by the NPN switch control logic of Labview.

PLC unit (Model: Allen Bradley Micrologix 1200, Rockwell Automation Inc. Milwaukee, WI) managed the soleniod valves connected to the the linear actuator and regulatorse. Figure 2 shows the wiring diagram between Labview and the pneumatic components.

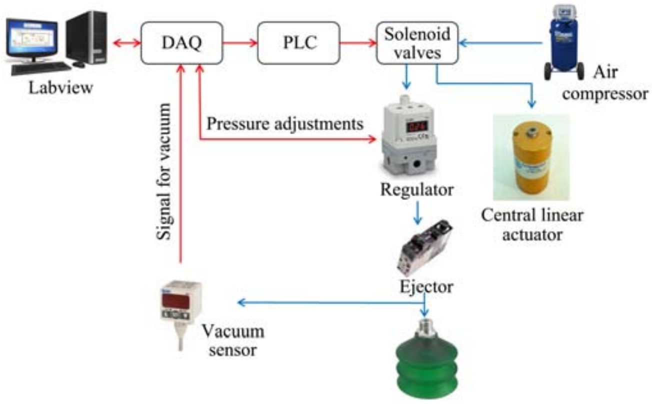


Figure 2 Pneumatic components and communication diagram

2.1.3 Pneumatic systems

The compressed air (827 kPa) was switched by a heavy duty solenoid valve to supply from the air compressor to the air manifold (1X3 Aluminum casted manifold). The air manifold distributed air flow to the linear actuator and regulators for the central vacuum units and finger vacuum units. A manual regulator adjusted the supplied air pressure to the linear actuator and a 5-port 3-way directional solenoid valve controlled stroke/retraction of the linear actuator (Pancake® air cylinder, FabcoAir Inc. Gainesville, FL). In the previous prototype model (You, 2015), it was found that the excessive stroking speed moved the target fruit from its original position and rapid retraction led to the drop the fruit from the central vacuum bellows. Therefore, two flow control valves were equipped at the both ports of the linear actuator.

2.2 Experimental methods

To guide the end effector design, dimensional and physical properties of the Washington Navels (Citrus *sinensis* cv. Navel) were inspected at the research field of the Plant Science Research and Education Unit (PSREU) of the University of Florida (Citra, FL). The fruit detachment force and torque of the prototype end effector was measured to determine the air pressure supplied to pneumatic and vacuum systems at the indoor Robot and Automation Research Laboratory of the University of

Florida (Gainesville, FL). The fruit picking performance was also evaluated throughout field assessments at the research grove of the PSREU of the University of Florida.

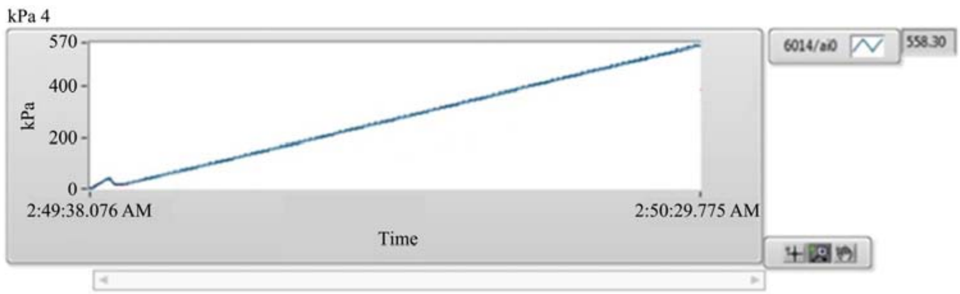
2.2.1 Dimensional properties and straight-line detachment forces

The dimensional properties of Navels were measured at the research field (Citra, FL) from 10 a.m. to 2 p.m. on October 25, 2014. These measurements provided a statistical estimate of the mean fruit size and variability. Longitudinal, lateral diameter and weight were measured for 240 arbitrarily picked fruits using Vernier Calipers and a compact weight scale. Eccentricity and oblateness, the parametric value, were calculated. The purpose of these measurements was to assist in designing the mechanical clearance in between finger contact points and thus the linkage lengths, select padding material for the fingertips to ensure enough compliance to accommodate the variability in fruit size, and then to determine the friction coefficient for the pad to fruit interface.

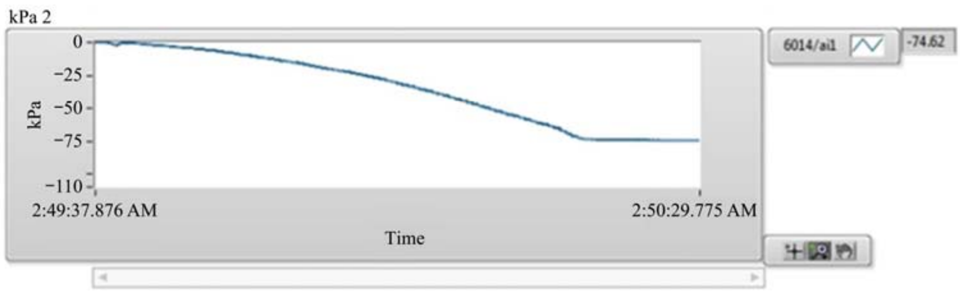
Straight-line fruit detachment forces were measured about 35 mm of pulling distance three different pulling angles, 90, 120 and 150 degrees using a portable force gauge concurrently with dimensional property measurements. The pulling distance represented the stroking length of the linear actuator and the pulling angle represented the initial approaching angle of the end effector. The test was repeated for 20 fruit per each pulling angles. These measurements established a vacuum pressure working range required for the central vacuum bellows to retract the fruit.

2.2.2 Measurement of fruit detachment force and torque

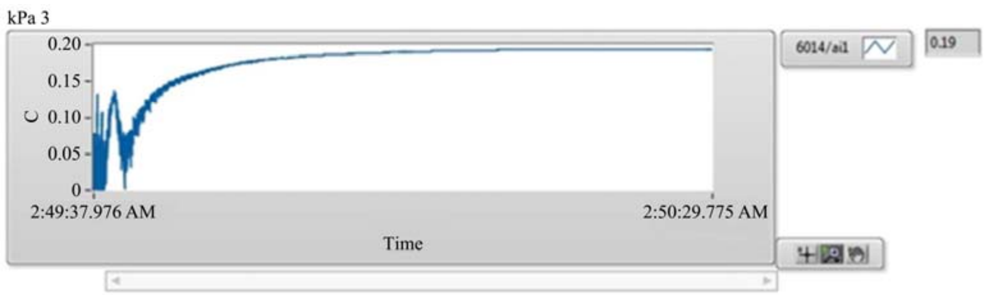
Prior to the fruit detachment force and torque tests, the coefficient of the transfer function between the supply input pressure and the generated vacuum pressure in the ejector module was found to be about 0.2 (Figure 3) throughout calibration test. The coefficient tended to increase up to 0.2 within the range of vacuum pressure from zero to –50 kPa, and over –50 kPa of vacuum pressure the coefficient maintains at 0.2.



(a) Supplied input air pressure



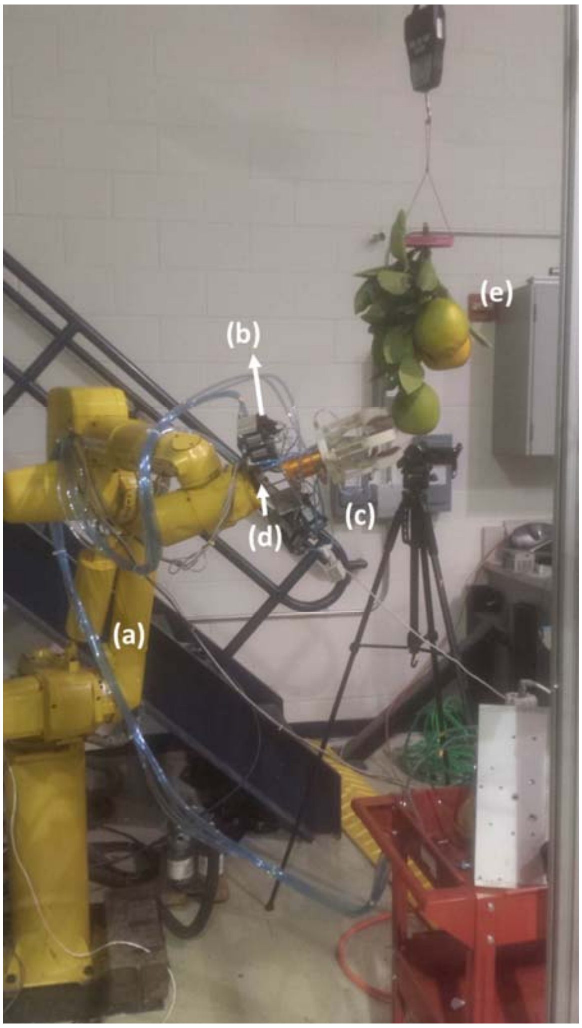
(b) Generated vacuum pressure



(c) Coefficient of linear transfer function between supplied pressure and generated vacuum pressure

Figure 3 Vacuum response for input air pressure

Forty Washington Navels collected from the research grove of PSREU were used in this measurement test. Each sample consisted of a branch segment that included branch, fruit, and leaves. Collected specimens were stored in a refrigerator at 10ºC for 48 hours before testing. Before the experiments, specimens were allowed to equilibrate at room temperature for approximately one hour and dry to eliminate moisture on their surface. Fruit cluster specimens were suspended by their supporting branches to a hoist on the overhead crane in the lab (Figure 4).



(a) 6 DOF manipulator (b) Ejector modules (c) end effector (d) force/torque sensor (e) sample fruits in a cluster

Figure 4 Fruit detachment force and torque measurements

The end effector was mounted on 6-DOF ARC Mate® robot manipulator. And a six-axis force/torque transducer (Mini 45 model, ATI Industrial Automation, Apex NC) was installed in the prototype end effector to measure the required force and torque to detach the fruit from its branch. A 6014 PCI DAQ board (NI Co. in Austin, TX) and Labview collected z-axis force and torque data in the form of an analog voltage signal. A Chebyshev analog low pass filter was adopted to eliminate periodic noise in transmitted signals. The initial fruit pulling angle was determined from results of the fruit separation force measurement test: 90-120 degree from the collinear axis of fruit stem. The air compressor discharged 500 kPa (±10%) of air to the linear actuator (400 N for stroke and 320 N for retraction of theoretical force).

Figure 5 shows the fruit picking operation sequences. All pneumatic valves and switches are activated by a start toggle switch of PLC unit (MicroLogix 1200, Rockwell Automation Inc. Milwaukee, WI). The central linear actuator strokes the central vacuum gripper to hold a target fruit and separate it from surrounding fruits. The isolated fruit is grasped by four vacuum gripping fingers and removed from its tree by ±360 degree of rotation and linear pulling back. Vacuum sensors keep monitoring real time vacuum pressure during the motion of pulling back which determines the success of picking. The cycle time goal was 4.5 seconds, which is 2.5 second longer than Flood's model (Flood, 2006), due to the time required to measure the force/torque during picking and to prevent damages on the plastic finger structures.

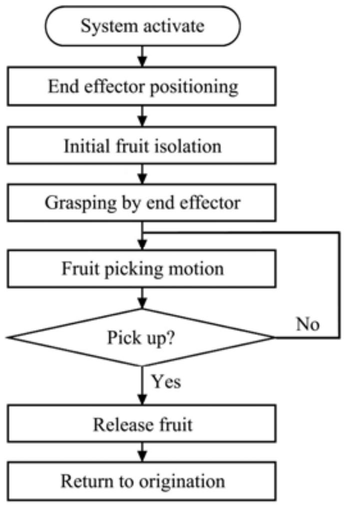


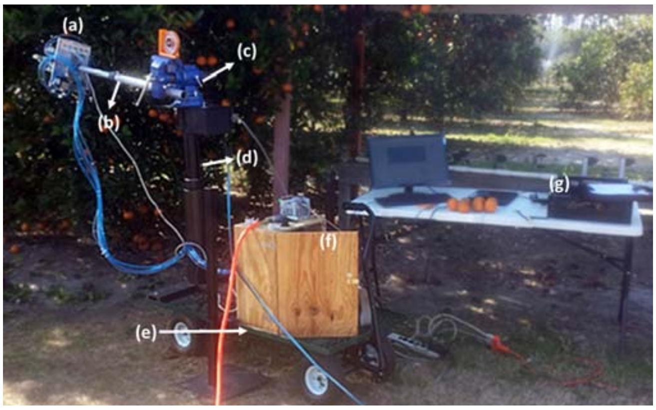
Figure 5 Fruit picking operation scheme

The ejector modules were controlled independently to prevent pressure drop and insufficient suction flow in the ejector module with increased distance from the primary port. The vacuum pressure was regulated independently by adjusting the primary air pressure.

The end effector was determined to pick up fruit at either 90 or 120 degrees based on the results of fruit detachment test with the first prototype end effector model (You, 2015) and measurements of the initial fruit separating force conducted in this study.

2.2.3 Fruit picking performance evaluation

A complimentary mobile manipulating system (Figure 6) was arranged to position the end effector near the fruit and to provide the end effector's rotation to pick fruit, in lieu of the ARC Mate® robot manipulator used in the laboratory test. The mobile manipulating system consisted of a double cylinder type pneumatic rotary actuator (DRQD-20-360, Festo Pneumatics Co. Japan), a custom designed linear expandable linkage, a multi directional swivel vise (Central Forge Co. Stafford England), an electrical telescopic lift and a flatbed garden cart (YTL International Inc. Cerritos CA). The fruit was picked using a ±360 degree of repeated rotation. The test system consisted of the end effector, the mobile manipulating system, a pneumatic control box, a desktop computer and a commercial 76 L and 1.4 MPa air compressor. A PLC unit controlled pneumatic valves, pressure regulators and vacuum ejector modules. Desktop computer was prepared to monitor the end effector's operation stage in ladder logics and to collect sensed pressure and vacuum data though PCI DAQ board and Labview solution.



(a) prototype end effector (b) 1 DOF expandable linkage (c) 2 DOF swivel vise (d) electrical telescopic lift (e) garden flatbed cart (f) system controller box (g) desktop computer

Figure 6 Fruit picking performance test set

To optimize the amount of air flow consumed by the ejector modules, four different vacuum control modes were adopted to during the fruit picking operation. In the first mode (Mode 1), the fruit was grasped by the central vacuum bellows and polychloroprene padded fingers, with the vacuum pressure activated during the rotation procedure. In the second mode (Mode 2), the vacuum pressure in the gripping fingers was deactivated, so that the fruit was held by the central vacuum bellows and frictional resistance of fingers. The third grasping mode (Mode 3) deactivated the central vacuum gripper while activating the finger vacuum grippers. The fourth grasping mode (Mode 4) was executed by only closing the padded fingers without vacuum gripping by either the central or finger vacuum pads. Each experimental case was conducted for ten fruits in each of the three-dimensional groups, A = 60~75 mm, B = 75~90 mm, and C > 90 mm.

3 Results and discussion

3.1 Dimensional properties and straight-line detachment forces

Idealized fruit grasping would occur for a spherical shaped object. However, a practical fruit model is a spheroid model, close to a sphere but not perfect. Since the gripping fingers attached to the fruit surface using planar contact, the radius of the fruit surface should be evaluated for firmness of grip. Table 1 shows the dimensional properties of fruits by longitudinal and lateral diameter and the parametric value of eccentricity. The Gaussian curvature was calculated to characterize the fruit surface which decided grasping performance of the suction bellow.

Table 1 Dimensional properties of sample fruit, *n*=240

	Long. Dia.	Lat. Dia.	Eccentricity	Min. K	Max. K [a]
Minimum (Min)	61.1	63.0	0.772	0.000356	0.000364
Maximum (Max)	99.5	106.0	0.565	0.001008	0.000168
Mean	84.7	89.9	0.321	0.000521	0.000623
Standard Deviation (STDV)	9.622	11.055	0.126	0.000154	0.001112

Note: [a] Gaussian curvature (mm).

Table 2 shows the maximum, minimum, mean, and standard deviation of a straight-line detachment force measured by pulling the fruit 35 mm back from its original position. The angle of pulling had a ±5° error range due to the difficulty of identifying the fruit stem's position among adjacent fruit. Fruit pulling within 90 degree required about 4±1 N detachment force to pick up the fruit illustrating the minimum straight-line detachment force among three intended angles. Higher detachment forces were usually inspected in higher pulling angles.

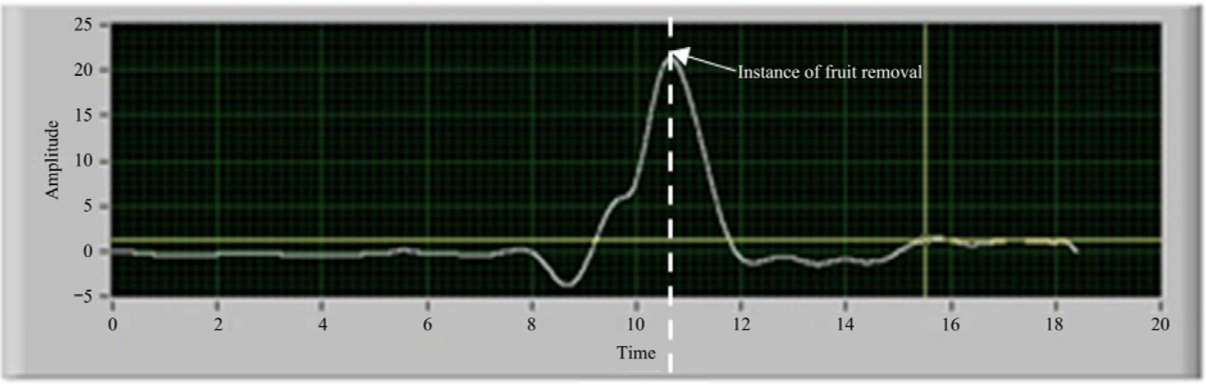
Table 2 Straight-line detachment force for given pulling angle, *n*=240

Force (N)	90 degrees	120 degrees	150 degrees
Min	2.3	10.7	14.1
Max	5.2	18	26.8
Mean	4	14.4	20.4
STDV	1.003	2.088	4.261

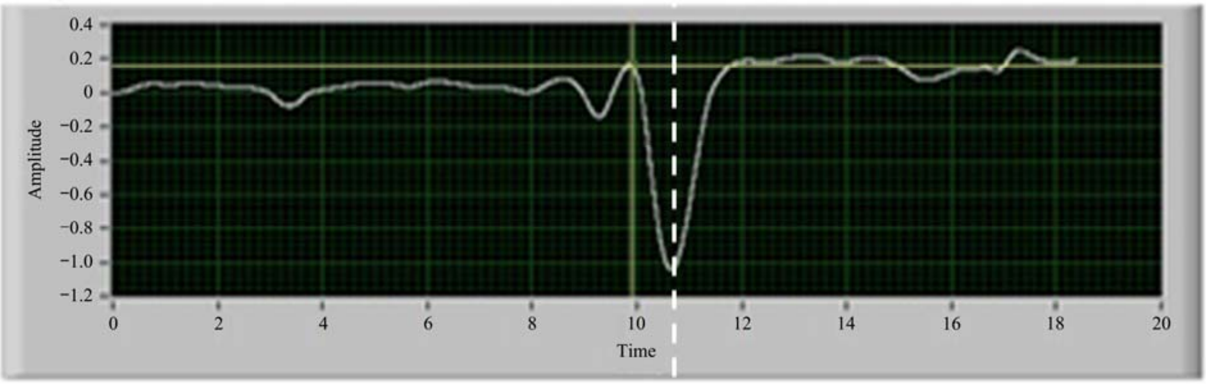
Note: * Three angles were between the axis of central cylinder and fruit dangling axis. ** Tests for each angle were repeated 20 times.

3.2 Measurement of fruit picking force and torque

The two graphs in Figure 7 illustrate processed signal of force and torque along z-axis for one cycle of fruit picking. At the instance of detachment of stem, the end effector's linear force and rotational torque reach to the maximum level at the same time. In this study, the peak force and torque value at the instance of fruit picking are defined as fruit detachment force and torque. Table 3 shows the statistics of fruit detachment force and torque for 20 trials with Washington Navels. The proportional gains of the force and torque sensor were set as -50.5 and 6.25, which were acquired by manual calibration using a Dillon Quantrol compact force gauge, on the 10th of February in 2015. The average value of fruit detachment force and torque was recorded at 16.70 N and 0.54 Nm.



(a) Detachment force



(b) Torque

Figure 7 Measurement of fruit detachment force and torque

Table 3 Statistics of fruit detachment force and torque

Model	Sample size	Mean	STDEV	Min	Max
Max Force (N)	20	16.70	6.5798	6.00	31.50
Max Torque (Nm)	20	0.54	0.2612	0.04	1.03

3.3 Fruit picking performance evaluation

The performance test showed that the end effector achieved 90.8% of fruit removal rate and 5% of in-stem removal rate with 90° of initial approaching angle and 67.5% fruit removal rate and a 3.33% in-stem removal rate with 120° of initial approaching angle for Washington Navels (*n*=240). No visible physical damage was found on the fruit surface except for peel plugging at the stem during separation. The fruit removal rate was reported with a mean diameter of samples and the percentage at which stems remained intact on the peduncle, shown together in Table 4.

The test with 90° of the approaching angle showed consistent fruit removal rate except for fruits in group C using mode 4. At both approaching angles, the end effector achieved 90% and higher removal rate with all vacuum control modes for fruits in group A in which 0% of stem remaining rate was recorded.

Table 4 Results of fruit picking performance test

90° approach angle													
	Mode #1 **			Mode #2 **			Mode #3 **			Mode #4 **			Total
Group *	A	B	C	A	B	C	A	B	C	A	B	C	
Removal rate [a]	100	100	80	100	100	90	100	80	90	100	90	60	90.8
Mean [b]	70.7	80.4	95.2	71.8	82.4	97.6	69.2	80.1	97.6	68.1	78.7	101	82.8
STDV [b]	3.58	7.21	3.48	2.82	5.54	4.66	2.7	5.48	4.92	3.04	4.88	2.83	8.42
Stem rate [c]	0	0	0	0	20	0	20	0	10	0	10	0	5
Length [d]	0	0	0	0	17.2	0	20.5	0	14	0	18.6	0	18
120° approach angle													
Removal rate	100	90	70	100	70	40	90	60	10	100	40	40	67.5
Mean	68.2	78.6	98.1	71.9	80.2	95.6	70.8	79.1	94.1	71.5	80.3	97.6	82.2
STDV	2.41	4.85	6.47	5.24	5.69	3.11	4.48	6.16	7.57	3.79	6.48	4.49	7.05
Stem rate	0	10	0	10	0	10	0	0	10	0	0	0	3.33
Length	0	10.5	0	12	0	15.1	0	0	10.7	0	0	0	12.1

Note: * Each group included 10 sample fruits; ** Each vacuum control mode described in Section 2.2.4; [a] Fruit removal rate (number of picked fruit/total trials) (%);[b] Mean diameter/Standard deviation for samples (mm); [c] Fruit removal rate with stem (number of picked fruit with stem/total trials) (%);[d] Length of belonged stem with picked fruit (mm).

4 Conclusions

The end effector's fruit detachment force range reported in this study, from 6 to 31.5 N, appeared similar to the results reported by Flood (2006), from 7 to 32 N. Differences can be attributed to seasonal or variety variability, or possibly from late winter frost damages at the fruit peduncle union.

The end effector picked up 90.8% of fruits successfully at the 90 degree of the approach angle. In particular, fruit picking using the second vacuum control mode achieved over 95% of fruit removal rate. The reported end effector demonstrated a significant improvement in harvesting efficiency over the first prototype model (You, 2015) achieving a higher fruit detachment success rate with lower fruit detachment force. Additionally, to further improve the reliably of grasping fruits of various sizes, the geometrical position of the vacuum pad should be more adjustable to the curvature of the contact area on the fruit surface. Also, it may be necessary to utilize vacuum ejector modules that can generate a higher vacuum pressure for the end effector to harvest fruits when the approach angle is larger than 120 degrees.

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