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Full Length Research Paper

Feasibility and influencing factors of laser cutting of tomato peduncles for robotic harvesting

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Due to the dissatisfactory effect of fruit detaching methods in robotic fruit harvesting, the laser may now be a new method to cut off the peduncle. In this paper, the feasibility of cutting tomato peduncles with 30 W, 980 nm fiber-coupled semiconductor laser was firstly verified by tests and calculations. The maximum power density of focusing spot and the depth of focus (DOF) were 4.95 W/mm^2 and 8.4 mm, respectively, so this laser was able to cut through a peduncle even under large position and angle errors between the focus lens and the peduncle in view of its lower burning temperature, smaller diameter, rougher surface and lower thermal conductivity. It was also found that the drilling through time was linearly correlated with the diameter of peduncle, negative correlated with the laser power and incident angle, binomial correlated with defocusing distance, respectively. The high-success-rate, high efficiency and energy-saving laser cutting can be achieved by adopting better quality or higher power laser and optimization of defocusing distance and incident angle in practical operation of robotic harvesting.

Key words: Feasibility, influencing factor, laser cutting, peduncle, harvesting robot.

INTRODUCTION

To perform tasks of fruit robotic harvesting, a fruit must be detached from the plant during robotic harvesting with appropriate methods, which is one of key technical difficulties to be overcome. Detaching of fruits is accomplished usually by wrist motion of the robot or by certain cutting device. Fruit detaching by wrist motion is much simpler which only need to grip the fruit and then to bend or twist it off relied on the friction force (Baeten et al., 2007; Bulanon et al., 1998, 2005, 2010; Hannan and Burks, 2004; Kondo et al., 1998a; Ling et al., 2004; Monta et al., 1998; Tanigaki et al., 2008). However, its success rate is limited related to posture of the fruit, joint structure of the peduncle. Meanwhile, how to avoid bruise of fruits by the fingers is still a large challenge, hence for more harvesting robots a variety of tools are adopted to cut peduncles.

Mechanical cutting devices are widely used in present harvesting robots (Allotta et al., 1990; Arima et al., 1996, 2003, 2004; Burks et al., 2005; Ceres et al., 1998; Cui et al., 2005; Guo et al., 2008; Hayashi et al., 1997, 2002, 2010; Kondo et al., 1996, 1998a, b, 2005; Lee et al., 2006; Shiigi et al., 2008; Takahashi et al., 2001). Any mechanical cutting device may consists of the cutter or scissor, the transmission and the driving system, so complexity, size, weight and energy consumption of the end-effector will increase obviously. Meanwhile, the complicated space distribution of fruits, branches and leaves in canopies of some fruits may limit the motion space of robot and lead to failure of the cutting operation. So mechanical cutting is suitable for plants whose xylems of peduncles are not developed and direction of peduncles is nearly uniform, such as cucumbers. In addition, it is inevitable for the transportation of viruses from one plant to the other and the fruit's water loss after the peduncle is reduced (Van Henten et al., 2002). Therefore, new thermal cutting techniques with electrodes, heating wires or laser were adopted in peduncle cutting of cucumbers and strawberries, respectively

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(Van Henten et al., 2002; Zhang et al., 2009). However, they need two electrodes or heating wires to touch the peduncle reliably and simultaneity to lead through the current, which is somewhat difficult in practice.

Compared with the above methods, laser cutting has several advantages. A large amount of energy is concentrated in a high-power laser beam which is focused by a lens on a small enough diameter, so the material is melted or vaporized quickly in the laser beam path (Heisel et al., 2001). Firstly, the tool-free laser cutting indicates that there is no physical contacts between tools and cutting materials (Choi and Li, 2006; Halim, 2008), so the transportation of viruses with cutting tool is avoided. Secondly, there is no interaction force between tool and the material (Bruzzone, 2002; Hernandez et al., 2007, 2010), which means the great gripping force that is loaded to fruit and manipulator is also avoided; it is very flexible and versatile to different fruits and vegetables without tool changes (Bruzzone, 2002; Choi and Li, 2006). Another important advantage is that this method is safer than the mechanical cutting since the high thermal effect only appears in focusing spot and the danger outside of the focus range is avoided, too (Heisel et al., 2001).

Although, the laser has been widely used in cutting operation of metal and non-metal materials in industry and the feasibility of laser cutting for either dry or wet wood has also been proven (Hernandez et al., 2007, 2010; Yusoff et al., 2008), it is usually applied to flat materials (Halim, 2008) and whether it is suitable to cut the cylindrical peduncles is still unknown. The purpose of this paper was to study the feasibility of laser cutting of peduncles and corresponding requirement to laser performance by tests and theoretical analysis. The effect of various factors on laser cutting efficiency is also of interest to the authors.

MATERIALS AND METHODS

One hundred “Jinpeng 5” tomato peduncles were collected randomly from a vegetable base in Zhenjiang City, Jiangsu Province, China and transported to the Laboratory of Modern Agricultural Equipment and Technology in Jiangsu University on 16 May 2010. All tests were carried out within 24 h at room temperature 20 to 30°C. The peduncles were labeled first and their diameters were measured with a micrometer caliper with sensitively of 0.01 mm.

Experimental apparatus

A peduncle laser cutting device was developed (Figure 1). Energy transformation efficiency of a 30 W, 980 nm fiber-coupled laser diode adopted in this device reached 49%, which is several times higher than the most commonly used CO_2 laser and Nd:YAG laser. The whole system, which is composed of the laser diode, thermoelectric cooler and protection and control circuit, is smaller enough and the fiber tip can reach anywhere in 3-D space which is ideal to perform tasks of robotic harvesting in limited canopy space. A focusing lens whose focal length is 50 mm was installed on the end-effector of the harvesting robot, which is connected with the fiber tip and driven by a mini DC motor system through a reliable bearing structure. To satisfy the need of harvesting fruits of different varieties, the tilt angle of focusing lens can be adjusted vertically between ±10°. This device was supplied with a lithium battery and controlled by a motion controller integrated in control system of the harvesting robot.

In these tests, the focusing lens was fixed on a testing bed by a fastening ring that could adjust the distance between the peduncle and the focusing lens (Figure 2). Two PMMA plates are mounted on a cradle whose vertical position can be adjusted through a screw bolt driven by a DC motor. Lateral position and vertical angle of the two plates can be also adjusted manually.

Measurement of focal length and diameter of focusing spot

To measure the actual position of the focusing spot, a 9 × 30 mm thin stainless plate was mounted on one mounting plate, which was then adjusted to be targeted by the laser beam. Subsequently, the distance between the stainless plate and the focusing lens was set as 30 mm, the laser was turned on in continuous mode, the optical output power was set as 15 W, and then the focusing lens was moved back and forth slowly until the laser spot on the thin stainless plate reduced to the minimum, which was observed and recorded by Sony HDR-XR100E digital video camera. The focusing spot was observed and its diameter was measured by image processing and the actual focal length was measured with the graduated rule.

Effect of different factors on drilling through time

Since any laser cutting operation begins with drilling, a series of laser drilling tests of tomato peduncles were performed. First, the thin stainless plate was removed and two ends of one peduncle selected randomly from tomato peduncles that have been labeled were mounted on the two mounting plates whose vertical position was adjusted slowly to be targeted by the laser beam by controlling the motor, then the following observations were made:

(1) To study the effect of peduncle diameter on drilling through time, end surface of the focusing lens was kept parallel to the mounting plate and the lateral distance from the focusing lens to the near surface of the peduncle was adjusted to the actual focal length that has just been measured, and then output optical power was set as 15 W. Eighteen peduncles were selected to be tested.
(2) To study the effect of output optical power on drilling through time, end surface of the focusing lens was kept parallel to the mounting plate and the lateral distance from the focusing lens to the near surface of the peduncle was adjusted to the actual focal length. Nine different output optical powers of 1, 2.75, 3.75, 5, 6.25, 10, 15, 25 and 30 W were tested. The test was performed three times at different positions along the longitudinal direction of peduncle for every output optical power.
(3) Defocusing distance refers to the distance from the actual focal spot to the near surface of peduncle, which is considered zero when it is set on the near surface, and above or below the surface is considered positive and negative, respectively (Han, 2004). To study on the effect of defocusing distance on drilling through time, end surface of the focusing lens was kept parallel to the mounting plate and output optical power was set as 15 W. Nine defocusing distances of -10, -7, -5, -3, 0, +2, +4, +6 and +8 mm were tested. The test was performed three times at different positions along the longitudinal direction of peduncle for every defocusing distance.
(4) To study the effect of the incident angle of laser beams on drill though time, the lateral distance from the focusing lens to the near surface of the peduncle was adjusted to the actual focal length and output optical power was set as 15 W. Nine incident angle of 0, 10,

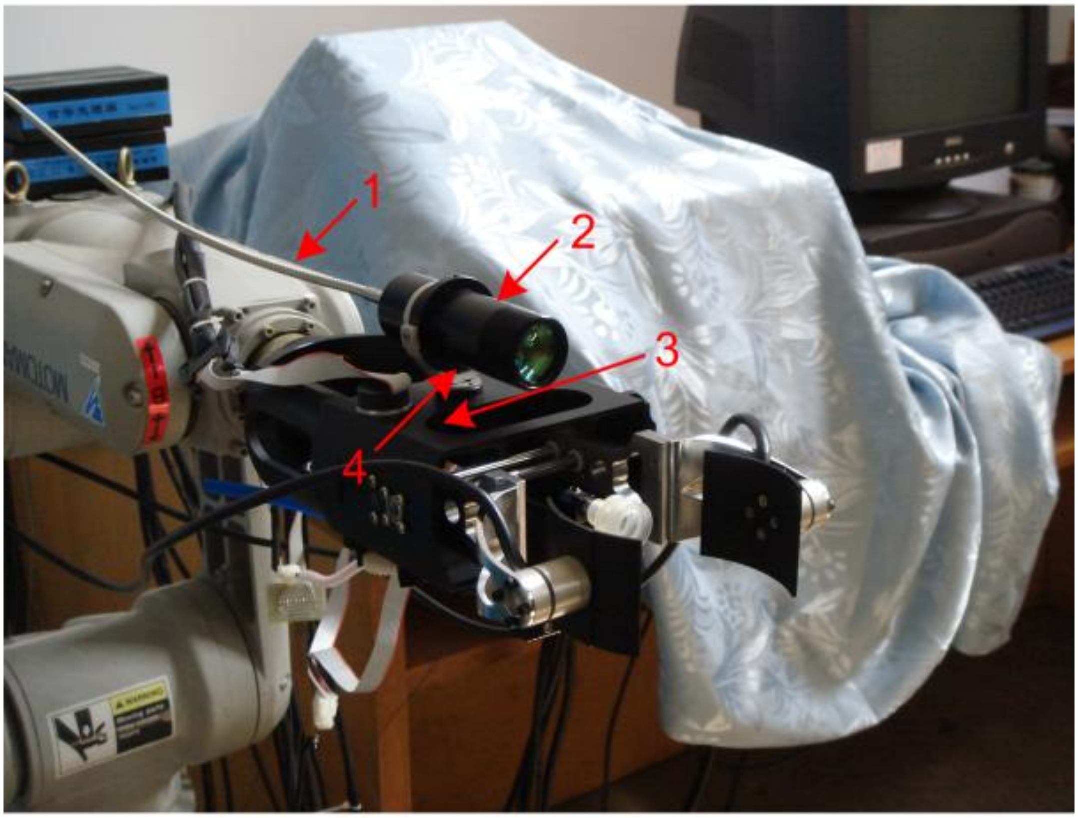

Figure 1. The peduncle laser cutting device mounted on the harvesting robot. 1: fiber; 2: focusing lens; 3. DC serve motor; 4: bearing structure

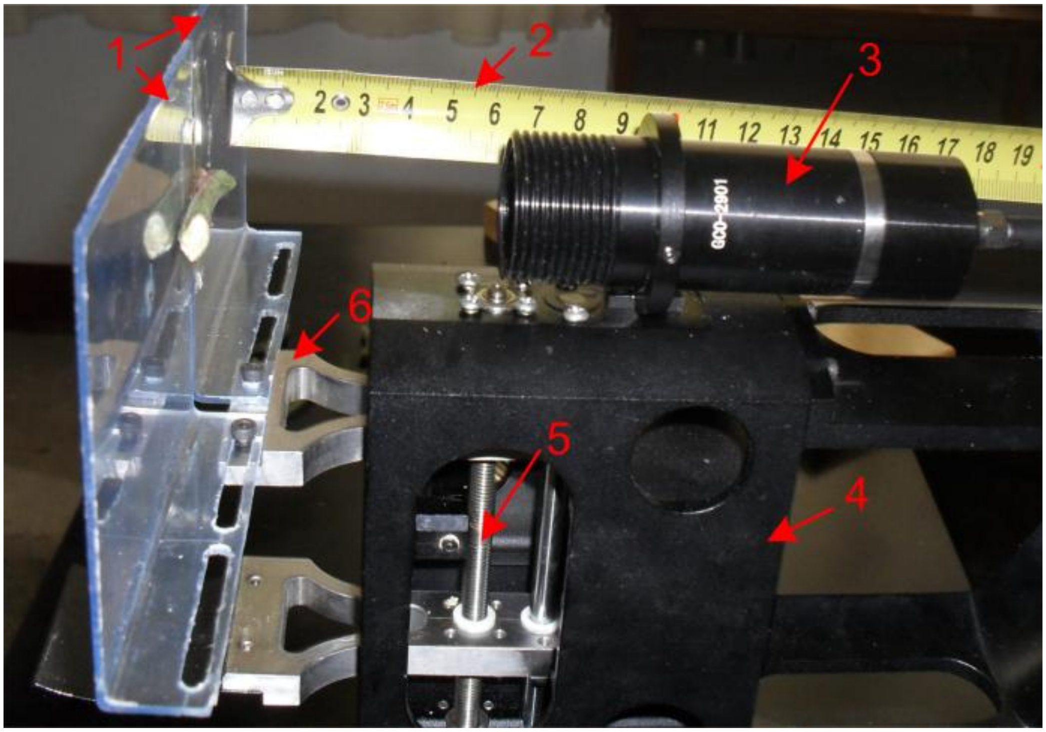

Figure 2. Test device of laser cutting of peduncles. 1: Mounting plates; 2: graduated rule; 3: focusing lens; 4: base body; 5: screw bolt; 6: cradle.

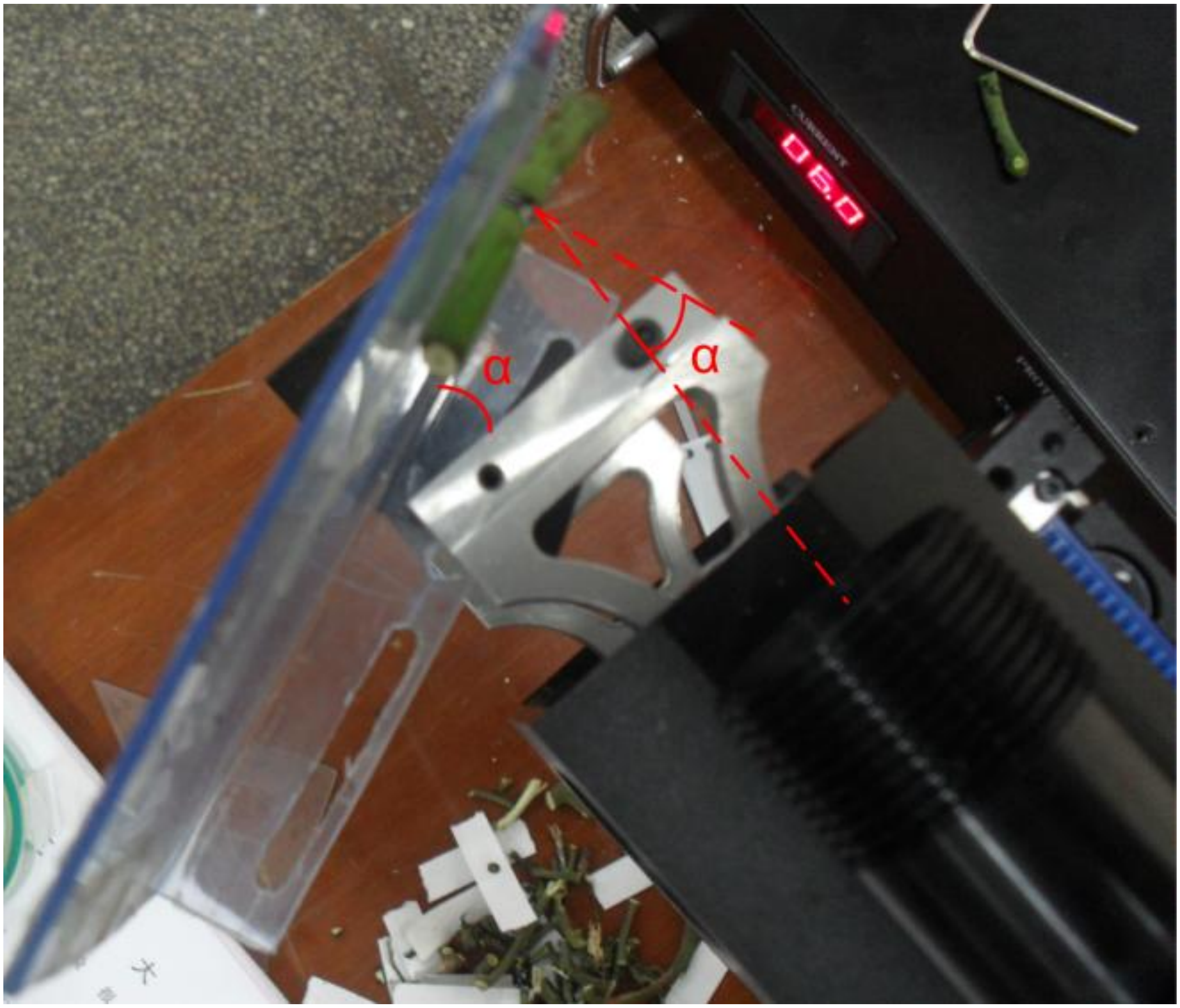

Figure 3. Test of laser cutting of peduncles for different accident angle.

20, 25, 35, 45, 50, 60 and 65° were tested (Figure 3). The test was performed three times at different positions along the longitudinal direction of peduncle for every incident angle.

The whole processes of the aforementioned tests were recorded by Sony HDR-XR100E digital video camera and the drilling through time was measured by video processing.

RESULTS AND DISCUSSION

Feasibility of laser cutting to tomato peduncles

Relation between operation performance and parameters of focal laser beam

In most industrial applications of laser cutting, cutting surface's quality is vital. However, in the laser cutting process of peduncles, only the feasibility and efficiency of peduncle laser cutting should be focused on. Both the feasibility and the efficiency are related to the parameters of focal laser beam which are decided by the quality of laser beam and the properties of focusing system (Figure 4). Diameter of focusing spot is essential in any laser processing which is as follows (Zuo, 2008):

$$d_f = 4K_f F \tag{1}$$

Where d_f is the diameter of focusing spot (mm), K_f is the beam parameter product (BPP) which is defined as the product of beam radius and the Beam Divergence half-angle and may quantify the quality of a laser beam and how well it can be focused to a small spot (mm•rad), F is f-number which is defined as the lens focal length divided by the beam diameter at the lens and may quantify the properties of a focusing system, d_f is expected to be smaller enough to get much higher power density. Relation between power density of the focusing spot and d_f is as follows:

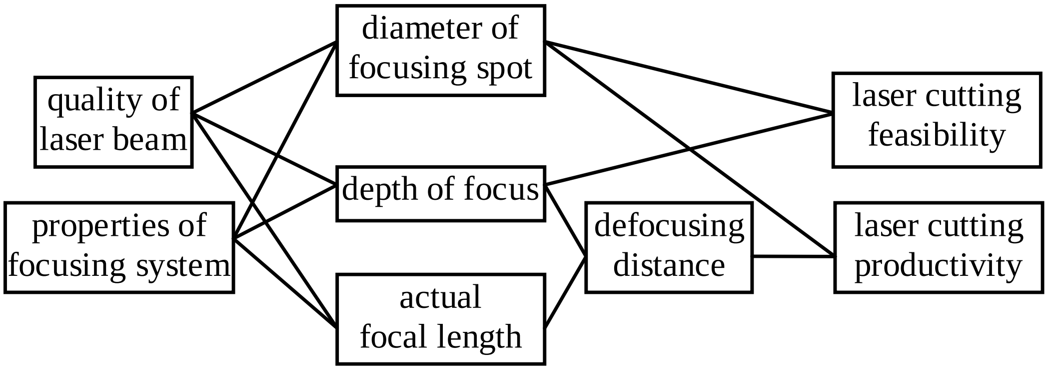

Figure 4. Relation between operation performance and parameters of focal laser beam.

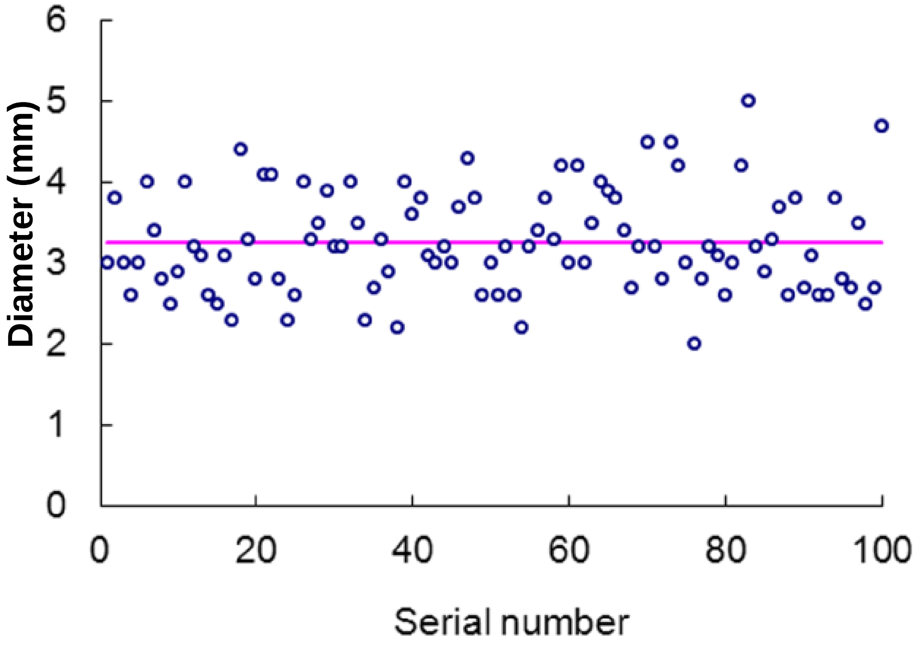

Figure 5. Diameter distribution of tomato peduncles.

$$\rho_0 = 4k_d k_t k_a P / \pi d_f^2 \qquad (2)$$

Where, ρ_0 is the power density of focusing spot (W/mm^2), P is the optical output power of laser (W), K is the communication efficiency ratio in air of the output optical power of a laser, K is the transmissivity of a focusing lens and K is the laser absorptivity on the irradiated surface. The other important parameter in laser processing is the depth of focus which is as follows (Zuo, 2008):

$$z_{Rf} = 8K_f F^2 \qquad (3)$$

Where, z_{Rf} is the depth of focus (DOF) that is the distance over which the focused beam can maintain satisfactory power density (mm). z_{Rf} is expected to be large enough to cut or drill through the materials of certain depth. While from Equations 1 and 2, size of d_f is positively related to z_{Rf}, the feasibility of peduncle laser cutting should be judged with the test results and calculation.

Diameter of tomato peduncles

Results show that diameter of tomato peduncles varied within the ranges of 1.99 to 5.05 with mean value of 3.26 mm (Figure 5). The standard deviation may reach 0.63, hence it is necessary for the focused laser beam to cut off most of peduncles in spite of the significant differences in diameter, which is entirely different

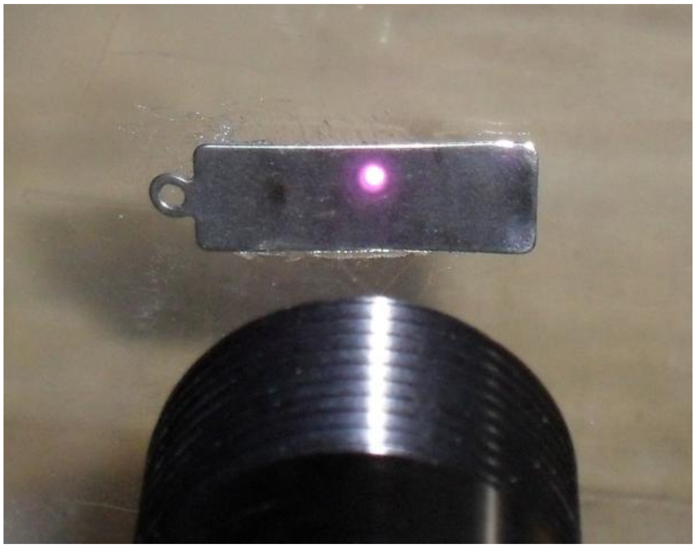

Figure 6. Near-infrared image of the focusing spot.

compared with standard material processing.

Focal length and diameter of focusing spot

A focal shift is inevitable in conventional lens systems and this may cause a corresponding change in the laser focal position, so the actual focal length is necessary to be measured. Measurement results indicated that it was 50 mm which meant the focal shift of lens system was small enough to be ignored. Although the diameter of focusing spot could not be observed with the naked eye since wavelength of this laser was in the near-infrared range, it could be observed through CCD of cameras. Measuring results by image processing indicated that the diameter of focusing spot was 2.10 mm (Figure 6).

Feasibility of laser cutting to tomato peduncles

In Equation 2, K was given a value of 0.98 since the laser beam entered into the focusing lens directly and communication loss of the laser power in this device mainly came from communication distance from the focusing lens onto the surface of a peduncle. K was given a value of 0.97 according to the instruction book of focusing lens and K was given a value of 0.60 according to the absorption spectrum of green plants (Kondo et al., 2004). So the maximum power density of focusing spot was calculated as 4.95 W/mm^2, which was lower to metal material processing and whose ability to drill or cut a tomato peduncle need to be studied with further test. Meanwhile, most tomato peduncles could not be cut off directly by just focusing the laser beam onto them compared with their diameter, so a rotation motion of the focusing lens was necessary.

Known *F* was 2 according to the instruction book of focusing lens, DOF could be calculated out as 8.40 mm substituting Equation 1 into 3, which ensured a successful drilling or cutting through operation theoretically compared with diameter of tomato peduncles.

Effect of different factors on drilling through time

Effect of peduncle diameter on drilling through time

During the laser cutting operation, tomato peduncles were drilled through at first. Drilling through time for different peduncles that were tested was between 6.8 and 15.2 s when the optical output power was 15 W. Since the power density of focusing spot was lower, the laser burned the peduncle to drill it, thus leading to carbonization in holes and a lower productivity.

To drill or cut flat materials, it has been widely proven that processing speed was negatively correlated with depth of materials, while processing speed increased more slowly to larger diameter due to decline of power density with increase of depth (Hermanns, 2000; Jin, 2008; Luo et al., 2005; Olfert, 2000; Shao et al., 2009; Xie et al., 2008b). However, test result indicated that the drilling through time of tomato peduncles was linearly correlated with the diameter, and fitting equation is as follows (Figure 7):

$$T = 2.92D \quad (4)$$

Where, T is the drilling through time(s) and D is the peduncle diameter (mm). Goodness of fit was 0.928, which may be attributed to the cylindrical surface of peduncle instead of flat surface (Figure 8). When laser beam is focused on the cylindrical surface, larger incident

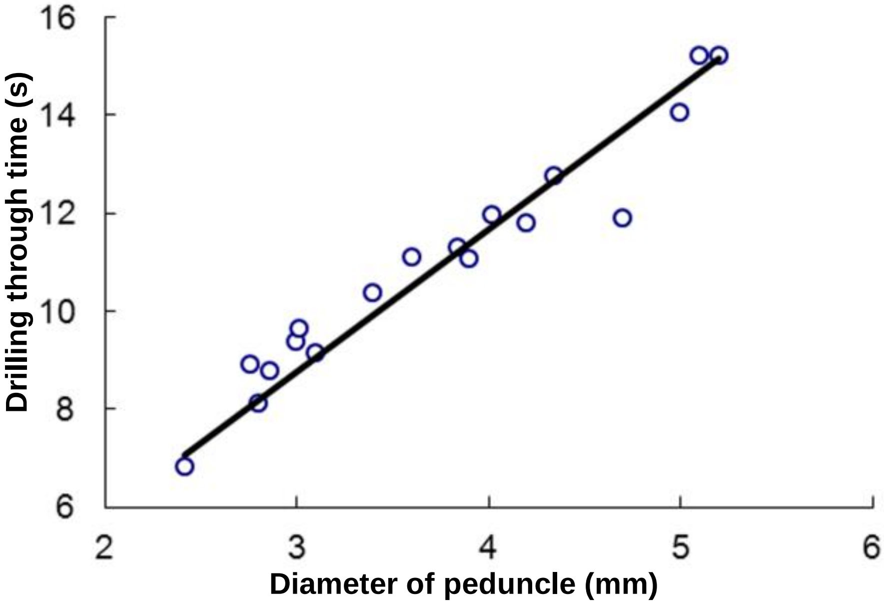

Figure 7. Drilling through time as a function of the peduncle diameter.

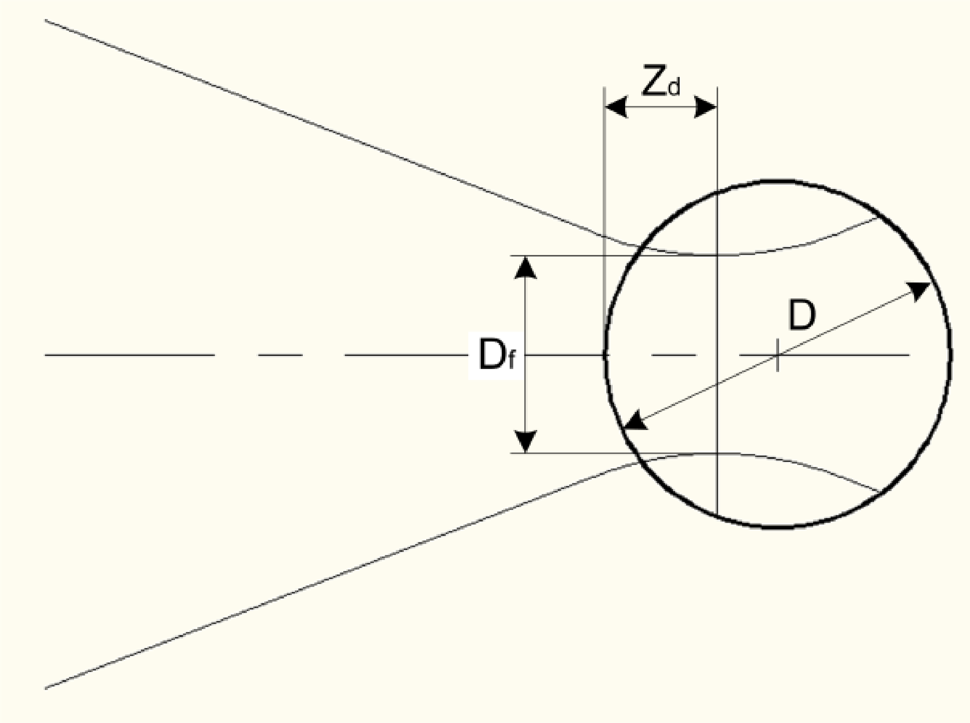

Figure 8. Schematic of the laser beam incidence to a peduncle in cross direction.

angle at the edge of the surface that is exposed to the laser beam reduces the average power density. To larger diameter, the incident angle at the edge may be smaller, which is helpful to make up for the nonlinear change of drilling through time with diameter.

Effect of output optical power on drilling through time

In the tests, in order to eliminate the effect of the peduncle diameter on the drilling through time, the test

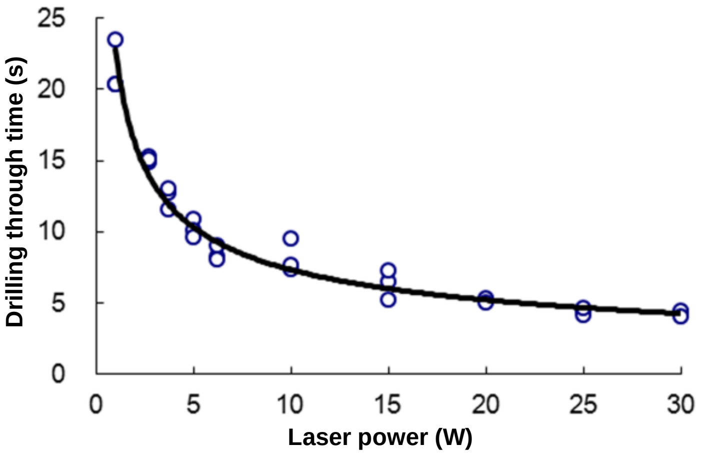

Figure 9. Drilling through time as a function of the laser power.

data of drilling through time were corrected for different diameter firstly. Corrected test data of relation between drilling through time and the laser power performs a good fit to Equation 5 (Figure 9):

$$T = 22.81P^{-0.49} \quad (5)$$

Goodness of fit is 0.967. When the laser power is larger, the effect of lessening drilling through time by increasing power is limited. Test results showed that the effect of the laser power on the drilling or cutting efficiency for different materials in different studies was inconsistent. Similar non-linear law was derived in laser drilling tests of 1Cr18Ni9Ti alloy, aerospace gas turbines, fiber reinforced plastics and laser cutting test of slates (Boutinguiza et al., 2002; Ishide et al., 1996; Liao et al., 1997; Naeem, 2008), while it was found in laser drilling test of stainless steel and laser cutting tests of die-boards, ST12 steel sheets that drilling through time or cutting speed was linearly correlated with the laser power (Hata et al., 2000; Liu and Xu, 2003; Walther et al., 2008; Xie et al., 2008b). In another test of laser cutting *Pseudotsuga sinensis* wood, a power function with power greater than 1 between cutting speed and laser power was derived (Peters, 1977). So the relation between drilling through time and laser power in the laser cutting of peduncles and its basic principles need to be further studied.

Effect of defocusing distance on drilling through time

Test result of drilling through time vs defocusing distance performs a good fit to Equation 6 (Figure 10):

$$T = 0.27Z_d^2 + 0.76 Z_d + 6.39 \quad (6)$$

Where, Z_d is defocusing distance (mm) and goodness of fit is 0.893. It was widely accepted that locating proper position of the focusing spot on workpiece surface and keeping it constant was essential in laser drilling and cutting either to improve operation efficiency, to extend processing depth or to improve processing profile and quality. Usually it was regarded as the best focal position near the under surface of an object since the power density was the highest on focusing spot and locating it near the under surface improved the laser energy distribution along material thickness (Hernandez et al., 2010; Lamikiz et al., 2005; Tong and Xu, 2009; Xie et al., 2008a, b; Zhang et al., 2008; Zhang and Fang, 2001). However, there were certain differences for different materials and needs, even contrary results might be gotten from some studies (Chen and Yang, 2009; Ge et al., 2008; Guan et al., 2005; Qu and Wang, 2001; Zhu, 2010)

In the process of peduncles laser cutting, it is necessary to set a proper negative defocusing distance to improve the cutting efficiency and extend the cutting depth in view of the cylindrical surface instead of flat surface, which makes use of the laser power more sufficiently than locating the focusing spot on the near point of the peduncle surface. In practical robotic harvesting, it is impossible to achieve ideal negative defocusing distance at any time attributed to the mechanical and visual error of harvesting robot; therefore, the laser cutting system should have better error tolerance to cut through peduncles. Test result indicated that peduncles were cut through even under a positive defocusing distance of 8 mm by this laser cutting device, which was more favorable.

Effect of incident angle of the laser beam on drilling through time

Test result indicated that the drilling through time increased with the incident angle, and when incident

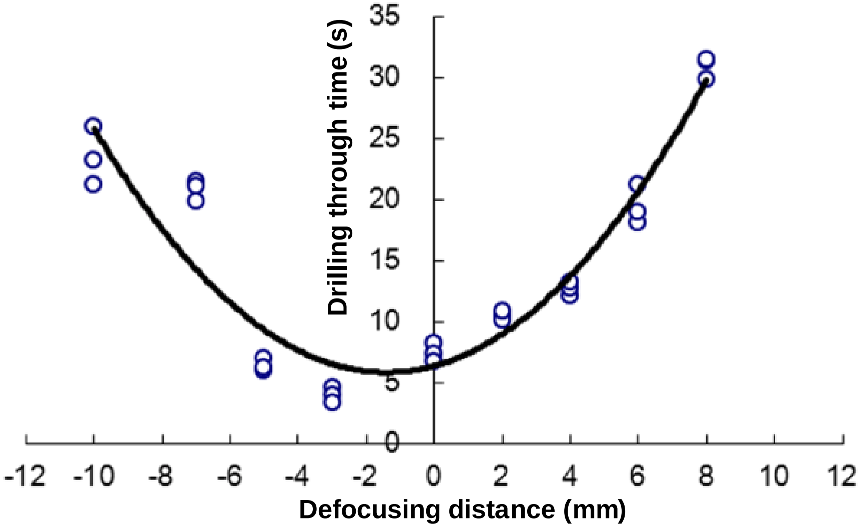

Figure 10. Drilling through time as a function of the defocusing distance.

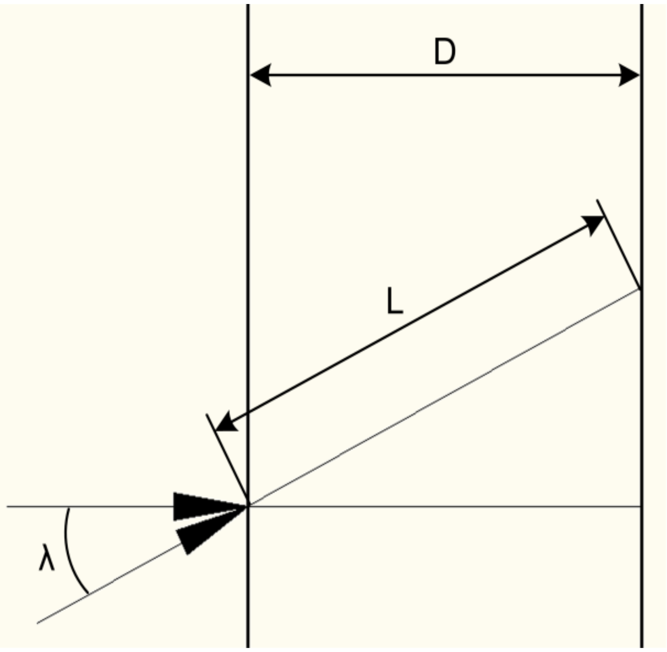

Figure 11. Schematic of the laser incidence to a peduncle in longitudinal direction.

angle was larger than a certain value, the drilling through time increased more rapidly. This phenomenon was easily understood for focusing spot becomes larger with increase of the incident angle and the average power density of focusing spot declines to prolong the drilling through time (Chen et al., 2007; Yang et al., 2009; Zuo, 2008). Meanwhile, actual length of drilling through path becomes longer to prolong drilling through time.

As shown in Figure 11, when the laser beam is focused on a surface at an angle, area of focusing spot is stretched from a circle to an ellipse, which decreases laser intensity by a multiplier of cosine of the incidence angle (Porter et al., 2007). The distance through the object is also dependant on the cosine of incident angle, only inversely (Porter et al., 2007). So the actual area of focusing spot for certain incident angle and the length of drilling through path in laser cutting of peduncles are as follows respectively:

$$A = A_0 / \cos\lambda \qquad (7)$$

$$L = D / \cos\lambda \qquad (8)$$

Where, A is the actual area of focusing spot for certain incident angle (mm^2); A_0 is the area of focusing spot when the incident angle is 0° (mm^2); L is the actual length of drilling through path (mm) and λ is the incident angle of laser beam (°). The corresponding average power density of focusing spot is as follows:

$$\rho = \rho_0 \cos\lambda \qquad (9)$$

Where, ρ is the average power density of focusing spot for certain incident angle (W/mm^2).

So simultaneous solution of Equations 5, 6, 8 and 9 is as follows:

$$T = T_0 \cos^{-1.49}\lambda \qquad (10)$$

Where, T_0 is the drilling through time when the incident angle is 0° (s). Test data of incident angle vs drilling through time performed a good fit to Equation 10 with a goodness 0.895 (Figure 12). This result indicates that the incident angle 0° is best to improve the operation efficiency in laser cutting of peduncles, and the operation efficiency will fall down rapidly when the incident angle is

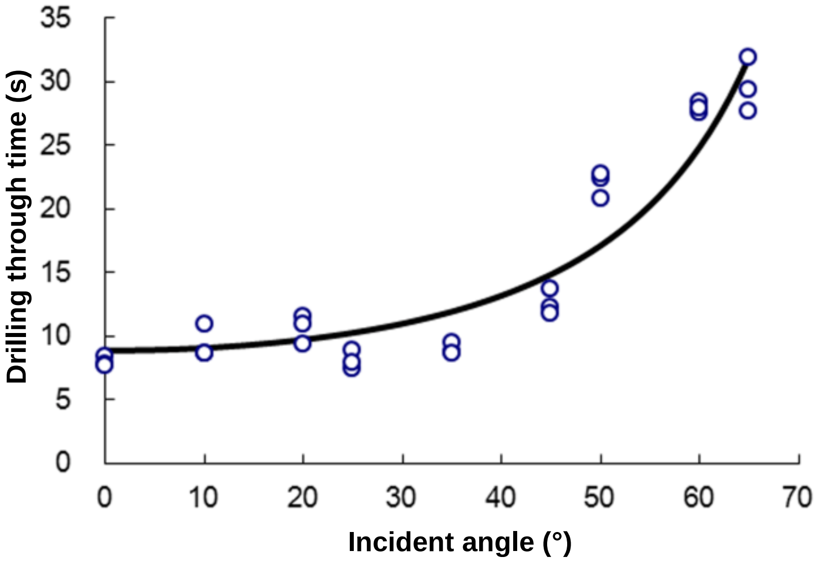

Figure 12. Drilling through time as a function of the laser incident angle.

above 35°. However, it is encouraged that there is not a threshold of incident angle, which means all peduncles can be able to be drilled through for any incident angle smaller than 70°, thanks to the lower burning temperature of tomato peduncles and enough depth of focus. To achieve laser cutting operation of peduncles in robotic harvesting, the ideal perpendicular posture and position is not always able to reach due to the limited space in tomato canopy, so it is very important to minimize incident angle by collision-freely optimizing posture and motion plan of the end-effector.

Conclusion

In this paper, tests and theoretical analysis to demonstrate the feasibility of laser cutting for tomato peduncles in robotic harvesting and study on effect of different factors on drilling through time with a newly developed peduncle laser cutting device were conducted. The following conclusions can be inferred:

(1) This laser cutting device can be applied in peduncle cutting based on two essential aspects. One is that the power density of focusing spot of this device is decided by both laser beam quality and properties of focusing system. To this laser cutting device, the diameter of focusing spot was measured to be 2.10 mm and the maximum power density of focusing spot reached 4.95 W/mm^2, which was found enough to burn and cut off one peduncle. Although the absorption of 980 nm wavelength laser by green peduncles is lower, the rough surface and lower thermal conductivity of peduncles are helpful to improve absorption and utilization of laser power. The other is that tomato peduncles can be drilled or cut through even under certain defocusing distance or incident angle due to the enough depth of focus of laser cutting device that reaches 8.4 mm and the lower burn temperature of tomato peduncles.

(2) All factors including peduncle diameter, laser power, defocusing distance and incident angle have a significant effects on the efficiency of peduncle laser cutting. Test data indicated a good linear correlation between drilling through time and diameter of peduncle, and the drilling through time was positively correlated with the incident angle and negative correlated with the laser power. In addition, the defocusing distance of 1.4 mm is best to minimize the drilling through time. To practical operation in robotic harvesting, the peduncle diameter is not unique, only the defocusing distance and incident angle can be optimized to improve the laser cutting efficiency. Test results indicated that the drilling through speed was slow because the power density was very low. To shorten the drilling through time, increasing the laser power may be an option, but it is preferred to increase the power density by selecting better quality laser such as fiber laser, to reduce the diameter of focusing spot. Meanwhile, the pulse mode (PW) instead of the continuous wave mode (CW) might be applied to get higher peak power or assist oxygen gas might be added to accelerate burn.

(3) It is usually impossible to cut off a peduncle directly just by focusing laser beam on it since diameter of focusing spot is smaller than that of most peduncles, so it is necessary to rotate the focusing lens driven by the motor. The rotation speed of motor should be decided based on further cutting speed test data and taken in consideration of cylindrical surface of peduncles. Although the laser cutting was proved to be feasible for peduncles, optimal control of its operation process

in future to achieve higher success ratio, higher efficiency and lower energy consumption..

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