BIOSYSTEMS ENGINEERING 171 (2018) 245–257

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Comparative study of mechanical damage caused by a two-finger tomato gripper with different robotic grasping patterns for harvesting robots

Baohua Zhang, Jun Zhou, Yimeng Meng, Na Zhang, Baoxing Gu, Zhenghong Yan, Sunusi Idris Idris*

College of Engineering, Nanjing Agricultural University, Nanjing 210031, Jiangsu, PR China

ARTICLE INFO

Article history:
Received 26 July 2017
Received in revised form
5 February 2018
Accepted 1 May 2018

Keywords:
Robotic gripper
Tomato grasping
Harvesting robot
Plastic deformation
Mechanical damage
Grasping pattern

The fragile structure of the tomato fruit body leads to susceptibility to bruising caused by the aggressiveness of harvest and postharvest processes. Thus, grasping without damaging the tomato fruits is a key barrier to the replacement of manual labour by robotic harvesting. In this study, a four-element Burger model was used to express reversible viscoelastic behaviour and deformation characteristics of tomatoes at early and middle red-ripening stages. Additionally, creep tests were conducted to obtain the viscoelastic parameters of the Burger model. The model for plastic deformation of tomato during grasping was finally developed based on input force, contact time, and viscoelastic parameters. In order to explore the least damaging grasping pattern, plastic deformation caused by three grasping patterns (denoted as Pattern I, Pattern II, and Pattern III) were investigated and compared in our study. A linear function, a Butterworth amplitude square function, and an exponential function were used to represent the velocity variations in the three grasping patterns during the robot grasping operation. This was used to solve the model of plastic deformation of tomato, and the changing rules of tomato plastic deformations under different grasping patterns were analysed under constant grasping time. The results indicate that grasping Pattern III is the optimal grasping strategy, the lowest plastic deformation of tomatoes is obtained with grasping time $t_0 = 1$s and grasping velocity $v_0 = 1$mm s^{-1} and the plastic deformations correspond to 0.0026 mm and 0.0098 mm for tomatoes at early and middle red-ripening stages, respectively. A grasping control experiment was also conducted under grasping Pattern III, and the correlation coefficient of 0.99 for the simulation and measured results indicated the rationality and feasibility of grasping Pattern III as the optimal grasping strategy. Our study provides a theoretical basis to optimise agricultural robot grasping.

* *Corresponding author*. Fax: +86 (025) 5860 6585.
E-mail address: zhoujun@njau.edu.cn (J. Zhou).

https://doi.org/10.1016/j.biosystemseng.2018.05.003

Nomenclature

Variables and functions

c_2	Symbol of the viscous element of the second layer (N s mm^{-1})
c_3	Symbol of the viscous element of the third layer (N s mm^{-1})
F_0	Initial contact force (N)
f	Complete contact force between the two-finger gripper and the tomato
$f_1(t)$	Force applied to elastic element k_1
$f_2(t)$	Force applied to the parallel viscoelastic units k_2 and c_2
$f_3(t)$	Force applied to viscous element c_3
g	Acceleration of gravity (9.8 N kg^{-1})
k_1	Symbol of the single elastic element of the first layer (N mm^{-1})
k_2	Symbol of the elastic element of the second layer (N mm^{-1})
k_h	Stiffness of the gripper (N mm^{-1})
R^2	Correlation coefficient
T_{ret}	Time of retardation (s)
$u(t)$	Grasping force input (N)
$v_1(t)$, $v_2(t)$, and $v_3(t)$	Grasping velocities of grasping Pattern I, Pattern II, and Pattern III (mm s^{-1})
$x(t)$	Complete deformation of the tomato
$x_1(t)$	Displacement of the elastic element k_1, and $x_2(t)$, $x_3(t)$
$x_2(t)$	Displacement of the parallel viscoelastic units k_2 and c_2, and $x_3(t)$
$x_3(t)$	Displacement of the viscous element c_3
x_h	Total displacement of the two-finger gripper during the grasping operation (mm)
X_p	Plastic deformation (mm)
μ	Coefficient of friction

Abbreviations

CPU	Central Processing Unit
FAOSTAT	Food and Agriculture Organization Statistical Databases
IP	Internet Protocol
RAM	Random Access Memory
SCHUNK	Brand name of gripper
TCP	Transmission Control Protocol
WSG	Specific model
WanfenII	Cultivar of tomato

1. Introduction

Tomato is a popularly cultivated fruit/vegetable that is highly favoured by consumers throughout the world due to its rich nutritional and health benefits. Data from Food and Agriculture Organization Statistical Databases (FAOSTAT) in 2014 indicates that more than 170 million ton of tomatoes were produced in the world (Li, Li, Yang, & Wang, 2013). Tomato fruits require gentle manipulation while harvesting due to their fragile appearance, heterogeneous structure and soft material. Tomato harvesting is conducted by skilled workers who easily handle the delicate product without damaging it (Dimeas, Sako, Moulianitis, & Aspragathos, 2015; Li, Li, & Liu, 2011). Workers cut the peduncle with clippers to retain stiffness of the tomatoes and extend the shelf life. A certain type of picking motion by using one hand, such as a combination of rotating and fracturing, is also observed. The mechanization and automation of tomato harvesting is examined to decrease the total amount of time spent in harvesting, number of farm workers, and high labour costs (Bac, Henten, Hemming, & Edan, 2014; Bulanon & Kataoka, 2010; De-An, Jidong, Wei, Ying, & Yu, 2011; Zhao, Gong, Huang, & Liu, 2016; Li et al., 2014).

Harvesting robots are designed to sense the complex agricultural environment by various sensors and use this information in conjunction with the goal of performing the harvesting actions (Carbone, Gherman, Ceccarelli, Pisla, & Itul, 2007; Edan and Miles, 1994; Zhao, Gong, Huang, & Liu, 2016). Extant studies on robotic harvesting commenced with orchard fruits in the 1980s (Hayashi et al., 2010). A recent review (Bac et al., 2014) suggests that a total of 50 harvesting robots were developed over the past three decades. The harvesting robots includes apple harvesting robots (De-An et al., 2011; Baeten, Donné, Boedrij, Beckers, & Claesen, 2008), orange harvesting robots (Lee & Rosa, 2006; Muscato, Prestifilippo, Abbate, & Rizzuto, 2005), and tomato harvesting robots (Kondo, Yamamoto, Yata, & Kurita, 2008; Ling et al., 2004). Most of the robots were tested under laboratory conditions. In the case of just a few of these harvesting robots, a comprehensive field test was conducted (Bac et al., 2014). The automation of the harvesting process typically requires a combination of three fields including fruit identification and localization, path planning of the manipulator, and fruit gripping, detachment, and deposition (Dimeas, Sako, Moulianitis, & Aspragathos, 2013). Harvesting robots were examined for several years. Nevertheless, harvesting robots are not mature to date. Most harvesting robots discussed in previous studies are not currently manufactured or sold (De-An et al., 2011). With respect to the fruit grasping, several challenges persist in the process of its practical use (Bac et al., 2014, 2017). The existing technical barriers include fruit recognition and location, robot guidance, and vision-based control problems. Further details are indicated in a previous review (Zhao et al., 2016) conducted by our team in Shanghai Jiao Tong University led by Professor Chengliang Liu. The challenges and future trends for robotic harvesting were reported in detail.

Grasping without damaging the fruits is a key barrier to the replacement of manual labour by robotic harvesting (Kitthawee, Pathaveerat, Srirungruang, & Slaughter, 2011; Ortiz, Blasco, Balasch, & Torregrosa, 2011; Blanes, Ortiz, Mellado, & Beltrán, 2015; Van Henten, Van't Slot, Hol, & Van Willigenburg, 2009). Fruit damage is highly relevant for economic feasibility because a grower cannot market a damaged fruit (Bac et al., 2017; Zhang et al. 2014, 2015a, 2015b). In the process of fruit grasping, product damage depends on both the aggressiveness of the harvesting machinery (end-effector) and fruit physical properties (sensitivity to bruising). Fruit sensitivity is related to its' physical properties and environmental conditions that determine the changing susceptibility