Computers and Electronics in Agriculture 127 (2016) 633–640

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Characterizing apple picking patterns for robotic harvesting

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ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form 18 July 2016
Accepted 19 July 2016
Available online 29 July 2016

Keywords:
Robotic apple harvest
Picking pattern
Grasping pressure
Picking-induced bruising

ABSTRACT

Fruit detachment is one of the essential tasks in apple harvest. The resistance of detaching an apple from the tree is largely influenced by picking patterns. This research aimed at gaining an understanding of fruit detachment process under different picking patterns, focused on characterizing those processes using a few key detaching parameters. It also aimed at identifying an effective robotic picking pattern using a three-finger gripper. To accomplish this goal, one manual and three robotic apple checking patterns were studied, by measuring and analyzing the minimal grasping pressure required to remove a fruit from the tree. The corresponding damage level on removed fruit was also analyzed. The results revealed that manual picking could create a bending moment which helped to reduce the required grasping pressure for fruit detachment, and resulted in no picking-induced fruit bruising on all collected samples. Results obtained from all three robotic picking patterns indicated that the use of a three-finger gripper required higher grasping pressure to detach apples, which resulted in higher percentages of picking-induced fruit bruising. It was found that one of the studied robotic patterns could offer a more manual-like performance than the other two robotic picking patterns. Further investigation assessing potentials and limitations of this identified robotic picking pattern on a more comprehensive scale to gain a deeper understanding of how this pattern works is recommended before it can be used as the base pattern for developing effective and efficient apple picking robots.

1. Introduction

Fruit detachment is one of the essential tasks in robotic harvesting of apple and other tree fruit crops. Detachment force necessary for removing fruit from a branch is influenced heavily by stem-branch characteristics and detachment patterns. Based on their studies, Alper and Foux (1976) found that axial tension was the dominant parameter in the fruit detachment process. It was also found that the tension component of detachment force is heavily affected by loading rate applied to fruit stems. In comparison, stem diameter had less influence on the force required to pull fruit from the tree (Gilman, 2003). Parameswarakumar and Gupta (1991) observed that the ratio of detachment force to fruit weight decreased with the increasing fruit maturity. Due to the elastic nature of fruit stem-branch systems, any change in bending angle will make the stem-branch system react with a bending moment on the stem-branch joint (Allotta et al., 1990).

Robotic fruit harvesting technologies have been studied extensively around the world over the past a few decades. Through those efforts, many novel ideas for end-effector design, control and motion planning of robotic devices have been reported (Baeten et al., 2007; Zhao et al., 2011; Li et al., 2013; Bac et al., 2014; Eizicovits and Berman, 2014). Robotic picking requires fruit detachment motions planned and performed with sufficient grasping forces applied to the target fruit (Tillett, 1993). Many picking end-effectors use either two or more fingers to grasp the fruit to detach it (Burks et al., 2005). Pulling or snapping the fruit may achieve highly efficient apple picking (Sarig, 1993), but requires a robotic end-effector to have sufficient grasping force to detach the fruit. To minimize grasp-induced bruising on harvested fruit, some robotic picking devices accomplish this process through grasping a fruit and cutting the stem to lower the require grasping force in picking (Ceccarelli et al., 2000).

Excessive grasping force will induce bruising damage on harvested fruit and results in an economic loss. Lewis et al. (2008) studied apple contact areas and stresses under static loading to determine the thresholds of grasping force under which fruit damage could be controlled within an acceptable level. They also found

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http://dx.doi.org/10.1016/j.compag.2016.07.024
0168-1699/

Nomenclature

b	brix of fruit sample (%)	L/D	ratio of fruit length to fruit diameter
f	firmness of fruit sample (kg·f)	T_d	detachment moment of stem-branch joint (N·m)
F_d	detachment force of stem-branch joint (N)	$T_s(\theta)$	elastic torque of stem-branch joint (N·m)
F_s	elastic force of stem-branch joint (N)	$T(\theta)$	bending moment of stem-branch joint (N·m)
F_t	tension force (N)	θ_b	bending angle of stem (°)
G	gravity of fruit sample (N)	θ_d	detachment angle of stem-branch joint (°)

that there are many factors, such as fruit temperature, ripeness and the radius of curvature that could affect the formation of bruises. Van Zeebroeck et al. (2007) found that a smaller radius of contact surface curvature could lead to more bruise damage because of increased peak stress. They also found that bruise damage during robotic picking was related to the impact level caused by static or dynamic grasping force, and the picking pattern and the stem-branch joint characteristics could affect such an impact (Van Zeebroeck et al., 2006). Javad and Najarian (2005) found that properly controlling the grasping force and end-effector motion could help to reduce the needed grasping force and therefore reduce bruising damage during robotic picking.

Therefore, it is desirable to gain a better understanding of required grasping force to support the development of robotic picking manipulations capable of minimizing harvest-induced fruit damage. Special attention should be paid to selecting suitable robotic picking patterns by taking both picking efficiency and picking-induced fruit damage into consideration. This reported study was to characterize the effect of commonly used picking motions and picking patterns on the harvest effort required for fruit detachment and resultant bruise damage during the picking process. The physical parameters of stem-branch joint including the detachment force, detachment angle and detachment moment were measured to obtain a prefer picking motion. Effect of a manual picking process with a finger pushing the stem (pattern 1) and three different robotic picking patterns using an instrumented glove (patterns 2, 3 and 4) on fruit detachment process was evaluated. The effect was evaluated in terms of grasping force and grasping pressure at contact points as well as corresponding levels of fruit bruising. This study aimed to provide the baseline information for determining an optimal robotic picking pattern from among the four patterns studied, which will help design a suitable robotic end-effector that would help keep the damage level in robotically picked apples at an acceptable level.

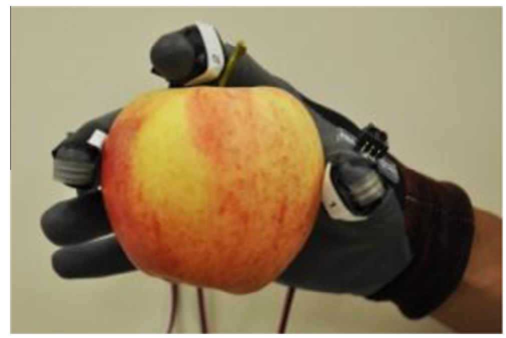

Fig. 1. Instrumentation glove used for evaluating picking motions (Sensor Model: GripTM, Tekscan, USA).

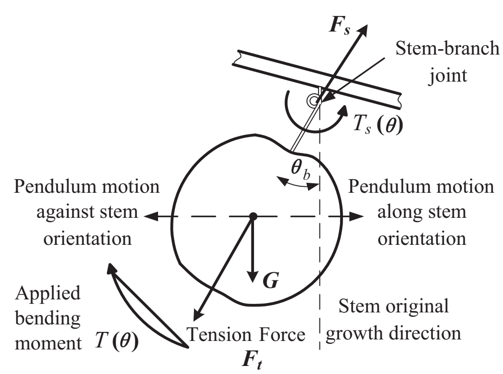

Fig. 2. Diagram of fruit-stem-branch system in equilibrium under various forces and moments.

2. Materials and methods

2.1. Apple picking motion

Apple picking motions (including bend-and-pull and pendulum motions) were investigated experimentally in this study using an instrumentation glove shown in Fig. 1.

Illustrated in Fig. 2, the fruit-stem-branch system is in equilibrium under the effect of gravity G, elastic force F_s, elastic torque of stem-branch joint $T_s(\theta)$, tension force F_t and the bending moment $T(\theta)$ exerted by the grasping fingers. The variable θ_b is the bending angle of stem during picking with respect to its natural growth direction. The stem-branch joint is assumed to be a torsional spring representing the lumped elasticity of the stem during detachment (Cooke and Rand, 1969).

One way of detaching fruit is to pick with only a pendulum action. In this process, the fruit stem was bent around stem-branch joint by exerting a bending moment without any tension on the stem. In picking experiments with bend-and-pull motion, apples were pulled along stem axial direction by exerting tension force while also bending the stem around stem-branch joint. The picking process involves a combination of pulling and pendulum actions. In this picking process, the detachment angle is the critical bending angle at which the fruit is detached from the branch.

Because the stretched branches and leaves often present obstacles to perform desired fruit picking actions accurately, it is very difficult to measure and record actual picking motion paths and fruit detachment angles accurately. To minimize the effect of such disturbances in measurement, tree branch specimens were cut from the orchard, and transported to a laboratory setup. Then, all leaves around the test fruit were removed before performing detachment experiments. The entire procedure was completed within four hours after the branch specimen was cut from the tree to avoid a big change in fruit-stem junction characteristics. To support the study of quantifying grasping force and detachment angle for different picking motions, a branch-grip test stand was designed and fabricated for holding a tree branch firmly at a required test position (Fig. 3). The test stand facilitated a consistent procedure for performing stem bending, fruit pulling and all other