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Preliminary Design of a Robotic System for Catching and Storing Fresh Market Apples

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Abstract: This paper presents the preliminary design of a two-link planar manipulator for fresh market apple catching. Rather than use the harvesting manipulator to place picked apples in a storage container, the secondary system catches and stores apples at the point of fruit separation in order to minimize path length and improve cycle time. Monte Carlo simulations were used to select link lengths and joint limits. The design includes two low cost stepper motors and a vacuum assisted end-effector. After fabrication, laboratory studies were conducted to measure the system's repeatability and validate the proof-of-concept. A conservative estimate of repeatability is 20 mm, which is within the catching end-effector's effective workspace. During integrated system testing in the lab, the secondary system caught all harvested fruit. Likewise, the pick-and-catch technique resulted in an approximately 50 percent reduction in overall cycle time compared to the conventional pick-and-place method. Future work will include development of an end-effector prototype with soft elements to minimize fruit bruising.

Keywords: Agriculture, Mechanization, Robotic manipulator, Robot kinematics, Monte Carlo simulation.

1. INTRODUCTION

Despite substantial advances in agricultural mechanization, fresh market tree fruit harvesting is still a labor-intensive operation dependent on a seasonal work force. To help reduce operational costs and address growing uncertainty about the future availability of agricultural workers, extensive research has been dedicated to mechanized tree fruit harvesting. The two harvesting methods considered are bulk harvesting with shake and catch systems (Peterson, et al., 1999; De Kleine & Karkee, 2015) and selective harvesting with robotics technology (Baeten, et al., 2008; Bulanon, et al., 2001; Tanigaki, et al., 2008; Zhao, et al., 2011). The shake and catch approach has generally resulted in damage levels that are unacceptable for fresh market fruit. Minimizing damage caused by fruit to fruit/branch (Zhou, et al., 2016) contact as well as damage resulting from fruit impact with the catching surface (Zhou, et al., 2016) are subjects of active research. Limitations of previous robotic platforms include insufficiently robust fruit detection and manipulation and high overall harvesting cycle times (Bac, et al., 2014).

One of our research goals is to advance the speed of robotic apple harvesting. We have recently developed and evaluated a preliminary robotic harvester (Silwal, et al., 2016) in a commercial apple orchard in Washington State (Fig. 1). The initial focus of testing conducted to date was fruit detection, fruit localization, and robust fruit detachment. A critical task of robotic apple harvesting is depositing the fruit in a storage container. The literature is not descriptive of the methods implemented for fruit storage, and it is not clear whether storage was an executed task included in the overall harvesting cycle times reported. A gravity fed hose attached to the end-effector has been considered for apple conveyance (Zhao, et al., 2011). However, observations from early field studies are that secondary mechanisms attached to the end-effector could snag on the tree canopy during fruit grasping. A hose may also be a constraint if motion or grasp planning is implemented for obstacle avoidance. Another method of storage could be to use the manipulator to place the fruit in a collection container. A disadvantage of this method is that it increases overall path length with negative consequences for harvesting cycle time. Simulations of robotic harvesting (Arikapudi et al., 2014) with two industrial manipulators show that transporting the fruit to the storage container consumes 40-65% of cycle time.

Fig.1. Field evaluation of a robotic apple harvester (Silwal, et al., 2016).

This paper is an extension of earlier field work and presents the preliminary design of a secondary robotic system for fruit conveyance and storage. The design incorporates efficiencies from both the shake and catch method and selective robotic harvesting. A robotic system with a grasping end-effector

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replicates human picking to selectively pick individual fruit in order to minimize damage. Rather than traverse to a storage container, the end-effector releases the fruit in the vicinity of apple separation where it is caught and then stored by a secondary planar manipulator. The robotic system can then pick the next fruit in the cycle along a path optimized to minimize cycle time. Sections 2 and 3 of this paper present the analysis, mechanical design, and system integration of the robotic catching system. Replicated picking studies with a laboratory set-up have also been conducted to validate the proof-of-concept. Future work to enhance the preliminary design is discussed in Sections 5 and 6.

2. ANALYSIS

The working environment for the robotic apple catcher is a well-maintained apple orchard employing the V-trellis system. In this modern orchard system (Fig. 2) branches are trained laterally along trellis wires and fruit distribution remains relatively close to the planar tree canopy. During fruit detachment, the robotic harvester uses an underactuated end-effector with three fingers (Davidson & Mo, 2015) to grasp the fruit and pull it a predetermined distance away from the canopy (Silwal, et al., 2016). The combination of the inclined trellis design and displacement of the apple away from the tree should ensure that a vertical path below the end-effector is obstacle free.

Fig. 2. V-trellis orchard system.

The manipulator shown in Fig. 1, which was mounted on the back of an electric utility vehicle (John Deere, Moline, IL), is a redundant, serial link design with seven degrees of freedom (DOF). The base joint is prismatic and the remaining six are revolute. The secondary catching system proposed in this paper is a two-link planar manipulator that will be placed below the harvesting manipulator. An important design step is to ensure that the catching system's workspace bounds all of the harvesting manipulator's possible fruit release positions. Monte Carlo simulations were used to select the planar manipulator's link lengths and joint limits. Lower and upper boundaries (Table 1) were selected for each harvesting manipulator joint according to the workspace region of interest. Note, the world x-axis is oriented from the manipulator base towards the tree canopy. Matlab's (Mathworks Inc., Natick, MA) random number function was used to generate a 100000 x 1 vector of uniformly distributed random numbers for each joint within its respective limits. For each row of joint coordinates, the manipulator's forward kinematics was used to determine the position of the end-effector. A filter was then applied to remove positions that resulted in the harvesting end-effector dropping a fruit above a mechanical component, like, for example, the prismatic base's transmission. The x-y coordinates of the remaining drop positions are shown as blue dots in Fig. 3. Similarly, random joint variables and forward kinematics were also used to plot the x-y coordinates of the planar arm's tip. Then, Matlab's convex hull function was used to determine the exterior and interior workspace boundaries of the scatter plot, which are depicted as red lines in Fig. 3. This process was repeated with various link lengths until the planar arm's workspace graphically bounded all possible fruit drop points. The workspace shown in Fig. 3 is for a planar arm with link lengths of 0.4 and 0.35 m.

Table 1. Harvesting manipulator joint boundaries constraining the Monte Carlo analysis used to determine all possible fruit release positions.

Joint #	Joint Type	Lower Boundary	Upper Boundary
1	Prismatic	-0.12 m	0.12 m
2	Revolute	-90°	90°
3	Revolute	90°	270°
4	Revolute	-90°	90°
5	Revolute	-225°	-45°
6	Revolute	-270°	-90°
7	Revolute	0°	180°

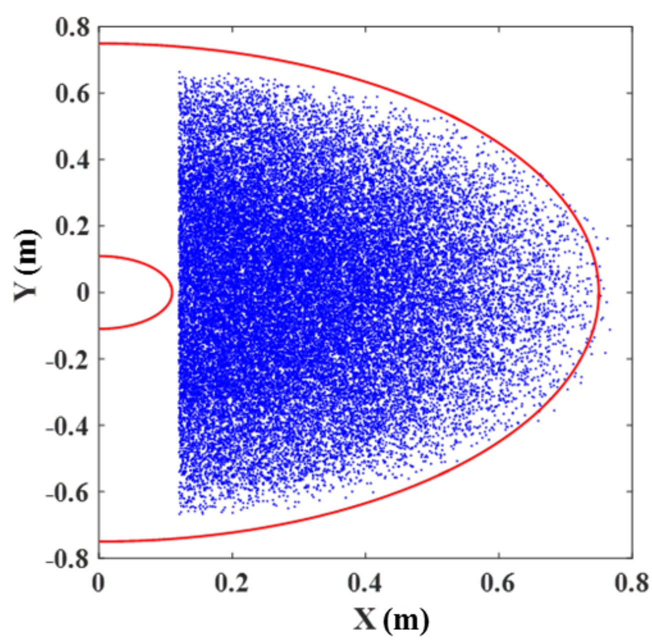

Fig. 3. Results of Monte Carlo analysis used to select the planar arm's link lengths. The blue dots show the x-y coordinates of the possible fruit release points. The red lines are the planar arm's interior and exterior workspace boundaries.