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Simulation to determination of significant parameters on apple stress for combing harvesting in trellis trained trees

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ABSTRACT

Standardized planting architecture is gradually replacing traditional hedge pattern. However, the development of harvesters adapted to the standardized planting architecture is relatively rare. This study proposed a combing harvesting method that was suitable for "vertical fruiting wall architecture" and developed the combing apple-picker prototype for experimentation. This research aimed to identify the significant parameters of apple stress in combing harvesting of vertical fruiting wall architecture through a simulation of an apple combing picker that inserts combing fingers into the "fruiting wall". According to the analysis of the hanging fruit structure of apples, the fruit detachment force, and a two-end fixed branch model, including contact force theory, seven parameters were selected as the factors in the simulation experiment. The rigid-flexible coupling model of combing apple-picker was established by using kinetic analysis and the finite element method. Compared with high-speed camera and simulation results, the simulation error was about 15.8 %, which proved the rigid-flexible coupling model can better simulate the detaching motion of an apple. The simulation results revealed that the significant parameters on apple stress were the rotation speed of the combing roller, the forward velocity of the picker, and the position of the combing finger on the apple ($p < 0.05$). The simulation method used here can be used for improvements in combing picker applications.

1. Introduction

Apples are the fourth most produced fruit in the world. Global production in 2018/19 is 68.7 million tons apples (USDA, 2019). Lifestyle and diet trends towards greater consumption of fruit and vegetables will most likely increase demand. Apple harvesting is high intensity labor (Chen et al., 2010), and labor cost is key variable affecting orchard profitability (Lordan et al., 2018, 2019). An effective apple harvesting system could reduce or eliminate the use of labor, reducing labor costs and enhancing future orchard viability (Bulanon et al., 2002).

In order to reduce the labor required harvesting, some scholars developed apple harvesters which apply impacting (BlancoRoldán et al., 2009; Upadhyaya et al., 1981), shaking (Peterson et al., 1999; Peterson and Monroe, 1977; Peterson and Wolford, 2003; Polat et al., 2007), and combing (Le Flufy, 1982a, 1982b) harvesting according to different planting architecture as early as the 1970s. Le Flufy proposed the "combing fingers" harvester for the hedgerow, which demonstrated harvesting efficiency of about 10 tone/h and fruit damage of about 23 %. Láng (1989) developed a Lincoln Canopy apple harvester which continuously shook the branches horizontally, with a removal percentage of more than 90 % for Red Delicious and other varieties. For use in narrow – inclined trellises, Peterson (2005) designed the over-the-row impact shaker which operated by the principle of shock vibration. Its fruit removal rate was about 90 %, and it yielded 53 %–72 % damage-free apples on five cultivars after years of trial optimization. However, between 20 % and 57 % of the removed fruit was stem-full, which is adverse to long-term storage (Peterson and Bennedsen, 2005). While apple harvesting technology and efficiency has improved over time, the evaluation of harvest efficiency and fruit quality are still far from viable for commercial application, and apple damage remains a key issue.

Traditional multi-dimensional architectures have developed into modern orchards with higher yields and more suitable for mechanized harvesting. Examples of such modern architectures include "vertical fruiting wall architecture" and "V-trellis" (Robinson, 2011). De Kleine and Karkee developed a double motor harvesting device suitable for "vertical fruiting wall architecture" and "V-trellis" (De Kleine, 2014; De Kleine and Karkee, 2015). The results indicated that the removal

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Experimental and simulation analysis of optimum picking patterns for robotic apple harvesting

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ABSTRACT

Robotic apple harvesting requires the motion planning of a series of movements to perform the efficient picking of fruit without bruises. The investigation of the underlying characteristics of fruit detachment picking patterns is an important basis for robotic harvesters. In this study, four basic picking patterns including horizontal pull, vertical tension, bending and twisting were performed in order to analyze the effects of picking patterns on fruit detachment. The tension parameter, which includes the horizontal pull and vertical tension, was found to be the dominant factor during the detachment process, with the vertical pull possibly leading to the pull-out of the stem. Apples with long stems were observed to require a large displacement and angle to break the branch-stem joint, which subsequently increased the risk of picking failure. Moreover, the detachment caused by the tangential force required a smaller detachment force. A dynamic simulation was performed to identify the optimal picking model, whereby detachment force and detachment time were used as the optimization parameters. The response surface methodology was used to determine the effects of the horizontal and vertical velocity on the detachment force and detachment time. Optimized results indicated the horizontal pull with a bending and twisting motion as the potential optimum combination. These results provide a theoretical basis for future studies on robotic apple harvesting.

1. Introduction

Global apple production exhibits a trend of continuous growth (USDA, 2017). Like many other fresh fruits, apple harvesting is both time- and labor-intensive, with workers requiring experience and skill (Davidson et al., 2016). However, the escalating demand and costs of labor have resulted in the requirement of robotic apple harvesters. Thus, robotic apple harvesters have been in the process of development for more than three decades, and several studies have been able to make enormous contributions to address the challenges of such systems (Baeten et al., 2008; Bulanon and Kataoka, 2010; Gu et al., 2012; Hohimer et al., 2019; Li et al., 2016a; Silwal et al., 2017; Zhao et al., 2011). Despite this, at present, no commercial robotic systems for apple picking exist on the market. This can be attributed to high manufacture costs, a low detachment efficiency, and environment complexities (Bac et al., 2014; Bloch et al., 2018).

Apple detachment depends on branch-stem characteristics and detachment patterns (Li et al., 2016b). The effectiveness of fruit detachment techniques is highly dependent on branch/fruit structures (Diener et al., 1965), and techniques are generally a combination of tension force, bending stress, and shear stress (So, 2003). Researchers have identified the fruit mass, fitness, equator diameter, and stem diameter parameters as having minimal influence on the detachment force (Gilman, 2003; Tong et al., 2014). Upadhyaya et al. analyzed the dynamic behavior of a limb-stem subsystem in impact harvesting using experimental and finite element methods and demonstrated that the stem pull was associated with the direction of the impact force and attachment angle of the stem to the spur (Upadhyaya and Cooke, 1981; Upadhyaya et al., 1981a, b). The response of the branch-stem joint to any changes in the bending angle of the twist-and-pull harvest method may result in fruit remaining attached to the plant (Allotta et al., 1990). Though the axial tension was considered to be the dominant parameter during the detachment process, the angle of the tension applied to the fruit stem significantly influenced the detachment force (Alper and Foux, 1976). Moreover, the required detachment force using bend-and-pull picking was much lower than that for a purely pulling motion (Torregrosa et al., 2014).

A commonly used strategy for early apple harvesters was the

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Investigating the dynamic behavior of an apple branch-stem-fruit model using experimental and simulation analysis

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ABSTRACT

In this study, we established an effective finite element model for branch-stem-fruit systems to: (i) simulate responses under different loads; and (ii) intuitively predict the breaking process of branch-stem joints. The constitutive parameters of fruit branches and apple stalks were measured based on the orthotropic transverse constitutive model. Moreover, the maximum traction force, maximum traction displacement and specific fracture energy of the abscission zone were estimated based on the cohesive zone model (CZM). The experimental and simulation results of the branch-stem sample tensile process and horizontal pull test demonstrated the more effortless ability of the tangential load to detach the fruit. Moreover, compared with the horizontal pull tests and simulation results, the maximum relative deviation was less than 10%, revealing that the branch-stem-fruit finite element model can accurately reflect the process of fruit detachment. This research provides a reliable finite element model of the branch-stem-fruit system for future studies on apple harvesting through tree shaking or robotic apple harvesters.

1. Introduction

Following the trend of previous years, global apple production reached high levels during 2018–2019. Currently, hand-picking remains the preferred method of fresh apple harvesting, except for several orchards that employ auxiliary platforms to reduce workers' workload (Elkins et al., 2011). The labor- and time-intensive apple industry faces severe labor shortages and high labor costs (He et al., 2017; Zhang et al., 2019). Therefore, improving apple harvest mechanization is crucial for the development of the industry, as well as increasing efficiency, reducing labor costs, and avoiding occupational diseases (Zhang et al., 2016).

Bulk and selective technologies are widely applied for mechanized apple harvesting (Peterson, 2005). Selective harvesting is achieved using a robotic harvester dependent on the fruit localization determined by sensors and the grasping of the robot arm. In contrast, bulk technology focuses on separating all the apples on the tree in a short period (e.g., by shaking the tree) and subsequently collecting them with a preset collection device (De Kleine and Karkee, 2015; He et al., 2017; Peterson et al., 1999). More specifically, the machine exerts a vibrational movement on the trunk or canopy of the fruit tree, detaching apples from branches due to their inertia force. Cooke and Rand (1969) presented a linear dynamics model that simplified the fruit-stem system into a linearized, three-degree-of freedom "double torsional spring" model to predict the natural frequency and vibration mode under free suspension. Verification tests were performed using apple, cherry, and grapefruit, yet the effect of the impact load on the fruit-stem system was not considered. Phillips et al. (1970) investigated the forced vibration response characteristics of fruit tree limbs. In particular, the secondary branch system of the primary limb was simplified to a finite element model mathematically deduce quality distribution, and internal and external damping in the length direction under several vibration modes. The study of Phillips et al., (1970) has particular significance in experimental designs and theoretical corrections or related systems. In a survey of the stem movement's influence, separation force and shaking frequency on fruit separation, Stafford and Diener (1973) used mathematical modeling to provide basic information for mechanical apple harvesting. Yung and Fridley (1975) performed a dynamic analysis on three primary limb models (secondary branch, leaf-twig and fruit-stem) using the finite element method. The consistency of the mathematical model and simulation results demonstrated the feasibility of investigating the dynamic response characteristics of complex fruit trees.

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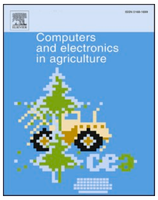

Simplified 4-DOF manipulator for rapid robotic apple harvesting

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ARTICLE INFO

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Apple harvesting
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Cycle time
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ABSTRACT

Fruit harvesting is time-consuming and laborious. Robots can harvest fruits with a high degree of automation, greatly reducing labor requirements, but are limited by their efficiency and high costs. In this research, a prototype apple harvesting robot was designed and constructed. The robotic prototype integrated a binocular camera, a 4-degree-of-freedom manipulator, a vacuum-based end-effector, and a mobile vehicle. The robot detected, positioned, gripped, detached, and placed apples. A manipulator controller was designed to realize rapid control execution. Picking experiments were conducted in a spindle apple orchard. Picking was tested using rotation-pull and pull patterns. The test results showed that the rotation-pull pattern was more effective picking apples than the pull pattern. The picking success rate of the rotation-pull pattern was 47.37% in the field orchard and 78% in the simulated orchard environment, with picking cycle time of ~ 4 s. The stem damage rate in the field orchard was 11.11%. The developed picking prototype realized the task of picking apples. Its primary advantage was its competitive picking cycle time, which provides a solid foundation for the future improvement of harvesting efficiency.

1. Introduction

Harvesting is one of the most labor-intensive parts of fruit production operations. However, with the continuous development of secondary and tertiary industries, the agricultural labor force has gradually shrunk, which has presented fruit production with an increasingly serious shortage of labor (Legun and Burch, 2021; Zhang et al., 2020c). Furthermore, the ongoing viral pandemic has restricted global travel and limited the mobility of agricultural labor force. This has further impacted the fruit industry which relies on a mobile seasonal labor force (Zhou et al., 2021). The time taken to manually pick apples accounts for 67% of the total annual fruit production time (Verbiest et al., 2020). To reduce labor requirements, harvesting robots can be used to conduct time-consuming harvesting tasks, which not only alleviates the contradiction between the rapid growth of fruit demand and the shortage of orchard labor, but can also effectively ensure the quality and safety of fruits (Jia et al., 2020; Yuan, 2020).

Fruit harvesting technology mainly includes semi-automatic harvesting technology, harvest-assist platforms, and robotic harvesting technology (Zhang et al., 2020c). Semi-automatic harvesting technologies mainly vibrate trunks (Peterson and Wolford, 2003), shake branches (De Kleine and Karkee, 2015; He et al., 2017), vibrate brush canopies (Hu et al., 2020; Liu et al., 2018), etc. to detach fruits, and then use catching devices to catch falling fruits (He et al., 2017; Zhang et al., 2020b). Semi-automatic harvesting technologies have high efficiencies, but have the tendency to bruise fruit in collisions between fruit and branches, other fruit, etc. (Zhang et al., 2020c). Harvest-assist platforms have recently been promoted in the market, but while they improve harvest efficiency, each auxiliary platform has a singular function and high price, and still requires 4 ~ 6 skilled fruit farmers to pick fruit (Bu et al., 2020b). The concept of a harvesting robot was first proposed by Schertz and Brown in the 1960 s (Schertz and Brown, 1968). Such robots are mainly composed of visual sensors, manipulators, end effectors, and mobile vehicles (Sarig, 1993).

Robot harvesting technology is an important means by which orchards can reduce their dependence on laborers and improve fruit quality. Bac et al. (2014) proposed picking cycle time as an important indicator of harvesting robot performance and investigated fruit harvesting robots reported from 1982 to 2012. Their results showed that the performance (i.e., picking cycle time) of the harvesting robots during

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