A Dual Motor Actuator Used To Detach Fruit By Shaking Limbs Of Fruit Trees

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ABSTRACT

Mechanizing the fruit removal operation during fresh-market apple harvesting will result in considerable cost savings for fruit growers. This study introduces a mechanical fruit removal technique that uses a unique limb shaking mechanism called a Dual Motor Actuator (DMA). The DMA was developed as an infinitely variable end-effector that applies rhythmic motions to a fruiting limb to remove fruit. The novelty of the DMA design is the use of two eccentrics mounted to electric motors that are pinned together to form a triangle with an adjustable base. In this paper, the development of the mechanism and a field study using two varieties of fruit ('Fuji' and 'Granny Smith') is reported. The fruit removed was classified based on three removal conditions (stem-intact, stempull, and spurpull) commonly used in the fresh-market apple industry. Stem-intact is the preferred classification whereas a limited percentage of spurpull will also be acceptable. Stem-intact fruit removal rates with the DMA were excellent for 'Fuji' (90 % avg) and moderate for 'Granny Smith' (50 % avg). The DMA end-effector provides an alternative mechanism to apply a controllable shaking pattern and rhythm. This precise limb acceleration method shows great potential for removing apples from a limb while maintaining fresh-market stem-intact quality fruit.

Keywords. Limb shaker, Mechanical Harvesting, Apples, Trellis, Actuation.

INTRODUCTION

Each decade, research in mechanized agriculture has investigated new devices and improved methods to increase efficiency in tree fruit production systems. Labor cost for fruit production systems is a variable that growers need to predict, and limit, in order to gain more capital. Harvesting activities for a crop of 'Gala' apples in Washington State can costs upwards of $1700 per acre (Gallardo et al., 2012). Considerable amounts of research in the United States during the late 1960's and into the 1970's focused mainly on two types of mass fruit removal systems: shaking and impacting. These studies extended into fruits such as: oranges, peaches, sweet cherries, tart cherries, olives, apples, mangos, and many other fruits. The overall goal, within each individual cropping system, was to efficiently remove the fruit while maintaining damage levels similar to hand harvesting. The harvesting work in most of these fruits still remains human driven; almost exclusively when marketing premium fresh-market grade fruit.

As described by (Srivastava et al., 2006, Tsatsarelis, 1987, Cooke and Rand, 1969) three modes of vibration, or oscillation, are critically defined and applicable to detaching fruit with vibration: twist, tilt, and pendular. Twisting describes rotational movement about the stem; a hanging apple spinning around its equator would experience the twisting mode. Tilting is defined as the apple rotating about the fruit stem calyx in a vertical rotation. This rotation can increase the likelihood of stempulls—fruit removed without a stem. When tilting is present, high tensile stresses can develop in the stem-calyx junction. "There is evidence that biological materials fatigue under repeated cycles of stress, each cycle of which is not individually capable of causing failure, but accumulatively will produce failure of the stem or stem-calyx junction" (Srivastava et al. 2006).

The third mode, the desired mode for fresh-market fruit removal, is pendular. Pendular mode can influence the apple stem motion about the stem-spur calyx. "The pendular mode is important to excite if the fruit is to be detached with the stem intact. It is much more difficult to excite this mode if the stems are relatively longer than the tilting mode" (Srivastava et al., 2006). There are difficulties to excite the pendular mode with long-stemmed apples using trunk applied spinning mass shaking systems due to the application of high frequency vibration. Mass shakers need to create enough energy transfer through the trunk to remove the fruit, which subsequently leads to an uncontrolled application of vibration mode. In most shaking applications, all three modes of vibration are present during mass shaking and will collectively result in fruit detachment. Cooke and Rand (1969) stated: "in some fruit removal processes, failure should be induced between the stem and the supporting member (such as apples and citrus fruits) for appearance and for the reduction of fruit contamination." Diener et al. (1965) investigated the most effective modes of fruit vibration as compared to optimizing the fruit removal condition using a slider crank mechanism. Their research focused on applied vibrations to a supporting structure, i.e. trellis, and they concluded that for fruit directly attached to the limb in oscillation, the calculated natural frequency had a fair detachment effectiveness. They also reported that a doubling in natural frequency resulted in tilting mode and a tripling of natural frequency resulted in twisting detachment. Their slider-crank mechanism was limited to a one inch stroke to prevent damage to the limb; a necessary consideration for the application of motion to a fruiting limb.

Shaking systems have been developed and are commercially available for many agricultural commodities. These systems excel when the fruit is destined for processing or has a hard shell, common in tree nuts such as walnuts and pecans. However, for fresh-market fruit, no shaking or impacting systems are widely used in the agricultural community today. Trunk shaking mechanisms have largely relied upon one, two, or three spinning masses to create multidirectional patterns (Srivastava et al., 2006). These orchard machines have booms that extend from the machine to clamp the trunk of the tree. A pre-determined pattern of certain frequency and amplitude is initiated using the spinning masses. Hydraulic power is mostly used for controlling these systems. Examples of commercially available trunk shakers are: Orchard-Rite-Monoboom (Yakima, Washington), Orchard Machinery Corporation-Shockwave Tree Shaker (Yuba City, California), COE Orchard Equipment-M7 Mono Boom Shaker (Live Oak, California). These systems are relatively obsolete and unseen in the fresh-market harvesting largely due to the damage caused to the product and furthermore there is relatively no control over the mode of vibration that is transferred to the fruit and stem junctions.

Apples typically grow around the lower portion of a branch. Although apples are not grown in a perfect pendulum orientation, this study focuses on apples hanging directly below a limb for consideration of the mechanisms ability to induce a specific excitation mode. Much work has been done to describe the equations of motion for a pendulum, as a classic example of mechanics. Likewise, the addition of a moving support has been published extensively including: horizontal, vertical, elliptical, and circular. The research conducted in this experiment considered three patterns of the pivot point: horizontal, circular, and half circle.

This research investigates a new mechanism that uses a rotating pivot point to empirically analyze the fruit removal outcome for some simple motions. This research focuses on the introduction of a new mechanism–dual motor actuator–to use low frequency rhythmic patterns and its effect on removing apple from a limb. A high frequency linear pattern is used as a supplemental comparison to the patterns of the dual motor actuator (DMA) using a hand-held actuation device. The comparison allows for a distinction between high frequency (3200 SPM) linear shaking and low frequency (150-300 RPM) patterns. This comparison includes fruit removal condition for the removed fruit. Specific objectives of this research were to:

1) Develop and evaluate a dual motor actuation mechanism to remove apples from a limb; and
2) Compare the dual motor actuator technique with a hand-held linear actuating end-effector.

Materials and Methods

Dual Motor Actuator Design and Prototype

A dual motor actuator was developed from concept by De Kleine and Ye at Washington State University in 2013. The novelty of this design is that it uses two eccentrics that are pinned together through two linkage arms to manipulate a trajectory applied to a point, as show in figure 1. The mechanism allows an infinite number of rhythmic patterns to be realized in a physically defined space related to the displacement, or radius, of an eccentric mounted to a shaft. The DMA can be used to apply patterns to limbs at low frequency, furthering the investigation of pendular mode excitation, not limited to linear actuation.

A rhythmic pattern was achieved through programming speed and direction of each electric motor. An advantage of using the electric motors compared to hydraulic motors was the increase in response speed. Using electrical components allowed rhythm to vary within a specific pattern for a defined duration. This system was designed to achieve more variability in shaking patterns than previous shaking systems that employ hydraulics and spinning masses.

The desired point (X, Y), or a shaking pattern, depended upon the angular position value sent to each motor. Pattern displacements were physically limited by the radial distance (r) from the linkage arm to the center of the eccentrics. Frequency was controlled by the speed of each motor.

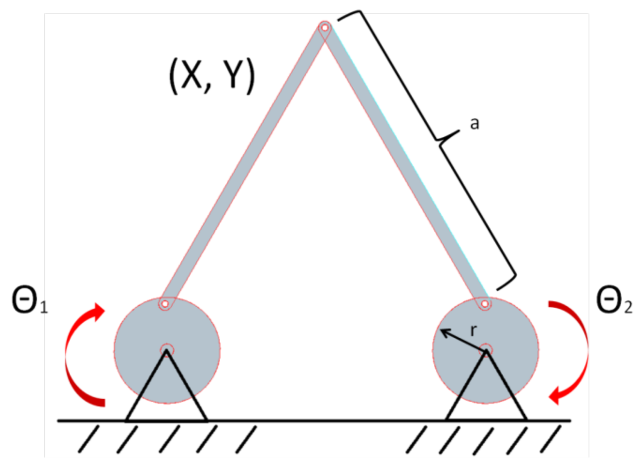

Figure 1. Free-body diagram for the dual motor actuator; θ_1 and θ_2 represent the angular motion, (a) is the length of the actuation arm, (X, Y) is the actuation arm end-point location.

DMA Prototype

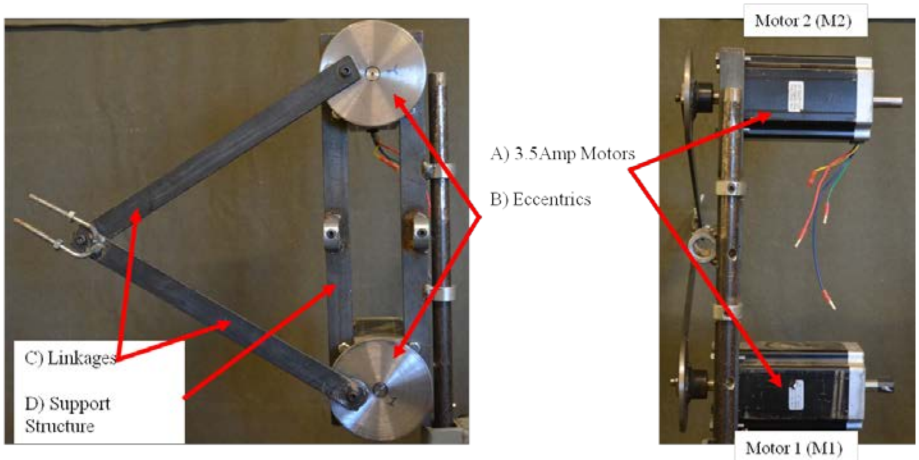

Figure 2. Dual Motor Actuator (DMA) prototype components.

The prototype DMA is shown in figure 2. The DMA prototype consists of two 1.8º, 3.5A, 1600 oz-in electric motors, two stepper drivers, and two 120VAC to 65VDC power supplies (www.longs-motors.com). A Powerbright 2300 W power inverter (www.powerbright.com) was used to invert 12 VDC to 120 VAC. An Arduino Mega (www.arduino.cc) was used to control the drivers and motors using a Pulse-Width Modulation (PWM) technique. Two steel eccentrics were mounted to the output shafts of the motors using a set screw. Each linkage bar was fabricated from 2.5 cm x 0.47 cm x 30 cm flat stock mild steel. A standard 0.63 cm x 5 cm U-bolt assembly was used to attach the DMA end point to a limb. A thing strip of rubber provided protection between the DMA and the limb.

Three levels of speed were used for each eccentric to generate each pattern with three different frequencies. A full-factorial experiment design using two parameters (direction of rotation and speed), each having three levels, was used to evaluate the removal classification. The testing order for each level was randomized using MiniTab 16 (www.minitab.com). Each experiment was replicated three times. Fruits on the branch were marked with an identification number. A selected branch was then clamped into the DMA (and the test was run. The fruit removal classifications (FRC) were: stem-intact, spurpull, and stempull (figure 3). Stem-intact is preferred for the fresh-fruit market.

Figure 3. Fruit removal condition (L-R): Stem-intact, spurpull, stempull.

Field Experimentals

Field Evaluation of DMA

Figure 4. Dual motor actuator experiment setup at Washington State University's Sunrise Orchard (Wenatchee, Washington) 2013.

Three shaking patterns were chosen to be performed on commercial grade ‘Fuji’ and ‘Granny Smith’ apples. ‘Fuji’ apples were grown in a fruiting wall architecture with tree spacing of 3 m x 1.1 m at a commercial orchard in Quincy, Washington. ‘Granny Smith’ apples were grown under tenting at Washington State University’s Sunrise Orchard in Wenatchee, Washington, in a 3 m x 0.6 m fruiting wall architecture. The experimental units were individual limbs and each limb was selected based on the accessibility and minimum number of fruit (3). An excitation was applied to the middle portion of the branch, halfway between the end of the limb and the limb-trunk junction (figure 4). Time was recorded as to when the majority of the fruit was removed or 15 s. If fruit was not removed after 15 s, it was considered as fruit left on limb.

Comparison with Linear Actuation (LA) end-effector

A field experiment was conducted to compare the performance of the DMA to a linear actuator (LA). The LA consisted of an 18 V linear actuator (Milwaukee Sawzall, Milwaukee WI) with a hook attachment, shown in figure 5. This device was hand-held and positioned by a human onto on a limb. This end-effector engaged branches on the tree, anywhere within the tree. A press-button trigger initiated a 53 strokes second^{-1}, 3.2 cm stroke, actuation. The trigger was depressed fully through each test and no distinction for frequency was made. The LA end-effector was pulled taunt to the branch during testing.

Figure 5. Hand-held high frequency linear actuator (right) used for limb shaking 'Fuji' and 'Granny Smith' apples.

RESULTS

DMA Field Evaluation

Fruit removal results are shown in Table 1. The fruit removal classification percent was reported as the average of apples removed for all three replications. For 'Fuji' variety, the highest percentage of stem-intact FRC occurred with the combinations of pattern 1 with rhythm 1, and pattern 3 with rhythm 1. The average stem-intact FRC percent for 'Fuji' using pattern 1, 2, and 3, was 90, 88, and 94 %, respectively. The average stem-intact FRC percent for 'Fuji' using rhythm 1, 2, and 3, was 93, 86, and 93 %, respectively. The lowest stem-intact FRC percentage for 'Fuji' was 75 % and occurred when using pattern 1 with rhythm 2. This pattern-rhythm combination also had the highest percentage of spurpulls for 'Fuji' throughout the entire experiment. Five out-of-the nine pattern-rhythm combinations resulted in a stem-intact removal classification percentage greater than or equal to 90 % for 'Fuji' variety.

Table 1. Fruit removal condition with dual motor actuator, averaged across all tests.

		Variety							
		Fuji				Granny Smith			
Pattern	Rhythm	stem-intact (%)	stempull (%)	spurpull (%)	Total Apples	stem-intact (%)	stempull (%)	spurpull (%)	Total Apples
1	1	100	0	0	16	29	64	7	14
	2	75	0	25	16	50	43	7	14
	3	95	0	5	19	46	54	0	13
2	1	80	13	7	15	50	39	11	18
	2	95	0	5	21	28	67	6	18
	3	89	0	11	18	41	59	0	17
3	1	100	0	0	12	47	47	5	19
	2	87	4	9	23	67	33	0	15
	3	95	0	5	20	46	31	23	13

The highest stem-intact FRC for ‘Granny Smith’ was 67 % using pattern 3 and rhythm 2. This pattern-rhythm also resulted in the second lowest stempull percent and zero spurpulls. The average stem-intact FRC percent for ‘Granny Smith’ using pattern 1, 2, and 3, was 42, 40, and 53 %, respectively. The average stem-intact FRC percent for ‘Granny Smith’ using rhythm 1, 2, and 3, was 42, 48, and 44 %, respectively. Tests in ‘Granny Smith’ resulted in stempull having a greater than 50 % occurrence, in four out-of-the nine pattern-rhythm combinations. The highest percent of stempull was 67 % using pattern 2 and rhythm 2. In all but two pattern-rhythm combinations, spurpulls were less than 10 %.

Harvest efficiencies using the DMA are shown in Table 2. Overall, the harvest efficiency in ‘Fuji’ was better than ‘Granny Smith’. The most inefficient harvest for ‘Fuji’ was not the same pattern and rhythm as ‘Granny Smith’. Two pattern rhythm combinations resulted in all apples being removed from the limb for both varieties: pattern 1 with rhythm 3 and pattern 3 with rhythm 2. The pattern-rhythm combination that had a significantly worse harvest efficiency for ‘Fuji’ was pattern 3 and rhythm 1. For the three test replications, the harvest efficiencies were 75, 33, and 60 %. Using pattern 3 and rhythm 1, resulted in the most amount of X,Y movement during a pattern with the slowest speed. A possible canceling effect may have taken place when using pattern 3 and rhythm 1 combination in ‘Fuji’. ‘Fuji’ variety has a longer stem than ‘Granny Smith’ which could potentially lead to more movement in the stem and not the apple. The lower mass of the ‘Granny Smith’s’ may have also influenced the relative movement between the branch, stem, and apple.

The results indicated that variety has a potential role on removal condition. A general linear model was used to statistically analyze the interaction between the FRC and pattern-rhythm setting. The only significant factor was variety. However, because the varieties were completely different, especially in horticultural characteristics, these results need further investigation. The difference in mass between the two varieties was significant. Mass for ‘Fuji’s’ averaged 300 g and 215 g for ‘Granny Smith’.

Table 2. Harvest efficiencies using the dual motor actuator.

	Harvest Efficiency (%)	
Pattern:Rhythm	Fuji	Granny Smith
1:1	88	93
1:2	89	80
1:3	100	100
2:1	89	95
2:2	100	93
2:3	100	64
3:1	56	100
3:2	100	100
3:3	100	92

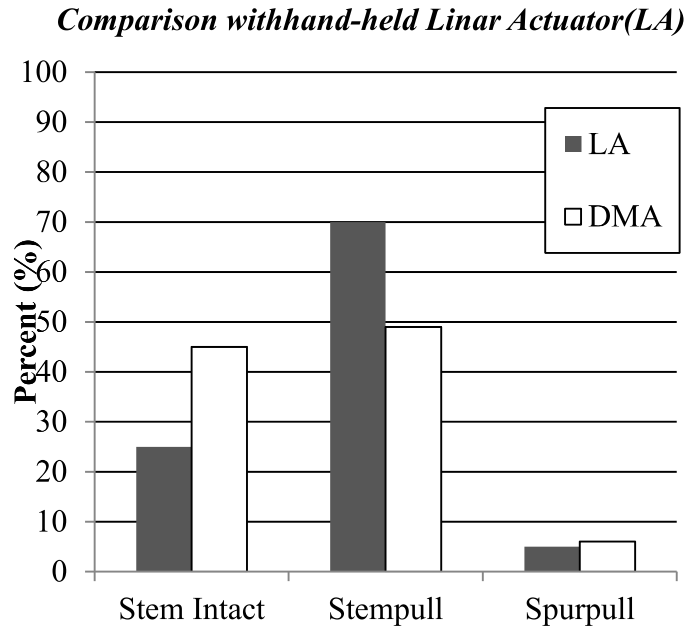

Figure 6. 'Granny Smith' fruit removal condition comparison: dual motor actuator and linear actuator.

The FRC results for 'Granny Smith' variety with LA and DMA are shown in figure 6. The 'Granny Smith' stem-intact FRC with DMA for all pattern-rhythm ranged from 28 to 67 %, and averaged 45 %. 'Granny Smith' stem-intact FRC removal rate averaged 2.3±1.4 apples per limb; the average number of fruit per limb was 5.2±1.5. 'Granny Smith' stem-intact FRC for LA was 25 % and for DMA was 45 %. Spurpull was similar for LA and DMA, approximately 5 %, for 'Granny Smith' variety.

DISCUSSIONS

A dual motor actuator (DMA) has the potential to generate and apply complex trajectory patterns to a limb, outside of standard trajectories that rotational mass shakers apply. Sharp, drastic, changes in motion can be realized using non whole-number ratios of wheel speed between the two rotating eccentrics. The patterns and rhythms achievable using the DMA provides a good tool, or mechanism, to further investigate and influence modes of vibration for apples hanging on a fruiting limb.

Results will likely vary from variety to variety and potentially be influenced by horticultural characteristics of the growing fruit. It is very difficult to predict the behavior of fruit that is touching one another or growing in clusters. Likewise, fruit growing on long limbs compared to short spurs makes this problem very difficult in solving analytically.

Growing conditions between the two varieties tested were not similar. 'Granny Smith' apples grew in a higher fruit density in tighter clusters than 'Fuji'. The reactions from apple to apple contact is virtually unpredictable but should be considered as a pattern and rhythm is applied. Very few apples were singularly growing however it was more common in 'Fuji' variety. The branching structures were different between the two varieties; 'Granny Smith' branches tended to be long and flexible while 'Fuji' branches were short and stiff. Neither orchard was formally trained with horizontal limbs—a horticulture practice that may help increase removal efficiency and predicted fruit removal condition. In some cases, fruit was not completely removed. It was observed that the remaining fruit was mostly located on a long flexible limb or close to the trunk.

Conclusion

A dual motor actuator (DMA) used in conjunction with a narrow fruiting wall orchard, can successfully remove apples from a limb. In field evaluation tests, five out-of nine pattern-rhythm combinations resulted in a stem-intact removal classification percentage greater than or equal to 90 % for ‘Fuji’ variety. The ‘Fuji’ stem-intact fruit removal condition (FRC) for all pattern-rhythm combinations ranged from 75 to 100 %. ‘Fuji’ stem-intact FRC for a high frequency linear actuated pattern was 80 %. The DMA had the highest overall stem-intact FRC compared to the linear actuator end-effector.

Harvest efficiencies for all pattern-rhythm combinations were much higher for ‘Fuji’ (90 % avg.) than ‘Granny Smith’ (50 % avg.). ‘Fuji’ variety had 100 % harvest efficiency (percent of apples removed to percent left on tree) for five out of the nine pattern-rhythm combinations. One pattern-rhythm setting (pattern 3 and rhythm 1) performed significantly worse than all of the others. It is possible that this combination did not have enough speed to remove the apples especially if the movement ‘canceled’ its own effect.

Further work including modeling and simulation is needed to completely expand the DMA into a fully optimized system. Investigation into a pulse, or shake-stop-shake method, could also improve and isolate movement to the pendular mode. A simple grasp and hold mechanism will further improve the end-effector engagement process to an individual limb. Because the dual motor actuator uses simple, off-the-shelf components, multiple end-effectors on the same positioning arm, or platform, could be economical for a fruit harvesting system.

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