A Systems Approach to Robotic Bulk Harvesting of Apples

D. L. Peterson, B. S. Bennedsen, W. C. Anger, S. D. Wolford

Abstract. *A unique robotic bulk harvester was conceived and developed to remove apples grown on narrow inclined trellises. The system combined mechanical harvesting technology with sensors and intelligent adaptive technology to identify an individual branch, determine fruit locations, position a Rapid Displacement Actuator (RDA) and a catching surface under the apples, and execute the RDA. Detachment was effected by rapidly displacing the limb away from the fruit. Requirements for a compatible tree training system were developed. Field testing demonstrated feasibility of the complete system. Fruit removal averaged 95% and detached fruit graded 99% U.S. Extra Fancy. Factors were identified to improve all aspects of the system and will require additional research.*

Keywords. *Mechanical harvest, Apple, Robot, Trellis, Quality.*

The supply of a skilled, harvest labor, work force is a concern of the apple industry in the United States (Warner, 1997). Attempts to mechanically harvest fresh market quality apples by mass removal techniques (shake/catch) from free-standing trees have not been successful (Brown et al., 1983; Peterson et al., 1994) due to excessive fruit damage. This damage occurs from: (a) excessive apple movement during detachment causing apple-to-apple, and apple-to-branch contact; (b) apple-to-branch contact when falling, and; (c) apple-to-apple contact on the catching surfaces since most of the apples fall in a short time period. Intelligent systems, in the form of robotic harvesters, have been developed to pick individual fruits (Grand d'Esnon et al., 1987; Harrell, 1987; Bourely et al., 1990; Kassay et al., 1994), but without commercial success due to the high costs and low capacity of these systems. These systems also have difficulty accessing all the apples on the tree.

Narrow inclined trellis systems for apples have been developed to space primary fruiting scaffolds equally along the trellis, and from the bottom to top of the wire support (Robinson et al., 1990; Robinson and Lakso, 1991). In addition to being very productive, these trellised systems have characteristics that may be compatible with mechanical harvesting such as providing sites for shaker attachment and an open non-overlapping branching pattern to minimize damage during apple fall. Upadhyaya et al. (1981a,b) found that impacting inclined apple limbs from below in a direction transverse to the limb nearly eliminated fruit movement during detachment, which should reduce detachment damage. Peterson and Miller (1996) used a hammer to manually impact limbs from below a "Y"-shaped canopy to harvest apples that graded 88% U.S. Extra Fancy. These results were promising, but they felt that applying the impact manually was not practical for a commercial operation. They also discovered that proper impact conditions could effectively remove apples from a section of a limb without causing excessive movement of the remaining apples located away from the impact point. They found that for effective fruit removal, limbs had to be displaced with a velocity ranging from 2.5 to 5 m/s and acceleration levels from 500 to 1270 m/s^2.

The idea behind our research was to develop a mechanical robotic bulk harvesting system for apples trained to a narrow inclined trellis. The system would combine mechanical harvesting technology with sensors and intelligent adaptive technology to identify an individual leader or branch as well as fruit locations, position a Rapid Displacement Actuator (RDA) and a catching surface, and proceed to detach and collect the apples. Harvesting sections of a limb minimizes the energy (and therefore the damage potential) required for fruit removal, and provides an opportunity to catch the fruit with little apple to apple interaction. By rapidly displacing the limb to effect detachment, excessive apple movement and damage should be avoided.

Objectives

The principal objective of this research was a proof of concept of a mechanical robotic bulk harvesting system for apples trained to narrow inclined trellises. Four sub-objectives were to: (1) develop training requirements for the narrow inclined trellis for compatibility with the harvesting technique; (2) design a Rapid Displacement Actuator (RDA), mechanical positioning system, and fruit catching system; (3) develop a control system to identify fruiting patterns, determine locations and automatically

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position and actuate RDA; and (4) test the system under field conditions to determine feasibility.

Trellis and Tree Design

Trees used in this study were 'Empire'/M9, planted in May 1994, and trained to a Y-trellis. The trellis had a vertical post 700 mm in height, and each 2-m arm was set at 52.5° from the horizontal. Two training systems were utilized. One system had trees spaced 0.6 m in the row with one main leader. The fruiting branches were not allowed to extend farther than 250 mm from the leader. Every other tree was inclined to opposite arms of the trellis, with the diameter of the main leader ranging from 12 to 30 mm. The second training system had trees spaced 1.2 m in the row with three leaders equally spaced (400 mm) on each side of the trellis arms. Fruiting branches were allowed to extend no farther than 200 mm from each leader. The diameter of the leaders range from 12 to 25 mm. In each system, fruiting branches directly above or below the leader were eliminated. Prior to 1998 the training on this orchard had been neglected. In May 1998 an extensive tree renovation was conducted to conform to the above training requirements.

Harvester Design

A three-wheel, all-wheel-drive power unit was used to support the robotic bulk harvester (fig. 1). The front wheel was steerable. The power unit used a 15 kW gasoline engine to drive a 57 L/min pressure-compensated, variable volume hydraulic pump. A digital video camera (Sony DCR-PC7, Sony Corp., Japan) was used to view the fruiting canopy. A black sheet was suspended above the limb to be harvested to block direct sunlight from the camera, and to deflect any apples that might be propelled above the canopy.

The RDA (fig. 2) was a hydraulic cylinder with a 28.6 mm bore and 47 mm stroke. Attached to the rod end was a 75-mm-diameter steel disk. Glued to this disk was a 25-mm-thick, 82-mm-diameter gum rubber disk that engaged the leader. A 3.8 L accumulator, pressurized to 8300 kPa, supplied fluid to the RDA to generate the required limb acceleration and displacement. The RDA was supported by a frame which was attached to the rod end of an extending cylinder. This cylinder, with a 308 mm stroke, was used to position the RDA against the leader. The extending cylinder was secured to a carriage (fig. 3). A mechanical conveyance system used rollers, tracks and a support structure to position the RDA along the row (x-axis) and parallel to the leader (y-axis, 52.5° to horizontal). Hydraulic motors and chain drives could position the RDA up to 0.89 m in the "x" direction and 1.49 m in the "y" direction.

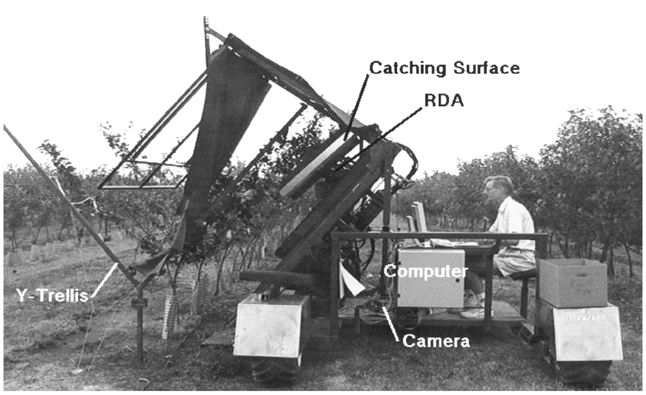

Figure 1–Overall view of robotic bulk harvester.

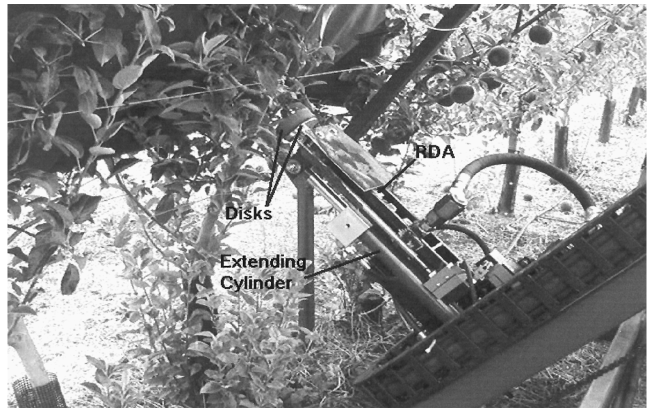

Figure 2–The RDA (rapid displacement actuator).

Figure 3–The RDA (rapid displacement actuator) translation system.

Design considerations called for a catching surface to be positioned around the RDA, to translate with the RDA, to be parallel to the trellis, and to catch and immobilize the fruit in the area of expected detachment. Our intent was not to capture all the apples but to determine the size and type of catching surface needed, and to provide a surface to catch fruit with no damage (so we could determine detachment damage). The solution implemented (fig. 4) was a 760 mm × 900 mm surface covered with pyramid-shaped blocks (1.8 kg density open-cell polyester foam, Wm. T. Burnett Co., Baltimore, Md.) glued to it. The base of each pyramid was 100 × 100 mm, and their height was 200 mm. The base was cut to an angle of 38° to allow an almost vertical orientation on the inclined surface. The tips of the foam rubber pyramids gave a very small area which the fruit could hit and rebound. The base of the pyramids were set at a 6 mm spacing, in an alternating pattern which created a matrix of pockets, to catch and wedge the apples.

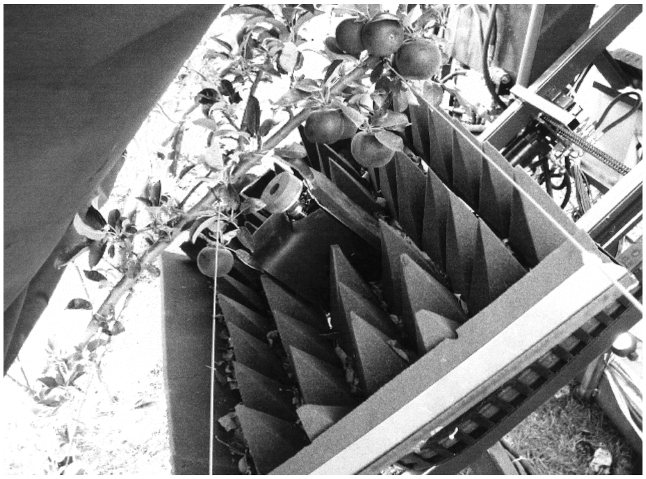

Figure 4–The catching surface for the robotic bulk harvester.

Control Systems

Three systems controlled the movement and function of the RDA. They were: (a) the imaging system for identifying the leader and finding the apples; (b) a decision system to determine where and how to employ the RDA; and (c) a motion control system which moved the RDA into position and applied the predetermined impulse to the leader.

Imaging System

As the machine was designed as a “proof of concept” and not a prototype, it was decided to construct the imaging system from existing parts rather than investing heavily in developing a completely new system. A Sony video camera (Sony DCR-PC7, Sony Corp., Japan) connected by a FireWire (IEEE 1394 Standard) to a HotConnect 8920 frame-grabber (Adaptec, Inc., Milpitas, Calif.) was used to capture images. The images were processed using the software package QuantIm (Zedec Technologies, Inc., Durham, N.C.). QuantIm software is well suited for development, because it offers an easy and convenient way of combining standard routines with user-written routines. Image processing routines were written using Microsoft Visual C++, version 4.0.

Lighting is a critical part of image processing, and is particularly difficult when the equipment operates outdoors. It was realized that a mixture of ambient and artificial light would be used in the field since it would not be possible to provide a cover to completely eliminate ambient light. Shielding would also be necessary during certain combinations of row orientation and time of day which would cause the camera to face the sun. The solution was to install black, 0.5-mm, fiber-reinforced neoprene drapery over the row. This blocked the sun, but created a need for artificial lighting. This was provided by two 55-W automobile fog lights which emitted a rectangular light pattern.

Since the system would be tested on red apples, our approach to analyze images was threshold segmentation in three colors. Different routines would have to be developed for green or yellow apples. By properly adjusting the threshold values, a reasonable segmentation could be achieved in most cases. The segmented image would show parts of the leader with side branches and fragments of leaves and other items irrelevant to the task. The routine located a prominent part of the leader and traced the rest of the leader up and down from that point.

Decision System

Several factors were considered when deciding where to employ the RDA. These include parameters which could be measured directly on each tree, such as number of apples, their position, and the structure of the leader and side branches. In addition to these parameters, *a priori* knowledge on items like variety of apples, ripeness, fruit retention force, etc., could help in determining the optimal position for applying an impulse. In a future development, these parameters will be combined with harvesting results in an attempt to construct an artificial intelligence system which can control the RDA. No such information was available at the time the software was developed. Consequently, two approaches to determining where to apply the impulse were employed: a geometric method for a fully automated operation; and a semi-automatic sequence controlled by an human operator.

The geometric approach relied on an algorithm that subdivided the branch into three segments. For each segment the number of apples and their position were determined. The algorithm then found the horizontal projection of the apples on the leader with the center of these projections initially being chosen to apply the RDA. This location was then checked against the position of the apples to determine if they were too close to the RDA. In that case, the algorithm would shift the RDA position up or down, searching for a new position.

The operator-controlled approach called for an operator to select the RDA action points by “clicking” on the image with the mouse cursor. The system would then read the selected position from the image and move the RDA to the corresponding location on the leader.

Positioning System

The task of the positioning system was to translate the pixel coordinates from the image to coordinates in space and then guide the RDA to that position. Two encoders were used to keep track of the RDA’s position, one for the X-position and one for the Y-position. The encoders were position sensors emitting a value between zero and 255 as their central shaft rotated with the hydraulic motors that moved the RDA. A simple linear function was found to sufficiently describe the relation between pixel values and encoder values. The image processing system performed the conversion from pixel to encoder values and stored them in a file.

A program written in Microsoft C/C^{++} 7.0 was used to control the positioning of the RDA. Outputs through the I/O board energized the solenoid-controlled hydraulic valves to position the RDA, and inputs from an I/O board were used to monitor the location of the RDA. The program controlled the following sequence: (a) read RDA position encoder values from the file; (b) move RDA to required × position; (c) move RDA to required Y position; (d) actuate the extending cylinder (motion was halted when a limit switch was activated as the gum rubber disk engaged the limb); (e) activate RDA (upon receiving signal from keyboard); (f) retract RDA (upon receiving signal from keyboard) and reposition RDA to initial position.

Test Procedures

Field tests were conducted in September 1998. At the beginning, midpoint, and end of the harvest period, detachment pull force was recorded on 30 randomly selected apples. At the midpoint of the harvest period four samples of 22 apples were also carefully hand harvested to serve as a control.

To conduct the harvest tests, the power unit was positioned along the row so the leader to be harvested was in the center of the camera image. An image was captured, and either processed automatically to determine RDA actuation position, or the position was manually selected from the computer image using the mouse. The coordinates were then fed to the positioning software and the harvesting cycle was initiated. After positioning the RDA, but before activation, the cycle was interrupted to determine if the RDA was in an acceptable position (gum rubber disk completely engaging leader). If the RDA was not in an acceptable position, the offset was recorded, the RDA was manually repositioned, and the harvest cycle continued. After fruit detachment, the apples were carefully removed from the catching surface and placed in tray packs for storage. All apples remaining in the canopy (± 35 mm from the RDA actuation point) and those detached but not captured by the catching surface were counted. If a second RDA actuation position was determined for the leader, the cycle was continued and procedures repeated as just outlined. If only one RDA actuation was necessary, the RDA was returned to the upper-rear position and the power unit was moved to the next leader.

Seventy leaders were harvested. On three leaders, acceleration data were collected at the RDA actuation point to characterize leader reaction. A digital video camera (Sony DCR-TRV900, Sony Corp., Japan) was used to record many of the fruit detachment events. The video was analyzed to characterize apple movement during detachment.

Hand-harvested and machine-harvested apples (captured by the catching surface) were held at ambient temperature for 7 to 10 days and then graded according to USDA fresh market standards. “Extra Fancy” grade permits one bruise 12.7 mm in diameter or several bruises with a total area not to exceed 127 mm^2; “Fancy” grade permits one bruise not to exceed 19 mm in diameter or several bruises with a total area not to exceed 285 mm^2. All other bruised apples were classified as “Bruised”. Apples with any skin breaks were classified as “Cuts and Punctures”. In the “Extra Fancy” category, apples with no bruising were also counted. During grading apples were also evaluated for stem pulls.

Test Results

Imaging System

The segmentation algorithm could be adjusted to locate apples in all test cases. Once set, the values were valid over a range of different lighting conditions. Finding the leader was more difficult. With proper adjustment, the routine would find most of the leader, but other parts of the structure and leaves would be included. Only six leaders were harvested without readjusting the threshold settings. The routine for tracing the leader performed adequately on well segmented images. However, prominent side branches and larger gaps in the central structure would frequently cause the tracking to fail. During harvest operations lighting varied considerably. A routine to adapt itself to shifting light conditions would be beneficial.

With the human operator-controlled “mouse selection” technique most of the image processing was eliminated. This approach performed particularly well, as it incorporated the knowledge and accumulated experience of the human operator.

Positioning System

A total of 108 positions were monitored for positioning precision. Each position comprised two coordinates, X and Y, yielding 216 positions in all (table 1). As the disk radius was 41 mm, any point within that distance from the desired position would still give a valid action. Offsets less than 10 mm were considered insignificant.

Table 1. Precision of positioning the RDA

	Offset from Center of RDA Disk					
	> 41 mm	40-20 mm	20-10 mm	Sum of Offset Values	< 10 mm (insignif-icant)	Total
Number of observa-tions (%)	1 0.5	5 2	16 7	22 10	194 90	216

Fruit Removal

The RDA was effective in detaching apples with removal averaging 95%. Leader acceleration (fig. 5) and velocity (fig. 6) values were well above those required for fruit removal. The RDA operated flawlessly with no maintenance required. Only clusters of two to three apples on thin hanger branches were not detached. Observations of video show that apples positioned below or to the side of fruiting branches were detached with little or no movement and fell downward (branches snapped away). Apples resting above and on branches were often propelled upward and often fell beyond the catching surface. The catching surface captured 63% of the detached fruit. Detachment pull force at the beginning, midpoint, and end of the harvest period averaged 2.49, 2.69, and 2.42 kg, with standard deviation of 0.99, 1.08, and 1.13, respectively, which is at the high range reported in the literature (Lang, 1989).

Fruit Quality

Apples harvested with the mechanical robotic bulk harvesting system and those carefully hand harvested showed no significant differences in fruit quality ($P = 0.05$, $df = 66$). Machine-harvested fruit graded 99.6% Extra Fancy (97.7% bruise-free Extra Fancy), 0.2% Fancy, and 0.2% Cut & Punctured. The carefully hand-harvested fruit graded 100% Extra Fancy. Apples with stem pulls were 17.9% for machine harvested and 9.1% for hand harvested (no significant difference, $P = 0.05$, $df = 66$). Although statistically not different, the trend is more stem pulls with machine harvest.

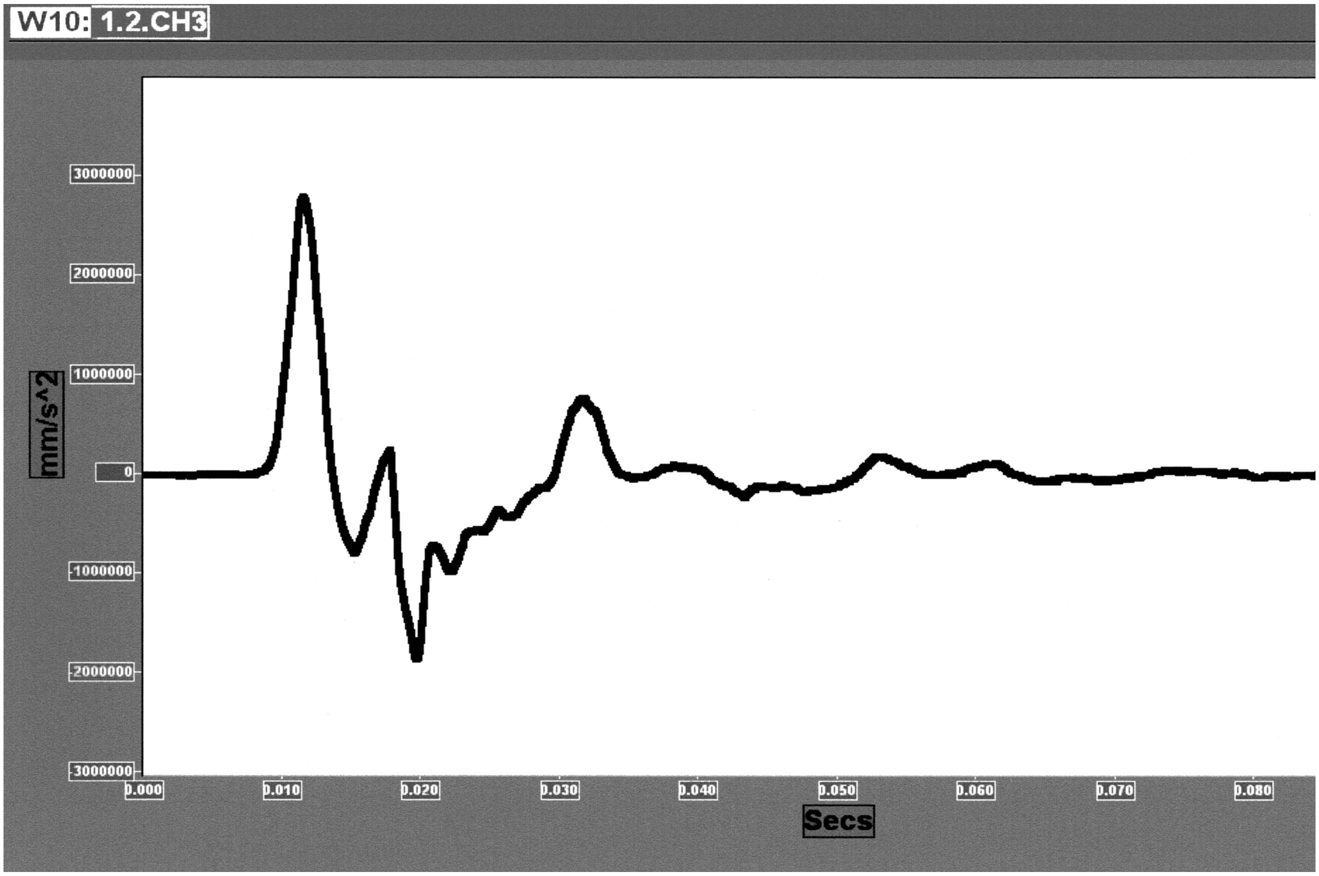

Figure 5–Typical limb acceleration generated by the RDA (Rapid Displacement Actuator).

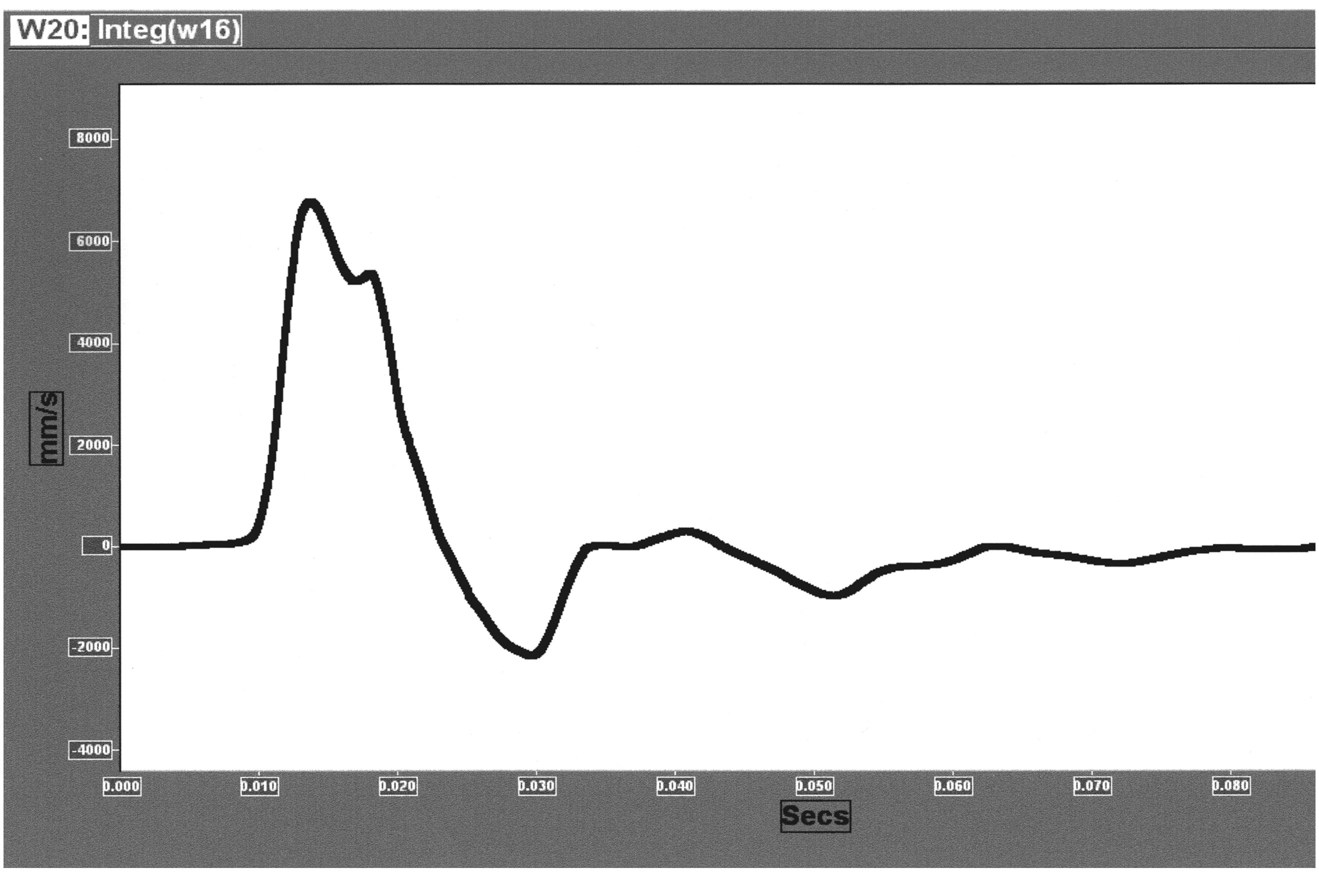

Figure 6–Typical limb velocity generated by the RDA (Rapid Displacement Actuator).

Conclusions and Future Research

The Y-trellis system was compatible with the mechanical robotic harvesting concept. Either individual trees (single leader) or multiple parallel leaders were acceptable. Fruit should be located to the sides and below branches to facilitate effective removal and collection. Training should remove long thin fruiting branches that make fruit detachment difficult. Considerable research is needed to determine cultivars and rootstocks most compatible with this training and harvesting system.

The control system demonstrated the ability to detect apples and limb location, determine detachment location, and position a fruit removal device. Leaves and multiple branching can cause problems in detecting the leader. Detection routines will need to be refined.

A control system in which a human operator selects the detachment location using a mouse pointer on captured images also seems feasible.

The RDA was effective in detaching apples with little damage. The RDA was simple in construction and required no maintenance during the field testing. The RDA generated the rapid leader displacement needed to minimize apple movement during detachment.

The catching surface proved to be too small to catch all the detached apples, but was effective in catching apples without inflicting damage. The quality of collected fruit was excellent. Future development will focus on creating a larger surface which will catch all the fruit. It will also be necessary to devise a way of transferring the apples from the catching frame to a bin filler.

During the research project three machine operational modes were conceived. Each will require additional research: (a) human operator positioning and activation of RDA with joystick-hydraulic controls without an imaging system; (b) use a simple imaging system to capture image, but let human operator determine detachment location with mouse (or pressure sensitive screen); and (c) fully automatic system as originally conceived.

As a proof of concept this harvesting approach was demonstrated as having potential. The challenge will be to develop a complete commercially acceptable system that maintains the quality and effectiveness demonstrated by this research.

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