Preliminary Results with a Vacuum Assisted Harvest System for Apples

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The harvest of specialty crops for the fresh market is labor intensive, and attempts at automation have been less successful than with field crops. Apple harvest is particularly difficult to automate because fruit suffer bruise damage easily. Nevertheless, market, social, and political forces have converged to make mechanical augmentation of harvest essential for the survival of the specialty crop industry in the U.S.

The challenges are enormous, as the constraints on candidate technologies include high performance, low cost, robustness, simplicity, and ease of repair. The opportunities and rewards, on the other hand, are commensurately great. Merely addressing these challenges is already inspiring a new generation of engineers and students to think creatively about problems in agriculture and related fields and to bring engineers and growers together (Kliethermes et al., 2010; Leslie et al., 2008; http://www.cascrop.com/index.php?option=com_content&view=article&id=1521&Itemid=666). Successful development technologies could reinvigorate the specialty crop industry, make it competitive in international markets, and employ segments of the population that have largely been excluded from the labor pool due to physical constraints.

The total value of U.S. specialty crops—$49 billion in sales—now exceeds the combined value of the five major program crops—$45.8 billion in sales (Schmoldt, 2007). However, despite the specialty crop industry's major contribution to the U.S. economy and the finding that "a secure domestic food supply is a national security imperative," U.S. specialty crop producers remain vulnerable to the real possibility of being eliminated within the next ten years (Schmoldt, 2007). This crisis stems in large part from dependency on a large seasonal workforce, coupled with increasing labor costs and decreasing availability of agricultural employees. In a socioeconomic technology adoption survey of growers conducted by members of our research team, harvesting was among the highest rated areas of need for advanced technologies to improve precision and efficiency in tree fruit production (Ellis et al., 2010).

Prior Approaches to Addressing Harvest Labor Inputs

Mechanical harvesting machines that utilized mass removal techniques were widely tested in the U.S. in the 1970s and 1980s. The machines were unsuccessful in harvesting fruit for the fresh market due to excessive fruit damage caused during fruit detachment, contact with limbs or other fruit while falling through a three-dimensional tree canopy, and bulk collection procedures (Peterson, 2005b).

Mechanical engineering efforts for specialty crops declined in the 1990s, and the focus shifted to the development of labor platforms for use with planar tree architectures. Fruit were still picked and placed in the bin by hand, but harvest efficiency was increased and fruit quality was similar to that which was conventionally harvested (Baugher et al., 2009a; Schupp et al., 2007). In the late 1990s, engineers began looking at automated bin filling technologies, but early designs resulted in excessive bruising of fruit (Peterson, 2005a). The complex fruit handling and equipment/operator interface was a major obstacle to developing semi-automated harvest systems.

Significant progress has been made on robotic harvest. However, insufficient fruit recovery and difficulties in developing both an end effector and a vision system that performs equal to the human hand and human visual system avert commercialization in the near future (Bulanon and Kataoka, 2010; Sarig, 1993).

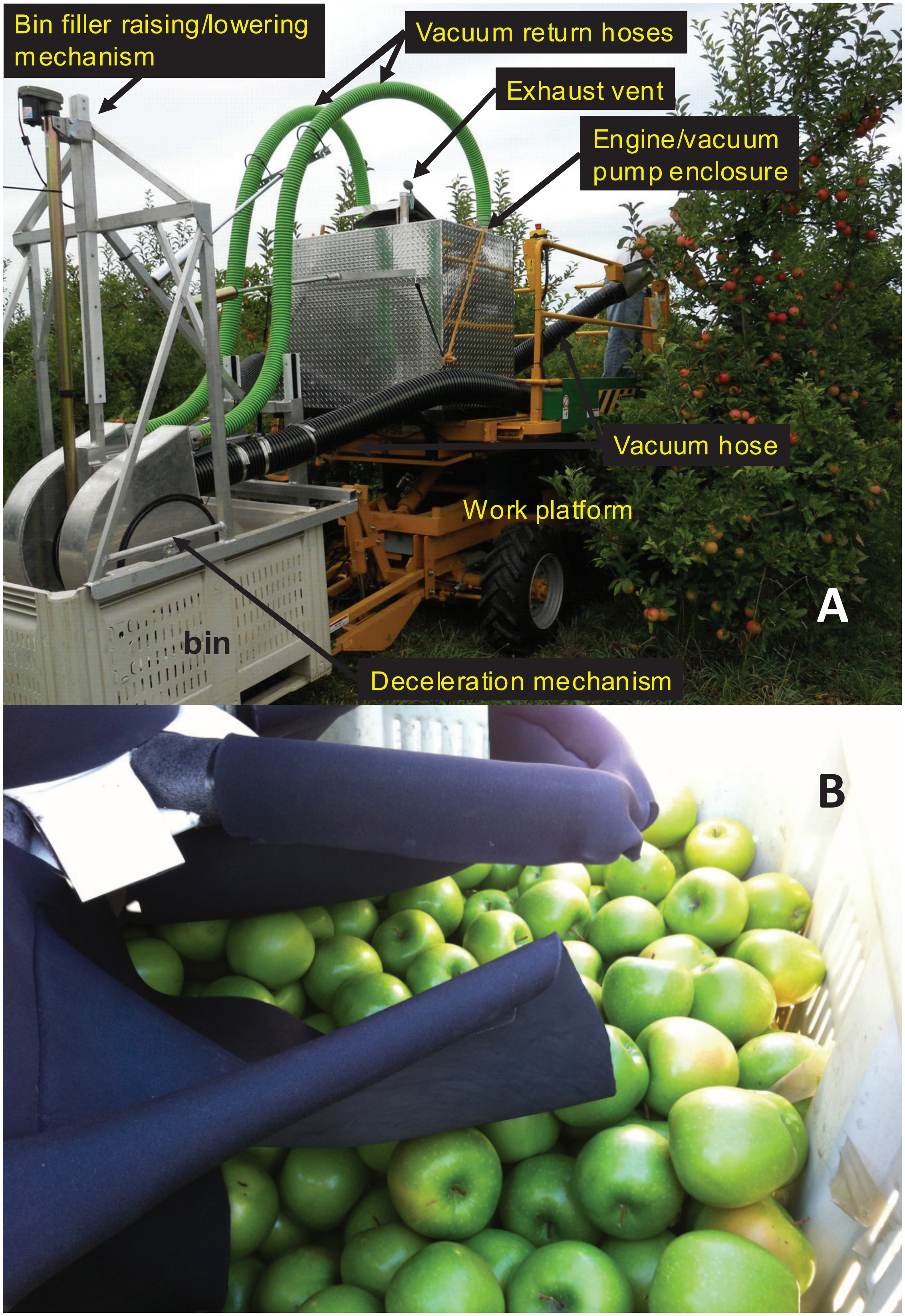

Figure 1. A. Components of vacuum-assisted harvest system. B. Elephant-ear distibutor in motion.

Current Research with Commercial Partner

In Fall 2011, with support from the Specialty Crop Research Initiative Project, “Comprehensive Automation for Specialty Crops” (Singh et al., 2011), our harvest team began working with a commercialization partner, DBR Conveyor Concepts, on a vacuum tube transport system and automated bin filler that could be retrofitted to existing grower equipment. Figure 1 shows the first prototype with the major components labeled.

Suction is provided by a pair of vacuum pumps driven by an internal combustion engine. The pumps and engine are in an enclosure mounted on the work platform. The vacuum pumps exhaust through a vent on the top of the enclosure. The exhaust pipe of the internal combustion engine is also at the top of the enclosure. Vacuum return hoses (green) lead from the pumps to the proprietary deceleration mechanism, which is the key innovation of this system. The vacuum pumps lower the internal pressure of the deceleration mechanism enclosure below ambient, causing air to flow through the vacuum hoses (black). Pickers place apples into the inlet to the vacuum hoses opposite the deceleration mechanism. The vacuum hoses are padded to prevent bruising of the fruit.

When a picker (partially hidden by the tree) places an apple into the vacuum hose, air flow into the hose is obstructed, leading to a differential pressure across the apple. The unequal pressure forces the apple through the hose. When it reaches the enclosure of the deceleration mechanism, its momentum propels into the deceleration mechanism, which has two functions. The first function is slowing down the apple and dropping it onto the flexible-flap bin filling mechanism (occluded by the bin in Figure 1A; shown in motion in Figure 1B). The second is to provide an airtight seal between the portions of the transport mechanism that are held below ambient pressure and the exit port of the deceleration mechanism of the enclosure.

Materials & Methods

Initial trials were conducted to assess fruit bruising at various stages in the augmented harvest system—(1) prior to entry into the vacuum tube (the control treatment), (2) after the vacuum tube and decelerator and before the elephant ears, (3) after the elephant ears but before the bin, and (4) after transport through the entire system. Bruising and corresponding USDA fruit grades were assessed as described in Kliethermes et al., 2010. Five replicates of either 15 or 20 fruit were randomly subjected to each of the treatments. The studies were first conducted on ‘Honeycrisp’ and ‘Daybreak Fuji.’ Based on the bruise findings, modifications were made to the harvest system to further prevent bruising, and a final study was conducted on ‘Golden Delicious,’ which is highly bruise-susceptible.

Commercial-scale efficiency trials were conducted on ‘Golden Delicious,’ ‘York,’ and ‘Pink Lady’ to assess labor productivity and fruit quality in apple orchard plots harvested with the vacuum assist system and a work platform compared to hand harvest and ladders. The same workers performed both treatments within a trial. The experimental design was randomized complete block with four multiple-tree replicates. Harvest times were compared for each treatment, and bruise evaluations were conducted on 100 fruit per treatment. Data from all trials were subjected to an analysis of variance and means were separated using Fisher’s protected least significant difference test.

Results & Discussion

The initial two trials to assess fruit damage on apples collected at various stages in the augmented harvest system revealed that changes should be made to the elephant ears to prevent bruising (Table 1). With ‘Honeycrisp,’ bruise volume in fruit collected from the elephant ears was higher than control fruit collected prior to the vacuum tube, although the effect on fruit grade was insignificant. In the trials with ‘Daybreak Fuji,’ bruise volume in fruit collected from the bin was higher than fruit collected prior to the vacuum tube, and the portion of fruit that graded U.S. Extra Fancy was reduced from 99 percent to 92 percent. Machine modifications to further reduce fruit damage eliminated bruising in the final trial with ‘Golden Delicious,’ and fruit graded almost 100 percent U.S. Extra Fancy.

Commercial-scale investigations on ‘Golden Delicious,’ ‘York,’ and ‘Pink Lady’ demonstrated increases in efficiency per acre of 10 to 49% (Table 2). The quality of machine-harvested fruit was equal to hand harvested fruit in the ‘Golden Delicious’ and ‘Pink Lady’ trials and was better than hand harvested fruit in the ‘York’ trial (Table 2). The cost/benefit beyond hand harvest was $245 to $517 per acre (Baugher et al., 2011; data not shown; www.cascrop.com).

From an engineering perspective, the vacuum as-

Table 1. Bruise volume measured on apples collected at various stages in augmented harvest system and corresponding effects on fruit graded USDA Extra Fancy.

Cultivar	Location of Sample	Bruise volume (mm^3)	U.S. Extra Fancy[z] (%)
Honeycrisp	Before vacuum tube (control)	2.0 b	
	After vacuum and decelerator	12.8 ab	96.0 a [x]
	After elephant ears	20.1 a	94.7 a
	From bin	8.3 ab	96.0 a
Daybreak Fuji	Before vacuum tube (control)	0.0 b	
	After vacuum and decelerator	13.5 b	98.7 a
	After elephant ears	14.7 ab	98.7 a
	From bin	34.6 a	92.0 b
Golden Delicious[y]	Before vacuum tube (control)	2.5 a	
	After vacuum and decelerator	7.9 a	99.9 a
	After elephant ears	10.4 a	99.8 a
	From bin	17.0 a	99.9 a

[z] Mean separation within columns and cultivars by Fisher's protected least significant difference at P=0.05 (Five replicates in each trial; n=20, Golden Delicious; n=15, Honeycrisp, Daybreak Fuji).

[y] Vacuum tubes, decelerators, and elephant ears modified to further reduce bruising prior to Golden Delicious trial conducted on October 11, 2010.

Table 2. Labor efficiency and fruit quality in apple orchard plots harvested with vacuum assist system and platform compared to hand harvest and ladders.

Cultivar	Harvest System	Harvest Time[z] (h/acre/ person)	Efficiency (% increase)	Fruit downgraded[y] (%)
Golden Delicious	Vacuum assist	33.35 b[x]	9.8	11.1 a
	Hand	36.98 a	--	15.6 a
York	Vacuum assist	24.69 b	49.2	6.0 b
	Hand	48.60 a	--	10.6 a
Pink Lady	Vacuum assist	37.47 b	19.4	5.3 a
	Hand	44.74 a	--	8.1 a

[z] Includes harvest of lower portion of trees by hand.

[y] Percentage of fruit downgraded determined from bruise evaluations conducted on 100 fruit per treatment from each of four replicates.

[x] Randomized complete block. Mean separation within columns by Fisher's protected least significant difference at P=0.05.

sisted transport system addresses a number of design challenges well. The entire system is simple, uses readily available materials and parts, and thus it is easy to maintain or repair. The vacuum tube and deceleration mechanism effectively move apples from the picker to the bin filling device with minimal bruising. The deceleration mechanism solves the important problem of isolating the vacuum from ambient pressure while providing a soft ejection for fruit. The modular design of the entire system makes it attractive to use with standard orchard equipment such as platforms and bin trailers.

At the same time there is room for further improvement. The biggest problems are that the vacuum pumps and the internal combustion engine are quite noisy, and working near the engine is hot. Another problem is that there are only two vacuum hoses. More hoses will be needed to allow more pickers to work at the same time to make the system cost effective. Our commercial partner is addressing these issues with their next prototype which will employ a single, larger but slower moving (and therefore quieter) vacuum pump driven by a hydraulic motor, with hydraulic power provided by the tractor towing the system. The new system will feature four vacuum hoses and deceleration devices. These improvements may be enough to make the vacuum assisted harvester not only viable technologically, but also economically profitable for growers.

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