Design Features and Bruise Evaluation of an Apple Harvest and In-Field Presorting Machine

A. K. Pothula, Z. Zhang, R. Lu

Abstract. *In-field presorting of apples, in combination with the harvest aid function, would have advantages of cost savings in postharvest handling and storage, reduced postharvest pest and disease problems, and better inventory management, while also enhancing harvest productivity. A new apple harvest and in-field presorting prototype was developed to help apple growers achieve these potential benefits. The prototype sorts and grades fruit based on color and size, using a machine vision-based sorting system with an innovative fruit singulating and rotating design (SRD), and it handles the graded fruit in the bins using newly designed automatic bin fillers. Bruise damage by impact is a critical factor in the development of the apple harvest and in-field presorting prototype. This article reports on the major design features of the prototype and experimental evaluation of the prototype for potential bruise damage. Experiments were conducted on 'Gala' and 'Fuji' apples to evaluate bruise damage potential under both empty and partially filled bin conditions. An impact recording device (IRD) was used to measure the impact magnitude in terms of peak acceleration (G) at all critical points of the machine, including harvest conveyors, main conveyor, flat conveyor, SRD, cup conveyor, bin filler, and bins. It was found that bruise damage mainly occurred during bin filling. The number of impacts recorded for the partially filled bin was reduced by 60%, compared to that for the empty bin, indicating that the impact between apples and the wooden bin's floor was a major cause of bruising. The maximum G value for the partially filled bin was measured at 34.5, while the measured G values were less than 20 from start to the point just before the bin filler, indicating no bruise damage. Bruise evaluation showed that no more than 9% of the test apples would be downgraded from 'Extra Fancy' grade for the partially filled bin condition. Higher G values for the empty bin condition suggested the need for further improvement to the discharge of apples from the bin filler to the bin to further reduce bruise damage.*

Keywords. *Apples, Bruising, Fruit, Grading, Harvesting, Sorting, Machine vision.*

Bruise damage causes quality loss and lower fruit quality grade (Siyami et al., 1998), and it is thus a major concern for the apple industry because bruised apples would be rejected or downgraded at wholesaling and retailing, resulting in financial loss for growers and retailers (Schulte et al., 1992; Lu et al., 2010). Bruise is related to compression, impact, or vibration, and it results in tissue failure that occurs beneath the skin without rupture of the fruit surface (Mohsenin, 1986). Fruit bruising can occur at each operation step during harvest and postharvest handling (including transport, storage, and packing) (Brown et al., 1993; Opara and Pathare, 2014). Most bruises in apples are caused by impacting hard surfaces or other apples due to higher incidence of impact and excessive force magnitude (Hyde, 1997; Van Zeebroeck et al., 2007).

With the increasing consumer demand for high-quality fruit and the need to reduce the potential economic loss resulting from quality-degrading bruise damage, it is important that bruise evaluation and mitigation methods and procedures be implemented during fruit handling operations. Electronic fruits have been widely used for real-time recording of the impacts that fruit would experience during handling operations. The instrumented sphere (IS), a spherical-shaped artificial or pseudo fruit that contains a tri-axial accelerometer, was first developed by researchers with the USDA-ARS and Michigan State University at East Lansing, Michigan (Tennes et al., 1988a, 1988b; Zapp et al., 1990) and later manufactured by Techmark, Inc. (Lansing, Mich.). Brown et al. (1990) evaluated about 25 commercial packing lines of apples and identified the critical points on the lines that caused potential bruise damage using an 89 mm diameter IS. Peak acceleration lines or threshold response lines (i.e., maximum acceleration, or *G*, vs. IS velocity change) were developed to help identify the individual impacts that are likely to cause apple bruise damage for different surfaces (Timm and Brown, 1991; Schulte et al. 1992; Pang et al. 1994). Apart from apples, the IS was also used for evaluating the bruise damage of other fruit and vegetable handling systems, such as avocado, papaya, and pineapple (Timm and Brown, 1991), potato (Hyde, 1992), tomato and bell pepper

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(Sargent, 1992), and peach (Lin and Brusewitz, 1994). The latest version of the IS with improved data acquisition capabilities and measurement accuracies, also known as the impact recording device (IRD), is now used worldwide (Jaren et al., 2016). However, the spherical-shaped IRD with the smallest size of 57 mm might not be suitable for measuring the dynamic behavior of fruit and vegetable products whose size and shape significantly deviate from that of the IRD. For example, potato tubers, typically of semi-ellipsoidal shape, are completely different from the IRD, whereas blueberries are small fruits (7 to 23 mm diameter) compared to the IRD of 57 mm diameter. Therefore, several customized electronic fruits resembling the shape and size of different fruits and vegetables have been developed and used for bruise evaluation.

Bruise damage of potato tubers was studied using electronic fruits of semi-ellipsoidal shape, such as the PTR 200 (SM Engineering, Nakskov, Denmark), TuberLog (ESYS GmbH, Damme, Germany), and Smart Spud (Sensor Wireless, Charlottetown, PEI, Canada) (Praeger et al., 2013). The PTR 200 is made up of two hemispheres of 53 mm diameter, joined by a cylinder of 53 mm diameter and 30 mm height, and it improved measurements of the dynamic behavior of potatoes, compared to the spherical IRD (Van Canneytt et al., 2003). Jaren et al. (2016) further reported that more realistic bruise evaluation data of potatoes were obtained by using new miniature devices, such as Mikars (ESYS, GmbH, Germany) and AMU (Institute for Agricultural Engineering, Bornim, Germany), which are implanted in real potatoes. Praeger et al. (2013) compared Mikars with IRD, Smart Spud, and TuberLog and reported that all devices differed in their capabilities of data evaluation and handling during measuring operations. Impact measurements for potatoes under both static and dynamic mechanical loads were taken using the PMS-60 (ATB, Bornim, Germany), which is a 62 mm diameter rubber ball embedded with pressure sensors (Herold et al., 1996). After comparing AMU with PMS-60, Shahbazi et al. (2011) reported that AMU recorded average impact loads that were 1.1 times higher than PMS-60. A berry impact recording device (BIRD) of 25.4 mm diameter spherical shape was developed for measuring the mechanical impacts of small fruits like blueberries (Yu et al., 2011a, 2011b; Xu et al., 2015). The wireless impact sphere, or WIS, is another device that is able to acquire, process, and visualize three-axis accelerations, allowing identification and measurement of rotations, vibrations, and impacts in real time (Roa et al., 2013, 2015).

The majority of impact bruising studies using electronic fruits have so far been conducted for commercial packing lines. Only a few studies have been reported on bruise evaluation (either manually or using electronic fruits) of mechanical harvesting or harvest aid machines. Peterson et al. (1997) developed an apple harvest aid machine for incline-trellised canopies and evaluated the machine by manually grading the tested apples according to the USDA bruise standards. The harvest aid machine resulted in a lower percentage of 'Extra Fancy' grade fruit, compared to conventional hand harvesting. Peterson and Wolford (2003) developed a fresh-market quality fruit harvester and evaluated the machine by manually grading the harvested apples according to the USDA bruise standards. They reported that the harvester produced 86% to 90% fresh market quality fruit and that cuts, punctures, and stem pulls were the major concerns for the machine. In a further study, Peterson and Bennedsen (2005) found that bruising was a crucial factor limiting adoption of the harvester. Peterson et al. (2010) developed a dry bin filler for apples and evaluated the bin filler by both manual and IRD methods. The bruise damage caused by the dry bin filler was less than 5%, compared to 8% by commercial bin fillers. Luo et al. (2012) conducted bruise evaluation of a vacuum harvester using the IRD and reported that the majority of the recorded impacts occurred in the vacuum tubes, followed by the bin. When the harvester was operated at the manufacturer's recommended vacuum pressure, only 23 impacts out of 478 tests were reported with 10% probability of bruise damage. In addition, 99.6% of apples harvested with the vacuum harvester were graded as 'Extra Fancy' (no bruising or total bruising areas smaller than 127 mm^2).

Apple harvesting in the U.S. mainly relies on seasonal farm labor. With the decreased availability of labor, along with increased labor cost, the demand for harvest aid machines is increasing. Consequently, we have seen increased use of harvest aid machines by growers in recent years, and a number of commercial harvest aid machines are currently available on the market. Zhang et al. (2014, 2016a, 2016b, 2017b) reviewed the status of apple mechanical harvest technology and concluded that harvest aid platforms have greater potential for commercialization at present, compared to semi-automatic harvesters and harvest robots. However, growers have been slow in adopting these machines because of concerns about high machinery cost, limited improvement in harvest productivity, and monotonic use function.

Currently, all harvested apples are collected in the same bins, irrespective of their quality grade, and transported to the packing house for controlled atmosphere or refrigerated storage and then for sorting and packing at later times. This practice of handling fruit without presorting in the field is not cost-effective (Lu and Lu, 2016). Separating the lesser value or lower (processing) grade fruit at the time of harvest would reduce the cost of postharvest storage and packing of processing grade apples, which are sold at a fraction of the price for fresh quality apples. Mizushima and Lu, (2011), Zhang and Heinemann (2017), and Zhang et al. (2017a) reported significant cost savings in postharvest storage, grading, and sorting if processing apples are removed at the time of harvest. Further, presorting can reduce pest and disease problems during postharvest storage and enhance inventory management. Considering these potential benefits, our laboratory developed a first-version apple harvest and in-field presorting prototype in 2013. This prototype was built on a commercial harvest trailer hauled by a tractor for meeting in-field operating conditions and incorporated with a low-cost computer vision system (Mizushima and Lu, 2013a, 2013b). The vision system sorts apples into two quality grades (i.e., fresh and processing).

This article provides an overview of the major design features and/or considerations of the apple harvest and in-field presorting machine and reports on the bruise damage evaluation results for the prototype. This information can be used for further development of a new-generation apple harvest and in-field sorting machine.

Overall System Design

The machine prototype was designed primarily for integrating low-cost computer vision technology with the existing apple harvest aid platform for automatic sorting of inferior or low-quality fruit from fresh market fruit. The in-field sorting system (figs. 1 and 2) was built as an add-on unit to a commercial box shuttle of five bins in order to reduce the overall system cost. The prototype mainly consists of the harvest conveyors, the main conveyor, the flat (or transitional) conveyor, the machine vision-based sorting system with an apple singulating and rotating device (SRD), the cup conveyor, and three bin fillers for handling graded apples (up to three quality grades, i.e., fresh, cull, and processing) into individual bins. Two to four pickers standing on the ground and two pickers standing on the harvest platforms hand-pick apples from the trees at two different heights as the harvester travels between rows. The pickers place harvested apples onto the harvest conveyors, and the apples are then conveyed to the main conveyor and flat conveyor before entering the SRD, where images of each apple are taken by the machine vision system for tracking, sorting, and grading based on size and color. The graded apples are then placed into cups on the cup conveyor, which transports the apples to the corresponding grade bins (fresh and processing) through the bin fillers. Detailed descriptions of each component of the system, along with its design features, are given in the following sections.

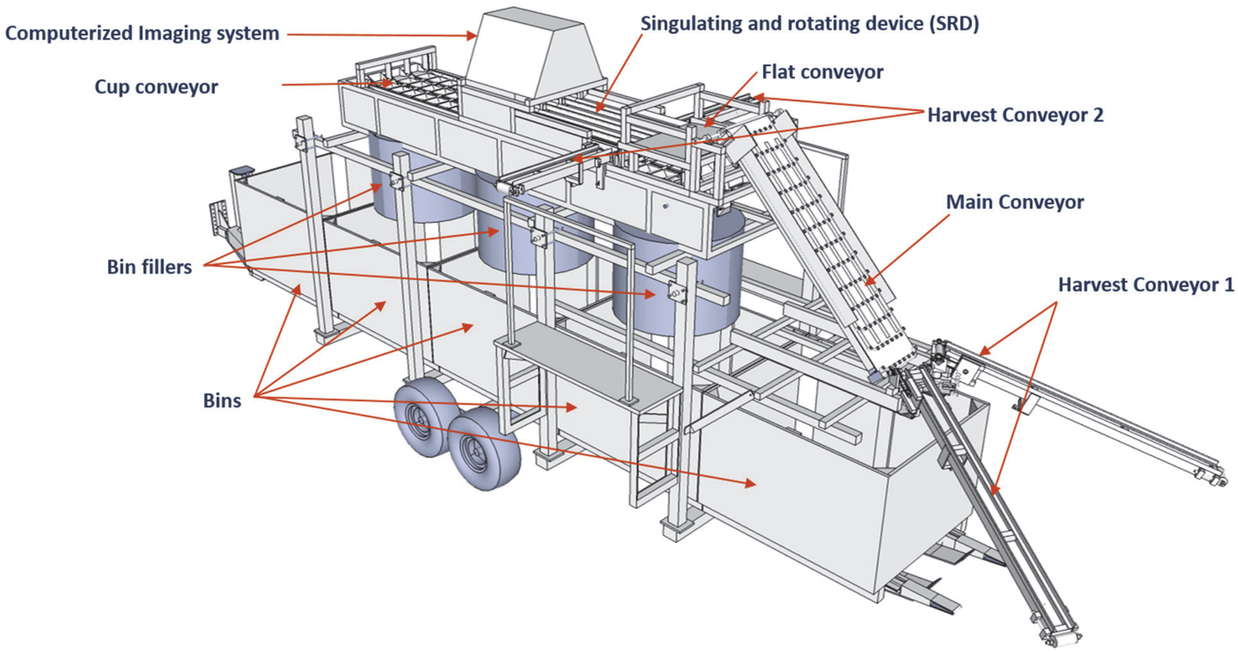

Figure 1. Diagram of the apple harvest and in-field sorting prototype.

Figure 2. Field testing of the apple harvest and in-field sorting prototype during the 2013 harvest season.

CONVEYORS

There are four types of conveyors on the apple harvest and in-field sorting prototype, including the harvest conveyors (two pairs), main conveyor, flat or transitional conveyor, and cup conveyor. These conveyors are used for smooth transport of fruit from one section to another section of the system. The belts for the harvest, flat, and main conveyors are made of smooth and durable 6.35 mm thick mat material (YogaAccessories.com, Richmond, Va.). One end of these conveyors is adjustable to maintain proper tension of the belt. The harvest conveyors are able to move up and down (with gas springs) and swing left and right (with vertical shafts), allowing the pickers to easily pick fruit from the trees and place the harvested apples on the conveyors conveniently. Mounted on the belts of the harvest conveyors are rows of 50.8 mm high soft fingers spaced 38.1 mm apart to prevent the apples from rolling back while being transported upward and to avoid apple-to-apple impacts during transport. The rows of fingers are spaced at 127 mm intervals on the belt to accommodate apples of all sizes and to prevent the picker from hitting the fingers while placing apples on the harvest conveyors. The fingers on the conveyors are made of 12.7 mm diameter plastic rods padded with weather-resistant EPDM foam tube (12.7 mm ID, code 4339T8, McMaster-Carr, Aurora, Ohio). The flat conveyor is used as a transition for smooth transfer of apples from the main conveyor and from the top harvest conveyors (harvest conveyor 2 in fig. 1) to the SRD.

SRD

The SRD singulates and rotates apples as they move forward into the machine vision chamber (Lu et al., 2016). The SRD consists of three pairs of variable-pitch worm screws (fig. 3b), which are able to handle up to 6 apples s^{-1} to accommodate the harvesting speed of six pickers. Each screw is made of multipurpose aluminum tube of 31.75 mm o.d. and padded with foam rubber tube of 31.75 mm i.d. and 9.53 mm thickness (McMaster-Carr, Aurora, Ohio). Wrapped on the surface of the foam tube are weather-resistant foam strips of 9.5 mm thickness and 12.7 mm width (McMaster-Carr, Aurora, Ohio), which are arranged at variable pitches to form the complete worm screw (fig. 3a). The pitch of the screw increases from 63.5 mm to 114.3 mm from the initial to final section. As the apples move from the initial smaller pitch to the larger pitch, they are aligned into three rows and then dispersed and singulated while rotating forward. The rotation enables each apple to expose its entire surface for imaging. The two screws of each pair rotate in synchronization in the same direction. Round dividers padded with foam sheet (fig. 3b) are placed at the location of pitch change, allowing only one apple to enter each pocket.

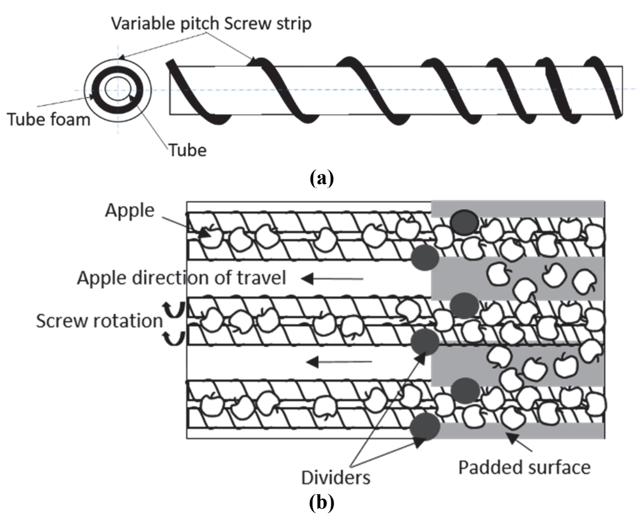

Figure 3. Schematic diagram of (a) single screw and (b) the multi-screw conveyor for singulating and rotating apples.

MACHINE VISION SORTING SYSTEM

The machine vision sorting system is housed in a chamber to avoid the effects of ambient light. It consists of a color CCD camera and eight 12 W, 0.61 m long fluorescent lamps. Approximately 10 to 20 images of each apple are collected by the color camera at a rate of 15 frames s^{-1}. An in-house developed computer program processes the collected images of each apple, keeps track of the apples, and determines the quality grade based on size and color. The user can set specific grading criteria by training the vision system based on the red and green color proportions of apples. The graded apples (i.e., fresh and processing) are conveyed to the cup conveyor and then transported to the corresponding bin fillers.

CUP CONVEYOR

Cup conveyors are commonly used for transferring graded apples in apple packinghouses. With commercial cup conveyors, the apples are dropped from the upper chain positions. Although simpler, such a design has a major drawback in requiring a large space between the upper and lower chains (fig. 4a), which is problematic for the in-field sorting system where space is limited. In addition, the conventional design poses challenges for the arrangement of the bin fillers. As such, we came up with a different design concept for the cup conveyor, which allows the cups to carry apples from the upper side to the low side and then release the apples into the bin fillers. As the cups transition from the upper side to the lower side (the left end of the conveyor in fig. 4a), they maintain a horizontal position, via special supports, so that the apples in the cups are held steady and not disturbed. This design achieves significant vertical space savings while also simplifying the arrangement of the bin fillers, as discussed in the next section.

Each cup in the cup conveyor is made of hard plastic with dimensions of 114.3 × 101.6 × 38.1 mm (fig. 4). Each row in the cup conveyor consists of three lanes of cups (fig. 4b) corresponding to the three pairs of variable-pitch worm screws of the SRD. The lanes are aligned just below the SRD, and the conveyor rotates on an endless chain (fig. 4a) in synchronization with the SRD. When a cup carrying an apple reaches the position of the corresponding bin filler, the machine vision software triggers the solenoid (fig. 4a) at that location to open the latch, which releases the cup and thus drops the apple into the bin filler is mounted directly beneath the cup conveyor.

BIN FILLERS

The bin filler plays a critical role in transferring apples

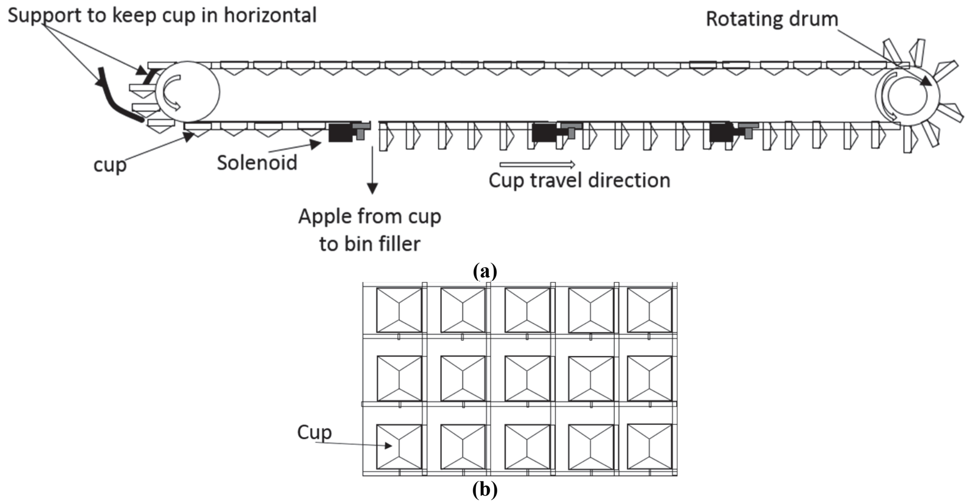

Figure 4. (a) Schematic diagram of the cup conveyor and (b) cup arrangement in three lanes.

from the cup conveyor to the bin. We came up with a unique design (fig. 5) that allows the apples to drop freely from the cup conveyor into the bin filler. Each bin filler spans the three cup lanes. Guarding curtains or adjustable roller shades are used to guide the apples into the rotating foam rollers. The two foam rollers rotate in opposite directions at the same speed to catch the apples freely falling from the cup conveyor and then convey the apples to the guiding slopes. Each foam roller of 50.8 mm diameter is padded with two layers of 25.4 mm memory foam (Carpenter, Richmond, Va.) to avoid bruise damage. The gap between the foam rollers is about 25.4 mm and is adjustable if necessary. The soft memory foam is compressed to absorb the kinetic energy of each falling apple, reduce its speed, and then discharge it to the guiding slopes, also padded with 25.4 mm memory foam, that direct the apples to the rotating wheel in two opposite directions (toward each other) for uniform distribution of apples in the bin (fig. 5). The rotating wheel, which is powered by a DC motor, is divided into four quadrants, each of which has a 6.35 mm thick soft mat shaped like an elephant ear (fig. 5), so that the apples are placed gently and evenly into the bin without causing bruise damage. Raising and lowering of the bin filler are accomplished with a linear actuator that is controlled by a programmable on-board microcontroller (not shown in fig. 5). Installed on the frame of the bin filler

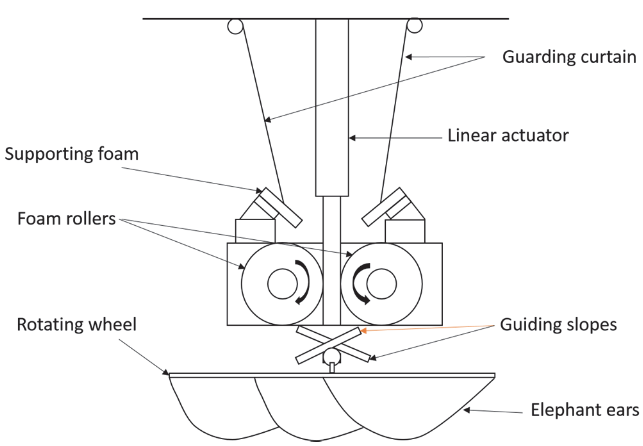

Figure 5. Schematic diagram of the bin filler.

are two sensors (not shown in fig. 5); one is used to record and monitor the filling process of the bin, and the other records the speed of the rotating wheel. The microcontroller processes the data from the sensors in real time and then determines when to actuate the linear actuator for raising the bin filler.

BRUISE EVALUATION EXPERIMENT

As described above, sufficient attention has been given in the design of the apple harvest and in-field sorting prototype to avoid bruise damage to apples. Soft padding is used, whenever possible, on the surfaces of individual components of the machine for transporting the apples from start to end to avoid or reduce bruise damage. Despite these efforts, the prototype should be further tested and evaluated in terms of bruise damage to apples. Hence, laboratory tests were conducted to evaluate the impacts to apples as they were moving from the start point (i.e., harvest conveyor) to the end point (the bin). Each critical or transition point between the start and end, including the harvest conveyor, main conveyor, flat conveyor, SRD, cup conveyor, bin filler, and bin, was labeled. Impacts to apples at these points were then recorded using the IRD. The collected impact data and apple bruise damage data were then analyzed for identification of the critical points that would have caused bruising damage to apples.

IRD EVALUATIONS

The IRD of 89 mm diameter, weighing 0.383 kg (Serial No. 333, Techmark, Inc., Lansing, Mich.), was used for testing apple impacts on the harvest and in-field sorting machine (fig. 6). It consists of a built-in tri-axial accelerometer with impact amplitude of 500 *G* (within 3% accuracy). The trigger threshold was set at 8 *G*. Velocity change and *G* values were recorded and collected through PCIRD software version 4 (Windows compatible) after the experimentation. Each impact recorded by the IRD was labeled with the corresponding component or critical point of the sorting machine. The impacts related to the transfer between components were recorded for the prior component. For example,

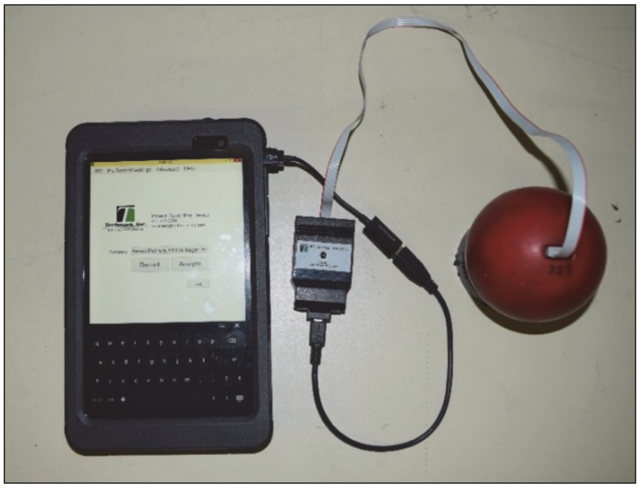

Figure 6. Impact recording device (IRD) connected to the communication interface with a USB communication cable.

when the IRD started at the lower end or starting point of harvest conveyor 1, the impacts recorded were labeled as harvest conveyor 1. When the IRD moved to the transition point between harvest conveyor 1 and the main conveyor, the impacts were still labeled as harvest conveyor 1. When the IRD reached the starting point of the main conveyor, the impacts were recorded as the main conveyor. Data points labeled start and end related to handling before and after running the IRD through the system. These data points related to the physical handling of the IRD being placed on the sorter and removed from the sorter.

To observe the effect of the bin filling condition on bruising, both an empty bin and a partially filled bin with three or four layers of apples were evaluated in the experimentation. Ten runs were done for the empty bin and for the partially filled bin, respectively. Each run was started with the label start (S). The IRD was placed with apples on the lower end of harvest conveyor 1 (C1), conveyed through the main conveyor (C2), flat conveyor (FC), singulating and sorting device (SRD), cup conveyor (C), and bin filler (BF), and then collected from the bin (B) with the label end (E).

Manual Evaluation of Bruises

Two apple varieties (i.e., 'Gala' and 'Fuji') harvested during the 2015 season were used for the bruise evaluation experiment. These apples were obtained from a commercial packinghouse in Sparta, Michigan, right after they were removed from controlled atmosphere storage. Approximately 30 to 40 apples were tested in each of three replications for each variety. All apples were pre-evaluated visually for any pre-existing bruises before passing through the harvest and sorting machine and then post-evaluated for new bruises after one day (24 h). The fruit were also peeled and evaluated for any missed bruises after the post-evaluation.

All the bruises present on the apples were considered, and bruise diameter was measured. The total bruise area for each apple was calculated by adding all bruises present on the apple after a trial run through the machine. Based on the USDA Fresh Market Standard, apples with a total bruise area $\leq$127 mm^2 were categorized as 'Extra Fancy'.

Firmness

Bruise susceptibility is variety-dependent, and varieties with higher flesh firmness are generally more susceptible to bruise damage (Van Zeebroeck et al., 2007). Further, firmness is an important parameter for measuring the maturity and quality grade of apples (Mendoza et al., 2014). After manual bruise evaluation, the apples were kept at room temperature for at least 16 h; thereafter, the firmness was measured by the standard Magness-Taylor (MT) test with a texture analyzer (TA.XT2i, Stable Micro Systems, Inc., Surrey, U.K.). The fruit skin, about 1 to 2 mm thick, was removed prior to the MT test, and the MT tests were conducted with an 11 mm diameter steel probe for a penetration depth of 9 mm at a loading speed of 2 mm s^{-1}. The maximum force (N) recorded was used as a measure of fruit firmness (Peng and Lu, 2006).

Results and Discussion

IRD Evaluations

The results obtained from the IRD evaluations are presented in figures 7 to 9. Each of these figures has two components, labeled a and b, corresponding to the empty bin and partially filled bin, respectively. The results presented in these figures represent the total impacts from ten runs or replications. Histograms of the impacts recorded by the IRD at different levels of peak acceleration (G) are given in figure 7 for the empty bin (fig. 7a) and partially filled bin (fig. 7b), whereas figure 8 groups the impacts for the individual com-

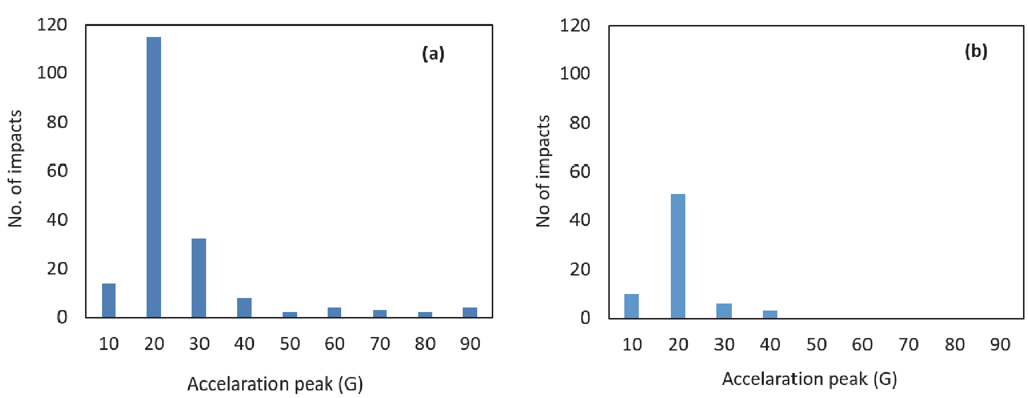

Figure 7. Histogram of impacts recorded by the impact recording device (IRD) during ten runs for different levels of peak acceleration (*G*) for (a) empty bin and (b) partially filled bin.

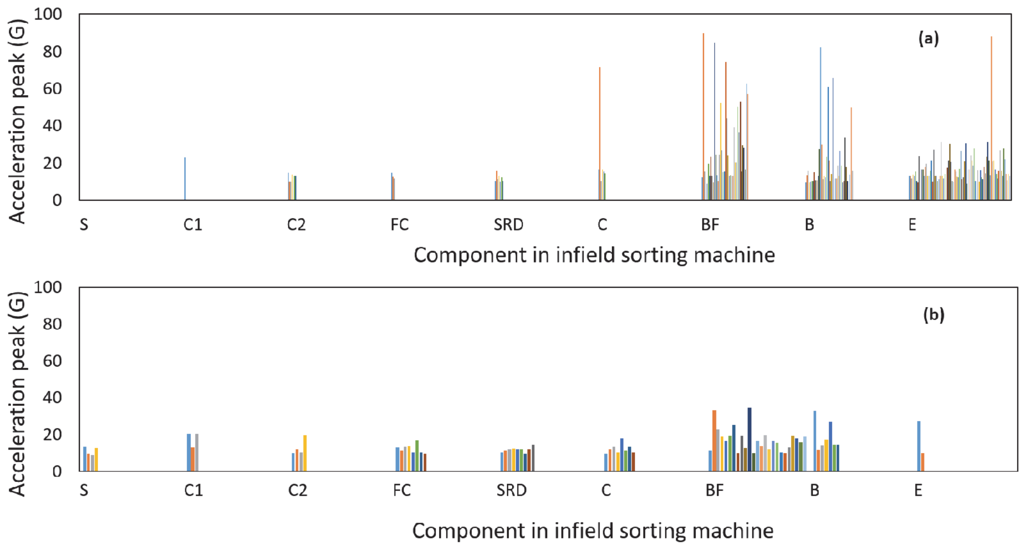

Figure 8. Total impacts occurring at different components in the apple harvest and in-field sorting machine during ten runs of the impact recording device (IRD): (a) empty bin and (b) partially filled bin (S = start, C1 = harvest conveyors, C2 = main conveyor, FC = flat conveyor, SRD = singulating and rotating device, C = cup conveyor, BF = bin filler, B = bin, and E = end).

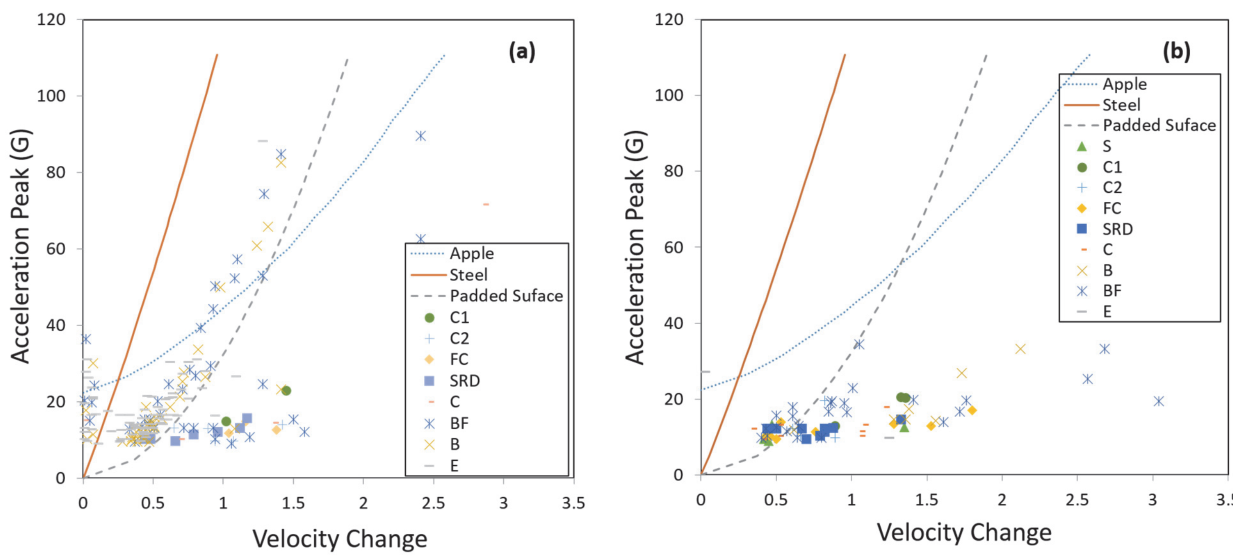

Figure 9. Peak acceleration (*G*) versus velocity change for (a) empty bin and (b) partially filled bin (S = start, C1 = harvest conveyors, C2 = main conveyor, FC = flat conveyor, SRD = singulating and rotating device, C = cup conveyor, BF = bin filler, = bin, and E = end). The dotted, solid, and dashed lines are the bruise damage reference lines for apple, steel, and padded surface, respectively.

ponents of the apple harvest and in-field sorting machine. Figure 9 shows all the impacts with respect to damage reference lines with velocity change and *G* values. Bruises caused by the empty bin and partially filled bin were expected to be different, and the results were analyzed separately for the empty bin and partially filled bin, as explained below.

Empty Bin

The IRD data collected from all ten runs for the empty bin indicated that most (>70%) of the impacts were less than 20 *G* (fig. 7a), which is considered non-bruising (Schulte, 1992). The vertical bars in figure 8 represent all impacts for each component of the system, grouped from start to end. All impacts occurring from start (S) to the cup conveyor (C), which include the harvest conveyors, main conveyor, flat conveyor, and SRD, were less than 23 *G* (table 1 and fig. 8a), except for one impact of 71.61 *G* on the cup conveyor. This impact might have been caused by an unusual jump of the IRD on the cup conveyor when it was being transferred from the SRD and is also shown in figure 9a, where the data point corresponding to the cup conveyor (C) with 71.61 *G* is represented by a velocity change of 2.86 m s^{-1}. However, this impact would have not caused damage due to its high velocity change because it is well below the damage reference line for steel (fig. 9a). The damage reference lines for steel, apple, and padded surface (fig. 9a) indicate that the safe peak acceleration recorded by the IRD increases with the velocity change at different rates for different surfaces.

The bin filler, bin, and end contributed about 87% of the total number of impacts (table 1) recorded by the IRD. Further, all the impacts that were above the damage reference line were caused by the bin filler, bin, and end (fig. 9a).

Table 1. Summary of impacts occurring for each component of the apple harvest and in-field sorting system when used with an empty bin.[a]

	All Components	System Component							
		C1	C2	FC	SRD	C	BF	B	E
Average number of impacts per run	18.4	0.2	0.6	0.3	0.7	0.6	3.8	3.9	8.3
Percentage of impacts per component	100.0	1.1	3.3	1.6	3.8	3.3	20.6	21.2	45.1
Maximum *G*	89.67	22.87	13.94	14.83	15.71	71.61	89.67	82.54	88.28
Average *G* per run	8.91	3.77	7.18	2.56	5.82	8.93	16.14	11.92	14.97
Standard deviation (10 runs)	5.03	8.17	6.32	5.41	6.23	13.57	14.03	10.28	6.83

[a] C1 = harvest conveyors, C2 = main conveyor, FC = flat conveyor, SRD = singulating and rotating device, C = cup conveyor, BF = bin filler, B = bin, E = end, and *G* = peak acceleration.

However, it was difficult to determine if the damages occurred in the bin filler or in the bin. Properly labeling of the impacts from the bin filler to the bin was extremely difficult due to poor visibility and the fast moving speed of the IRD. Only a fraction of a second was needed for the IRD to drop from the bin filler. Visual inspection and audible thumps suggested that the damaging impacts were mainly related to the release of the IRD from the bin filler to the empty bin. Except for the bin filling and apple to bin interactions, the IRD results suggest that apples would not have been bruised when they moved from the harvest conveyor to the cup conveyor, and the design of these components is acceptable.

Partially Filled Bin

When the bin was partially filled with apples, the total number of impacts were reduced to 70 (table 2 and fig. 7b) from 184 for the empty bin (table 1), which represents about a 60% reduction in the number of impacts. When the bin was empty, apples hit, bumped, and rolled on the floor of the wooden bin, and they could also hit the side walls of the bin before coming to a stop. On the other hand, the movement of apples in the partially filled bin was much less. The maximum *G* value recorded for the partially filled bin was 34.46 (table 2), and about 87% of impacts were non-bruising impacts with less than 20 *G* (fig. 8b). Only one impact, labeled E, exceeded the damage reference lines (fig. 9b). Some mishandling of the IRD or movement after reaching the bin may have caused this occurrence. Handling of the apples throughout the entire system appeared acceptable. Overall, bruise damage occurrences were reduced greatly after the bin had been filled with at least one layer of apples, due to the reduced rolling of apples after being released from the bin filler to the bin and the decreased levels of impact occurred between apples, rather than between the apples and the hard wooden floor of the bin.

It seems evident that the damaging impacts found in the IRD evaluation for the empty bin were the result of the IRD exiting the bin filler and impacting the floor or side walls of the empty bin. Similar results were reported by O'Brien et al. (1980) and Berlage (1981). There were also a few impacts in the range of 30 *G* corresponding to the bin filler (BF) and bin (B) (fig. 8b), but these impacts did not cause damage because they were well below the damage reference line for steel (fig. 9b). Velocity change is directly related to the dropping height of apples. With an increase in velocity change, *G* also increases. However, few impact points were above the padded surface reference line, which indicates that acceleration of the apples from the bin filler to the bin was the major cause of impact damage in the apple harvest and infield sorting machine. Hence, further impact mitigation measures or improvements should be considered for the machine.

Manual Evaluation of Bruising Damage

Manual evaluation showed that 'Gala' apples were less sensitive to bruising damage compared to 'Fuji' apples (table 3), which could be because 'Fuji' apples (with an average firmness value of 77.36 N and standard deviation of 9.9 N), were firmer than 'Gala' apples (with an average firmness value of 60.82 N and standard deviation of 12.4 N) and thus more susceptible to bruising. The empty bin caused more damage to the apples compared to the partially filled bin, which generally is in agreement with the findings of the IRD tests. With the empty bin, only 87.3% of 'Gala' apples were evaluated as 'Extra Fancy', compared to 95.7% as 'Extra Fancy' with the partially filled bin, when these apples were visually inspected before removal of the peel. After the peel was removed, bruise evaluation results showed only 72.9% 'Extra Fancy' apples for the empty bin, compared to 91.3% for the partially filled bin, which is lower than the results obtained before peeling. While a similar trend was observed for 'Fuji' apples (table 3), a much lower percentage of 'Extra Fancy' apples was obtained for the empty bin than for the partially filled bin when the apples were evaluated either before or after peeling. 'Fuji' apples were much more susceptible to bruising when the bin was empty. The large discrepancies between the percentages of 'Extra Fancy' 'Fuji' apples before and after removal of the peel suggest that visual inspection underestimated the bruise damage areas when the peel was present. Another reason could be that removal of the peel made visible some small, less severe bruises in the test apples, thus resulting in overall higher estimation of the total bruise area for individual apples. It is

Table 2. Summary of impacts for each component of the apple harvest and in-field sorting system when used with a partially filled bin.[a]

	All Components	System Component								
		S	C1	C2	FC	SRD	C	BF	B	E
Average number of impacts per run	7	0.4	0.3	0.4	0.8	0.9	0.8	2.5	0.7	0.2
Percentage of impacts per component	100.0	5.7	4.3	5.7	11.4	12.9	11.4	35.7	10.0	2.9
Maximum *G*	34.46	13.22	20.44	19.60	17.08	14.52	17.85	34.46	33.15	27.24
Average *G* per run	6.43	2.36	5.36	3.68	4.78	7.18	8.71	14.18	7.94	3.70
Standard deviation (10 runs)	3.60	5.02	8.87	6.05	6.26	6.28	6.40	8.08	11.57	8.82

[a] S = start, C1 = harvest conveyors, C2 = main conveyor, FC = flat conveyor, SRD = singulating and rotating device, C = cup conveyor, BF = bin filler, B = bin, E = end, and *G* = peak acceleration.

Table 3. Average percentages of 'Extra Fancy' (overall bruise area ≤127 mm^2) apples based on visual evaluation of intact and peeled fruit.[a]

Variety	Partially Filled Bin: Before Peel Removal	Partially Filled Bin: After Peel Removal	Empty Bin: Before Peel Removal	Empty Bin: After Peel Removal
'Gala'	95.7 ±5.5	91.3 ±6.7	87.3 ±4.2	72.9 ±10.6
'Fuji'	94.4 ±1.9	91.1 ±1.9	75.0 ±7.8	56.5 ±8.1

[a] Values are means ± standard deviations of three replications.

also possible that some of the small bruises may have existed before the bruise damage study but were not detected during the initial visual inspection. While the bruise evaluation results for both varieties in the partially filled bin test are satisfactory, further improvement to the bin filler is needed to reduce potential bruise damage of apples when they are released from the bin filler into the bin, especially when the bin is empty or has not been filled with at least one layer of apples.

Conclusions

An automatic in-field sorting prototype, combined with a harvest aid function, was developed to help apple growers achieve labor and production cost savings in harvest and postharvest storage and packing. The prototype included several innovative design features for fruit sorting, conveying, and bin filling. Bruise evaluation of the prototype was conducted, using an impact recording device (IRD), for two varieties of apple with both empty and partially filled bin conditions. The IRD evaluation showed that high levels of impact to the apples mainly occurred at the points labeled bin filler (BF), bin (B), and end (E). After further comparison of the IRD and manual bruise evaluation data for the empty and partially filled bin conditions, it was concluded that the impacts of apples with the wooden floor of the empty bin were likely the main cause of apple bruising. Both the IRD data and the manual evaluation confirmed that apples were properly handled throughout the entire system, with 91% or more apples being rated as 'Extra Fancy' after the bin had been filled with at least one layer of apples. However, excessive bruise damage occurred when apples were released from the bin filler to the wooden floor of the bin. Hence, further improvement of the discharge of apples into the bin (i.e., control of the bin filler's speed and height as well as the design of its "elephant ears") is needed to further decrease bruise damage.

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