DEVELOPMENT AND PRELIMINARY EVALUATION OF A NEW BIN FILLER FOR APPLE HARVESTING AND IN-FIELD SORTING MACHINE

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ABSTRACT. *The bin filler, which is used for filling the fruit container or bin with apples coming from the sorting system, plays a critical role in the self-propelled apple harvest and in-field sorting (HIS) machine that is being developed in our laboratory. Two major technical challenges in developing the bin filler are limited space in the HIS machine and high throughput. A literature review showed that despite many different types of bin fillers currently available for in-field use, none of them is suitable for the HIS machine because of their large size, use of the bin rotating design concept, and high unit cost. Effort has thus been made on the development of new bin filling technology for use with the HIS machine. The new bin filler mainly consists of a mechanical system with a pinwheel design and an automatic control system. A key innovation in the mechanical system is the use of two foam rollers to catch freely falling apples, which has greatly simplified the bin filler design and also made the system compact and lower in cost. The control system is mainly composed of an onboard Arduino microcontroller and three sensors (one infrared sensor and two Hall effect sensors) to monitor and measure the status of apples filling the bin as well as the rotational speed of the pinwheel. A program was developed for the Arduino microcontroller to record and process the data from the sensors in real-time to achieve automatic control of the bin filling. Laboratory tests with 'Gala' apples demonstrated that 97% of apples that had been handled by the new bin filler were rated Extra Fancy grade, and its performance exceeded the industry's requirement for bruising damage to apples.*

Keywords. *Apples, Automatic control, Bin filling, Bruising, Harvest, Sensors, Sorting and grading.*

Currently, manual harvest of apples using ladders and picking buckets or bags is still prevalent in the U.S. This traditional harvest method has overall low harvest efficiency and high strength requirements for workers (Peterson, 2005; Luo et al., 2012; Zhang et al., 2016b). In recent years, apple growers have become increasingly concerned about labor availability and cost. Hence, they have begun to look for alternative harvest methods to address these issues. Harvest platforms provide an immediate, practical solution to mitigate the labor availability and cost issues, and hence they have been increasingly used by growers in the U.S. in recent years (Baugher et al., 2009; Lehnert, 2013, 2014; Sazo and Robinson, 2013; Zhang et al., 2014, 2017a). Many different commercial harvest platforms are now on the market. Some of these platforms completely eliminate ladders and buckets by allowing workers to pick apples from elevated platforms and then place the apples on conveyors, while others still require workers to carry buckets for temporarily holding apples and then manually unload the apples into bins carried on the platforms. Overall, the use of these harvest platforms has improved the pickers' harvest productivity because the pickers no longer need to move, climb, and descend ladders, which take up more than 15% of harvest time (Zhang, 2015). However, the improvement in harvest productivity by adopting these platforms varies greatly (Robinson and Sazo, 2013) depending on the design of individual platforms as well as whether additional worker's time is needed for operating the platforms and handling bins.

One issue with the current apple harvest methods, either manual or platform-assist, is that all harvested apples of different quality grades (including fresh market, processing, and even defective) are placed in the same bins, and they go through the same postharvest handling procedures until the packing operation, during which fresh market grade fruit are separated from processing or defective fruit (Mizushima and Lu, 2011a, 2013a, 2013b). Hence, processing or defective fruit incur the same level of cost as fresh market fruit for postharvest storage and packing. This could result in significant reductions in profitability for growers and packinghouses because of the high cost associated with postharvest handling, especially when high percentages of processing or defective fruit are present (Mizushima and Lu, 2011b). Moreover, defective fruit are susceptible to pest and disease problems during storage, which could easily spread to high-quality fruit in the same bin, with the potential of causing

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devastating losses to growers and packers (Peterson et al., 2011). Hence, some growers have used in-field manual sorting as a potential solution to address the issue of mixed-quality apples in the same bin (Schotzko and Granatstein, 2005). However, in-field manual sorting is not cost-effective for growers, as it can negatively affect the pickers' harvest productivity. Most growers would not accept decreased fruit harvest productivity because of concerns over harvest labor shortage and short harvest time window (Zhang et al., 2016c). Pickers also do not have incentive to perform in-field manual sorting because they are usually paid on a piece-rate basis (McCurdy et al., 2003), and manual sorting could reduce their overall income due to decreased harvest productivity. Moreover, it is difficult for pickers to effectively separate fresh market fruit from processing fruit based on color and size, which are two major criteria that are used for grading apples.

Currently, commercial harvest platforms only have the harvest-assist function with limited sensing and automatic control features (Jones, 2015). Our laboratory recently developed a new apple harvest and in-field sorting (HIS) machine that combines the functions of harvest assistance and in-field sorting, among others, in order to maximize the economic benefits to apple growers (a further description of the machine is given below). In the design of the HIS machine, the bin filler is a crucial part of the whole system because it receives and places apples from the sorter and/or conveyor into the bin. Because of the limited space of the HIS machine, the bin filler needs to be compact so that it can be fully incorporated into the machine. The bin filler must handle apples gently to avoid or minimize bruising damage. Moreover, because the fruit is sorted into two or three quality grades simultaneously, multiple bin fillers are needed for the machine. This means that the bin fillers need to be simple and low in cost in order to keep the overall cost of the machine within a reasonable price range. With the use of multiple bin fillers, it is also crucial that they operate independently and automatically, with minimal or no human involvement during normal operation. Over the years, a large number of bin fillers have been developed or patented, some of which are currently being used for commercial harvest platforms. However, as shown by the brief review of the current status of bin filling technology (a detailed description is given below), none of these bin fillers can meet the specific requirements of the HIS machine. Subsequently, we have made considerable efforts in the development of new bin filling technology that is simple, compact, and low in cost, while being able to operate automatically and independently.

This article first gives a brief introduction to the current status of bin filling technology and an overview of the major features of the HIS machine. It then provides a detailed description of the development of an innovative bin filler for the HIS machine. Finally reported are the performance of the mechanical and control systems of the new bin filler and experimental evaluation of the bin filler on bruise damage to 'Gala' apples.

Materials and Methods

Current Status of Bin Filling Technology

Generally, there are two types of bin fillers, i.e., wet and dry (Peterson et al., 2010). Wet bin fillers use water as a carrying medium to place fruit into the bin, while dry bin fillers use mechanical methods (e.g., rotary pinwheels) to deliver fruit to the bin. A wet bin filler generally is not a suitable choice for in-field use because it can spread disease inocula from infected to non-infected fruit, needs a large volume of water, and has to deal with the wastewater (Hanks, 2006; Peterson et al., 2010; Schupp et al., 2011).

Based on where dry bin fillers are used, they can be further categorized into in-house and in-field. In-house bin fillers are mainly used in fruit packinghouses, while in-field bin fillers are used with harvest platforms. A large variety of in-house bin fillers have been developed for commercial use over the years (Main, 1996, 1998; Hanks, 2006; Peterson et al., 2010, 2011; Phil Brown Welding, 2016). However, their bulky size, complexity, and high cost prevent adoption for in-field use. Hence, several types of bin fillers for in-field use with different harvest platforms have been developed by commercial companies and researchers. The bin filler for the DBR apple harvester (Lehnert, 2010; Phil Brown Welding, 2016) employs a pinwheel design in which the bin remains stationary. While relatively simple, the DBR bin filler did not produce even distributions of fruit in the bin, and its automatic lifting function did not perform satisfactorily (personal observation during an orchard demonstration in Sparta, Michigan, on 6 October 2015). The bin filler developed by Zhang et al. (2014, 2016a) and Zhang and Heinemann (2017) also uses the pinwheel design concept, but it is only suitable for two pickers at a throughput of no more than 2 apples s^{-1}, which cannot meet the throughput of 6 fruit s^{-1} required by the HIS machine. However, most in-field bin fillers are based on the bin rotating design, which has been used with the Cornell harvester (Millier et al., 1973; Rehkugler et al., 1976), the Pluk-O-Trak machine (Munckhof, 2016), the Revo harvest system (Revo S.R.L., Cavareno, Italy), and the USDA-ARS apple harvest-assist platform (Peterson and Wolford, 2002, 2003a, 2003b). These bin fillers could present some safety concerns when operated in the field, considering that each bin weighs about 400 kg when fully filled. Moreover, the bin rotating design cannot be adopted when multiple bins are in operation simultaneously, which is the case for our HIS machine. Additionally, these bin fillers need much space to mount and operate, thus presenting major technical challenges for adaptation to our HIS machine. Hence, a new type of bin filler needs be developed for the HIS machine.

Overview of Apple Harvest and In-Field Sorting Machine

A self-propelled apple harvest and in-field sorting (HIS) prototype machine was designed and constructed in 2016 (figs. 1 and 2) in collaboration with a commercial horticultural equipment manufacturer in Michigan. With this new machine, two pickers stand on the ground and four stand on platforms at two different elevations to pick and then place fruit onto the harvest conveyors, which convey the fruit to

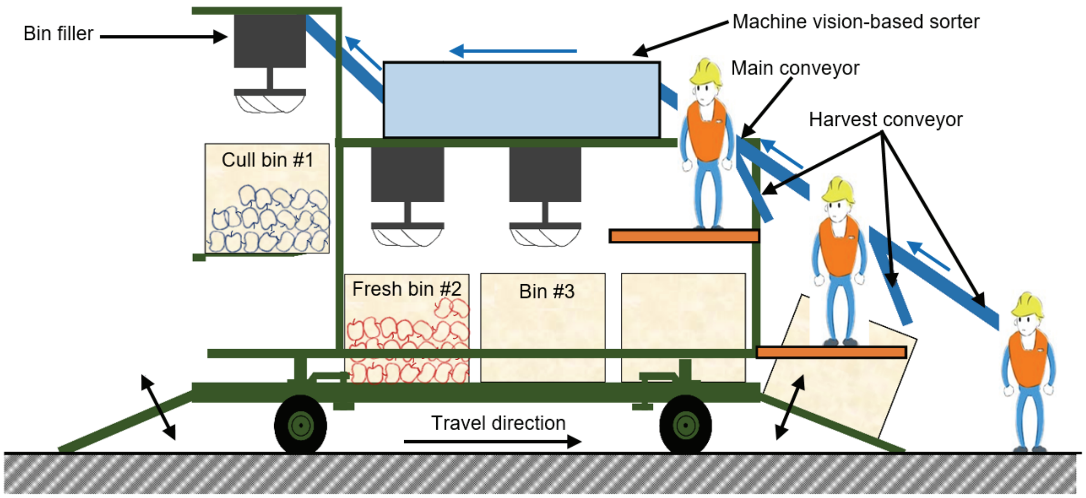


Figure 1. Schematic of the apple harvest and in-field sorting machine (Pothula et al., 2016).

Figure 2. Apple harvest and in-field sorting machine prototype being tested in a commercial orchard in Michigan during the 2016 harvest season (Zhang et al., 2017c).

the main conveyor. After exiting the main conveyor, the fruit enter the machine vision-based sorter. A specially designed conveyor of worm screw type is used for rotating and moving the fruit forward, during which time the fruit are aligned in linear sequence and singulated (i.e., separated by a specific distance between adjacent fruit) (Lu et al., 2016, 2017). As the fruit enter the imaging chamber, a digital color camera, mounted at the top of the sorter, takes 10 to 20 images of each fruit, depending on the actual fruit conveying speed, at a rate of 15 images s^{-1} under artificial illumination (i.e., LED lighting). An in-house developed computer program then processes the acquired images to grade each fruit based on color and size (the defect detection function is yet to be integrated). As the fruit arrive at the end of the sorter, the computer activates the corresponding sorting mechanism based on the grading results to guide the apples into different bins to separate fresh market apples from processing apples. Another important feature of the machine is the automatic and continuous handling of empty and full bins, which is critical for improving harvest efficiency but is not discussed here because it is not directly related to the bin filler development.

MAJOR CONSIDERATIONS FOR THE BIN FILLER

There are three bin fillers for the current version of the prototype machine to meet the need to sort apples into two quality grades (i.e., processing and fresh). At any given time, two bin fillers are in operating status, whereas the third bin filler serves as a backup bin when one of the operating bins is full. The bin filler plays a critical role in receiving apples exiting from the sorter (for fresh bin #2 in fig. 1) or the conveyor (for cull bins #1 and #3 in fig. 1) and then placing the apples in the bins evenly without causing bruising damage.

Generally, the bin fillers need be compact so that they can be incorporated into the machine within the limited space available. They should cause minimal or no bruising damage to fresh apples (although the requirement for processing apples can be somewhat lower). As required by the apple industry, at least 95% of the fruit that have been handled by the bin fillers should be graded Extra Fancy (Peterson et al., 2010). Each bin filler needs to operate automatically and independently with minimal or no human involvement during normal operation. Because of the rugged working conditions (e.g., water, dust, and rough and uneven terrain), these bin fillers should be simple and reliable in performance, as well as low in cost.

The bin filler's dimension requirements are shown in figure 3. The distance from the sorter to the top of the bin (A in fig. 3) is 0.86 m, and this sets the vertical dimension limit for the bin filler when it is in the fully retracted mode. Because the bruising thresholds (i.e., the drop height at which bruising begins to occur) for hard surfaces (e.g., wood) and between apples are 10 and 20 mm, respectively (O'Brien, 1980; Hyde, 1997), the bin filler should maintain a drop height of less than 10 mm for discharging apples. Thus, at the initial filling stage (left diagram in fig. 3) and during the filling process, the bin filler should be fully inserted into the bin and maintain contact (i.e., zero distance) with the bin floor (at initial filling) or with the apples already in the bin to avoid bruising. A typical commercial bin has dimensions of 1.22 m length (C in fig. 3), 1.02 m width (not shown in fig. 3), and 0.81 m height (B in fig. 3). In the fully extended mode (initial filling), the bin filler is also at its maximum length of 1.68 m (i.e., the total of A and B in fig. 3). Thus, the bin filler should have a stroke equal to or greater than the bin height (B in fig. 3, or 0.81 m), and its overall dimensions are determined by the dimensions (i.e., length and width) of the bin.

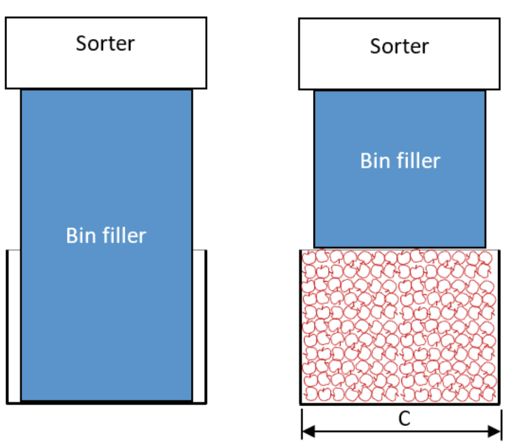


Figure 3. Bin filler's dimension requirements for initial filling (left) and end of filling (right), where A is the distance between the sorter and bin, B is the bin height, and C is the bin length (bin width not shown).

Table 1. Specific requirements for the bin filler.

Requirement	Specification
Length in fully retracted mode	≤0.86 m
Length in fully extended mode	≥1.68 m
Stroke	≥0.81 m
Width[a]	≤1.02 m
Length[a]	≤1.22 m
Throughput[b]	≥6 apples s^{-1}

[a] Corresponding to the bin dimensions.
[b] Three lanes with throughput of ≥2 apples s^{-1} in each lane.

System throughput is another important design consideration. The machine was designed for throughput of 6 apples s^{-1} (assuming that each worker picks one fruit per second). Hence, the bin filler system should have the capacity to handle at least 6 apples s^{-1}. As apples enter the sorter, they are singulated and aligned in three lanes. This means that the bin filler needs to handle apples at a speed of 2 apples s^{-1} $lane^{-1}$. The major design requirements for the bin filler are summarized in table 1.

MECHANICAL SYSTEM

Based on a literature review and the technical and dimensional requirements for the bin filler (table 1), it was decided that the spinning pinwheel design (Lehnert, 2010; Phil Brown Welding, 2016) would be the most feasible approach for the current machine. The bin spinning method or the spinning cylinder brush, which are commonly used with commercial harvest platforms, were not chosen because of the limited space and the need to operate multiple bin fillers in the HIS machine. During the initial filling stage, fruit need to descend a maximum distance of 1.68 m from the sorter to the bin. Hence, it would be neither practical nor efficient to use a vertical fingered belt or similar design. After comparing and evaluating various design concepts, we decided to adopt a special speed reduction mechanism that allows apples to fall freely from the sorter. The key consideration for the mechanism was to have the ability to catch freely falling apples, without causing collisions between falling fruit, and then discharge the apples to the pinwheel quickly (at a throughput of at least 2 apples s^{-1} $lane^{-1}$) and evenly. As shown later, adoption of the free-fall concept led to great simplification of the bin filler design. The mechanical system of the bin filler is shown schematically in figure 4. The system consists of a track guide, fruit speed reduction or receiving foam rollers, guiding panels, and distribution pinwheel.

The track guide, consisting of guiding curtains (adjustable wind shade; Newell Brands, Hoboken, N.J.) and sliders (drawer slider; Fulterer, Inc., Ontario, Cal.), needs to be retractable, and its stroke is equal to or greater than the height of the bin (i.e., 0.81 m). The retractable guiding curtains guide falling apples to the gap between the two foam rollers (a detailed description is given below). The distance between the two guiding curtains is larger at the top than at the bottom, forming a funnel-like shape, to ensure that apples fall directly into the gap between the two foam rollers. The guiding curtains should also be able to absorb the falling apples'

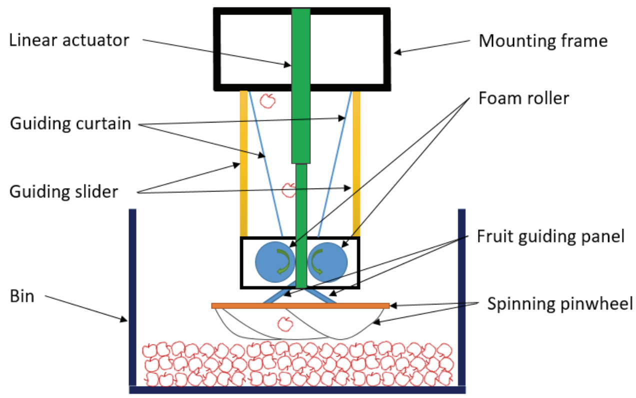


Figure 4. Schematic of the bin filler.

kinetic energy and not allow the apples to bounce around. When bouncing occurs, the bouncing apple may collide with later falling apples because of the relatively high throughput (2 apples s^{-1} $lane^{-1}$). Vertical movement of the bin filler is achieved with a linear actuator and two guiding sliders.

The two foam rollers (fig. 5), mounted immediately beneath the guiding curtains, receive the fruit and fully absorb the apples' kinetic energy (the maximum speed of apples arriving at the foam rollers is approximately 6 m s^{-1}) without bouncing and bruising the fruit, and then discharge the apples promptly (within ~0.5 s) without causing a delay. If apples bounce back or cannot be discharged within 0.5 s, then apple-to-apple collisions at the foam rollers can cause serious bruising damage. To assist with fruit discharge, the two foam rollers rotate in opposite directions (toward each other). The foam rollers have a diameter of 140 mm (B in fig. 5), with a soft and resilient outside layer (25.4 mm thickness memory foam; Carpenter, Inc., Richmond, Va.) and a hard core (foam roller; Isokinetics, Inc., De Queen, Ark.). The elasticity of the soft foam is 13.0 kPa, which was measured in compression tests with a texture analyzer (TA.XT2i, Stable Micro Systems, Surrey, U.K.). The hard core has a diameter of 60 mm (A in fig. 5), and the center-to-center distance between two foam rollers is 165 mm (C in fig. 5).

The foam rollers provide an effective means of catching the falling fruit. Because the outer layer is soft, it does not cause any bruising damage to the apples. At a rotating speed of 45 rpm, the foam rollers theoretically discharge apples in 0.3 s (assuming that apples are discharged when the foam rollers rotate 90°) and, at the same time, greatly slow the speed of the falling apples. As the apples fall into the gap between the rotating foam rollers, they are driven by the rollers and then discharged before later apples arrive. The gap between the two foam rollers when not compressed (~25 mm) needs to be smaller than the diameter of smallest apples (>25 mm) to prevent apples from falling freely. In addition, the gap between the two foam rollers when compressed to their maximum (~105 mm) needs to be larger than the diameter of largest apples (<100 mm) to avoid damage caused by pressing the fruit against the hard core of the rollers. The construction of the two foam rollers allows apples with diameters ranging from 25 to 105 mm to pass smoothly. After exiting the foam rollers, two fruit guiding panels, which are installed just below the foam rollers but in opposite directions, guide the apples to the distribution pinwheel mounted immediately below (a detailed description is given later). The use of foam rollers greatly simplifies the bin filler's design and makes the entire system compact and easy to construct.

After exiting from the guiding panels, the apples drop to three specific areas (corresponding to the three lanes). The distribution pinwheel aims to distribute apples from the three small dropping areas to the bin uniformly without causing bruising damage. The current pinwheel has four compartments, each consisting of a soft, deformable, floating pad, to move apples from the place where they drop to a place with fewer apples. Additionally, the four compartments also act as a cushion between the falling apples and the apples already in the bin to avoid direct collisions.

Four 12 VDC motors are used in this design, with two motors (~25 W, ~45 rpm) to power the foam rollers, one motor to power the pinwheel (~25 W, ~20 rpm), and one linear actuator (~50 W, speed of ~7 mm s^{-1}) that lifts the unit of the foam rollers, guiding panels, and distribution pinwheel (UFGD).

Control System

The operation of the bin fillers is fully automated through the onboard control system, which mainly consists of microcontrollers and sensors. The control system has two major functions: detecting the level of apples in the bin, and triggering the linear actuator to lift the UFGD as fruit are filling into the bin.

Microcontrollers

An open-source microcontroller platform (Arduino UNO R3, Arduino LLC, Ivrea, Italy) collects and processes real-time data from the sensors and decides when to lift the UFGD. Once the decision to lift the UFGD is made, the Arduino microcontroller activates the linear actuator through specially designed circuitry consisting of two relays (Jameco Electronics, Belmont, Cal.). Before lifting the UFGD, the microcontroller first confirms the status of the Hall effect sensor mounted on the linear actuator to determine if the bin

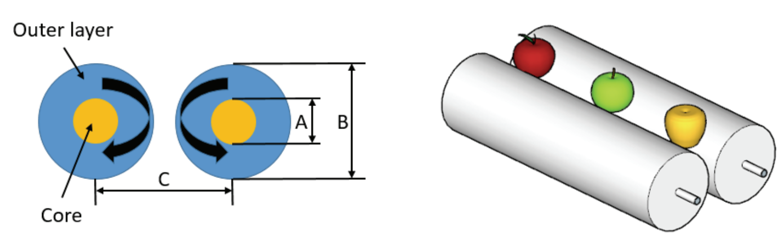


Figure 5. Schematic of the foam rollers in side view (left) and 3-D model (right), where A is the diameter of the hard core (60 mm), B is the diameter of the outer layer (140 mm), and C is the center-to-center distance between the two foam rollers (165 mm) (Zhang et al., 2017b).

is fully filled. If the bin is already filled, the microcontroller activates the automatic bin handling system (not presented in this article); otherwise, the UFGD is lifted. Another microcontroller (Scorpion XL 2.0 DC motor driver, Robot Power, Olympia, Wash.) controls the speed of the pinwheel motor. If the motor speed is too high, the pinwheel will cause damage to the apples during distribution, whereas if the speed is too low, apples will accumulate on the pinwheel. The motor driver microcontroller is connected with and controlled by the Arduino microcontroller.

Sensors

Three sensors are used in the control system, including one IR sensor and two Hall effect sensors. The IR sensor (GP2Y0A41SK0F, Sharp Devices, Munich, Germany) obtains the fill level of apples in the bin by measuring the maximum distance between the IR sensor (fixed on the frame above the pinwheel) and the pinwheel's floating pads. As the bin is filled with apples, the maximum distance between the IR sensor and the pinwheel's floating pads decreases because the increased apple level in the bin pushes the pinwheel's floating pads upward. A distance threshold is preset in the software developed for the Arduino microcontroller, which compares the real-time data obtained from the IR sensor and then decides if the UFGD should be lifted.

Two identical Hall effect sensors (MiniInTheBox, Seattle, Wash.) are used, with one monitoring the pinwheel's rotating speed (rpm) and the other indicating if the linear actuator is fully retracted (and thus the bin is fully filled). Two magnets, which are used to trigger the Hall effect sensors, are installed on the spinning pinwheel and at the bottom of the cylinder tube of the linear actuator, respectively. When the magnet mounted on the pinwheel approaches the Hall effect sensor, the sensor is activated to send the distance data to the Arduino microcontroller, which then calculates the pinwheel's speed (rpm). When the bin is fully filled (and the linear actuator is in its fully retracted position), the Hall effect sensor is activated to trigger the Arduino microcontroller to activate the automatic bin handling system to unload the fully filled bin to the ground and then move an empty bin into the positon vacated by the full bin.

Control System Circuitry

Based on the requirements for handling the bin filler, a circuit for the control system was designed (fig. 6). The Arduino microcontroller controls the Scorpion microcontroller, which determines the motor speed for the pinwheel. The two motors for the foam rollers are directly connected to the 12 VDC power source. The Arduino microcontroller activates the linear actuator via a circuit consisting of two relays. A fuse (20 A at 12 VDC) is used for system safety. A voltage regulator is used to power the microcontrollers.

Software Development

A software program for the Arduino microcontroller was developed to perform the described functions, including communication with the sensors to obtain real-time data, data processing to make decisions on lifting the UFGD, and activation of the linear actuator. Figure 7 shows the flowchart of the bin filler's software program. Four steps are conducted to decide whether to lift the UFGD: calculating the pinwheel speed (RPM), obtaining the maximum distance (Distance) between the IR sensor and the floating pads, comparing RPM and Distance with the preset values, and checking the bin's filling status. When both RPM and Distance are smaller than the preset values, and if the bin is not fully filled, the linear actuator lifts the UFGD. If the bin is already filled, the automatic bin handling system is activated. For calculating the pinwheel speed, the system time is recorded by the Arduino microcontroller three times as the magnet mounted on the pinwheel approaches the Hall effect sensor. When the magnet approaches the Hall effect sensor a fourth

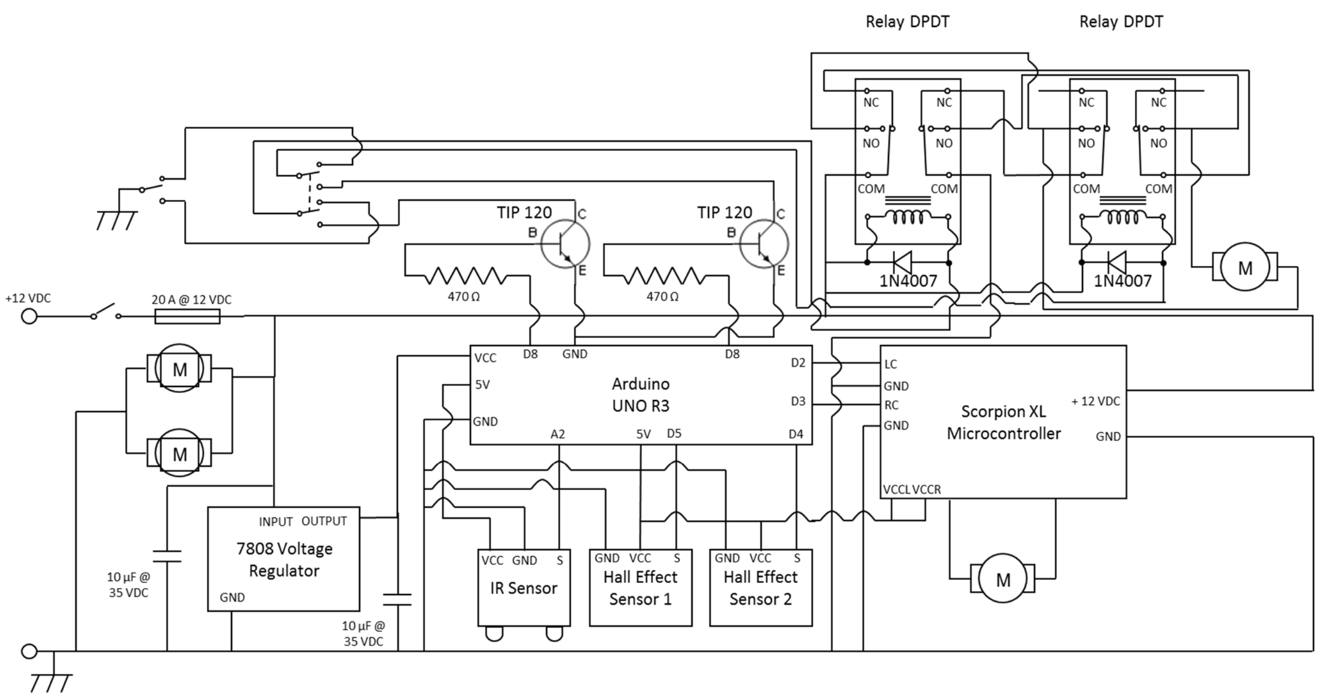
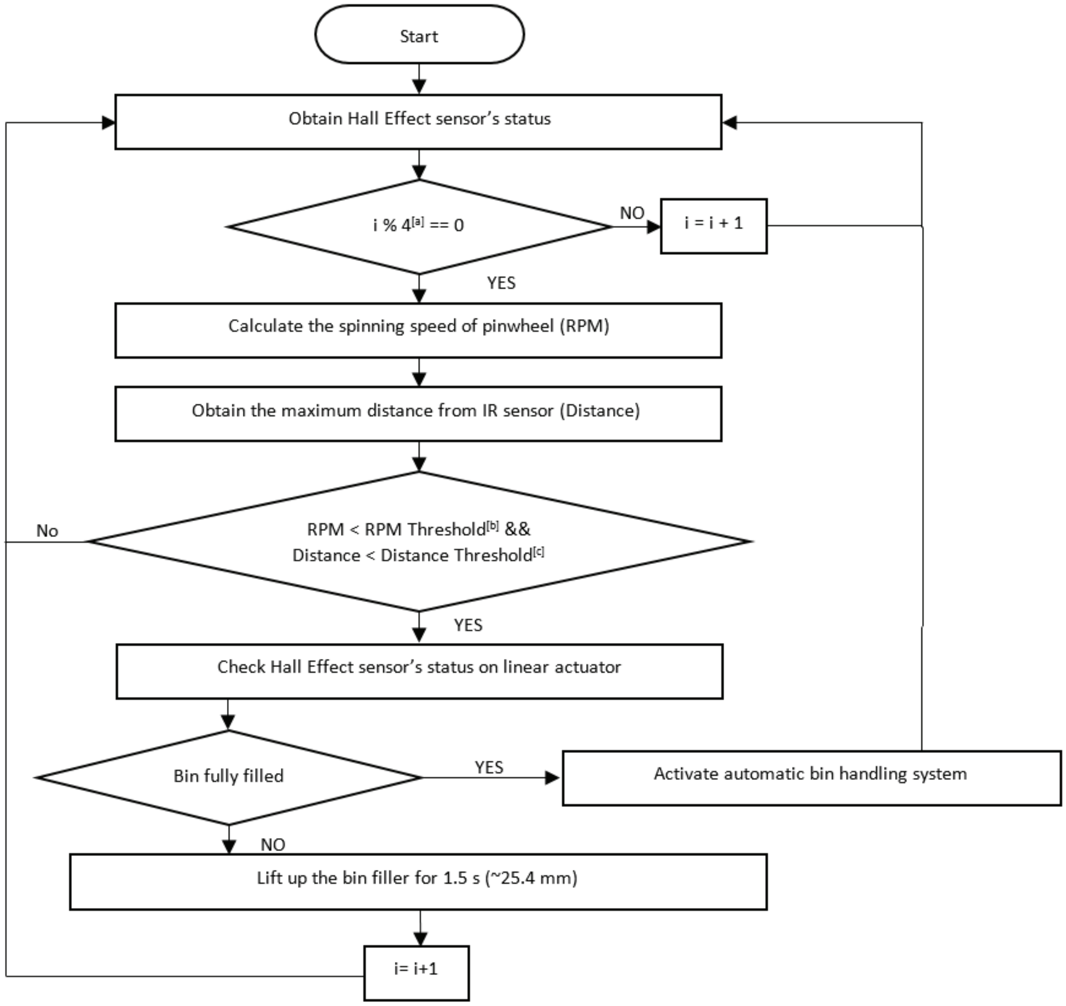


Figure 6. Schematic of the control system circuitry for the bin filler.



[a] When the magnet is detected by the Hall effect sensor, the counter (i) is incremented by 1. Four rotations are needed to calculate the pinwheel's speed.
[b] RPM Threshold is the preset pinwheel speed threshold.
[c] Distance Threshold is the maximum distance threshold between the IR sensor and the pinwheel's floating pads.

Figure 7. Flowchart of the software for automatically monitoring, recording, and controlling the bin filler.

time, the Arduino microcontroller uses the three recorded times to calculate RPM; thus, four pinwheel rotations are needed to calculate RPM.

Laboratory Tests of the Bin Filler

After completion of the design and assembly of the mechanical and control systems of the bin filler, preliminary laboratory tests were conducted for evaluating the system's reliability and its performance in terms of bruising damage to apples, which is critical for handling fresh apples.

Three bushels of 'Gala' apples (total of 260 fruit) were obtained from a commercial packinghouse in Sparta, Michigan, in July 2016 and kept in cold storage at 2°C (35°F) prior to the experiment. The diameter and height (between the stem and calyx ends) of the apples were measured to be 70.7 ±4.3 mm and 69.0 ±4.6 mm, respectively, with maximum and minimum diameters of 82.0 and 59.0 mm and maximum and minimum heights of 81.6 and 55.5 mm. The dimensions of the apples were well within the foam rollers' working range of 25 to 105 mm. Because there were pre-existing bruises on the test apples, each apple was pre-checked manually, and all bruises were marked with a permanent black marker. Hereafter, the discussion of bruises only refers to newly created bruises, not the pre-existing bruises. The apples were taken out of cold storage and kept at room temperature (~22°C) for about 4 h before the experiment. Two people, standing at two sides of the bin filler (simulating two lanes), dropped apples at a speed of approximately 2 apples s^{-1} $person^{-1}$. Because the three lanes are independent, the system would meet the design requirements if one lane works satisfactorily. The dropping position was directly above the gap between the two foam rollers, at a distance of approximately 1.5 m.

The pinwheel speed is a crucial factor affecting apple bruising incidence and, based on previous and preliminary tests in this research, the pinwheel speed was set at 18 rpm via the motor driver. If the speed is too low, the pinwheel will not discharge apples promptly, causing apples to clog the floating pads; if the speed is too high, apples will exit the floating pads at high speeds, potentially causing bruising. The threshold value set in the program was 15 rpm (RPM Threshold in fig. 7), and the distance threshold value set in the code for the IR sensor was 152 mm (Distance Threshold in fig. 7). If the distance threshold is too small, apples may

Table 2. Classification of bruise damage (Peterson et al., 2010).

Class	USDA Fresh Market Standard	Bruise Specification
1	Extra Fancy	No bruising
2	Extra Fancy	Bruise diameter ≤3.2 mm (1/8 in.)
3	Extra Fancy	Bruise diameter 3.2 to 6.4 mm (1/8 to 1/4 in.)
4	Extra Fancy	Bruise diameter 6.4 to 12.7 mm (1/4 to 1/2 in.) or area of several bruises <127 mm^2
5	Fancy	Bruise diameter 12.7 to 19 mm (1/2 to 3/4 in.) or total area of multiple bruises <283 mm^2
6	Downgraded	Bruises larger than the tolerances in Fancy
7	Downgraded	Cuts or punctures of any size

clog at the floating pads; if the distance threshold is too large, apples may drop too far from the floating pads and exit with high speeds, potentially causing bruising. When the real-time pinwheel speed was less than 15 rpm and the real-time maximum distance detected by the IR sensor was less than 152 mm, the linear actuator lifted the UFGD about 25.4 mm if the bin was not fully filled.

After testing with the 260 apples, the apples were collected from the bin carefully (to avoid extra bruising) and tested two more times to better assess the performance of the bin filler. After the laboratory experiment, all apples were kept at room temperature (~22°C) for 24 h to allow bruises to develop. Thereafter, each apple was peeled and evaluated based on the USDA Fresh Market Standards, as shown in table 2 (Peterson et al., 2010).

Results and Discussion

Mechanical System

The mechanical system was run numerous times in the laboratory environment to evaluate its performance and reliability. The linear actuator and sliders were sufficiently stable for moving the UFGD up and down smoothly. The guiding curtains moved up and down smoothly according to the linear actuator movement while remaining tight all the time. When apples did not directly drop into the gap between the foam rollers, they sometimes collided with the tight curtains. When this happened, it was observed that the collisions between the apples and curtains did not cause bruising to the apples due to the flexibility and tightness of the curtains. The falling apples did not bounce around or backward, nor collide with other falling apples. For apples that directly dropped in the center of the gap, the foam rollers discharged the fruit at a speed controlled by the foam rollers. For apples that did not drop directly into the gap but dropped onto the surface of a foam roller, the rollers guided and transported them quickly into the gap without causing collisions with later apples. When the bin filler was tested with 780 apples (260 apples per run with three replications) at a throughput of 2 apples s^{-1} lane^{-1}, apple-to-apple collisions at the gap of the foam rollers were not observed, suggesting that the system worked satisfactorily at this throughput. Hence, the foam rollers met the design requirements of absorbing most of the fruits' kinetic energy without bouncing fruit around, and discharging apples within 0.5 s. After exiting the foam rollers, apples arrived at the pinwheel via the guiding panels. In this experiment, apple distribution via the pinwheel was only evaluated visually, which was satisfactory. However, further tests, along with a quantitative distribution evaluation, are needed to fully evaluate the performance of the bin filler in distributing apples in the bin. Overall, the mechanical system functioned satisfactorily and reliably during the preliminary laboratory tests, which bodes well for satisfactory in-field performance.

Control System

Monitoring the Pinwheel Speed

The Arduino microcontroller obtained real-time data from the Hall effect sensor. When the magnet mounted on the pinwheel was not detected by the Hall effect sensor, the Arduino microcontroller returned a value of "0", whereas when the magnet appeared below the Hall effect sensor, the microcontroller returned a value of "1". A sample of real-time data obtained by the Arduino microcontroller from the Hall effect sensor, which was used to calculate the pinwheel's rotating speed, is shown in figure 8. The times recorded by the Arduino microcontroller when the magnet was within the Hall effect sensor's range of detection for the first, second, and third times were 817, 4001, and 7196 ms, respectively (fig. 8). Thus, the two time intervals were calculated to be 3184 and 3195 ms, respectively. This corresponded to 18.8 rpm, which is greater than 15 rpm (the preset RPM Threshold), and hence there was no need to lift the UFGD.

Monitoring the Apple Level in the Bin

The Arduino microcontroller recorded data from the IR sensor, from which the distance between the IR sensor (mounted at a fixed place above the pinwheel) and the pinwheel's floating pads was calculated in real time. Because of the pinwheel's rotation and the inclined shape of the floating pads, the obtained real-time distance varied with time. Each pad was attached to the pinwheel with a horizontal bar. When the bar appeared immediately below the IR sensor, the minimum distance was obtained. When the bar spun away from the IR sensor, the real-time distance increased gradually to the maximum value. The maximum distance was used for determining the apple level in the bin. The maximum distance decreased as the bin was filled with more apples, thus pushing the floating pads upward. After the maximum distance had been reached, the recorded data decreased sharply

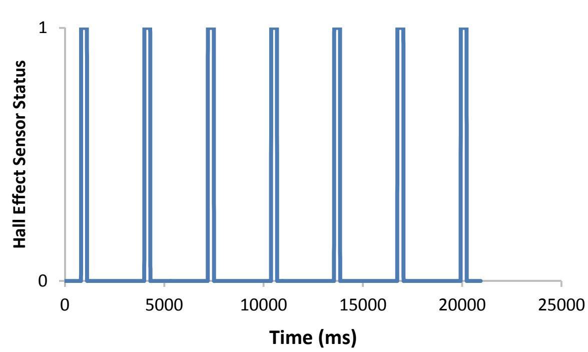


Figure 8. Real-time data obtained by the Arduino microcontroller from the Hall effect sensor, where "0" indicates that the magnet was not detected by the sensor, while "1" indicates that the magnet was detected by the sensor.

to the minimum value, because the horizontal bar again appeared in the sensor's field of view after one revolution, and then increased as a floating pad entered the sensor's detection zone. The Arduino microcontroller obtained data from the IR sensor continuously for about 500 ms, which guaranteed that at least one floating pad was fully detected. A sample of real-time data obtained by the Arduino microcontroller from the IR sensor is shown in figure 9. The maximum distance recorded (fig. 9) was 228.6 mm, which is greater than the preset threshold of 152 mm. Thus, no action was needed to lift the UFGD.

During the preliminary tests, the control system performed satisfactorily and reliably overall. With the increasing level of apples, the UFGD was lifted automatically at the right time to maintain the desired distance between the pinwheel and the apples. If the UFGD was lifted too late, the pinwheel would be saddled with too many apples, which is not desirable for uniform distribution of apples in the bin. If the UFGD was lifted too early, the distance between the pinwheel and the apples would be too large, increasing the chance of causing bruising damage due to the large free-fall distances.

Apple Bruise Evaluation

Based on the newly generated bruises, the apples were classified, based on USDA Fresh Market Apple Standards (table 2), as Extra Fancy, Fancy, or Downgraded. If categorized as Extra Fancy (no newly created bruises or just small bruises with total bruise area less than 127 mm^2), the apples were of fresh market quality. However, if categorized as Fancy and Downgraded (large size bruises, cuts, and/or punctures), the apples were considered processing apples or culls.

The cumulative apple bruising results from the three tests are shown in figure 10. It can be observed that: 30% of apples were not bruised at all (class 1), 91% of apples were Extra Fancy grade (classes 1 to 4), 7% of apples were Fancy grade (class 5), 2% of apples were Downgraded (class 6), and no apples had cuts or punctures (class 7). Because the apple bruising conditions were accumulated (9% in total) during the three drop tests, it was reasonable to assume that only about 3% apples had been bruised in each drop. Commercial apple bin fillers are required to have 95% or more apples be Extra Fancy grade (Peterson et al., 2010), and our bin filler had 97% in the Extra Fancy grade. Hence, the bin filler would be suitable for use as a modular system for the HIS machine. Additionally, our bin filler has potential to be adopted for other commercial apple harvest platforms and for use in packinghouses. However, the apples used for the tests in this study had been in controlled-atmosphere storage for about nine or ten months. It is well known that bruise susceptibility depends on the condition of the apples; generally, apples are more susceptible to bruising when freshly harvested than after storage (Hyde, 1997). Hence, more extensive evaluations of the bin filler are needed, especially in orchard environments.

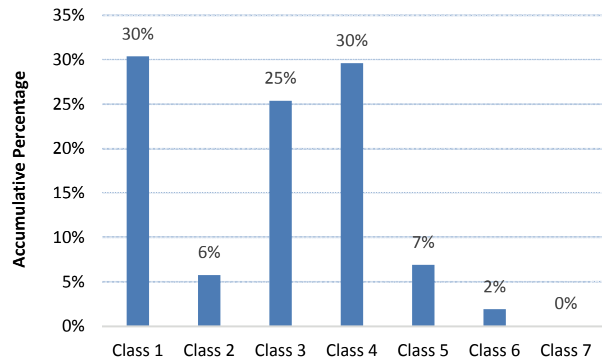


Figure 10. Cumulative quality grading results for 'Gala' apples after three tests with the bin filler (classes 1 to 7 are based on USDA Fresh Market Standards, see table 2).

Compared to the bin fillers reported in previous studies, our bin filler performed quite satisfactorily overall. After

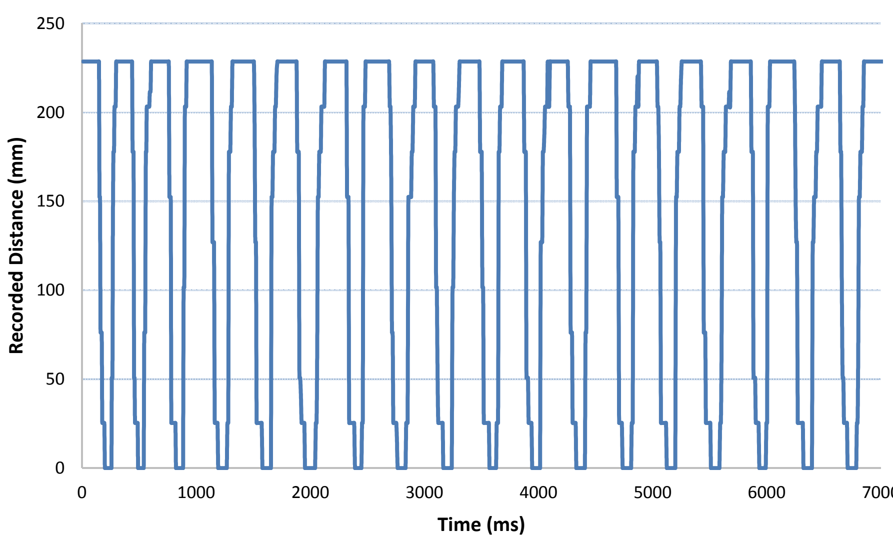


Figure 9. Real-time data recorded by the Arduino microcontroller for the distance between the IR sensor and the pinwheel's floating pads. The real-time data were first rounded down to the nearest integer in inches and then converted to mm; the value of 0 mm means that the distance between the sensor and the floating pad is less than or equal to 25.4 mm.

testing their new bin filler at 6 apples s^{-1}, Peterson et al. (2010) reported that approximately 97% of the apples ('Fuji' and 'Golden Delicious') were graded Extra Fancy after being handled by the bin filler, which is the same as our result. However, they also reported cuts and punctures (class 7 in table 2) in some apples, which did not occur during the tests of our bin filler. Schupp et al. (2011) tested the DBR vacuum apple harvester in an orchard (the filling speed was not reported but assumed to be approximately at 3 to 4 apples s^{-1}) and reported that about 94% of apples ('Golden Delicious', 'York', and 'Pink Lady') handled by the bin filler were graded Extra Fancy. Zhang et al. (2016b, 2017a) reported that 98% of 'Fuji' apples were graded Extra Fancy when their two bin fillers were tested in the field. However, both bin fillers were tested at a filling speed of 2 apples s^{-1}, and it is anticipated that more bruises would occur if they ran at a higher speed (e.g., 6 apples s^{-1}).

CONCLUSION

A new apple bin filler, which mainly consists of mechanical and automatic control systems, was developed for incorporation into the new apple harvest and in-field sorting machine. A major innovation of the bin filler was the use of a pair of foam rollers to receive apples falling freely from the sorting system and then release them at a lower speed without causing bruising damage. This innovative design makes the bin filler much simpler, more compact, and easy to mount on the harvest and in-field sorting machine developed by our laboratory, and it can be easily adapted to other harvest platforms. An onboard microchip controller, coupled with an IR sensor and two Hall effect sensors, was used for automatically measuring and controlling the distance of the bin filler relative to the apple level in the bin and the rotating speed of the pinwheel. The bin filler demonstrated satisfactory performance when tested at a speed of 4 apples s^{-1} with two lanes. Bruise evaluation tests showed that about 97% of the apples that had been handled by the bin filler were rated Extra Fancy, exceeding the 95% requirement for commercial bin fillers for fresh market apples. Although the bin filler showed satisfactory performance in laboratory tests, in-field conditions are much more complex than laboratory conditions. The travel and vibration of the machine in an orchard and uneven or sloping ground could affect the apple trajectory from the sorter to the foam rollers. Additionally, apples picked in an orchard may have twigs or leaves, which could cause improper functioning of, or even damage to, the foam rollers (e.g., piercing of the soft memory foam, or clogging at the foam rollers), thus causing bruising or even cuts or punctures of the apples. Thus, further in-field tests of the bin filler are needed for different apple cultivars with a large range of fruit sizes to ensure that the bin filler meets the operational requirements for orchard use.

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