Augmented Fruit Harvesting

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1. Introduction

The Comprehensive Automation for Specialty Crops (CASC) project comprises twelve efforts ranging from the development of autonomous vehicles for navigation through orchards to smart traps for detecting insect infestation to scouting technologies for machine vision for crop load and ripeness evaluation. This technical report documents a design study for the Augmented Fruit Harvest effort of CASC. While this effort is only one of a dozen with CASC, it has the potential to have the greatest economic impact on orchard operations.

The primary focus of the augmented fruit harvesting research effort is to identify and develop fruit harvesting solutions that enable growers to reduce their harvesting production cost as well as decrease the amount of fruit damaged during harvest. The largest contributing factor to harvesting production costs is the cost of labor. Therefore, the design philosophy governing our engineering decisions is to determine what designs have the greatest potential of reducing grower's input costs. Our approach is to develop systems that enable current workers to simply harvest fruit more efficiently as compared to current practices, rather than focusing on replacing the laborer entirely. While considering ways of improving worker efficiency, careful attention is still considered for creating solutions that enable a reduction in fruit damage during harvest. Overall, these two factors were the leading design requirements used in determining conceptual augmented fruit harvesting solutions.

The end-users of the augmented fruit harvesting designs can be categorized into two areas based upon the size of the grower and the geographical location of the orchards. The distribution of apple production for the top producing states in the United States is shown in Table 1. Clearly, one can identify the distinct variation in apple orchard acres between the West and East coasts. In addition to acreage, the geographical layout of orchards in the East and West coast are different as well. From various field visits to apple producers, the harvesting practices from each region require different approaches. The average orchard acreage in Pennsylvania is on the order of 100-200 acres, while the median orchard size in Washington is 400-500 acres [2, 3]. By taking this into consideration, there are currently two approaches underway to develop products for each size of producer. First, the larger orchards are most suitable for fruit harvesting solutions that potentially require a significant capital investment. Second, our team is focused on developing solutions that provide the largest benefit at the smallest possible capital investment. This approach should provide the greatest value to small-scale producers regardless of location, but should benefit large-scale producers as well.

Table 1. Top apple-producing states based upon acres [1].

State	Area (acres)
1. Washington	158,000
2. New York	42,000
3. Michigan	35,000
4. Pennsylvania	21,500

2. Fruit Harvesting

We conducted a review of apple fruit harvesting to better understand the current harvesting practices utilized by fruit growers, as well as to determine what limitations and inefficiencies exist in those process. The harvesting process consists of four stages: positioning, picking, transport, and bin filling as shown in Figure 1. The first stage is for a worker to position him/herself so he/she is able to harvest the desired pieces of fruit. The second stage is the actual removal of the fruit from the tree. The third stage is transporting of the fruit to the bin. The fourth stage is filling the bin with all the harvested fruit.

One important note is that not all harvesting systems currently used by growers are divided into these distinct stages. Some of the stages are combined, but all harvesting operations have some configuration of these four stages. For example, positioning can include a manually positioned ladder or an elevated orchard platform. Currently all fruit picking is performed by workers. In regards to transport and bin filling, some harvesting systems combine these stages as in the conveyor harvester shown in Figure 2 (left), while other systems require the human worker to perform the transport and bin fill stages during harvest, shown in Figure 2 (right). Regardless, the fruit harvesting process requires some way of transporting fruit to a bin and filling the bin when the fruit arrives. This stage of our research focused on identifying alternatives to current practices in fruit transport and bin filling. In our opinion the largest productivity losses occur when the worker is spending time handling fruit while not being able to continuously focus on harvesting the next piece of fruit.

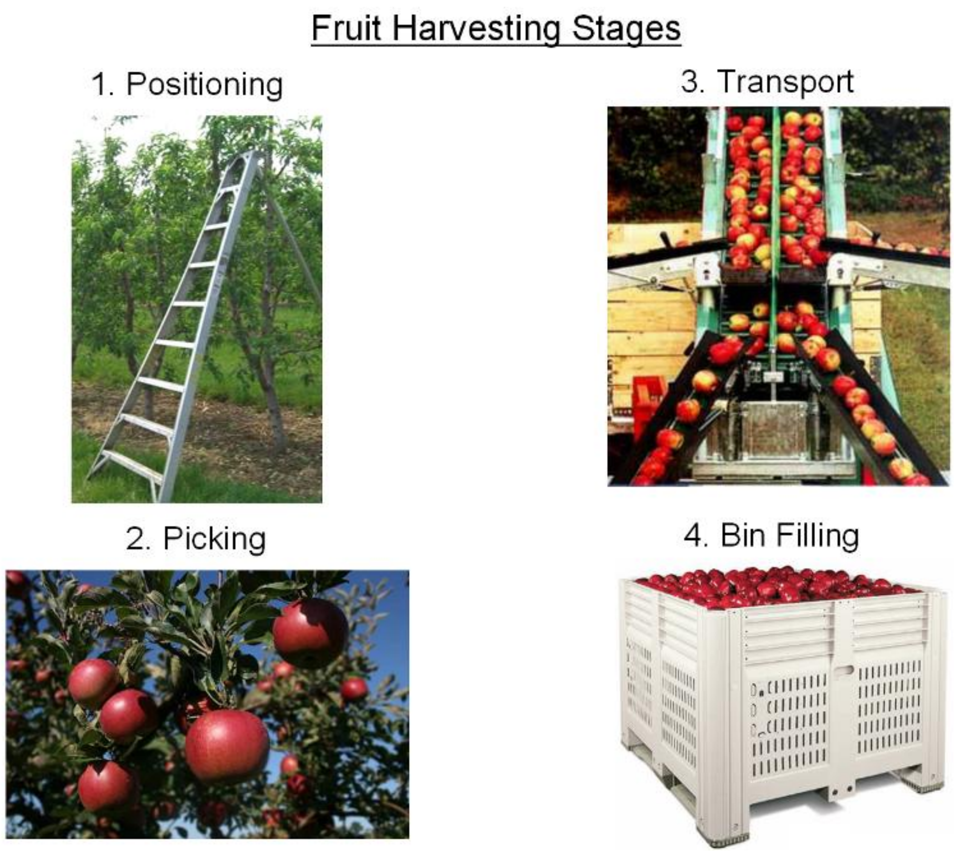


Figure 1. The four fruit harvesting stages.

Figure 2. Conveyor harvester (left) and orchard platform (right) used to harvest fruit [4,5].

3. Design Requirements

There are very few commercial machines for fruit harvest against which we could benchmark our concepts. Consequently, we compared our solutions with the traditional practice of harvesting fruit with a ladder and a bag. At this point it is premature to quantitatively compare our ideas with existing alternatives. Instead, we determined eight evaluation criteria that we used to qualitatively assess each design concept: (1) cost, (2) complexity, (3) robustness, (4) weight, (5) ergonomics, (6) ease of integration, (7) productivity, and (8) potential for fruit damage. These criteria are described below. Based on these criteria, we will determine which concepts should be developed further, and these will be quantitatively assessed when prototypes are designed and tested.

<u>Cost:</u> The cost for each proposed design was estimated based upon the cost of hardware and components necessary to fabricate a preliminary product. As further research is conducted these estimates may vary significantly, but the important idea is to identify the relationship between the costs for all of the proposed designs.

<u>Complexity:</u> Complexity is an important factor that determines the amount of skill or operator input required to utilize a system. Three contributors to complexity are the number of active/passive components, type of operator control, and relative measure of hardware/fabrication complexity. Active components are defined as those that actively monitor and control the system with human or computer assistance. Passive components, on the other hand, perform no monitoring or control function. For each design all active and passive components are identified and explained. The type of control can include human, semi-automated, or fully automated control. Control is identified as the component responsible for making the decisions necessary for the system to function, either human or machine control. Finally, the hardware/fabrication complexity relates to the need for complex machining operations (e.g. milling versus stamping) and complex assembly (e.g. manual versus automated). Our evaluation of complexity as a whole is a relative measure with three levels: low, medium and high.

Robustness: Robustness refers to the capability of a design to withstand the rigors of normal operating conditions. We considered the following four aspects: (1) the number of mechanized components, which is determined by approximating the number of hardware components required by the design; (2) the estimated number of machine cycles before maintenance or repair is required. The determination of what a machine cycle is for each design will vary and is outlined in the following descriptions of the designs; (3) the failure modes, which are used to identify wear items or complex parts that have the potential of fatigue and failure over time; and (4) the estimated downtime for routine maintenance or repair under normal operating conditions.

Weight: Current harvesting practices are extremely labor-intensive and are very fatiguing to a worker. We considered (1) the amount of weight the human is supporting and (2) the amount of weight the machine is supporting, both in pounds. However, we evaluated the weight borne by the human not only by the amount, but also by what part of the human body will bear the weight. Devices are generally supported by the hands, shoulders, or hips. Thus, a 10 lb. weight supported by a person's hips can usually be considered a low weight, while a 10 lb. weight supported by the hands can be considered large.

Ergonomics: Ergonomics is taken into consideration due to the amount of human motion during harvest. Each alternative was evaluated against four factors: (1) operation requirements, which is the number of distinct tasks needed to operate the device; (2) the complexity of motion, which is a relative measure between the current practice and the proposed alternative – categorized as either more, less or similar; (3) the repetition of motion, which is determined by identifying the number of repetitive tasks required by the design; and (4) the posture of the worker such as standing, sitting, or bent over.

Integration with Current Practices: An important aspect of any design is the ease or difficulty of integrating it with current orchard practices or systems. Integration is studied from three points of view: (1) Modularity, which is a relative measure between the current practice and the proposed alternative -- either low, medium or high; (2) systems changes to existing orchard equipment that growers must make to use the design, for example fitting passive apple distributing device to a bin; and (3) additional components or materials that the grower must supply, such as gasoline for a portable air compressor.

Productivity: The primary design requirement for all harvesting alternatives was enhanced productivity. We considered two aspects: (1) the fruit harvesting rate, which is the number of apples harvested per hour, and (2) the percentage of damaged fruit, which is the ratio of the number of damaged fruit to the total number of fruit harvested expressed as a percentage.

Potential for Fruit Damage: We estimated the potential for fruit damage by considering (1) fruit singulation (which is 1 minus the probability that a fruit collision will cause bruising) and (2) control of fruit impact speed. . A singulation parameter of 100% means that fruit will never strike each other with sufficient force to cause bruising, while a singulation parameter of 50% means that half the time fruit will be bruised by colliding with other fruit. The largest contributing factor to fruit bruising is the fruit impact speed . However, in the following design reviews no specific speed is provided, because the threshold for fruit damage is not well understood and varies from variety to variety. Instead, we evaluate the degree of control, with machine control being superior to human control, because of consistency.

4. Designs

Using harvest productivity and fruit damage as the two most important design criteria, we developed seven alternative concepts for augmenting the fruit transport and bin filling components of fruit harvesting. For each alternative harvesting system presented below, we strive to provide enough information to enable growers to assess and provide feedback on the concept's potential for increasing productivity and decreasing fruit damage in a cost-effective way. Therefore, we anticipate that we will modify the concepts as we receive input from growers and extension personnel.

4.1 Hand-held/Wearable Devices for Enhanced Fruit Transport

"Feeding" is a method used by expert pickers to transport fruit from the tree to a shoulder mounted bag, often utilized while picking fruit with a standard ladder. These very productive workers pick the fruit with one hand and gently toss it to their other hand, which is positioned near the opening of the bag. After catching the fruit, they deposit it gently into the bag. This method is extremely efficient because it practically eliminates arm motion since the receiving hand does not move to get the fruit from the picking hand -- the fruit is simply tossed. While most workers are extremely fast, harvesting approximately one apple per second on average, workers who use the "feeding" technique pick even faster. However, this technique requires significant skill, because to use this technique efficiently the worker must toss an apple without looking at the receiving hand -- the worker is essentially "juggling" apples.

Our goal for this concept is to reduce the skill needed for workers to use the feeding technique. The ideas is simple—provide a device that a worker wears or holds on the receiving hand to make catching the apples without dropping or damaging them easier. These devices provide a larger receiving area than a human hand, and energy absorbing material to prevent fruit damage. Figure 3 shows two concept designs for hand-held/wearable device. The first is essentially a hand-held padded dish. The second is padded glove, much like a baseball mitt, although it may need more energy absorbing material than a baseball mitt, since a baseball is much harder than an apple. Energy absorbing padding is required on the inner surface of the glove to absorb the kinetic energy of the apple without damaging it. The worker can simply rotate their wrist and place the apple into the harvest pouch.

Table 2 shows a qualitative assessment of the proposed hand-held/wearable devices in relation to the evaluation criteria discussed above. This harvesting alternative is compared against the current practice of dropping or handling fruit with a bare hand. The most appealing aspects of this concept are its simplicity, low cost, and ease of integration with current practices. The cost should be less than that of a baseball mitt, which is on the order of $100.

The complexity of using a hand-held/wearable device is rather minimal with the laborer undoubtedly determining his/her best technique for using the device. Another advantage of using this device is that it requires no changes to current harvesting practices and is simply located on the harvester's hand. Some potential disadvantages of this concept are that the worker might still need to develop some skill for tossing and catching, and the need to remove the device for performing other operations during harvest, such as emptying the bag of apples. The device must handle many thousands of apples, therefore the energy absorbing material must be carefully selected or wear could be a problem. Overall, we believe this concept has the ability to provide growers with more efficient harvest workers while requiring minimal capital investment or training. This concept could be easily tested at minimal cost as well.

Figure 3. Hand-held/wearable device for "feeding." (Left) Hand-held padded dished with strap for hand. (Right) Padded glove.

Table 2. Qualitative assessment of the harvest glove.

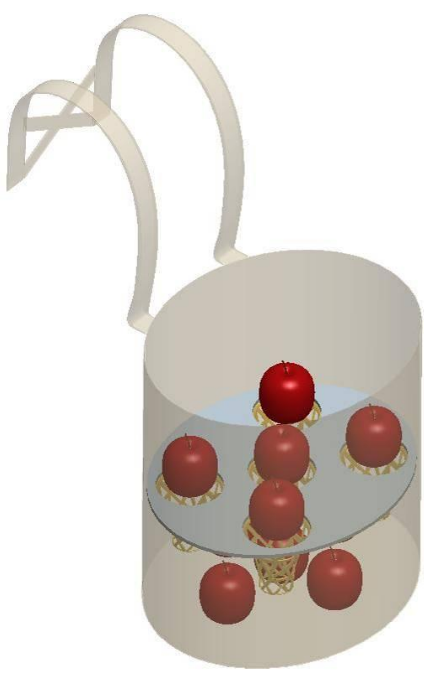
Hand-held/Wearable Device	
Cost	
- Estimated Cost	< $100
Complexity	
- Active/Passive Components	passive energy absorption material
- Automated/Human Control	human
- Hardware/Fabrication Complexity	low
Robustness	
- Number of Mechanized Components	none
- Number of Machine Cycles	< 2,000,000 apples
- Failure Modes	replace material
- Average Repair Time	5 min
Weight	
- Amount Human Supporting and Location	+3 lbs. human hand
- Amount Machine Supporting	none
Ergonomics	
- Operation Requirements	< 5
- Complexity of Motion	Less than current
- Repetition of Motion	fill glove
- Posture of Human	standing
Integration with Current Practices	
- Modularity	high
- Current System Changes	none
- Additional Components Required	none
Productivity	
- Fruit Harvesting Rate per Unit Time	increase
- Percentage of Damaged Fruit	reduction
Potential for Fruit Damage	
- Fruit Singulation	70-80%
- Fruit Transport Speed	human-controlled

4.2 Bag Enhancements

Fruit damage can occur during the filling and the emptying of the shoulder-mounted bag . To prevent fruit damage during filling, workers must carefully place fruit individually in the bag on top of the current fruit layer. This consumes time, which of course reduces the harvest rate of a worker. Similarly, workers must carefully empty the bag into the bin to avoid fruit damage, which again takes time. Workers therefore are constantly compromising harvesting rate with the potential for fruit damage.

Our idea is to alter the design of the bag or provide add-ons to existing bags so that workers can simply drop the fruit into the bag without bruising the fruit (Figure 4). These features should enable workers to continuously drop apples into their bag. The first design consists of canvas flaps with conical nets. The concept is similar to that of a basketball net, which absorbs much of the energy of a basketball as it falls through the net and simultaneously alters the trajectory of the ball. The second design is simply a series of alternating cantilevered flaps of energy absorbing material that in principle should deliver the incoming apple to the top layer of apples already in the pouch.

Table 3 presents a qualitative assessment of the concept based on the evaluation criteria in comparison to the current practice of using an open bag and placing the fruit by hand. The concept of modifying the pouch to reduce fruit damage while increasing the filling rate is by no means limited to the two designs presented here, of course. We offer these two designs as illustrations of some possible solutions that reduce current inefficiencies.



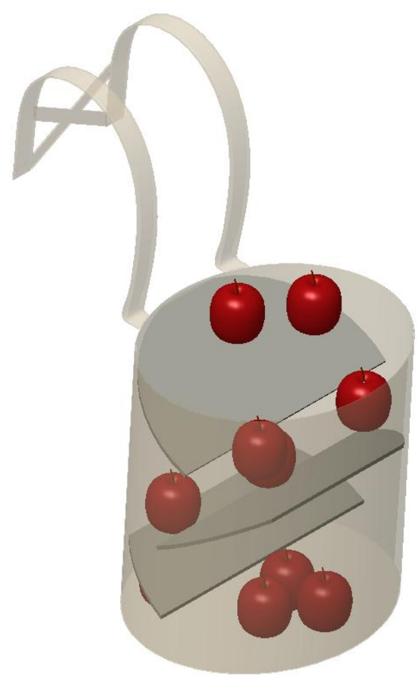


Figure 4. Shoulder-mounted fruit bag equipped with energy absorbing enhancements for increasing the filling rate without fruit damage. (Left) Drop nets. (Right) Energy absorbing flaps.

Table 3. Qualitative assessment of pouch enhancements.

Pouch Enhancements			
Cost		**Ergonomics**	
- Estimated Cost	< $150	- Operation Requirements	< 5
		- Complexity of Motion	Less than current
Complexity		- Repetition of Motion	fill bag
- Active/Passive Components	passive energy absorption material	- Posture of Human	standing
- Automated/Human Control	human		
- Hardware/Fabrication Complexity	low	**Integration with Current Practices**	
		- Modularity	high
Robustness		- Current System Changes	modify bags
- Number of Mechanized Components	none	- Additional Components Required	none
- Number of Machine Cycles	< 1,000,000 bags filled		
- Failure Modes	replace material	**Productivity**	
- Average Repair Time	5 min	- Fruit Harvesting Rate per Unit Time	increase
		- Percentage of Damaged Fruit	reduction
Weight			
- Amount Human Supporting and Location	+3 lbs. shoulders	**Potential for Fruit Damage**	
- Amount Machine Supporting	none	- Fruit Singulation	50-70%
		- Fruit Transport Speed	human controlled

The primary advantages of this concept are its low cost, potential for significant increase in harvest rate productivity while decreasing the percentage of fruit damaged, and ease of integration with current practices. The integration of this system with current practices requires either retrofitting current bags or purchasing new bags with the enhancements. One potential disadvantage of the net design concept is that the worker has to manually adjust the height of the net as the bag is filled with apples. The flap design, on the other hand, does not require any height adjustment from the worker as the bag is filled. A potential disadvantage is that the modifications will add some additional weight to the bag. Another potential disadvantage is the possibility of tangling or fouling of the nets or flaps. Still, we believe these modifications have the potential to significantly increase the efficiency of current practices.

4.3 Net-based Passive Apple Distributor For Bin Filling

The primary method of transporting apples from orchards to a processor is to fill bins, which are then trucked to the packing facility. There are various methods of filling the bins, but for the majority of harvesting operations the bins are manually filled by workers. Manual filling occurs often in two ways, either directly placing the apples from the tree into the bin (Figure 2) or emptying a shoulder-mounted harvest bag. Both practices are time consuming because the worker spends a significant amount of time transporting and placing the apples in the bin. The ideal scenario would enable a worker to pick apples essentially continuously with the transport and bin-filling operations requiring only a small fraction of the time spent picking the fruit.

Table 4 presents a qualitative assessment of the concept based on the evaluation criteria in comparison to the current practice of using an open bag and placing the fruit by hand. The concept of modifying the pouch to reduce fruit damage while increasing the filling rate is by no means limited to the two designs presented here, of course. We offer these two designs as illustrations of some possible solutions that reduce current inefficiencies.

Using this ideal scenario as the goal, we set about developing a passive bin-filling concept that would enable workers to quickly empty their bags in the bin or to simply toss apples to a bin without damaging the fruit. Our initial concept is shown in Figure 5. A net is positioned a short distance above the top layer of apples in the bin. As apples are poured into the bin the nets serve to dissipate the kinetic energy of the apples and to distribute the apples evenly over the top layer of apples already in the bin. Again the concept of a basketball net is a useful analogy for visualizing how this design would work.

The design requires a worker to adjust the height of the net with respect to the varying apple level in the bin. We depict a hand-operated crank mechanism for the height adjustment, but of course this operation could be motorized with the worker simply pushing a button to raise (or lower) the height. Also, height adjustment could be automated, with some yet undetermined method for sensing the level of the apples in the bin (for instance, an ultrasonic distance sensor), but this would add complexity and cost to the concept. A qualitative assessment of the proposed passive energy absorption apple distributor with respect to the various design criteria is shown in Table 4. The most difficult category to assess for this system is robustness.

An advantage of this concept is that workers do not need to lean into the bin to gently empty their bag. Also, workers harvesting on an orchard platform can simply toss apples into the bin without damaging the fruit. One disadvantage of using the system is that it must be moved from bin to bin in the orchard, but the device should be relatively light and still manageable for a human to handle. Overall, this concept should allow much faster filling of apple bins while decreasing the percentage of damaged fruit.

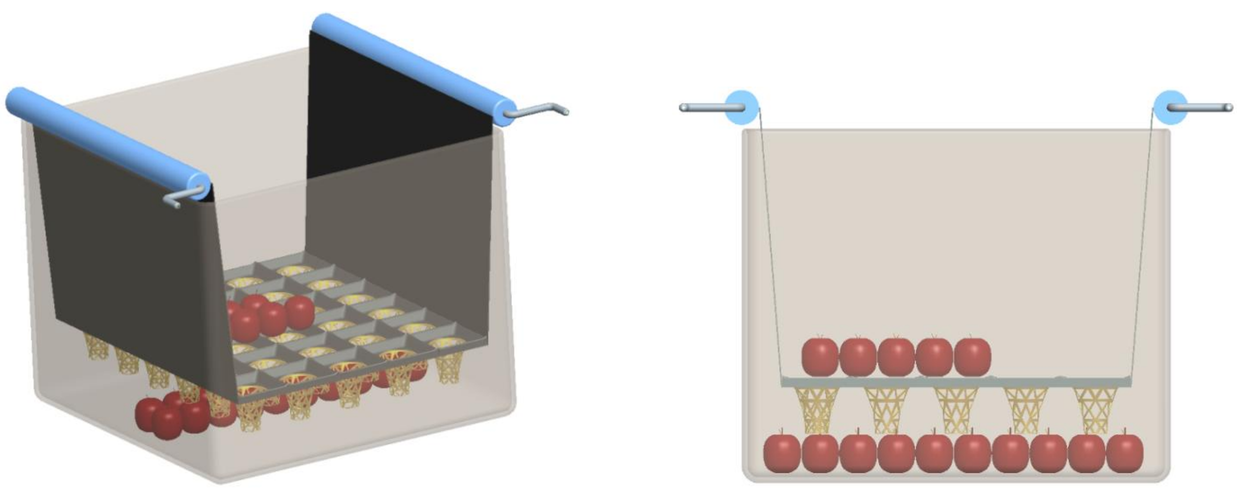


Figure 5. A conceptual model of a net-based passive energy absorption apple distributor for bin filling. (Left) Isometric view. (Right) Side view.

Table 4. Qualitative assessment of a passive energy absorption apple distributor.

Net-based Passive Apple Distributor for Bin Filling			
Cost		**Ergonomics**	
- Estimated Cost	< $450	- Operation Requirements	< 5
		- Complexity of Motion	less
Complexity		- Repetition of Motion	fill bin net, adjust layer height
- Active/Passive Components	passive energy absorption material	- Posture of Human	standing
- Automated/Human Control	human		
- Hardware/Fabrication Complexity	low-medium	**Integration with Current Practices**	
		- Modularity	high
Robustness		- Current System Changes	install on bin
- Number of Mechanized Components	< 10	- Additional Components Required	none
- Number of Machine Cycles	< 10,000 bins filled		
- Failure Modes	replace material	**Productivity**	
- Average Repair Time	10 min	- Fruit Harvesting Rate per Unit Time	increase
		- Percentage of Damaged Fruit	reduction
Weight			
- Amount Human Supporting and Location	none	**Potential for Fruit Damage**	
- Amount Machine Supporting	+ 30 lbs. on bin	- Fruit Singulation	50-70%
		- Fruit Transport Speed	human controlled

4.4 Energy Absorbing Grate for Apple Distribution and Bin Filling

An alternative bin-filling concept using the same passive energy absorbing strategy is an energy-absorbing grate as depicted in Figure 6. In this system, the kinetic energy of the fallings is absorbed by cubes (or other shapes) of energy absorbing foam resting on top of or suspended from a grating. The grating is either a lattice of ropes affixed to a frame or rigid structural material covered by energy absorbing foam. Again, the idea is allow workers to toss or dump apples in the bin, and the energy absorbing foam cubes will allow the fruit to gently fall on the top layer of apples without bruising. As with the net-based apple distributor for bin filling, the workers must manually adjust the height of the grate as apples fill the bin, but as mentioned previously this operation requirement can be automated. Also, workers must transport the complete system from one bin to another after the bin is filled. We believe that it will be possible to build the system to be light enough that one to two workers could easily accomplish this task.

A potential disadvantage of this approach is that some manual or motorized agitation of the medium may be required to ensure that all apples fall through the grating. Ideally the size, shape, and distribution of the energy absorbing foam will allow the apples to easily move through the grating while minimizing fruit damage.

Table 5 shows the qualitative assessment of the proposed energy-absorbing grate for apple distribution. Overall the evaluation of this concept is very similar to that of the net-based apple distributor.

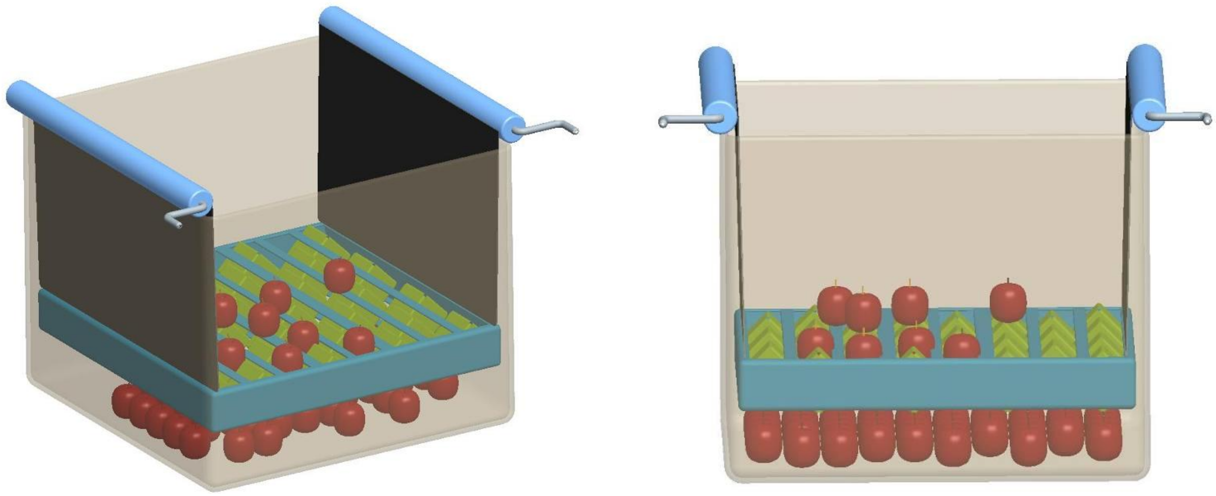


Figure 6. Conceptual model of a granular absorption medium apple distributor design. (Left) Isometric view. (Right) Side view.

Table 5. Qualitative assessment of a granular absorption medium apple distributor.

Energy Absorbing Grate for Apple Distribution and Bin Filling

Cost

- Estimated Cost	< $500

Complexity

- Active/Passive Components	passive energy absorption material
- Automated/Human Control	human
- Hardware/Fabrication Complexity	low-medium

Robustness

- Number of Mechanized Components	< 20
- Number of Machine Cycles	< 9,000 bins filled
- Failure Modes	replace material
- Average Repair Time	10 min

Weight

- Amount Human Supporting and Location	none
- Amount Machine Supporting	+30 lbs. on bin

Ergonomics

- Operation Requirements	< 5
- Complexity of Motion	less
- Repetition of Motion	fill bin medium, adjust layer height
- Posture of Human	standing

Integration with Current Practices

- Modularity	medium-high
- Current System Changes	install on bin
- Additional Components Required	bin mounting hardware

Productivity

- Fruit Harvesting Rate per Unit Time	increase
- Percentage of Damaged Fruit	reduction

Potential for Fruit Damage

- Fruit Singulation	50-70%
- Fruit Transport Speed	human controlled

4.5 Pneumatic Self-Adjusting Apple Distributor for Bin Filling

We developed the concept of the pneumatic self-adjusting apple distributor to eliminate the need for workings to repeatedly adjust the height of the net-based apple distributor and the energy absorbing grate. The pneumatic system depicted in Figure 7 automatically adjusts its height to the top layer of apples. The principle behind the design is to alternate the inflation two or more sets of cylinders composed of a rubbery polymer. Figure 7 depicts the alternating cylinders in green and yellow for clarity. The inflating cylinders “climb” on the top layer of apples in the bin as the fill level increases. Cylinders themselves absorb the energy of the dropping apples by keeping the air pressure in the cylinders to a minimum, and if necessary, an energy absorbing foam shell will cover the cylinders.

Table 6 shows a qualitative assessment of the proposed pneumatic self-adjusting apple distributor. The estimated cost of this system is somewhat greater than the previous two apple distributor systems because this design requires a supply of pressurized air. Thus, this system requires a power supply to operate an onboard air compressor. However, the required pressure is low, and the compressor can be relatively small. The required additional components should be both compact and relatively lightweight.

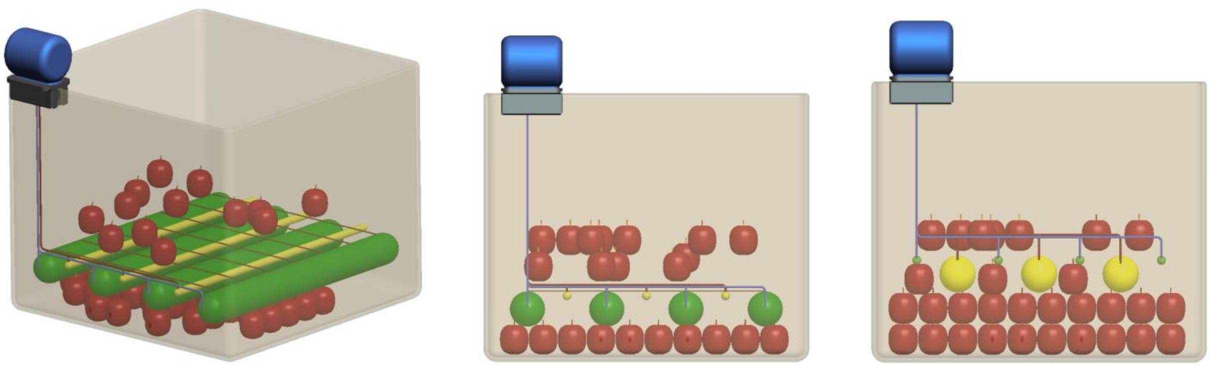


Figure 7. Conceptual model of a pneumatic self-adjusting apple distributor. (Left) Isometric view. (Center) Green cylinders inflated on lowest layer of apples with yellow cylinders deflated. (Right) Yellow cylinders inflated on the next lowest layer of apples with green cylinders deflated.

The main advantages of this system are that it operates completely in open-loop to properly adjust the height without worker intervention while the energy absorption is still completely passive. This should translate to greater worker efficiencies during harvest and reduced fruit damage. The inflating elements could potentially be other shapes, too, but the cylindrical shape seemed easiest to build and configure. In our opinion, this system might have the greatest overall potential, among all designs considered here, to increase the rate of fruit harvest and reduce the amount of fruit damage at low cost.

Table 6. Qualitative assessment of a pneumatic self-adjusting apple distributor.

Pneumatic Self-Adjusting Apple Distributor

Cost

- Estimated Cost	< $1,500

Complexity

- Active/Passive Components	passive energy absorption material
- Automated/Human Control	automated
- Hardware/Fabrication Complexity	low-medium

Robustness

- Number of Mechanized Components	< 25
- Number of Machine Cycles	< 9,000 bins filled
- Failure Modes	component failure
- Average Repair Time	10 min

Weight

- Amount Human Supporting and Location	none
- Amount Machine Supporting	+30 lbs. on bin

Ergonomics

- Operation Requirements	< 5
- Complexity of Motion	less
- Repetition of Motion	fill bin
- Posture of Human	standing

Integration with Current Practices

- Modularity	medium-high
- Current System Changes	install on bin
- Additional Components Required	bin mounting hardware, air supply

Productivity

- Fruit Harvesting Rate per Unit Time	increase
- Percentage of Damaged Fruit	reduction

Potential for Fruit Damage

- Fruit Singulation	50-70%
- Fruit Transport Speed	human controlled

4.6 Active Roller Apple Distributor for Bin Filling

The last apple distributor bin concept considered in this report is shown in Figure 8. The energy absorbing mechanism is a combination of active and passive elements. The speed of an apple when it drops onto the top layer of apples already in the bin is determined by the height of the rollers above the pile of apples. Apples are dropped onto the wedges made of energy-absorbing foam or directly onto the slowly rotating rollers also covered with energy-absorbing foam. Exit velocities of every apple are actively controlled by the rotation speed of the rollers. This system ensures that apples are gently placed on the top layer of the bin, ideally yielding no fruit bruising. A qualitative assessment of the proposed active roller apple distributor is shown in Table 7.

The active roller design requires manual adjustment of the roller height as apples fill the bin, but there are undoubtedly methods for automating this step. This design clearly has a higher cost and is more complex than others presented here. Other potential disadvantages of the active roller system include the higher weight and the requirement for an external power supply. A potential significant disadvantage of this design is that it might be too heavy for workers to carry from a filled bin to an empty one. Thus this system may be limited to applications on platform harvesters. As further design revisions are conducted, the weight of the device could be potentially reduced to a level that a worker can move the system from bin to bin. Also, since the rollers are actively controlled, a portable power supply is necessary. Overall, the roller bin filler has the greatest potential to ensure no fruit bruising occurs while emptying apples into a bin, but this significant advantage may be outweighed by the disadvantages of its higher cost, higher complexity, and higher weight.

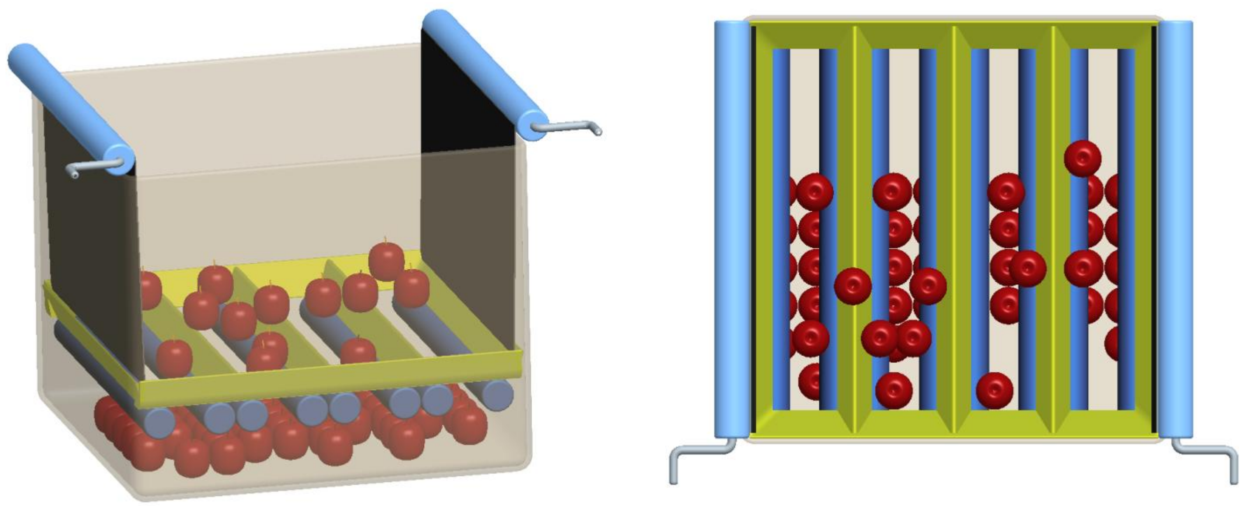


Figure 8. Active roller-based apple distributor for bin filling. (Left) Isometric view. (Right) Top view. The green wedges composed of energy absorbing foam guide apples onto the slowly rotating blue rollers covered with energy absorbing foam.

Table 7. Qualitative assessment of an active roller apple distributor.

Active Roller Apple Distributor

Cost	
- Estimated Cost	< $3,750
Complexity	
- Active/Passive Components	active roller control
- Automated/Human Control	automated
- Hardware/Fabrication Complexity	medium-high
Robustness	
- Number of Mechanized Components	< 150
- Number of Machine Cycles	< 8,000 bins filled
- Failure Modes	component failure
- Average Repair Time	30 min
Weight	
- Amount Human Supporting and Location	none
- Amount Machine Supporting	+500 lbs. on bin

Ergonomics	
- Operation Requirements	< 10
- Complexity of Motion	less
- Repetition of Motion	fill bin, adjust layer height
- Posture of Human	standing
Integration with Current Practices	
- Modularity	medium
- Current System Changes	install on bin
- Additional Components Required	bin mounting hardware, power
Productivity	
- Fruit Harvesting Rate per Unit Time	increase
- Percentage of Damaged Fruit	reduction
Potential for Fruit Damage	
- Fruit Singulation	50-70%
- Fruit Transport Speed	machine controlled

4.7 Singulated Transport Conveyor

Even a casual observer would readily note that pickers spend a lot of time walking from the tree to the bin and back when they are not picking from a platform harvester. Even on a platform, workers must turn around to empty their bags in the bin, or turn around to place fruit in the bin one at a time. It is therefore desirable for workers to simply place fruit on a transport system that moves the fruit from the worker to the bin while preventing collisions between fruit.

Ideally this transport system would move with the worker as he/she bends down to pick low hanging fruit. The system would necessarily be motorized or powered in some way, because the lip of the bin will be higher than some of the fruit on the tree. Figure 9 shows existing singulating conveyors, which are stationary with respect to the bin. We envision modifying these systems to move with a worker as he/she crouches and stands to reduce the movement required of the worker. The conveyor would be constructed to be light and flexible and enclosed to prevent workers from tangling themselves in the moving parts. Currently, singulated conveyors are use on conveyor harvesters previously shown in Figure 2, and nearly 100% fruit singulation is attainable. This design is the least developed of all of the concepts in this report, and would require the most work to implement successfully. However, there are promising designs that implement similar capabilities as shown in Figure 10.

Figure 9. Singulated conveyor fruit transport system [6].

Table 8 shows a qualitative assessment of the singulated conveyor system for the evaluation categories. The primary application of such a system is obviously an orchard platform. By utilizing a worker guided transport system, the worker will not need to move to conveyor, which should result in significant increases in the fruit harvesting rate while ensuring a lower fruit damage percentage by using a singulation technique. However, some disadvantages of this concept system are the cost and the number of mechanized components. Alternative designs with pneumatic transport of apples might reduce the cost and complexity of the transport.

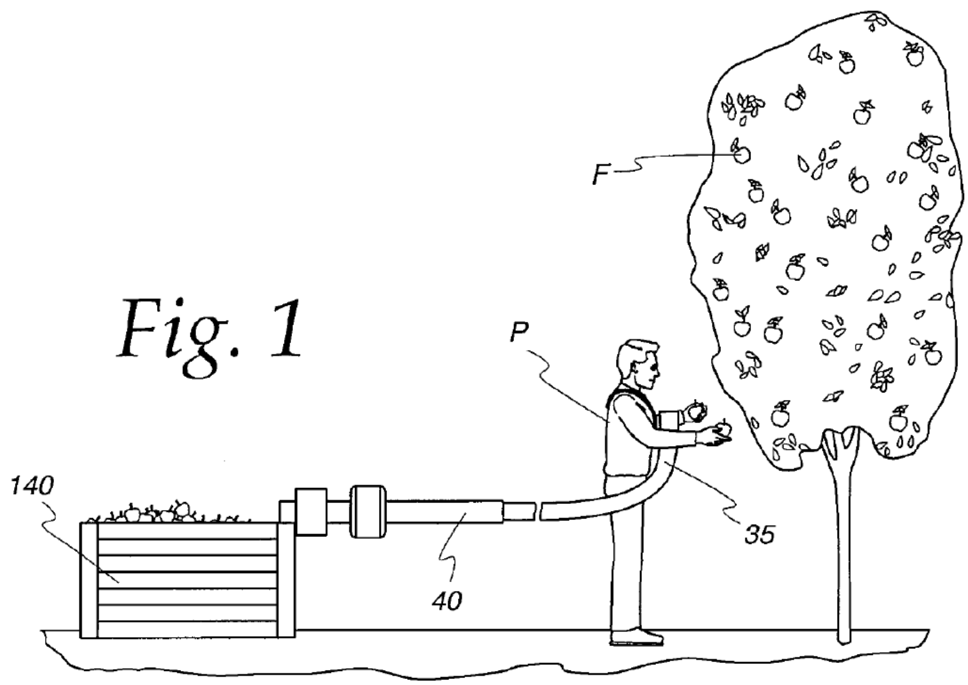


Figure 10. Person picking apples from a tree and placing the apples in a transport system [7].

Table 8. Qualitative assessment of a singulated conveyor.

Singulated Transport Conveyor			
Cost		**Ergonomics**	
- Estimated Cost	< $4,000	- Operation Requirements	< 10
		- Complexity of Motion	less
Complexity		- Repetition of Motion	fill conveyor
- Active/Passive Components	active rubber conveyor	- Posture of Human	standing
- Automated/Human Control	semi-automated		
- Hardware/Fabrication Complexity	medium-high	**Integration with Current Practices**	
		- Modularity	medium
Robustness		- Current System Changes	install on platform
- Number of Mechanized Components	< 400	- Additional Components Required	mounting hardware, power
- Number of Machine Cycles	< 500,000 apples		
- Failure Modes	component failure	**Productivity**	
- Average Repair Time	30 min	- Fruit Harvesting Rate per Unit Time	significant increase
		- Percentage of Damaged Fruit	reduction
Weight			
- Amount Human Supporting and Location	none	**Potential for Fruit Damage**	
- Amount Machine Supporting	+200 lbs. platform	- Fruit Singulation	98-100%
		- Fruit Transport Speed	machine controlled

5. Conclusions and Recommendations

Our research focus for this quarter was to develop low cost, low complexity concepts for increasing the efficiency and reducing fruit damage during fruit transport and bin filling. We chose these stages because they seem to offer the greatest potential for productivity increases, and because other players—e.g., IONco and Picker Technologies—are addressing the harvest process in a different manner.

In total, seven design concepts were created which provide more efficient alternatives to bag filling, bin filling, and fruit transport. Table 9 summarizes the results. These assessments are, of course, only qualitative estimates that must be verified by actual prototypes. The focus of our efforts during the next quarter will be (1) to identify which design concepts have the most potential for implementation based upon input from growers and extension personnel, and (2) to begin conducting experiments or constructing actual prototypes for testing.

6. References

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Table 9. Qualitative assessment of proposed alternative fruit harvesting designs.

	Hand-held/ Wearable Device	Bag Enhancements	Net-based Passive Apple Distributor	Energy Absorbing Grate for Apple Distribution and Bin Filling	Pneumatic Self-Adjusting Distributor	Active Roller Distributor for Bin Filling	Singulated Transport Conveyor
Cost							
Estimated Cost	< $100	< $150	< $450	< $500	< $1,500	< $3,750	< $4,000
Complexity							
Active/Passive Components	passive energy absorption material	passive energy absorption material	passive energy absorption material	passive energy absorption material	passive energy absorption material	active roller control	active rubber conveyor
Automated/Human Control	human	human	human	human	automated	automated	semi-automated
Hardware/Fabrication Complexity	low	low	low-medium	low-medium	low-medium	medium-high	medium-high
Robustness							
Number of Mechanized Components	none	none	< 10	< 20	< 25	< 150	< 400
Number of Machine Cycles	< 2,000,000 apples	<1,000,000 bags	<10,000 bins filled	< 9,000 bins filled	< 9,000 bins filled	< 8,000 bins filled	< 500,000 apples
Failure Modes	replace material	replace material	replace material	replace material	component failure	component failure	component failure
Average Repair Time	5 min	5 min	10 min	10 min	10 min	30 min	30 min
Weight							
Amount Human Supporting and Location	+3 lbs. human hand	+3 lbs. shoulders	none	none	none	none	none
Amount Machine Supporting	none	none	+ 30 lbs. on bin	+30 lbs. on bin	+30 lbs. on bin	+500 lbs. on bin	+200 lbs. platform
Ergonomics							
Operation Requirements	< 5	< 5	< 5	< 5	< 5	< 10	< 10
Complexity of Motion	less	less	less	less	less	less	less
Repetition of Motion	fill glove	fill bag	fill bin net, adjust layer height	fill bin medium, adjust layer height	fill bin	fill bin, adjust layer height	fill conveyor
Posture of Human	standing	standing	standing	standing	standing	standing	standing
Integration with Current Practices							
Modularity	high	high	medium-high	medium-high	medium-high	medium	medium
Current System Changes	none	modify bags	install on bin	install on bin	install on bin	install on bin	install on platform
Additional Components Required	none	none	bin mounting hardware	bin mounting hardware	bin mounting hardware, air supply	bin mounting hardware, power	mounting hardware, power
Productivity							
Fruit Harvesting Rate per Unit Time	increase	increase	increase	increase	increase	increase	significant increase
Percentage of Damaged Fruit	reduction	reduction	reduction	reduction	reduction	reduction	reduction
Potential for Fruit Damage							
Fruit Singulation	70-80%	50-70%	50-70%	50-70%	50-70%	50-70%	98-100%
Fruit Transport Speed	human controlled	human controlled	human controlled	human controlled	human controlled	machine controlled	machine controlled