Title

Testing of a Fruit-Catching System Using Simulations and Accelerometer Readings

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Testing of a Fruit-Catching System Using Simulations and Accelerometer Readings

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Abstract

With the increase in agriculture prices, reduced farm labor supply, and a higher population, fruit production must increase in the future. Shake-catch harvesting is a method where a tree's trunk is shaken, and the fruits fall and drop onto catching surfaces. Existing designs cause excessive fruit damage and hence are used only for processing fruits or nuts. This work focuses on designing, building, and testing an apparatus for catching fruits in free fall without causing damage. First, several design variants were considered, and one design was selected. Next, a small-scale system was designed using CAD and built. Fruit-dropping on this system was simulated in ANSYS to predict fruit impact characteristics. Also, the simulation was calibrated by dropping an artificial instrumented fruit and measuring the impact characteristics. Finally, real fruit drop experiments were performed using cling peaches to assess the system's capability to collect fruit without causing damage. The calibrated simulation will be used in future work to explore more design alternatives, guide material selection, and perform system optimization.

I. INTRODUCTION

1. MOTIVATION

Nearly all stone fruit (peaches, plums, etc.) are harvested by hand, an expensive and labor-intensive process that requires large crews to work long hours to achieve a simple job. Teams of 15-20 people use ladders and large picking bags strapped around their neck and shoulders to pick fruit manually for long hours. Each fruit is picked from the tree one by one, and carefully placed into the bag carried by the worker to not bruise the fruit. Any dropped product (anything that hits the floor or has too much bruising) is separated into the juicer bin. This product goes to making juice instead of being sold fresh, and it also fetches only about a third of the price as fresh fruit. Once a bag is full, the worker empties their bag into a bin. The bin is then transported to a dump tank where the fruit is washed and transported for storage and distribution. Throughout this process, the fruit is susceptible to bruising, which can easily cause rotting in the fruit, making the fruit unacceptable for sale or processing (e.g., in the case of cling peaches that are canned).

Figure 1: Workers collecting cling peaches.

Workers have to work very carefully to not bruise the fruit since this is the number one factor determining the fruit's value and acceptance rate by processors and consumers. The fruit is picked slightly green to ensure freshness when the fruit reaches the consumer. However, an indirect benefit of the somewhat green fruit is that it is harder to bruise than ripe fruit. Workers work long hours to pick fruit trees cleanly and on time before the fruit ripens. The window for fruit picking can vary, but the longer the fruit stays after the window, the more susceptible it is to diseases, pests, or over-ripening, causing it to be wasted. Crews must work long hours in sometimes dangerous situations (tall ladders, excessive heat) to pick the fruit in the available window.

Many researchers and inventors have tried for decades to automate the process of harvesting fruit from trees (Lamouria et al., 1961). Robotic selective harvesting is a technology under development but faces significant challenges and is not applicable to trees with large canopies. An alternative approach is mass-harvesting using the “shake-catch” method. Commercial shake-catch harvesters utilize trunk or canopy shaking. Canopy shakers insert multiple shaking rods into canopies and are widely used for small bush-type trees (e.g., blueberry) and to some degree for large citrus trees, for juice. Trunk shakers grasp the tree trunk tightly and apply mechanical energy in the form of mechanical vibration or impacts, which eventually causes fruits to detach. Shake-catch harvesting is restricted to nuts with hard shells (e.g., almonds, pistachios), or to fruits that are to be processed (e.g., tart cherries), because of extensive fruit damage.

2. PREVIOUS APPROACHES

Damage may be induced at any stage of the harvesting process; however, it is well known that the most important – and difficult to overcome - source of fruit damage during shake-and-catch harvesting is due to fruit impacting against tree branches as they fall through the canopy (Lamouria et al., 1961). More fruits are injured this way (skin and flesh punctures, bruises) than falling onto and then over the catching-handling apparatus (Fridley et al., 1975).

Multi-level fruit catching systems have been proposed in the past to reduce fruit damage during fall by reducing the average fruit drop distance, and consequently the probability of fruits hitting a branch or other fruit before being caught. Rehkugler & Markwardt (1971) developed a system for apples that inserted soft rods in canopies (Fig. **2; top-left**). Although long fruit drops and large punctures were reduced, fruits trickled down through the rods and the number of smaller bruises increased. Millier et al., (1973) built a system with large inflatable tubes made of 7-mil polyurethane supported by long PVC pipes. Tubes inflated after insertion and collected apples at different levels (Fig. 2**; top-right**). Fruit collection depended on fruits rolling on the catching surfaces and resulted in damage; 74-92% marketable "U.S. No. 1" McIntosh apples were harvested. Mehlschau et al., (1977) developed a system that inserted inflated rods in the canopy and intercepted and collected fruits at intermediate heights (Fig. 2**; bottom-left**). The machine was designed for hedged or semi-hedged tree rows having a thickness of not more than 8 ft. They reported harvesting 90% marketable Bartlett pears and 85% plums, compared to 61% and 72% with an under-the-tree conventional catch frame respectively. Although these results were very promising, cheap and readily available seasonal labor, along with concerns that mechanization put people out of work, stopped further R&D that could improve the performance of such machines and expand their scope to other canopies**.** Recently, He et al., (2018) re-visited shake-catch approaches, and studied targeted branch shaking of trellised, planar tree architectures (Fig 2; bottom-right).

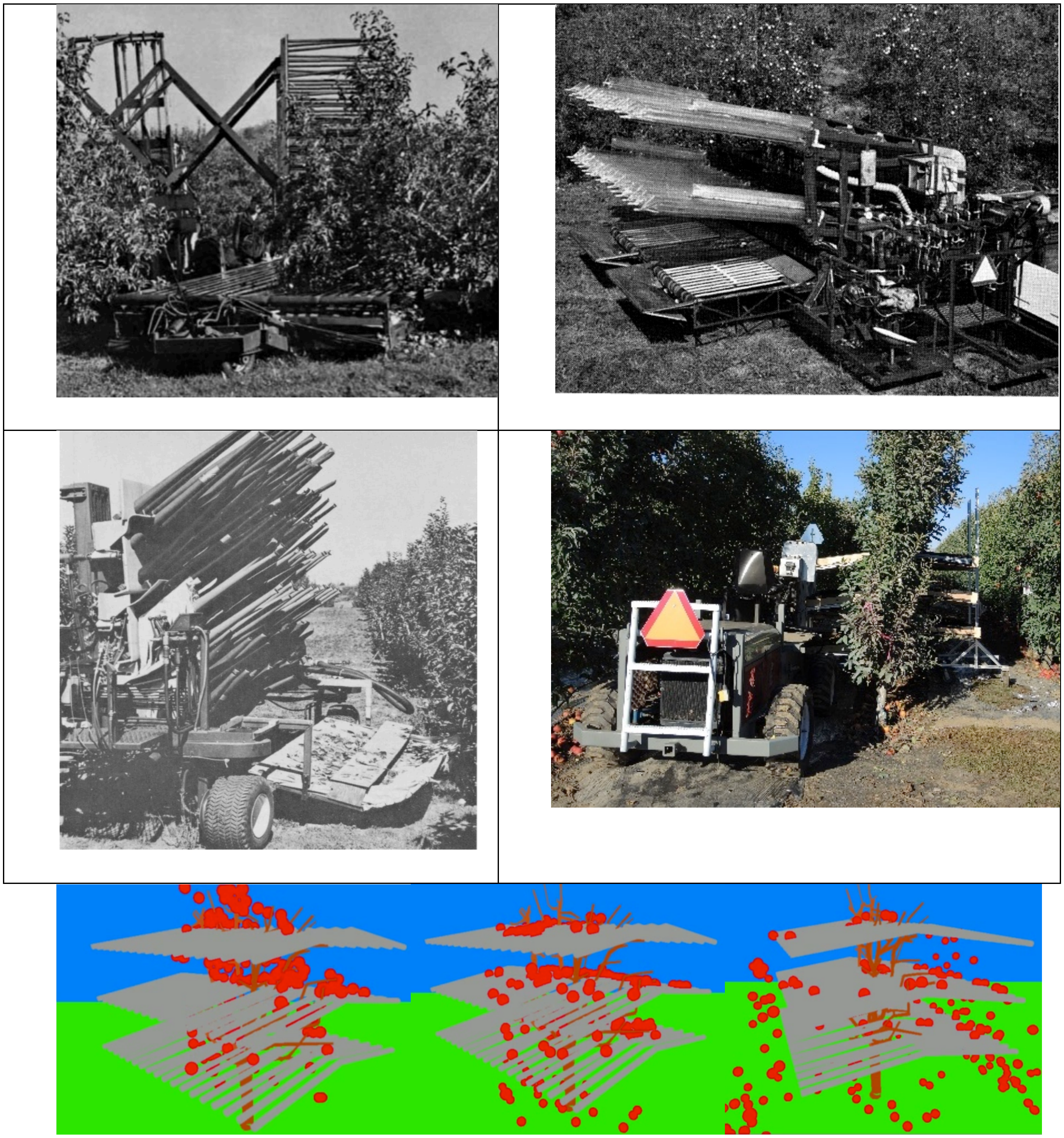

Figure 2: Top-left: Soft rods in the canopy slow down apples (Rehkugler & Markwardt, 1971); Top-right: Apples roll on inflated tubes at multiple heights (Millier et al., 1973); Middle-left: Fruits are collected at several heights by inflatable rubber rods (Mehlschau et al., 1977); Middle-right: Multi-layer shake-and-catch system for apples (He et al., 2018); Bottom: Multi-catch fruit system simulation (Munic et. al., 2016).

These results show great promise for shake-catch fruit harvesters. They also confirmed that soft catching surfaces can catch fruits and reduce damage, if they are located at small distances under the fruits. However, building variants of shake-catch systems is a very expensive and slow process that could benefit from computer-aided design and development. More specifically, we need to model fruit fall through tree canopies and fruit impact on compliant catching surfaces to accelerate the design of alternative fruit-catching systems. Very few researchers have worked on simulating fruit drop through a tree canopy and fruit interactions with catching surfaces. Software was developed by Munic et al., (2016) that utilizes 3D models of tree branches and fruits to compute fruit motions (falling, bouncing, rolling) during interaction with simple surfaces using an open-source physics engine (Fig. 2 Bottom). However, this work did not incorporate the calculation of the impact accelerations on the fruits or the possible damage. Researchers at Ondokuz Mayis University (2020) have compared fruit drop results between accelerometer measurements and fruit damage using velocity change. Oztekin & Gungor (2020) were also able to match the results between the accelerometer and the fruit damage to predict potential damage to the fruit. This proved useful in their research for finding reasons why fruits could be damaged during harvest and packaging.

3. RESEARCH OBJECTIVES

The objective of this research is to be able to match a simulator to real fruit droppings on a fruit catching apparatus. To achieve this the apparatus must be designed and built. To tests the effectiveness of the apparatus artificial fruit droppings will be conducted on the system. A simulation will then be tuned to match the artificial accelerometer readings. The last step will be to get real fruit dropping results on the apparatus to test its effectiveness and to quantify the simulation with real field data.

After the apparatus is designed and built, a simulator will be developed. The simulation using ANSYS will be able to predict the fruit damage of the current setup. To validate the simulation results, they will be compared to accelerometer results. Both the simulation and the accelerometer produce velocity changes, forces, and other parameters that predict damage, such as bruising and punctures to the fruit. The simulation and accelerometer will be compared to each other to ensure that the simulation gives accurate values. Then, the system will use real fruit to predict a model between the simulation, the accelerometer, and the damage that the fruit experiences during the drop.

Once the simulation comes close to predicting fruit damage, the simulator can test different fruit catching methods. The method we used to tune the simulator can then be tested to see if it works. We would need fruit damage to be under the bruising parameter of the fruit for any apparatus being tested with the simulator to be deemed successful.

The advantage of having a simulation tuned specifically to fruit damage is that farmers can predict the damage to the fruit before having to harvest the trees. If the simulation shows a promising result, they can decide to harvest the fruit using the tested apparatus. The simulation will yield similar results to the actual harvest.

II. SYSTEM DESIGN AND FABRICATION

1. Catching System Requirements

There were three critical points in the initial design of the catching system. They are listed below in order of importance. The catching system must

1. Catch the fruits without causing them damage (bruising, punctures, etc.)
2. Be easily extended into a tree canopy and retracted from it
3. Be able to move around the trees without damaging the tree or the fruit it will be carrying

The first point is the most important. To compare the fruit catching system to natural fruit picking, the arms (a part of the system that will catch the fruit) must not damage the fruit more than the pickers will. To be able to do this, the fruit must land on a soft surface. The fruit may also not bump or roll too much to avoid significant damage. The major impact that the fruit will have in testing is the initial drop from the branch where it is attached to where it will land. The initial landing spot must be soft and be able to catch the fruit with minimal impact.

A separate machine will shake the tree, and a different machine will have to extend the arms and insert them into the tree. They then must be designed to enter and exit the tree reasonably quickly. Trees are not all uniform, and they also vary vastly depending on the type of fruit they grow. However, the point is not to build a perfected catching system for one specific tree but to build something that will be a good all-around system for different stone fruit trees. The arm must be brought into the tree from the row where the machine will travel. The arms have to be able to be extended but must also be brought back to retrieve the fruit. They must be lightweight to extend easily into the tree without putting too much force on the machine carrying the load, since the arms will essentially be cantilever beams when loaded.

When the arms are first extended into the tree, they will not be controlled in any direction other than depth. The machine carrying the arms can move along the row, but the actual arms will only be controlled into and out of the trees. To achieve this, the arm requires a broad catching area. This is particularly evident in Figure 3, where the peach trees' wide canopy necessities correspondingly wide arms to effectively capture the fruit. Arms will be extended on each side of the tree. To extend into the tree, the arms will be propelled in. They have to be flexible to go over or push smaller branches to get close to the tree's center to catch as many fruits as possible. They must also be able to be withdrawn from the tree with the fruit still on the arms without dropping the fruit.

Figure 3: Peach trees in Yuba City

2. Catching System Design

Taking these three critical points into account, an initial design had been developed by Prof. Vougioukas, the project's PI, and Dennis Sadowski, the Bio-Automation Lab's Development Engineer. The main idea was to connect blocks and form a "block chain". This block chain can be extended (Fig. 4) and retracted using an appropriate – still in development – actuation system. Each block is riveted and bolted to the next block to create a chain. Small pieces of aluminum flat bar are then machined to be used as the connecting piece between each block. This allows the blocks to pivot up each other, but they lock rotation or downward movement. The "block chain" is essentially locked; it can only move from the yaw axis, and the blocks can be rolled up but not down. Thus, they can be supported from one point (where they are propelled from), and they will not roll over when fruit hits the arms. The holes on the side of the arms are meant to hold the catching surfaces. Because the arms are very (1.5" x 1.5" x 3") narrow, they cannot catch the fruit by themselves. If the arms were made wider, they would then be very heavy and could not be supported by the machine that would support them. Instead, the arms can hold some type of material to be able to catch more fruit without adding an excessive amount of weight.

Figure 4: Extended block chain assembly.

In the first phase of this thesis, a CAD model was developed for the initial design (Fig. 5). A material selection had to be made to find something suitable to stick in the holes that the block chain will have. The material to hold up the fruit had to be rigid enough to not fold under the load of the fruit but soft enough to not damage the fruit when it lands on the material. The holes can be made bigger or smaller. Since the wall thickness of the material is small (0.07 inches), the size of the holes does not make a big difference in the arm's balance. The material used in the holes must be tube-like to be held in place while the fruit falls.

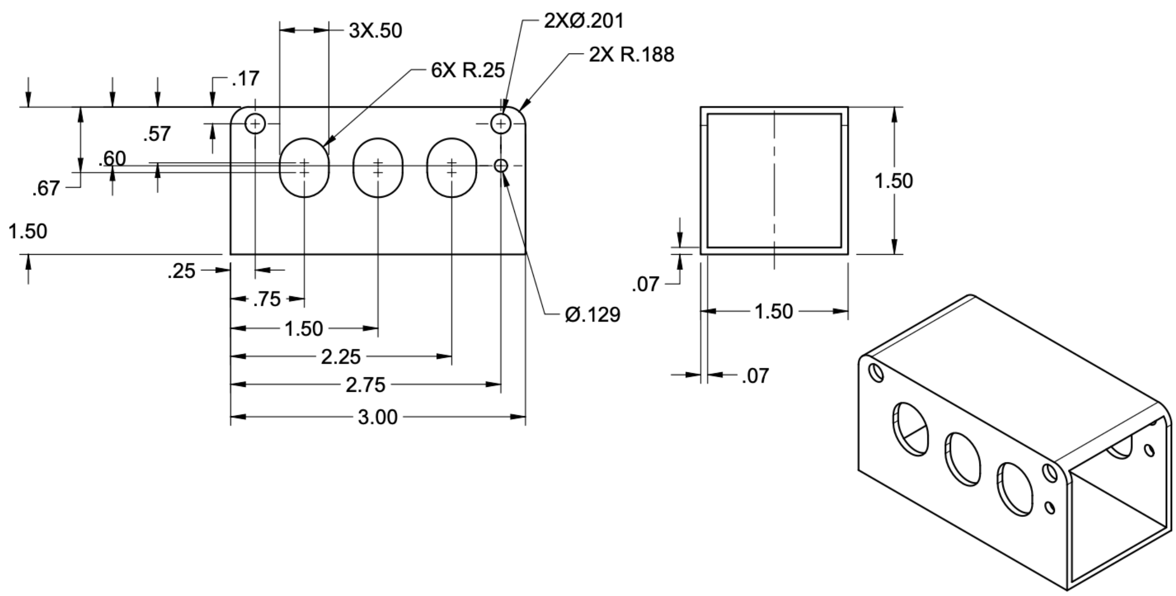

Figure 5: Drawing of the block

Figure 6: The two possible designs, “loop” on the left and “fingers” on the right.

Figure 7: Loops method no middle support.

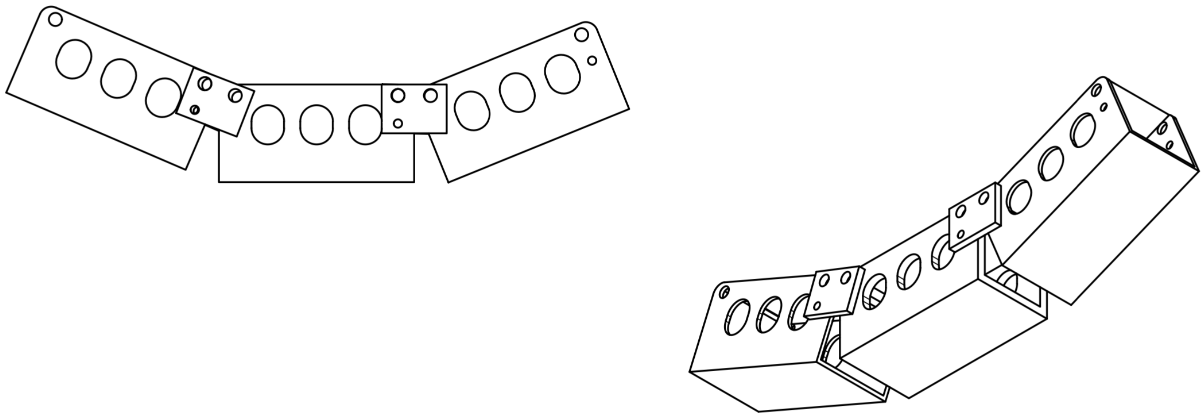

Figure 8: Drawing for the arms assembly, noting the rotation the arms can take

As seen in Fig. 6, two design considerations were given. The one on the right is the fingers approach. The hydraulic hose is cut to about 9 inches long, and a broom-like gathering system is used. This approach was thought to be the best design for gathering stone fruit, such as peaches. However, after quickly testing the fingers, the obvious flaw was that the fruit was dropping through the catching system. A simple peach drop of 8 inches would go right through the fingers, a better solution would have to be found. Since the fingers are firmly supported only on one end, the fingers essentially become a cantilever beam. The load of the fruit, especially if it lands on the end, is too much for the fingers to support, and they bend down, allowing the fruit to drop. Another possible solution was to fix the other end on another set of blocks. That way, both ends would be supported. The issue is that the arms would not be as maneuverable, and the footprint would be much larger. For this reason, this idea was ruled out. Since multiple arms would be inserted into each layer, the fingers would sit atop another arm. Even with the help of the middle support (Figure 6: right) the fruit continued to fall. Although there will be more layers of arms at the bottom to catch the fruit that goes through, the fruit might hit more branches as it travels down. A better design would be if more than one side of the tubes were supported while considering the restrictions previously mentioned.

The design on the image on the left is what we decided to go with. More holes had to be milled on the blocks. A looping solution was found to counter the large force of the fruit falling on the end of the fingers. The hydraulic hose is cut in large sections to be looped around the block. This creates a loop at each end of the block, as seen in Fig. 6. The hole of the loop created is still too large because of the material's rigidity, so some strong tape can be used to close the gap. That way, if the fruit fell on the material, it would be held up. The loops extend over the neighboring arm, like they would in the field. This allows the loops to have more support to hold up the fruit unlike in Figure 7. Later, some testing was done to determine if the loops held up the fruit, and the results were positive.

3. Material Selection

There are two main pieces of the arm, the boom (Fig. 8) and the loops (Fig. 6). The booms will be extended outwards, with the loops fixed to the holes drilled into the booms. So, the booms must be rigid and strong enough to support the load. The weight also must be considered, since they are mechanically supported; of course, a lower weight is better. The top of the boom will receive some impact from the falling fruit. So, the top of the boom must be soft to minimize the impact of the fruit falling on it.

The loops have to be strong enough to support the fruit, but they also have to be soft enough to support the impact of the fruit without damaging the fruit. Two ideas were considered. Previous experiments, like Fridley's (1975), had used foam-like material. Our lab had also previously used a plastic-like material that could be inflated to hold the fruit. Overall, we had a choice of which material to use. Testing also had to take place to ensure that the material chosen would not bruise the fruit.

Component	**Pros**	**Cons**
Circular Foam	• Very soft material • Easy to buy • Can maneuver through branches	• Hard to loop • Too elastic; it bends under any load (no rigidity)
Inflatable tubes	• Lots of movement while still being rigid. • Soft material, almost like a pillow • Can adjust the hardness easily	• Have to have a pump to inflate them • Tubes must be inflated, requiring the installation of air lines • Prone to ripping, which will cause the fruit to drop
Hydraulic Hose	• Can bend very easily • Strong but not hard • Sticks right into the blocks (Figure 9); no adhesive is needed	• More expensive than the other two options

Table 1: Material Selection

From Table 1, we decided to try hydraulic hose, which is made of a thick rubber. The hose used has a very small internal diameter with a strong shell that can hold internal pressure. Although we do not need it to hold internal pressure, the thick shell gives the material more rigidity while still being soft enough to not bruise the fruit.

The top part of the boom will be covered by the fingers lying on top when the arms get pushed into the tree. However, if needed, a foam pad can protect the fruit while it is falling in case some of it hits the booms and not the arms.

Aluminum was chosen as the material for the boom. It will be strong enough to support the load and light enough not to be too heavy and slope too far down. Steel was also a possible candidate for the booms, but it was too heavy, and the extra strength that it would have provided was not enough to counteract how much heavier it is than aluminum.

4. System Fabrication

Aluminum square tubing in 20ft sections was bought. The first step was to cut the tubing on a horizontal band saw.

Figure 9: Cut sections of square tubbing

The holes were milled out on a mill after the material was cut into 3-inch sections. A conversational program was written to mill out the holes. The holes must be wide enough to hold the hydraulic hose but snug enough so that the hose does not fall out when the fruit load hits the hose. So, the perfect size was not a round hole but more of an ellipse. The ellipse was programmed on the mill, and then an ½ inch end mill cut out the shape.

Figure 10: The manufacturing of the arms

For the blocks to be able to close and open properly. A radius has to be cut on the top of each block. This creates clearance for blocks to mate properly. A corner radius endmill was used to cut through the material to create the radius on each end of the block.

The holes for the screw and the rivet were also programmed on the conversational mill but were drilled out instead of cut. The engineering drawing for the block is shown in figure 10. The small connector pieces were also drilled out to the same pattern as the block. Figure 11 shows the full assembly with the arms rotational capability in action.

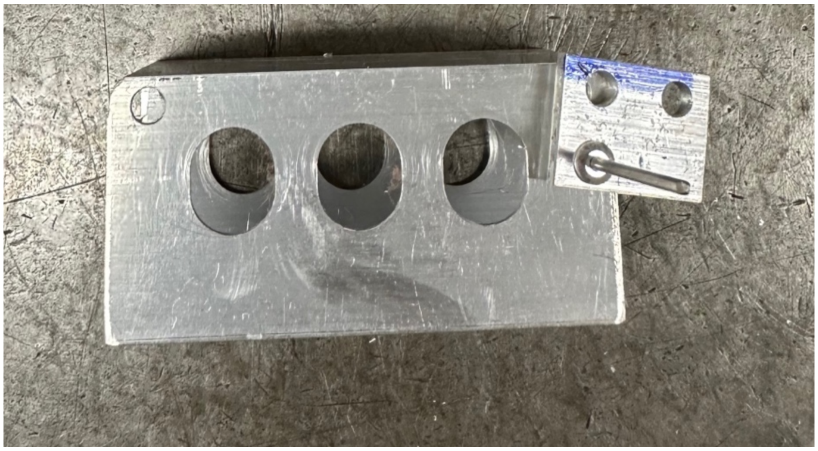

Figure 11: The final assembly of the block, with the rivet still fully intact

III. SYSTEM EVALUATION

1. Methodology and Experimental Design

A few tools are needed to conduct our experimental design. ANSYS student version 2022 was used for the simulation part of the experiment. ANSYS is a finite element analysis tool that allows CAD software to be analyzed for modeling solutions. The second tool being used is called an IRD (impact recording device) and this is an accelerometer manufactured by a company called Techmark. The IRD is a small accelerometer about the size of a grape. The IRD comes together with a soft plastic shell the size of a peach. The shell surrounds the IRD to give a more accurate measurement to a real-life peach. The specifications of the IRD are given in Table 2. The shell comes in two parts and is fastened to each other using 4 screws. For the rest of this paper when IRD is mentioned it is assumed the IRD has the shell around it, unless otherwise specified.

	Weight (Ounces)	**Diameter (inches)**
IRD	0.45	1.00
Shell	8.55	3.00
Together	9.00	3.00

Table 2: Size reference for IRD

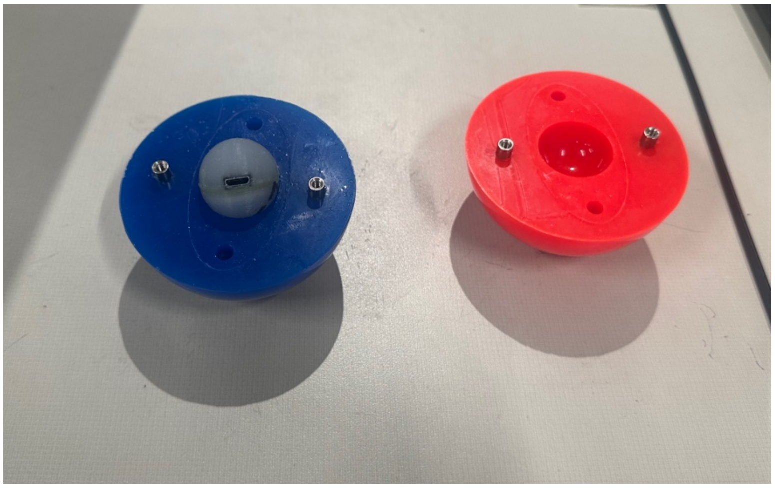

Figure 12: The IRD in the shell.

To test the damage that the fruit will endure, the three methods of testing are:

1. Simulation of explicit dynamics using ANSYS.
2. Accelerometer readings using an IRD fruit test recording device.
3. Real fruit drop experiments.

The basis and procedures for each method are shown below.

A. Simulation (ANSYS)

Procedure: Once the CAD model of the catching system (fingers and blocks) has been developed, the entire model will be transferred to ANSYS: the fingers, the block, and the fruit. The entire system's geometry must be meshed. There are a few ways to run the simulation but using a *gravitational drop* under Explicit Dynamics is the easiest way to get the result. The end time for the gravitational drop is 1.75 seconds, with the number of cycles being 1e+7. A few parameters are needed to be inserted such as the height of the drop and the materials being used. Some materials are already in ANSYS such as aluminum for the block and rubber for the hose. The specific materials used are Aluminum alloy for the blocks, and Rubber 2 for the hose. These materials closely resemble to the materials used in the peach study. The peach's properties can be manually inserted.

Density	**982 (kg/m^3)**
Elastic Modulus	**5.67E+06 (Pa)**
Young's Modulus	**.2**

Table 3: Peach Properties Finney E.E. (1967)

A few things must be adjusted to give accurate results. The threshold for the results to be accurate have to be close to the IRD results, but also that the results are easily able to be duplicated. The size of the mesh elements can be made bigger or smaller and the results should stabilize. The most important thing to change is the mesh of the system. The mesh size chosen was a “fine” mesh. The “fine” mesh element size is .005 m If the mesh is made bigger then the results are a bit off, so the "fine” size is chosen. The distance of the drop is inserted, along with boundary conditions. The tubes are connected to the block and the tubes are also sitting on top of an adjoining block, these two points are the fixed supports. Once the system is solved the results are then given.

Expected Results: The velocity change at different points on the system is given. The velocity change that is important is at the peach's drop zone. The drop zone is the expected spot of the drop of the peach. Essentially the peach for these experiments should drop on the tubes preferably somewhere in the middle of the tubes between the end of loops and the aluminum block. This drop zone allows the experiments to be replicated in all three (ANYS, IRD, and real fruit drops) scenarios so that all the results can be matched up properly. A probe can be used to find the results at specific points in the system. Some other results are also given, such as the force of the impact and the deformation.

B. Accelerometer (IRD)

Procedure: Once the system is built, both the arms and the fingers of the model can be tested by performing drops with an artificial fruit, containing the IRD. The shell is then dropped from specific heights onto the arms. The data collected by the accelerometer is the change in velocity and the g's experienced at impact. The g's is the acceleration at impact, essentially how hard the impact was. The peach stopped dropping so there was a force to stop that movement. This force can tell a lot about the damage that can be seen on the peach. The change in velocity will give the energy change which will also help paint the picture of how much damage the peach is expected to have.

Figure 13: Setup of IRD drop

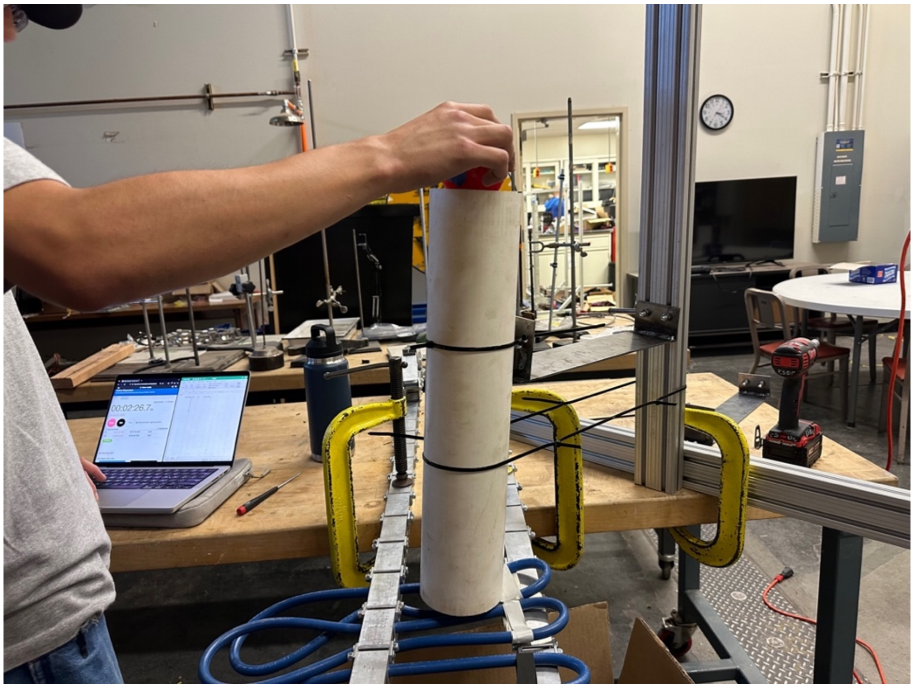

Figure 14: Impact recording device (IRD) drop

Ten drops for each height will be performed to acquire enough data to perform statistical analyses. Repeating the procedure is easy. A tape measurer will be used to ensure that the drop height is the same for a set of drops. The accelerometer may pick up some noise during the drop, especially if a bounce occurs during the impact. Using a stopwatch for when the first impact occurs suffices to get the correct results.

Expected Results: The outcomes of the experiments are the velocity change and the g's experienced during the drop. The velocity change will be used to find the change in energy and compare it with the simulation. The g's will determine if the arms keep the fruit from experiencing a damaging range of values that could bruise the fruit during harvest. The sensor is expected to roll or sometimes fall through or over the fingers. In the real model, there will be more arms to catch it. But in the laboratory setting, we only have one arm. So, if the sensor falls to the floor, the drop will be repeated. For each height, 10 clean drops should suffice.

C. Real Fruit Drop Experiments

Procedure: In the real fruit drop experiments, the same setup is used as in the artificial fruit (IRD) drop experiments. The only difference is that now real fruit is used instead of the sensor. The same heights will be used for easy comparison, and the procedure will be the same: drop the fruit on the arms, collect the fruit, and place it in a box for later analyses.

PVC pipes cut to the height of the drop will be used to guide the fruit down to the landing zone. Tape is placed under the PVC pipe with its sticky side up so that when the fruit hits the loops, the impact location is marked on the peach. The person analyzing the peaches will be able to know exactly where the expected bruising will occur, and they can look at this specific area for signs of bruising.

Figure 15: Fruit dropping onto the arms at 4 inches.

The peaches used will be harvested from an orchard in Yuba City. They will be collected in the least intrusive way possible. They will be clipped and barely touched to preserve their freshness as if they were still hanging on the tree (Figure 16). They will then be transported to the lab to run the experiment. After the experiment is run, all peaches will be placed in boxes with bubble wrap and transported to the UC Davis postharvest lab to be analyzed.

Figure 16: Harvesting cling peaches in the orchard.

The fruit will be tested for bruising. They will be closely analyzed for any internal and external bruising. The researchers at the postharvest lab will split the peaches open to check for internal bruising. They will also note the color of the peaches and look for any external bruises. Each bruise will be measured in millimeters, along with which peach it came from. An issue with real fruit droppings compared to IRD drops is that fruit is at different maturity levels and thus bruises differently. To consider this, each peach is given a rating depending on its maturity. A softer peach is easier to bruise, so we give it a different rating to take this into account when we do the analysis.

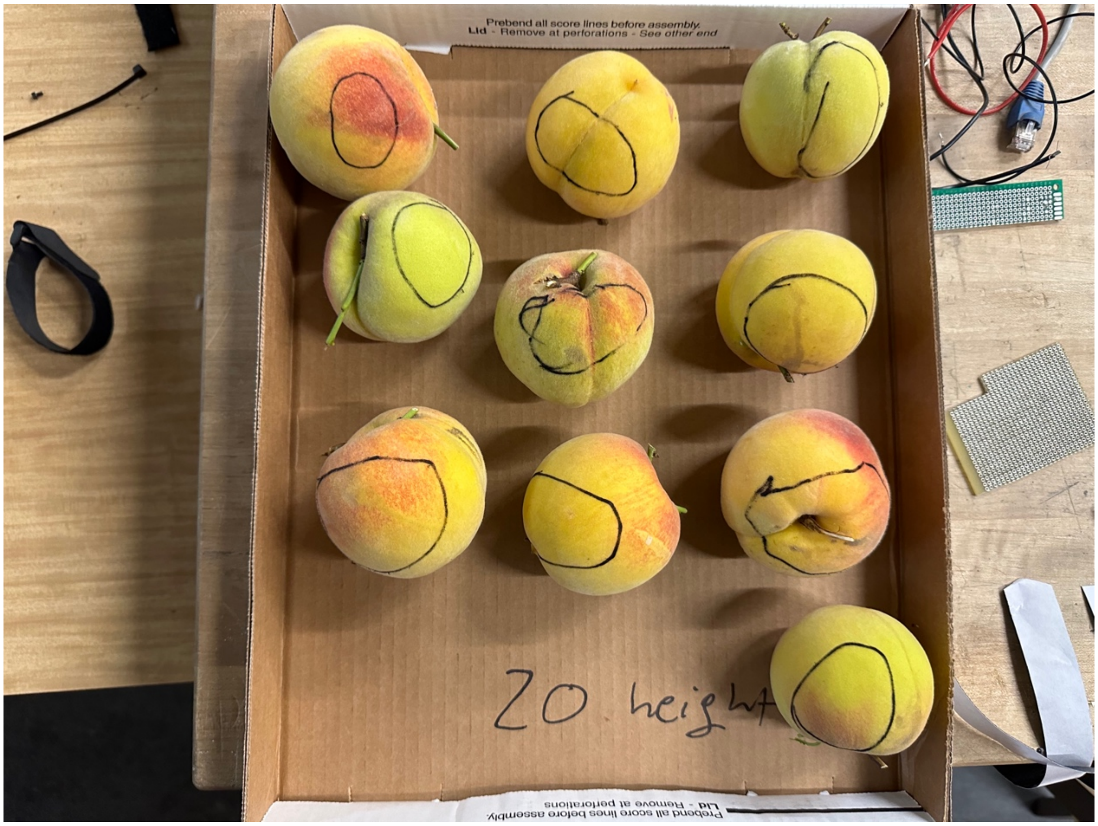

Figure 17: Fruit circled where the bruising is expected.

Expected Results: Fruits dropped from a bigger height are expected to bruise more than fruits dropped from a lower height. Given that the system has been designed to minimize fruit damage, the bruising should be generally low. The fruits will be inspected by the Postharvest lab at UC Davis, and the results will be given.

2. Expectation

The three tests should produce similar results, although each produces different data. The IRD tests will produce the benchmark results. The IRD results are what most farmers and factories use to test damage to the fruit. The simulations should yield very similar results to the IRD. The IRD data can be verified by various papers showing impact on the peaches during harvest Oztekin & Gungor (2020). So, once the simulations start producing similar results to the IRD, it can be noted that they produce correct results.

IV. RESULTS

1. Instrumented Artificial Fruit Drop Experimental Results

The arms were tested in laboratory conditions before fully testing the arms and fingers under real-world conditions. The initial experiments were to test two main points:

1. Will the fruit be able to stay on the arms?
2. Will the fruit not be significantly damaged once it lands on the arms?

Point one is easy to test and can be visually inspected. Most of the fruit did stay on the arms after the drop. However, a baseline must be established to test the second point. Even though, eventually, the final test will be done with real peaches, we want to test the current setup with something that will be easier to determine if it is working or not before we fully commit to that plan.

The easiest way to test whether the peaches will bruise is to use an accelerometer in the shape of a peach. Various companies make devices that can be used for this purpose, but Techmark makes one specifically for agriculture applications.

The IRD velocity change will then be compared to the simulation results to ensure the simulation is tuned correctly to get the correct results. And the force will be used to determine if the fruit will be damaged.

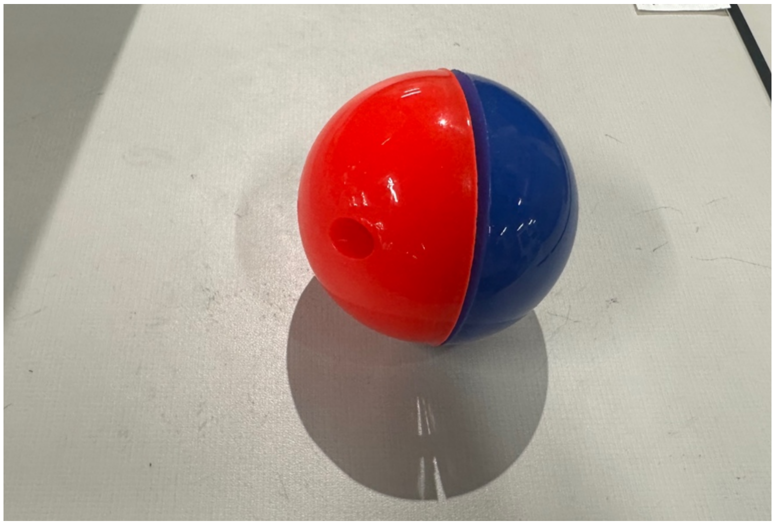

Figure 18: The shell once it is closed.

This IRD can give both g's and the velocity change of each impact. These values will be used to calculate the damage the fruit will endure during the drop. The simulation gives various results, but the one needed for damage is velocity change. Velocity change directly leads to damage because it is a factor in the following formula. The only other variable needed is the mass of the object being dropped.

$$\Delta E = \frac{1}{2} * m * \Delta v^2$$

Equation 1: Change in energy observed by the peaches in a non-elastic impact.

The *m* is the mass of the peach/IRD, and the velocity is received from either the IRD or the simulation; these two numbers will be compared in the results section. The mass used will be $1/3^{rd}$ of a pound, which is a common value for the size of a peach. These numbers will be used to tune the simulation.

Two things are accomplished from these numbers. The formula will assess fruit damage and determine if our setup works correctly. The numbers themselves will be used to see if the simulation works properly and matches the numbers from the IRD.

So, the first step is to get a baseline of numbers from the IRD drops.

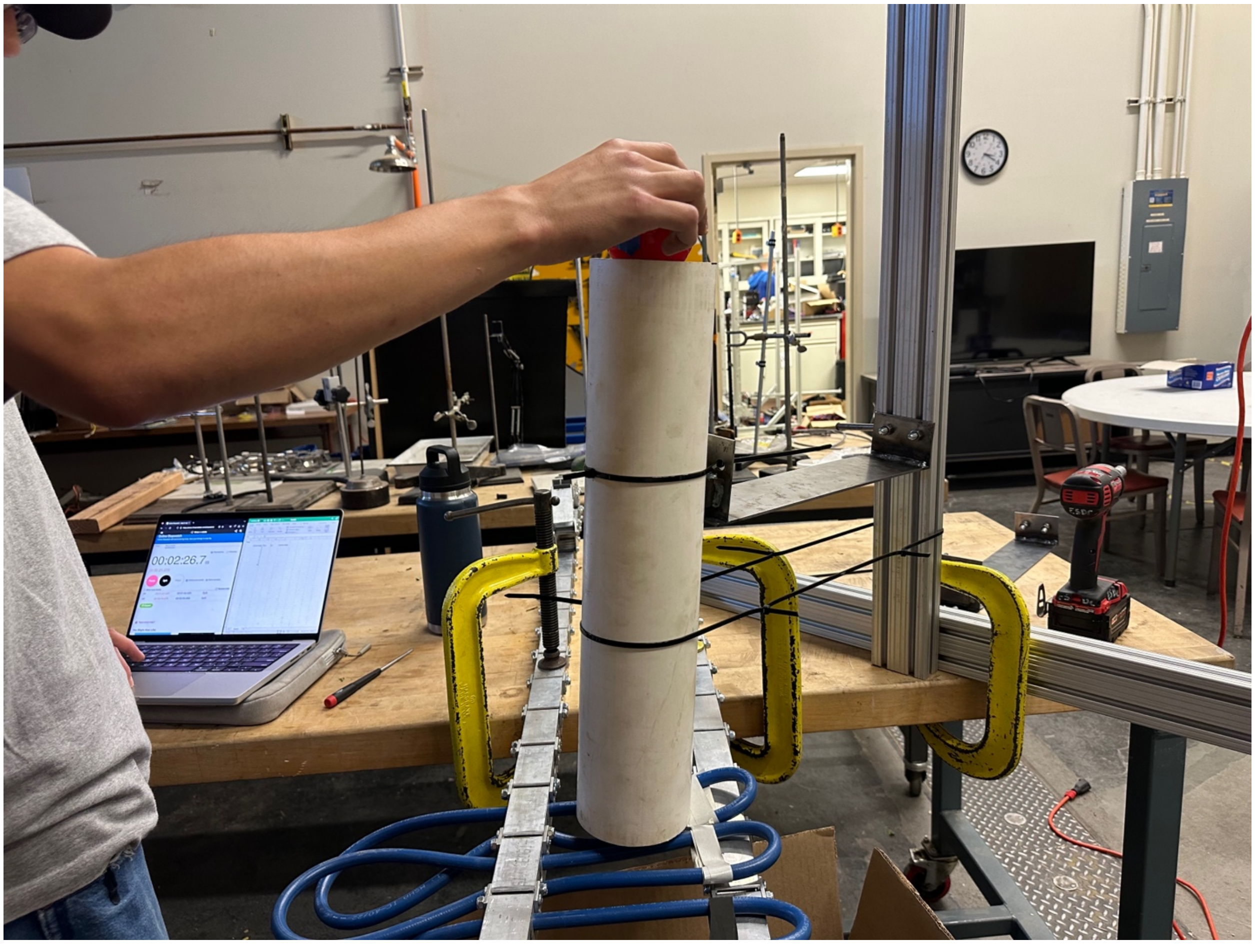

Figure 19: IRD Dropping.

As mentioned in the methodology section, we perform drops at different heights in succession. First staring with a drops for 4 inches, then increasing the height to 8, 12, etc. All drops

4" Height (in)	g's	Velocity Change (m/s)	Duration (ms)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	10.2	0.27	5.12
9	13.11	0.37	5.12
10	0	0	0

8" Height (in)	g's	Velocity Change (m/s)	Duration (ms)
1	11.66	0.47	5.38
2	0	0	0
3	0	0	0
4	0	0	0
5	11.31	0.32	5.12
6	10.95	0.03	1.54
7	10.77	0.25	3.07
8	12	0.4	5.63
9	10.2	0.13	3.07

10	10.77	0.29	5.12

12" Height (in)	**g's**	**Velocity Change (m/s)**	**Duration (ms)**
1	11.66	0.07	1.02
2	14.14	0.16	2.82
3	12.65	0.18	3.07
4	11.83	0.06	1.02
5	12.17	0.16	3.07
6	11.49	0.21	2.82
7	14.14	0.31	5.38
8	13.27	0.25	3.07
9	12.17	0.16	3.07
10	14.14	0.15	3.07

16" Height (in)	**g's**	**Velocity Change (m/s)**	**Duration (ms)**
1	17.89	0.24	3.07
2	32.35	0.24	3.33
3	16.12	0.19	3.07
4	11.83	0.16	3.07
5	10	0.19	2.82
6	14.14	0.17	2.82
7	14.97	0.21	3.07

8	12.81	0.21	3.07
9	17.2	0.18	3.07
10	17.66	0.28	3.07

20" Height (in)	**g's**	**Velocity Change (m/s)**	**Duration (ms)**
1	21.35	0.36	3.33
2	24.74	0.31	3.07
3	22.36	0.38	3.07
4	22.36	0.39	3.07
5	20.4	0.82	7.17
6	18.87	0.35	3.07
7	17.66	0.36	3.07
8	12.17	0.22	3.58
9	21.26	0.4	3.07
10	18	0.2	2.82

Table 4: IRD results

Height (inches)	**Mean**	**Median**	**Standard Deviation**
4	0.064	0.000	0.137
8	0.189	0.190	0.180
12	0.171	0.160	0.075
16	0.207	0.200	0.037
20	0.379	0.360	0.170

Table 5: IRD averages for velocity change

	Mean	Median	Standard Deviation
4	2.331	0.000	4.962
8	7.766	10.770	5.382
12	12.766	12.410	1.073
16	16.497	15.545	6.153
20	19.917	20.830	3.483

Table 6: IRD averages for g's

Values of zero exist because the accelerometer inside the artificial fruit does not record accelerations below 10 g's (they are considered insignificant for fruit damage). This can cause some issues in the analyses, because, in most cases, the results can be omitted, but the reading is not a true zero. Instead, what can be done is take them as zero for 4 inches since it is the only one with a significant number of drops.

These numbers will be used as a benchmark to compare fruit damage that previous researchers have collected and whether our catching mechanism will work. They will also serve to compare with the simulations.

These numbers must be consistent, as shown in the following graph.

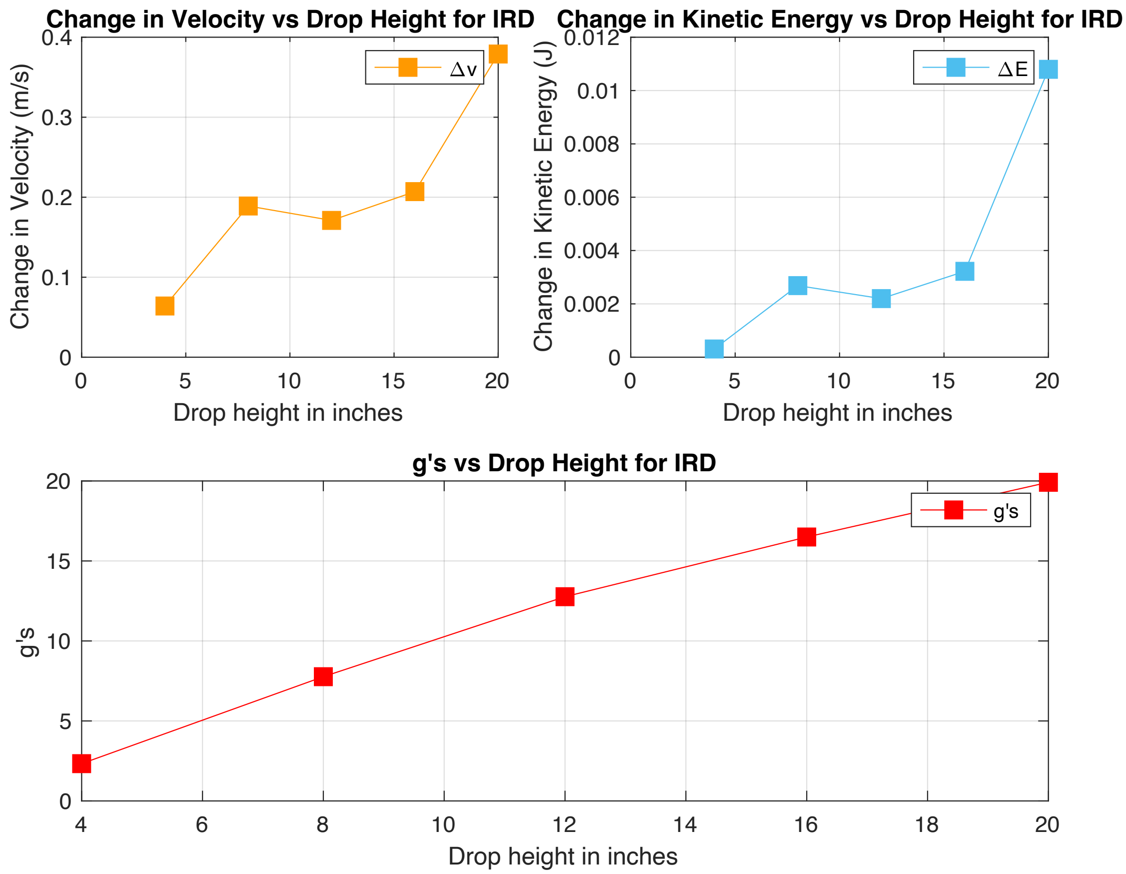

Figure 20: Initial Drop Tests for IRD.

The first graph (top left) shows the velocity change. This measurement comes directly from the IRD software. Velocity change will also be given directly by the ANSYS simulation. These points are our benchmark for the simulation. They will be directly compared to tune the simulation. The experiment was conducted a few times for the numbers to stabilize. Even though a lot of planning and preparation went into the experiments sometimes the peach would roll or would have a funny bounce, throwing off the final number. So once the 10 drops were all viewed as normal and consistent drops, those were the numbers used. The graphs all use the average numbers from Tables 4 and 5.

The second graph (top right) shows the change in energy, which will be helpful to determine the damage to the fruit. The velocity change is used to determine the energy change using equation 1. The energy change will be used to compare to the real fruit droppings. When both numbers are plotted, the trend of fruit damage can be correlated to real results, which will be the fruit droppings.

The last graph is the g's (gravitational force equivalent) the IRD experiences at the impact. The spikes observed by the IRD are plotted in the graph per the height at which the drop occurs. The plot shows a clear increase in the g's experienced by the fruit as the drop increases. This is expected because the fruit falls longer, and thus, the impact can cause more bruising on the fruit.

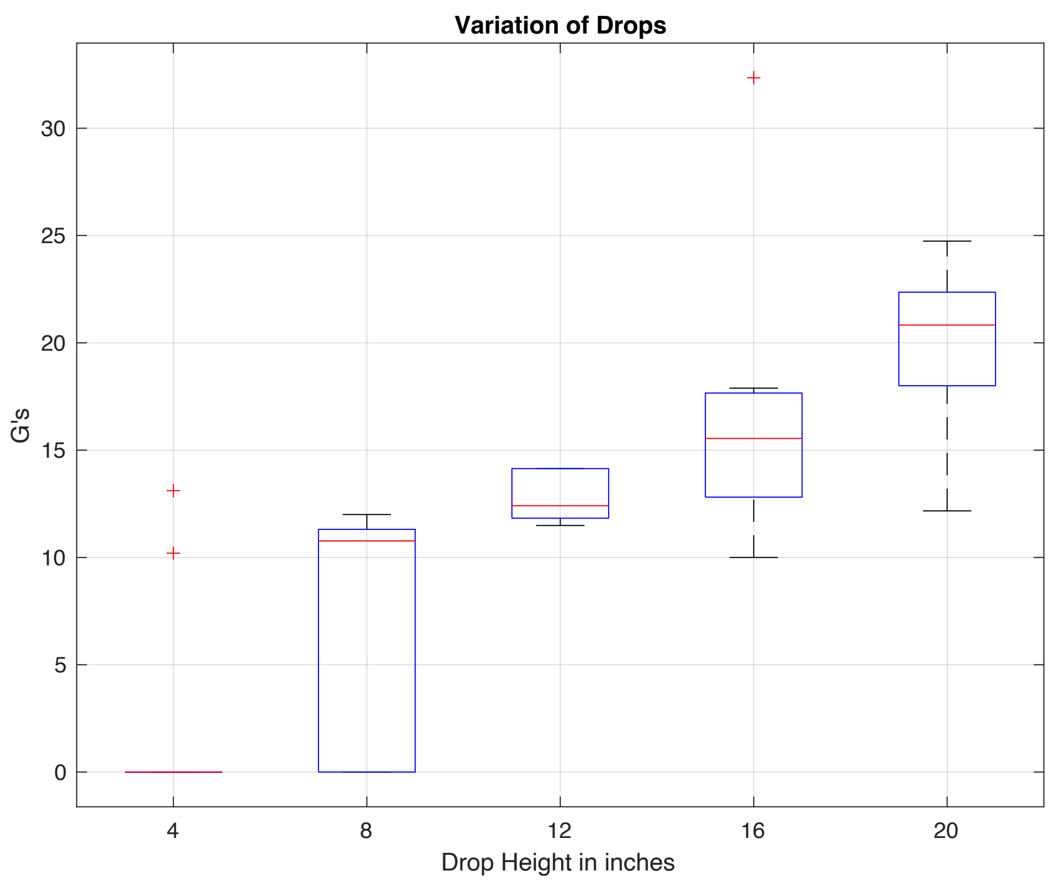

Figure 21: IRD box plot for g values

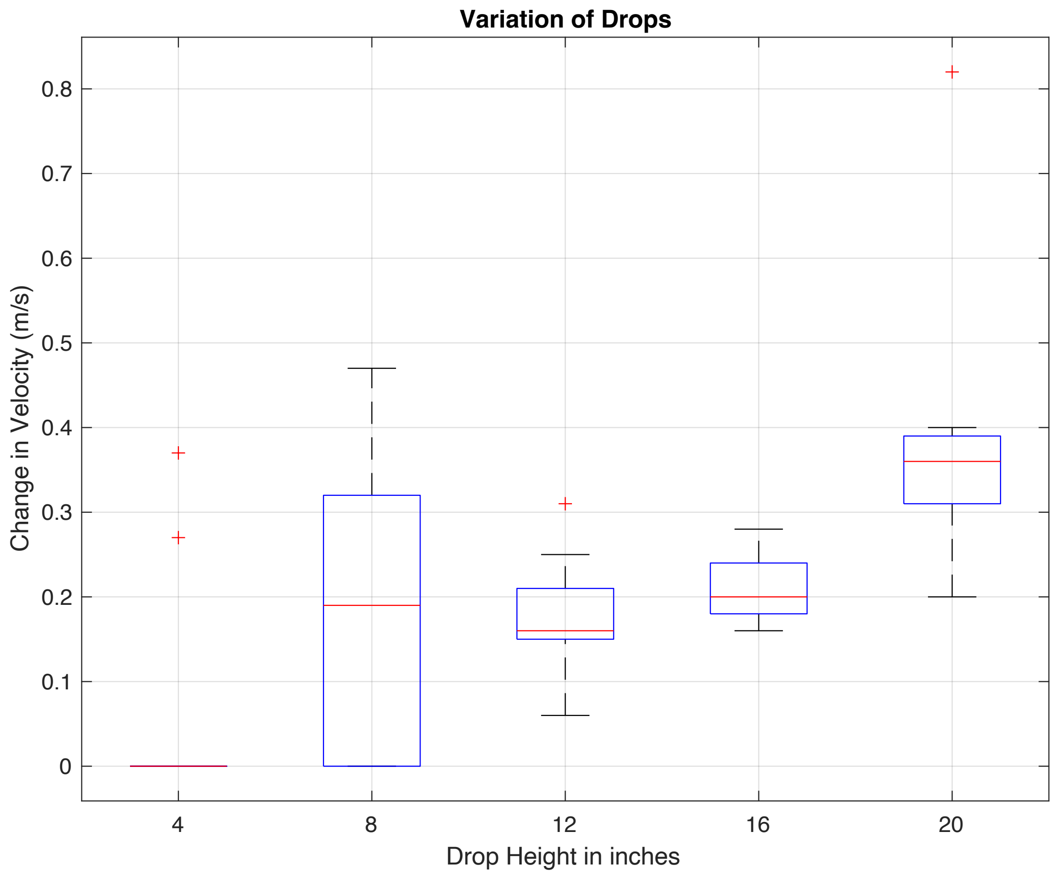

Figure 22: IRD box plot for velocity change

Figures 21 and 22 are box plots of the IRD data. They show the variation of the data collected from the IRD. As seen in both box plots, the IRD has a hard time registering the drops at 4 inches. Most of the data is read as zero's, but 2 points are shown as outliers in the plots. In the rest of the data there are a minimal number of outliers. The data is well condensed and shows a typical variation for drops. The drops were replicated many times, until the box plots were observed to have a consistent trend.

2. Fruit-Drop Experimental Results

Once the fruit was carefully collected from orchards in Yuba City, the fruit was taken back to UC Davis. The fruit was drop tested in the same way as the IRD was tested, at the same heights and location of the drops. Some peaches were slightly more ripe, to combat this each drop used the same amount of ripe and unripe peaches to get rid of the variance. The UC Davis Postharvest Lab then analyzed the fruit to check for bruising.

Figure 23: Peaches being examined for bruising.

	Average Inner Bruise (mm^2)	Average Depth (mm^2)
Control	350.00	4.50
Pickers Harvest	13.10	3.33
4' height	68.57	3.00
8' height	0.00	N/A
12' height	83.00	4.50
16' height	20.50	3.00
20' height	4.80	3.00

Table 7: Peach results

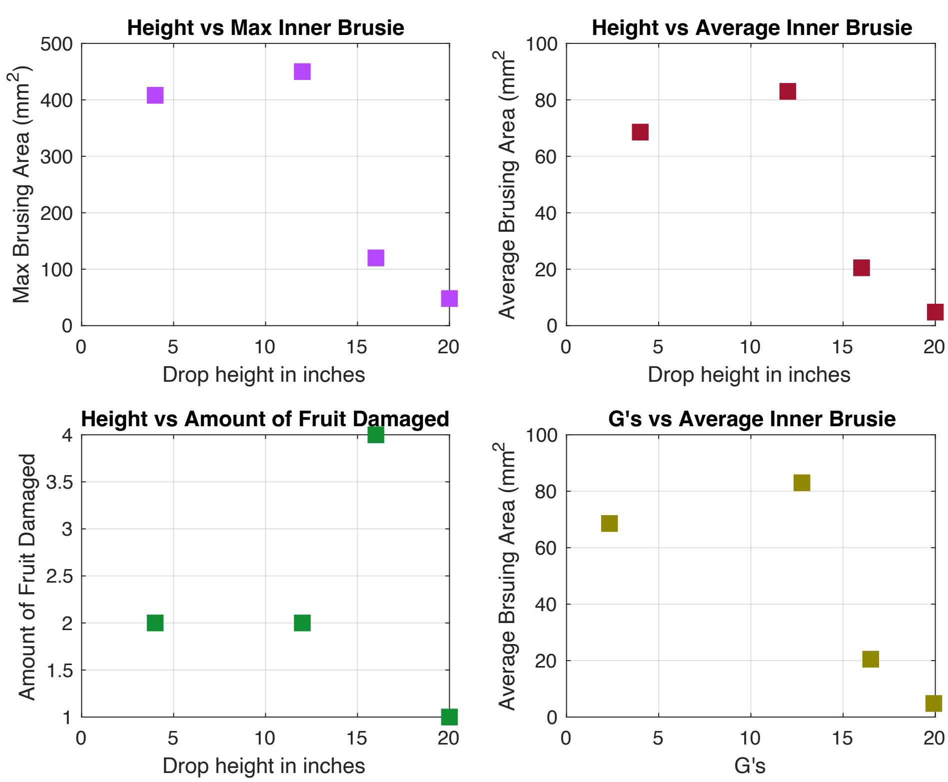

Figure 24: Results from the cling peach drop experiments.

The results from the peach drops are shown above. In the third graph for Figure 24 (bottom left) amount of fruit damaged refers to the actual amount of fruit damaged out of 10. Each height had 10 drops, so the higher the number, the more fruit that was damaged at that height. The peaches did not experience any outer bruises in any of the drops, which is good. The issue is that there was no clear indication of increased bruising at increasing height. As shown in the graphs, the bruise data was scattered. There was no bruising at the 8-inch drop (reason it was omitted), but there was some bruising at the 4-inch drop. Another interesting point is that the control fruits, which were never dropped and just harvested straight from the tree, had some bruising, possibly present before harvesting or caused during the transport to campus. It is encouraging that the results do not suggest that the arms are causing significant amounts of bruising as the drop height increased. The 8-inch drop height resulted in the lowest damage. The highest number of peaches bruised was at 16 inches. However, the bruises are not bigger in size compared to smaller drop heights. The upper right graph shows this. The 16 inch drop height has a lower average bruising size than for the 12 inch drop.

The results shown in the fourth graph (bottom right), "G's vs Average Inner Bruise," build a "connection" between the artificial and the real fruit drops. This graph shows bruising as a function of g's. The bruising should be increasing with a higher drop force, however it has the same scattered data as the other graphs, since there is no clear indication to an increase in bruising.

3. Simulation Results

The simulations were executed, and their results were compared to the results from the IRD drops.

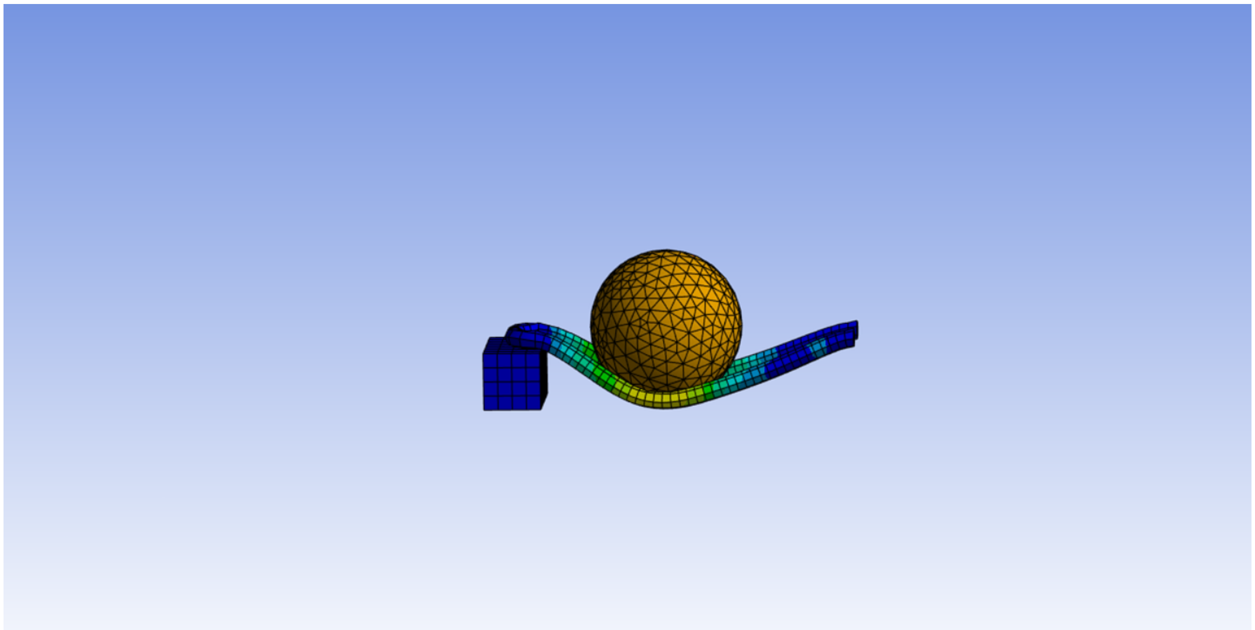

Figure 25: Velocity Change**.**

Height (in)	Velocity Change (m/s)	% Error IRD and Simulation
4	0.07	8.60
8	0.19	0.53
12	0.25	31.60
16	0.28	26.10
20	0.38	2.60

Table 8: Simulation velocity change.

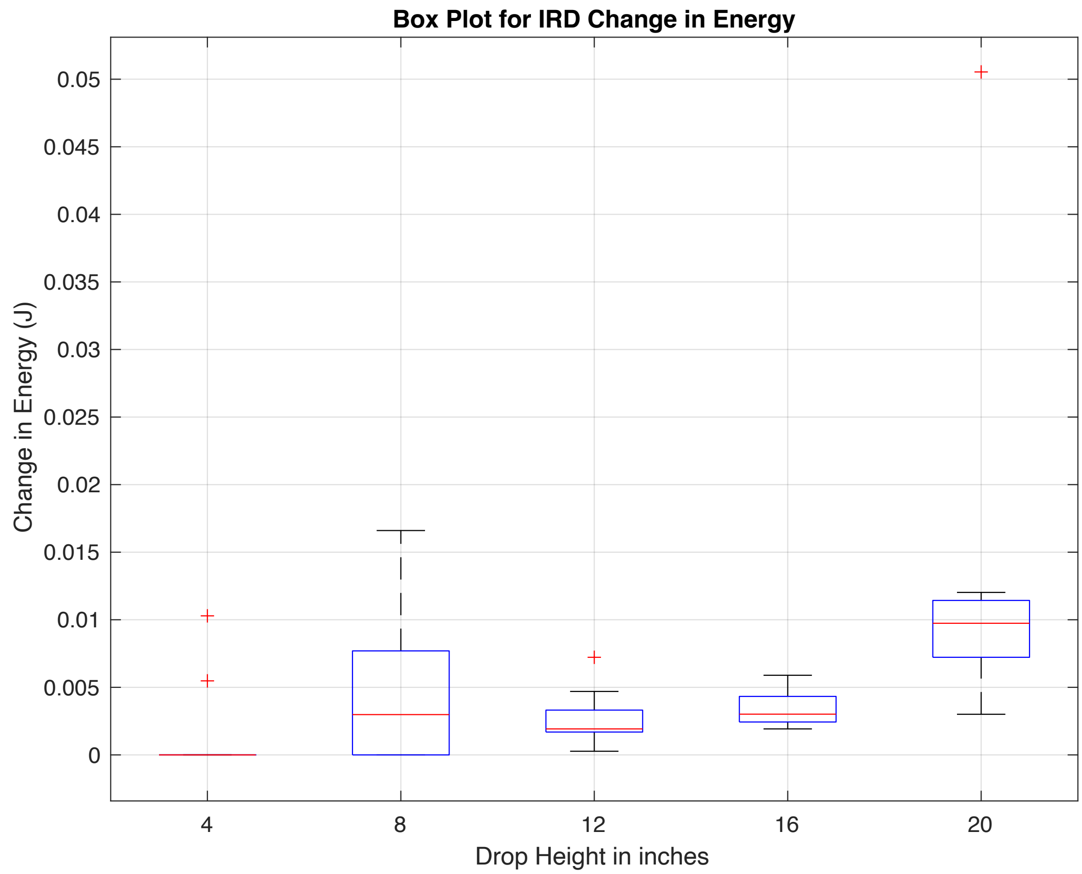

Figure 26: Box plot for IRD change in energy.

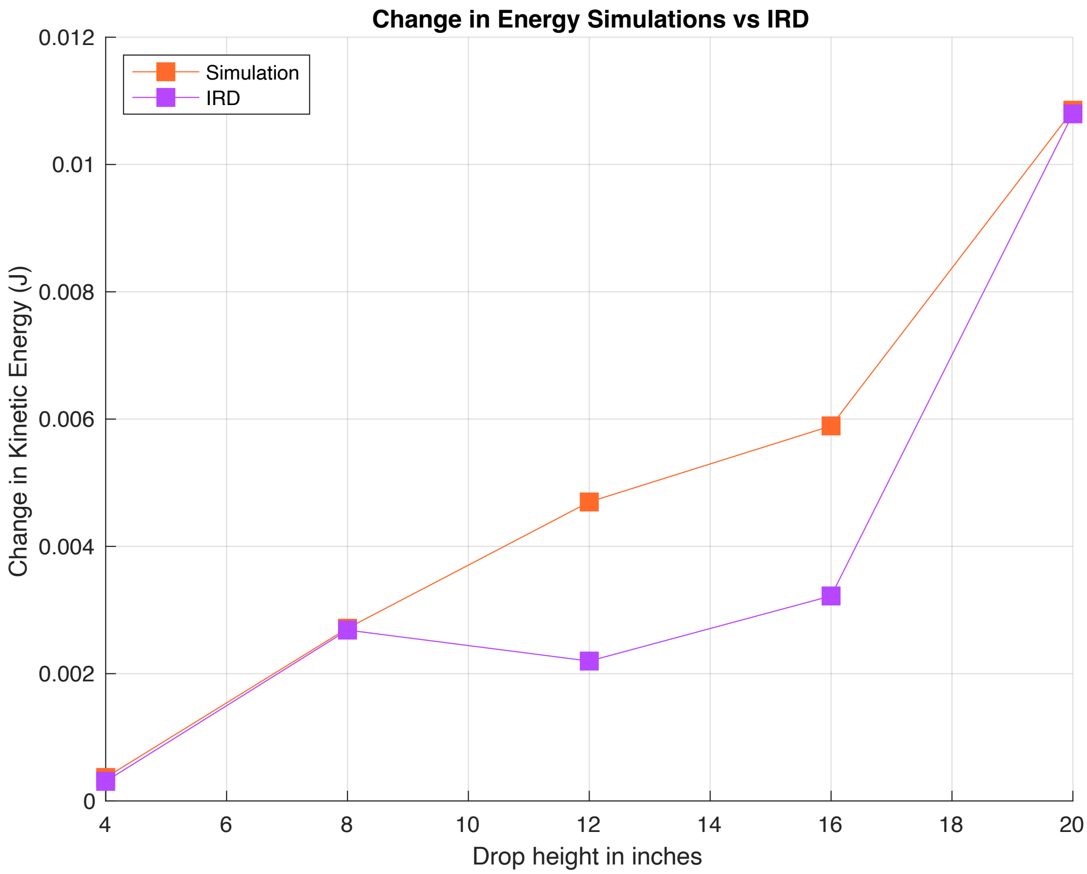

Figure 27: Change of energy from IRD and simulated drop experiments.

Table 8 shows the velocity change calculated by the simulations. The results are rounded to the closest hundredth. The probing action on ANSYS is used to find these numbers. The bottom part of the peach is the part that is inspected for the change in velocity. ANSYS gives the velocity at all points on the peach. The probing action in ANSYS allows a measurement reading at a specific spot. The peach lands at the landing zone, approximately the same distance from the end of the block that the IRD drops at, the probe is used to measure the velocity change the peach is experiencing during the drop. Figure 25 shows the different velocities at each point of the peach and the tubes, however it is difficult to read the numbers from just the color on the peach. Using the probe gives the specific measurement (velocity in this case) at any point on the peach. The reading is made right before and right after the impact, at the same point. The simulation is paused before the impact to make the first reading and then after the impact to make the second reading.

The comparisons between the simulation and the IRD is then shown in Figure 27. The numbers come from equation 1. Table 5 has the change in velocity for the IRD numbers, and the simulation numbers come from Table 8. The average error is 13.4% with a max error of 31.6% and a minimum error of 0.53%. Figure 26 shows the box plot for the change in energy recorded by the IRD. It shows that most of the data is very concentrated with only a few outliers. Figure 27, which uses the data from Figure 26 shows that the data is fairly accurate in comparison to the simulation data. The simulation was changed a few times in order to get these results. As previously mentioned the correct mesh sizing was found by decreasing the size of it until the results started to match up well to the IRD. Further decreasing the size of the mesh did not produce better results. The numbers start to deviate after about 8 inches. However, they continue to stay close to each other. The simulation line also follows the same trend line as the IRD, which is encouraging.

V. CONCLUSION

The simulation did end up matching the IRD. This was one of the principal objectives of this research. The velocity change ended up matching the results in most of the heights. The only part where the numbers do not match up exactly is at the middle heights. The simulation continues to follow an upward trend whereas the IRD drops tail off for the middle heights (12 and 16 inches). The simulation matches up closely to the IRD at the beginning and at the end. The IRD drops do not increase from 8 to 12 inches, the simulation does which is where the deviation starts to occur. However, the IRD then jumps at the 20 inch drop and matches up well with simulation. The ANSYS simulation perfectly replicates the drop each time with the height being the only change, and in the real world, this is not possible to replicate. The IRD also drops at one point each time, but different things affect the result, in other word it is not as repeatable as the simulation. It lands on another spot of the shell, or the hose might not react the same way as before, and all of these factors lead to a range of values instead of just one value, like in the simulation. In a perfect world the simulation would perfectly match with the average IRD values however this is just not possible. That is why a box plot of values is given for the IRD. The IRD is less consistent because it is not a computer iterating values each time, it is just an accelerometer with no control system so the values will vary. Many IRD tests were conducted, not to try to match to the simulation results but to deliver consistent numbers. The simulation was then tuned to get to as close as possible, however because the IRD does not always follow a direct path but instead is a free drop, the simulation slightly diverts from the IRD. The important thing is that the numbers follow the correct trend line and that the results of the simulation fall within the values of the IRD drops. The average error is 13.4 % and most of the error comes from the two middle heights.

The value of 0.25 (Table 8) shown in the simulation thus can be seen as one of the values were there is the most parity between the IRD and the simulation. However, as shown in Table 4 (12 inch results) this value is well within the range of the IRD values, and actually one of the drops is exactly 0.25, but it is on the high end as shown in the box plot Figure 22. The simulation is giving slightly higher values, however, the IRD and the simulation result for the 8 inch drop are pretty much the same number. The parity between the IRD and the simulation is negligible in these smaller drops, which is where most of the drops would occur in the real world. Each layer of the tree will receive a new layer of arms, so most of the drops will occur under 12 inches.

With these simulation results, researchers can move forward with this design. The simulation numbers are accurate to what the IRD is showing. Another positive note is that since the simulation matches the IRD results, the values of g's that the IRD is recording can be taken as real values. Even at a 20-inch drop, all of the g's are under 25 g's.

There has also not been much research on the damage various fruits - cling peaches are of interest in this thesis - can absorb before they start experiencing actual damage. A few articles have generated some data for other fruits. Tomatoes, for example, start experiencing damage at 35 g's Brecht (1992). So, the benchmark should be around there for the peaches. The peaches should be good after going through this harvesting method since they are harder than tomatoes and thus their bruising threshold should be higher.

The last result was to inspect the real peaches for damage. Since none of our peaches experienced that 35 g threshold, they should be fairly damage-free. And that is what the results show. There is no real correlation between the height at which the peaches were dropped and the damage to the peaches. However, this is a bit expected from the IRD and simulations. The velocity change is climbing the higher the drop is, but not by a huge amount that would be noticeable in a real fruit drop setting. The change in energy further demonstrates this, the IRD shows an almost flat line (Fig. 20**; top-right**), until the 20-inch drop in which a peak does occur. However, a 20 inch drop is not expected in a real world setting since most of the drops occur at around 12 inches. Since the IRD is not picking up a large change in energy, it is expected for the fruit to not have significant damage.

In Figure 24, we can see a bit of a spike at the 12-inch height (top left), and the amount of fruit damaged is at a max of 16 inches (bottom left). However, there is no consistent increase in damage, whether the average size of the bruise, the amount of peaches bruised, or the maximum size of the bruise. This can, however, be taken as a positive in that our harvesting system will not cause damage to the fruit. The control was the fruit with the highest bruises, even though it never went through the arms. The harvester, in other words, did not cause more bruising than what the fruit had already experienced in the picking and ripening process. This means that the harvesting system will not damage the fruit more than human picking. So not only is it more cost effective since you don't have to pay workers, but the fruit is picked with minimal damage compared to hand picking.

In future work, the tunning of the simulation can be improved. As talked about in the results section the numbers started to deviate from the IRD and the simulation. Although most of the error can be attributed to the IRD, the simulation can also be further improved. One possible way of improving it is to simplify the geometry. The entire CAD model was used in this simulation, however, simplifying the parts that are simulated might give better and faster results. The entire CAD needed to be modeled for this study to give a complete picture of the experiment. However, a possible improvement can come from simplifying the geometry and changing boundary conditions to keep the same scope of the study, while simplifying the geometry to see if the results change.

In a future study the peaches used in the experimental section can be further analyzed. The peaches gave wide results, and a possible improvement is to be more careful about the way the peaches were transported to the lab and the freshness of them. The peaches that were harvested were all picked from similar trees but some were slightly more mature than others. The trip to campus was driven very carefully to not bruise them, but we ran out of bubble wrap so it is possible that some of the more mature peaches, those that were riper, could have been damaged internally on the trip back without us noticing. The peaches were all bruise free from the outside. Internal damage cannot be observed until they were opened. It is possible that some of the peaches used in the experiment were already damaged internally. A way to improve this is to wrap each peach individually in newspaper instead of covering them in bubble wrap. This would have been the best way to transport them, however we are not sure if the trip damaged them, but it would be a good way to remove a possible variable of bruising.

VI. References

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